Aquafeed Twin Screw Extrusion Processing

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Abstract

Aquatic feeds require specific physical and nutritive properties and have to comply with the fish behaviour. Fish meal and fish oil are frequently used as raw materials together with cereals (binders) and additives such as vitamins and minerals. Other protein sources are found in the diets to complement or replace fish meal, for example soybean flour. Fish oil can be partly substituted by vegetable oils.

Aquafeed extrusion processing lines consist of well defined unit operations which aim at converting feed mixes into texturized, shaped and stable aquafeed pellets. Such unit operations including raw mix preparation (grinding in particular), extrusion processing, drying, fat coating and cooling are discussed. Special emphasis is presented on those unit operations which affect the quality of aquafeed pellets. These include pre-conditioning of feed mixes (heat balance, hydration time, and residence time distribution), thermo-mechanical cooking in twin screw extrusion processing and aquafeed pellet texturization (control of SME and pellets density, in particular).

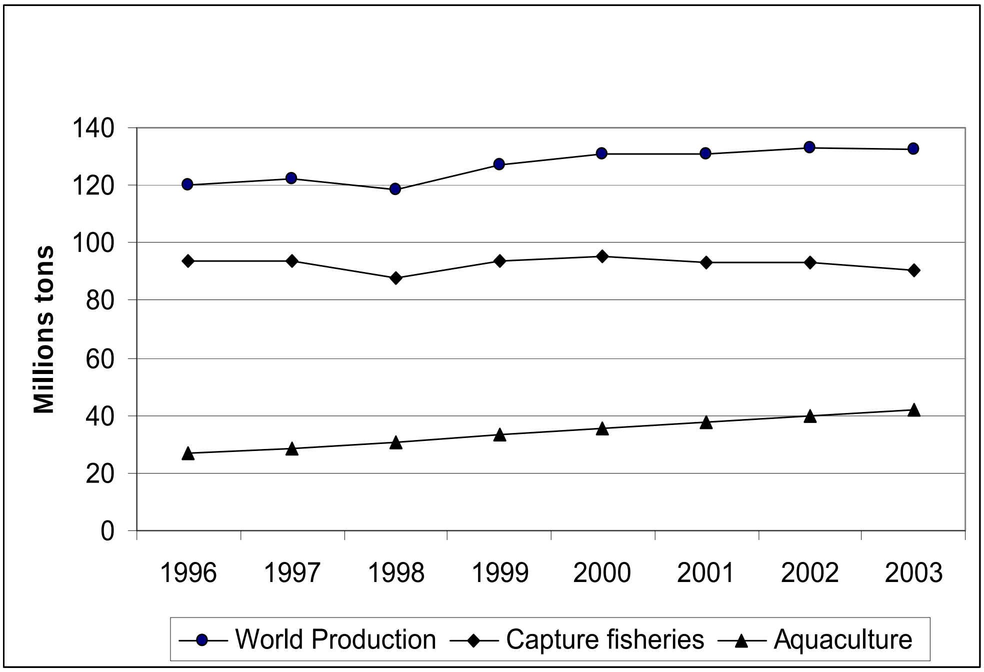
Keywords: Extruded aquafeed pellets, Feed mix grinding, Pre-conditioning, Extrusion cooking, Twin screw extrusion.

Introduction

Fresh water aquaculture is said to be a few thousand years old. It was reported that Egyptians were breeding tilapia 4500 years ago, and the common carp was cultured in 1500 BC in China. Marine aquaculture developed 1500 years ago along the Mediterranean Sea in Greece, Egypt and Rome with mullet, oysters and cockles (Bryceson, 2005).

These farming techniques spread throughout the world with an acceleration in the last two centuries and represent today a significant part of the human food production. Aquaculture contributed 41.9 millions tons in 2003 (aquatic plants excluded), to the global human consumption of fish of 103 millions tons and up to 40% of aquatic animals eaten in 2003 in the world were farmed (FAO, 2004). It is interesting to note that the annual worldwide growth was 8.9% per year in average during the last 20 years while in the same time the growth rate for captured fishes was only 1.2% per year, and 2.8% per year for the land-based meat production. If the global fish production has increased, it is mainly due to aquaculture as the capture fisheries remained constant around 95 millions tons per year (Figure 1).

