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REGIONAL WOOD ENERGY DEVELOPMENT PROGRAMME IN ASIA
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IMPROVED SOLID BIOMASS BURNING COOKSTOVES:

A DEVELOPMENT MANUAL

In Collaboration With

Asia Regional Cookstove Programme
and
Energy Research Centre of Panjab University, Chandigarh

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FOREWORD

For more than 15 years development organizations, research institutes and hundreds of volunteers and specialists have been engaged in the development, testing and dissemination of improved cookstoves throughout the developing world of Asia, Africa and Latin America. Conceived as a major way to combat deforestation, increased efficiency of domestic cooking stoves was the major focus of researchers and high targets of dissemination the concern of forest officials. Unfortunately, not all programmes lived up to the expectations raised, a major reason being the lack of adequate attention to social, economic and institutional issues related to introducing improved cookstoves. Based on the earlier experiences a new approach has been adopted in many countries in which improved cookstoves are more integrated into the overall objectives of rural and urban development. This is reflected in the broad range of sectors becoming involved in ICS introduction, e.g. energy, forestry and health sectors, women in development and rural development.

On the scientific side, considerable progress has been made with matching scientific theories of efficient combustion with the needs of easy installation, use and maintenance. Many reviews and assessments of ICS programmes have also contributed to a better understanding of the key factors in their success. As a result of all these efforts there are now thousands of publications and articles on improved cookstoves. This large amount of information has been useful for ICS experts, but not always for field staff, who need a comprehensive and informative document that covers all major issues of ICS introduction.

The Regional Wood Energy Development Programme in Asia (RWEDP) from its very beginning in 1985 has given much attention and resources to the introduction of ICSs in its member countries. Several workshops and seminars on various aspects of ICSs have been organized and recently three documents on national ICSs have been published for China, India and Thailand.

During this period it has become quite clear that a key factor in the success of ICS introduction is the commitment and knowledge of field staff. Often these field staff lack basic information on ICS development and dissemination. The present manual provides them an insight into the complexity and the potential of ICS introduction. It has been written in such a way that it introduces the field worker to ICSs within a relatively short period. It is hoped that young scientists and students of wood energy conversion will equally benefit from the manual.

The author of this manual, Prof. S.K. Sharma, Director of the Energy Research Centre and Honorary Dean of the Chemical Engineering College of Punjab University has taken up the challenge of bringing together all relevant information on ICSs in a concise and comprehensive way. RWEDP wishes to express its deep appreciation for his contribution to ICS development and his tenacity in the preparation of this manual.

Dr. Aroon Choincharn, Wood Energy Conversion Specialist of RWEDP provided the development framework for the manual and technical support throughout the process of its preparation. Mr. Auke Koopmans of Green Fields, Thailand, and Harry Oosterveen of RWEDP assisted with reviewing and editing and Ms. Maria Nystr6m of the Lund Committee on Habitat Studies provided highly useful comments and information for chapter 7, "The kitchen: An integral part of the cooking system". Typing and text layout were done by Ms. Panpicha Issavasopon and Ms. Navaporn Liangcheevasonthon of RWEDP. I thank them all for their commitment and for the high quality of the support provided.

The financial contribution and technical comments from the Asia Regional Cookstoves Programme (ARECOP) are also gratefully acknowledged.

We hope that the present development manual will stimulate interaction between the many ICS field workers and scientists from Asia and elsewhere. Their comments, advice and/or additional contributions may become valuable inputs for a revised version which we intend to publish in due course.

Egbert Pelinck
Chief Technical Adviser

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LIST OF SYMBOLS

A	area size	m^2
[a]	ash content	-
c_p	specific heat	J/kg-K
[c]	carbon content	-
d	diameter	m
F	view factor	-
f	friction factor	-
Gr	Grashoff number	-
g	constant of gravity	m/S^2
H_f	combustion/calorific value	J/kg
H_L	latent heat of evaporation	J/kg
H_c	chemical heat	J/kg
H	head in	m
h	height	m
h	heat transfer coefficient	W/m^2K
[h]	hydrogen content	-
k	thermal conductivity	W/m -K
m	mass	kg
[m]	moisture content	-
n	amount of material	mol
Nu	Nusselt number	-
[o]	oxygen content	-
P	power	W
Pr	Prandtl number	-
p	pressure	kg/m^2
Q	energy, heat	J
q	heat flux/transfer rate	W
r	radial distance, radius	m
s	thickness	m
Re	Reynolds number	-
t	time	s
T	temperature	K
V	volume	m^3
V	volume flow	m^3/s
v	velocity	m/s

Greek symbols

α	thermal diffusivity	m^2/s
α	resistance coefficient	-
β	thermal expansion coefficient	l/K
Δ..	difference	-
ϵ	emissivity	-
λ	excess air factor	-
η	efficiency	%
ρ	density	kg/m^3
σ	Stephan-Boltzmann constant	W/m^2K
ξ	power density	kW/m^2
ν	volatile fraction	-
ν	kinematic viscosity (p/p)	m^2/s
μ	viscosity	kg/ms
Φ	volume of stoichiometric air	m^3/kg

Indices

a	ambient
av	average
b	boiling
c	charcoal
cc	combustion chamber
ch	chimney
des	design
e	end
va	evaporation
f	fuel
fb	fuelbed
fl	flame
fo	food
g	gas
i	initial
od	oven dry
p	pot
rad	radiation
res	resistance
s	simmering
w	water

1 INTRODUCTION

1.1 Development Background

In the past, traditional sources of energy such as fuelwood, charcoal, dung, etc. were the only sources of energy used for all types of applications. It is only during the last 250 years that fossil fuels such as coal, oil and gas and electricity have emerged as major sources of energy in most developed countries. However, nearly 75% of the world's population which lives in the developing countries continues to depend on the traditional sources of energy for most of their energy requirements. This is also evident from table 1.1 which shows that in some Asian countries the traditional sources of energy accounted for about 60-90% of the total amount of energy consumed.

In particular, the domestic sector relies heavily on traditional sources of energy, mainly for cooking, for which traditional stoves are often used. These stoves are usually thermally as well as environmentally inefficient and hence create drudgery and problems for the users. Field evidence from many countries in Asia, Africa and Latin America shows that the introduction of improved cookstoves (ICSs) has brought considerable benefits to rural and poor urban households (Foley and Moss 1983, Foley et al 1984, FAO/RWEDP 1991, Ramakrishna 1991, Barnes et al 1992, etc.).

Table 1.1 Sectoral energy consumption as a % of total for some Asian countries

Country	Commercial energy		Fuelwood and/or charcoal		Residues, dung, etc.		Total traditional energy sources			Year and source
	Domestic	Others	Dom.	Oth.	Dom.	Oth.	Dom.	Oth.	Tot.	
Bangladesh	3.8	9.8	11.7	3.4	57.6	13.7	69.3	17.1	86.4	1981/BEPP, 1987
Bhutan	1.5	11.3	75.1	11.8	0.6	0.0	75.7	11.8	87.2	1988/FAO, 1991a
India	---	---	---	---	---	---	---	---	39.1	89/90 Est. 5)
Indonesia	12.6	33.1	50.9	3.5	---	---	---	---	54.3	1979/WB 1980 3)
Myanmar	0.6	12.0	84.1	---	2.5	0.8	86.6	0.8	87.4	1990/WB 1990a
Nepal	1.2	4.4	92.8	1.5	0.0	---	92.8	1.5	94.4	1982/WB 1983a
Pakistan	7.1	40.1	41.2	11.6	1)	1)	41.2	11.6	52.8	1991/Ouerghi'92
Philippines	10.1	44.8	32.6	5.3	3.5	3.6	36.1	8.9	45.1	1989/WB 1992b
Sri Lanka	6.6	21.6	59.0	10.3	2)	2.3	59.0	12.6	71.8	1990/CEB 1990
Thailand	8.8	60.9	18.9	2.4	1.2	7.6	20.1	10.0	30.3	1988/NEA 4)
Vietnam	2.0	24.0	29.6	4.4	34.7	5.2	64.3	9.6	73.9	1988/FAO 1992a

Note: *"Others" includes Industry, Transport, Agriculture, Commerce, Government as well as Other uses. Conversion losses have not been accounted for. -- denotes "No data available" while 0.0 denotes "Negligible amount"*

1) *Residues are included under fuelwood*
2) *Domestic fuelwood consumption apparently includes residues also*
3) *The Domestic sector includes Government use as well as use by Commerce*
4) *The Domestic use includes use by Commerce as well*
5) *Estimate, based on WRI/UN data for commercial energy and unofficial World Bank data for traditional sources of energy.*

1.2 Development Approach

While recognizing that fuelwood saving and energy conservation are universally accepted as important issues, these rarely are the sole reason for users to start using an ICS. In fact, it is increasingly recognized that the introduction of ICSs has done little, if anything, to arrest deforestation and/or environmental degradation as these problems are much more complex and, as such, can not be solved simply by the introduction of an ICS. Nevertheless, due to the multiple social benefits ICSs bring to the users, mainly women, many countries have decided to start and/or continue to pursue improved cookstove programmes (ICPs). These benefits of ICSs include:

- Saving of fuels and, directly or indirectly, saving of time due to the stoves' higher thermal efficiency. Cooking can often be done faster while the saving of fuel implies that less time is required to acquire it and/or money spent to purchase it. For example, it has been estimated that in Nepal nearly 200-300 person days (mainly women and children) per year per household are spent in the collection of wood (Singh et al 1984). With the use of an ICS, this period can be substantially reduced and the time saved can be used productively for other purposes.

- More complete combustion and/or the use of a chimney results in less smoke and soot emitted from the fire which, in turn, makes the kitchen a healthier place in which to work. Smoke emitted from biomass combustion causes serious indoor pollution, which affects the health of the cooks, most of whom are women and children. It has been estimated that the concentration of some of the pollutants, emitted due to the combustion of biomass, may exceed 10-100 times the WHO limits (Smith 1986). Exposure to smoke has emerged as one of the major concerns in the rural areas of the developing countries (WHO 1992). With more complete combustion less soot is developed and the cooking pots remain cleaner and, as a result, less time is needed to clean the pots.

- Additional benefits of ICSs include a reduction in safety hazards such as less exposure to heat resulting in a better work environment, better hygiene due to availability of hot water for washing, protection from burn injuries and fire, etc.

Besides the direct and indirect benefits for the users, there are also socio-economic benefits such as providing job opportunities through the production, sale and maintenance of ICSs, etc. Thus it can be concluded that ICSs can make a significant contribution in rural development provided that efficient and durable stoves can be introduced which fulfil all, or most, of the requirements of the users and ultimately bring with them improved standards of cooking and living for the majority of the people.

Studies have shown that the users of ICSs are also concerned about other important features of cookstoves such as: low fuel consumption and emissions, low cost, quick cooking, convenience of operation and maintenance, flexibility to use existing kitchen utensils, fuel and cooking practices, ease of propagation of fire and control of heat without much supervision and safety of operation. Even though cooking is the major requirement of the user, there are other important applications of ICSs such as space heating, smoking food items and agriproduce to preserve them, and water heating both in the household sector as well as in the small scale industrial sector like agro-industries, *gur* and *khandsari* establishments, etc. Hence, it is imperative that a unified design-development approach is used in the development of efficient fuel combustion systems taking social, cultural, scientific, economic, ergonomic, and health aspects into consideration.

1.3 Objectives of the Present Study

A vast amount of literature has appeared in the last 15 to 20 years, covering almost all aspects of stove development, especially in the areas of hardware development and technologies (e.g. design, testing, stove material, stove production techniques, etc.). Unfortunately, much of it is widely scattered and it is difficult to get a good overview of the status of technological advancement in the stove field. This has lead to duplication of efforts and lack of coverage for certain subjects. In some cases, stove technology has become an academic and highly technical subject, far beyond the understanding of the common research worker. Conversely, many stove promoters consider an ICSs to be a very low level intermediate technology and hence often introduce crude stove products to the people for use.

It is, therefore, considered that a concise but simplified treatise on scientific knowledge relating to biofuel cookstove technologies, which could facilitate the work of a large number of junior and middle level stove researchers, is sorely needed. This manual is an attempt to address such a need and endeavours to provide a challenge to stove experts to improve on the technological developments explored herein.

2 HISTORICAL REVIEW OF COOKSTOVE DEVELOPMENT

2.1 Early History

Evidence, found from archaeological excavations at Chou Kutien in China, indicated that the Peking man (*Homo erectus pekingnensis*), who lived in caves some 400,000 years ago during the first ice age, knew how to use fire (Bronowski 1973). At that time, fire was presumably used mainly for warmth rather than for cooking. The application of fire to cook food became apparent some 100,000 years ago, in the early part of the Upper Palaeolithic Period. During that period, the aim of cooking perhaps was to render food into a more digestible form. The making and use of refined stone implements and the mastery of fire can be considered important steps towards human civilization which took off only about 12,000 years ago, when man had begun domestication of some animals and cultivation of plants (Bronowski 1973). With the passage of time, human tastes gradually developed and later became sophisticated with many gastronomic innovations, the use of a wide range of food materials as well as cooking techniques.

During the earlier ages, cooking was presumably done over an *open-fire* with fuel arranged in a pyramid configuration. This mode of cooking, primarily for roasting meat, had major drawbacks: dispersion of the flames and heat during windy conditions, a lack of proper control over the fire, exposure to heat and smoke as well as fire hazards. However, at the same time, heat and smoke had also certain benefits such as food preservation and/or protection against large animals, insects/rodents and providing warmth during the cold seasons.

A major step towards the evolution of other cookstoves was the development of pots of various shapes and sizes. This necessitated the modification of the open-fire to create *shielded-fires* in order to balance the pot over the fire. The simplest form of the shielded-fire was a three-stone arrangement in which stones were arranged at approximately 120 degrees to one another on level ground. Besides, allowing a cooking pot to rest firmly on it, this arrangement also partly saved the fire from the vagaries of wind and slightly increased cooking efficiency. However, by and large, the three-stone fire still suffered similar drawbacks as the open-fire.

Subsequently, the shielded-fire was changed to a U-shaped mud or mud/stone enclosure with an opening in the front for fuel feeding and combustion air entry. Three small humps (made of the same mud material) were positioned at the top rim of the enclosure and acted as a pot rest, induction point of secondary air needed for better combustion of volatile matter and for the exhaust gas exit. In order to conserve heat from the hot flue gases and to enhance cooking productivity, additional pot holes were later added. These pot-hole enclosures were connected by a tunnel. All the above mentioned innovations in the cookstove design were made mainly by the users in light of their own experiences. These innovations did increase the efficiency of the stoves to some extent, but health and other hazards remained.

Despite human evolution and the developments which have taken place in stoves and fuel, it is amazing, however, to observe that currently most of the estimated 75% of the people who live in the developing world, are still largely employing the three-stone or the shielded-fire for cooking and using traditional sources of energy such as fuelwood and other biomass similar to their pre-historic ancestors several thousand years ago. In many cases people have actually moved backward to the use of agricultural residues and dung for fuel.

2.2 The Recent Past

In the early 1950's in India the first phase of ICS development started with technological attempts to improve the design of biomass-fired stoves. Because of the appalling smoky working environment of many Indian kitchens in which women had to cook, improved multi-pot stoves were introduced (Raju 1953). These stoves, which were of the high-mass and shielded-fire type, had a chimney to remove smoke from the kitchen and had adjustable metal dampers to regulate the fire. Theodorovic (1954) was the first to conduct controlled laboratory tests on biomass burning ICSs in Egypt, although he did not measure the thermal efficiency of the stoves. Systematic studies on measuring cookstove efficiency was conducted by Singer (1961) in Indonesia on a high-mass mud stove with similar design features to those introduced by Raju.

The oil crisis of the 1970's brought energy issues to the forefront once again and improved cookstove programmes (ICPs) were considered as a solution to the fuelwood crisis as well as a means to arrest deforestation and/or desertification. During this second phase of ICS development, extensive research and development studies were undertaken and a more sound technical base was laid as a result of detailed thermodynamic, heat transfer and aerodynamic studies. More systematic testing and design procedures were gradually established. However, the major thrust was on fuel saving while the socio-economic and cultural aspects of cooking were largely missing. A large number of biomass burning improved cookstove (ICS) models began to proliferate, especially from the laboratories in many developing and developed countries. For roughly 10 years, during the early 70's and 80's, various international donors had a very strong influence on improved cookstove development promotion and assistance all over the world, particularly in Asia, Africa and Latin America. Unfortunately, the impact of these aid programmes proved to be short lived. This was basically due to the inability of the programmes to meet the expectations and actual requirements of the users, a lack of long term development objectives, systematic institutional arrangements and appropriate local manpower development. Many ICPs could not sustain themselves and as soon as the government/donor funding stopped, the programmes ceased to operate. Those programmes that survived, however, managed to get local government commitments for long term support.

During the third phase, which began as recently as the late 80's, the emphasis shifted towards the needs of stove users based on lessons learned from the second phase. It was found that, in addition to the above mentioned criteria, factors such as cooking comfort, smoke free kitchens, convenience and safety in the use of the stove were considered by the users to be as important as fuel saving.

2.3 The Present

A recent global survey (Ramakrishna 1991) conducted by the Energy and Policy Institute of the East-West Center, Hawaii, for the Energy Sector Management Assistance Programme (ESMAP) of the World Bank has shown that the goals for improved cookstove programmes, as shown in table 2.1, have substantially expanded and are now rather diverse. The results show that there appears to be a distinct pattern of prioritizing ICP objectives in different geographical regions. For example, the greatest importance (83% of ICS programmes) was placed on smoke reduction in Southeast Asian countries while this had a lower priority in Latin America (56% of the ICS programmes). Increased fuel efficiency was rated very high in all four regions but very low in Latin America. On the contrary, an increase in the welfare of the poor and improvements in the status of women were ranked highest in Latin America. The results of this survey provide an interesting overview of the activities of ICPs in different parts of the world. One of the significant findings was that apart from the benefit of fuel and money savings, other benefits such as smoke reduction, time saving, safety in the kitchen, income generation, improved status of women, increased environmental awareness, etc. have also been included as programme objectives.

Table 2.1 Survey of importance of objectives for various ICS programmes (%)

Objective	Latin America	West Africa	East/Central Africa	South Asia	Southeast Asia	TOTAL
	n = 16	n = 18	n = 48	n = 26	n = 12	n = 120
Increase fuel efficiency	44%	72%	79%	65%	75%	70%
Reduce smoke emissions	56	67	67	65	83	67
Reduce deforestation	56	83	50	46	42	54
Save money	37	56	67	23	42	49
Improve status of women	56	11	31	42	17	33
Increase welfare of the poor	69	17	27	23	25	30
Save time	25	44	29	27	25	30
Safety	44	11	29	27	8	26
Increase environmental awareness	25	39	23	19	17	24
Generate income	6	0	31	23	33	22
Save fuel in community	31	11	12	23	25	19
Skill development	37	6	14	15	17	17
Create jobs	6	0	25	15	25	17
Community and institutional development	37	neg.	10	27	25	16
Prevent soil degradation	19	17	12	19	8	15
Others	19	6	2	12	8	8

Note: *The table shows the frequency with which the objectives were ranked "1" on a scale where 1 = Very important, 2 = Important, 3 = Less important, 4 = Not important and 5 = No opinion.*

Source: *Ramakrishna, 1991*

The regional expert consultation on ICS development held in Udaipur, India (FAO/RWEDP 1991), where the status of South Asian ICS programmes was reviewed, common problems and constraints identified and strategies and future directions discussed, resulted in four comprehensive sets of conclusions and recommendations on issues related to: research and development, programme management, policy and institutions, and involvement of women. The general consensus of the meeting was that: "Future ICP programmes should follow a wider *systems approach*. Programmes should look at not only the introduction of ICSs but also at improved kitchens, cooking practices, utensils and fuels." In addition, the role of improved stoves in reducing harmful emissions and greenhouse gases through cleaner combustion was also highlighted. In short the major concern, in the modern context, has been focused on indoor air quality, the linkage between the functionality of stoves and kitchens, and the elimination of cooking drudgery as well as the method of dissemination.

3 PRINCIPLES OF IMPROVED COOKSTOVE DESIGN AND DEVELOPMENT

3.1 Definitions

In order to ensure a clear understanding of the information presented in this chapter, the definitions of some important terms that will be used in relation to the improved cookstove design and its principles are explained below.

The *improved cookstove* or *ICS*, in this context pertains to the solid biomass fuel burning system in which heat is produced, by combustion, for immediate use in domestic cooking. As will be discussed in the next section, ICSs can also perform other tasks, depending on the design purpose arising from the user's needs. Such a stove may perhaps be termed an *improved stove (IS)* which can be used for numerous applications, namely: cooking, food preservation/drying, domestic heating and other social and cultural activities.

Biomass fuel denotes solid biomass either in a raw or processed form. This includes fuelwood, charcoal, agri-residues, briquettes, etc. While fuelwood is generally preferred in domestic cooking, residue fuels in sticks, leaves, straw and granular forms are also increasingly used due to fuelwood scarcity. As will be discussed shortly in sections 4.1 and 4.2, each type of biomass fuel has different properties and burning characteristics.

Combustion is the process through which the fuel and air chemically interact at sustainable elevated temperatures. The combustion process is dependent on the physico-chemical properties of the fuel, quantity and mode of air supply, and the conditions of the surroundings. All these parameters are discussed in sections 3.5.1, 4.3, 4-4. and 5.1.

Heat transfer is the process by which the heat generated from combustion is transferred (or purposefully targeted) at a heat absorbing surface. However, it is only possible to transfer a part of the heat released on combustion to the food in the cooking vessel, while the rest is dissipated to the surroundings by different mechanisms of heat transfer, namely: conduction, convection, and radiation. In a normal cookstove design, the losses to the surroundings are suppressed and the transfer of heat to the contents of the pot is maximized. A detailed discussion is presented in section 3.5.2.

Fluid flow is the movement mechanism of fluid, like air, gases and vapours, through a medium under normal or artificial pressure. Knowledge of fluid flow principles is essential for understanding the flow of air and flue gases through the stove, flow passages, and chimney. The application of fluid flow principles are required to understand the combustion process, convective heat transfer and the chimney draft mechanism.

Knowledge of material science plays an important role in the selection of materials for stove construction. Properties of materials have an important bearing on durability, cost, method of construction, heat losses, safety, and the scale of the production system. Material issues are discussed in sections 3.5.4, 5.4, and 5.5.

3.2 ICS Design Perspective

The thermal performance of an ICS depends upon the efficiency of the heat conversion system, e.g. conversion of chemical energy of fuels into thermal energy. It also depends upon the efficiency with which the thermal energy produced is transferred to the delivery systems, especially the cooking vessel and its eventual transfer to the food being cooked.

Thus, an ICS designer should have a complete understanding of the complex interaction between the different processes that take place in a cookstove, e.g. combustion, heat transfer and fluid flow. Some of these parameters are controllable while others are non-controllable and a stove designer should be well aware of these factors. Figure 3.1 provides a conceptual process consideration for an ICS design. A designer should not look at the stove as an isolated device but should visualize it as a part of the broader “kitchen system”. The design of a cookstove, therefore, should aim at enhancing the overall productivity of the kitchen system, taking into consideration health, safety, sanitation as well as energy efficiency. Indoor air pollution is becoming a major global concern and the health and kitchen aspects of this, related to ICSs, are discussed in more detail in chapters 6 and 7.

```
                                                          +))‣NATURAL
                                      +)‣CONVECTION)))))))1
                                      *                   .))‣FORCED
                  +)‣HEAT TRANSFER))))3)‣CONDUCTION
                  *                   .)‣RADIATION
                  *
                  *                   +)‣LAMINAR
                  /)‣FLUID FLOW)))))))1
                  *                   .)‣TURBULENT
                  *
PROCESS)))))))))))1                   +)‣MASS TRANSFER
CONSIDERATIONS    *                   /)‣HEAT TRANSFER
                  /)‣COMBUSTION)))))))1
                  *                   7)‣THERMODYNAMICS
                  *                   .)‣KINETICS
                  *
                  *                   +)‣THERMAL PROPERTIES
                  .)‣MATERIAL SCIENCE)3)‣CHEMICAL PROPERTIES
```

Figure 3.1 Processes in stove design

3.3 Stove Classification

A large number of ICS models, based on different construction materials, fuel and end use applications, have been developed during the last 10-15 years. A proper ICS classification is essential for identifying a model suitable for a particular group of user, target area, method of production and dissemination, keeping in view the cooking requirements and the availability of construction materials and fuels. Accordingly, ICSs can be classified into various categories:

a) Function

Mono-function stoves. An ICS which performs primarily one function, such as cooking or any other single special function such as fish smoking, baking, roasting, milk simmering, etc.

Multi-function stoves. In many areas, apart from cooking, an ICS can also be used for other purposes or in combination, such as for water heating, room heating, fish/meat smoking, grain/flour roasting, simmering of milk, etc.

b) Construction material

ICSs are mainly made of single materials: metal, clay, fired-clay or ceramics and bricks or are hybrids in which more than one material is used for different important components. Classification based on the material helps in selecting an appropriate design on the basis of locally available raw materials, skills for fabrication and necessary production facilities (e.g. centralized/decentralized) in the target area. The cost of an ICS and its expected service life can also be reflected in this classification, including its portability.

c) Portability

On this basis, an ICS can be classified as *fixed* or *portable*. Metal and ceramic ICSs are normally portable in nature and can be moved indoors or outdoors while clay/brick, clay/stone ICSs are generally high mass and thus are fixed. Stoves in this category can be further sub-divided into different categories depending on the number of pot holes, e.g., single, double and triple.

d) Fuel type

The performance of different ICSs, having the same function and constructed with the same materials, will ultimately depend on the type of fuel used. In some cases, an ICS may be rendered practically inoperable when switching over to fuel types for which it was not constructed. For example, an ICS primarily designed for fuelwood would not perform at all with rice husks or sawdust. Similarly, an efficient charcoal ICS may perform very poorly with fuelwood or agri-residues. Four major types of ICSs, based on fuel classification, normally encountered are: charcoal ICSs, fuelwood ICSs, granular/loose agri-residue ICSs, stick-form agri-residue ICSs, cow dung cake ICSs, and briquetted biomass-fuel ICSs.

From the discussion above, it can be seen that the classification provides critical information on a number of ICS design issues such as end use applications, technology and its transfer, cost, durability, fuel compatibility, etc.

3.4 Design Criteria

A cookstove is best considered as a consumer-specific device. Both engineering and non-engineering parameters need to be taken into consideration in designing an appropriate ICS. This makes the exercise much more complex when compared with the design of other types of engineering equipment or of a kerosene burning stove. ICS design considerations can be classified into three major criteria, namely: social, engineering, and developmental & ecological. Interlinkages between these parameters, as presented by Verhaart (1983a), are shown in figure 3.2.

Most of the designers, particularly in the first phase of ICS development (1950-1970), as mentioned in section 2.2 tended to use the social approach and designs of improved features such

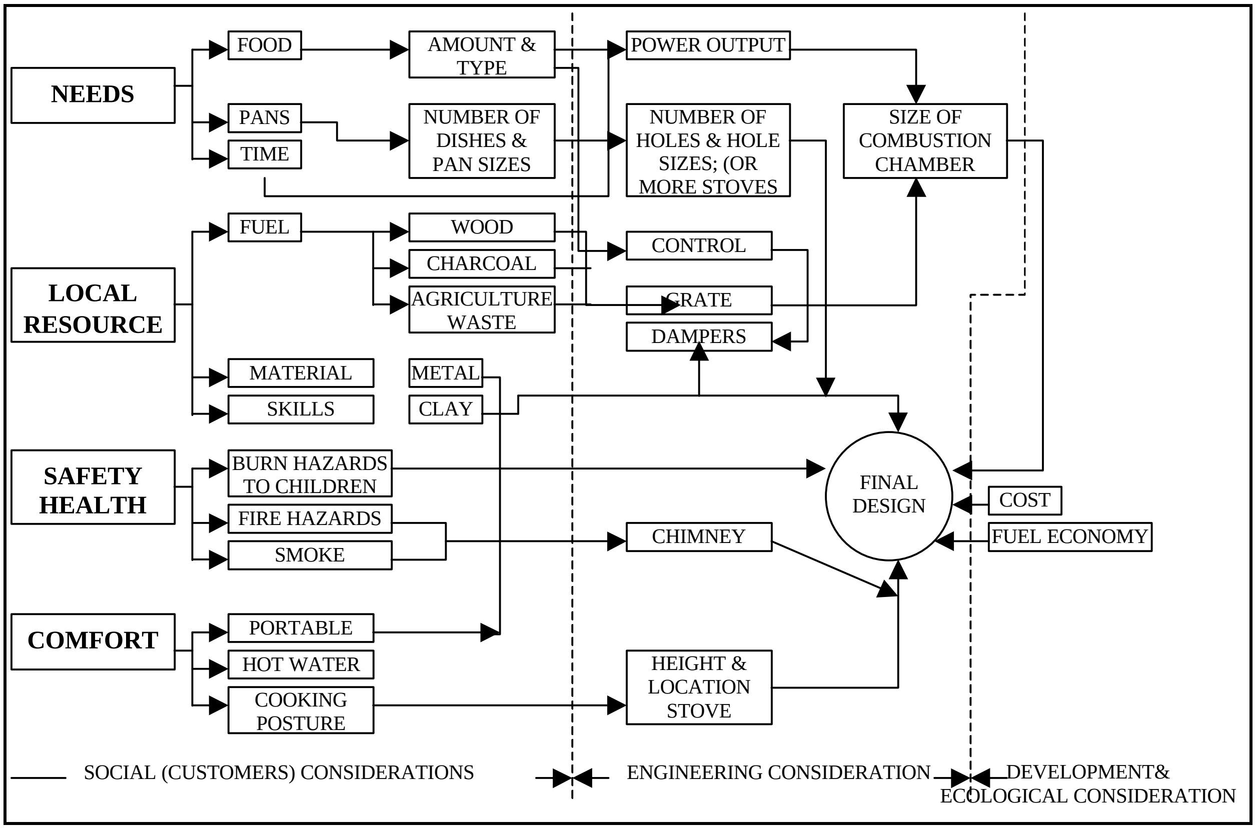

Figure 3.2 Design considerations for a stove

as chimney, damper and baffle were developed without first undertaking rigorous technical analysis. As a result many of the cookstoves propagated low thermal efficiencies and did not provide any relief to the users in terms of fuel saving. The damper also proved to be a major hurdle as its use was the cause of a high rate of burn injuries and its disuse led to excessive fuel consumption.

The engineering approach was used by a large number of the ICS designers during the second phase (1970-1980). Well engineered, complex designs showing high thermal performance in the laboratory were developed. However, in these designs very little importance was given to traditional culinary practices, social aspects, local resource availability and ICS maintenance, etc. A large number of very well-engineered ICSs developed using this strategy again failed to make a lasting impact. The main reason for this failure was that most designs failed to satisfy the diverse cooking requirements of the users who belonged to different socio-cultural milieux and lived in diverse geographical areas. For example, in a two-pothole ICS model developed by this author (Sharma 1989), the power output was equally distributed in both combustion chambers to ensure simultaneous cooking on both pot holes. The design was thermally efficient but it failed to a attract the users as more time and effort was required to cook a meal. Besides, puffing of the local bread on the first pot hole was inadequate. Based on this feedback, a new model Akash (FAO/RWEDP 1993a) with higher power output on the first pot hole was developed in 1991. It has been widely accepted by the users and about 30,000 units have been disseminated so far. The third phase, from the late 80's onwards, saw a progressive use of the unified design approach in which most, if not all, criteria were incorporated. These are further elaborated below.

3.4.1 *Social factors*

Two important social factors regarding the ICS design are the user's needs and the local resources. A stove designer must take into consideration various needs of the target group, such as: cooking tasks, cooking utensils, size of cooking operation, and some specific operational parameters. Cooking tasks can be divided into four categories based on cooking temperatures and cooking media (Verhaart, 1983a):

a) Boiling
Water is used as a medium in this type of cooking. This sets the upper temperature limit of this mode of cooking at only 100°C. The mixture of food and water is brought to the boil and is allowed to simmer till the completion of exothermic reaction in the food. An initial period is designated as the high power phase and the later period is known as the low power phase.

b) Frying
Oil is used as a medium in this type of cooking. The upper temperature limit of this mode of cooking is dependent on the boiling temperature of the oil, which is generally between 200-300°C. Frying is a high power input process as cooking is to be completed normally in a short duration, otherwise the food may get burned.

c) Baking
This process can be accomplished either in an oven or on an open pan (e.g. puffed unleavened local breads, like Indian *chapatti*, *roti* and *rotla* and *nan* of Pakistan). In an oven, heat is transferred by convection and radiation from the oven walls, while conduction is the heat transfer mode for open-pan baking. It is also a high power input process.

d) Grilling
In this mode of cooking, heat is transferred to the food primarily through radiation and to some extent through convection. It is a very high power input process and hence an intense heat source is required.

In addition to the four different cooking tasks as identified by Verhaart, two more cooking tasks can be identified:

e) Steaming
In many Asian societies, in particular among Chinese and Southeast Asians much food is prepared by steaming in which the operating temperature is very close to boiling temperature. High power input is preferred at the initial stage of cooking. After the boiling starts, a low power mode similar to simmering is normally used.

f) Pressure cooking
While in many developing countries, pressurized cookers are expensive and have to be imported, in some developing countries they are being produced at low cost. The pressurized cooking mode is similar to boiling, except that the temperature is considerably above water boiling point. The operating period, however, can be as short as one third of the normal boiling practice, thus helping to save considerable cooking time and cooking fuel, besides imparting improved flavours.

Though cooking techniques as described above appear simple, the actual cooking is still largely an art and depends on the perception of the cook and cultural considerations. Nevertheless, an established norm for the cooking task will help in evolving stove designs and cooking vessels.

3.4.2 Stove power output and other related needs

Besides the cooking modes mentioned above, in designing an ICS, the heat requirement, cooking time and frequency for a specific cooking operation also need serious consideration. Cooking time depends on the quantity of food to be cooked and the stove power as well as the number of items to be cooked. Power output and its mode of regulation on various pot-holes is optimized mainly on the basis of the requirements of the user. Pot and pan size and shape also have an important bearing on the design of the stove, especially on the heat transfer characteristics. A detailed discussion on cooking vessels can be found in section 5.4.

Thus, it is extremely important to gather information on various needs of the user in terms of culinary practices and type of vessels and pot sizes being used before undertaking the design exercise.

Further introduction of new features requiring operational skills on the part of users should be done with care, as they can stand in the way of acceptability. For example, stoves with dampers, which required periodic manipulation were rejected by the users and necessitated the development of damperless models (Sharma 1990c).

Apart from cooking there can be other related domestic operations on the same ICS such as space heating, food processing, water heating for bathing and clothes washing, etc. The acceptability of a new design can be enhanced if some of these daily chores could be accomplished utilizing a new design.

3.4.3 Local resources

Another important consideration in the design of a cookstove is the appraisal of locally available resources, especially types of fuel available, construction material, infrastructure and skills for the ICS production and distribution system. Diverse biomass fuel mixes normally are used in the developing countries for cooking such as fuelwood, charcoal, agricultural and animal residues and/or combinations of these. A cookstove designed for fuelwood will not perform well with cow dung due to the low density of the fuel and excessive amount of ash produced on combustion.

The construction material has an important bearing on the design of the model. In a location where metal sheets are not available, it becomes necessary to design ICSs using other locally available materials such as clay, bricks, ceramics etc.

