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MANUFACTURE AND EVALUATION OF A SINGLE PASS ROTARY COOLER FOR AQUATIC FEED PELLETS

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ABSTRACT

Cooling is one of the most important post-processing operations in the production of extruded aquatic feed pellets. In this study, a rotary pellet cooler of simple design was manufactured, and the effect of different operating parameters on the final quality of extruded floating and sinking aquatic feed (low density 0.538g/cm^3, medium density 0.789g/cm^3 and high density 0.915g/cm^3) was investigated. The cooler parameters that were studied included air suction velocity (2.32, 3.76, 4.35 and 5.87 m/s), cooler horizontal angle (10, 15, 20 and 30^o) and turning speed (5, 10, 15 and 20 rpm). Results indicated that the most effective operating range for these parameters was 3.76-4.35 m/s, 10-15 rpm and 10^o, respectively, which led to a cooling efficiency of 72.8-74.5%, and good quality aquatic feed pellets with 8.3-9.1% output moisture content, 0.0% molding percentage after 2 months of storage, 0.1-0.8% losses and 0.8-1.7% unpelleted mash..

Practical Applications

An effective cooling system for extruded aquatic feed pellets can significantly reduce the energy costs involved in drying for long term storage, and also minimize product losses during post-processing operations. Counter-flow rotary coolers, like the one described in this manuscript, are manufactured and sold commercially by a few companies. Such coolers also provide very efficient drying, and separation of unpelleted mash and broken pellets, however there are scant data in literature on their performance. The current study aims to fill this gap, and results are relevant to all coolers of similar design. The rotary air cooler that was designed, manufactured and evaluated in this study will be very useful for small-scale industries involved in the production of both floating and sinking aquatic feed, and can lead to greater efficiencies and cost-effectiveness.

INTRODUCTION

Pelleting of feed ingredients for poultry and various animals, like cattle, goats and sheep, has many benefits including greater energy density, nutrient homogenization and ease in ingestion. Pelleting of various agricultural residues is also undertaken for other purposes including production of combustible fuel and absorbent materials. Extrusion and pellet milling with die and rolls are the two pelleting methods commonly used by feed industry and studied by researchers (Maier and Bakker-Arkema 1989; McMullen *et al.* 2004).

Maier and Bakker-Arkema (1989) studied the production of pellets by extrusion. Ground feed ingredients were extruded through dies ranging in diameter from 4 to 12 mm. After extrusion, the pellets were cooled before being placed in storage. Also, stored pellets needed to be ventilated occasionally to prevent spoilage. They concluded that knowledge of the thermal properties (specific heat, thermal conductivity, and thermal diffusivity) of the pellets is needed in the efficient design and selection of coolers and ventilation equipment for poultry litter pellets. McMullen *et al.* (2004) used a laboratory pellet mill to produce pellets from poultry litter. Due to the high mineral content of poultry litter, samples were mixed with 3% vegetable oil to lubricate the die and to ensure that the pellet die will not clog during pelleting. Before passing through the pellet die, the temperature of the litter was increased to 75°C by injecting steam and by the use of a heat gun that blew hot air through the litter. Due to frictional heating during pelleting through the 3/16" (4.76 mm) diameter die, the temperature of the pellets exiting the die increased to 85°C ± 2°C. After pelleting, the pellets were cooled in an environmental chamber set at 22°C and 40% relative humidity.

Quality of the final pellets depends on the process before the die (milling and mixing), pelleting conditions and the process after the die (drying and cooling).For the pellet milling process, there is a general agreement on the contribution of different factors on the durability of feed pellets (Behnke 1994; Turner 1995; Thomas *et al.* 1997). The relative role of diet formulation is reported to be 40%, while that of particle size, steam conditioning, die specifications and cooling/drying are 20, 20, 15 and 5%, respectively. When including an expander in the conditioning process, the distribution becomes 25, 15, 40, 15 and 5%, respectively, for diet formulation, particle size, steam and expander conditioning, die specifications, and cooling/drying.

Extended stability of pelleted feed depends on effective cooling and drying immediately after their production, even though these post-pelleting operations have the least relative contribution. Often only cooling is undertaken as the high product temperature facilitates removal of moisture without additional energy consumption. Pellet cooling is therefore undertaken to remove - 1) heat added to the product during steam conditioning and then extrusion and/ or pelleting, and 2) excess moisture resulting from steam conditioning. Pellets that are not properly cooled can have reduced durability due to stresses in the pellet between the cooled outer layer and the warmer center, which induces cracks in the pellets. Also during the cooling process, soluble components in the feed re -crystallize and create bonds between particles (Maier and Bakker-Arkema 1992). Thus the cooling process improves pellet durability, and consequently sticking in bins is prevented and breakage and crumbling during handling and transporting minimized. It also reduces the possibility of spoilage from mold. However, from the standpoint of pellet quality, the pellet cooler is generally considered as the weak link in a feed mill (McEllhiney 1986).

In the conventional extrusion process for feed production, pelleted products exit the die at about 60-85°C and 12-17.5% moisture. During cooling, air is forced through the pellets to quickly reduce the temperature and to remove a specific amount of moisture from the material (Robinson 1984). In the pellet milling process, pellets leave the die at temperatures of 60-95°C and moisture contents of 12-18%. Pellets are cooled, mostly using forced air, immediately after the die to within 5°C of ambient temperature, and to within 0.5% of the original moisture content of the feed ahead of the conditioner (Turner 1995). In general, for long term storage, the final moisture content of the pellets should be less than 12-13% (Robinson 1984; Maier *et al.* 1992).

Factors affecting cooling efficiency include cooling time, bed depth, degree of packing, and air flow rate. Ray *et al.* (2004) studied air flow resistance during cooling of pelleted products of four sizes and shapes (circular cross-sections with 4.0, 6.7 and 19.4 mm diameters, and rectangular cross section with 33.2 x 34.9 mm dimensions). The effect of "loose" and "packed" fill were tested for each product size except for the cubes, which was tested at loose fill only. The pressure drop was higher for the packed fill, but the similar trends for variation of airflow with pressure drop was observed for both conditions. Three bin shapes (round, square, rectangular) containing equal airflow areas were also tested, and no significant effect of the same on air flow resistance was detected. Maier and Bakker-Arkema (1992) established that the most important operating and design parameters for a pellet cooling system are bed depth and air-to-pellet mass flow ratio. Fundamentally, both are airflow resistance parameters. They added that the cooling time may range from about 4 to 15 min.

Counter-flow rotary coolers are manufactured and sold commercially by a few companies. Such coolers also provide very efficient drying, and separation of unpelleted mash and broken pellets, however there are scant data in literature on their performance. The current study aims to fill this gap, and results are relevant to all coolers of similar design. For this purpose, a rotary cooling system for cooling of feed pellets was manufactured in-house, using a simple but robust design. The main criteria for determining the most effective operating range for any cooler are the physical characteristics of the end product. Lichtenberg *et al.* (2002) reported that physical characteristics of pellets such as durability, moisture uptake, storage stability and rupture need to be measured in order to quantify pellet quality during exposure to varying environmental conditions (such as high humidity and temperature), and to handling equipment used during storage, transportation and utilization of the pellets. In this study, cooling efficiency, pellet losses with circulating air, unpelleted mash percentage and mold formation were some of the pellet quality parameters that were investigated for evaluating the cooler performance.