Figure 1: Yearly aquaculture production, from 1996 to 2003 (FAO, 2004)



In 2003, the consumption of fish per capita in the world amounted to 16.3 kg; in China alone this value is estimated at 27.7 kg/capita. China is the major world contributor to the aquaculture industry as 70% of the total farmed aquatic animals (including finfishes, shellfishes, and molluscs) are produced in China, most of them being fresh water species such as carps (Table 1).

Table 1: Main producing countries in aquaculture (2002)

Country	Thousands tons	%
China	27 767.3	69.8
India	2 191.7	5.5
Indonesia	914.1	2.2
Japan	828.4	2.0
Bangladesh	786.6	1.9
Thailand	644.9	1.6
Norway	553.9	1.4
Chile	545.7	1.4
Vietnam	518.5	1.3
United States	497.3	1.2
Sub Total (Top Ten)	35 248.4	88.3
Total world	39 798.6	100

As far as the geography is concerned, over 88% of the worldwide production is achieved by ten countries and among them, seven are located in Asia. Considering the main farmed animals, we find that few species dominate the global production (Table 2). For example, most of these species are produced in Asia; salmonids are mainly farmed in Europe and Chile, and oysters (*Crassostrea gigas*) in South East Asia and North America.

Table 2: Main species produced in aquaculture (2002)

Species	Thousands tons	%
Carps and other cyprinids	16 692.1	41.9
Oysters	4 317.4	10.8
Miscellaneous freshwater fishes	3 739.7	9.4
Clams, cockles, arkshells	3 430.8	8.6
Salmons, trouts, smelts	1 799.4	4.5
Tilapias and other cichlids	1 505.8	3.8
Mussels	1 444.7	3.6
Miscellaneous marine molluscs	1 348.3	3.4
Shrimps, prawns	1 292.4	3.2
Scallops, pectens	1226.5	3.1
Sub total (top ten)	36 797.1	92.3

What about the future? The growth rate for aquaculture will decrease slightly from 8 to 9% down to 4 to 5% per year, and some forecasts (FAO, 2004) predict a production in 2030 of 83 millions tons for the aquaculture and 93 millions tons for capture fisheries. The worldwide consumption of fish should reach 20 kg/year per capita in the same period. Aquaculture will grow in Latin America and in Africa, starting with fresh water species on land, and then moving to marine species. New species with high value will be farmed in the developed countries. The need for aquafeed pellets will therefore increase.

The Range of Aquafeed Pellets

Many farmed aquatic animals, on land or marine based, are cultured in closed environments: e.g., basins, tanks, cages, etc. The fishes are not able to get on their own, the necessary feed (nutrition) for their basic needs such as for metabolism (e.g., breathing, movement, digestion), reproduction and growth. It is therefore necessary to provide and control the required feed in order to optimize the culture conditions. The feed has to comply with specific physical and nutritional requirements.

Physical Characteristics of Aquafeed Pellets

Pellet Size

It is necessary to provide the right pellet size adapted to the mouth of the animal and in exact quantities with all the pellets having the same dimensions (size). Direct extrusion allows for the manufacture of feed pellets with diameters starting from 0.5 mm up to 30.0 mm. Other processes such as extruding, then crushing and sieving are used to manufacture crumbles down to smaller sizes of 0.2 to 0.3 mm; while recent cold extrusion techniques reportedly produce small round particles for feeding salmon larvae.

Texture

This relates to the hardness, brittleness and cohesiveness of the pellet. The fish has to ingest a complete piece. A brittle pellet may disintegrate quickly in water, creating pollution and giving low ingestion rates. Water stability may be an issue for many species. For example, shrimp are slow feeders: with ingestion times ranging from minutes up to hours. The feed (granulate state) must be cohesive and its nutrient composition must be preserved before it is ingested.

Density

All aquatic species do not have the same behaviour in water. Some fishes are living or lying on the bottom (demersal species), while some others stay in the water column (pelagic species). There are fishes that will feed actively (salmonids), while others wait for the slow sinking pellets to approach them. Some animals such as shrimp eat on the bottom and are attracted by leaching substances from the pellet. Therefore, the density of aquafeed pellets has to be adapted to the behaviour of the fishes in order to increase the chance for them to ingest the feed. Sinking properties depend not only on product density, but also on other factors such as water salinity and temperature.