Local fabricating skills and the type of fabrication infrastructure available must be taken into consideration when designing a stove. In the absence of proper infrastructure, it may not be possible for the local manufacturer to replicate intricate designs. This will have an important influence on the dissemination strategy. For example, on the basis of heat transfer considerations, ceramics appear as a better construction material. However, lack of fabrication facilities and transportation bottlenecks in a number of developing countries are major hurdles in adopting this strategy. On the other hand, involvement of potters, using traditional techniques, for fabrication of fired clay models in the villages will be a much better option. This strategy will not only generate local employment but will also overcome transportation bottlenecks as well as a better interaction between the users and ICS manufacturers.

3.4.4 Economic factors

The cost of an ICS depends on the construction material and fabrication complexity. An extremely efficient model will not find favour with the users if it is beyond their purchasing capacity. Such ICSs cannot penetrate the market without the support of the government. This factor must be taken into consideration at the design stage itself.

The stove should be sturdy, so that frequent maintenance is not required. The design should be such that the parts which need periodic cleaning are easily accessible and the parts susceptible to wear and tear are easily replaceable at a reasonable cost. In addition, these should be easy to replicate by local artisans, using traditional or simple tools.

The design of the stove should also take into consideration the cost involved in organizing production. For example, an intricate design that requires expensive machine tools for fabrication can be a difficult proposition in the target (rural) area. At the conceptual stage itself, a designer should know if the final product is to be built by the user, a craft person or a commercial operation. Commercial operations can be divided into different categories, depending on the size and product range such as repair shop, one person production unit, traditional artisan (blacksmith/potter/metal sheet worker), medium size production unit, and specialized product factories. The cost of the production system and its economic viability on the basis of the delivery/dissemination must be taken into consideration while designing a cookstove.

3.4.5 Environmental factors

Thermal efficiency and combustion efficiency which may work against each other in some cases must be taken into consideration in the design of the ICS. Many designers often concentrate on increasing thermal efficiency at the expense of combustion efficiency, thus creating environmental problems, especially in non-chimney models. Although, ICSs with a chimney are environmentally safe as far as the kitchen atmosphere is concerned (but not always to the outside environment), they are more costly and difficult to design due to problems of excessive draft and of transportation bottlenecks as many chimney designs are fragile (e.g. asbestos cement and ceramic pipes).

Protection from fire and burn injuries must be given due attention in the design of an ICS. This can be accomplished by the selection of proper construction materials, proper design of the cowl and other parameters of the stove. Ceramic and metal designs require more safety precautions to avoid burn injury than thick walled clay stoves. The design should not only take precautions against sparks and burns but should give equal importance to stability against tilting while stirring the food during cooking, especially in the portable stoves. For example, as per Indian Standard (IS:13152, see FAO/RWEDP, 1993a), a portable stove should be stable against a tilt of 15 degrees. Cooking comfort of the cook in terms of cooking posture and ergonomics are other important considerations. Some users prefer right hand cooking positions while others may prefer left hand cooking positions. This consideration is important in the placement of the fire-box position in the design of fixed models.

Meteorological conditions have an important bearing on the portability of the stove. During hot and humid conditions, outside cooking is preferred while during cold weather conditions cooking is mainly done indoors. Thus geographical and meteorological conditions should be given due consideration in the design of the ICS. Stoves which do not blacken the pots are preferred by the users as less cleaning is needed.

Based on the above discussion of the environmental factors, the need for a new development approach which aims to improve the efficiency of the kitchen system rather than the stove alone is apparent. This can be done by using an integrated approach, taking all the above mentioned factors into account. Further discussion on such an integrated approach to the design of cooking system can be found in Chapter 7.

To conclude, at the conceptual stage of the design itself, a stove designer should take as many as possible, if not all, of the above design factors into consideration.

3.5 Design Principles

As mentioned earlier, the thermal performance of an ICS system depends upon the efficiency of the heat conversion system e.g. the conversion of the chemical energy of a fuel into thermal energy, the efficiency with which the thermal energy produced is transferred to the cooking vessel, the system with which the combustion products move through an ICS and finally also the types of material used for the construction of the stove.

A designer therefore should have a complete understanding of the complex interaction between the different processes such as: combustion, heat transfer, fluid flow taking place in a cookstove and how the material used for stove construction has an influence on these factors. A brief resume with regard to these factors is presented in this section while reference is made to those chapters or sections where the parameters are covered in more detail.

3.5.1 Combustion process

The combustion process is dependent on the physico-chemical properties of the fuel (size, shape, density, moisture content, fixed carbon content, volatile matter, etc.), quantity and mode of air supply (primary and secondary air) and the conditions of the surroundings (temperature, wind, humidity, etc.). All these parameters are covered in detail in chapter 4.

3.5.2 Heat transfer

Only a part of the heat released on combustion is transferred to the food in the cooking pot. For example, it has been estimated that for cooking rice, in theory, an equivalent of about 18 grams of wood per kilogram of cooked food is required to heat the rice and water to the boiling point as well to provide the amount of heat necessary for the chemical reaction to cook rice. In practice, however, about 160 grams of wood is required to accomplish this task, even with improved cookstoves. It is clear that a large part of the heat is lost to the surroundings through three distinct heat transfer mechanisms: conduction, convection, and radiation (see also fig. 3.3 a, b, c and d). In order to minimize the losses to the surroundings and maximize the transfer of heat to the food in the pot a thorough knowledge of heat transfer mechanisms and their underlying principles is required to determine the reasons for the losses, how these losses can be reduced through modifications of the design of the cook stove, etc.

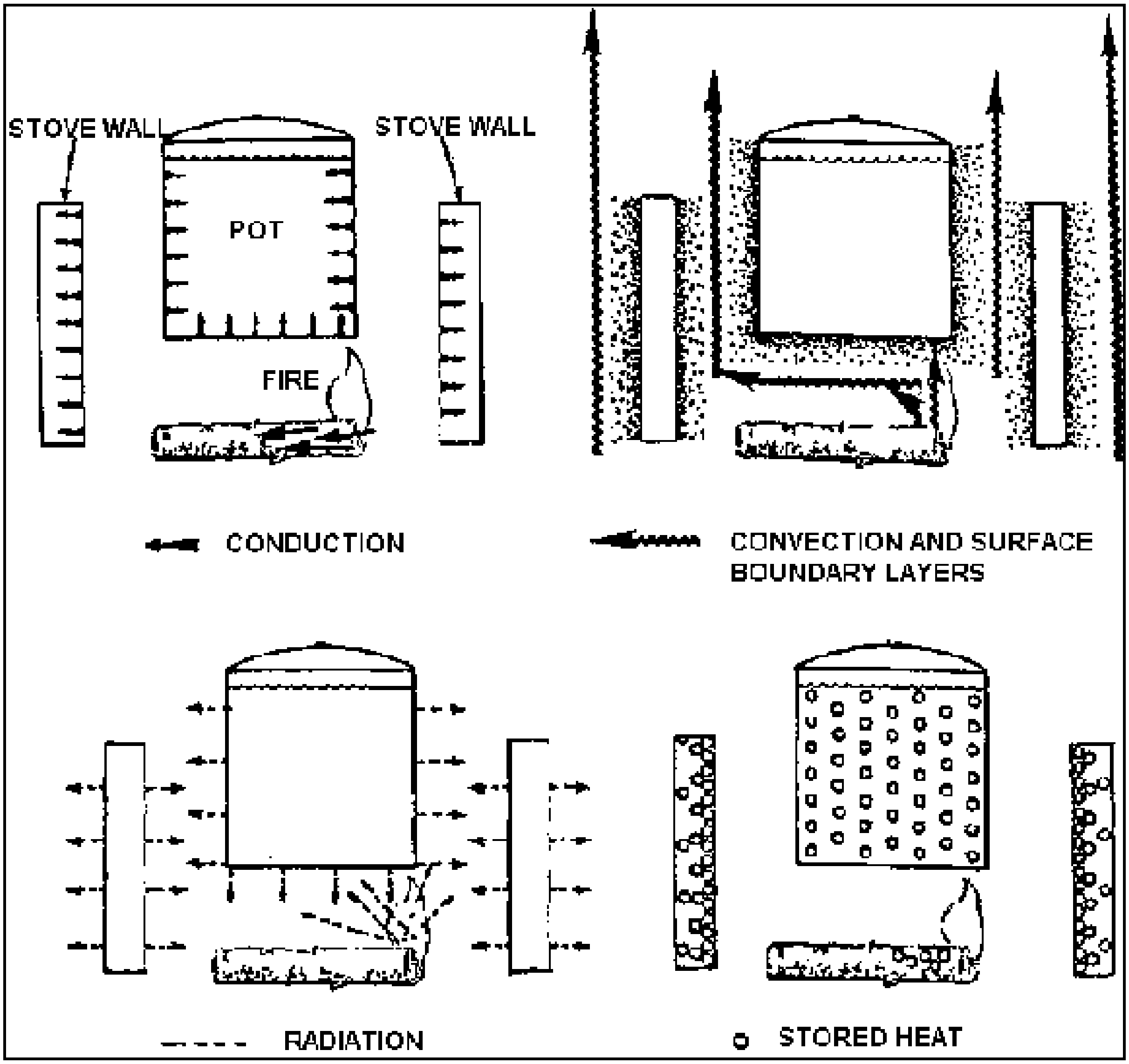

Figure 3.3 Conduction, convection, rediation and store heat. From: Baldwin 1986

a) Conduction

Molecules are closely packed in solids. Whenever there is a temperature gradient these molecules tend to distribute and equalize their kinetic energy by direct interaction. This mechanism of heat transfer is known as conduction. In metals, heat is conducted additionally by the movement of high velocity free electrons from high temperature regions to low temperature regions, where they collide with and excite atoms. In general, heat conduction by free electrons is more significant than adjacent atoms exciting each other.

The transfer of heat through conduction can be calculated using the following equation (Fourier conduction law):

$$q = -\frac{k \times A \times (\Delta T)}{\Delta X} \tag{3.1}$$

where q is the rate of heat transfer, k the thermal conductivity, A the area, ΔX the thickness of the surface through which the heat is conducted and ΔT being the difference in the temperatures of the hot and cold sides. $\Delta X/kA$ is called the thermal resistance.

However, the use of this equation alone for calculating the surface loss gives values which are many thousands of times the actual values. This is due to the non inclusion of the resistance of the surface boundary layer of air as well as the resistance due to the dirt or the oxide layer in the above expression. With the inclusion of these resistances, the equation takes the form:

$$q = \frac{A \times \Delta T}{\frac{1}{h_1} + \frac{\Delta X}{k} + \frac{1}{h_2}} \tag{3.2}$$

where $1/h_1$ and $1/h_2$ are the inner and outer surface resistances and h_1 and h_2 are convective heat transfer coefficients respectively. These will be discussed in detail in the next section.

The ability of a material to store heat is another important factor in conductive heat transfer. This is measured by its specific heat, which is the energy required to raise the temperature of 1 kg of its mass by 1°C. The change in the total amount of heat stored ΔQ, when the temperature of the stove with mass m is changed by ΔT, is given by the equation

$$\Delta Q = m \times c_p \times \Delta T \tag{3.3}$$

where c_p is the specific heat of the material of the stove.

It can be inferred from the above equations that massive stoves will warm up slowly, while lightweight stoves will heat up and dissipate heat quickly. However, the lower heat loss from thick walls is completely offset by a greater absorption of heat due to the storage effect. Only a small part of this heat can be recuperated as useful heat. Hence, thin walls are generally preferred if cooking is intermittent. Massive stoves have therefore an advantage if the cooking is carried out throughout the day.

It can be concluded from the above discussion that the thermal inertia of the stove is a direct function of the specific heat and mass, while the rate of heat transfer is a function of thermal conductivity. Thus, in order to increase the rate of heat transfer to the pot material, a high thermal conductivity of the pot material is preferred. In other words, an aluminum pot will help in faster cooking as compared to fired clay pots. Similarly, in order to reduce losses from the walls, materials having a low thermal conductivity such as mud or clay are better. In the case of metal stoves, the application of an insulation layer can substantially reduce the losses. Regions of interest from the viewpoint of conduction are:

- Transfer of heat from the pots to the contents of the pot;
- Loss of heat through the stove walls;
- Transfer of heat from the flame to the interior of the wood;
- Storage of heat in wood, pot and its contents and the body of the stove.

b) Radiation

Energy in the form of heat radiation is emitted by all bodies above the absolute temperature due to molecular and atomic motion as a result of the internal energy of the material. The internal energy is proportional to the temperature of the body in the equilibrium state. The ability of an object to emit and absorb radiation is given by its emissivity and absorptivity, which are usually functions of the wavelength of the radiation. The emissivity and absorptivity of a black material are equal. Heat radiation is absorbed, reflected, and transmitted when these come in contact with any solid body. The radiation is emitted over a range of wavelengths. The emitted radiation has a maximum intensity at the wavelength given by Wien's law with *T* being the absolute temperature.

$$Maximum\ wavelength = \frac{2897.8}{T}\ microns \qquad (3.4)$$

In a cookstove, as shown in fig. 3c, the regions of interest from the radiation point of view are:

! Radiation emitted by the flame;
! Radiation exchange between the inner walls, pot and the wood;
! Radiation loss to the atmosphere from the wall, pot, chimney, and the opening of the fire box.

From equation 3.4, it can be concluded that radiation emitted by the burning flame is in the range of the visible spectrum while that emitted by the stove surfaces at lower temperature is in the range of infrared radiation. Burning black carbon particles in the flame make it luminous (yellowish) with luminous flames emitting more radiation than the non luminous (bluish) flame such as from a charcoal fire. This is caused by the higher emissivity of the black carbon particles.

Radiation from the flame, which accounts for nearly 14% of the total energy released from the fire, plays an important role in heating the fuelwood. This accelerates the release of volatiles, that support the flame, thus partly controlling the rate of combustion. Hot glowing wood and hot walls of the combustion chamber also radiate heat which is absorbed by the cooking vessel.

The rate of heat transfer by radiation, which is one of the most important modes of heat transfer in the combustion chamber is given by the Stefan-Boltzman law for black bodies.

$$q = F \times A \times T^4 \qquad (3.5)$$

where σ is the Stefan-Boltzman constant, which is equal to $5.6697 \cdot 10^{-8}$ W/m^2 K^4, *A* is the emitting area of the object in square meters, and *T* is its temperature in K.

Black bodies have an absorptivity equal to 1, regardless of wavelength. Such bodies are impossible to find in actual practice. In actual practice, bodies behave as grey bodies, which absorb only a fraction of radiation impinging on it. For these bodies, the Stefan-Boltzman law is modified as:

$$q = E_m \times F \times A \times T^4 \qquad (3.6)$$

where E_m is the emissivity of the material.

It can be inferred from these equations that the energy emitted by a body is strongly dependent on the temperature. An increase in temperature by just 10% increases the heat output by 50%. Another important parameter in radiative heat transfer is the View Factor (VF) between the emitting surface and the absorbing surface. The View Factor is the fraction of energy emitted by one surface that is intercepted by the second surface. It is determined by the relative geometry of the two surfaces.

The total power radiated by a black body as a function of temperature and the View Factor versus the distance between fire bed and pot/radius of fire are presented in figures 3.4 and 3.5 (Baldwin 1986). The energy emitted by the fire bed corresponding to its temperature is calculated from figure 3.4, while the View Factor is determined from figure 3.5. These graphs are extremely useful for designing the fire fire box of a cookstove.

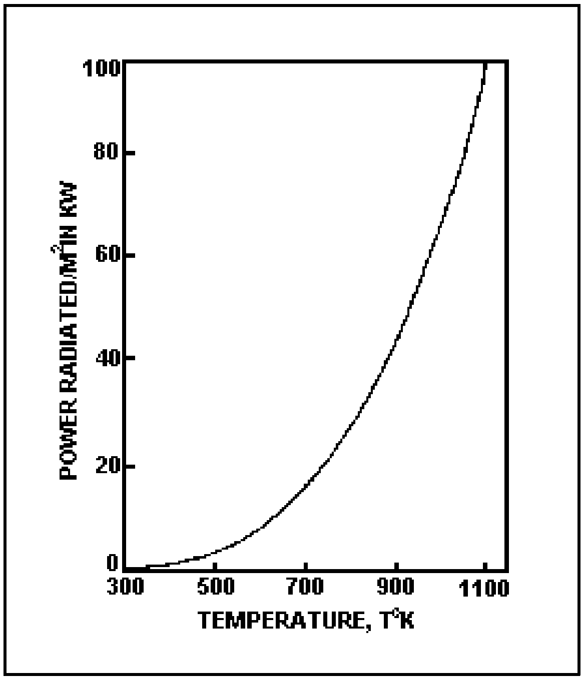

Figure 3.4 Total power radiated by a black body as a function of the temperature

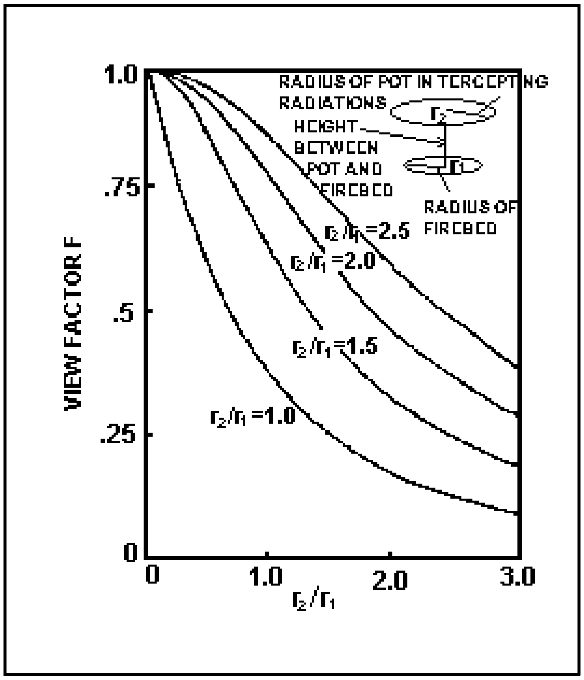

Figure 3.5 View Factor versus the height to the pot

The energy intercepted by the cooking pot from the fire bed can be calculated from the following equation if the View Factor is known.

$$\text{Energy intercepted by the pot} = \text{Power emitted by the firebed} \times A \times VF \tag{3.9}$$

For example: Consider a pot with a diameter of 20 cm (r_2) placed 9.5 cm (h) above the fire bed having diameter (r_1) and cylindrical single pot stove having height above fire bed equal to 9.5 cm (h). The value of the View Factor for values of h/r_2 (0.95) and r_2/r_1 from fig. 3.5 is 0.8. This means that 80% of the radiation emitted by the fire bed strikes the pot bottom. From fig. 3.4, if the temperature of the fire bed is equal to 900°K, it will emit 0.40 kW/m^2. Using equation 3.7, the energy intercepted by the pot is 1.0 kW.

Radiative heat transfer from the fire bed in a cookstove can be increased, either by increasing the fire bed temperature (by controlling the air supply to the fire bed) or by increasing the View Factor. The latter can be increased by either decreasing the distance between the pot and the fire bed or by increasing the diameter of the pot. However, too small a distance between the pot and the fire bed will result in quenching of the fire resulting in incomplete combustion and increased emission of CO and hydrocarbons.

This distance should be more than the combined height of the fuel bed and the flame length. Flame length is dependent on the type of fuel. The fuels with high volatile matter will produce longer flames. The length of the flame can be reduced by generating turbulence through design innovations. In the case of cookstoves with chimneys, induced draft modifies the flame length. The distance between the fire bed and the pot should be optimized taking into account its effect on the emissions in naturally ventilated stoves as well as in the induced draft stoves.

c) Convective heat transfer

Convective heat transfer involves the transfer of heat by the movement of fluid (liquid or gas), followed by conductive heat transfer between newly arrived hot fluid and the matter. Depending on the type of driving force involved in the movement of the fluid, heat transfer by convection takes place by two distinct mechanisms. When movement of the fluid takes place as a result of the buoyancy force created by the temperature difference, the phenomenon is known as natural convection. On the other hand when the fluid is forced to flow by a blower or a fan or by windy conditions, the phenomenon is known as forced convection.

Convective heat transfer is the predominant mode of heat transfer in cookstoves. Hot gases, produced from the combustion of fuel, heat the pot through convective heat transfer. The cooling of the stove and the heating of the space also takes place through this mechanism.

In convective heat transfer, fluid flow and heat transfer take place simultaneously. The theoretical analysis requires the solution of continuity, momentum and energy conservation equations simultaneously. This makes the solution complex. The problem can be simplified by introducing the concept of boundary layer resistance. The boundary layer concept assumes that most of the resistance to the heat transfer is present in the thin boundary layer adjoining the solid surface and not within the solid material and flowing hot fluid. The velocity across this boundary layer varies from zero, at the wall, as a result of friction, to the mainstream velocity, at its outer edge. The heat is rapidly carried away by the solid and the fluid main stream, on respective sides of the boundary layer. The conductivity of the stagnant gas layer is very low, hence this is the controlling resistance, which limits the heat transfer from the flowing gas to the solid surface, such as the pot on a cookstove.

The rate of heat transfer can be increased by reducing the resistance in this boundary layer. This can be done by increasing the velocity of the gas stream which reduces the thickness of the boundary layer, thus reducing the resistance to the conductive heat transfer across it to the solid surface. Even with these simplifications, the solution of the resulting equations is still complex.

In natural convection the hot gas temperature decides the flow as well as the heat transfer rates, which in turn decides its temperature. This inter-dependence of the controlling parameters makes the theoretical analysis of natural convective heat transfer extremely complicated. In order to circumvent this problem, an empirical approach is generally used for the analysis of convective heat transfer problems. In an empirical approach, the convective heat transfer is estimated using a general equation:

$$q = h \times A \times)T \tag{3.7}$$

where q is the heat transferred from the hot gas to the solid surface (pot surface/wall surface in the case of a cookstove), A is the area of solid surface across which the flow of heat takes place, h is the convective heat transfer coefficient, and ΔT is the difference between the temperatures of the hot gas and the solid surface.

The heat transfer coefficient, h can be either determined experimentally or theoretically (in some specific cases). The heat transfer coefficient can be calculated empirically using the Nusselt number. The Nusselt number is the ratio of the characteristic length of the system and the thickness of the local boundary layer. It is defined as hd/k, where h is the heat transfer coefficient, d is the characteristic length of the system, and k is the thermal conductivity of the fluid (hot gas). The characteristic length is a function of the system configuration. For example, in the case of a flow through the cylindrical pot hole in a cookstove, it is equal to the diameter of the pot hole. In the case of a flow between the two vertical walls, it is the distance between them. For flow over a free surface, as in the case of a stove surface, it is the distance from the leading edge.

In the case of heat transfer by natural convection, generally encountered in naturally vented cookstoves, the Nusselt number can be evaluated from the relation:

$$Nu = C \times (Gr \times Pr)^n \tag{3.8}$$

where Gr and Pr are the Grashoff and Prandtl numbers respectively which are defined as:

$$Gr = \frac{g \times B \times T \times l^3}{\mathrm{L}^2} \tag{3.9}$$

$$Pr = \mu \times \frac{C_p}{k} \tag{3.10}$$

where g is the acceleration due to gravity, B the volumetric expansion coefficient (approx.= $1/T$), T is the temperature difference between the surface and the ambient, µ the viscosity of the fluid, k the thermal conductivity and υ the kinematic viscosity. For flow over vertical cylindrical surfaces, the characteristic length l is equal to the heoght.

In cookstoves the values of C and n are taken as 0.53 and 0.25 respectively. For other configurations any standard text book on heat transfer can be consulted. However, data on actual situations encountered in cookstoves are lacking and there is a need to undertake experimental work to determine these constants.

Table 3.1 Values of the constants *C* and *n* for some standard configurations

Configuration	*Gr * Pr*	*C*	*n*
Hot vertical plate	10^4 - 10^9	0.59	0.25
	10^9 and more	0.13	0.333
Horizontal plate, hot side up	10^5 - 10^7	0.54	0.25
Horizontal plate, hot side down	$2*10^7$ - 10^{10}	0.14	0.333
Vertical parallel plate	$2*10^3$ - 10^5	0.20	0.25
	$2.1*10^5$ $1.1*10^7$	0.71	0.333

In the case of forced convection, the Nusselt number is described by the equation:

$$Nu = C_f \times Re^{x} \times Pr^{y} \tag{3.12}$$

with *Re* being the Reynold's number, which is the ratio of the inertial forces in the fluid and the viscous forces and is defined as:

$$Re = \frac{d \times v \times \upsilon}{\mu} \tag{3.11}$$

where *d* is the diameter, *v* the velocity of the fluid, ρ the density of the fluid and μ the viscosity of fluid. C_f is a constant and depends on the system configuration.

A critical value of the Reynold's number defines the transition from laminar to turbulent flow. For flow in a pipe, the critical Reynold's number is 2,300, while for flow along a single wall the value is $5x10^5$. Values of the constant of the forced convection equation for some typical situations are given in table 3.2. For others, any standard book on heat transfer should be consulted.

Table 3.2 Values of the constant of the forced convection equation for typical configurations.

Configuration	*Re*	C_f	*x*	*y*
Laminar flow parallel to a flat plate	$< 3*10^5$	0.332	0.5	0.333
Turbulent flow over a flat plate	$> 3*10^5$	0.664	0.5	0.333
Laminar plane stagnation		0.57	0.5	0.4
A-symmetric stagnation to flat plate		0.93	0.5	0.4

In cookstoves, the regions of interest from a convective heat transfer point of view are (Baldwin 1986):

! Hot gas plume from the fire;
! Stagnation point of plume on the pot;

! Wall jet along the pot bottom and or sides, where the hot gases flow outward and upwards;
! Flow through tunnels, chimney, over baffles, and in the gap between the pot and wall in the case of stoves with pots;
! Outer hot surfaces of pots, stoves and chimney.

The convective heat transfer problems in a cookstove are complex as strongly accelerating flows with varying temperature difference in the direction of flow are encountered. Hence, conventional solutions for hydro-dynamically and thermally stable flow give approximate results.

3.5.3 Fluid flow

A thorough knowledge of fluid flow principles is also essential for understanding the flow of air and flue gases through the stove and the chimney as well as for understanding how these influence the combustion process, the transfer of heat from the hot flue gases to the pots in the different chambers and the heat losses from the pots and the different stove components of the stove to the surroundings.

The induction of air required for the combustion of fuel in the combustion chamber and the subsequent flow of the combustion products through various chambers and connecting tunnels is governed by the principles of fluid flow. The suction effect, responsible for the induction of air into the combustion chamber, is created as a result of the flow of flue gases through the chimney. The amount can be estimated by the application of principles of fluid flow. The steady state flow of fluid is governed by the continuity equation which is based on the principle of conservation of mass. According to this equation the mass of fluid passing all sections per unit of time is constant. This can be represented by the following equation:

$$D_1 \times A_1 \times V_1 = D_2 \times A_2 \times V_2 \qquad (3.13)$$

where ρ is the density, *A* is the area and *V* is the velocity. This equation can be used to calculate the velocity of the flue gases and air at different locations in the stove.

Based on the applications of conservation of energy to the flow of fluid, an equation known as Bernoulli's equation can be derived. For the steady state flow of low pressure gas in which there is a negligible change in internal energy, the equation can be described as:

$$H_{st} + H_{dy} + H_{po} = H_{tot} \qquad (3.14)$$

where H_{st} is the static head, H_{dy} is the dynamic head, H_{po} is the potential head and H_{tot} is the total frictional head. The head is expressed in meters and is equal to $\triangle P/\rho$ where $\triangle P$ is the pressure loss and ρ is the density. The potential head or H_{po} is equal to H_z where *z* is the elevation above any given level in meters. All other parameters are discussed in detail in appendix 1.

In some cases a sudden expansion and contraction is encountered during the flow of flue gases through the tunnels and the chambers. The frictional loss H_{fr} due to the sudden expansion of a duct with a cross sectional area of A_1, where the mean velocity is V_1 into a duct with a larger cross sectional area of A_2 where the velocity is V_2 is given by the expression:

$$H_{fr} = \frac{(V_1 - V_2)}{2\ g_c} \tag{3.15}$$

where g_c is a conversion factor having a numerical value equal to the acceleration due to gravity.

3.5.4 Material science

The materials used to construct a stove have a distinct bearing on the durability, cost, heat losses, safety, the skills required to make a stove and the scale of production envisaged, etc. The stove designer should therefore have a good understanding of how the material influences these factors. Some of the material properties for cooking vessels are described in more detail in section 5.4, while material properties for stove construction are presented in section 5.5.

4 WOOD AND BIOMASS COMPOSITION, PROPERTIES AND COMBUSTION CHARACTERISTICS

4.1 Biomass Composition

Biomass is a term used to signify any kind of biomass in solid form used for fuel, especially fuelwood, charcoal, dung cake, agricultural and other biodegradable solid residues. It is the major source of fuel for domestic cooking and numerous rural applications in the developing countries. Biomass is the product of the photosynthetic reaction of carbon dioxide and water. It consists of three basic elements: carbon, oxygen and hydrogen, which are present in the complex macroscopic polymeric forms. These forms are:

Cellulose	$(C_6H_{10}O_5)x$,
Hemicellulose	$(C_5H_8O_4)y$ and
Lignin	$(C_9H_{10}O_3(CH_3O)_{0.9\text{-}1.7})z$.

The composition of these constituents varies with the plant species. In the case of wood, for example, *hardwoods* generally contain about 43% cellulose, 35% hemicellulose and 22% lignin, while *softwoods* contain nearly 43% cellulose, 28% hemicellulose and 29% lignin (Shafizadeh and De Groot 1976). Biomass consists of three major elements: carbon, oxygen and hydrogen with the approximate proportion of about 50% C, 6% H and 44% O on a moisture and ash free basis. In general it can be represented by the empirical formula of $CH_{1.44}O_{0.66}$. Ash, with a few exceptions, is normally considered as a minor component in biomass. Further discussions on ash can be found in section 4.1.4.

The moisture content of biomass, in natural form, varies over a wide range from as 50% (on dry basis) for very dense hardwood species grown in arid areas to a few hundred percent for the very light wood species grown in swamp or moist areas. In practice, biomass needs to be first dried to a level preferably in equilibrium with the working environment. The term *equilibrium moisture content* or EMC has been used to denote that situation. For wood the natural EMC generally ranges from 7-15% depending on agro-climatic conditions and season of the year. For more details, please consult "Water in Wood" (Skaar, 1972).

The heat of combustion of biomass based fuels is dependent on the percentage of the three main constituents. Lignin has the highest (26.63 MJ/kg), while holocellulose (cellulose and hemicellulose) has a value of 17.46 MJ/kg. Therefore, wood with a greater percentage of lignin has higher heat of combustion. Coniferous (fir and pine) and a number of other wood species contain a considerable quantity of resinous substances that have much higher calorific values than lignin. The proportion of hydrogen and oxygen in cellulose is the same as that in the water molecule, thus there is no contribution of hydrogen towards the calorific value. The heating value of wood, therefore, depends on its carbon and resinous constituents (while keeping its moisture content constant). The combustion and pyrolytic characteristics of woody biomass, as will be explained in later sections, depend on the relative proportion of the constituents, namely: cellulose, hemicellulose, lignin and in some cases the ash content. Physico-chemical characteristics of these constituents, which have an important bearing on the combustion characteristics, are shown in figure 4.1 and are further described in the following sections.

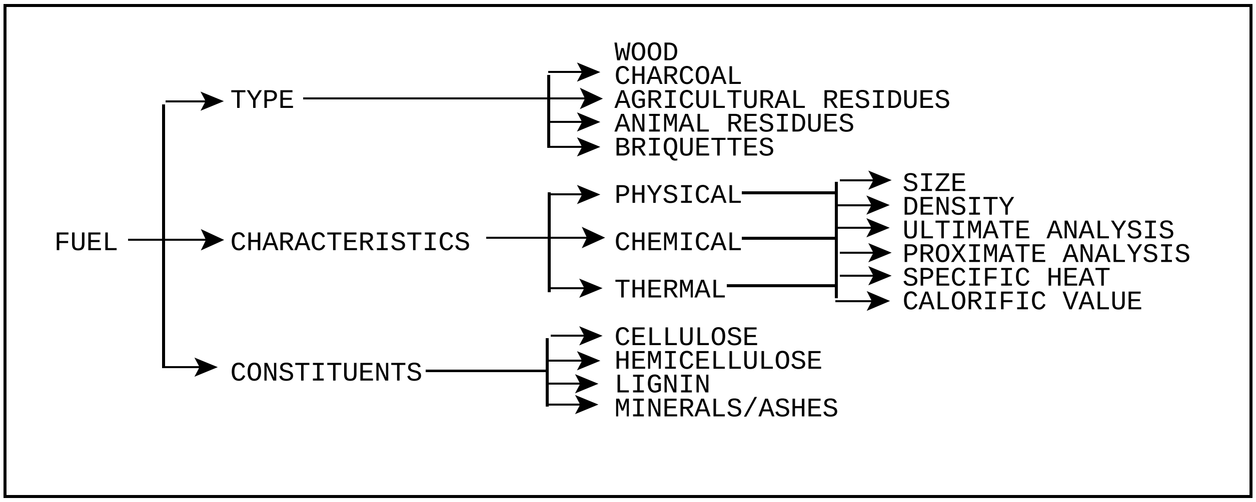

Figure 4.1 Properties of biomass

4.1.1 Cellulose

Cellulose is a glucon polymer consisting of a linear chain of B(1,4)- glucopyranose units having an average molecular weight of 100,000. A highly inert crystalline structure within the microfibrils is provided by the aggregation of these linear chains. The behaviour of cellulose, when subjected to a high temperature, is of great interest for understanding the combustion behaviour of biomass. It has been found (Shafizadeh 1982) that the pyrolysis of cellulose takes place in two stages, at temperatures below and above 300°C. The main processes taking place below 300°C are: the reduction in the degree of polymerization; the appearance of free radicals; the elimination of water; and the formation of carbonyl and carboxyl groups which are assumed to get converted to carbon monoxide and carbon dioxide with the formation of some char. During the second stage at temperatures above 300°C, the formation of char, tar, and gaseous products takes place. The major component of tar is levoglucosan (38-50%), which vaporizes and decomposes as the temperature is further increased.

4.1.2 Hemicellulose

Hemicellulose is a mixture of polysaccharide, mainly composed of glucose, mannose, galactose, xylose, arabinose, 4-O-methyl glucuronic acid and galacturonic acid residues. The molecular weight is less than 30,000. It has an amorphous character. Out of all the macroscopic components, hemicellulose is thermally the most sensitive and its decomposition takes place in two stages, between 200-260°C. These stages are: decomposition of the polymer into soluble fragments and/or conversion into monomer units which further decompose into volatile products. Hemicellulose gives more gas, less tar and char as compared to cellulose. The main components of tar are organic acids such as acetic acid, formic acid and and a few furfural derivatives.

4.1.3 Lignin

Lignin is a random polymer of substituted phenyl propane units, which yields aromatics on processing. It is amorphous in nature. It acts as a main binder for the agglomeration of fibrous components. Decomposition of lignin takes place between 280-500°C. It yields about 55% char and a liquid product, known as pyroligneous acid which consists of 20% aqueous component and 15% tar residue (on dry lignin basis). The aqueous component comprises of methanol, acetic acid, acetone and water. The tar residue mainly consists of homologous phenolic compounds such as phenol, guaiacol, 2,6-dimethoxy phenol, etc. About 10% of the lignin gets converted into gaseous products, namely: methane, ethane and carbon monoxide.