MATERIALS AND METHODS

Components of the Single-Pass Rotary Cooler

A single-pass rotary cooler was locally manufactured using a simple design. The cooler rested on a frame with an adjustable base, and consisted of a feeding unit, a cooler barrel, an air suction unit and a power transmission unit, as showed in Figure 1. The different components of the cooler are described in greater detail below.

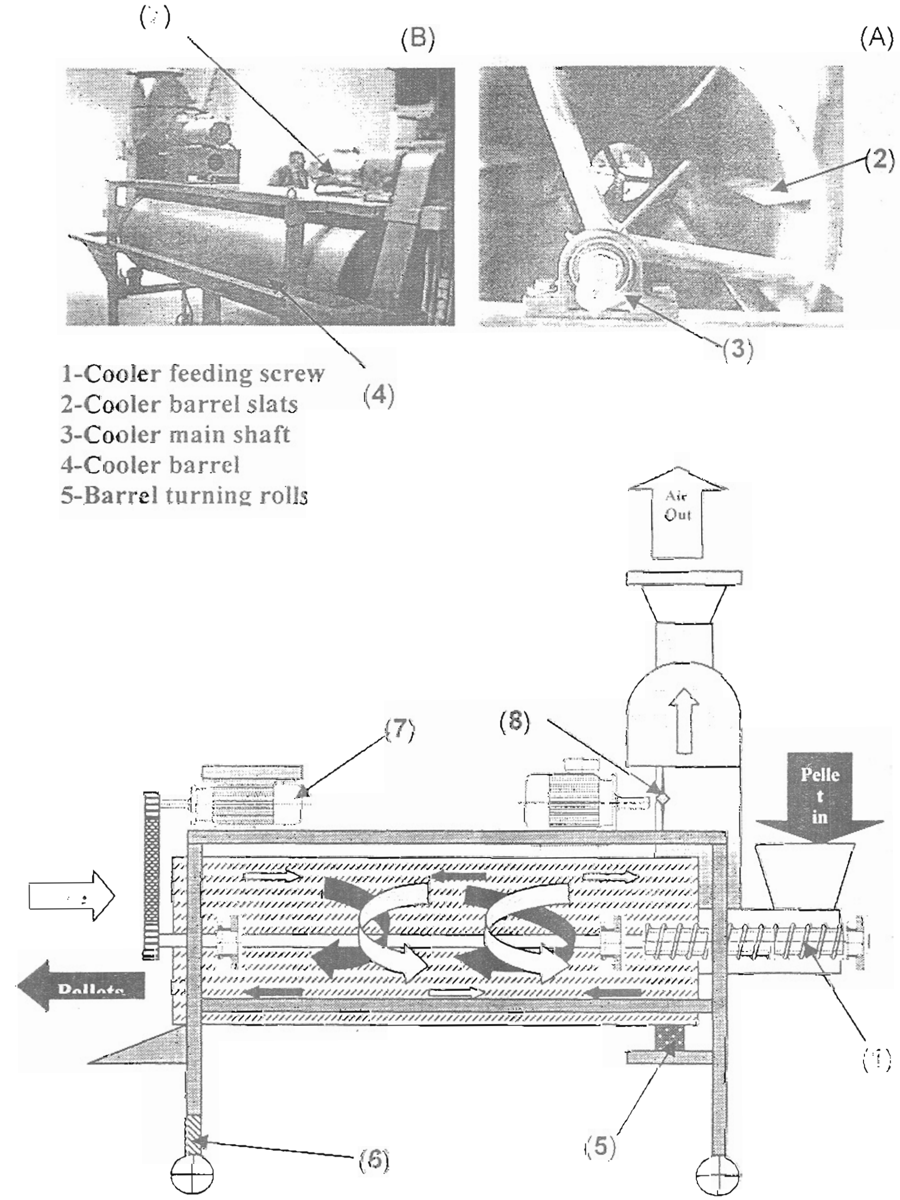

Figure 1. (A) Pictures of the single pass rotary cooler showing its layout and (B) cross section of the cooler.

Feeding unit: Pellets from the extruder were transferred to the cooler feeding unit via a conveyor belt. The feeding unit consisted of a feeding bin and a feeder screw. The feeding bin was 40 cm high, with inlet dimensions of 25x25 cm and outlet dimensions of 15x15 cm. It had a holding capacity of 20 kg aquatic feed (for pellets with 4 mm diameter and 7mm length). The feeder screw was anchored on the rotary shaft of the cooler below the feeding bin, and was designed to transfer incoming pellets from the bin to the rotary barrel. The screw dimensions were - 55 cm length, 18 cm diameter and 4 cm pitch.

Rotary barrel: The rotary barrel was the main chamber of the cooler where the cooling, moisture removal and mash separation operations took place. The barrel length was 200 cm, diameter 60 cm, and wall thickness 0.4 cm. It was attached to both ends of a rotary shaft by three links each, and was supported on the outside by two rollers on the cooler frame. Along the length of the inside wall of the barrel, there were ten equally spaced slats (200x15x0.2 cm) designed for conveying the pellets forward and maximizing their contact with circulating air.

Air suction unit: The air suction unit consisted of a suction fan and an air chamber at the inlet end of the cooler. The air flow was counter to the flow direction of the pellets, which helped in increasing the retention time of the pellets and the overall performance of the cooler. The suction fan had a diameter of 25 cm, and was powered by a 0.746 kW (1 hp) motor with a variable frequency or inverter drive. The air speed through the cooling chamber could be controlled by the fan speed. The air suction chamber transferred the warm, moist air from the barrel to the ambient through an output tube of 15 cm diameter.

Cooler frame and adjustable base: The cooler frame, designed for supporting the rotary barrel, was made using 10x10 cm steel struts. The frame had adjustable steel legs (5x5 cm) on the cooler output side. The height of these legs could be changed in order to control the cooler angle and thus the retention time of pellets inside the cooler. The cooler motor and air suction fan were fixed above the barrel to a steel base of dimensions 200x65x10 cm.

Power transmission unit: The cooler power transmission unit consisted of the 1.492 kW (2 hp) main motor and a gear box. The motor output shaft speed was 30 rpm, and power was transmitted to the rotary shaft of the cooler by two gears and a chain. The cooler shaft was 5.5 cm in diameter and 240 cm in length.