Storage and handling

After manufacturing, aquafeed pellets are put in sacks or big bags, transported, stored, and finally distributed manually or through mechanical systems such as pneumatic conveyors and automatic distribution units. The pellets must resist abrasion, attrition and crushing during this process. It should not create fines which are costly sources of pollution and uneaten feed. Additionally, the pellets have to keep their original composition and avoid any leakage of oil or any other coated substances.

Composition of Aquafeed Pellets

All aquatic species have its own specific nutritional requirements, be it protein content, fat, carbohydrate, vitamins, oligo-elements or minerals (Kaushik, 2004a) as shown in Table 3. These needs may vary depending on the age of the animal, the seasons, the breeding conditions, during reproduction or growth periods. This is a key factor when considering the economic aspect of intensive aquaculture and also the availability of raw materials worldwide such as fish meal and fish oil.

The nutrients included in the pellets also have to be available. Phosphorous, for example, may be bound to phytic acid in some raw materials. When un-absorbed and rejected by the fishes, phosphorous may create biological pollution as it is readily taken up by aquatic plants and may lead to algae blooms. Fishes have different enzymatic abilities to degrade starch. For those species which are poorly endowed with amylases, it is necessary to fully gelatinize the starch (used as a binder) to facilitate easier enzyme action and digestion.

Raw Materials in Aquafeed Pellets

Diets must comply with the essential nutrient and energy required for the normal metabolism, reproduction and growth of the fishes (Kaushik, 2000). Species show variable and specific needs. The ratio of crude protein/crude fat is an important factor as fishes can use proteins as an energy source. Therefore diet formulations have evolved to include a higher fat content.

Ideally, it is expected that fishes use proteins for its growth only, and fat as the main source of energy. This way, the nitrogen excretion from the feed into the water is lowered and good feed conversion ratios (FCR) are achieved. Some diets for Atlantic salmon are formulated with a crude protein/crude fat ratio of 1:1.

Table 3: Fatty acids needs versus fish species (juveniles and adults)

Species	Essential fatty acids	Content of fatty acids (% dry weight)
Fresh water		
Common carp	18:2 ω6	1.0
	18:3 ω3	0.5 to 1.0
Grass carp	18:2 ω6	1.0
	18:3 ω3	0.5
Nile tilapia	18:2 ω6	0.5
Tilapia zilli	18:2 ω6	1.0
Rainbow trout	18:3 ω3	0.7 – 1.0
	PUFA ω3	0.4 – 0.5
Channel catfish	18:3 ω3	1.0 – 2.0
	PUFA ω3	0.5 – 0.75
Arctic charr	18:3 ω3	1.0 – 2.0
Marine		
Gilthead sea bream	PUFA ω3	0.5 – 1.9 (DHA:EPA = 0.5 to 1.0)
European seabass	PUFA ω3	less than 1.0
Turbot	PUFA ω3	0.8
Yellowtail	PUFA ω3	2.5
Grouper	PUFA ω3	DHA > EPA
Asian seabass	PUFA ω3	1.0

Table 4: Use of fish meal and fish oil versus cultured species in 2001 (Kaushik, 2004b)

Species	Fish Meal % of worldwide availability	Fish Oil % of worldwide availability
Salmonids	12.7	34.6
Other marine fishes	9.7	10.9
Shrimps	8.3	3.8
Cyprinids	6.6	0.0
Eels	3.0	1.3
Tilapia	1.2	1.0
Milkfish	0.6	0.4
Cat fish	0.4	0.5

Fish meal is widely used as the basic protein source in aquaculture diets, but it will have a limited availability in the future (Table 4). It appears to be a costly ingredient for protein and many research works have been conducted on the substitution of fish meal by other proteins sources such as soybean, rapeseed, cereals, pulses (peas, lupine) and also plant protein concentrates.

Soybean flour is commonly found in diets at levels which can reach 50% (for crustacean); and a supplementation with methionine seems to improve growth performance (Kaushik et al., 1995). It must be noted that soybean meal has to be pre-treated in order to reduce its anti-nutritional factors content. This is usually done through heating and also fermentation of the soybean, while the use of hydrolytic enzymes can also be used to enhance the nutritive value (Khajarern et al., 2005). The availability of phosphorous can also be improved by processing the soybean flour with enzymes such as phytase.