4.1.4 Minerals and Ashes

Biomass contains a number of inorganic compounds which do not burn but are left as ash after combustion. Depending on the type of biomass, the ash content varies from less than 1% for wood to as high as 20-25% for rice husk. Ash contents for various plant parts are shown in table 4.1. Ash comprises CaO, K_2O, Na_2O, MgO, SiO, Fe_2O_3, P_2O_5, and Al_2O_3. CaO and K_2O constitute nearly 50% and 20% of the ash, respectively. The fusion temperature of the ash of different types of biomass is also shown in table 4.1. From the table, except for corn cobs and dhaincha stalks, the fusion temperature is above 1,100°C. This temperature range is well above the temperatures encountered in the fire-box of the majority of the ICSs. Nevertheless, when fuels with a high percentage of ash are used in a cookstove, ash may fast accumulate in it. This will adversely affects the flow of air in the cookstove. The situation becomes particularly severe for the stoves which have a grate. The periodic removal of the ash becomes necessary, otherwise the stove performance will be very much impaired due to the inadequate flow of air. On the other hand, a thin layer of ash helps in the distribution and preheating of incoming air, thus enhancing the combustion efficiency.

Table 4.1 Properties and characteristics of ovendry biomass

No.	Biomass	Volatiles	Fixed carbon	Ash	Carbon	Hydrogen	HHV	LHV	Ash deformation temperature	Ash fusion temperature
		(%)	(%)	(%)	(%)	(%)	MJ/kg	MJ/kg	(°C)	(°C)
1.	Arhar stalk	83.47	14.76	1.77	46.75	6.55	15.00	14.85	1250-1300	1460-1500
2.	Bagasse	75.10	16.87	8.03	45.71	5.89	19.50	19.37	1300-1350	1420-1450
3.	Bamboo dust	75.32	15.59	9.09	43.86	6.64	16.02	15.87	1300-1350	1400-1450
4.	Cotton stalk	70.89	22.43	6.68	43.64	5.81	18.26	17.85	1320-1380	1400-1450
5.	Coconut coir	70.30	26.77	2.93	47.17	6.54	18.20	17.79	1100-1150	1150-1200
6.	Corn cob	80.20	16.20	3.60	45.31	7.16	15.58	15.23	800-900	950-1050
7.	Dhaincha stalk	80.32	17.01	2.67	56.45	8.99	19.63	19.43	800	800-900
8.	Groundnut shell	68.12	24.97	6.91	44.78	6.08	17.20	17.06	1180-1200	1220-1250
9.	Jute stick	75.33	19.00	5.67	54.77	8.20	19.45	19.01	1300-1350	1400-1450
10.	Kikar (Acacia)	77.01	22.35	0.64	45.89	6.08	20.25	19.79	1300-1350	1380-1400
11.	Mustard shell	70.09	14.48	15.43	46.20	6.21	17.61	17.47	1350-1400	1400-1450
12.	Pine needle	72.38	26.12	1.50	48.21	6.57	20.12	19.97	1250-1300	1350-1400
13.	Rice husk	60.64	19.90	19.48	40.10	6.03	13.38	13.24	1430-1500	1650
14.	Sal seed leaves	60.03	20.22	19.75	46.74	6.72	18.57	18.42	1200-1250	1350-1400
15.	Sal seed husk	62.54	28.06	9.40	48.12	6.55	20.60	20.13	1450-1500	1500-1550

Source: Grover, 1990

4.2 Methods for Assessing Biomass

The determination of the different constituents of biomass requires intricate analytical methods and it may not be possible to undertake such a task in an ordinary laboratory as advanced facilities and skilled manpower are needed. In view of this, simpler methods such as proximate analysis and ultimate analysis are used to determine the characteristics of the biomass for combustion applications. Apart from these, the calorific value and the rate of devolatilization are other important properties which throw light on the combustion characteristics of biomass.

4.2.1 Proximate analysis

The proximate analysis involves, by using simple test methods, estimating the main constituents of biomass which have a direct influence on the combustion characteristics, e.g. the moisture content of a biomass sample, the amount of volatiles, fixed carbon (char) and the amount of ash. All these components of the proximate analysis are related in some way to the combustion characteristics of the biomass. For instance, the contribution of flaming and glowing combustion in a biomass combustion process depends on the proportion of volatile matter and fixed carbon in it while the moisture content of biomass has a strong influence on its calorific value. A few examples of approximate calorific values of wood having different moisture contents are given in table 4.2.

A proximate analysis starts with the determination of the moisture content. This is necessary as the moisture has a direct influence on the determination of the other constituents, in particular the amount of volatile matter.

Table 4.2 Calorific value of wood at different moisture contents

Condition of wood	Calorific value (kJ/kg).
Freshly cut wood	8,200
Air dry wood	15,500
Oven dry wood	18,800

Source: …

Wood, like other types of woody biomass, has a porous structure and consists of a twisted hollow network of capillaries. The network has a capacity to hold considerable amounts of water. As a result, the overall density is substantially modified, which influences its combustion and other properties. A high moisture content in the biomass slows down the combustion process which results in the reduction of the combustion chamber temperature. As a result, complete combustion of the volatile matter becomes difficult, resulting in the deposition of unburnt carbon particles in the chimney, in the form of soot. These deposits increase resistance to the flow of the flue gases. At the same time soot particles will stick to the bottom of cooking pots which affects the heat transfer and makes cleaning of the pots more difficult.

The moisture content of biomass can be estimated by taking a small pre-weighed sample. The sample with an initial mass of M_i is placed in an drying oven in which a temperature of 105°C is maintained. Every 6 hours the change in mass is noted and the process is continued till the mass becomes constant (M_e). The moisture content [m] in percent of the biomass on dry basis is then calculated as:

$$[m] = \frac{M_i - M_e}{M_e} \times 100\% \tag{4.1}$$

The second step in a proximate analysis is the determination of the amount of volatile matter. The volatile matter of biomass is that component of the carbon present in the biomass, which, when heated, converts to vapour. In almost all types of biomass the amount of volatile matter, which is a function of the carbon to hydrogen ratio is high and will be about 70%-80% of the weight of the dry biomass.

The amount of volatile matter is determined by heating a dried ground sample of biomass with an initial mass of M_i in a closed crucible in an oven with a temperature of 600°C for six minutes followed by heating the sample in an oven with a temperature of 900°C for another six minutes. The amount of volatile matter υ in percent, present in the biomass is equal to the loss in the weight and is calculated as:

$$\mathrm{L} = \frac{M_i - M_e}{M_i} \times 100\% \tag{4.2}$$

After the volatile matter, the amount of ash is determined. Ash is the noncombustible component of the biomass. The higher the amount of ash in a fuel, the lower is the calorific value of the fuel. The amount of ash is determined by heating a dry sample of biomass in a crucible in a furnace which is kept at 900°C. The amount of residues left is weighed and the amount of ash [*a*] in percent is calculated as:

$$[a] = \frac{M_i - M_e}{M_i} \times 100\% \tag{4.3}$$

The final step in the proximate analysis is the determination of the amount of fixed carbon [*c*] by using mass balance calculations. The amount of volatiles is the difference between 100 and the sum of the moisture content [*m*], the amount of ash [*a*] and the amount of volatiles υ in a sample of biomass calculated as:

$$[c] = 100\% - ([m]\% + [a]\% + \imath.\%) \tag{4.4}$$

Table 4.3 shows some typical values of a proximate analysis for some types of fuels. Even though a proximate analysis in very helpful in predicting the combustion properties of wood, it is not possible to correctly predict the availability of carbon for the combustion of biomass as the amount of hydrogen (H), oxygen (O) and nitrogen (N) also play a role. The determination of these constituents requires a more detailed analysis of the energy and material balance. This is normally done through the so-called ultimate analysis.

Table 4.3 Proximate analysis of some fuel types

Component	Agri/Tree residues	Wood	Coal
Fixed carbon	10-20	15-20	60-80
Volatile matter	60-85	70-85	20-30
Ash content	1-20	1-3	5-40

Source: Grover 1990

4.2.2 Ultimate analysis

The ultimate analysis involves the estimation of the important elements of biomass such as: C, H, O, N, and S. Other impurities like phosphorous and chlorine are almost absent in the case of biomass, although these are very important in the case of coal. An ultimate analysis coupled with gas analysis data is required to make the overall material and energy balance calculations for a combustion process. The heat of combustion of most of the fuels, chars, and volatiles can be calculated from the ultimate analysis data using the following empirical correlation:

$$H_n^{250^\circ C} = (394.1 \times [c] - 230.2)\ [kJ/kg] \tag{4.5}$$

where H_n is the calorific value and [*c*] is the amount of fixed carbon in percent.

An ultimate analysis can be done by using a chemical method in which carbon (C) and hydrogen (H) are burnt in a platinum crucible in a stream of air to produce carbon dioxide (CO_2) and water. These are absorbed in chemical reagents and the percentage of C and H are estimated (refer to ASTM D3174-76). Oxygen (O) can be determined by the difference, if the ash contents are known. Besides the chemical method, an automatic CHN analyzer can also be used for this purpose.

4.2.3 Calorific value

The calorific value of a fuel is defined as the amount of heat evolved when a unit weight of fuel is completely burned and the combustion products such as CO_2 and H_2O are cooled to a standard temperature of 298°K. It is usually expressed in kilo joules (kJ). The calorific value of any given species of biomass is dependent on the moisture content and its density as stated in the previous section.

The calorific value is termed as *gross calorific value* when the sensible and latent heat of the condensation of water, produced during combustion, is included in the value. However, in actual practice such as in a stove, any moisture in the fuel as well as that formed by the combustion of hydrogen is carried away through the stack as water vapour. For that reason the heat of condensation of water is not available as useful heat and has to be subtracted from the gross calorific or *higher heating value* resulting in the *net heating* or *lower heating value*.

In order to calculate the net heating value, the value for latent heat of vaporization of water is taken as 2.45 MJ/kg at 25°C. This is equivalent to 421 kJ/gr.mole of hydrogen or 218 joules for each % of hydrogen per kilogramme of fuel.

The calorific value is determined by a bomb calorimeter. A sample of air dried biomass with a known mass is burnt in an atmosphere of oxygen in a stainless steel high pressure vessel, known as a bomb. This bomb is placed in a calorimeter which is a highly polished outer vessel containing a known amount of water with a known temperature. The combustion products CO_2 and H_2O are allowed to cool to the standard temperature. The resulting heat of combustion is measured from the accurate measurement of the rise in the temperature of water in the calorimeter, the calorimeter itself and the bomb. The calorific value so estimated is the gross calorific value.

4.2.4 Rate of devolatilization

The combustion characteristics of biomass as well as other solid fuels are mainly dependent on the pyrolysis, e.g. the manner in which the volatiles are released and combusted above 250°C. Pyrolysis can be defined as the thermal cracking of the original wood constituents under the influence of heat, resulting in the formation of combustible volatile matter and char. These ultimately will burn with flaming and surface (glowing) combustion respectively. Except for the extractives (extraneous or resinous materials), no other constituent of wood is combustible in the form it exists.

The pyrolysis mechanism has been pieced together from devolatilization studies in which the rate and the character of volatiles, generated from biomass when subjected to heat, is estimated. The *rate of* *devolatilization* is defined as the percent weight loss per degree rise in temperature. It depends on: the rate of heating, the temperature, the residence time and the physical shape and size of the biomass.

Pyrolysis processes, as visualized from devolatilization studies, can be depicted as follows (see also figure 4.2): The first stage of pyrolysis is the transformation of cellulose to an oxygen rich intermediate, identified as levoglucosan. After this, the reaction may proceed along several alternative branches, depending upon the controlling parameters. Some of these can be outlined as follows: (1) the production of a group of compounds, collectively called tar, due to the transportation of levoglucosan from the cellulose matrix; (2) the formation of char due to repolymerization, cracking or cross-linking; (3) depolymerisation to lighter volatile products including CO, CO_2, ketones, esters, aldehydes, organic acids and free radicals which either could (4) inhibit char formation or (5) initiate autocatalysis. The volatiles are generated due to the escape of the stable lighter compounds. All these steps have been depicted in figure 4.2. Understanding of the pyrolytic path followed during the combustion process for different fuels under different conditions, makes the devolatilization studies very important from the point of view of the design work.

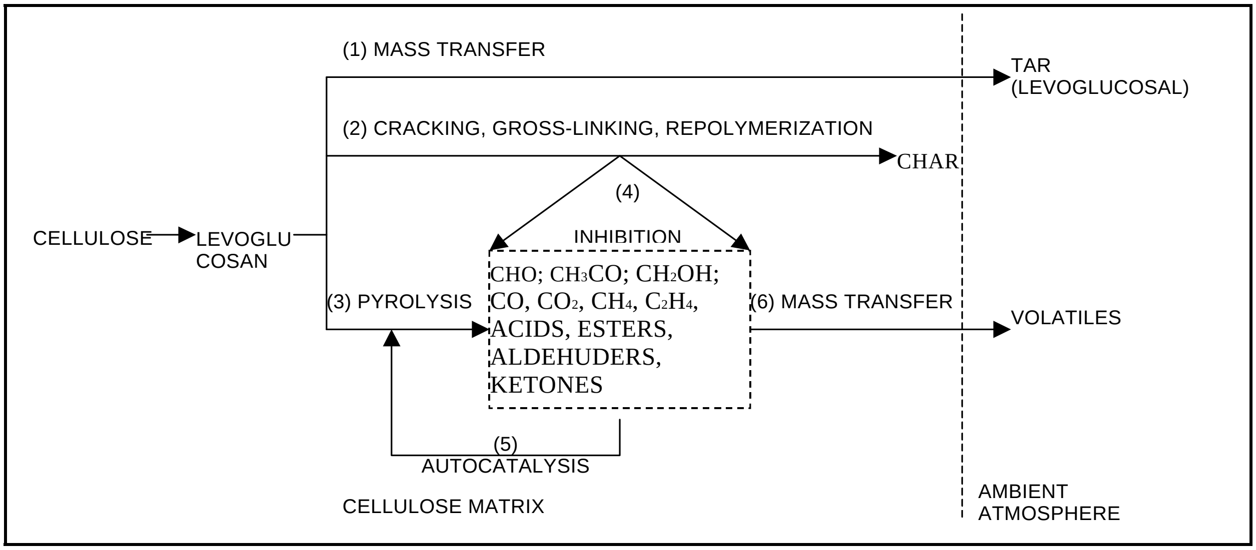

Figure 4.2 Possible reaction pathways for thermal degradation of cellulose under rapid heating conditions

Modern techniques like differential scanning calorimetry (DSC), thermogravimetry (TG), differential thermal analysis (DTA) and derivative thermogravimetry (DTG) are used to determine the rates of devolatilization and an understanding of the pyrolytic process. In this method, a continuous loss of weight of the sample due to thermal decomposition as a function of temperature and time, when subjected to a linear heating rate,is estimated. Percent conversion is calculated at different temperatures. However,the evaluation of the pyrolytic process is extremely complex, which can be judged from the fact that nearly 37 volatile components have been detected during the pyrolysis of cellulose alone. The amount of pyrolytic products given off under high heating rate conditions, which are generally encountered in wood fires have been reported by Adam (1980) as in table 4.4. Proximate and ultimate analysis of various types of biomass were presented earlier in table 4.1.

Table 4.4 Composition of pyrolysis products

Composition in mass fractions		Composition in mole fractions	
Char	0.20	Methane	0.20
Water	0.25	Carbon Monoxide	0.45
Tar	0.20	Hydrogen	0.17
Pyrolysis gas	0.35	Others	0.18
TOTAL	1.00	Total	1.00

Source: Verhaart, 1983a

4.2.5 Thermo-physical properties

Important thermo-physical properties of biomass fuels which control the combustion process are: calorific value, density, thermal conductivity, thermal diffusivity. Different wood species can be characterized by the density. The bulk density of different types of wood may vary between a low 100 kg/m^3 (balsa wood) to over 1,000 kg/m^3 such as many hardwood species e.g. Gucayacum officinale. However, most wood species fall between 400-800 kg/m^3. Studies on the effect of density on the quality of combustion are still inconclusive (Prasad 1983).

Thermal properties of the wood are highly anisotropic due to the fibrous nature of the material. For example, thermal conductivities of wood in longitudinal direction are twice those in the transverse direction. Similarly, permeability, which is a measure of the penetration of moisture, is 10,000 times greater in the longitudinal direction than in the transverse direction. Thermo-physical properties such as density, conductivity, and thermal diffusivity of different wood species are given in table 4.5. For more details please consult “Transport in Wood” (Siau, 1984).

Table 4.5 Density, conductivity and the thermal diffusivity of different wood species

Wood species	Density kg/m^3	Conductivity in W/m°C		Thermal Diffusivity m^2/s	
		Transverse	Longitudinal	Transverse	Longitudinal
Fir	540	0.14	0.34	18.7×10^{-8}	45.9×10^{-8}
Mahogany	700	0.16	0.31	16.6	32.3
Oak	820	0.21	0.36	18.7	32.1
White Pine	450	0.11	0.26	17.8	42.1
Teak	640	0.18	0.38	20.1	43.5

Source: Kanury, A. et al, 1970

4.3 Wood Combustion

The process of release of thermal energy from fuel is known as combustion. Biomass fuel is the stored solar energy in the form of chemical energy of its constituents, as a result of photosynthetic reaction, as explained earlier in section 4.1. This energy is released during combustion reaction, in which oxygen reacts with the chemical constituents of wood to produce carbon dioxide and water, with the release of heat. Photosynthetic and combustion reactions are reversible reactions,which can be depicted by the following simplified equation:

$$CO + H_2O \underset{\text{Thermal Energy}}{\overset{\text{Solar Energy}}{\rightleftharpoons}} CH_2O + O_2 \qquad (4.6)$$

The physico-chemical processes involved in the storage of chemical energy in the fuel and the subsequent conversion of this energy into heat are complex in nature. Any combustion process can be depicted by the fire triangle shown in figure 4.3. The figure shows that for self-sustained combustion, three components are essential, namely: fuel, air and heat. Combustion is a complex process in which processes of devolatilization, cracking and combustion take place almost simultaneously. The amount of energy released during combustion reaction depends on the temperature, pressure, the products of reaction and the state of water produced. These last two factors are important because incomplete combustion will result in the production of carbon monoxide and other combustible materials, which results in the loss of potential energy of fuel. Liquid or vapour state of water, produced during combustion of hydrogen in the fuel, will effect the net heat released. This complex process is depicted in figure 4.4 and takes place in three stages, as explained in the following sections.

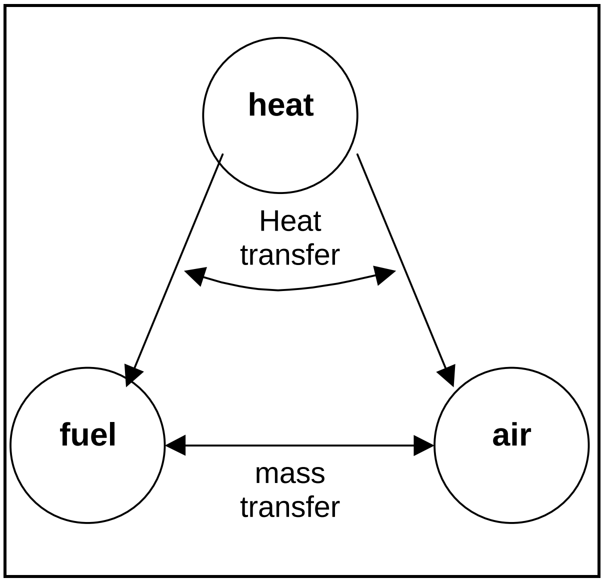

Figure 4.3 The fire triangle

4.3.1 Stage 1 combustion

Easily combustible kindling (such as tree leaves, wood shavings, scrap paper and kerosene) on burning, raises the temperature of the spot on which the radiation from the flame is incident. This heat gets distributed throughout the material due to conductive heat transfer, thus raising the temperature of the material. When the temperature rises to 100°C, drying of wood takes place due to loss of absorbed and weakly bound water. This process continues into the deep interior; a part of the heat of combustion is utilized in this endothermic process (heat consuming). Hence, the higher the moisture content of the wood, the greater is the loss of energy.

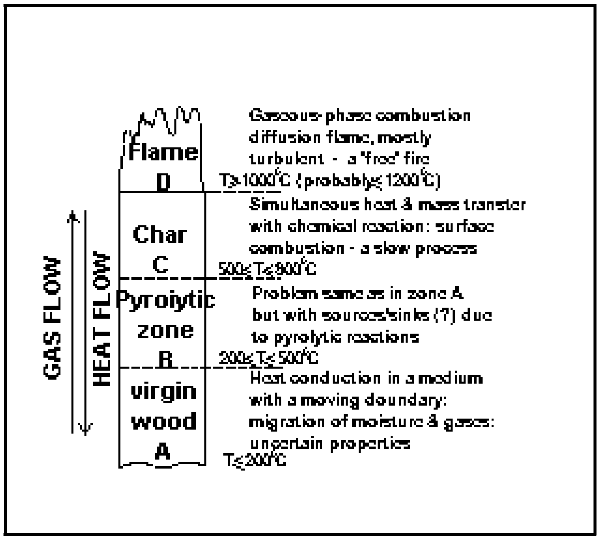

Figure4.4 Processes and temperatures in a burning piece of wood (Hasan Khan and Verhaart 1992)

4.3.2 Stage 2 combustion

As the temperature is raised further, the pyrolytic decomposition of the wood starts. At a temperature of about 150°C, the release of volatile matter begins along with the appearance of semi-liquid tar. In case this stage gets prolonged due to quenching of the flame, the fuel starts smouldering and dark or grey/blue smoke with a strong smell is given off. This results in the loss of some useful energy of wood. The tar gets deposited in the tunnels and chimney resulting in their choking as mentioned earlier in section 4.2.1. There is also the danger of fire in the chimney due to the spontaneous combustion of the deposited tar. Tar also gets deposited on the cold surface of the pots resulting in their blackening.

4.3.3 Stage 3 combustion

Volatile matter, being at a higher temperature, rises due to the buoyancy force. During the rise, it mixes with the surrounding air. This mixture of volatile matter may reach the combustible limit and get ignited, if sufficient heat is available. The flame resulting from combustion may persist if the heat released from the flame is sufficient for sustained release of more volatiles from the burning surface. Otherwise, it will flash back to the surface. Self-sustained combustion commences at around 225°C and reaches a peak at about 300°C. During this stage, heat released by the combustion process is more than the combined losses and hence there is a net positive release of heat.

Thus, it can be concluded from the above discussion that for the evaluation of the combustion process, the understanding of the pyrolysis process and the subsequent burning of the released volatile matter and char is necessary. The second stage determines the extent and nature of volatiles and the char generated while the third stage determines the extent to which the potential heat in the volatile matter and char is released. The pyrolytic process as explained earlier (section 4.2.4) suggests that, for the best design of the stove, the following factors (which govern the rate of pyrolysis) must be taken into full consideration: the temperature, rate of heating, residence time of biomass in the combustion chamber and physical characteristics of the fuel such as size and shape. Furthermore, an understanding of the heat level required for ignition as well as for the maintenance of combustion and their dependence on the thermo-physical properties such as density, specific heat, thermal conductivity, calorific value and moisture content is essential.

4.3.4 Combustion of the products of pyrolysis

Combustion of the products of pyrolysis of biomass, in particular, char and volatiles, takes place in two modes, flaming combustion of the volatiles and glowing combustion of the char. The complete process is shown in figure 4.5.

a) Combustion of volatiles

The composition of the volatiles is variable and depends on the temperature of pyrolysis and the length of time that these volatiles are subjected to an elevated temperature. Thus, the combustion of volatiles is a complex process. The higher the temperature of the pyrolytic zone, the more severe is the cracking of the higher molecules into smaller ones, which in turn burn more readily. Wood fires generally produce a diffusion flame. This consists of a jet of flammable gas with a combustion reaction taking place at the air-gas interface, resulting in the formation of hot gaseous combustion products and heating the remainder of the gas to some extent. The products of combustion are lighter due to their high temperature resulting in a vertical rise-up. During the ascent, these products also entrain some surrounding air.

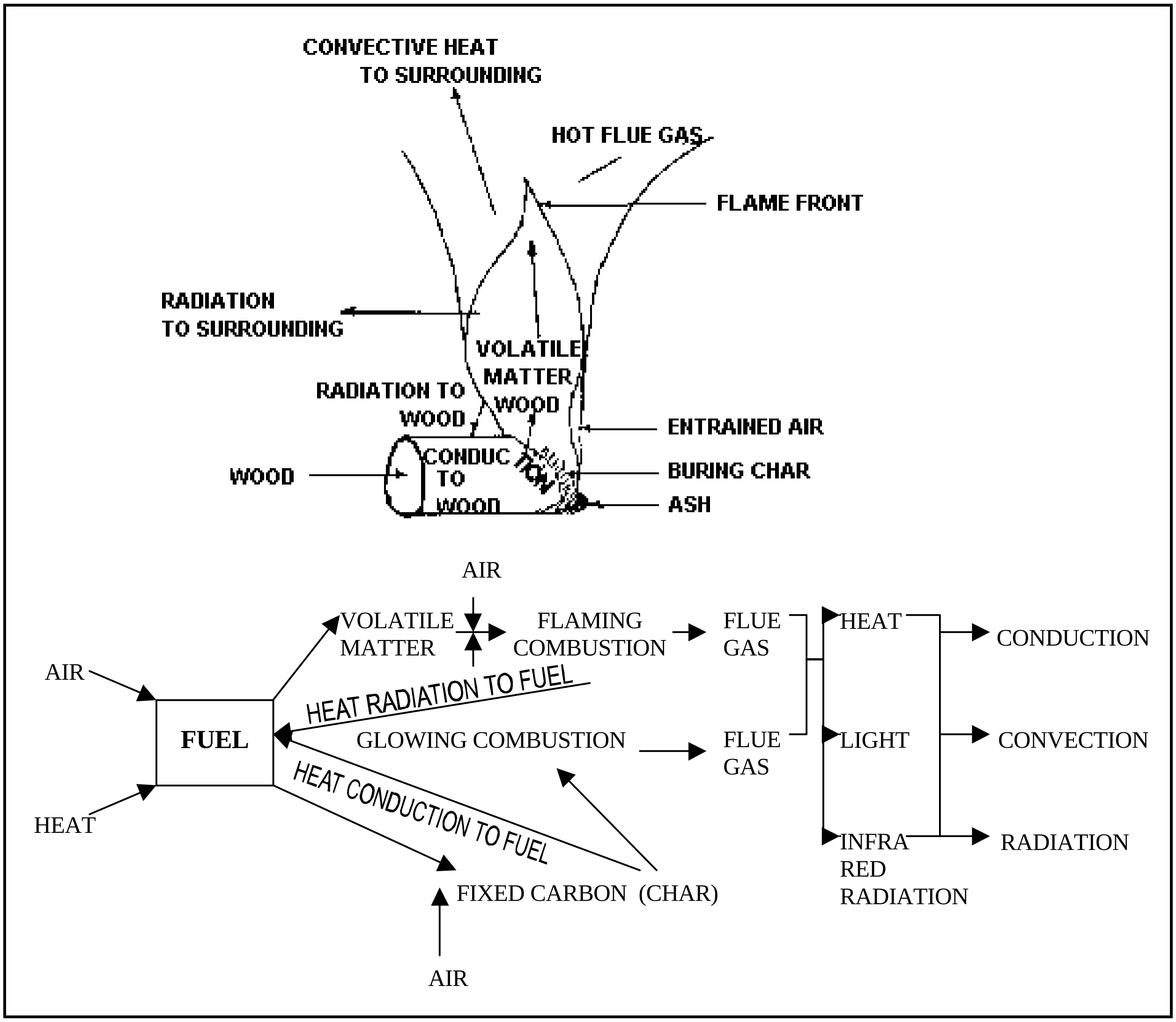

Figure 4.5 Wood combustion

Another process, which takes place simultaneously is the diffusion of air into a jet of gas through the difference in the partial pressure of the constituents. Diffusion of air into unburnt volatile material at high temperature results in the combustion of volatile material. Soot and unburnt chemical compounds are formed if the temperature of the combustion zone is not sufficient. Temperature can fall below ignition temperature due to the quenching effect of the entrained air or the contact of the flame with a cold surface. If the residence time of the flammable gas at a higher temperature is long, then hydrocarbons of progressively higher carbon contents are formed due to partial oxidation.

b) Glowing combustion

Char, which is a solid carbon residue left after the release of volatile matter, burns with a glowing flame. When the combustion takes place at the surface, carbon dioxide is formed with the liberation of heat. However, if the combustion reaction takes place in the bed or char at high temperature, then carbon dioxide is reduced to carbon monoxide. This must be burnt with secondary air to produce carbon dioxide and heat. Otherwise,it will result in the loss of potential heat as well as cause pollution.

4.3.5 Combustion reactions

During the combustion process a number of chemical reactions take place. These reactions do not simply involve the addition of oxygen to carbon and hydrogen, in the fuel, to produce heat. There is a combination of a number of primary, as well as secondary reactions in which the products of the primary reactions also take part. The principal reactions can be summarized as shown in the following box. A plus sign indicates an exothermic reaction (evolution of heat) while a minus sign indicates an endothermic reaction (heat absorbed). The heat of reaction corresponds to a base temperature of 25°C at constant pressure and in the state as indicated. The extent of completion of these reactions is dependent on a number of factors, namely: equilibria, specific reaction rate, and contact catalysis. Reaction 2 (see box) predominates at temperatures below 600°C, while Reaction 1 predominates at temperatures above 800°C. Performance of a combustion system on the whole, depends on the physico-chemical and thermochemical properties of the fuel.

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1 $C \text{ (graphitic)} + O_2 \text{ (gas)} \rightarrow CO_2 \text{ (gas)} + 178{,}430 \text{ kJ}$

2 $C \text{ (graphitic)} + CO_2 \text{ (gas)} \rightarrow 2CO \text{ (gas)} - 78{,}210 \text{ kJ}$

3 $2C \text{ (graphitic)} + O_2 \text{ (gas)} \rightarrow 2CO \text{ (gas)} + 100{,}230 \text{ kJ}$

4 $2CO \text{ (gas)} + O_2 \text{ (gas)} \rightarrow 2CO_2 \text{ (gas)} + 256{,}640 \text{ kJ}$

5 $2H_2 \text{ (gas)} + O_2 \text{ (gas)} \rightarrow 2H_2O \text{ (gas)} + 219{,}300 \text{ kJ}$

6 $C \text{ (graphitic)} + H_2O \text{ (gas)} \rightarrow CO \text{ (gas)} + H_2 \text{ (gas)} - 59{,}540 \text{ kJ}$

7 $C \text{ (graphitic)} + 2H_2O \text{ (gas)} \rightarrow CO_2 \text{ (gas)} + 2H_2 \text{ (gas)} - 40{,}870 \text{ kJ}$

8 $CO \text{ (gas)} + H_2O \text{ (gas)} \rightarrow CO_2 \text{ (gas)} + H_2 \text{ (gas)} + 18{,}670 \text{ kJ}$

4.3.6 Effect of moisture on combustion of wood

Combustion characteristics of wood are influenced by the presence of moisture in it. The moisture content is defined as the mass fraction of water, on a dry wood basis (section 4.2.1). The effect of moisture on the heat value of wood is given by:

$$B = \frac{B_o}{1 + [m]} - [m] \times (C_p \times)T + L) \qquad (4.7)$$

where [*m*] is the moisture content, *L* is the latent heat of evaporation, *B* the heat of combustion of wood as fired, and B_o the lower heat of combustion of oven dried wood.

Studies conducted by Era and Saima (1976) showed that the stove efficiency is greatly dependent on the moisture content of the wood. It has been found that the minimum intensity as well as energy required for ignition increase with the increase in its moisture content. An upper limit of moisture is reached when it becomes too difficult to maintain combustion, even in the presence of substantial heat input. This is because the net heating value is less than the heat required for combustion. This limiting value is reached at moisture content of about 67% (dry basis) or so. At this level of moisture, the calorific value gets reduced to about 5,000 kJ/kg from 18,500 kJ/kg for wood with about 10% moisture content.

Controlled experiments undertaken for estimation of the effect of moisture on combustion show that there is a fall in the efficiency with increase in moisture in the wood. However, the highest efficiency is achieved at a moisture content of about 5%. This can be attributed to the sudden/too fast release of heat in the case of bone dry wood.

The time taken by the fire to reach the peak value in the initial stage of fire and the thickness of the fuel bed depends on the moisture content of the wood. Once the peak power is reached, the fuel bed is hot enough to evaporate moisture without any problem. However, the peaking period also depends on the fire lighting and tending method. The maximum power of volatiles $P_{V,max}$ is also dependent on the moisture content of the wood and has been found to decrease with increase in moisture and becomes constant at a power density of 14 watts/sq.cm.

4.4 Combustion Controlling Factors

Important factors which influence combustion are:

- ! Physical and chemical properties of the fuel;
- ! Fuel/air ratio;
- ! Temperature of the flame/envelope;
- ! Mode of fuel supply;
- ! Primary and secondary air supplies.

4.4.1 Physical and chemical properties

As stated earlier, the combustion process in a cookstove is greatly influenced by the relative proportion of macroscopic constituents of the biomass, namely: cellulose, hemicellulose and lignin. The relative proportion of these constituents varies in different species of biomass. A cookstove designed to burn fuels rich in cellulose will require a better control of secondary air due to production of more volatiles. On the other hand, primary air considerations become more important in a fuel containing more lignin. See sections 4.1 and 4.2 for more details of physical and chemical properties.

4.4.2 Size and shape of the fuel

Volume to surface ratio of the wood fuel is dependent on its size. This ratio has an important bearing on the combustion characteristics of the wood and other woody biomass. Fire penetration rate, which is the rate at which the char boundary advances into the virgin wood is a function of volume/surface ratio (v/a),as is given by equation:

$$\text{penetration rate} = \frac{\text{power output} \times \text{volume/surface ratio}}{\text{volatile fraction} \times \text{total fuel used} \times \text{net cal. val.}} \qquad (4.8)$$

where, power output in kW, volume/surface ratio in mm, total fuel used in kg, net calorific value in kJ/kg. Power output of a fire is given by equation:

$$power\ output = \frac{sum\ of\ individual\ charges \times net\ calorific\ value}{total\ duration\ of\ experiment} \qquad (4.9)$$

With the increase in volume /surface ratio, CO/CO_2 ratio also increases due to increase in the release of volatiles, which remain unburnt as a result of insufficient availability of air.

4.4.3 Primary and secondary air supplies

The introduction of the right amount of air alone is not enough. It is important to introduce it at the right point and time. The air supplied from below the grate in which it reacts with the solid biomass/char is known as *primary air*. While the air which is introduced from above the grate and which reacts with the volatile matter is known as *secondary air*. The relative amounts of primary and secondary air will depend on the proportion of fixed carbon and volatile matter in the biomass fuel, respectively. This will decide the area of the openings for induction of primary and secondary air. Primary air is supplied through the holes in the grate or the side opening. It has been found that it is not possible to get a power output of more than 4 kW in a shielded fire when side holes are used for the air inlet.

4.4.4 Fuel/air ratio

A fuel can burn only in the presence of air, which supplies the oxygen required for combustion. A proper air to fuel ratio is essential for efficient combustion of fuel. Both rich (deficient in air) and lean (deficient in fuel) fuel/air mixtures will result in incomplete combustion. Wood contains nearly 43-44% oxygen and hence a major part of the oxygen required for combustion is supplied by the wood fuel itself while the rest is to be provided from the air. This is in contrast to other solid fuels like coal where a large amount of oxygen from the air is required.