Evaluation of Cooling Performance

Aquatic feed pellets were produced on a single screw extruder using dies with 4.00 mm diameter circular openings. The average dimensions of the medium and high density sinking pellets were 4.0 mm diameter and 5.0 mm length, while those for the low density floating pellets were 4.4 mm diameter and 5.6 mm length. The cooler performance was evaluated based on the following measurements: 1) cooling efficiency (%), 2) pellet output moisture content (%), 3) pellet molding percentage (%) after storage for 1, 2 and 3 months , 4) unpellet mash percentage in the final product (%), and 5) pellet loss (%) percentage with air output

The air temperature and relative humidity during the cooling study ranged between 16.3-18.0°C and 57.2-59.7%, respectively. The cooling efficiency was calculated using the following relation –

$$\text{Cooling efficiency}\,(\%) = \frac{T_1 - T_2}{T_1} x100 \quad (1)$$

where, T_1 and T_2 are the pellet input and output temperatures (C°). The pellet and air temperatures were monitored using thermocouples. Pellet moisture contents were measured using the oven drying method (140°C for 2 h) and expressed on a wet basis. Molding of pellets was measured by visual evaluation. This was a subjective measurement, and involved taking a representative sub-sample and counting the number of pellets that had mold growth (greenish in color). Pellet losses with air output were evaluated by letting the air from the output tube pass through a porous collection bag. The mass of material in the bag was measured and expressed as a percentage of the total mass of pellets (30 kg) that passed through the cooler. A fraction of the product from the extruder was in the form of unpelleted mash. The cooler was designed to separate this mash from the rest of the pellets via the output air stream. Unpelleted mash in the final product was a measure of the separation efficiency of the cooler, and was presented as a percentage of the total mass of pellets.

Experimental Design and Statistical Analyses

The cooling performance in relation to floating and sinking aquatic feed pellets of three different average densities (low density - 0.538 kg/m^3, medium density - 0.789 kg/m^3 and high density - 0.915 kg/m^3) was evaluated. The process parameters studied were air suction velocity (2.32, 3.67, 4.35 and 5.87 m/s), cooler horizontal angle (10, 15, 20 and 30°) and rotary speed (5, 10, 15 and 20 rpm). This constituted a 3 x 4 x 4 x 4 factorial experimental design. All performance characteristics were measured in duplicate, except for molding percentage, which was measured in triplicate because of its subjective nature. Significant effects ($p<0.05$) of various independent variables on performance characteristics were evaluated using analysis of variance (ANOVA) with main effects and two-way interactions. Pair-wise comparison of means was conducted using the t-test ($p<0.05$) with the Bonferroni adjustment, and the corresponding error bars were included in all figures.

RESULTS

Cooling Efficiency

Cooling efficiency is a very important parameter for evaluation of any cooling system and it takes into accounts both the input and output temperatures of the pellets. The input temperature or the temperature of the pellets entering the cooler ranged between 43.6 and 61.7°C. Lower density pellets had higher input temperature. After cooling, the pellet output temperature ranged between 23.0 and 43.8°C, depending on the cooler operating parameters. The output temperature after cooling is important, not only as a measure of cooling performance, but also from the point of view of packaging. Lower temperature leads to less evaporation of moisture and less subsequent condensation on the pellet surface, reducing the chances of molding.

The effects of various variables on the cooling efficiency are shown in Figure 2 and described below.

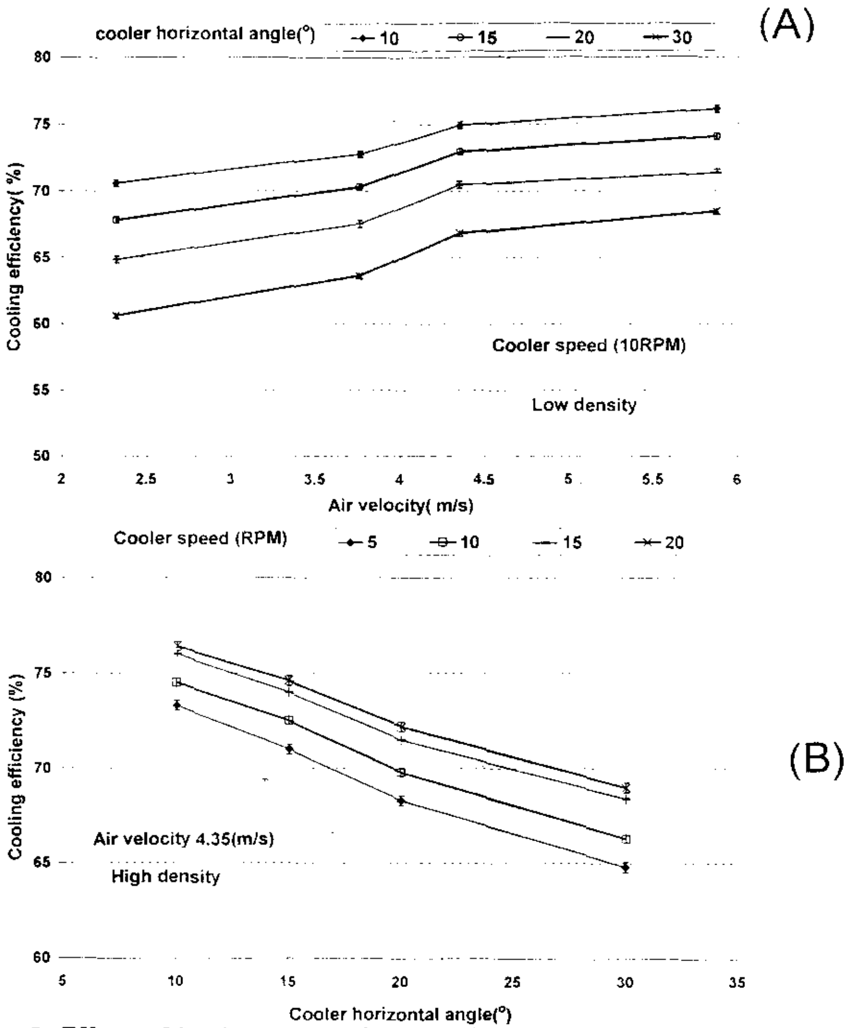

Figure 2. Effect of horizontal angle (A and B), air velocity (A) and cooler turning speed (B) on cooling efficiency. Data is shown for both low (A) and high (B) density feed, although trends for all densities were virtually identical. Error bars represent the standard errors from the t-test for pair-wise comparison of means.

The cooling efficiency ranged between 58.2 and 78.0 %. All four treatments had a significant effect on cooling efficiency. However, significant interactions were not observed between cooler speed, cooler angle and air velocity, therefore data from only representative subsets of treatments are presented in Figure 2. Also results for only low and high density feed are shown in Figure 2 as data for medium density feed followed the same trends.

Effect of cooler horizontal angle

Figure 2 shows the effect of cooler horizontal angle on the pellet output temperature at different air velocities and cooler speeds. At the cooler speed of 10 rpm, increasing the cooler angle from 10 to 30° decreased the cooling efficiency for low density pellets by 16.3, 14.8, 12.2 and 11.2 %, at air suction velocities of 2.32, 3.67, 4.35 and 5.87 m/s, respectively (Figure 2-a). Same trends were observed at other cooler speeds and feed densities (Figure 2-b). At a higher horizontal angle, pellets traveled faster through the cooler due to gravity, thus reducing their retention time in the cooler. Since heat transfer is a time-dependent process, lower retention time led to higher output temperatures and less cooling efficiency.