Fish oil availability is also limited (Table 4). New alternatives have to be found to ensure a sustainable aquaculture industry. The use of vegetable oils as partial replacement in species such as rainbow trout, Atlantic salmon, European sea bass and gilthead sea bream have not shown any significant changes in sensory evaluations (Kaushik, 2004a). Further studies on the replacement of fish oil in diets are currently being conducted worldwide.

Binders are mainly used in diets to keep the texture, and improve the water stability and also pellet durability. Wheat flour is widely used but its starch must be gelatinized to create a 3-dimensional matrix. Extrusion technology is a thermo-mechanical treatment which improves the degree of gelatinization. The digestion by the animals is improved and consequently, the feed conversion ratio as well. Other micro-ingredients such as vitamins, amino-acids, attractants, pigments, minerals are also added in fish diets depending on the fish needs.

The processing of aquafeed pellets can be done by either pelletizing or extrusion cooking technology. Numerous publications present the process characteristics of these technologies, as well as their impact on the final quality (Kaushik, 2000; Storebakken, 2002). It must be said that extrusion processing is widely employed and recognized in aquafeed manufacture as extruded pellets show a much better quality compared to pelletized pellets.

The ability to control the floating and sinking properties (bulk density) of pellets, along with the possibility to increase the fat content, makes extrusion cooking technology much preferred in aquafeed manufacturing. Additionally, the extrusion cooking process allows the cooking of feed mixes which can texturize and shape the resulting pellets towards advanced end-use properties.

Although extrusion technology is more expensive than pelletizing, its payback is definitely beneficial due to its positive impact on process productivity, process flexibility, the environment and feed conversion ratios. This is why extrusion cooking technology is largely used in aquafeed processing plants.

Key Process Issues of Aquafeed Production

As mentioned, the product range of aquafeed pellets possess a wide range of characteristics depending upon the final destination of the pellets. Therefore, processing lines must operate with various feed recipes, and produce a wide range of pellets with different sizes and functional properties. Processing lines should also satisfy drastic economical constraints to ensure the profitability of the aquaculture business.

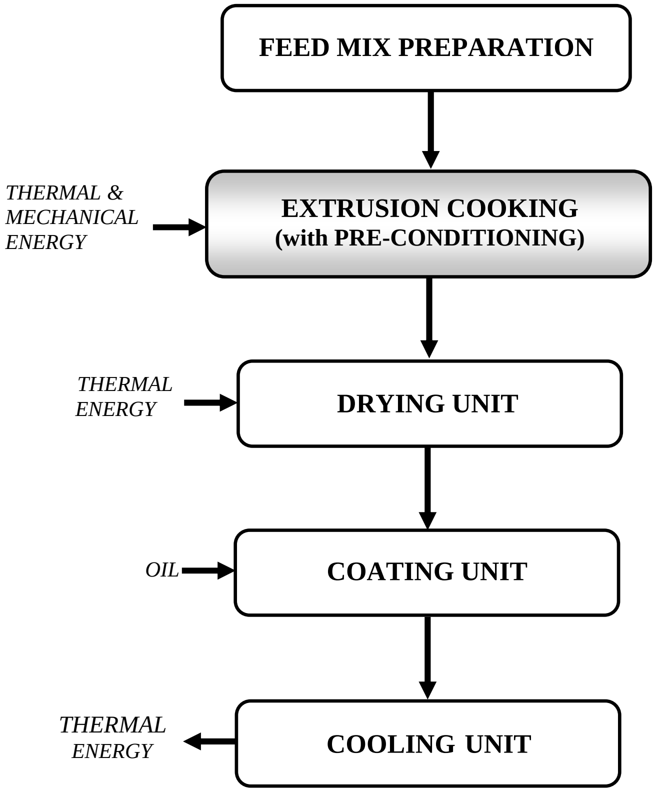
It has been mentioned that extrusion technology has brought significant technical and economical advantages in the production of aquafeed pellets, thanks to its process flexibility and reliability. It must be noted that aquafeed quality depends not only on extrusion parameters, but also on a large number of variables distributed all along the processing line. These are discussed according to the process diagram shown in Figure 2.