Due to the heterogeneous nature of the solid biomass combustion process, only a part of the air entering a combustion chamber is utilized in the chemical process of combustion, while the rest of the air simply passes through the cookstove. Thus, it becomes necessary to admit more air, than theoretically required. An *excess air factor* of 1.5 to 2.0 is generally recommended for good combustion. In other words, one kg of wood needs 1.4 kg of oxygen at NTP or 6.5kg of air. Applying the excess air factor of 2, then the total quantity of air needed becomes 13 kg. To raise this amount of air to the average flue gas temperature of 450°C would require heat of 5.85 MJ. The excess air factor can be determined also from the percentage of carbon dioxide in the flue gases, which can be measured with the help of an Orsat apparatus. Carbon dioxide content increases with a decrease in the excess air factor and vice versa.

In actual practice, even when the theoretical minimum amount of air, or a little more, is supplied for combustion, the carbon may not get fully oxidized to carbon dioxide. In such situations, the fraction of carbon converted to carbon dioxide as well as carbon monoxide is estimated and used for calculating the amount of air required for combustion from ultimate analysis of the wood. This can be calculated by the following correlation (Prasad et al, 1983):

$$n_{a.st} = \frac{1}{0.21}\left[(1 - \frac{1}{2} \times f) \times \frac{[c]}{12} - \frac{y}{32}\right]\ [mol] \qquad (4.10)$$

where, $V_{a.st}$ is the stochiometric amount of air required for combustion, *p* is the % of carbon in the wood, *f* is the fraction of wood that is converted into CO, *y* is the percentage of oxygen minus eight times the percentage of hydrogen.

The design of the air inlet in the fire box is based on this value. Experiments show that there is a sharp increase in the CO formation if the excess air factor falls below 2. However, the excess air factor required for complete combustion of fixed carbon and volatiles is not necessarily the same. Jusu (1987) proposed that no excess air is required to burn charcoal on the fuel bed. In that case, even if excess air is supplied to the fuel bed, it will act as secondary air and the combustion of charcoal will not benefit. The rate at which primary and secondary air must be supplied depends on the heat requirement during cooking and the way the fire is tended.

4.4.5 Temperature of the flame

Combustion can be hindered if the flame comes in contact with a cold surface, due to the quenching effect. The temperature of the gases near the cold surface decreases below the ignition temperature, due to loss of heat to the cold surface, irrespective of the presence of hot gases nearby. Thickness over which no flame exists, known as quenching distance, is a function of temperature of the surrounding/enclosure and decreases with the temperature. Incomplete combustion is responsible for soot deposition on the cold surface or the smoke in the flue gas. Thermal stratification due to quenching can be reduced by generating artificial turbulence, to ensure the mixing of gas and air and increase residence time. This can be easily done by introducing design innovations.

From the thermodynamic and heat transfer perspective, the flame temperature should be as high as possible. This depends on the calorific value and the excess air factor. One of the major reasons for the popularity of open-fire cooking is rapid cooking of food as the pot is surrounded by the flame, the temperature of which exceeds 800°C. The thermodynamic efficiency of the combustion process is given by the ratio $(T_2\text{-}T_1)/T_1$, where T_2 is the highest temperature attained by the flame and T_1 is the outlet temperature of the gas. Thermal efficiency is more dependent on the flame temperature than the flue gas outlet temperature as the latter varies within a small range. Actual temperature is difficult to measure as there is a variation in local temperature at different points in the flame, since air/fuel mixing as well as combustion processes are not instantaneous. Hence, a theoretical flame temperature is generally used in the combustion calculations. The theoretical flame temperature (*TFT*) is given by the equation:

$$TFT = \frac{\text{sensible heat in fuel and air} + \text{heat of combustion}}{\text{total quantities of combustion products} \times \text{mean specific heat}} \qquad (4.11)$$

This shows that the theoretical flame temperature is not only a function of the calorific value of wood but also of the excess air factor. Under perfect combustion conditions and the use of a theoretical quantity of air for combustion, the flue gas should contain only carbon dioxide, water vapours and nitrogen. However, under actual conditions, the products of combustion contain unburnt materials such as carbon monoxide, hydrogen and solid and liquid materials which form smoke. In addition, considerable heat losses take place in the combustion chamber. Because of this the actual flame temperature is usually 30-170°C lower than the theoretical flame temperature.

4.4.6 Fuel supply

Combustion is also influenced by the mode of fuel supply. Fuel can be supplied in three modes, namely: continuous, stored and batch. In cookstoves using solid fuel, it is generally supplied in batch mode in which fuel is supplied in charges of small quantities. A number of charges are, therefore, needed in one cooking job. The power output of the fire cycles between minimum and maximum from the instant of charging to the time when generation of volatiles is at a maximum. A lot of heat is absorbed by the fresh charge which is responsible for low power output. Thus, it can be concluded that the smaller the charge of the fuel, the more unsteady is the behaviour of the fire. The storage mode of fuel charging requires sufficient care so that the bulk of the fuel does not come in contact with the high temperature, which will result in uncontrollable spontaneous combustion.

4.4.7 Concluding remarks

A number of attempts have been made by different researchers to define a universal criterion for self sustained combustion. It has been concluded that ignition is related to the temperature at any point inside the material attaining a certain value. The temperature distribution for different boundary conditions has been reported by Carlsaw and Jaeger (1959). Steward (1974) derived a correlation, based on the minimum incident energy for ignition depending on the Newtonian cooling coefficient, based on the experimental results of Simms and Law (1967). A variation of +15% to -50% between the theoretical and experimental results was found. This may be due to lack of understanding of ignition in the gas phase and the interference of other parameters such as fuel thickness, configuration of fuel in the bed and bed voidage.

5 IMPROVED COOKSTOVE TECHNOLOGIES

5.1 Combustion in Small Enclosures

The developmental approach to cookstove design, as explained in section 1.2 and sections 2.2-2.3, has been shifting from fuel efficient stoves to emission efficient stoves. A high performance stove should be efficient from both these perspectives, so as to ensure conservation of the fuel as well as the environment. This will not only reduce the drudgery of the users but will also save them from the harmful effects of the pollutants emitted during combustion. One of the strategies adopted in a large number of designs is to improve thermal efficiency and provide a chimney for the removal of smoke. Although this strategy helps in improving the indoor air quality, the quality of combustion is questionable in a number of designs. A better approach would be to increase the heat transfer as well as the combustion efficiency. An increase in the heat transfer results from the efficient transfer of heat produced during combustion and a reduction in the losses from the body of the stove. Combustion efficiency can be enhanced by ensuring complete combustion. A complete conversion of chemical energy to heat with a minimum (but sufficient) amount of excess air can take place if the following conditions are met:

- High temperature in the reaction zone;
- A requisite supply of the oxidant (air) and its complete mixing with the fuel;
- Adequate residence time of the reactants (air and fuel) under the above conditions in the reaction zone.

In case any of these conditions is not met, the combustion reaction will not proceed to completion, resulting in the emission of pollutants and the loss of potential heat. In contrast to liquid or gas fuel burners, it is extremely difficult to meet these conditions in heterogeneous combustion, as is the case in cookstoves using solid biomass fuel. Whenever there are reducing conditions due to a deficiency of air or an excess amount of volatile matter in the combustion zone, free carbon and hydrocarbon compounds escape from the combustion zone without complete combustion, resulting in the formation of soot and other toxic poly-aromatic hydrocarbons. Thus the design and operating parameters are as important as the fuel parameters. As shown in section 4.1, there is very little variation in the chemical composition and energy density (energy/unit mass or volume) in woody biomass. However, there is a significant variation of other properties among different types of fuels: wood, agriculture residues, dung cakes, etc. This variation in the properties has a profound effect on the overall efficiency and hence must be taken into consideration in the design of cookstoves. In addition to these, there are a number of process factors, which must be taken into consideration as well, so as to maximize efficiency and minimize emissions. These can be divided in to three distinct categories, namely: *design*, *fuel* and *operational factors*:

Fuel factors:	Physical and chemical properties of fuel such as volatile matter, moisture, ash, etc.
Operational factors:	Burn rate/size of the fuel ratio, volume to surface ratio, mode of fuel supply, cooking time, etc.
Stove factors:	Fuel/air ratio, temperature of flame and/or envelope, mode of fuel supply, primary and secondary air, mass of the stove, etc.

Due to inconsistencies in the measurement techniques and the small data base, it is difficult to predict quantitatively the effect of these variables on the overall efficiency. However, the qualitative effects of some of these factors on combustion and thermal efficiency are given in table 5.1

A critical examination of the factors given in table 5.1 shows that the fuel parameters are uncontrollable as they depend on the type of fuel. On the other hand, operational parameters such as fuel size and fuel feeding are user specific, while the stove parameters are design specific. It can be further observed that on a qualitative basis, the stove factors and some of the operational factors are competing factors. However, the data base is inadequate for a quantitative evaluation of the effect of these parameters on the combustion and heat transfer efficiency. At times, contradictory conclusions have been drawn by different authors. This is partly due to a lack of proper understanding of various process principles during which the combustion takes place in small enclosures, and partly due to the inadequacy of the experimental procedures used.

Table 5.1 Qualitative effect of different factors on thermal and combustion efficiency

Factors	**Action taken to**	
	Minimize emissions	**Maximize efficiency**
Fuel factors		
- Ash contents	Minimize	Minimize
- Volatile contents	Minimize	Minimize
- Moisture contents	Optimize @ 25%	Optimize @ 10%
Operational factors		
- Burn rate	Maximize	Minimize
- Size of fuel charge	Minimize	Minimize
- Ratio of charge size to burn rate	Minimize	Minimize
- Volume to surface ratio	Maximize	Maximize
Stove factors		
- Combustion confinement	Minimize	Maximize
- Temperature	Maximize	Minimize
- Excess air	Optimize	Optimize
- Preheated primary air (down draft stove)	Maximize	Maximize
- Mass, short cooking time	Minimize	Minimize
- Mass, long cooking time	Maximize	Maximize
- Time during burn	High early	Low early
- Altitude	-	-

Source: Smith, 1987

It has been estimated (Sangen 1983) that the overall efficiency, during combustion at a particular value of the burning rate, depends on the characteristics of the enclosure (semi enclosed combustion chamber, enclosure without chimney, enclosure with chimney, etc.). With an increase in the burning rate, the heat transfer efficiency decreases, while the combustion efficiency increases. The nature of the combustion operation such as steady/ unsteady combustion, short term/intermittent operation, which is controlled by the ratio of the burn size and the burn rate, has a profound influence on the overall efficiency of the cookstove.

Burning of wood in small enclosures can be classified as controlled combustion in contrast to free burning of wood in an open fire. However, the operation of the cookstove is dynamic in nature because of the interdependence between the rate of combustion, rate of induction of air and the draft. The rate of combustion is strongly dependent on the manner in which the combustion air is supplied. In the case of small enclosures, the combustion takes place due to the pressure field set up as a result of the upward movement of combustion products and entrainment of air through the fire-box opening and the grate, if provided. On the other hand, combustion in open-fire is maintained through the laminar or turbulent entrainment of outside air, depending on the size of fire. Hence, apart from combustion, fluid flow considerations are equally important in the design of an ICS.

5.1.1 Design considerations

The *rate of heat output* from a fire in an enclosure is assumed to be composed of two components: heat released from charcoal and heat released from the combustion of volatile matter. This assumption is valid for the entire combustion process, in low power fires and during the steady state period at modest power levels as well. However, for large power levels, this assumption will not be valid as the fuel bed will consist of wood under various stages of thermal decomposition. Even in low and medium fires, it is difficult to estimate the rate of burning of charcoal or volatiles independently. Based on various assumptions the design power has been defined (Bussman et al 1983) as:

$$P_{des} = 0.7 \times (P_c + P_{v.max}) \tag{5.1}$$

where $p_{v.max}$ is proportional to: the fire penetration rate, volatile fraction, charge weight, heat of combustion of volatiles, and the area to volume ratio of the wood pieces.

The rate of heat output is controlled by the volumetric flux of air and depends upon the size of the opening of the fire-box and grate hole openings. The burning characteristics of fire in small enclosures can approach the combustion in an open-fire if the size of the fire-box opening and the grate opening is increased substantially. Thus, the amount of heat released from a cookstove can be controlled by controlling the size of the fire-box and the grate openings and/or using other strategies such as the provision of dampers or building up of a resistance in the flow path.

Unfortunately, very little information is found in the literature with regard to experimental data on the combustion behaviour of wood in ventilated controlled fires as encountered in an ICS. However, extensive studies have been conducted in order to be able to estimate the fire load in relation to the fire resistance in buildings. The only difference in the configuration of these studies and that of cookstoves is that the side opening serves both as outlet and inlet for the combustion products in buildings, while these are discharged from the top or a separate side outlet in the case of cookstoves. On the basis of these studies, combustion in small enclosures can be characterized by an opening factor defined as:

$$A \times H^{½} \tag{5.2}$$

where A is the area of the side opening and H its height.

For a small opening factor (small air flow), the mean burning rate during flaming combustion for a certain range of fire load densities (weight of fuel per unit area) is almost proportional to the air flow rate but independent of fire load density. However, with a large opening factor (large air flow) the burning rate approaches a constant value. Under these conditions, the system tends to approach the limiting conditions of the open-fire, where the burning rate increases in proportion to the fire load/surface area.

It has been estimated that for ventilation controlled fires, a minimum of 15 grams of fuel per cm^2 of area opening is required. The proportional regime lasts till the measured flow is about 10 litres per second. These conditions should be satisfied in the design of ICSs, as the combustion of wood in an ICS falls in the category of the proportional regime. The combustion has a tendency to become turbulent between 260°C and 290°C (Micuta 1981) if the air supply is not restricted. But this can be done by reducing the air supply or the draft or both.

It can be concluded that combustion in small enclosures, as applicable to solid biomass burning cookstoves, is not properly understood. There is a need to undertake extensive controlled experimental work on the quantitative estimation of the effect of various parameters such as fuel, stove, and operational parameters on the combustion as well as heat transfer efficiency.

5.2 Influence of Sub-system Design on Optimum Efficiency

The design of an ICS involves the application of heat transfer, combustion and fluid flow principles in order to attain complete combustion of the fuel with a minimum amount of excess air, maximum transfer of heat from the flame and the flue gases to the cooking vessel, and a minimum loss of heat to the surroundings. This can be accomplished by optimizing and/or incorporating various subsystems in the stove, as shown in figure 5.1. These subsystems are:

- firebox/combustion chamber and stove walls;
- grate;
- air/fuel inlet;
- flue/chimney;
- baffles;
- dampers;
- connecting tunnels.

5.2.1 Fire-box/combustion chamber

This is the chamber in which the combustion of the fuel takes place. It has provisions for entry of fuel and air required for the combustion process. Different configurations for entry of fuel and air are discussed in later sections. The chemical energy of the fuel is released in this chamber in the form of heat. The engineering design of the fire-box is very important in order to ensure complete combustion and the efficient delivery of this heat to the cooking pot. The design of the fire box is based on the average power output P_{av} of the cookstove in kW, which is defined as:

$$P_{av} = \frac{\Sigma \Delta m_f \times H_c}{t_T} \tag{5.3}$$

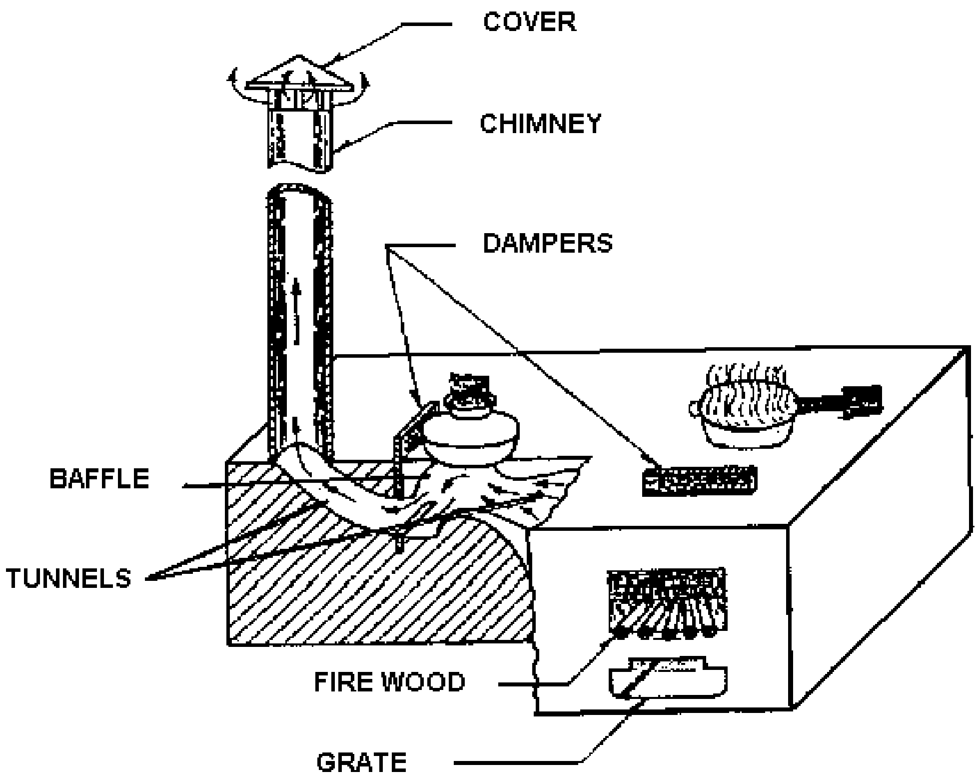

Figure 5.1 Isometric view of Dhaula Dhar chullah

where $\Sigma\Delta m_f$ equals the sum of the individual wood charges during the experiment, H_c is the net calorific value of the fuel and t_T is the total burning time. Equation 5.3 can also be written as shown in equation 5.4 where Br_{av} equals the average burning rate:

$$Br_{av} = P_{av} \times H_c^{-1} \tag{5.4}$$

Through substitution, equation 5.4 can also be written as follows:

$$Br_{av} = \frac{V}{V_{th}} \tag{5.5}$$

where V is the volumetric flow rate of primary air and V_{th} is the theoretical amount of air required for combustion.

The design of the combustion chamber must take into account the effect of some of the competing factors such as heat transfer and combustion quality. Efforts to maximize the heat transfer deteriorates the quality of combustion and vice versa (see table 5.1). On the basis of studies conducted on open fires (Bussman 1988) and pyrolysis considerations, the combustion chamber can be assumed to be composed of two sections, namely: the *charcoal combustion* section and the *volatiles combustion* section.

The volume of the charcoal section depends on the power output required, the mass of wood charged, the packing density and the burning characteristics of the wood or other woody biomass under consideration. It can be calculated by using equation (5.6):

$$H_{cc} = \frac{\Delta M_f}{x \times p_f \times A_{cc}} \qquad (5.6)$$

where ΔM_f denotes the fuel charged (kg), x is the packing density, p_f is the density of the fuel, A_{cc} is the cross-sectional area of charcoal bed and H_{cc} equals the height of the charcoal bed.

$$A_{cc} = \frac{P_{design}\ [kg]}{P_{density}\ [kg/m^2]} \qquad (5.7)$$

In the case of an ICS with a grate, the power density depends on the type of grate. The diameter, calculated by the use of equation (5.7) gives a smaller diameter of the fire-box in relation to that of the pan, which results in a lower efficiency. From his studies on open fires, Prasad (1981b) concluded that the heat output from the combustion system increased with the increase of the fuel bed diameter and its thickness. However, a large fuel bed thickness hampers the efficient combustion. The diameter of the user's pot and the quantity of the food cooked should also be taken into consideration in deciding the fuel bed diameter. The radiation input to the pan increases with:

- the decrease in fuel bed diameter to pot diameter ratio for a given height of pot above the fuel bed;
- a reduction in the pot height above the fuel bed for a given fuel bed diameter to pot diameter ratio.

In designing the charcoal section, the contribution of the convective heat transfer should also be taken into consideration. A detailed analysis of the heat transfer characteristics of the open- and shielded-fires as applicable to cookstoves is presented by Bussman (1988) and Prasad (1981b). In the design of the volatile combustion section, the height of the flame is taken into consideration. If the height of this section is less than the height of the flame, the flame will touch the cold pot which will result in it being quenched. This leads to incomplete combustion resulting in tar deposits and an increase in the emission of pollutants.

Based on the experimental studies on flame heights in open fires, Herwijn (1984) concluded that the flame height of an open-fire can be expressed by:

$$H_{fl} = C_2 \times P^{2/5} \qquad (5.8)$$

where P is the power output and C_2 is a constant, which depends on the type of grate. Values of this constant are: 75 mm/kW$^{0.4}$ for a fire with a grate and 110 mm/kW$^{0.4}$ for fires without a grate, for the test using oven dry white fir (wood). The use of this correlation results in higher heights of the volatile combustion section. A number of studies have been conducted to evaluate the effect of the height of the pan on the efficiency of the stove by Vermeer and Sielcken (1983), Sulilatu et al (1984), and Bussman (1988). The results from these studies are contradictory and inconclusive. A combustion chamber height of 150-180 mm has been suggested by Joseph (1979) for stoves without a grate. The combustion chamber height is a critical parameter and has a profound influence on the efficiency. A low combustion chamber height will result in incomplete combustion resulting in the production of smoke due to the condensation of the volatiles. On the other hand, too high a combustion chamber results in a greater entrainment of air, resulting in the quenching of the flame, thus reducing the radiation and convective input to the cooking vessel.

In order to decrease the radiation losses from the flame envelope and increase the heat transfer area between stove and the vessel, the combustion chamber shield is extended so that the vessel can be sunk in the combustion chamber. This configuration can help in reducing the radiation losses, increasing heat transfer area, and convective heat transfer. However, it puts a limit on the size and the shape of the vessel. Soot also gets deposited on the sides of the vessel.

An important factor which must be taken into consideration while designing the fire box is that a stove design, based purely on heat transfer considerations, may not perform the cooking at a rate preferred by the user, as both are competing factors. It is advisable to sacrifice some efficiency at the expense of the user's convenience. Otherwise, the acceptability of the ICS will be drastically reduced (Sharma et al 1992).

The design power should be based on the time required for cooking. Data on the time required for different cooking operations on a cookstove, as a function of quantity of food at maximum power, is not available in the literature. In the absence of this data, correlations based on testing of gas cooking range (GIVEG 1968) is used for the design. These can be expressed as:

$$t_b = 550 \times M_f^{0.38} \tag{5.9}$$

where t_b is the time for cooking and M_f the mass of the food to be cooked. Based on this, the maximum power can be defined as:

$$0 \times P_{max} \times t_b = M_f \times C_p \times (T_b - T_i) \tag{5.10}$$

where η is the efficiency, P_{max} the maximum power, C_p the specific heat of food, T_b the temperature of boiling and T_i the initial temperature.

The application of the results obtained from open-fires based on naturally aspirated fires, as encountered in chimneyless stoves may be valid. However, the use of these in ventilated fires, i.e in the stoves with a chimney, require close scrutiny. Geometric characteristics of the flame get modified due to the net positive suction effect of the chimney. Even in metal stoves with a top plate and without a chimney, the flame characteristics get modified. Data on these aspects is lacking in the literature.

Another important aspect of the fire box design is the reduction of heat losses from the side wall(s), as the temperature in the fire box is very high. Reduction of the heat loss through the stove wall requires the detailed analysis of the conduction process which has been presented in section

3.5.2. Lightweight walls will heat up much faster than thick walls. Walls made out of conducting material like metal will also heat up faster. However the heat loss from the combustion chamber depends on the rate of increase in the temperature of the wall and the amount of heat stored in the wall, which eventually gets lost to the outside. Thus, a wall made of a low thermal conductivity material will result in a lower thermal loss from its outer surface. It is also desirable to make stove walls of high specific heat material, like clay and concrete, as thin as possible. While designing a cookstove there is a need to make a compromise between reduced losses and the ability of the stove to withstand the load of the cooking pot and food inside it. A lightweight metal stove without outer insulation will attain a high outer surface temperature, which will result in higher surface losses and may cause burn injuries. The use of insulating material or a double wall construction can substantially reduce the surface losses from the fire-box.

A cylindrical fire-box of uniform diameter can accommodate cooking vessels with a diameter equal to or greater than the fire-box diameter. In order to accommodate vessels of diameter less than the diameter of the fire-box, either a reducer ring is used or steps of progressively smaller diameter are provided in the firebox itself, so as to accommodate pots of different diameters.

A *side opening* in the stove serves the purpose of air and fuel inlet. In stoves without a grate, the burning rate, and hence the temperature, is controlled by this side opening. Often this opening is also used for baking of traditional items e.g. local breads, peppers, etc. Apart from serving these useful functions, it causes considerable radiation and convective losses. Thus, a side opening has a profound influence on the efficiency of the cookstove. The side opening for air is calculated on the basis of the volumetric flow rate of the air using the following correlation (TERI 1982):

$$V = 29.7 \times A \times h^{1/2} \times (1 - T_a/T_i)^{1/2} \qquad (5.11)$$

where T_a and T_i are the temperatures of ambient air and the average temperature of the bed, A is the area of the side air entrance, and h is the height of the air entrance.

In the case of a stove with a grate, the smaller of the two areas (that of grate or the side opening) is used in the above equation. As the side opening is also used for fuel feeding, its design should take into account the resistance offered by the fuel to the flow of air.

A number of configurations have been used by different designers for the supply of primary and secondary air. Functions of primary and secondary air have already been explained in section 4.4.3. In the cookstoves with a grate but without a side opening, the primary air is supplied from below the grate and separate openings are provided above the fuel bed for the secondary air. In some cases, vessel mounts act as an opening for the secondary air. When side openings are provided along with a grate, the air enters from the side opening(s) as well as through the grate. The relative proportion of the flow of air depends on the extent of resistance encountered through these openings. In cookstoves with side openings without a grate, both primary as well as secondary air enters through the side opening(s).

Cookstoves with a cylindrical fire-box and a side opening are mainly used when cooking is done with long logs of wood or with long-stemmed agricultural residues, such as cotton sticks and coconut fronds. When loose biomass is used, the feeding is done either from the top or through a slanting grate. However, in some designs of the ICS, the feeding of wood in small pieces or charcoal is done from the top. In these stoves, the cooking vessel has to be removed before each feeding.

5.2.2 Grate

The use of a grate in a cookstove improves the combustion efficiency due to a more uniform distribution of air in the fuel bed as a result of better mixing of air with the volatile matter. This results in an increased rate of combustion with a steady flame, thus reducing the losses from the sides of the chamber as the flame does not touch the sides. Air also gets preheated during its passage through the hot fuel bed. Apart from these advantages, the grate reduces the conduction losses from the fuel bed as well as charcoal formation. The formation of carbon monoxide as well as the loss of unburnt volatile matter is reduced at the same time. It facilitates the removal of ash, while retaining the charcoal. The choice of a correct grid spacing of the grate is very important. It has been suggested that the free space should be approximately 25-30%. However, in a properly designed cookstove, it should be based on the air requirement for the design power.

The volumetric flux of air required to generate a specified power is a function of $A_v \times h^{1/2}$, as stated in equation 5.11 above. The volumetric flux will be controlled by the lesser of the two areas, namely the area of side entrance and that of the grate. If the area of grate opening is larger than the side opening, it becomes inert. On the other hand, if the grate opening area is less than the side vent, it controls the power rating of the stove, as the rate of aspiration is dependent on this opening. Too small a grate opening will result in a large pressure drop across the grate.

Another useful function of the grate is that it helps in keeping the fire compact. De Lepeleire (1981) suggested a slope of 45° for the combustion chamber with a grate. However, View Factor considerations, as outlined under the radiation section (section 3.5.2b), must be taken into consideration as well for a proper design of the combustion chamber.

The *grate to pot distance* has a great influence on the efficiency of the stove. Changes in this distance bring changes in the View Factor and the surface area of the vessel. This affects the radiative heat transfer. While the View Factor between fuel bed and the pan decreases, the View Factor between fuel bed and wall, and the wall and the pan increases. When the wall temperature is high, the radiation from the side wall is not negligible as compared to that from the fuel bed. In addition, changes in the flow resistance take place. As a result, changes take place in the gas flow and the gas temperature. This influences the convective heat transfer. Thus it can be concluded that the grate to pot distance has to be optimized taking into consideration other geometric parameters of the stove.

Grates can be made from a large number of materials, such as cast iron, mild steel sheet, mild steel rods, mild steel strips and clay/ceramic. However, the cost, the formability, and the durability have to be taken into consideration in the selection of material.

5.2.3 Pot hole/rim design

For the efficient operation of an ICS, especially one using a chimney, a proper design of the rim of the various chambers of the cookstove is very important. A rim should be designed in such a manner that the flue gases do not escape from beneath the pot. A tapered design of the rim is preferred as cooking vessels of different diameters can be accommodated without a loss of flue gases. In the channel type stove without a chimney, the hot flue gases from the combustion chamber are allowed to expand over a large tapered rim to increase the convective heat transfer. In this type of stove a proper design of the rim becomes very critical, otherwise the thermal as well as the combustion efficiency will be considerably reduced.

5.2.4 Chimney

In wood burning ICSs, sufficient air has to be provided in order to achieve complete combustion. This is accomplished by providing sufficient air openings in the fire-box of naturally aspirating stoves. However, in multi-pot stoves, even with a large opening an additional positive suction head is required to overcome the resistance offered by the flue passages. This is accomplished by providing a chimney which creates suction at the top as a result of the temperature difference between the hot gases at the base of the chimney and the ambient air. As a result, flue gases are drawn from the stove and air is induced into the cookstove. Three forces control the motion of fluid through the cookstove. These are:

- Buoyancy force created by the fire;
- Draft created by the chimney as results of the temperature difference between the base of the chimney and the outside air and the height of the chimney;
- The opposing frictional forces.

The optimum performance of the stove depends on the interplay of these forces. These forces can be manipulated by modifying the design parameters. The buoyancy force can be changed by changing the rate of burning of the fuel. The draft can be changed by extracting more or less heat for the second pot hole, which will change the temperature of the flue gas at the base of the chimney. The same effect can be created by changing the height of the chimney. The frictional forces can be manipulated by changing the design of the flue passages and the diameter of the chimney as well as through the provision of damper(s).

In an ideal situation, the buoyancy force should be equal to the draft under the first pot hole so as to create a balanced flow whereby the flame will rise up to the first pot and then move to the side tunnel. Such an ideal situation is difficult to obtain in the cookstoves due to the variability of the fuel quality and the combustion characteristics. Under these conditions it is recommended to design a stove with a positive draft in spite of the fact that the stove will receive less heat than a well shielded open-fire as observed by Nievergeld (1981), Visser and Verhaart (1980).

The chimney should be designed in such a manner that it should not only be sufficient to overcome the resistance offered by the flow passages in the cookstove, but should also create sufficient draft for the induction of a proper amount of air. The pressure balance on the chimney can be represented by the equation:

$$P_s net = D_{st} - P_{dyn} - P_{res} \tag{5.12}$$

where $P_s$net is the net suction pressure in the chimney, D_{st} is the static draft, P_{dyn} is the dynamic pressure loss and P_{res} is the pressure loss due to the flow path resistance. All the parameters of this equation are discussed in detail in the appendices.

The proper selection of the chimney diameter is also important. A large chimney diameter will result in faster combustion which in its turn will result in large flue gas losses. If the diameter of the chimney is too large, the hot gases may flow in the form of slug flow without contributing towards the draft. On the other hand, flow resistance in a very small diameter chimney is very large and the kinetic loss due to the high velocity would also be large. Thus, a major part of the draft produced by the chimney will be used in overcoming these resistances in the chimney itself. If the resultant draft is insufficient to overcome the resistance in the flow passages, it will result in back flow. While selecting the diameter, the build up of creosote and tar in the chimney must also be taken into consideration. It will reduce the effective diameter. The volumetric flow through the chimney is very sensitive to the diameter of the chimney. It has been suggested that the average velocity in the chimney should be between 0.4 to 1 litre per second.

The capacity of a chimney in terms of volumetric flow increases as to the square root of its height, with other parameters remaining constant. However, the volumetric flux is almost proportional to the square of the chimney diameter. Due to the more sensitive nature of dependence of the volumetric flux on the diameter as compared to height, the former is in practice used more frequently to control the volumetric flux. A 10% increase in diameter will increase the volumetric flux by 21%. However, to achieve the same increase, the height has to be increased by as much as 44%.

Apart from these considerations, practical aspects, such as the extension of the chimney by 75 cm above the highest point of the roof, necessary both from the point of view of safety as well as for preventing down draft which sometimes occurs around buildings, should also be kept in mind while designing a chimney.

The resistance offered by the cowl should also be taken into consideration. The provision of a cowl is essential to prevent rain water from entering the chimney and also to prevent sparks from flying out of the chimney and setting thatched roofs of rural houses on fire. This discussion clearly brings out the fact that a chimney should not be considered as merely a means for the disposal of smoke produced due to the improper combustion of fuel. An optimally designed chimney is essential for the proper functioning of the cookstove at its rated output.

However, many single-pot designs do not have a chimney. In these cookstoves, vessel mounts are provided to support vessels while at the same time these mounts leave an opening through which the flue (exhaust) gases are vented. The draft in these stoves is created due to the flow of the flue gases in the upper portion of the stove above the grate. In such stoves, the clearance between the upper rim of the stove and the pot bottom becomes a critical dimension. The height of the mounts has a considerable effect on the efficiency of the cookstove, and hence needs optimization. The height of the vessel mount is a function of the volume of the flue gases generated, which in its turn depends on the burning rate and excess air factors. Increasing the height of the mount will result in a fall in the temperature of the flame envelope which transfers heat to the pot. At the same time radiation losses from the flame will increase due to the exposure of a greater area of the flame to the environment. On the other hand, a radical decrease in the height of the mount will result in emission of smoke and soot as a result of condensation of the volatile matter. Optimum heights of the mounts, as a function of the combustion chamber height and the burning rate, as suggested by Bhatt (1983) are given in table 5.2.

Table 5.2 Optimum height of the combustion chamber and vessel mounts

Fuel burning rate in kg/hour	Optimum height of vessel mounts in mm.	Optimum height of the combustion chamber in mm.
0.5	30	65
0.8	40	88
1.4	50	110
2.0	60	140
3.0	65	160
5.0	70	180
10.0	75	210

5.2.5 Baffle

A baffle is an obstruction introduced in the flow passage below the second and/or third pot, depending upon stove configurations. It is an important component of an improved multi-pot hole stove with a chimney. A number of designs of baffles such as flat, round, rectangular, spherical, and wedge have been tried in different ICS designs. A baffle serves a number of functions such as: improving convective heat transfer, increasing the residence time, directing the flue gases towards the pan, increasing radiation to the pot, and reducing the flow through the stove.

An increase in the velocity of the burnt gas, as a result of a reduction in the flow passage gap between the top surface of the baffle and the bottom of the pot, increases the convective heat transfer coefficient and hence the heat transfer to the pot. The extra mass of the baffle below the pot absorbs heat from the burnt gases. Part of the absorbed energy is radiated back to the pot, but the absorbed heat also increases the baffle's temperature. Due to resistance in the flow passage as a result of the baffle, the residence time of the flue gases increases, resulting in increased heat transfer. Wedge shaped or raised platform type baffles help in directing the hot flue gases towards the pot, on being discharged from the tunnel, irrespective of the relative values of buoyancy and drag forces.