Effect of air suction velocity

At the cooler speed of 10 rpm , increasing the air suction velocity from 2.32 to 4.35 m/s raised the cooling efficiency of low density feed by 5.9, 7.1, 8.0 and 3.0 % at horizontal angles of 10, 15, 20 and 30°, respectively (Figure 2-a). Further increase in air velocity from 4.35 to 5.87m/s increased the cooling efficiency only slightly (by 1.2 to 2.4 %). Similar trends were observed at other cooler speeds and feed densities (data not shown). Due to the counter-flow design of the cooler, higher air suction velocity led to increased resistance to pellet flow and thus greater retention time in the cooler barrel. Retention time increased from 464 to 635 s, as air velocity increased from 2.32 to 5.87 m/s. Air velocity also greatly affects the rate of heat transfer from the hot pellets to the cooler air, with higher velocity leading to a greater heat transfer coefficient. The combined effect of increased retention time and greater heat transfer rate led to lower output temperature and increased cooling efficiency with increase in air velocity.

Effect of cooler turning speed

At air velocity of 4.35 m/s, increasing the cooler speed from 5 to 15 rpm increased the cooling efficiency for high density pellets, although a substantial improvement in efficiency was not observed as cooler speed was increased from 15 to 20 rpm (Figure 2-b). Similar trends were observed at other air velocities and feed densities (data not shown). At a higher turning speed, increase in agitation of the pellets would lead to greater contact surface area between the pellets and air, and thus lead to increased heat transfer. Although an increase in turning speed would also lead to faster transit of pellets through the cooler and reduced retention time, the effect of increased agitation probably dominated.

From these results, it is clear that increasing the air velocity and cooler turning speed resulted in diminishing improvements in cooling efficiency. In other words, there are continuous improvements in cooling efficiency as air velocity and cooler turning speed increases, but the percent increase in cooling efficiency is markedly lower beyond air velocity of 4.35 m/s and turning speed of 15 rpm, as is clear from Figures 2-a and 2-b. Both higher air velocity and turning speed lead to greater energy consumption. Based on our observations (although no data is presented), higher turning speed also increases the risks of damage to the pellets and, as described later, leads to higher pellet losses with the output air. Therefore, air velocity of 4.35 m/s, turning speed of 15 rpm and horizontal angle of 10^{0} could be the best operating parameters from the point of view of cooling efficiency, while minimizing energy costs. However, other parameters such as moisture content, molding, losses and unpelleted mash percentage, however, need to be considered before deciding on suitable operating parameters for high cooler performance.

Pellet Output Moisture Content

A primary outcome of the cooling process is removal of moisture from the pellets leading to lower water activity and inhibition of mold growth. Drying also leads to increased pellet durability. The pellet output moisture content is therefore a very important parameter, from the point of view of stability during handling and long term storage. The moisture of the pellets entering the cooler ranged between 14.9 and 15.8 %. Lower density pellets had lower input moisture content. The effects of various variables on the output moisture content are shown in Figure 3 and described below. After cooling, the pellet output moisture content ranged between 7.4 and 12.3 %, depending on the density and processing parameters. All four treatments had a significant effect on output moisture. However, significant interactions were not observed between cooler speed, cooler angle and air velocity, therefore data from only representative subsets of treatments are presented in Figure 3.

Effect of pellet density and air suction velocity

Unlike output temperature, the output moisture was substantially affected by pellet density as shown in Figure 3-a. At the same process conditions (air velocity, horizontal angle and cooler speed), lower density pellets were dried more effectively, and the output moisture content was substantially higher (by 8-10 %) for the medium and high density sinking pellets as compared to the low density floating pellets. The drying process can be divided into two stages – the constant rate period and the falling rate period (Geankoplis 1993). In the former, drying takes place only at the surface of the pellets with moisture from the interior continuously replenishing the surface moisture. The rate of moisture removal in this stage depends on the air characteristics (velocity, temperature and relative humidity), and product temperature and surface area. In the falling rate period, the drying front moves to the interior of the pellets, and porosity become a critical factor that controls the drying. Less porous materials would have lower effective moisture diffusivity, leading to slower drying rates and higher final moisture.

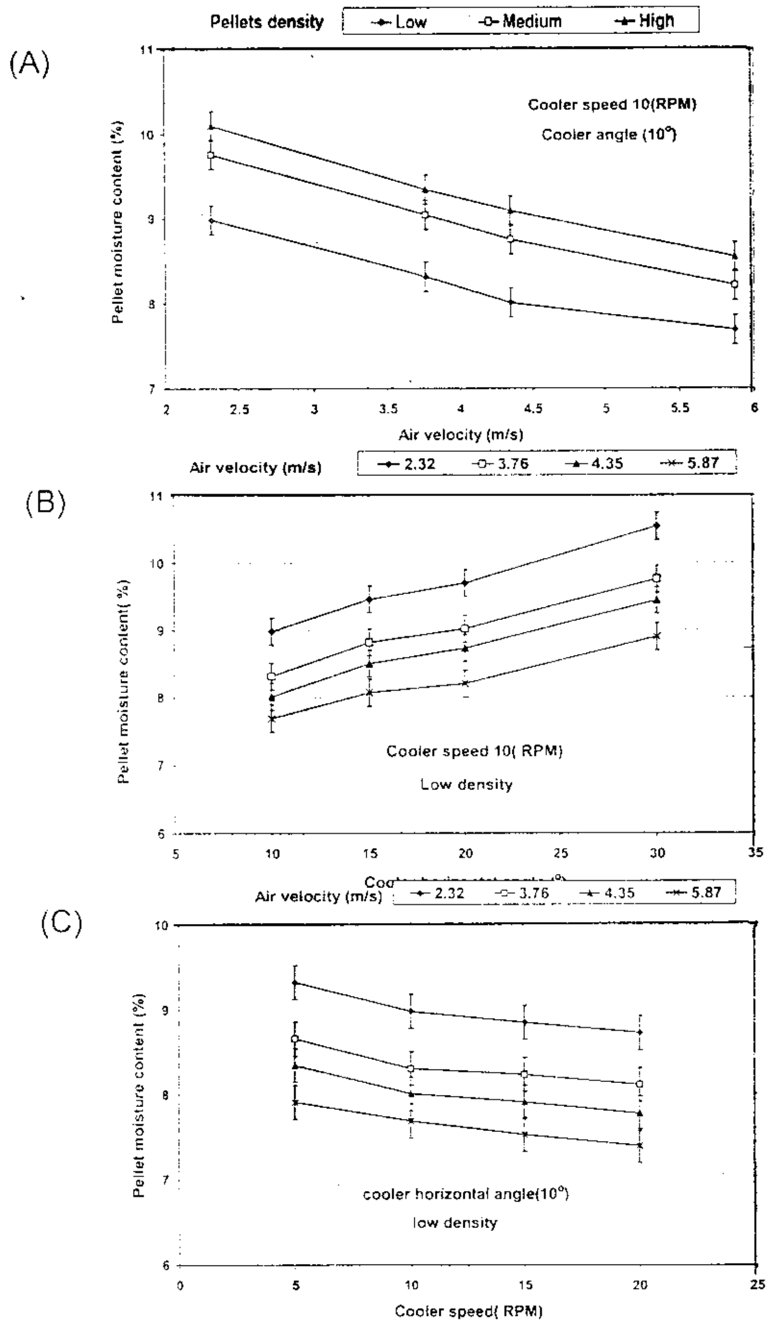

Figure 3. Effect of air suction speed (A, B and C), pellet density (A), cooler angle (B) and turning speed (C) on the pellet output moisture content. Error bars represent the standard errors from the t-test for pair-wise comparison of means.