Feed Mix Preparation

The first step of the aquafeed processing line classically consists of “Feed mix preparation”, which aims at selecting the raw materials, reducing the particle size and mixing the ingredients. Raw material selection and feed mix preparation have a significant impact on the texture, uniformity, nutrition and economic value of the final product.

Once the ingredients are selected according to the final use of pellets, an important unit operation in feed mix preparation includes reduction of particle size and mixing of the different ingredients. Particle size reduction concerns mainly biopolymer-based raw materials (starchy components, proteinaceous ingredients), and much attention must be paid to it as it may bring many benefits. It reduces the wear and increases the capacity of the downstream extruder. The lower the particle size, the lower the wear through abrasion in the melting section of the screw configuration, and the higher the melting and cooking capacity of the extruder.

Figure 2: Process diagram of aquafeed extrusion processing



Besides, particle size should account for the final size of the pellets. In general, grinding guidelines are as follows:

- for die openings up to 3 mm, the largest particle size should not be larger than 1/3 of the die opening;
- for die openings larger than 3 mm, the largest particle size should not be larger than 1.5 mm.

Smaller particles improve pellet durability and water stability, and decrease pellet friability. Obviously, when cooking smaller particles by extrusion, complete and homogeneous melting and cooking of the biopolymer-based ingredients will occur, and this tends to improve the strength and mechanical resistance of the final pellet structure.

Finely ground feed ingredients also bring beneficial nutritional effects such as improving the digestibility and bio-availability of nutrients, thanks again to complete and homogeneous melting and cooking of the ingredients. This is particularly important since most species of fish, crustacean and shellfish have a very short digestive tract.

However, particle size reduction needs to be optimized as ultra fine grinding may generate damages from the nutritional standpoint. In fact, the process of size reduction generates heat, due to high frictional and attrition forces. Under these processes, starch can be damaged (dextrinization) and proteins denatured at high temperatures. Fats and oils can vaporize and dissipate out of the feed; while added supplements can be destroyed or modified resulting in them being less bio-available. Much care must then be taken to control the conditions of particle size reduction, the temperature increase in particular.

Hammermills and air swept pulverizers are commonly used for grinding the raw materials in aquafeed processing. Hammermills offer high efficiency, low heating and reduced aspiration requirements. But, they are limited in the finished particle size that can be achieved. Typical finished ground ingredients are in the range of 95-99% less than 500 microns, with an average particle size of 200-300 microns. When especially equipped, hammermills are able to grind feed ingredients as fine as 95-99% less than 250 microns, with an average particle size of 100-175 microns. Air swept pulverizers can achieve finished ground ingredients in the range of 95-99% less than 150 microns, with an average particle size of 40-75 microns.

The milled feed ingredients are conveyed to a mixer in which the main, flour-based stream is homogeneously mixed with some additives. Then, it is fed to the extrusion cooking unit.

Extrusion Cooking of Feed Mix

The second step of the aquafeed processing line aims at cooking the dry feed mix, and texturizing and shaping the aquafeed pellets. This unit operation consists of 3 sub-units:

i) pre-conditioning
ii) thermo-mechanical cooking
iii) die texturization and shaping

Pre-conditioning involves the heating, pre-humidifying and pre-cooking of the feed mix. This is achieved by adding steam and liquid water while the feed mix is quasi-fluidized in the pre-conditioner, thanks to its rotating shaft-paddle assembly. Key variables of pre-conditioning are temperature, residence time, filling ratio and degree of mixing; their impact on pre-conditioning will be discussed more in depth later in this chapter (section on Pre-Conditioning).

Figure 3: Shafts-paddles assembly of a twin shaft Pre-conditioner (with CLEXRAL permission)

Among the advantages of pre-conditioning are increased extrusion capacities and reduced starch damage and nutrient losses. This is because part of the mechanical energy normally supplied in the extruder is replaced by thermal energy supplied in the pre-conditioner. Besides, pre-conditioning also leads to a significant reduction of screw wear in the extruder, as a result of the hydration of the feed mix in the pre-conditioner which reduces the abrasiveness of the feed particles.

In general, the pre-conditioner has a figure-eight shape with two counter-rotating shafts that are centred in each half of the cross-section. Screwed to the shafts are a series of adjustable paddles, whose orientation and wall clearance can be adjusted (Figure 3). Paddles can be oriented in a forward direction to convey the mix, or reverse to fill the pre-conditioner, or neutrally to enhance mixing as well as increase the residence time.