A number of experiments were conducted by Prasad (1983) to study the effect of various baffle constructions on the efficiency of the Nouna stove. It was concluded from this study that apart from increasing the efficiency of the second pot as a result of increased convective and radiative heat transfer, the efficiency of the first pot also increases. This was attributed to the higher combustion temperature caused by the flow of a lesser amount of air through the stove, resulting in greater radiative heat transfer. Convective heat transfer also improves as the baffle prevents the flame from turning away from the first pot resulting in quick heating of the pot, which helps in faster cooking of the food. It was observed that the relative efficiency of the modified Nouna stove improved by 50% for the first pan and 180% for the second pan, over the traditional one, due to the introduction of the baffle. However, data on the effect of the baffle shape, and the gap between baffle top and pot bottom on the hydrodynamics characteristics and efficiency is lacking in the literature.

Optimizing the baffle gap is essential, as it is the most critical dimension. Too small a gap will introduce large resistance in the flow passage, thus effecting the air induction, which adversely affects the combustion characteristics. On the other hand, a large gap will result in reduction in the heat transfer to the pots. Studies conducted on the effect of baffle height on the performance of a cookstove (Sharma 1990c) showed that an increase of 10 mm in the clearance between pot bottom and baffle, in a damperless model, manifests itself in the loss of 150 g/h at a burning rate of 1 kg/h. A gap in the range of 35-75 mm has been recommended.

While designing the baffle shape, it is essential to take into consideration the user's needs also. For example, wedge shaped baffles get damaged with the use of round bottomed pots or pans if the diameter is smaller than the pot hole diameter. This was experienced in India and necessitated the modification of the baffle design to suit the requirements of the users (Sharma 1990c).

5.2.6 Connecting tunnels

In the multi-pot stoves, different chambers of the stove are connected with each other and to the chimney through tunnels. These tunnels have been made in different shapes and sizes by various authors. Some of the most widely used designs are cylindrical, diverging and converging tunnels. These tunnels may not be treated as simply connecting passages for the flow of flue gases between different chambers. The shape and size of these tunnels have a great influence on the combustion process in an ICS. As explained in section 5.2.4, net positive suction head which is responsible for the induction of air in the stove, depends on the flow resistances offered by the flow passages. Diverging and converging tunnels offer more resistance to flow due to sudden expansion and contraction, respectively. Similarly, smaller diameter tunnels will create more pressure drop. Pressure drop through the flow passages has been discussed in detail in appendix 1. An excessive pressure drop is not always disadvantageous. Sometimes it is intentionally introduced to improve the performance of a stove as has been done in the development of damperless models (Sharma 1991). Similarly the turbulence can be created for increasing the heat transfer coefficient by the use of converging tunnels.

5.2.7 Damper

Power output of a stove can be controlled either by varying the fire diameter or by controlling the air induction in the stove. The former method can be applied only to the open fires, where the power output can be varied by varying the fire diameter (Prasad 1981b). The use of a damper, which is a movable plate, in the flow passage has been proposed for controlling the air supply, and hence the power output. Dampers can be made from metal sheet or stone or clay block. Two positions of dampers are generally recommended. These are at the bottom of the chimney and at the mouth of the fire box. The dampers are generally rectangular in shape. However, overlapping trapezoidal dampers have been found to be better, due to efficient control of air when long pieces of wood are used (Sharma 1983).

Studies undertaken by Prasad (1981a) showed that the damper position hardly influences the efficiency when baffles are provided in the flow passage. This has been attributed to the existence of a main pressure drop over the baffle. This was a very important observation from the point of cookstove design, as the function of controlling the air supply in a stove could be performed by the baffle itself.

A damper, placed at the bottom of the chimney has been found to increase efficiency, as a result of reduced draft. However, for the proper functioning of the damper, it is essential that the flow resistance of the different elements of the stove such as flow passages, air inlet and chimney should be approximately equal to one another. It is difficult to accomplish this in the design of a cookstove due to the difference in the flow of air at the inlet and the flow of flue gases in the flue passages, as a result of density difference. Draft or the driving force is governed by the temperature at the chimney bottom, which in turn is governed by the power output of the fire. Theoretical modelling along these lines is lacking in the literature. In actual practice the minimum draft is achieved by manipulating the chimney damper in such a manner that the smoke starts emitting from the fire-box mouth, indicating a balanced flow.

In spite of some useful functions of the dampers, it has been observed that rural women are reluctant to use these dampers for various reasons, such as burn injuries, use of thick logs of wood, and inability to puff *chapattis* in the combustion chamber. As most of the improved models being propagated are designed to work with dampers, their acceptance level in the field has been found to be very low, due to large consumption of fuel (contrary to the claims of the designers) as a result of the non-use of dampers.

In order to solve this problem a damperless model of cookstove was developed by Sharma (1991), after undertaking detailed hydrodynamic and heat transfer studies. A resistance equivalent to the resistance of the damper was introduced in the flow passage, by re-designing the baffle. This innovation saved the Indian cookstove program from catastrophe. This shows that the baffle design should be based on hydrodynamic considerations, so as to achieve a balanced flow. This will eliminate the need for dampers.

Thus, it can be concluded from the above discussion that it is not possible to design an efficient stove without the integration of the different sub-systems or components as mentioned above. These components must be designed after the application of various scientific principles as stated in different sections of this manual.

5.3 Cooking Utensils

Besides cookstoves, cooking utensils are also important components of the culinary (cooking) system. Cooking utensils can be subdivided into two main groups e.g. cooking vessels such as cooking pots, frying pans, kettles, etc. and other utensils used for food preparation like meat grinders, chopping knives, spoons, etc. Although food preparation utensils may not have a direct bearing on energy use, they are important as food can be better pre-prepared with these utensils so that the cooking of food can be sped up and as a result time and fuel can be saved.

With regard to cooking vessels there are many types available which can be sub-divided according to numerous parameters as shown below:

- materials used: aluminum, copper, brass, sheet metal, cast iron, stainless steel, ceramic, pottery, glass, etc.;
- shape: flat or spherical bottom, etc.;
- operating characteristics: atmospheric or pressurized;
- type of operation: boiling, frying, etc.;
- size: diameter and height.
- specialized design: energy saver with thick aluminum bottom or copper, etc.

All of these cooking vessels have one thing in common: food or liquid is kept inside the vessel where it is heated from the outside by a fire generated in a stove.

5.3.1 Material characteristics

The heat transfer from the fire to the cooking vessel takes place by radiation and convection and its subsequent transfer to the food in the vessel is governed by conduction and convection. The thermal properties of the cooking vessel material such as, thermal conductivity, thermal diffusivity, heat transfer coefficient, and emissivity of the material of the cooking vessel itself have an important bearing on the heat transfer from the fire to the food as well as with regard to surface losses. The thermal diffusivity influences the rate of heating or cooling. A material with high thermal diffusivity will acquire uniform temperature in a short time and uneven stresses are also reduced. Thermal diffusivity is defined as:

$$\alpha = \frac{k}{\rho \times c_p} \tag{5.13}$$

where α is the thermal diffusivity, k is the thermal conductivity, ρ is the density and c_p is the specific heat of the material.

The heat transfer from the fire to the contents of the cooking vessel is governed by conduction and convection principles, which have been discussed in detail in section 3.5. A high thermal conductivity (*k*) of the pots helps in better transfer of the heat to the food. Thus aluminum pots transfer heat much faster than ceramic and pottery vessels and can save energy as compared to the latter, as far as the utilization of energy is concerned. However, the losses to the surroundings from the aluminum and other metal cooking vessels will be higher than for clay based cooking vessels.

The overall heat transfer coefficient of aluminum is 18 $W/m^2{}^\circ C$, about double that for clay pots for which the heat transfer coefficient is about 9.7 $W/m^2{}^\circ C$. Copper or its alloys have even better heat transfer characteristics. However, acidic types of food, when stored in vessels made out of this material, make the food unfit for human consumption. Because of the superior heat transfer characteristics, cooking vessels are sometimes fitted with a double bottom part with a thick copper sheet attached to the metal bottom of the cooking vessel. Stainless steel vessels are favourable from heat transfer and corrosion considerations. However, the cost is quite high compared to aluminum. Thus in the developing countries, use of aluminum vessels will be effective both from the viewpoint of heat transfer and cost.

The emissivity of the material of the cooking vessel influences the amount of the heat radiated from or absorbed by the wall of the vessel. A layer of soot on the surface of the vessel will increase the heat losses, and should therefore be discouraged.

It has been estimated (Geller et al. 1983) that the material of the cooking vessel has a strong influence on the efficiency. The average efficiency for meals in which two or more aluminum pots are used has been found to be twice that obtained with clay pots. The lower efficiency obtained in the case of clay pots, as explained earlier, may be due to one or more of the following reasons: a greater resistance offered by these pots to heat transfer; a greater emissivity of the clay pots; an increased evaporation loss due to leakages from the lid which in general does not have a close fit with the cooking vessel; and finally vapour transpiration losses due to the porous nature of the clay pots. Despite the thermal weakness, clay pots are preferred for several traditional dishes due to the enhancement of flavour, because they keep the food warm, and other reasons.

5.3.2 Geometric factors

The rate of radiant energy transfer between the fire and the pot is governed by the geometric factors of the vessel. A flat bottomed vessel will receive more heat through radiation than a round bottomed vessel. However, a round bottomed vessel will transfer the heat to the contents of the vessel in a more efficient manner than a flat bottomed vessel, as a larger surface area is involved, one of the governing factors through which the thermal efficiency is strongly influenced. The surface area to the volume ratio of the utensil should be large so as to ensure a longer residence time between the cooking vessel and the flue gases. However, the surface area, in relation to the volume of the cooking vessel, should not be too large and a cooking vessel should be used whose surface area to the volume is at an optimum level. This will ensure that the overall heat transfer from the fire to the food will be at the optimum level, too.

5.3.3 Operating characteristics

Cooking vessels may be pressurized and non pressurized. In the boiling types of cooking, the use of a pressure cooker can speed up the cooking process, as the boiling temperature in the vessel increases with the pressure in the vessel. This rise in temperature of the food contents increases the rate of the physico-chemical process of the cooking.

A non-pressurized vessel with a tight fitting lid can greatly reduce the evaporation losses when the vessel is being heated up to the boiling temperature. During simmering, the role of a lid in reducing vapour losses from the cooking vessel is less decisive as the vapour is under pressure and can escape, especially when the lid is not tight fitting. Condensation of steam on the inner side of the lid also takes place, which results in large losses through the lid to the atmosphere, if the lid is made from a conducting material. For example, it has been estimated that a 0.5 mm thick aluminum lid will loose approximately 700 W/m^2 in still air as compared to 233 W/m^2 when a wooden lid, 3 cm thick, is used. If conducting lids are used, the power control of the fire becomes more important as far as the reduction in heat loss during simmering is concerned.

The use of a so-called hay-box can also reduce fuel consumption considerably. A hay-box is a container which is lined with some insulating material such as straw, other agricultural residues, waste paper, etc. Food is brought to the boiling point on a stove and is then placed inside the hay box. The food gets cooked by the residual heat of the food. In the boiling type of cooking, this is an important method for initiating energy conservation and time saving measures.

Thus, it can be concluded from this discussion that the use of proper cooking vessels, designed on the basis of the heat transfer and fluid flow considerations, can play an important role in the conservation of energy.

5.4 Stove Construction

Cookstove construction methods are primarily dependent on the material of construction. Even the design of a cookstove itself is also influenced to a great extent by the material of construction. In addition, the modes of fabrication, cost, efficiency, durability and safety of a stove depend on the material of construction. Thus, proper selection of the stove construction material is of paramount importance and is the first step towards the design and development of the ICS.

5.4.1 Criteria for selection of material(s), construction methods and strategies

The selection of materials of construction depends on a number of factors, which can be grouped into three main categories: economic factors, operational factors and design factors.

a) Economic factors

Economic factors include the cost and technological factors. The cost factor is one of the most important parameters from the point of view of affordability by the users in the developing countries. The cost of the stove comprises material cost, fabrication cost and transportation cost. The technological costs, such as the method of fabrication and repair should also be taken into consideration, even at the conceptual stage as these have an important bearing on the overall cost of the ICS (see also section 3.4.4).

b) Operational factors

A biomass burning cookstove is subjected to severe operational stresses, which may be mechanical, thermal or chemical. The cookstove material should offer a maximum resistance to these stresses. Some of the important parameters which need consideration are: strength, impact resistance, thermal stresses (steady/unsteady/shock) and phase stability at the operating temperature. The resistance to thermal loss is also important from efficiency and safety considerations.

The cookstove material is also subject to severe chemical stresses which manifest themselves in different forms of corrosion, especially mild steel. This problem gets compounded due to the high temperature. These issues must be taken in to consideration in the selection of the material.

c) Design factors

In some designs, a number of the stove components may have intricate shapes, while in others the leakage in and out from the stove may pose a serious concern. Thus, the malleability of the stove construction material also plays an important role with respect to these issues.

The stove construction materials can be divided into two main categories, namely: metals and non-metals. Metals can be further subdivided into other categories, namely: galvanized or non-galvanized sheet metals, cast iron, aluminum, etc. Non-metals are ceramic, fired clay, mud, etc. Besides, there are hybrid stoves which are made out of a combination of materials either metal and non-metal or from combinations of materials from the same group.

5.4.2 Construction problems and prospects

The relative advantages and disadvantages of different construction materials, with respect to different properties, can be shown as in table 5.3.

Table 5.3 Properties of stove construction materials

Type of material	Malle-ability	Impact resistance	Thermal shock	Cost	Insulation properties	Long term stability	Production facilities
Cast iron	G	G	G	M	P	G	Factory
Steel	M	G	G	G	P	M	Artisan
Aluminum	G	M	G	M	P	M	Factory
Unfired clay	G	P	P	G	G	M	Built in situ
Fired ceramics	G	M	P	G	M	M	Potters
Cementitious materials	G	M	M	M	M	M	Fac./ Artis.

Note: G denotes Good, M denotes Medium and P denotes Poor.

It can be concluded from the table that clay and cast iron have the most favourable properties for the construction of stoves. That is the main reason for the widespread use of cast iron to construct stoves, in particular in developed countries, where cost considerations are not an overriding factor. On the other hand, clay which is available at no cost is the most preferred material in the developing countries. However, hybrids like metal clad ceramics and/or castable ceramics have shown great promise as a material for stove construction as these combinations can overcome some of the drawbacks of both the categories.

Clay stoves such as mud, mud/brick, mud/stone stoves, etc. are widely used in most of the developing countries. This is not only because of the low cost and high availability, but also due to the ability of the artisans or the owners to build the stove without any direct financial cost.

In spite of these advantages, clay has certain inherent problems. Its properties differ from place to place due to variations in the proportion of different components of the clay such as clay (particles smaller than 2 µ), sand (particles with a size over 20 µ, and silt (particle size between that of clay and sand). With too much clay, the mass dries quickly, shrinks a lot (often unevenly) and is prone to cracking. Too much sand will make the stove more fragile, while too much silt results in flaking of the surfaces in contact with the flame and hot gases.

However, the properties of the clay can be favourably modified by adding one or more of the deficient components or some additional additives. For example, in the absence of clay, molasses or raw sugar can be used as a binder. The following mixtures have been suggested by VITA and ITDG (1980), as shown in table 5.4.

Table 5.4 Suggested mixtures of soil/sand

Soil type	Mixing Proportion		
	Clay soil %	Sand %	Clay/sand mix ratio
Pure clay soils	15-25	75-85	1:5 to 1:3
Clay/sand soils	25-35	65-75	1:3 to 1:2
Clay/silt soils	25-35	65-76	1:3 to 1:2

Source: VITA/ITDG, 1980

Cookstoves made out of un-fired clay deteriorate quickly as water (in the form of rain or moisture in the atmosphere), food and water spilling during cooking, the constant exposure to high temperature and the stove being knocked by the cooking vessel results in erosion of the clay. As a result, the critical dimensions of some of the stove components such as pot seats, tunnels and baffles, for which the retention of the shape is very important for obtaining high performance, are easily altered.

These problems can be solved by the development of fired clay/ceramic stoves and liners. These stoves can be mass produced in industrial establishments or by village potters, on a decentralized basis. However, the preparation of a proper mixture and composition of the clay to make these types of stove, is extremely important. The mix should have a sufficiently high amount of non-clay materials (sand, grog, etc.) as this will improve the resistance to thermal shock, a major reason why ceramic stoves often fail. The production of ceramic stoves, in particular from clay which has a high non-clay content, requires considerable skill. Fortunately, the firing temperature range of kilns used by the traditional potters and the tile factories, is quite low and this helps in making a more heat resistant stove. Research has shown that stoves fired at relatively low temperatures, 700-800°C, have a better thermal shock resistance than those fired at higher temperatures (HSE, 1992).

5.4.3 Construction technologies

As stated above, the technologies for construction are dependent on the material of construction and the scale of production (owner, artisan, factory based). Various issues involved pertaining to these technologies are discussed below.

a) Metal stoves

Metal stoves can be fabricated from metal sheet and or cast iron. Sheet metal stoves can be fabricated at a central location in a factory or by an artisan. Factory based production systems have the advantages of rapid production, quality control and relatively low cost. However, less job opportunities are generated per unit produced as compared to artisan based or dispersed production systems. Keeping in view the large number of unemployed in most developing countries, there could be socio-economic fall outs. In addition, in these developing countries there are often transportation bottlenecks which will create considerable problems in ICS dissemination. In the case of metal stoves, if the design of the top/bottom plate is intricate or the shapes are contoured, expensive stamping equipment and dies and large power load are required. On the other hand, simple shapes can be fabricated by an artisan using simple sheet metal working tools like cutters, shears, hammers and riveting or welding equipment. Corrosion problems are quite critical in sheet metal stoves. A suitable thermal resistant enamel/paint can enhance the life of the steel, by inhibiting corrosion.

b) Clay stoves

The relative advantages and disadvantages of clay as a material of construction have been discussed in the previous section. The properties of the clay composite depends on the relative proportion of clay, sand, and silt. Clay is responsible for plasticity and cohesion, while sand and silt provide grittiness and smoothness.

Clay based stoves can be built by the block, mould and the pre-fabricated clay slab methods. In the case of the block method, a block is prepared from the clay containing chopped agricultural residues as reinforcement, and cow dung as a binder. It is allowed to dry for some time and the pot holes, tunnels and baffles are carved out with the help of a sharp blade. In the mould method, internal metal moulds are set as per design in a box. Prepared clay is packed around these and is allowed to set. After initial setting, the moulds are removed, dressed and the stove is allowed to set. The third method involves the placement of prefabricated slabs in the required configuration and these are plastered with prepared mud.

Although these mud based stoves have a short life span, they have the advantage of being built by local artisans or the users themselves. These provide opportunities for maintaining local skills and/or employment and expensive tools are not needed. Maintenance can be done at local level using local materials.

c) Ceramic/fired clay stoves

Ceramic stoves require special refractory clay or the local clay has to be modified with additives such as rice husk ash, grog (fired clay in powder form) to improve the thermal and mechanical shock resistance. The main function of the grog is to disrupt the organized structure of fired clay body so as to arrest the propagation of cracks. Ceramic stoves can be moulded in factories using mechanized equipment. They are fired in specially designed kilns which can be regulated according to the time/temperature firing schedule.

On the other hand, fired clay stoves can also be made by the traditional potter using traditional tools like a potter's wheel and a traditional kiln. In order to increase the quality and productivity, both these equipments can be modified. Besides helping maintain the traditional crafts, ICSs prepared by the traditional potters have the advantage of generating local employment, eliminating transport bottlenecks, and ease of maintenance .

5.5 Improved Cookstove Testing

5.5.1 Why test cookstoves?

The testing of an ICS involves a systematic approach to the evaluation of the useful and adverse characteristics of a particular model. It is helpful for comparing different models from the end-use point of view, or for selecting one model from the wide range of models available. Testing also helps in gaining in-depth knowledge about the performance of the individual components which is useful for undertaking further design modifications or incorporating other design features. It allows a better understanding of the processes of combustion, heat transfer, and fluid flow taking place in the stove from the point of view of heat utilization. Without testing it is not possible to quantify the observations on the parametric studies for further evaluation. It will permit the comparison of the results of tests conducted at different places. Thus testing is one of the most important tools from the points of view of quality control and design. It also helps in the dissemination of the technology, by demonstrating to the user the relative advantages of efficient models. In spite of these implications standardized testing methods have yet to be established to afford a universal comparison.

5.5.2 Criteria for testing

Keeping in view the above discussion, a versatile test procedure should have the following features:

a) The test should be simple and easy to perform, at different stages such as in the laboratory, factory, and field.
b) The results of the test should be easy to interpret by the different actors such as: developers, research scientists, implementors, public opinion makers, planners, and the users.
c) Results should be reproducible, within reasonable limits.
d) The test should be versatile so that it is applicable to a wide range of end use applications.
e) It should be able to simulate cooking, as closely as possible.
f) It should be able to predict the effect of different parameters which influence the performance of the stove.

An analysis of the above mentioned requirements indicates that it is not possible to achieve all the objectives within only one test. This is why there have evolved so many test methods and why a number of indices for evaluating the performance of ICS have been proposed.

5.5.3 Indices for testing

The indices proposed for testing the stoves are: the overall thermal efficiency or first law thermal efficiency; the second law thermal efficiency; the specific task fuel consumption and the specific per day fuel consumption.

! Overall thermal or first law efficiency. This indicates the energy-wise performance of the cookstove. It establishes the ratio between the energy output to energy input.

! Second law thermal efficiency. This is a measure of the task index and is the ratio of the actual work output to the maximum work for the same task.

! Specific task fuel consumption. This is defined as the measure of fuel required per unit task output. A task could be cooking a standard meal or producing a jaggery batch, etc.

! Specific per day fuel consumption. This is the ratio of the fuel used over a period to carry out a specific task such as cooking meals for a number of persons over the number of days in that period.

For other tests such as on the combustion quality, the stove safety test, material of construction, etc, the reader may refer to test methods as approved in the India and China compendiums (FAO/RWEDP, 1993a, 1993b).

5.5.4 Overall thermal efficiency testing methods

A number of methods have been proposed to evaluate the overall efficiency of the cookstove. These are: (1) constant heat output method,(2) constant temperature rise method,(3) water evaporation method,(4) constant time method,(5) cooking simulation test,(6) process simulation test for non-cooking stoves. These are described below:

a) Constant heat output method

A known amount of water at ambient temperature is heated in a pot on the stove till it attains a temperature of 96°C. At this point it is replaced by another vessel with the same quantity of water at ambient temperature. The process is repeated till the completion of the combustion process. The efficiency, η, of the process is calculated as:

$$0 = n \times M \times c_p\,(96 - T_a) + M \times \frac{c_p\,(T_b - T_a)}{H_c} \times W \qquad (5.14)$$

where M is the quantity of water in each pot, T_a and T_b are the ambient temperature and the highest temperature attained by the last pot. H_c is the heat of combustion, W is the amount of fuel burnt, n is the number of times cold vessels have been placed on the fire and c_p is the specific heat of the water.

b) Constant temperature rise method

This method is similar to the constant heat output method except that the fixed quantity of water is heated through a fixed rise in temperature ΔT (e.g. 20-30°C) and time t required for this rise is measured. Experiments are repeated a number of times and the average time t_m is calculated.

$$0 = \frac{M \times c_p \times)T \times t_t}{t_m \times W} \times H_c \qquad (5.15)$$

where t_t is total time during which heat output is measured.

c) Constant time method

In this method a fixed quantity of water, M, is heated for a fixed time, t_c, and the rise in temperature is noted. The process is repeated and an average temperature rise, T_{ave}, is calculated:

$$0 = M \times c_p \frac{T_{ave}}{H_c} \times W \times \frac{t_c}{t_t} \qquad (5.16)$$

where t_c is the constant time interval and t_t is the total time.

d) Water boiling test

The water boiling test is a laboratory test which can be used to compare the performance of two or more stoves under similar controlled conditions, or the same stove under different conditions. It simulates the boiling/simmering type of cooking to some extent only. As a result, it does not necessarily reflect the actual stove performance, when food is cooked. A known quantity of water is heated on a cookstove. The volume of water evaporated after complete burning of the fuel is determined. The thermal efficiency, η, is calculated as:

$$0 = \frac{M \times c_{pl} \times (T_b - T_a) + M_1 \times c_{pv} (T_b - T_a) + M_2 \times H_L}{H_c \times W} \qquad (5.17)$$

where M is the mass of water initially in the cooking vessel, M_1 is the mass of the vessel and M_2 is the mass of water evaporated. C_{pl}, C_{pv} are the specific heat of the water and the specific heat of the vessel, respectively, and H_L is the latent heat of vaporization.

In order to simulate the actual process of boiling in a cooking process, which comprises cooking and simmering, the water boiling test has been modified.

In the modified method, the total test period is divided into two parts, namely, the high power phase (heating or cooking period) and the low power phase (simmering period). The rating of a cookstove is good according to this method if a certain mass of water can be quickly boiled during the high power phase and a small quantity of fuelwood is used during the low power phase. The performance of different stoves is evaluated by estimating the thermal efficiency, the specific standard consumption and the power output of the fire (P_H) during the high power phase. During the low power phase, efficiency measurements are not taken, only the power output of the fire (P_s) and the specific fuel consumption is taken into consideration. The specific fuel consumption in this phase is defined as the amount of fuelwood required to keep a known quantity of liquid just below boiling point for a specific period of time.

The higher the ratio of maximum to minimum power output (defined as the turn down ratio), the greater is the potential for fuel saving. The results of the water boiling test depend on a number of factors, both controllable and uncontrollable:

! Fuel conditions - Fuel surface to volume ratio and the calorific value, density and moisture.

! Load conditions - The number of vessels, the mass of the vessels, the thermal mass of the vessel, the thermal conditions of the vessel, the thickness of the vessel, the specific heat of the vessel, the exposed surface area of the vessel, projected area of the vessel which sees the flame, the emissivity of the vessel material, the area of water evaporation surface, the thickness of the soot deposits, the presence and absence of lid and the lid material and finally the cooking substance properties.

- Environmental conditions - Air temperature, water temperature, wind velocity, atmospheric pressure, relative humidity and the kitchen environment.

- Operating Conditions - The feeding and burning rates, the flame temperature, the mass of water load, the accuracy of measuring instruments and the age of the cookstove (as the material may become degraded with use).

A detailed analysis of the effect of some of these factors on the overall efficiency is available in the literature (Bialy 1986a, Bhatt 1983, Geller 1983, and VITA 1985). Out of all the thermal efficiency tests mentioned above, the water boiling and specific fuel consumption methods are the ones which are most frequently used to determine the thermal efficiency of the stove. This is because the constant temperature rise method and the constant time method are only approximate methods, while the constant heat output method is time consuming.

5.5.5 Specific task fuel consumption or cooking test

Cooking tests are performed in order to evaluate the performance of a cookstove while actually cooking food. These tests differ from the water boiling test in respect of the medium to which the heat is transferred. In contrast to water in the water boiling test, food is used as a medium in cooking tests.

Water boiling and cooking tests also differ from each other on the basis of the final state of the cooking substance. In water boiling tests the onset of boiling is the final stage. However, the final stage in cooking is difficult to define as it depends on the perception of the user. It makes these tests user- specific in nature. Cooking tests can be performed in the laboratory, as well as in the field and involve the preparation of standard meals (preferably by the real user or the cook), adopting the culinary practices of the target groups. These tests shed light on different components of the cooking process such as the stove performance, cooking process, fuel used and the time spent during cooking, as well as general observations on smoke and heat emissions. Controlled cooking tests are dependent on a number of factors:

- Composition and physical properties of food,
- Type of cooking operation,
- Mass of food to be cooked,
- Method of preparation of food,
- Type of vessels used.

Within the controlled cooking tests there are again variations in the tests. The controlled cooking tests can be further sub-divided in:

- Single food cooking test,
- Single meal test,
- Full day cooking test (kitchen performance test),
- Process simulation test.

In order to evaluate the relative performance of the cookstoves, it is essential that in all cases the controlled cooking test should be conducted in such a manner that at least the controllable factors, as mentioned above, are kept constant as far as is possible.

a) Single food cooking test

This test involves the cooking of a single item of the meal. It is the simplest form of the cooking tests.

b) Single meal/controlled cooking test

In this test a standard meal is defined on the basis of the requirements of the target group and the quantity of fuelwood required to prepare the standard meal, consisting of various dishes, is determined. It is normally conducted in a laboratory or in the field (actual kitchen) by trained staff who know how to cook traditional dishes. The main aim of this test is to evaluate the relative use of fuel and time in cooking a meal on different stoves and to gauge the ability of the stove to effectively perform the culinary practices of the target group. This test is more complicated than the single food cooking test as the preparation and cooking of a full meal is more difficult to control than cooking a single food item. In contrast to the rigidly fixed test procedures in a water boiling test, flexible procedures are used for the controlled cooking test depending on the type of meal cooked, the stove design and the manner in which the stove is used. However, for consistent results, efforts are made to keep constant those variables which influence the fuelwood consumption during the cooking process. These are the shape and size of the cooking vessels and the type and size of the fuelwood. This is done by preparing the same meal, in the same type of pot, at the same location and time, and in the same way. The cooking efficiency is calculated by the following equation:

$$0 = \sum_{j=1}^{m} \frac{\left\lfloor \left(\sum_{i=1}^{n} m_i \times c_{pi} \times)T + m_i \times p_i \right) + \left(m_w \times L \right) \right\rfloor}{W \times C} \tag{5.18}$$

where c_{pi} is the specific heat of each food item, p_i is the heat of chemical reactions occurring during the cooking process per unit food item, m_w is the mass of water evaporated during cooking, i denotes constituents of one food item and j denotes each food item.

The results of controlled cooking test are comparable, when the same sequence, procedure, and conditions are used.

c) Specific per day fuel consumption test/controlled kitchen performance test

This is a field test in which the relative performances of two stoves, in terms of fuelwood consumption, when used under normal household conditions are compared. The results of this test establish whether a new stove is actually capable of saving fuel. This test takes into account different cooking tasks, such as baking, frying boiling, food reheating, tea preparation, milk boiling, preparation of snacks, etc., performed during the day. This test simulates the actual use of a stove much better than a single meal test. However, much more effort on measurements as well as skills is needed to perform this test. Before performing this test, a typical schedule of meal and operations and their relative timing is established. The mass of the food items, the cooking vessel and the stove design are also fixed.

The fuel consumption of a family is measured over a period of several days, with traditional as well as improved stoves under actual living conditions and is then compared with each other. Controlling factors, such as the number of persons which take a meal, the type of food. Additional chores performed, which influence fuel consumption should also be taken into consideration.

In this test, the amount of fuelwood at the beginning and at the end of each test is measured. It is a prolonged test and the results are depicted in terms of *specific consumption per day*, which is defined as:

$$\text{specific consumption per day} = \frac{\text{kg fuelwood consumed in total days}}{\text{number of persons} \times \text{number of days}} \tag{5.19}$$

In this test, data should be collected from at least five households and the test should be conducted over a period of at least five consecutive days (preferably seven). The specific consumption per day gives a good indication of the energy-wise performance of the kitchen, but does not reveal why and how.

The procedure for conducting the water boiling test, the controlled cooking test and the kitchen performance test have been described in “Testing the Efficiency of Wood Burning Cookstove” (VITA 1985).

5.5.6 Test selection criteria

A critical analysis of the testing procedures of ICSs, described above, shows that none of the tests is complete in itself. Hence, a combination of these tests has to be used to study the complete performance of an ICS. For example, the controlled cooking test is intermediate to the water boiling test and the controlled kitchen performance test. The water boiling test is used for a quick evaluation of the stove design parameters. It is also used to study the effect of operational parameters such as fuel characteristics, burning rate, etc. on the performance of the ICS. Thus, the water boiling test can be used not only to evaluate the relative performance of the different stoves, but also to help the designers optimize different parameters. Water boiling tests may simulate the cooking of food by the boiling process. However, for other cooking operations like frying, baking, smoking, steaming, etc. the performance conditions are entirely different and the water boiling test may not reflect the true performance index of the stove from the user's point of view.

While the water boiling test is performed according to a rigid format, the controlled cooking test uses variable procedures depending on the type of meal cooked, the manner in which the stove is used and the intended design of the stove. This test completely simulates the actual cooking and the stove is subjected to more realistic, though controlled, conditions.

Controlled kitchen performance tests are performed after the controlled cooking test in order to evaluate the energy conservation impact of the new stove on the kitchen energy use and gives far more realistic performance results of the stove under actual conditions, than the controlled cooking test.

It can be concluded from the above discussion that the results of cooking tests are expressed in terms of measured fuel consumption and/or specific fuel consumption, and efficiency. The measured fuel consumption is a valid parameter if the type and quantity of food cooked are similar. The specific fuel consumption (SFC) takes into account the variation in the mass of cooking substance if it is not very large. However, variations in the composition are not taken into consideration. Hence, the SFC should only be used as a criterion to compare the performance of the stoves if the foods cooked are similar. On the other hand, efficiency measurements take into consideration the variation in mass and composition of the food substance, and hence are a better criterion for measuring the performance of uncontrolled/controlled cooking tests.

5.5.7 The concept of efficiency

The concept of efficiency is based on the thermodynamic considerations which are used to evaluate the performance of a device. It is an engineering concept and according to the first law of thermodynamics, the efficiency of a device for a specific operation, is the ratio of the energy output to the energy input. The second law of efficiency is the ratio of the actual work output to the maximum possible work output, for the same task. While the first law of efficiency gives the energy-wise performance, the second law gives the efficiency of the devices to perform a given task. In a wood fired cookstove, heat is generated by partial combustion of wood. Some of the heat so generated is transferred, by radiation and convection, from the fire bed and the flue gases to the vessel, and some of it is utilized for cooking food. The remainder of the heat is lost to the environment, through various heat transfer mechanisms, as described in section 3.5.2. The final residual heat of the flue gases is lost to the environment by dilution. The heat balance of a two-pot mud stove is shown in figure 5.2. Results of the thermal performance of a single pot cookstove and simmering stove (Hara), a two pot medium size (NPIC2M) and a large size (NPIC2L), and a three pot medium size (NPIC3M) and a large size (NPIC3L) cookstove are presented in table 5.5 (Sharma et al 1992).