Figure 3-a also shows the effect of air suction velocity on the output moisture content of pellets. At cooler speed of 10 rpm and horizontal angle of 10^o, increase in air suction velocity from 2.32 to 4.35 m/s, decreased the output moisture by 10.2, 10.4 and 10.0 %, for low, medium and high density pellets, respectively. Further increase in air suction velocity from 4.35 to 5.87 decreased the pellets output moisture content by 4.0 to 6.2 %. Same trends for the effect of air velocity were observed at different horizontal angles and cooler turning speeds (Figures 3-b and 3-c). Similar to the output temperature, decrease in pellet output moisture with increasing air suction speed was due to higher air resistance and retention time in the cooler. Moreover, higher air velocities would lead to increase in the surface mass transfer coefficient, and thus increase in the drying rate as well.

Effect of cooler horizontal angle

For low density pellets and at a constant cooler speed of 10 rpm, increase in horizontal angle from 10 to 20^o led to an increase in the pellet output moisture by 8.0, 8.5, 9.0 and 6.6 %, at air suction velocity of 2.32, 3.67, 4.35 and 5.87 m/s, respectively (Figure 3-b). Further increase in cooler angle from 20 to 30^o raised the pellet output moisture by 7.6 to 9.1 %. Data for different cooler speeds and pellet density had similar trends. Similar to output temperature, the increase in moisture content of the cooled pellets with increasing horizontal angle was due to decrease in retention time.

Effect of cooler turning speed

For low density pellets and at a horizontal angle of 10^o, increasing the cooler turning speed from 5 to 10 rpm decreased the pellet output moisture content by 3.6, 4.0, 4.1 and 2.8 %, at air suction velocities of 2.32, 3.67, 4.35 and 5.87 m/s, respectively (Figure 3-c). Further increase in the turning speed from 10 to 20 rpm decreased the output moisture by 2.3 to 3.8 %. It was clear that cooler turning speed had relatively less effect on output moisture as compared to other parameters. Similar to the output temperature, the slight decrease in output moisture on increasing the cooler turning speed could be due increase in agitation and greater contact surface area between the pellets and air.

Pellet Molding Percentage After Storage

As discussed earlier, one of the primary goals of cooling and drying after the pelleting process is to decrease the pellet moisture content to an optimum level and enable a prolonged storage period without any mold formation. As expected, trends for the proportion of pellets that developed mold or molding percentage (Figure 4) closely mirrored that of output moisture content. For molding studies, storage time (1, 2 and 3 months) was an additional factor that was studied. All treatments had a significant effect on the molding percentage. Significant interactions were also observed between storage time, cooler angle and air velocity. Molding percentage ranged from 0 to 48.2 % depending on duration of storage (1, 2 or 3 months), feed density, and cooling process parameters. As the duration of storage increased, so did the molding percentage (Figure 4).

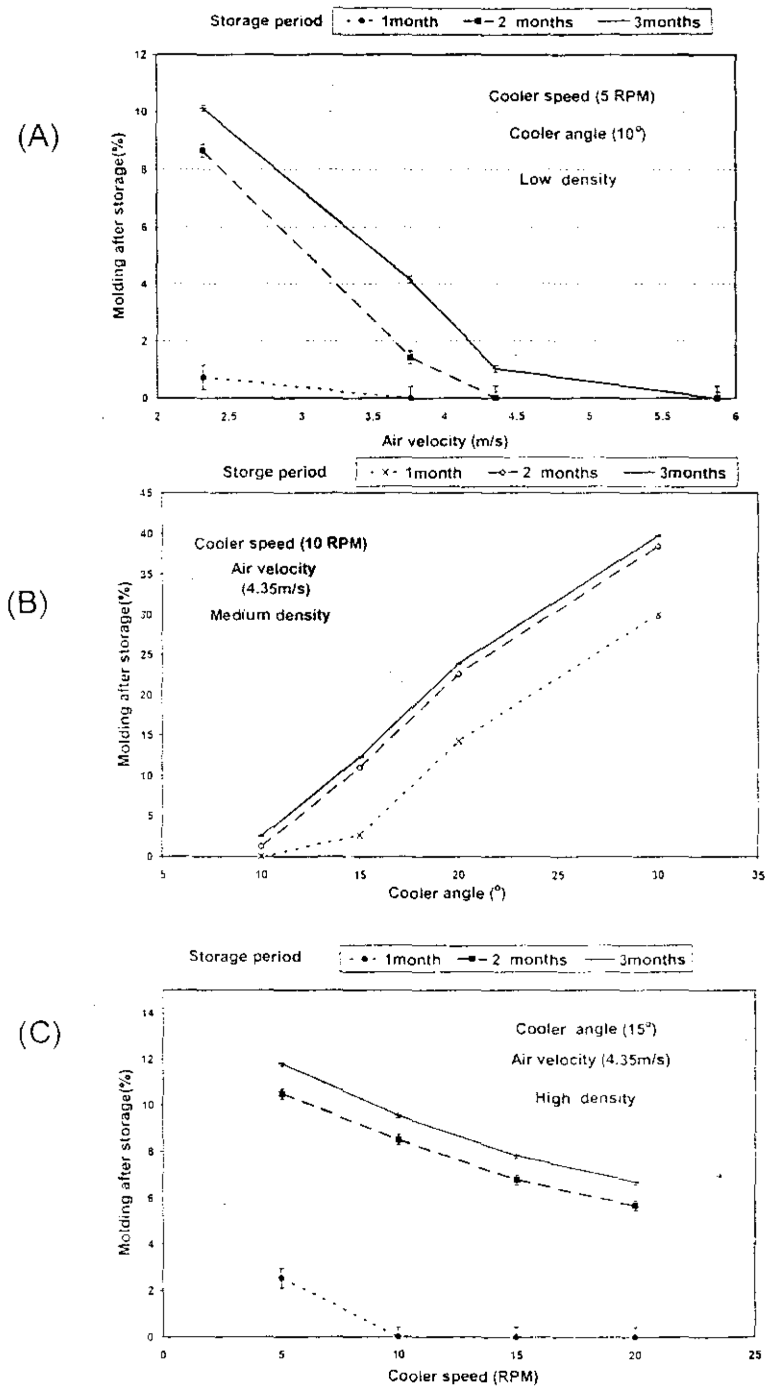

Figure 4. Effect of air suction velocity (a), cooler angle (b) and cooler speed (c) on pellet molding percentage after storage for 1, 2 and 3 months. Error bars represent the standard errors from the t-test for pair-wise comparison of means.