Thermo-mechanical cooking of pre-conditioned feed mix

The feed mix is submitted to a controlled, thermo-mechanical cooking treatment which consists of converting biopolymer-based components into an amorphous state, and mixing amorphous biopolymers with all the other feed ingredients, to obtain a homogeneous melt at the exit of the cooking section of the extruder. In particular, starch ingredient needs to be well cooked and fully gelatinized so that its binding effect can be expressed when achieving pellet texturization. Thermo- mechanical cooking of the feed mix in an extruder requires two energy inputs:

- mechanical energy input defined mainly by screw speed and screw configuration, and
- thermal energy input determined by direct steam heating and indirect barrel heating.

Two types of cooker extruder can be used in aquafeed production i.e., single screw extruder and twin screw extruder. The single screw extruder has been extensively used, particularly for processing simple recipes and producing basic pellets. Single screw extruders have major drawbacks in that:

i) it is not very flexible in terms of rheology of the mix being processed due to the presence of fat in the recipe;
ii) the screw has to be full to avoid purging, which makes screw speed and mix throughput totally dependent;
iii) the cooling efficiency in the last barrel section is low, which leads to a lack of temperature control of the cooked melt; and
iv) the mixing degree in the screw-channel is very low, which gives heterogeneity in the melt matrix.

These factors limit the operational range of single screw extruders, and make open the window for the introduction of intermeshing, co-rotating twin screw extruders.

Twin screw extruders are able to process consistently, with a high level of flexibility, large range of raw materials because of its positive pumping action. It is also possible to starve feed the machine as screw speed and throughput are independent, and the cooling efficiency in the last part of the barrel is high, which allows for good control of the melt temperature. The mixing temperature in the screw channel is also very high, which gives a homogeneous melt.

Although twin screw extruders are more expensive than single screw extruders, they have been extensively used in aquafeed industry since the

early 80's, thanks to their high level of process flexibility and productivity, and pellets consistency. In addition to that, new ranges of twin screw extruders do bring advanced functionalities as being able to operate at high screw speeds (from 400 to 800 rpm), L/D ratios of 16 to 28, so that to apply the required Time-Temperature-Shear history in the screw-barrel assembly, which determines the cooking extent of the feed mix.
As far as the heat transfer is concerned, the design of barrel modules of newer twin screw extruders are optimized to allow more heat exchange than previous models, particularly in the cooling section. This is of importance in aquafeed extrusion processing as this improvement allows for accurate control of the melt temperature at the die, and consequently a very efficient control of the expansion of the melt at the die.

The new range of CLEXTRAL twin screw extruders so-called EVOLUM, benefits from such advanced engineering and processing functionalities:

i) high screw speed processing (currently up to 800-900 rpm), which means high process capacity on a wide range of feed mixes;
ii) high cooling capacity (roughly twice as compared with previous ranges of extruders), that is high pellets quality on a wide range of bulk density (300 to 750 g/L);
iii) optimized, reliable extruder design, which leads to minimized investment cost as feed-oriented twin screw extruder.

Texturization and shaping of aquafeed pellets, is achieved through a die system equipped with a die-face cutter. Although the die-cutter assembly is the cheapest sub-unit of the aquafeed processing line, it is one of the most important one as it determines the physical quality of the finished pellets. In fact, the design and the process variables of the die-cutter assembly aim at converting the rheological properties of the cooked melt into an expanded structure of the pellets; and the resulting structure defines the end-use characteristics of the pellets such as bulk density, durability, water stability.

Finally, but not the least, the design of the die-cutter assembly needs much attention to allow the aquafeed producers to quickly change pellet sizes and reduce to minimum the production downtimes.

Pellet Drying

After die face cutting, the wet aquafeed pellets are conveyed to a dryer in order to reduce the moisture content from 20-24% down to 8% to 10%. Of course, moisture reduction is the main purpose of the dryer. Normally, 2325 kJ/kg are required for water removal in the drying process. The impact of drying on pellets quality and operating cost can vary tremendously, depending upon the design of the dryer, and drying parameters.