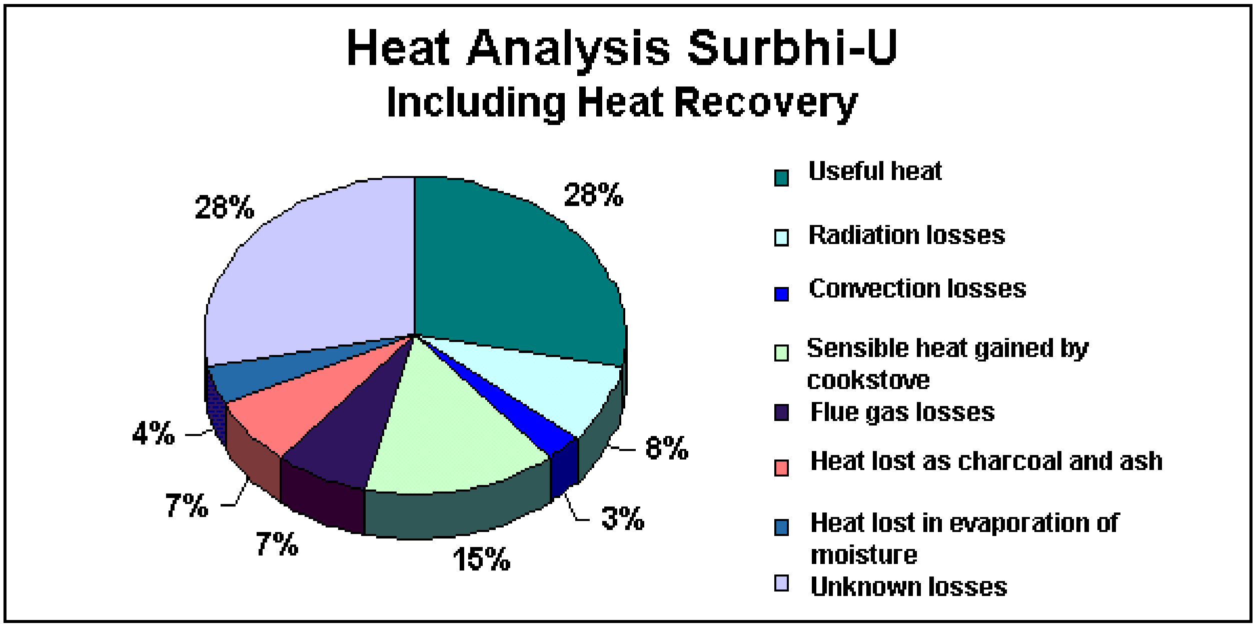

Figure 5.2 Heat analysis NPIC2M

A number of partial efficiencies have been defined (VITA 1985) taking into account the effect of various losses that take place at different stages in a cookstove. These are:

Table 5.5 Results of the thermal performance of various stoves

Performance of Unified Model

Parametres		Single pot	Sohnihara	NPIC 2M	NPIC 2L	NPIC 3M	NPIC 3L
Surface area	m²	0.38	0.28	0.79	0.84	0.91	1.02
Fire box area	m²	0.017	0.027	0.035	0.044	0.039	0.032
Stove weight	%	42	56	104	128	136	290
Useful heat	%	25.15	24.36	23.48	25.68	27.0	28.65
Sensible heat gained by pots	%	0.1827	0.167	0.3643	0.1981	0.2846	0.2212
Radiation losses	%	3.59	4.43	7.38	5.76	7.1	7.09
Convection losses	%	1.34	1.69	3.26	2.20	3.73	4.10
Sensible heat gained by stove	%	4.20	8.01	12.36	18.93	18.33	39.09
Flue gas losses	%	20.59	8.9	12.92	7.8	5.53	11.26
Heat lost as charcoal and ash	%	3.02	6.3	1.77	2.91	1.25	2.70
Heat lost in evap. Of moisture in fuel	%	0.79	0.79	0.79	0.79	0.79	0.79
Heat lost to moisture from H_2 in fuel	%	3.93	3.93	3.93	3.93	3.93	3.93
Heat lost due to CO	%	0.00088	0.0101	0.0015	0.0013	0.0015	0.0388
Unknown losses	%	37.2	41.5	33.8	39.8	32.0	1.4
CO	%	0.08	2.7	0.13	0.12	0.26	0.04
CO_2	%	3.4	5.9	3.0	3.1	6.1	3.4
CO/CO_2	%	0.024	0.046	0.043	0.039	0.040	0.012
Charcoal	g	5	85	5	25	0	10
Ash	g	50	10	25	35	25	60
Flue gas temperature	°C	241	250	138	95	121	125
Burning rate	kg/h	1.0	1.5	1.0	1.5	1.0	1.5

(i) Combustion efficiency: $0_c = \dfrac{\text{heat generated by combustion}}{\text{energy potential in fuelwood}}$

(ii) Heat transfer efficiency: $0_t = \dfrac{\text{gross heat input to the pan}}{\text{heat generated}}$

(iii) Pot efficiency: $0_p = \dfrac{\text{gross heat input - surface losses}}{\text{gross heat input}}$

(iv) Central efficiency: $0_r = \dfrac{\textit{heat absorbed by the food}}{\textit{net heat input to the pot}}$

(v) Overall efficiency: $0' = \dfrac{\textit{net heat absorbed by the pot}}{\textit{energy potential in fuelwood}} = 0_c \cdot 0_t \cdot 0_p$

(vi) Cooking efficiency: $0_{c'} = \dfrac{\textit{heat absorbed by the food}}{\textit{energy potential in fuelwood}}$

The thermal efficiency of a device could be based on the measurements of steady state or unsteady state operations. In the case of steady state operations, the measurements can be taken at any given moment, while in the case of unsteady state operations, the input and output values are measured and integrated over the entire process. Most of the real life processes fall under the second category. Another index of performance is the specific energy consumption which is defined as the amount of energy input required to perform a given task.

While applying these indicators, it should be kept in mind that efficiency is not an absolute physical quantity but a self-defined ratio which depends on the conditions under which a process takes place and how input/output are measured, thus serving only as a guideline. Efficiency may be reproducible in a system having a standard performance like an internal combustion engine. However, combustion of biomass in a cookstove is a variable process because thermodynamic efficiency of a cookstove depends upon a large number of factors such as stove design, fuel composition, vessel design, culinary practice, meteorological conditions and operational variables such as fire tending and rate of heat supply, etc. Most of these factors are variable in nature and hence the thermodynamic efficiency of a cookstove is not a unique property of the cookstove. Thus, it has a limited utility and cannot predict the actual fuel consumption. *The efficiency is a design tool rather than a means of predicting field performance of ICS*.

The stove performance can also be expressed in terms of specific consumption (SC) which measures the fuelwood required to produce a unit output. For cooking, this can be expressed by the equation:

$$SC = \frac{\textit{mass of fuelwood consumed}}{\textit{mass of food cooked}} \qquad (5.20)$$

There is a link between SC and the cooking efficiency which can be expressed as shown in the following equation:

$$0 = \frac{1}{SC} \times \frac{c_{pf} \times)T}{H_c} \qquad (5.21)$$

Where c_{pf} is heat capacity of specific food and H_c is the calorific value.

The specific consumption appears to be a better index for expressing the performance of a cookstove and describing the wood consumption pattern, for planning exercises. During the simmering operation in water boiling tests, the efficiency is close to zero, while the SC will not become infinity. Results of the water boiling tests show that the overall efficiency and the specific fuel consumption show a similar trend.

It can be concluded from the above discussion that the cooking efficiency can be checked more realistically in controlled cooking tests. In order to draw realistic conclusions, the water boiling test, specific fuel consumption, turn down ratio, as well as the evaporation rate should also be specified.

6 ENVIRONMENTAL AND HEALTH IMPLICATIONS

6.1 Environmental Issues

There are two main environmental issues related to biomass conservation (especially the tree/forest biomass): its generation and maintenance and its sustainable use for various purposes, including fuel. While many contributions to the environment from the generation of trees have been well- recognized, the use of tree products, unfortunately, is generally considered problematic to conservation and as such people are often discouraged from their immediate or future use. The persistence of the tree/forest preservation bias is considered a major constraint in the development of a conservation strategy in which the need for tree products for local people's daily survival and productive activities is recognized.

As numerous economic and socioeconomic benefits can be derived from the sustainable utilization of trees and wood products, both at micro and macro levels, it is essential to establish a long term perspective on the wise use of the valuable resource in which people themselves could fully participate in their production, maintenance and use for their own benefit as well as the nation's. Biomass/wood energy development, as a part of this long term strategy, has an important role to play in serving both rural and environmental development goals in most developing countries, if not all.

In the rural domestic sector, especially in many populated Asian countries (eg. China, India, Bangladesh, Nepal, Pakistan and Vietnam), rural people are adopting much poorer quality, more polluting fuels for cooking, such as dungs, crop residues and grasses. This is largely the result of long neglect and/or poor management of land and land based resources. To help these people return to fuelwood use is desirable. From the health point of view, such a movement back to wood would be of great benefit to rural development, since nearly two billion Asian rural people still live in very poor cooking conditions.

6.2 Health Effects Related to Domestic Biomass Fuel Burning

Table 6.1 shows health implications of major pollutants that are normally emitted from biomass burning. Figure 6.1 shows the potential of CO toxicity according to concentrations and exposure time.

Although a number of studies have been carried out in developing countries (China, Guatemala, India, Kenya, Nepal, Papua New Guinea, Zambia, etc) on the health effects related to indoor air pollution as caused by biofuel cooking, the subject is not fully understood. The main reason for the inconclusive nature of the evidence is an insufficient database and the uncontrolled nature of these studies, conducted over a short period of time. In addition, many other confounding factors on health (besides indoor pollutants) are also common and there are difficulties in conducting a study which requires the comprehensive establishment of past health records, behaviours of the subjects and lengthy monitoring of their related activities.

Despite some knowledge gaps, the World Health Organization, based on a consultation (WHO 1992), concluded that “there is growing scientific evidence to support the numerous anecdotal accounts relating high biomass smoke levels to important health effects”. At the same time, it admitted that “more research is sorely needed”.

Table 6.1 Mechanisms of principal health effects from major pollutants

Pollutant	Mechanisms of health effects
Carbon monoxide	Inhalation into respiratory system Absorption into blood from lungs Elevated carboxyhemoglobin (HbCO) levels Reduced oxygen to body tissues Possible cilia-state impact on lung clearance
Particulates	Inhalation into respiratory system Deposition in respiratory tract Irrigation and toxicity
Benzo (a) pyrene	Inhibition into respiratory system Deposition and absorption in lungs Metabolic activation Precursor to cancer
Formaldehyde	Irritation of mucosa Toxicity to cilia Reduction in lung clearance ability Possible carcinogen

Source: Smith, 1987

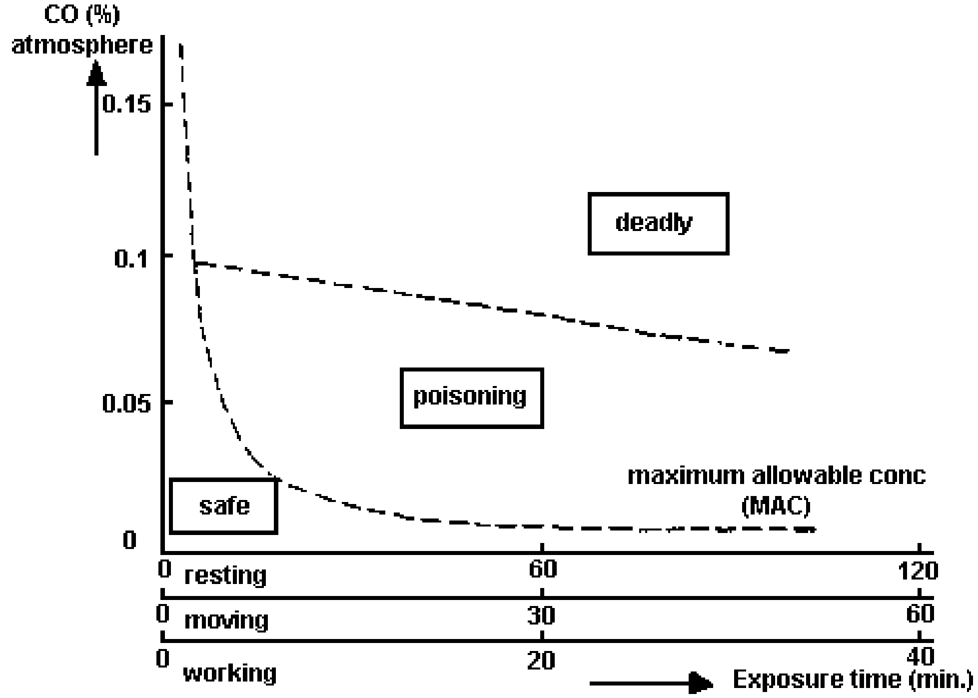

Figure 6.1 Effect of carbon monoxide concentration in the atmosphere as a function of exposure time for various conditions of labour.

Based on those studies mentioned above, two types of respiratory diseases related to biofuel burning smoke have been established, namely: Chronic Obstructive Lung Disease (COLD) in adults and Acute Respiratory Infections (ARI) in infants and young children. Both of these diseases are prevalent among families using biofuel in traditional open-fires or traditional stoves in unvented conditions. “Cor Pulmonale” (heart disease secondary to COLD) has also been found to be prevalent and to develop earlier than average in non-smoking women who cook with unvented biomass stoves (Pandey 1988). Other health effects such as adverse pregnancy outcome (low birth-weight), cancer, etc. are also suspected from biomass burning smokes (tobacco smoking as well as unvented cooking fire). For detailed discussions on biofuel and health, please refer to Smith (1987), WHO (1992).

Pandey (1985), studied the impact of domestic smoke pollution on the respiratory functions and established a direct link between smoke pollution and chronic bronchitis. His study showed a positive interaction between domestic smoke pollution as well as tobacco smoking on lung function. Another study undertaken in rural China, where fuelwood, crop residues and coal are used in households (WHO 1992), reported that among the first ten causes of death of rural Chinese, respiratory diseases rank first, with a mortality rate 73% higher than their counterparts in cities, in spite of a much worse level of outdoor air pollution in cities. Smith (1986) studied the exposure of women to indoor air pollutants, during cooking on traditional stoves using biomass fuel, in four Indian villages. It was found that total suspended particulate (TSP) exposure averaged nearly 7 mg/m^3 and bezo-a-pyrene (BaP) about 4,000 mg/m^3, which is many times more than the permissible limits. In addition, due to improper ventilation and air movement in the kitchen, women and children are exposed to the combined effect of elevated temperature and high humidity in the kitchen which makes working conditions very uncomfortable, especially in the hot and humid climates.

Studies conducted on the estimation of emission factors in traditional cookstoves using solid biomass (Ahuja et al 1987), showed that CO emission ranged from 13-68 g/kg for fuelwood to 26-67 g/kg for dung cakes and 20-114 g/kg for crop residues; for suspended particulates the values ranged from 1.1-3.8, 4.1-7.8 and 2.1-12.0 g/kg for these fuels, respectively. The results have indicated that emissions from both dung cakes and crop residues are 2-3 times higher than fuelwood on a per unit heat delivered basis. Unfortunately, the predominant fuels used in the rural Indian households are either dung cakes or crop residues (due to fuelwood resource scarcity).

This has resulted in a large build-up of the pollutants in the kitchen due to the inherent poor ventilation conditions. This is the reason that the most prevalent polluted environment in the world is to be found indoors, in the rural areas of developing countries. To a certain extent, it may affect the health and productivity of the exposed masses of rural people in the developing world.

Data on smoke emission factors and exposure levels in various kitchen conditions rarely exists. These studies have become more important in the light of evidence that *clean combustion and thermal efficiency are often competing* (see chapters 5 and 8).

Therefore, in order to evaluate the full implication of this problem, there is an urgent need to undertake controlled studies on different aspects of the occupational hazards of smoke. A comprehensive programme should be carried out in earnest over an extended period to study/monitor the indoor air quality caused by biofuel cooking in different agro-climatic regions of the world so as to fully visualize the magnitude of health problems associated with it. The impact of meteorological and ventilation factors, which have a profound effect on the indoor air quality, also need in-depth study. Data on the relative importance of different variables, such as environmental, thermal, social, ergonomical, hygienic etc., contributing to indoor air pollution is lacking and needs comprehensive studies in order to come up with improved solutions.

6.3 Emission Characteristics of Biomass Fuels

In theory, the complete combustion of biofuel in a combustion device like a cookstove should result in the release of just carbon dioxide and water, which do not fall under the category of pollutants. However, it is very difficult to ensure complete combustion in traditional cookstoves and/or ICSs due to the heterogeneous nature of the combustion process, lack of proper control, and design constraints as explained earlier in chapters 3-5. Thus, the emission of pollutants during small scale biomass combustion is unavoidable, in or outside the kitchen. The level of pollution will vary depending on the types of stoves and fuels used.

There exists a wide variety of biomass fuels that are used in cookstoves such as fuelwood, dung cakes, crop residues and grasses/weeds. Apart from these naturally occurring fuels, there are processed fuels such as charcoal and briquetted fuels. The physical and chemical characteristics of the fuel has an important bearing on the combustion characteristics and vary with the type of fuel. Physical and chemical properties of biomass fuel have been presented in detail in chapter 4.

While an ideal fuel and improved cooking system, suitable for rural people has yet to be evolved, the best strategy now is to reduce the products of incomplete combustion (PIC) from the cookstoves as much as possible. Additional discussions are also presented in section 6.4 below.

Table 6.2 shows the emissions from different types of fuels for three major applications: large scale industrial furnaces, small scale residential heating stoves and domestic cooking stoves. It is noted that the pollutants emitted as particulates, sulphur dioxides, nitrogen oxides, hydrocarbons and carbon monoxide are less in the case for larger scale combustion systems than the smaller ones. In fact woodfuel can be burned clean, compared to oil or coal, at a larger scale. Due to its small scale (1-5 kW power output) and short/intermittent operation in nature, it is difficult to always have complete combustion in the domestic cooking stove.

While observing that the quantity of pollutants emitted from biomass burning cookstoves, as shown in table 6.2, is relatively large, it should be pointed out that these pollutants, are based on traditional cooking with thermally inefficient stoves operating mostly without sire grate.

The studies on the role of ICSs, in reducing the indoor air pollution level in Nepal showed that the average exposure rate of total suspended particulates (TSP) dropped from 8.2 mg/cu. m. to 3.0 mg/cu. m. with the introduction of chimneyed ICSs. Carbon monoxide and formaldehyde concentrations dropped from 82.5 ppm to 11.6 ppm and 1.4 ppm to 0.6 ppm, respectively. The impact of the use of ICSs on the indoor air quality was studied by Ramakrishna (1989). In her study, half of the 200 households investigated were using traditional stoves while the other half were using ICSs. Results of this study showed that the concentrations of CO in households using ICSs were much lower than in those using traditional stoves. However, no significant conclusion could be drawn in respect of the degree of exposure to TSP. In a study conducted in Gujrat, India, it was found that in closing a 2 m^2 hole in the ceiling of a small kitchen, the air exchange rate dropped by a factor of 14 and the emission exposure to the cook increased by a factor of 8.

Development of ICSs as recently shown in India, China (FAO/RWEDP 1993a, 1993b) and in Thailand (AIT 1993) have shown low CO emission values.

Table 6.2 Typical air pollution emissions for fuels and combustion systems

System/Fuel	**Estimated thermal efficiency**	**Fuel used** to deliver 1 GJ of useful energy	**Particu-lates** grams per kg fuel burned	**Sulphur oxides** grams per kg fuel burned	**Nitrogen oxides** grams per kg fuel burned	**Hydro carbons** grams per kg fuel burned	**Carbon monoxide** grams per kg fuel burned
Industrial (>20kW)							
Wood	70	89 kg	6	0.6	4	4	5
Bituminous coal	80	43 kg	65	18	8	0.5	1
Residual oil	80	33 lit.	3	42	8	0.1	0.6
Distillate oil	90	31 lit.	0.3	41	3	0.1	0.7
Natural gas	90	28 m^3	---	---	---	---	---
Residential (>5kW)							
Heating stoves							
Wood	50	130 kg	21	0.2	1.4	50	130
Anthracite coal	65	49 kg	1	4	5.0	1.3	20
Bituminous coal	65	53 kg	10	30	3.0	10	100
Distillate oil	85	33 lit.	0.4	41	2.5	0.1	0.7
Natural gas	85	30 m^3	---	---	---	---	---
Cooking stoves*							
Wood (tropical)	15	420 kg	9	0.6	0.7	7.5	80
Cow dung (Hawaiian)	15	530 kg	20	6	7.0	7	83
Coal (indian)	20	220 kg	1.2	10	2.0	10	120
Coconut husk	15	480 kg	35	7	7.0	7	110
Natural gas	80	32 m^3	---	---	---	---	---

Source: Smith (1987)

Wood, 15% moisture (dry basis), 16 MJ/kg
Bituminous coal, 10% ash, 1% Sulphur, 29.2 MJ/kg
Anthracite coal, 0.2% Sulphur, 31.5 MJ/kg
Indian coal, 0.5% Sulphur, 23 MJ/kg
Hawaiian cow dung, 0.3% Sulphur, 15% moisture, 12.5 MJ/kg
Coconut husk, 15% moisture (dry basis), 14 MJ/kg
Residual oil, .944 specific gravity, 45.9 MJ/kg

* Excluding natural gas, cooking efficiency and emissions of biomass fuels and coal are based on traditional stoves without any grate.

Despite the merits of ICSs and their achievement in enhancing cleaner combustion and/or the evacuation of pollutants from the kitchen, from the environmental and health point of views, it is important to recognize that, technically, there are nearly 180 polar, 75 aliphatic and 225 aromatic hydrocarbon compounds which have been identified in wood smoke (Smith 1987). Out of these, 17 toxic compounds, which account for 4.8% of the particulate mass, have been designated as “priority pollutants” by US/EPA because of the evidence of their toxicity. Fourteen compounds, which make up 0.5% of the particulate matter are carcinogenic, while 6 are cilia-toxic and mucous-coagulating agents, and 4 are cancer initiating/cancer promoting agents. These emissions are acidic in nature with pH between 2.8-4.2.

The exposure level to important pollutants and the duration of exposure has been studied in a number of developing countries, where biomass is used as a fuel. Data is presented in table 6.3.

Table 6.3 Exposure of women and children to pollutants during cooking

Pollutant	Cooking emission factor	AER	Concentration during cooking	Multiple of recommended standard	Equivalent dose packs of cigarettes/day
CO	40 mg/kg	7.5	200 mg/m^3	5 (WHO)	1.98
BaP	1.0 mg/kg	7.5	5,000 mg/m^3	800 (USSR)	29.00
TSP	2 gm/kg	7.5	15 mg/m^3	75 (Japan)	3.95
HCHO	0.4 gm/kg	7.5	20 mg/m^3	16 (Europe)	11.00

Source: (Smith 1987)

Cooking burn rate = 1.5 kg/h
Cooking duration = 3 hours

Respiration rate = 1.1 m^3/h
Room volume = 40 m^3

Ambient and occupational air quality standards have been established in a number of countries as shown in table 6.4. It can be seen from table 6.3 that the exposure of women and children to pollutants during cooking exceeds the standards recommended by WHO and a number of countries.

Table 6.4 Ambient and Occupational Air Quality Standards

Pollutant	Averaging time	WHO recommen-dations	Japan	Philippines	United States	
					Occupational	Public
Particulate matter	year	40-60 µg/m^3	-	-	-	75 µg/m^3
	day	100-150 µg/m^3	100 µg/m^3	100 µg/m^3	5000 µg/m^3*	260 µg/m^3
	hour	-	200 µg/m^3	250 µg/m^3	-	-
Sulphur dioxide	year	40-60 µg/m^3	-	-	1300 µg/m^3*	0.03 ppm
	day	-	0.04 ppm	0.14 ppm	*	0.14 ppm (365 µg/m^3)
	hour	-	0.1 ppm	0.3 ppm	-	
Carbon monoxide	day	-	10 ppm	-	-	-
	8 hours	9 ppm (10000 µg/m^3)	20 ppm	9 ppm (10000 µg/m^3)	50 ppm (55000 µg/m^3)	9 ppm
	1 hour	35 ppm (40000 µg/m^3)	-	30 ppm	-	35 ppm (40000 µg/m^3)
Nitrogen dioxide	year	-	-	-	-	0.05 ppm (100 ugm^3)
	day	-	.04-.06 ppm	-	4.5 ppm (9,000 ugm^3)	-
	hour	0.1-0.17 ppm (190-320 ugm^3)	-	0.1 ppm	-	-

* for 8 hours

Source: (Smith 1987)

When cooking using traditional stoves, on average only 10-15% of the potential heat in the fuel is utilized by the pot for the actual cooking. The remainder of that potential heat (85-90%) is dissipated to the kitchen environment in the form of heat and smoke, resulting in the rise of the kitchen temperature and pollution to uncomfortable levels, especially where kitchen ventilation is lacking. This situation also applies for many ICS models with no chimney and/or insulation, despite their double heat utilization efficiencies of up to 30-35%. In the boiling and steaming modes, for example, a large quantity of the water used is dissipated in the form of steam, which drastically increases the relative humidity in the kitchen. All these kitchen pollutants, including heat, steam, oil, and spice fumes not only render the air inside the kitchen unhealthy to breathe, but also make the indoor environment very uncomfortable for cooks, especially in the humid tropical climates.

Therefore, it is important for development agents to be aware of and fully understand this situation so that the assistance provided will lead to the alleviation of such a basic problem.

6.4 Strategies for Improvement of the Kitchen Environment

From the preceding discussions, there appears to be an urgent need to save a large section of the human population living in the rural areas of the developing countries from the harmful effects of kitchen pollutants, emitted from solid biomass burning cookstoves and from unhealthy cooking practices. Figure 6.2 below provides a general overview of the kitchen environment. Various strategies for improving the kitchen environment are possible, such as: improved stove design, fuel upgrading, improved ventilation, and switching to clean fuel.

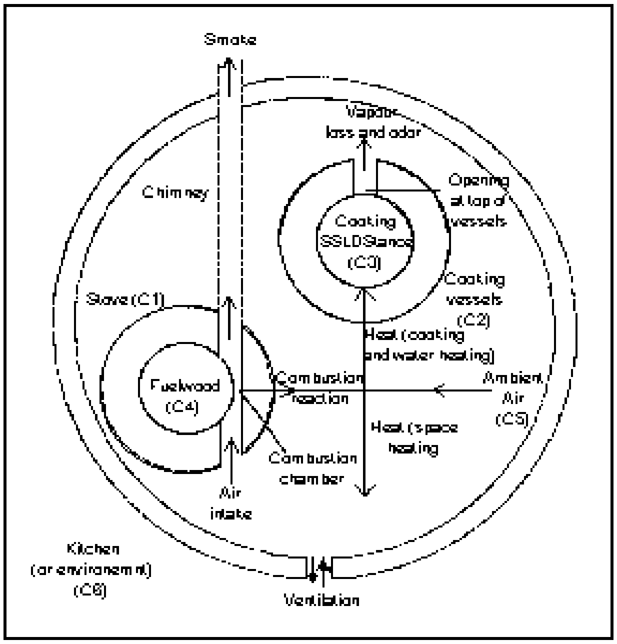

Figure 6.2 Generalised representation of component interactions in a domestic heating operation (Baily 1986b)

6.4.1 Improved stove designs

Design improvements normally involve the introduction of a chimney and the incorporation of other critical features for improving both combustion and heat transfer efficiencies. While combustion efficiency measures the extent of conversion of chemical energy to heat, heat transfer efficiency measures the fraction of the released heat delivered to the pot and food. The emission of the pollutants is inversely proportional to the combustion efficiency and the overall efficiency is inversely proportional to the amount of fuel used. A number of operational parameters, such as size and shape of fuel, burning rate, moisture contents, excess air factor etc. are also critical. These must be optimized in the light of discussions in earlier sections of this manual. Based on the application of these principles, a number of designs of improved stoves, with and without chimneys have been developed, and many have been widely disseminated.

6.4.2 Fuel upgrading

As explained in section 4.1, solid biomass fuels contain a high percentage of volatile matters. The quality of combustion depends on the completeness with which the volatile matter is burnt. Hence, solid biofuels with less volatile matter, such as pyrolysed fuel, will burn cleaner. Changing over to the modified biofuel forms such as charcoal, torrefied wood, briquettes, biogas, alcohol etc. can improve the indoor air quality, due to less emissions. Use of catalytic converters for flue gas control can also help in reducing pollution from traditional biofuels. However, cost may stand in the way of their use.

6.4.3 Ventilation improvement

This can be a less expensive short term measure to improve indoor air quality, as simple changes can have a large impact on air exchange rates and indoor concentrations of pollutants. Besides the kitchen door, windows, wall slits and other forms of ventilation should be encouraged. Wind directions will have an important bearing on the design of the kitchen and the installation of openings. More studies are needed to guide such improvements, scientifically.

6.4.4 Switching to other clean fuels

Cooking fuels, in gas form such as natural gas and LPG, in liquid form such as kerosene and ethanol, and in specialized form such as electricity, are more appropriate and usually preferred for cooking in most societies. These fuels, in fact, already appear in the higher rungs of the fuel ladder. Therefore, there exists a natural tendency of users to move up whenever such clean fuels are affordable and accessible. However, in practice, a mass movement to these fuels is very unlikely due to rural poverty and the poor country economic performance of the public and private sectors. As witnessed today, fuelwood/biomass fuel is still widely used for domestic cooking in all developing Asian countries (see chapter one).

Thus, it can be concluded from the discussion in this chapter that the effect of the pollutants (emitted from combustion of biofuels during cooking) on the health of women and children should be of grave concern. There is a need to use various strategies, either singly or in combination to curb the level of emissions. While designing improved cookstoves, it is essential to give as much importance to emissions as to thermal energy efficiency. There is a need to undertake a holistic approach to pollution problems by studying emissions in various kitchen systems, instead of taking the improved cookstove as the only major intervention.

7 THE KITCHEN: AN INTEGRAL PART OF THE COOKING SYSTEM

7.1 Kitchen and Stove Nexus

Because cooking is the most important chore in a household, the kitchen is the focal point of household activities. Cooking involves a number of functions including the preparation and cleaning of food ingredients, fuel preparation and firing, cooking of dishes according to fire intensity or custom, serving preparation, washing of utensils during cooking and after serving, kitchen clean-up, planning for future meals, etc. In addition to these main functions, there are also a number of other supporting functions such as fuel collection and bringing water for cooking (both of which often require considerable travel), picking fresh vegetables/spices from home garden, milling of grains, etc. These activities are normally performed by women and/or young girls, especially in rural areas of most societies. Furthermore, rural women often have to help or provide additional work on the farm or earn supplementary income from various activities. In addition, due to high exposure to unhealthy kitchen environments (dark, smoky, hot and humid with poor ventilation), cooking constitutes an occupational hazard for women. Due to their social obligation, most women rarely have time for relaxation nor time to pursue income generation activities or education.

Improved cookstove development, as mentioned in chapters 1 and 2, began during the 1950's for social reasons (smoke evacuation/health) and continued during the 70's from the perception of fuel scarcity and from the late 80's has become an integral part of a broader concern for kitchens and the environment. A critical look at past ICS research and development work indicates that very little attention was given to important aspects of cooking beyond the stove itself, such as the conditions in traditional kitchens. Hardly any effort was made to integrate improved cookstoves with improvements in the kitchen so as to gain overall energy efficiency, cooking productivity, comfort and convenience.

However, as was stated at the Sub-regional Expert Consultation on improved cookstove development programmes in South-Asian countries held in Udaipur, India in 1991, the kitchen is not only neglected in stove programmes. The culinary area or the kitchen plays a very important role in housing design but in practice the kitchen is often neglected, both in modern construction and by housebuilders themselves (Nystrom and Jere, 1991). Despite considerable progress made in subsystem designs to increase the fuel efficiency and combustion efficiency and to remove smoke, a broader approach to the improvement of the domestic energy system (including the role of women as kitchen managers), incorporating the kitchen element into improved cookstove development, has yet to evolve.

The first step in this direction is to understand the inter-relationship between the cookstove and the culinary or kitchen system.

The culinary system has three components, namely: culinary *area* (kitchen), culinary *practice* (food types) and culinary *function* (cooking operations).

Analysis of these three components shows that the ICS is linked only partially with the culinary system, which involves a large number of pre- and post-culinary functions also. Figure 7.1 illustrates how the various components of meal preparation are related to each other and to the general social context of particular communities at different levels

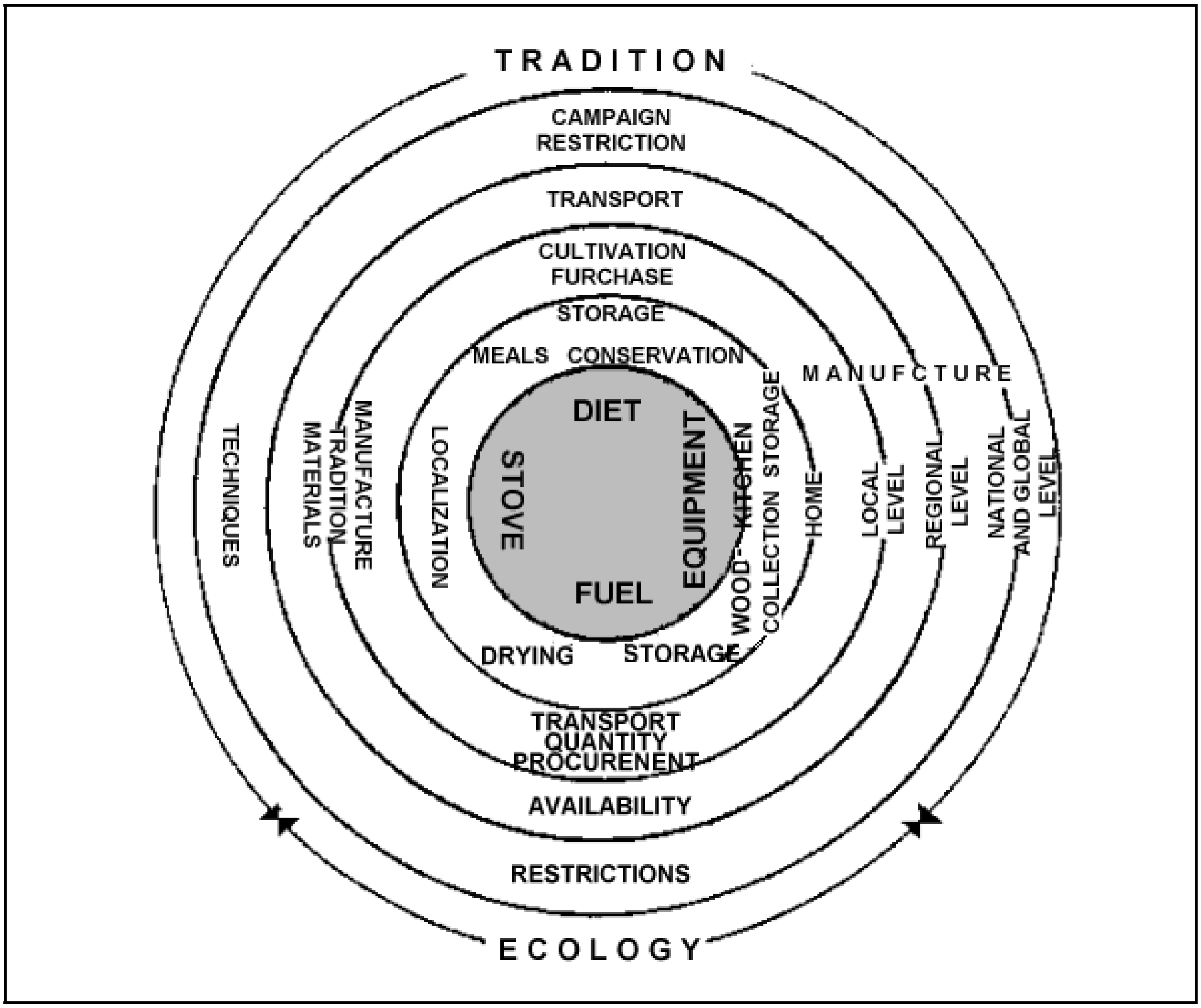

Figure 7.1 A circle diagram illustrates how components of meal preparation are related to each other and to the general societal context at different levels.