Molding percentage also increased as density of pellets increased. However, irrespective of density and with the right combination of process parameters, the cooler was able to dry the pellets to low enough moisture for complete inhibition of mold growth up to a storage period of 3 months. This reflected the efficacy of the cooler design.

Effect of air velocity, cooler angle and turning speed

For low density feed, at cooler speed of 5 rpm and horizontal angle of 10^{o} (Figure 4-a), increase in air suction velocity from 2.32 to 3.67 m/s or higher decreased the molding percentage from 0.73 to 0.00 % after one month storage. Increase in air velocity from 2.32 to 4.35 m/s or higher decreased the molding percentage from 8.7 to 0.0 % after two months of storage. After 3 months of storage, increase in air velocity from 2.32 to 4.35 m/s reduced the molding percentage from 10.1 to 1.0 %, but only pellets processed at air velocity of 5.87 m/s had no mold growth. Similar trends, with regards to the effect of air velocity, were observed for medium and high density feed, and different cooler angles and speeds.

For medium density feed, at air velocity of 3.67 m/s and cooler speed of 10 rpm, increase in cooler angle from 10 to 30^{o} increased the molding percentage from 0 to 30.0 %, 1.2 % to 38.4% and 2.5 to39.7 % for storage periods of 1, 2 and 3 months, respectively (Figure 4-b). Similar trends, with regards to the effect of cooler angle, were observed for low and high density feed, and different cooler speeds and air velocity.

For high density feed, at air velocity of 4.35 m/s and cooler angle of 15^{o}, increase in the cooler turning speed from 5 to 10 rpm decreased the molding percentage from 2.55 to 0.00%, 10.49 to 8.52% and from 11.82 to 9.56% at storage periods of 1,2 and 3 months respectively, (Figure 4-c)

Unpelleted Mash Percentage

As described earlier, a fraction of the product from the extruder is usually in the form of unpelleted mash. The final product after cooling also has some fines generated due to mechanically induced stresses in the rotary cooling process, although these are relatively low at the low turning speeds at which such coolers are operated. The amount of unpelleted mash and fines in the packaged feed is a big concern for industry.

The cooler in this study was designed to separate unpelleted mash from the rest of the pellets via the output air stream. Amount of mash in the final product was a measure of the separation efficiency of the cooler. The effects of various variables on the unpelleted mash percentage are shown in Figure 5 and described below. All four treatments had a significant effect on mash percentage. Significant two-way interactions were not observed between most parameters, except for cooler angle and air velocity, therefore data from only representative subsets of treatments are presented in Figure 5. The unpelleted mash percentage varied from 0.2 to 9.4 % depending on the processing parameters.

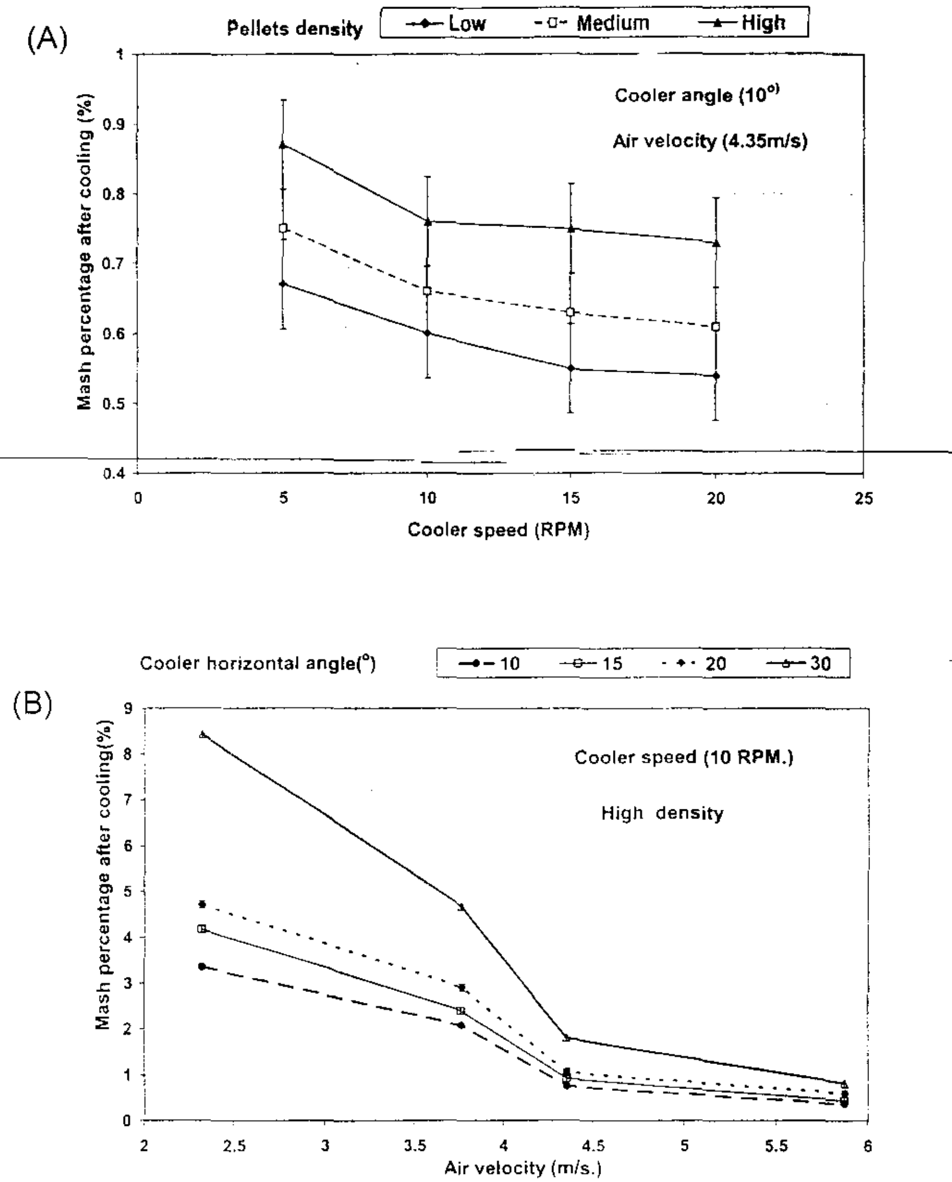

Figure 5. (A) Effect of pellet density and cooler turning speed on unpelleted mash percentage, and (B) effect of air suction velocity and cooler angle on unpelleted mash percentage. Error bars represent the standard errors from the t-test for pair-wise comparison of means.

Mash percentage increased as the density of the feed increased, irrespective of the cooling process parameters (Figure 5-a). This is because the higher density feed was processed at mild extrusion conditions (lower specific mechanical energy and temperature) leading to poorer pelleting efficiency.