The dryer aims at applying uniformly, heat energy over the whole surface area of the pellets through the action of turbulent air movement surrounding the pellets. This air movement is maintained by a low partial vapour pressure. The heat energy is transferred to the pellets by heat convection, with the transfer rates strongly dependent upon the degree of turbulence around the pellets. The heat energy is transferred within the pellets by heat conduction from the surface through towards the center of the pellet, and the transfer rate depends mainly upon the temperature gradient and the porosity of pellets. When heating up the water within the pellet, the partial vapour pressure of the water increases as a result of the increasing temperature. This generates a moisture gradient which induces water diffusion out of the pellets and the turbulent drying air then carries the moisture away from the surface of the pellet.

Several factors control water removal from the pellets. These include:

i) Air related factors. Dependent on the air flow characteristics around the pellets, and temperature and humidity of the drying air.

ii) Pellets related factors. Dependent on the initial moisture content and temperature, porosity and size of the pellet.

The design of the dryers should be optimized from the aerodynamics and thermal standpoints. The principle of contacting drying air with pellets is also an important design factor, so that moisture removal with respect to pellet quality (low fines generation, low damages to pigments and palatability ingredients) and drying economics (low energy losses, low moisture variance). In aquafeed processing lines, extruded pellets are generally dried on one of the following dryer designs:

i) Horizontal belt dryer. These are based on a single or multiple passes, moving belt; single pass air flow as well as re-circulating air flow are used.

ii) Vertical counter flow dryer. The pellets continuously enter through the top of the dryer, and they are distributed into a square or round drying vessel, where they move down while the drying air goes up. Vertical dryers show significant operational advantages such as: higher thermal efficiency, lower footprint, lower maintenance and capital costs.

iii) Fluidized bed dryer. This is where the pellets are fluidized by the drying air. Although the air-to-pellets contact is ideally achieved, this design is not much used in processing units.

Though significant improvements in pellets drying have been achieved during the last decade, it must be noted that further developments are still required to operate more consistently with regards to pellets quality and operating cost.

Fat Coating

As seen in the first part of the chapter, aquafeed pellets are lipid-rich feedstuffs, and fat must be added to reach the targeted composition, according to fish needs (energy and nutrition).

Fat addition is commonly done after drying; however some fat can be added directly as well in the twin screw extruder up to about 5% as this helps to fine tune the bulk density. As aquafeed pellets come out of the dryer, oil is added to hot pellets through coating. This can be carried out by two ways:

i) Under atmospheric pressure. Oil is sprayed on to the pellets in an inclined rotating drum ; oil temperatures around 40°C are common to ensure enough fluidity to oil and thus distribute it easily on pellets. Oil diffuses from the surface through to the centre, and is stored into cavities of pellets structure. The design of the spraying system together with the rotating effect of the drum should ensure a homogeneous exposure of the pellets to the oil spray. Presently, continuous, atmospheric fat coating allows achieving 30% total oil content in some extruded pellets.

ii) Under vacuum pressure. Air is withdrawn from the various cells and pores inside the pellets; when the desired vacuum pressure is reached, spraying of oil takes place. Then, the vacuum is released which presses the oil into the pellets structure. The capillary forces also help the oil to penetrate some distance into the pellets, while the surface stays relatively dry. This process allows the addition of more oil into the pellets, while ensuring a dry surface. It is possible to achieve more than 40% total oil content (salmon feed, for example).

Since its introduction in the late 80's, vacuum coating is now very well recognized and used as it brings significant advantages with regards to pellets quality (higher yield of fat addition, dry surface of pellets, ability to maintain different added ingredients inside the pellets). It operates through a batch process, with typical cycle time of 4 to 7 minutes.

Cooling of Pellets

Cooling of the pellets is required after fat coating to remove excess heat, and thus prevent any condensation which can occur in the storage bins, or in the final packages. Condensation occurs when air-water vapour mixture is cooled to or below the corresponding dew point temperature. At high relative humidity approaching 100%, the dew point equals the ambient temperature; so, only slight amount of cooling of the ambient air will generate moisture condensation. At a low relative humidity, say 30%, larger temperature changes can occur before moisture condensation.

Practically, the pellets temperature should be cooled within about 5°C of the temperature that the package will be exposed to during storage or transportation. It means that in winter time, chilled air may have to be used to lower the temperature of the pellets to safe levels; while in summer time, ambient air is usually satisfactory.