Although the ICS does help in improving the indoor environment of the culinary area and reducing the time spent in cooking/collecting fuelwood, many users do not see any economic benefits from the time saved nor perceive the pollution problem as dangerous, due to other benefits obtained such as timber and thatch preservation, mosquito repulsion, fish/meat smoking, prevention of insect/rodent invasion on foodstuff, or their general acceptance of these conditions. Thus improvement of the cookstove performance alone does not appear very attractive to the rural people.

In contrast, limited experiences from Nepal (RECAST/RWEDP, 1993) and Vietnam (Nystrom 1992) have demonstrated that the simple application of kitchen management principles, coupled with a few changes in the physical arrangement of the kitchens of rural women, were eagerly received. The application of this kitchen development approach, however, requires a thorough understanding of the role of each component in upgrading the culinary system in the kitchen of rural people and it is clear that further research on this topic is required.

7.1.1 Stove functions

Bialy (1986b) describes in figures 7.2 and 7.3 energy use, the role and different functions of a stove and its attributes of operations and its relations to various components.

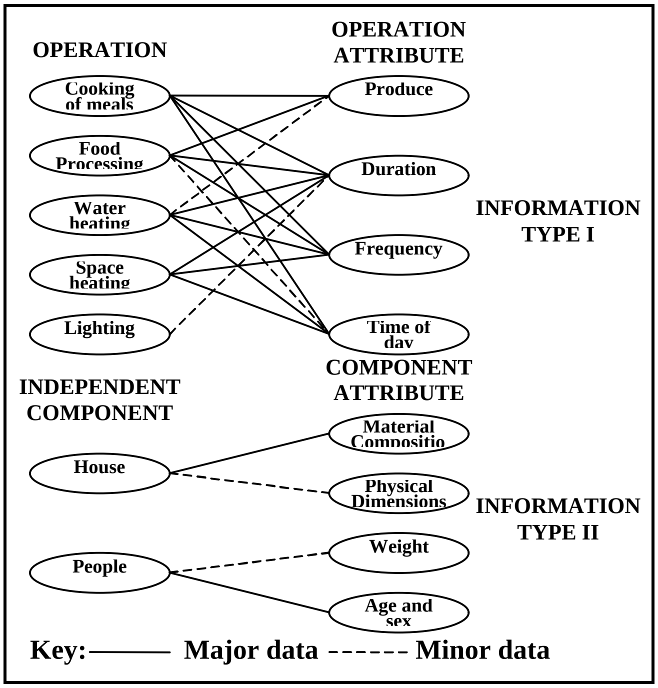

Figure 7.2 Attributes of operations and independent components (Bialy, 1986b)

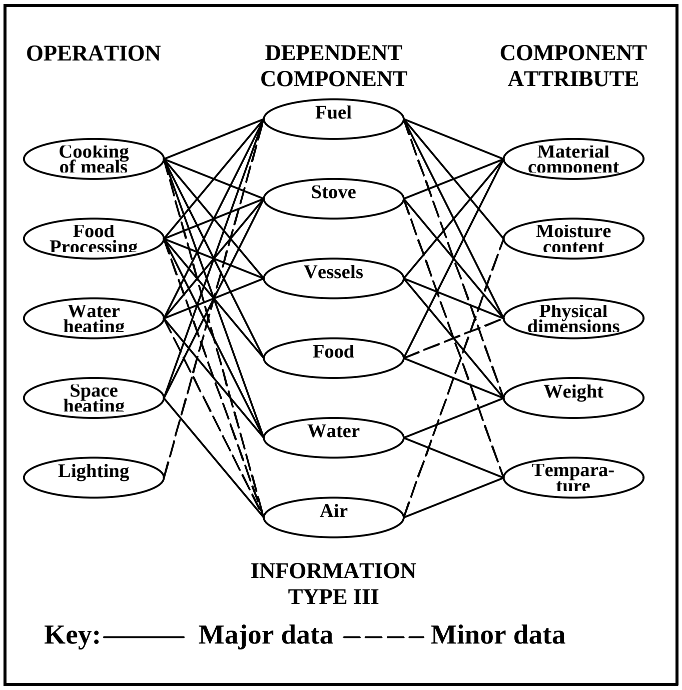

Figure 7.3 Attributes of dependent components

7.1.2 Culinary functions

The first step in this direction would be to understand the role of the cookstove in the culinary functions. Culinary functions, as shown in figure 7.4, involve collection and storage (fuel, water, and food), food preparation (washing, cleaning, cutting and grading), firing stove, cooking, dining and washing of utensils. Most of these functions are overlooked or have not been taken into full consideration in the designing of kitchens in most developing countries.

This is the major cause of poor working and sanitation conditions in the kitchen. Accumulation of solid, liquid and gaseous wastes generated from various cooking operations, especially cooking oil/spice fumes and odours and the absence of waste disposal provisions have often led the kitchen in many developing countries to be called the “dark place” of the house. The workload of women also increases due to lack of storage facilities and insufficient working space in the culinary area. As a result, women, the casual cooks, are obliged to perform some of these

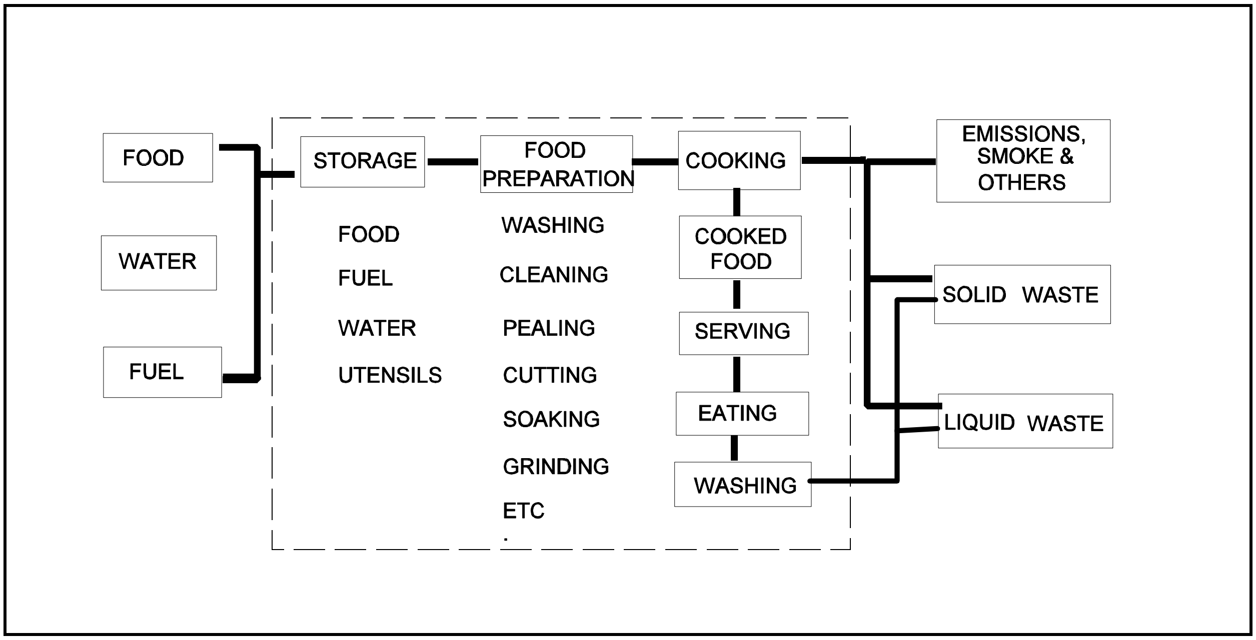

Figure 7.4 Culinary and related functions of a kitchen

functions outside the kitchen and hence make numerous trips to fetch foodstuff, vessels, fuel, water etc. The trips would have been unnecessary if the kitchens were properly designed.

Apart from food, fuel and stove, supporting facilities such as a work bench, storage racks/cupboards (for food, utensils, fuel, etc.) and provisions for washing and a disposal system for waste material are also required to create an efficient kitchen, as shown in figure 7.5. The placement of the various utilities should be done from an ergonomic point of view after undertaking work function studies which aim to enhance productivity and reduce the fatigue of the cook. Logically, housewives want to improve cooking performance and efficiency, so that their time and effort can be minimized while overcoming problems related to health and cooking comfort. By addressing these issues in addition to achieving fuel saving and clean combustion objectives, ICPs can achieve the wide acceptance of appropriate ICS models.

7.2 Kitchen Design Considerations

Within a dwelling system, the character of the kitchen is important. A kitchen, separated from a single family house, cannot be treated in the same way as a kitchen in an apartment or in a multi-story building. The location of the separate kitchen in relation to the rest of the dwelling is easier to design than a kitchen in an apartment (Nystrom, 1992).

The placement of the kitchen vis-a-vis the rest of the building can have a profound effect on the quality of the indoor climate due to the transmission of heat and food odours, produced during cooking, to the rest of the dwelling. Kitchens should not be placed adjacent to utilities such as toilets and animal sheds. Some studies show that the kitchen should be separated from the rest

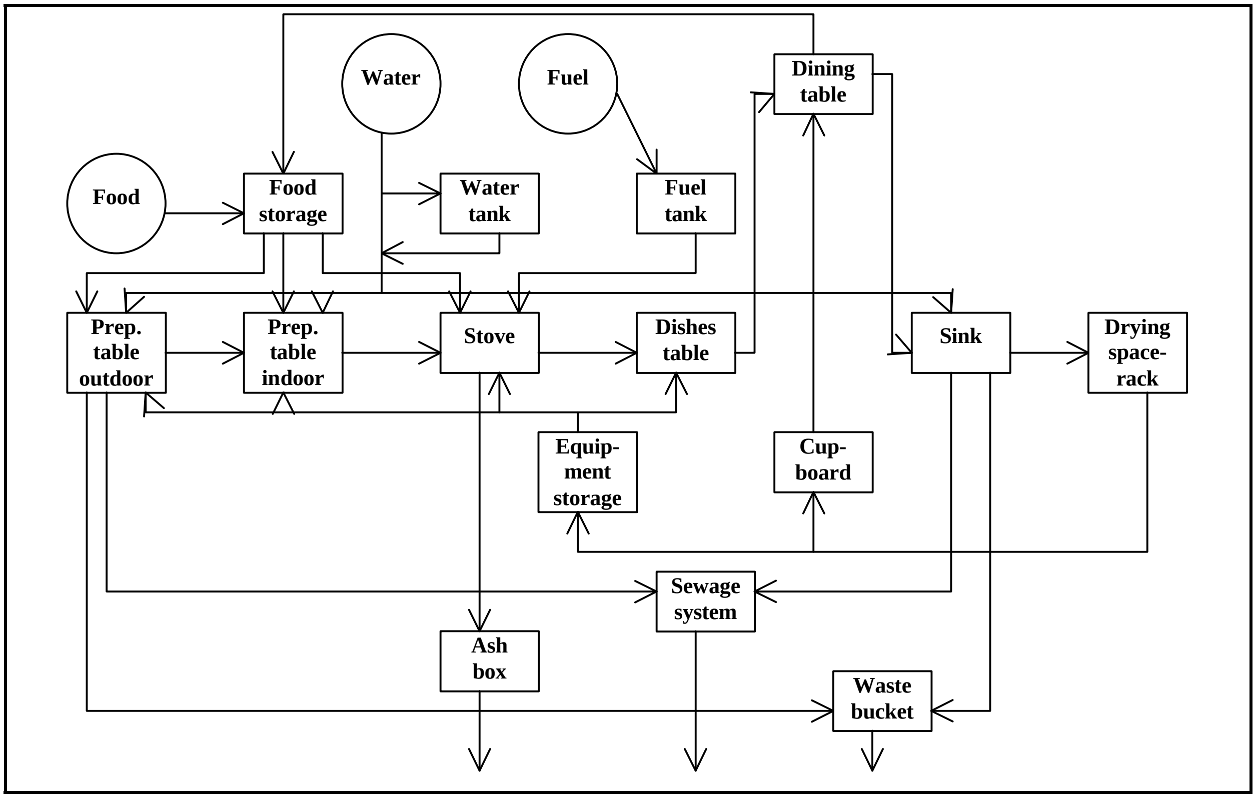

Figure 7.5 Supporting equipment and articles need also a place in the kitchen

of the building, especially in warm and humid climates and should be planned according to prevailing wind and ventilation considerations (Nystrom 1992).

The placement of the kitchen vis-a-vis the rest of the building can have a profound effect on the quality of the indoor climate due to the transmission of heat and food odours, produced during cooking, to the rest of the dwelling. Kitchens should not be placed adjacent to utilities such as toilets and animal sheds. Some studies show that the kitchen should be separated from the rest of the building, especially in warm and humid climates and should be planned according to prevailing wind and ventilation considerations (Nystrom 1992).

The design of the kitchen must take into consideration the functions it is expected to perform for the particular group within society. Human movement patterns in the kitchen, which are a function of culinary activities and associated practices, should be taken into consideration for defining the working area of the kitchen. Special attention should be given also to the storage of kitchen equipment, as it is important from an ergonomic point of view, and it should be placed according to the flow pattern for different activities (Nystrom. 1992).

The number and type of various utilities such as cookstove, work bench, storage cupboard, washing and waste disposal system should be located in such a manner that they cause least drudgery and ensure better hygienic conditions. Natural lighting and ventilation are two important aspects in assigning space for various functions. Thus, the optimum design of a kitchen should take into consideration the interplay between activities, equipment and the use of kitchen space for various functions. There is also a direct relationship between the fuel choice and culinary practices. For example, ergonomic studies show that the open-fire is more conducive to cooking in the squatting position while the standing position is preferred with kerosene and LPG.

7.3 Kitchen Air Quality

Indoor air quality in a kitchen can be improved by a number of strategies such as improved stove design, fuel upgrading, and improved ventilation, as explained in section 4.6. The first two strategies have been discussed in detail in that section. The improved ventilation strategy involves the provision of a chimney or a hood to vent the smoke produced or to increase the air exchange rate.

Indoor air quality is a direct function of the air exchange rate (AER), which is defined as the rate at which the indoor air is exchanged with the outside air and it is expressed as the volume of air exchanged per unit of time. AER depends on the number and placement of window and door openings. In addition, meteorological conditions such as temperature, humidity and wind conditions considerably influence the AER. Air exchange rates can be measured using different techniques such as the tracer gas technique (Smith 1987) and the air pressurizing technique.

The passive tracer gas method has recently been tested in the research cooperation programme in Vietnam on" Kitchens, Living Environment and Household Energy". Measurements took place in an occupied flat and in an experimental flat. This method is useful but a drawback is that the analysis can be made only in a few countries (Nystrom and Stymne, 1993).

It has been shown that, apart from the vent area/kitchen volume ratio, the AER is dependent on the relative location of these openings. It has been further observed that in addition to prevailing wind conditions, the channelling effect due to lanes and adjacent buildings has a profound effect on the AER. The position of the stove in relation to window and door openings in the kitchen is therefore important from the indoo air point of view. From studies conducted at the Lund Centre for Habitat Studies (LCHS), it was concluded that the best location for the placement of a chimney is at the part of the kitchen which has least movement of air (Nga and Nystrom, 1990).

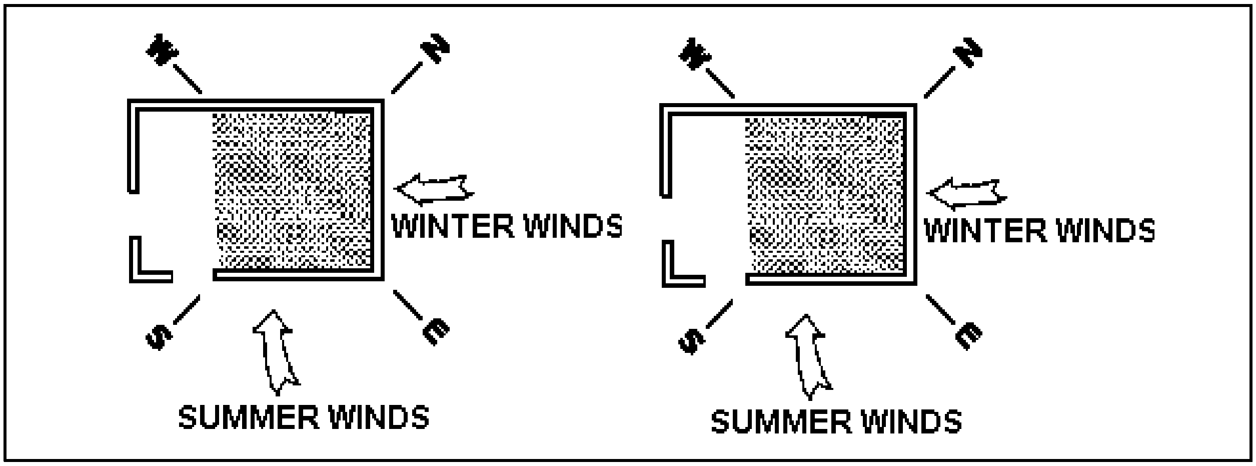

Figure 7.6 Cross ventilated kitchens and the placement of stoves. The kitchen should be placed according to prevailing winds (Nga and Nystrom 1990)

7.3.1 Ventilation and building materials

Experiences from Nicaragua also showed that the movement of air is different in a room with bamboo walls that act as filters from that in a room with solid bricks (Nystrom, 1991). Figure 7.7 shows a "mini-skirt" model which allows diffuse ventilation of the kitchen (Andersson, 1992)

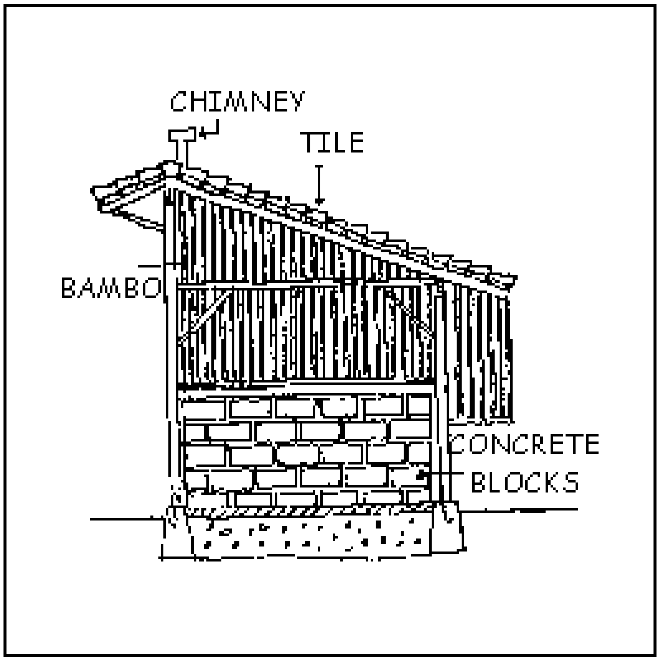

Figure 7.7 "Miniskirt model" with an upper part of bamboo and lower part of concrete blocks

7.3.2 Chimneys and hoods

Different types of hoods have been tested in pilot kitchens in Burkina Faso and Vietnam. Development work is taking place in Vietnam concerning different passive smoke evacuation systems. The so-called "Cooking Window" has given promising results and further design- and experiments on a full scale are being undertaken (Nystrom 1993).

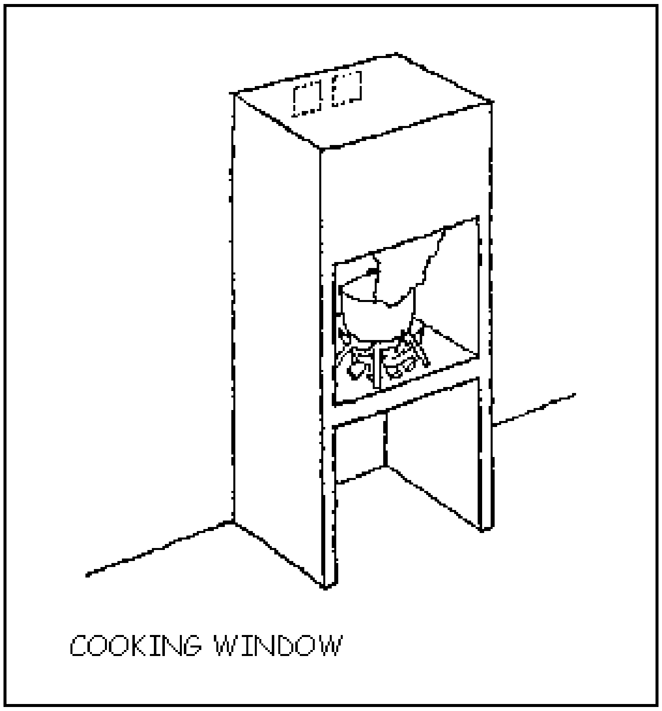

Figure 7.8 Hood from a pilot kitchen in Burkina Faso

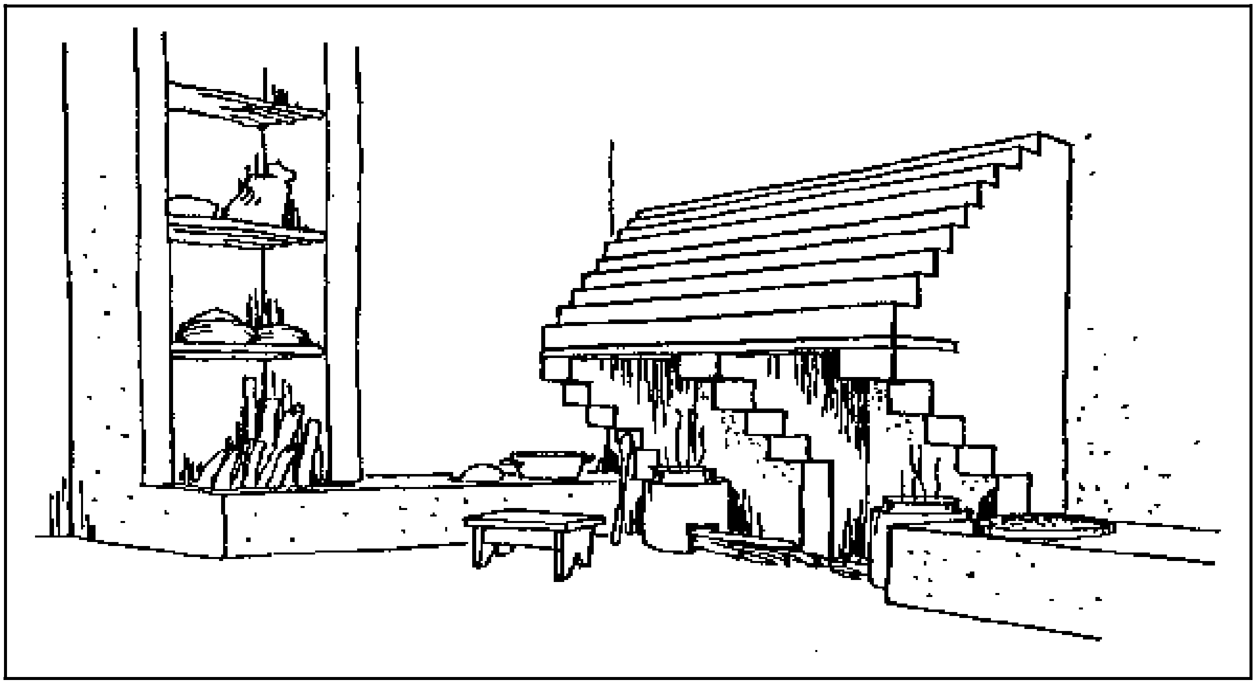

Figure 7.9 The "Cooking Window" tested in Vietnam (Nguyen Trong Phuong, 1993)

8 IMPROVED COOKSTOVE AS COMBINED TECHNOLOGY

A large number of ICS models have been developed in different parts of the world. A number of these stoves have consistently shown high performance in the laboratory as well as in field and have been adopted by a large number of users. The major reason for the better performance of these designs is their better thermal and combustion performance. This has been accomplished by the applications of different principles namely: heat transfer, combustion, fluid flow etc., as explained in sections 3.5 of this manual, in addition to economic and social needs (section 3.4).

Different strategies adopted for improving the thermal efficiency of these stoves are based on improving the thermal and the combustion efficiencies. Thermal performance of a stove is governed by the following equation:

$$\mathbf{Q = U * A * . T} \qquad ....(8.1)$$

In order to increase the heat transfer to the pot, the overall heat transfer coefficient, U , area exposed to the flame and flue gases, A, and flame temperature, T, need to be increased. Overall heat transfer coefficient, U, is mainly composed of convective and radiative heat transfer coefficients. Convective heat transfer coefficient can be increased by either increasing the velocity of the hot gases emitted in the combustion process or creating the turbulence in the heat transfer zone. This can be done by forcing the hot gases to flow through a narrow channel beneath the stove, created by extending the rim of the stove.

Radiative heat transfer can be improved by improving the emissivity. Luminous flame has a greater emissivity as compared to non luminous flame. However, luminous flame also results in greater soot formation, which will result in the loss of potential heat of the wood in the form of unburnt carbon. Thus this strategy will not be very useful. However, radiative component of heat gain from the flame can be increased by increasing the temperature of the flame. This can be done by increasing the flame temperature and increasing the shape factor. Flame temperature can be increased by reducing excess air factor and preheating the air by making it flow through the annulus between the outer cladding and the combustion chamber. Excess air factor can be reduced by regulating the air entering the stove, either by the use of damper(s) or introduction of additional resistance in the flow passage(s) by modifying baffle design or tunnels. However, excessive control of air can increase emissions.

Heat transfer area can be increased by increasing the number of pot holes in the stove. In a single-pot stove, the heat transfer area can be increased by lowering the pot in the fire-box and allowing the hot flue gases to pass around the pot. This can also be done by extending the rim of the stove around the pot.

Heat losses can be reduced by providing insulation on the outer surface of the stove, by using low thermal conductivity material for construction, by providing cavity wall with air insulation, by avoiding massive construction wherever possible to reduce storage losses especially for intermittent cooking.

Many of the measures discussed above have been incorporated by different designers in their models developed for increasing the thermal and combustion efficiencies, and reducing the heat losses. Most the designs of ICS developed by various developers can be grouped under four categories namely:

- Multipot hole stoves
- Channel type stoves
- Nozzle type stoves
- Chimneyless stoves

Figure 8.1 shows the salient features of these stoves.

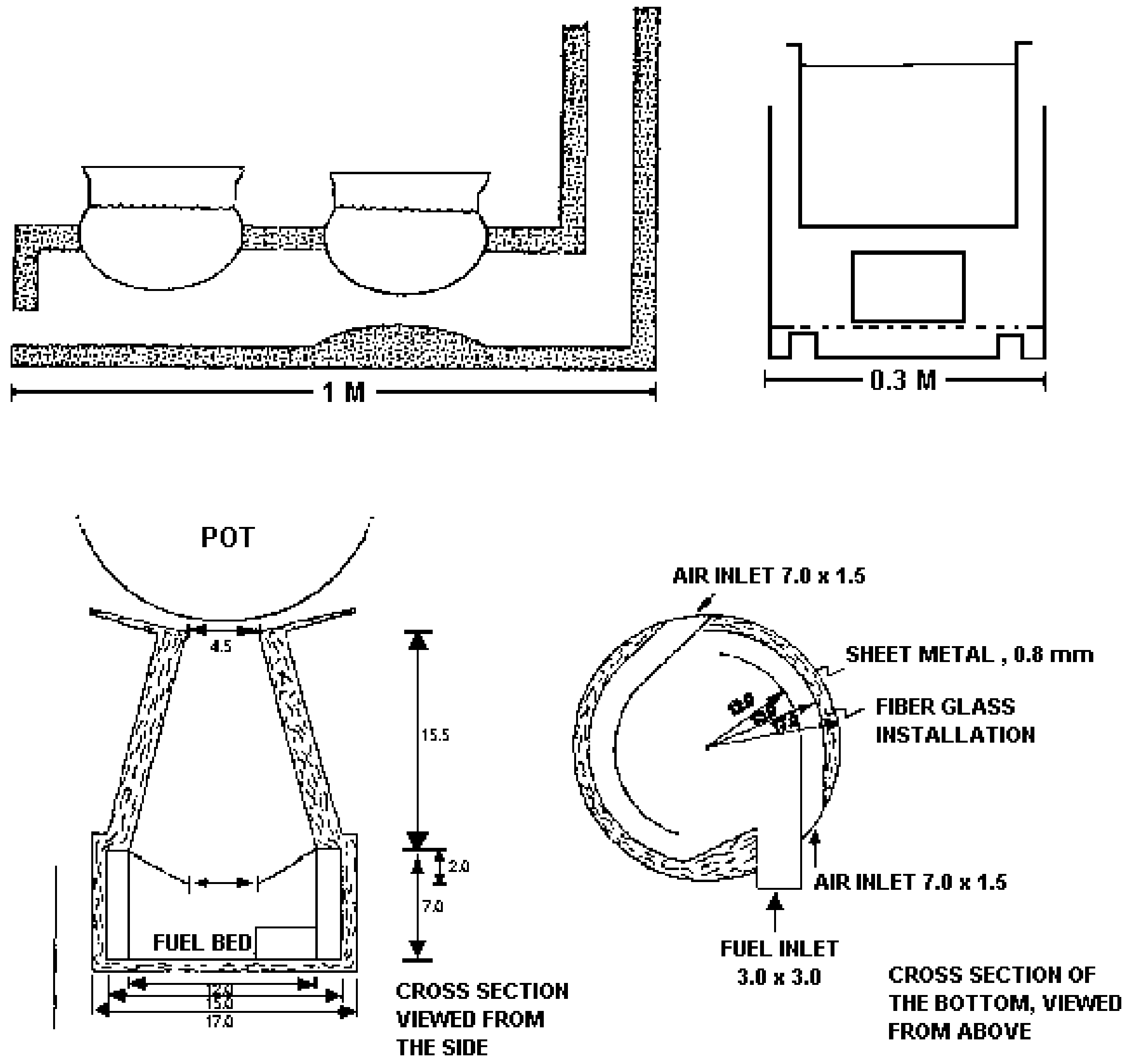

Figure 8.1: Illustrations showing multipot hole stove (top left), channel type stove (top right) and nozzle type stove (below)

8.1 Multipot Hole Stoves

In this design, two or more pot holes are provided so as to increase the surface area exposed to flame and hot gases, thus increasing the thermal efficiency. Major R & D efforts have been directed towards the development of multipot stoves, due to the following reasons:

- ease of construction using local tool and skill,
- use of locally available clay for fabrication,
- ability to take pots of different shapes and sizes,
- large fire-box to accommodate big size fuelwood and cowdung cakes,
- ability to cook two or more items of food at the same time.

In a large number of the ICS models, most of the important components such as pot holes, tunnels, baffles, and chimney etc. have been designed after under taking detailed optimisation studies.

An example of this type of stove is "Rohini", the model developed by the author (Sharma 1990). This model has been designed for a medium size family, consisting of four to five members, especially in the hilly areas where water heating is required throughout the year. The stove can be fueled with fuelwood, dung cakes and agricultural residues and has found wide acceptance in hilly states of India. More than 5,000 units have been disseminated in "Himachal Prades" alone. The production cost estimate is Rs.55-80 (US$ 2.2-3.2).

In this model, heat transfer surface area has been increased by incorporating three pot holes. Two pot holes were designed for cooking operation, while the third was designed for heating water. The excess air factor was reduced by modifying the tunnels and baffles after undertaking detailed fluid flow studies. This innovation helped in eliminating the dampers which were used in most of the earlier models for controlling the draft for induction of air. Use of dampers had a number of drawbacks such as periodic manipulation, chances of burn injuries, difficulty in the puffing of unlivened bread and excessive consumption of wood, when not used. Tunnels and baffles were designed in such a manner that the first pot hole received nearly 60% of the heat input, while the rest was distributed in second and third pots. Radiative heat transfer was improved by optimising the view factor. Fire-box and air openings were designed for a burning rate of 1 kg/h. This burning rate was based on field studies carried out by the author to ascertain the average wood burning rate used in the target area by an average family. Detailed heat transfer analysis was undertaken to study its performance at burning rates of 0.5 kg/h, 1.0 kg/h, and 1.5 kg/h. Results showed that

Table 8.1 Effect of the wood burning rate on the pot heating rate

Burning rate (kg/h)	Burning period (h)	Heating rate (°C/minl.)					
		Burning period			Recovery period		
		I	II	III	I	II	III
0.35	1.0	0.5	0.4222	0.55	0.7428	0.1857	0.1166
0.50	1.0	0.8711	0.6555	0.6666	1.1750	0.4333	0.2833
1.00	1.0	1.28	1.3333	1.60	2.0571	0.7428	0.4857
1.50	1.0	1.6941	1.3714	1.15	4.9333	1.10	0.3454
1.00	2.0	1.1666	1.5555	1.5555	4.0277	0.75	0.3

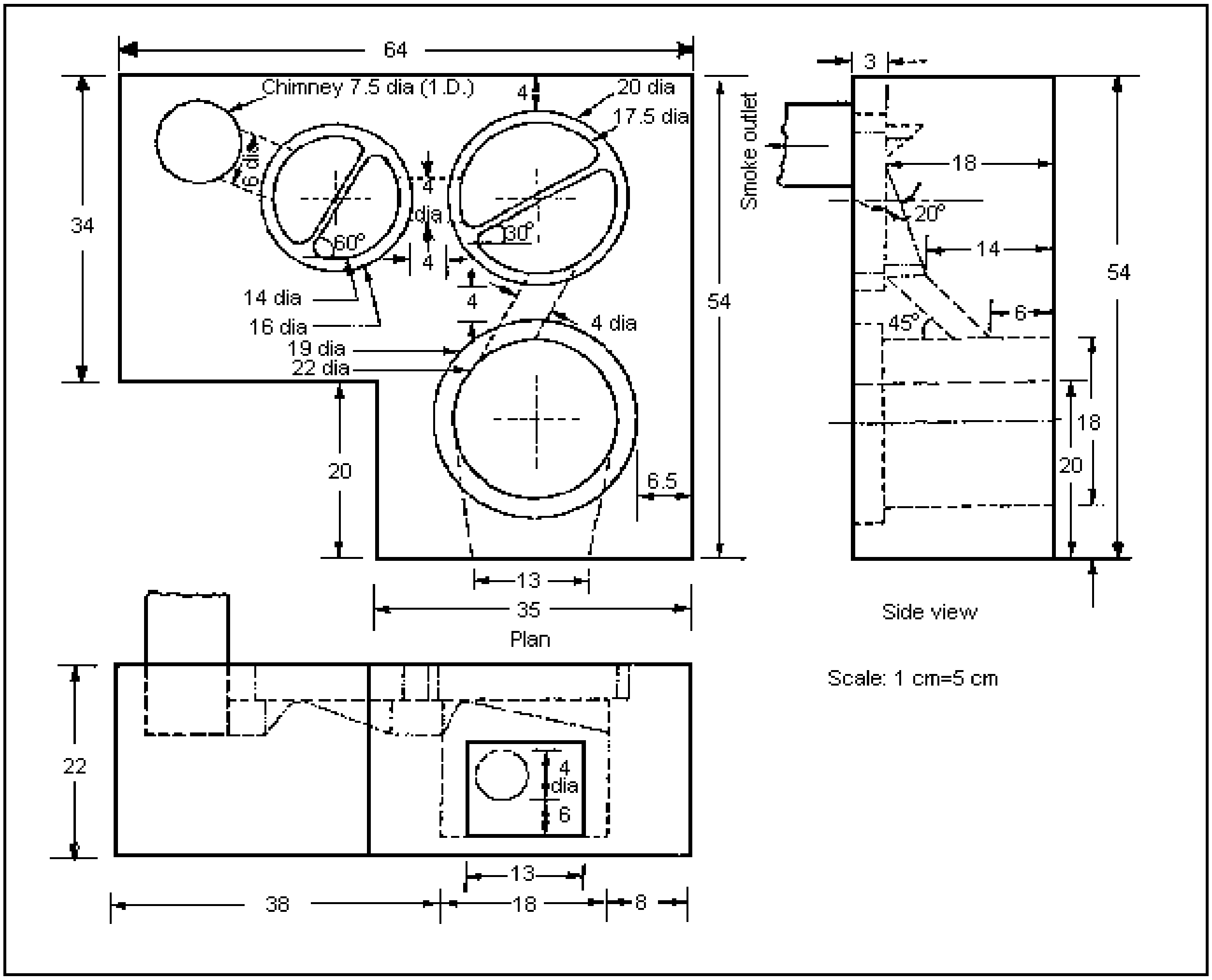

Figure 8.2: The Rohini three-pot stove

the efficiency of this ICS was not unduly affected by operation at wood burning rates lower than the intended design rate of 1kg/h. However, at higher burning rates the efficiency showed a fall, which can be attributed to the throttling affect of the tunnels and the baffles. This resistance was intentionally introduced so as to cause back draft when excessive amount of fuel is charged into the stove, which is the general tendency in the rural areas. Reverse flow of smoke through the fire-box gives a visual indication to the user that she/he is using more fuel. During optimisation studies, it was noticed that the height of the tunnel from the bed in the fire-box influences the heat transfer to the pot very much. This can be attributed to the changes in the flame configuration brought about by the changes in the tunnel configuration. Drawings of Rohini model are shown in figure 8.2 and selected test results are given in tables 8.1 and 8.2.