Effect of air velocity, cooler angle and turning speed

At air suction velocity of 4.35 m/s and cooler horizontal angle of 10°, increasing the cooler speed from 5 to 20 rpm decreased the unpelleted mash percentage by 14.9, 18.7 and 16.1 % for low, medium and high density pellets, respectively (Figure 5-a). The greater degree of drying associated with higher turning speed led to a net decrease in mash percentage. Same trends were observed for different air velocities and cooler angles. These results should be interpreted carefully as even higher cooler speeds could cause greater mechanical damage to the pellets, leading to a net increase in mash percentage.

For high density sinking aquatic feed, at a cooler turning speed of 10 rpm (Figure 5-b), increase in air suction velocity from 2.32 to 4.35 m/s decreased the unpelleted mash percentage sharply from 3.4 to 0.8 %, from 4.2 to 0.9 %, from 4.7 to 1.1 and from 8.4 to 1.8 %, at cooler horizontal angles of 10, 15, 20 and 30°, respectively. Further increase in the air velocity from 4.35 to 5.87 m/s decreased the mash percentage from 43.4 to 54.4 %. Same trends were observed for low and medium density feed, and for different cooler speeds. Results indicated that it is very important to select the optimum combination of cooler turning speed and air velocity for minimal mash percentage.

For high density sinking feed, at cooler turning speed of 10 rpm, increase in cooler horizontal angle from 10 to 20° led to increase in the mash percentage from 3.3 to 4.7 %, from 2.1 to 2.9 %, from 0.8 to 1.1 % and from 0.4 to 0.6 %, at air suction velocity of 2.32, 3.67, 4.35 and 5.87 m/s, respectively (Figure 5-b). Further increase in cooler angle from 20 to 30° increased the mash percentage by 78.5 to 105.6. The sharp increase in mash percentage on increasing the cooler angle to 30° at the lowest air suction velocity of 2.32 m/s could be due to drastic reduction in pellet retention time in the cooler barrel. Similar trends were observed for medium and high density feed, and for different cooler speeds.

Pellet Loss Percentage with Air Output

Pellets, especially ones with lower density, tend to get blown away with the output air from the cooler. This leads to substantial losses. The effects of various variables on pellet losses are shown in Figure 6 and described below. All treatments, except for cooler speed, had a significant effect on pellet losses. Significant two-way interactions were not observed between most parameters, except for pellet density and air velocity. As for other results described earlier, data from only representative subsets of treatments are presented in Figure 6. Pellet loss percentage ranged between 0 and 17.7 %, and was higher for lower density feed (Figure 6-a).

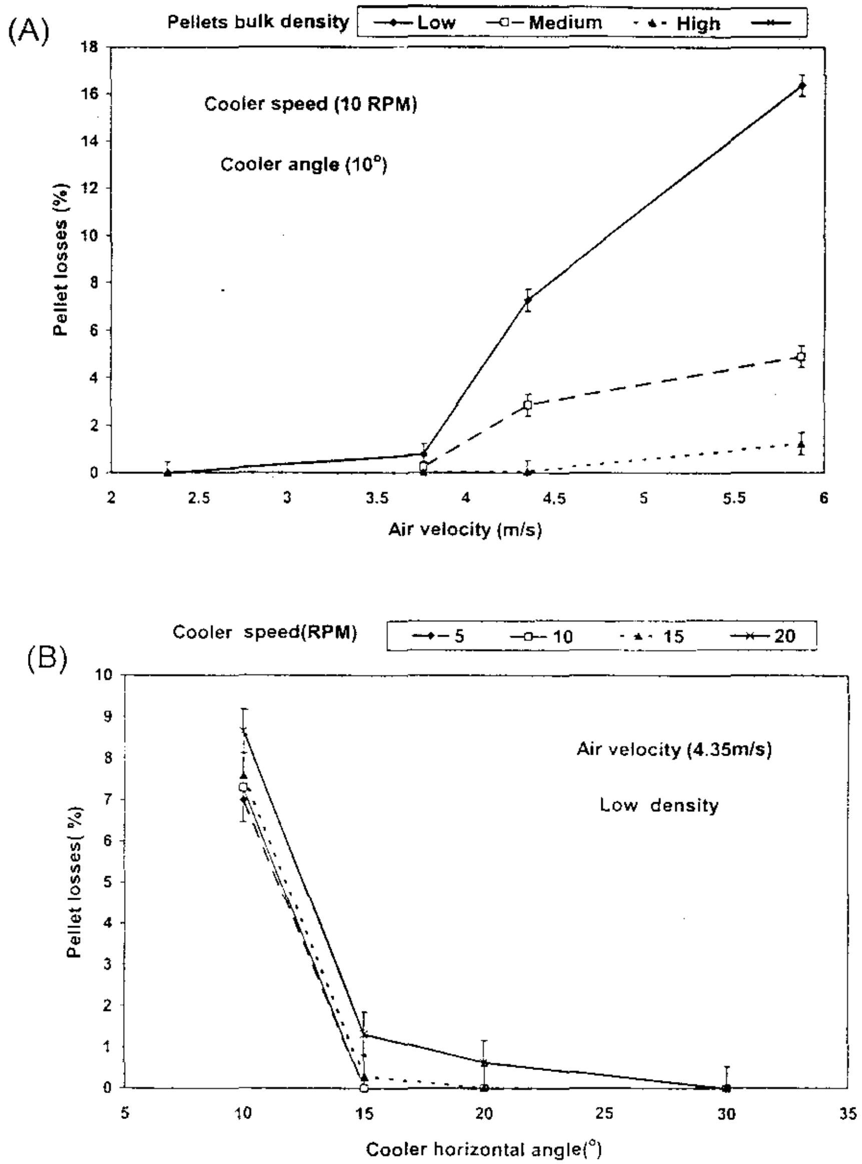

Figure 6. (A) Effect of pellet density and air velocity on pellet losses with output air, and (B) effect of cooler turning speed and horizontal angle on pellet losses with output air. Error bars represent the standard errors from the t-test for pair-wise comparison of means.

Effect of air velocity, cooler angle and turning speed

Air suction velocity is the most important factor influencing the pellets losses in the cooler unit, however an optimum level of various process parameters should be selected for maximum cooling performance. For a cooler angle of 10^{o} and turning speed of 10 rpm, increase in air suction velocity from 2.32 to 4.35 m/s increased the pellets losses from 0.0 to 7.291 %, 0.0 to 2.872 % and 0.00 to 0.07 % for low, medium and high density pellets, respectively (Figure 6-a). Further increase in the air suction velocity from 4.35 to 5.87m/s increased the pellets losses up to 16.4 %. No pellets losses (0.0%) were observed at air suction velocity of 2.32 m/s, irrespective of the feed density. Similar trends were observed for different cooler angles and turning speeds.

For low density feed, at air suction velocity of 4.35 m/s, increase in cooler angle from 10 to 20^{o} decreased the pellets losses sharply from 7.0 to 0.0 %, 7.3 to 0.0 %, 7.6 to 0 % and 8.6 to 0.6 % at cooler speeds of 5, 10, 15 and 20 rpm, respectively (Figure 6-b). At cooler angle of 30^{o}, no pellet losses (0.0%) were observed at all cooler speeds. Similar trends were observed for medium and high density feed, and different air velocities. The drastic decrease in pellet losses on increase of the cooler angle above 10^{o} could be due to the decrease in pellets retention time in the cooler.