Pellet cooling is carried out by drawing ambient or chilled air through a pellets bed via a centrifugal fan. The required residence time to cool the pellets depends on three main variables:

i) Convective heat transfer. The convective heat transfer between the cooling air and the pellets, and the thermal conductivity of pellets which depends on pellets density. The higher the density, the lower the porosity, and the higher the thermal conductivity.

ii) Pellet size. The larger the pellets diameter, the higher the residence time required to lower the temperature of the pellet.

iii) Temperature gradient. The temperature decrease required which is defined as the temperature of the pellet at the inlet and the targeted pellet temperature after cooling.

Horizontal belt coolers and vertical counter flow coolers can be used to cool aquafeed pellets. But, vertical coolers are widely recognized as the standard cooling equipment in aquafeed processing lines, as they offer many advantages over horizontal coolers: higher thermal efficiency, better sanitation, lower footprint and low operating cost, in particular.

Main Unit Operations and Technologies

Although all unit operations of aquafeed processing line require much attention to optimize both pellet quality and economics, the extrusion cooking unit remains the most important one when considering its direct impact on pellet quality, and the ability of the processing line to match future challenges such as the evolution of raw materials sourcing and capacity increase of the lines. It is therefore important to analyze in depth the extrusion cooking unit, and particularly the physical mechanisms which govern its process functions and the design of related technologies.

Pre-Conditioning.

Pre-conditioning is necessary for thermo-mechanical cooking (case of twin screw extrusion) and die texturization.

Process Functions and Governing Factors

Pre-conditioners are used to pre-heat and pre-humidify dry feed mixes, by mixing them with steam and water. Thus, heat and water must be uniformly distributed within particles to avoid temperature and moisture gradients before cooking in the extruder. This prompts a basic investigation of the heat and mass transfer between components of the three-phase gas (steam)/liquid (water)/solid (feed mix) medium inside the pre-conditioner.

Practically, when feeding the slightly superheated steam and liquid water in the pre-conditioner, the steam heats the feed particles through condensation. The pre-conditioning process needs a minimum amount of steam to heat up the feed mix and liquid water to the required temperature. Pre-conditioning temperature is governed by the energy balance in the pre-conditioner.

Condensed steam, together with water, generates a thin film of water around the particles. Thus, when the cold particles are surrounded by the hot saturated steam, the temperature and moisture content of the particles increase but not instantaneously.

Two factors govern the rate of heating and swelling of the particles. The first is the film resistance at the surface of the particle; this relates to the quality of the contact between the fluid and the particles. The better the fluid/solid contact, or the higher the degree of mixing, the lower the film resistance. The second is the rate of heat and moisture flows inside the particles; this is the internal resistance governed by the heat and water diffusivities. The higher the heat and water diffusivities, the higher the rate of heat and moisture flow, and the lower the internal resistance.

In case of feed mixes at ambient temperature, the heat and water diffusivities are nearly 10^{-7} m^2/sec and 10^{-9} m^2/sec, respectively; diffusivity coefficients increase when temperature increases. It occurs that the ratio between heat diffusivity and water diffusivity is around 100, meaning that the heat transfer is much faster than the water transfer within the particles. Therefore, for a given temperature, the water transfer governs the residence time in the pre-conditioner.

Heat Balance in the Pre-conditioner : Pre-conditioning Temperature.

In the pre-conditioner, the temperature of feed mix and liquid water increases from the inlet temperature (roughly the ambient temperature) to the targeted exit temperature of the pre-humidified feed mix (about 85°C), thanks to the latent heat supplied by steam condensation (Figure 4). Assuming that the pre-conditioner operates adiabatically, that all steam is converted into liquid water, and that the outlet temperature of wet feed mix is around 85°C, the energy balance as applied to the pre-conditioner allows to estimate the amount of steam required (as expressed in kg/100 kg dry feed mix), as a function of moisture content of the wet feed mix (Table 5). This estimation represents the minimum amount of steam supply; it defines directly the outlet temperature of the wet feed mix. In practice, an extra amount of steam (from 10 to 20%) is needed to account for energy losses in the pre-conditioner.

Figure 4: Feed mix pre-conditioning: inlet and outlet flows