8.2 Channel/Shielded Fire Stoves

In channel type or shield-fire stoves, hot combustion gas is forced to pass through a small annulus between the cylindrical fire-box and the cylindrical side of the pot. This increases the

Table 8.2 Variation of heat gained by individual pots with wood burning rate

			Burning period				Heat recovery period			
Burning rate (kg/h)	Burning period (h)	Charcoal (g)	Total useful heat (kcal)	% heat gained by each pot			Total useful heat (kcal)	% heat gained by each pot		
				I	II	III		I	II	III
0.35	1.0	10	293.7	69.36	19.41	11.23	36.0	72.22	18.06	9.72
0.50	1.0	15	412.0	67.50	22.79	9.71	68.5	68.61	18.98	12.41
1.00	1.0	65	886.0	56.09	28.17	15.73	120.4	64.29	21.59	14.12
1.50	1.0	100	1,040.1	65.33	25.18	9.49	309.8	74.44	17.69	7.88
1.00	2.0	40	1,737.8	58.55	29.35	12.11	307.6	72.72	14.76	12.52

velocity of flue gases and enhances the heat transfer coefficient. However, fraction of the total thermal energy of the gas entering the channel that is transferred to the pot (defined as channel efficiency) is critically dependent on the channel gap. Modeling studies (Baldwin 1986) showed that for a 10 cm long channel (L), the channel efficiency drops from 46% for an 8 mm gap (G) to 26% for a 10 mm gap (see figure 8.3). It was also concluded from this study that the length of the channel is also dependent on the channel gap. From figure 8.3, it shows also that, for a 4 mm gap, nearly all energy can be recuperated in the first 2-3 cm length of the channel. Thus in this particular configuration, channel length more than 5cm is of no use. When the channel gap is increased to 6 mm, the first 5 cm channel length recuperates 57% of the energy in the gas, the next 5 cm length recuperates additional 16%, while in the next 5 cm length, an additional 8%, and so on. Although narrow gap is useful from the heat transfer point of view, it severely limits the thermal power of the stove due to high resistance created by the small gap to the flow of gases. Effective heat transfer area also increases in channel stoves as hot gases flow around the pot in the channel gap. It can be concluded from this discussion that the selection of material of construction and fabrication facilities for channel ICSs must be selected with care, otherwise thermal efficiency will be adversely affected due to the faulty construction of the gap. In addition this type of stove can accommodate pots with only limited variation in size in which it puts severe restrictions on the part of users.

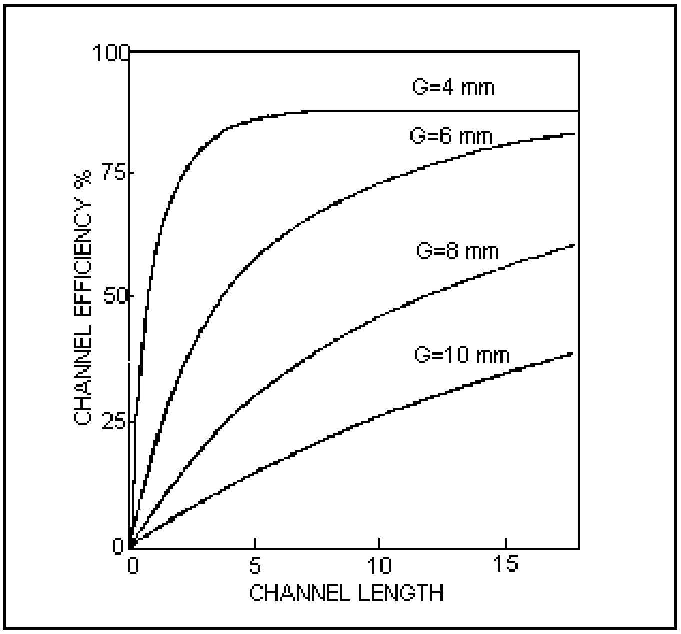

Figure 8.3: Channel efficiency as a function of channel length for various channel widths (Baldwin 1986b)

A fuel efficient design, Mai Sauki stove was developed by Bussman (1988) is shown in figure 8.4. Stove was designed for an average family in Niamey, consisting of 6 persons and using a pan diameter of 30 cm. Power density of 200 kw/m^2 (20w/cm^2) was chosen for the design. This

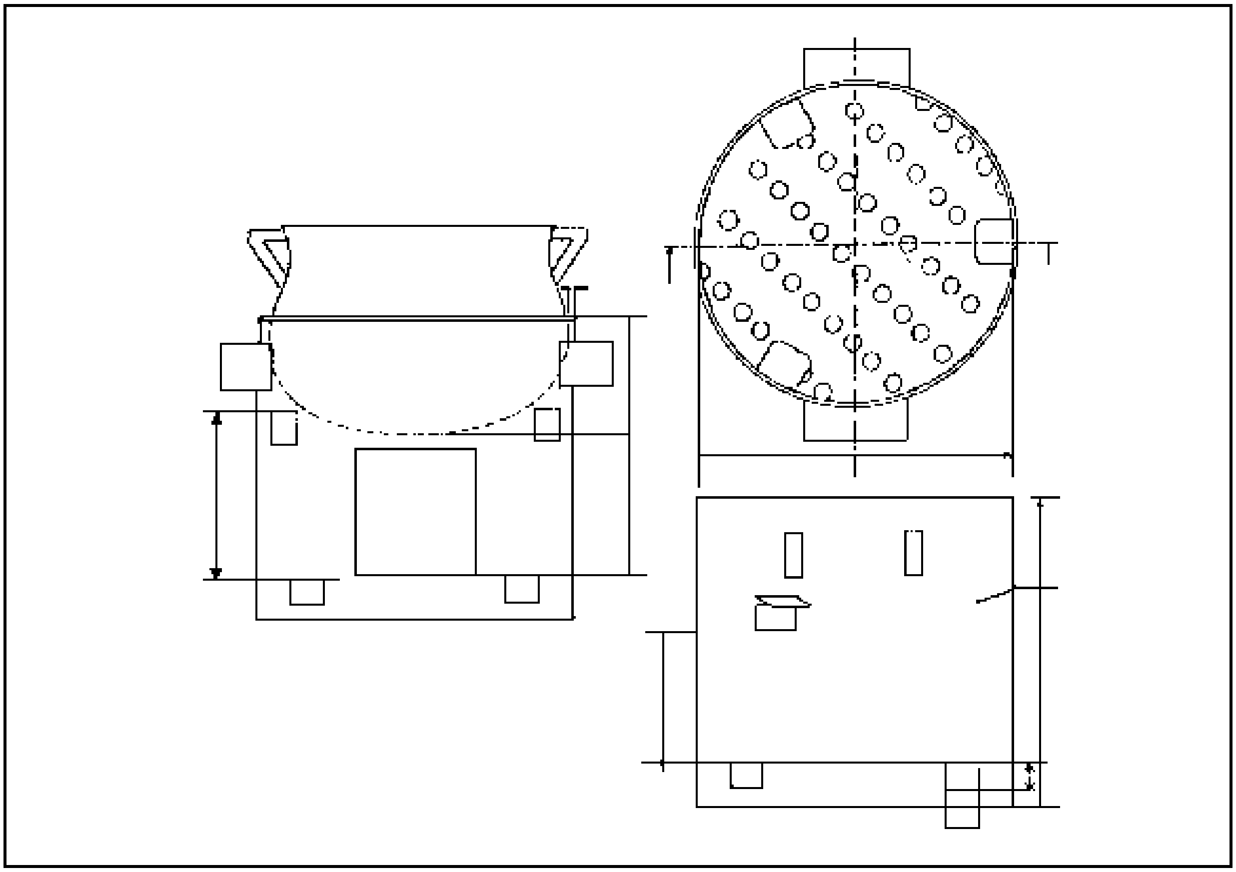

Figure 8.4: Mai Sauki Woodstove (Bussman 1988)

is a value at which Visser's shielded-fire gave maximum efficiency. The shield height, combustion chamber height, and the stove body height were optimised on the basis of in-depth studies on combustion, heat transfer, and fluid flow. Efficiency of the stove remained constant at nearly 35% even when the grate to pan distance was varied from 8.5 cm to 12.5 cm and the grate hole area varied from 5% to 50% With the increase in the channel gap from 5 mm to 12 mm, the efficiency dropped from 35% to 30%. A shield pan gap (G) of 5 mm and a shield height (L) of 50 mm was found to be optimum. It was observed from the detailed optimisation studies that the area of the primary air holes should be equal to the secondary holes, including fuel loading opening for better performance. As a result of these optimisation studies, not only thermal efficiency increased substantially, but a material saving of around 15% was also achieved. Cost of production in informal sector, at the prevailing prices, was calculated at 615 FCFA as of early 1987, nearly 40,000 stoves were sold.

8.3 Nozzle Type Stoves

In these stoves, flow of the hot gas is accelerated by forcing them to flow through a narrow combustion chamber before it come in contact with the pot. It is then decelerated by making it flow over the tapered top plate to increase residence time, so as to allow better contact between hot gases and the pot.

Based on this principle, a portable single-pot pottery model, "Sudha", was developed by the author (Sharma 1992). The stove shown in figure 8.4 was designed taking into account needs of the socially unprivileged sections of the society. The model is suitable for production on decentralised manner by the trained potters. Stove can accommodate flat or round bottom pots, 20-30 cm in diameter. Any type of fuel such fuelwood, twigs, cow dung, agriculture residues and briquettes can be used with this stove. This stove can be used as a fixed stove or portable one. It is suitable for medium size family having 6-8 members. The production cost estimate Rs.30-40 (US$ 1.2-1.6). Drawings are given figure 8.5.

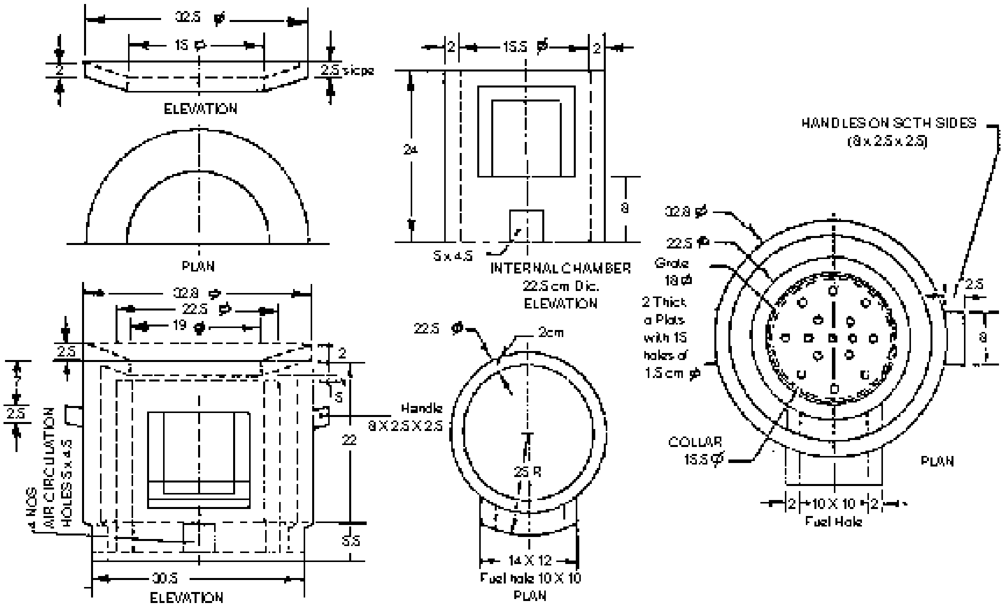

Figure 8.5: "Sudha" a single-pot pottery ICS (Dimensions in cm.)

The following measures were taken in order to increase the thermal and combustion efficiency. Thermal efficiency has been increased by increasing the convective heat transfer coefficient by forcing the flue gases to flow through the channel created between pot bottom and the tapered top plate of the stove as explained earlier. This also increases the residence time of the flue gas with the cooking vessel, which results in better heat transfer. Radiative heat transfer has been increased by increasing flame temperature. This has been ensured by preheating the secondary air in the annular space between the outer and the inner barrels. Hot secondary air mixes with products of combustion below the top plate resulting in the combustion of the unburnt volatile matter. Due to extended top plate the residence time is sufficient to ensure complete combustion. This has been confirmed by the low CO/CO_2 ratio (0.0126) at the optimum burning rate of 1 kg/h. Combustion efficiency has been further improved by incorporating a pottery grate. Excess air factor has been controlled by optimising the air opening and the height of the channel below the cooking pot. Results show that this is a critical dimension as the heat transfer efficiency and the combustion efficiency are both dependent on this. Thermal efficiency decreases from 40% to 26% when the height of the channel (gap) increases from 1 cm to 2 cms. This can be attributed to the quenching effect of induced cold air from the sides. This has been experimentally confirmed by the fact that the CO/CO_2 ratio increases from 0.01 to 0.03 with the increase in the height of the channel from 1cm to 2 cms. The cookstove has been optimised for the burning rate of 1 kg/h, which is the one used in the existing cookstoves in the target area. This optimisation is confirmed from the heat transfer studies as the thermal efficiency lower at burning rates above and below the optimum value. **Turn down ratio** of the cookstove was 2. This is the ratio of the highest and the lowest burning rate at which the stove still has suitable combustion characteristics.

This cookstove has been prepared from the fired-clay. This material has been chosen from the point of view of ease of fabrication by the village potter using local clay and local tools. It will not get damaged during rains and will retain the dimensions, which is not possible with the clay models. The model is suitable for use in hot and humid climate due to its portable nature. However, fragility is still a problem, which can be eliminated by using metal cladding. Although it will add on to the cost. Some of the test results are shown in figure 8.6 and table 8.3.

Table 8.3 Variation of efficiency and CO/CO$_2$ with the pot height from the top plate

Burning rate kg/hr	Height of the pot (cm)	Efficiency %	CO/CO$_2$ %
1.0	1.0	40.54	.0126
1.0	1.5	26.90	.0346
1.0	2.0	26.20	.0300

8.4 Chimneyless Stoves

In this type of stove, vessel mounts are provided to support the cooking pot. These stoves are similar to the traditional single pot stoves. However, all critical dimensions such as aspect ratio (view factor) of the fire-box, position of the grate, height of the mount, openings for the primary and secondary air,height above the ground in the case of stoves with legs,etc are optimised in the improved design. Optimisation of all these parameters is essential for the improvement of combustion and thermal efficiency of the stove. These stoves are fabricated in metal or fired clay/pottery from the point of view of portability. In order to eliminate burn injuries in the case of metal stove and to reduce breakage in the pottery models, an outer cladding has been provided in some models.

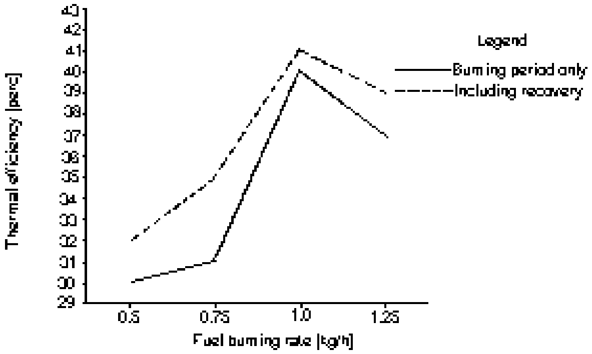

Figure 8.6 Thermal efficiencies and combustion characteristics of “Sudha” ICS

chimneyless stove,"Priagni" (figure 8.7) was developed by Jayaraman and Butt of Central Power Research Institute in Bangalore, India. This stove is available in four sizes, namely, small, medium, large and extra large for meeting the requirements of different sizes of the families/users. Pot sizes varying from 18-30 cm. in diameter can be used on these stoves. They are fabricated from sheet metal/cast iron or incombinations. Specifications and drawing of this cookstove is shown in figure 8.6. Sheet metal stoves can be fabricated in a small scale manufacturing unit having facilities for welding, cutting, grinding, and punching of sheet metals. Cast iron version can be fabricated in a small scale casting shop. About 3 million units of this stove have been disseminated in different parts of the India (FAO/RWEDP 1993). This stove is suitable for fuelwood and twigs. The production cost, depending on the specifications, ranges from Rs. 105-188 (US$ 4.2-7.5).

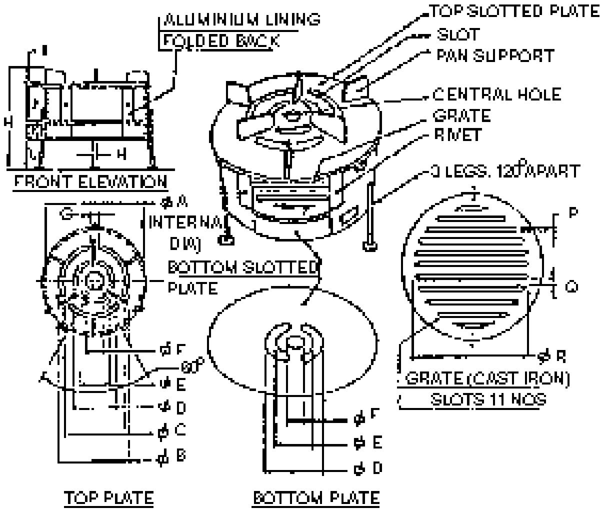

Figure 8.7: Priagni, a single pot metal ICS

As stated earlier, distance between the grate and the pot is very critical. Studies conducted on a large size model of Priagni (Antika 1989) as reported in table 8.4 show that the thermal efficiency increases with the decrease in the grate to pot distance up to 6 cm and is constant at the lower distances between the stove and pot. Results further show that as the distance between pot and the stove decreases, C0/C0$_2$ ratio increases. Indicating that the combustion efficiency decreases substantially. Thus it can be concluded that the stove parameters have to be optimised carefully, otherwise the performance of the stove will be very poor.

Table 8.4 Thermal efficiencies and combustion characteristics of "Priagni" ICS

Distance between the pot & stove top plate (cm)	Efficiency (%)	Average CO (ppm)	CO/CO$_2$ ratio	Charcoal Left (gms)
10	24.0	305	0.0167	80
10	24.4	373	0.0148	75
8	28.6	745	0.0240	235
8	27.8	1,195	0.0354	185
6	32.5	727	0.0300	165
6	32.5	1,331	0.0370	262
4	32.3	1,005	0.0420	N.D.
4	32.7	3,757	0.0520	235
2	32.3	2,316	0.0560	315
2	31.8	2,118	0.0810	325

Four ICS models, as given above, are only a few representative examples, out of a large number of improved stoves models developed by various designers by applying some of the innovative techniques as explained above. However, it will be pertinent to mention that these innovations have not been decided arbitrarily. In most of the cases, they have been arrived at after rigorous application of the principles of combustion, heat transfer, and fluid flow. In addition, extensive experimental optimisation studies have also been undertaken, where theoretical knowledge has not reached a stage that it can be applied to design a particular subsystem. There is also no end to the human endeavor in exploring uncharted territories. Thus new innovations will continue to be introduced in the existing models of the cookstove so as to further increase their performance and also satisfy the needs of the users.

9 FUTURE NEEDS FOR R & D

The main emphasis of the earlier cookstove R & D was on product development, with less concerns on other aspects related to the requirements of users in cooking, as presented in various chapters. Therefore, R & D in the future should attempt an alternative, "integrated system" approach so that essential related technologies and knowledge will be appropriately incorporated. R & D attention should be focussed and/or built upon the development of the subsystems so as to improve the performance of the total cooking system. Economic, cultural, and social needs of the users, including health and environment implications must be taken into full consideration right from an initial stage of R & D planning itself.

Despite long and considerable development efforts made on the ICS development, both in basic scientific and social aspects, a number of gaps still exist in some critical areas. Some of the broad subjects which need attention are:

9.1 ICS Monitoring and Evaluation

Most of the surveys, undertaken to evaluate the benefits of the ICPs, at national or global level, are qualitative in nature. For future reviews, there is a need to incorporate measures for the quantitative estimation of various benefits and/or impact of ICSs and ICPs. Such estimations are necessary to show to national planners the actual benefits accrued to the households. There is a need for further refinement of monitoring and evaluation tools and techniques for a fair and balanced evaluation of the programme, on the quantitative basis.

9.2 Combustion

Although, a large number of studies have been conducted to optimize the height between the pan and the fuel bed, the results are contradictory and still inconclusive. This is an important parameter, from the point of view of emission characteristics of the stove. The main reason for this disparity is the application of the results of the open-fire in the design. These results are valid only for naturally aspirated fire. Therefore, its application to the ventilated fires in the ICS with chimney require modifications. In depth studies are needed as the geometric characteristics of the flame in most ICSs get modified. The effect of top plate configuration on the flame characteristics in metal ICSs is not properly under stood. Design of inserts for promoting air turbulence, is another area of interest, for improving combustion efficiency. Detailed studies on the pyrolysis of composite fuels are also needed.

9.3 Heat Transfer

The convective heat transfer problems in the cookstove are complex, as strongly accelerating flows are encountered with variable temperature difference in the direction of flow. Detailed studies are needed since conventional solutions for hydrodynamically and thermally stable flows only give approximate results. Similarly, values of constants, in empirical equations (such as given in 4.3.9 in section 4.3) for predicting the heat transfer coefficient, are available for standard configurations only. Data on actual situations encountered in cookstoves is lacking and therefore experimental works to determine these constants are needed.

There is also a need to conduct studies on the optimization of baffle dimensions by undertaking hydrodynamic and heat transfer studies, as this has a profound effect on the efficiency, especially of the multi-pot and chimney stoves.

It is difficult to design a cookstove with a balanced flow due to inter dependence of flow of gases with the temperature at the chimney base and the power out put of the fire. Due to dynamic nature of the process, there is a cascading effect. Theoretical modelling on these lines is lacking in literature.

9.4 Transient Heat Transfer Studies

It is essential to conduct in-depth heat transfer, aerodynamic and, combustion studies on cookstoves, for further upgradation of the efficiencies of the existing models. Most of the present studies are based on steady state models, hence, their application to situations actually encountered in cookstoves may be questionable. Keeping in view the dynamic nature of the combustion process in cookstove, it is necessary to undertake numerical analysis based modeling studies for designing fuel efficient ICSs. Some studies in the area of software development are described as under.

The computer simulation programme has been developed for determining the flow rates and heat transfer through the channel in the channel type stove, assuming an initial gas temperature at the channel entrance. The programme has the capability to calculate convective heat transfer in the second and subsequent pots (in the case of multi-pot stoves). With the help of this simple empirical model, it is possible to study the expected trends in the performance of the cookstove, as results of dimensional changes of the ducts and gas temperature (Baldwin 1986).

A computer simulation model based on finite difference numerical technique for calculating transient heat loss through the walls of cylindrical and spherical type combustion chamber has been developed (Baldwin 1986). Heat loss coefficient can also be calculated by this programme.

For monitoring the transient behavior of the various processes taking place in a cookstove, it is essential, to design computer based dedicated data acquisition and transient process monitoring interactive system with graphics capability. A personal computer based real time data acquisition system is being developed (Sharma 1991). The system has features for making faster calculations and real time operations with capability to capture, store, retrieve and/or analyze data for dynamic thermal analysis studies. Heat transfer model using numerical analysis techniques for evaluating the performance of a cookstove has also been developed by the author. A PC based software has also been developed for evaluating the thermal performance of a single or multiple pot cookstove. The software has graphic capability also (Sharma 1992). Further, there might be some other aspects which have not been documented.

The need to undertake further comprehensive studies in this very important area can not be overstated.

9.5 Environmental Issues

This is the vital and least understood area of ICS technology. There is a need for a comprehensive programme to monitor the indoor air quality in different agro-climatic regions over a period so as to visualise the magnitude of health problems associated with the biomass fuel burning indoor. This aspect is not been fully understood, due to very limited number of studies. The impact of meteorological factors, which have a profound effect on the indoor air quality, also need in-depth study. Data on the relative importance of different variables such as environmental, thermal, social, economical, hygienic in contributing to indoor air pollution is lacking and needs comprehensive studies.

Data on smoke emission factors, exposure levels in the kitchens is virtually non existent. These studies have become more important in the light of evidence that clean combustion and thermal efficiency are competing factors.

9.6 Kitchen Design

Design of thermally, environmentally and ergonomically efficient kitchen is important in attempting to set a development norm for rural household living condition. There exists a need to develop efficient designs of rural kitchen from health, safety, productivity, and drudgery reduction points of view. Intensive studies are needed to develop techniques for improving ventilation, internal lighting in different agro-climatic regions through AER studies, so as to upgrade the indoor environment. In-depth studies are needed for evaluating the interaction between various parameters of the kitchen subsystems. Studies on the inter-relationship between kitchen and overall indoor and outdoor environment may deserve an attention.

Functional aspects of kitchen on the (women) cook ergonomics and culinary practices are also not properly understood. Impact of local environmental conditions, economic, socio-economic and cultural factors in the design of rural kitchen needs better understanding.

There is a need to explore the use of passive solar concepts for orienting windows and doors in the design of low cost thermally and environmentally sound kitchens and housings, especially in the rural areas. Integrated studies on kitchen layout and ergonomics are needed to reduce the drudgery of women in cooking and other related operations both in and outside the kitchen. At present, very little thought is being given on storage and waste disposal in the design of the kitchen system.

9.7 Improved Utensils

The areas which need some investigations are improved materials and improved vessel designs for better heat transfer and/or more convenient to use and maintained. Low cost production of kitchen utensils such as pressure cookers, meat girders as well as stove sub-components (eg. reducing rings, flame arrester, thermal shield, hand blower etc).

9.8 Improved Culinary Practices

Studies supporting social attitude and behavioral changes that can help bringing about an accelerated change in improved cooking practices which save time, energy and environment should be highly encouraged. The practice such as pre-soaking of dried beans, cutting/girding of meat into small pieces, using just enough water for boiling/steaming operation, selection of appropriate types and size of pots/pans for cooking, getting recipes and cooking utensils ready before starting the fire, use of hay- box, pot lid, drying of fuelwood with residual heat, cutting of fuelwood in small pieces. etc. can significantly improve an overall cooking performance by any count, including fuel and time savings.

9.9 Stove Construction Materials

This is an important area for cost reduction, increasing durability and decentralized production systems for ICSs. These issues are extremely important for long term sustainability of the improved cookstove programme.

Corrosion studies on different components of the stove, when subjected to corrosive compounds produced during combustion of fuelwood and biomass at higher temperatures, are lacking in the literature. Stove material is also subjected to severe chemical stresses which manifest themselves in different forms of corrosion. This problem gets compounded due to high temperature in the fire-box and spillage of the food ingredients. Studies are needed to understand this phenomenon, and to find a suitable thermal resistant enamel/glazing materials which can enhance the life of the steel by inhibiting corrosion.

There is a need to develop new material of construction, which can overcome the drawbacks of existing materials of construction. Some specific issues which need in-depth study are: development of mud additives for enhancing resistance of mud stove against weathering; cost effective ceramics material for stove construction as well as low investment ceramic production system; low cost additives for clay formulation that improved thermal and mechanical strength of fired clay stoves, etc. Experiment data on thermal stability of various clay mixes, in temperature range of interest, is still much lacking.

Coral sand degrades when subjected to high temperature. There is a need to develop composites, which can withstand high temperatures for application in coral islands.

9.10 Heat of Chemical Reaction

Studies on heat of chemical reaction on different types of foods are required as these are important for better under standing of the cooking process, and the performance of a cookstove. Data on heats of chemical reactions is lacking.

The design power of a cookstove is based on the time for cooking. Data on the time required for different cooking operations on cookstove, as a function of quantity of food at maximum power is not available in literature. In the absence of this data, correlations based on testing of the cooking range (GIVEG 1968) is being used. There is a need to under take these studies for better design practices.

9.11 Improved Performance of ICS:

R&D efforts are highly recommended for development of the ICSs with even higher thermal efficiency (40% and above), clean combustion, low cost, with multi-fuel & multi-function capability. Stoves for loose biomass for which they are widely used is another critical but gray area of research.

9.12 Commercial Stoves

To promote income generation activities in the rural area, there is a need to develop biomass based combustion systems/furnaces for; commercial food processing, agro processing, and other allied industries. Stoves for area specific applications, such as space heating, water heating and large scale cooking still need considerable development efforts.

9.13 Biofuel Upgradation Techniques

Raw biomass as fuelwood and various agri-residues can be improved via compaction, pyrolysis, liquefaction and gasification. In theory, these technologies are reasonably well established. However in practice, due to various development constraints as economic, techno-economic/economy of scale, market and marketing, investment support, etc., they are only applied in limited scale. Relating to the solid biomass burning cookstove, in particular, improved biofuel production R & D to reduce those constraints mentioned would be highly desirable, especially on briquettes and carbonized fuels. Policy research in the development of sustainable biomass energy systems, in a long term, may add a good impact for the biomass based improved stove development in futuristic form like alcohol.

9.14 Stove Testing, Standardisation and Quality Control

Modifications are needed in the existing tests, prescribed for evaluating the performance of the stoves, both in laboratory and field. There is a need to incorporate tests for material quality, manufacturing accuracy, smoke and other emissions, thermal and mechanical shock. There is also a need for evaluating the relative performance of different tests.

9.15 Final Challenge

Stove technologies are indeed very complex. In spite of the efforts of large number of researchers, spread over a period of nearly half a decade, the technological implications are far from complete comprehension. Thus, overcoming such knowledge gaps would remain challenging subjects for concerned scientists for years to come.

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Appendix 1 CHIMNEY AND NET POSITIVE SUCTION HEAD

Static draft

The weight of a column of hot gas is less than the weight of an equivalent column of ambient air at the base of chimney, thus creating a lower pressure. This results in creating a suction effect, as fluid flows from a region of high pressure to a region of low pressure. Static draft can be calculated by the equation :

$$\Delta P_{start} = h_{ch} * (\rho_a - \rho_g)[kg/m^2] \qquad \text{. . . . . (A-1)}$$

Where h_{ch} is the height of the chimney, and ρ_a and ρ_g are the densities of the outside air at the chimney base and the flue gas respectively.

Dynamic pressure loss

Kinetic energy loss due to the flow of gases through the chimney is known as dynamic pressure loss. It increases with an increase in the velocity of the gas. A small diameter chimney will result in greater loss. On the other hand, gases will flow in the form of slug flow without contributing towards the draft, if the diameter is too large.In a large diameter chimney, the cold air flows down the chimney in the cold season. It has been suggested that for optimum operation,the average velocity through the chimney should be between 0.4 to 1 m/s (Verhaart compendium 1981). The dynamic pressure loss can be calculated by the equation:

$$\Delta P_{dyn} = \frac{p_g * v^2}{2 * g} \qquad \text{. . . . . (A-2)}$$

Where g is the constant of gravity and v is the velocity of the gas.

Frictional pressure loss

The loss of pressure due to the friction encountered during the flow through passes which have different shapes in the cookstove and the chimney are known as friction pressure losses. From the fluid dynamic point of view, all these shapes can be grouped into different geometric shapes such as: (a) Straight channels of uniform cross section, (b) bends, (c) sudden expansion, and (d) sudden contraction. The pressure loss due to flow friction is given by the equation:

$$\Delta P_{fr} = \frac{f * h_{ch} * \rho_g * v^2}{2g * d_h} \qquad \text{. . . . . (A-3)}$$

where; f is the friction factor, d_h is the hydraulic diameter, which is defined as 4X the cross sectional area/wetted perimeter.

The value of the friction factor depends on the flow regimes, which may be either laminar or turbulent, depending upon a dimmensionless parameter known as Reynold's number. The Reynold's number is defined as:

$$\Delta R_e = \frac{d_h * v * \rho_g}{\mu} \qquad \text{........ (A-4)}$$

where µ is the dynamic viscosity.

In order to calculate the flow resulting from this draft,the resistance to the flow must be known for pot holes and flue ducts depending upon the design. For ease of calculation, the flow path is split into different geometric shapes such as straight channels, right angled bends, sudden expanding and contracting sections, etc. Resistance coefficients for various components are given in the literature[1]. A detailed analysis of fluid flow principals as applicable to cook stoves has been presented in "A Woodstove Compendium" (De Lepeleire e.a 1981). The net suction pressure available for a chimney with a height h_c and diameter d is given by equation:

$$\Delta P_{net} = h_{ch} * (\rho_a - \rho_g) - \frac{\rho}{2g} * v^2 - \alpha * \frac{h_{ch}}{d} \qquad \text{........ (A-5)}$$

where α is the resistance coefficient. The influence of the density of the flue gas on the temperature is given in table A.1.

There is not much variation in the density with the change in the molar composition of wood. At higher elevation, the pressure and density of the ambient air decreases. The effect of elevation on air pressure and density is shown in table A.2.

Table A.1 Density of flue gases

Temperature of flue gas in ^{o}K	Density of fluegas
600	**0.597 - 0.580**
700	**0.512 - 0.497**
800	**0.448 - 0.435**
900	**0.398 - 0.386**
1000	**0.358 - 0.348**
1100	**0.325 - 0.316**
1200	**0.298 - 0.290**
1300	**0.275 - 0.267**
1400	**0.256 - 0.248**
1500	**0.238 - 0.232**

Note:The density of flue gases is valid for complete combustion of wood with the moisture contents from 0-36% with a molar formula of $C_X H_Y O_Z$ as a function of absolute temperature with an oxygen deficiency factor O_d of 0.1 with X=3.486, Y=5.0 and Z=1.0125

Table A.2 Effect of elevation on density of air

Elevation in m. above sea level	Air pressure and density relative to that at sea level
0	1.000
500	0.944
1000	0.892
1500	0.842
2000	0.795
2500	0.751
3000	0.709
4000	0.632
5000	0.564

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[1] ASHRAE Handbook and Product Directory 1975, Wood Burning Encyclopedia by Shelton and Shapiro, 1976 and table 3.4 in Murgai, 1982.