The effect of cooler turning speed on pellet loss percentage can also be seen from Figure 6-b. For low density pellets, at air velocity of 4.35 m/s, increasing the cooler speed from 5 to 20 rpm increased the pellets losses from 7.0 to 8.6 %, 0.0 to 1.3 % and 0.0 to 0.6 % at cooler horizontal angle of 10, 15 and 20^{o}, respectively, while no differences were observed at cooler angle of 30^{o}. Greater degree of agitation at higher cooler speeds probably led to increase in pellet losses with the output air. Same trends were observed for medium and high density feed, and different air velocities.

DISCUSSION

Based on the above results, the most effective settings for cooler operating parameters (air suction velocity, turning speed and cooler angle) were determined for both sinking (high and medium density) and floating (low density) aquatic feed. Long term storage of pellets (molding percentage), pellet quality (mash percentage) and also losses during cooling (with output air) were all important criteria for determining the effective operating range. Lowest possible air velocity is desired so as to reduce pellet losses with output air. On the other hand, lower air velocity reduced the degree of drying and cooling, leading to higher molding and mash percentage. For two months storage, the least possible air velocity that led to zero molding for low density floating feed was 3.76 m/s at 10 rpm turning speed and 10^{0} cooler angle. Also at these settings pellet losses and mash percentage were acceptable (only 0.8% and 1.6%, respectively). This corresponded to output temperature of $28.5^{0}C$, cooling efficiency of 72.8% and output moisture of 8.3%. Similarly, for medium density sinking feed, the best operating parameters were 3.76 m/s air velocity, 15 rpm turning speed and 10^{0} cooler angle. This corresponded to output temperature of $27.3^{0}C$, cooling efficiency of 73.9%

and output moisture of 8.9%, and resulted in 0.5% losses, 1.7% mash percentage and 0% molding after two months of storage. For high density sinking feed, the most effective operational settings were 4.35 m/s, 10 rpm and 10^0 for air velocity, turning speed and cooler angle, respectively, and resulted in 26.7^{0}C output temperature, 74.5% cooling efficiency, 9.1% output moisture, 0.1% losses, 0.8% mash percentage and 0% molding after two months.

CONCLUSION

The cooling process is one of the most important and technically challenging operations in the pelleting industry. The contribution of pellet cooling to the overall pellet quality has been reported to be around 5-10 %. The rotary barrel cooler described in this study had a simple but robust design, and would be of great use in small scale pelleting operations. The selection of the optimum process parameters for cooling would depend on the type of pellets, pellet density and dimensions. For the floating and sinking aquatic feed pellets tested in this study, the amount of pellet losses with output air during cooling and final pellet quality (molding and mash percentage) were the criteria used for selecting the most effective settings for operating parameters. Depending on the pellet density, the best operational ranges were determined to be 3.67 -4.35 m/s for air suction velocity, 10-15 rpm for cooler turning speed and 10^0 for cooler horizontal angle. It is suggested that the performance of this cooler be studied in greater detail for other types of pellets, and its design be further developed for larger scale utilization. Also for reduction of pellet losses, use of a screen in the output air stream could be evaluated in the future. It is true that the operating parameters for best performance mentioned in the manuscript are specific to the cooler that was studied, but the trends are generally applicable.

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تصنيع وتقييم مبرد دوار أحادي الاتجاه لتبريد أعلاف الأسماك المنتجة بنظام البثق

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تجفيف وتبريد الأعلاف السمكية المنتجة بنظام البثق تعد من اهم العمليات التي تؤثر في جودة الأعلاف المنتجة بما يمثل نسبة ٥-١٠% من أجمالي تاثير العوامل الميكانيكية والفزيقية الاخري علي جودة الاعلاف ذلك علاوة على اهمية هذه العمليات على زيادة كفاءة التخزين .ونظرا لارتفاع اسعار مثل هذة الوحدات المستوردة وارتفاع طاقاتها الكهربية المستهلكة فأن هذا البحث يهدف الي تصنيع وتقييم مبرد دوراني مبسط احادي التجاة لتبريد اعلاف الاسماك ودراسة تاثير عوامل التشغيل المختلفة وكثافة العلف المنتج على اداء وكفاءة التبريد ومدي صلاحية هذة الاعلاف للتخزين بما يناسب الوحدات الانتاجية الصغيرة فى المزارع السمكية. وكانت عوامل الدراسة كالاتي:

١- كثافات مختلفة للاعلاف المنتجة غاطس وطافي (٠,٥٣٨-٠,٧٨٩- ٠,٩١٥) كجم /م٣

٢- سرعة الهواء داخل وحدة التبريد (٢,٣٢-٣,٦٧-٤,٣٥) م/ث

٣-زاوية ميل المبرد (١٠-١٥-٢٠-٣٠) درجة

٤-سرعة دوران المبرد (٥-١٠-١٥-٢٠) لفة/د

ومن خلال القياسات التالية تم تقييم اداء المبرد وتاثير عوامل الدراسة على جودة الاعلاف المنتجة وكانت كالتالي:

درجة حرارة الاعلاف المعبئة بعد التبريد- كفاءة التبريد-نسبة الرطوبة فى الاعلاف المعبئة بعد التبريد- نسبة الاصابة بفطريات التعفن بعد فترات تخزين لمدة شهر وشهران وثلاثة اشهر- نسبة الاعلاف المهشمة والسائبة فى شكائر التعبئة-نسبة الفواقد من الاعلاف مع الهواء الخارج من وحدة التبريد.

وقد اشارت النتائج الي ان افضل عوامل التشغيل كانت سرعة هواء ما بين ٣,٦٧و ٤,٣٥ م/ث وزاوية ميل المبرد١٠ درجة علي الافقي وسرعة دوران وحدة التبريد ما بين ١٠ و١٥ لفة /د وذلك لكل من اعلاف الاسماك الغاطسة (مرتفعة الكثافة) والمعلقة(متوسطة الكثافة) والطافية(منخفضة الكثافة) وكانت النتائج كالتالي:

درجة حرارة الاعلاف بعد التبريد ما بين ٢٦,٧-٢٨,٥ درجة و كفاءة التبريد ما بين ٧٢,٨-٧٤,٥% و نسبة الرطوبة فى الاعلاف عند التعبئة مابين ٨,٣-٩,١% ونسبة الاصابة بفطريات التعفن بعد فترة تخزين لمدة ٦٠ يوم ٠,٠٠% ونسبة الفواقد مع هواء التبريد ٠,١-٠,٨% ونسبة الاعلاف المهشمة والسائبة في شكائر التعبئة بعد التبريد ما بين ٠,٨-١,٧% .ويوصي البحث باهمية دراسة هذا النظام لاستخدامة فى مختلف انواع الاعلاف الحيوانية نظرا لبساطة التصميم وارتفاع الكفاءة وانخفاض تكاليف تشغيلة عن المبردات الاخري.