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PERFORMANCE EVALUATION OF A NOVEL DESIGN OF FEED PELLETS VERTICAL COOLER

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ABSTRACT: This work aims to report a novel design of feed pellets vertical cooler named as double bed vertical cooler (DBVC). The proposed DBVC is assessed experimentally using sinking fish feed pellets produced by a ring-die pelletizer under different operating parameters including the position air double vacuum fans, height of the feed pellets as a function of pellet retention time inside the cooler and different widths of sieve slit. The performance evaluation of DBVC was performed and compared to performance of the single bed vertical pellet cooler (SBVC) that used commercially in the feed pellets industry in Egypt. The comparison was carried out at constant cooler's capacity of 2 Mg/h for both coolers in terms of the performance indicators such as; output pellets temperature and moisture content, cooling efficiency, pellet durability, required specific energy.. etc. Moreover, the two types of coolers have been analyzed from the economic point of view using the life cycle cost (LCC) method. Under the best operating conditions for both cooler, the obtained results showed that the temperature and moisture content for the outlet pellets were reduced by about 5.55% and 10.60%, respectively by using DBVC. Using DBVC gave slight increase in cooling efficiency and pellet durability by about 3.35% and 4.60%, respectively over SBVC with an explicit reduction in the required cooling energy by about 30.83%. From the economic aspect, the total capital cost and total cooling cost per unit of production for DBVC are lower than SBVC by 73.91% (the price difference between them saving 4885.87$) and 61.26% (saving 0.77 $/Mg), respectively. Ultimately, it is clear that the DBVC proved a high performance and saved the costs of feed pellet cooling process.

Key words: Feed pellets, novel design, double bed vertical cooler, cooler performance, cooling cost.

INTRODUCTION

The feed pellets manufacturing using any ration formula consists of many serial processes including: milling the different raw materials (*e.g.* yellow corn, soy bean meal, fish meal), conditioning (mixing, adding additives and moisture), pelleting, cooling or drying. Noting that, to achieve the intended nutritional composition of a feed, the ration formula should be measured and mixed according to a recipe (**McMullen *et al.,* 2004**). Generally, Quality of the final pellets depends on the process before the die (milling and mixing), pelleting conditions and the process after pelleting (drying or cooling). For pelleting process, there is a general agreement on the contribution of different factors such as pellet durability as well as the post-pelleting operations represent in pellets cooling and drying (**Thomas *et al.,* 1997**). In the manufacturing process of the feed pellets, the mixture of raw materials enters the conditioner and steam is added to purify the mixture from bacteria such as; salmonella and achieve the correct consistence to be able to be compressed in pellets form, where in the pellets receive an approximate temperature of 80°C and a water content of about 15% wet basis (**Andersson and Johansson, 2008**). The produced pellets receive additional heat due the friction inside the forming die holes of pelleting machine. The feed

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pellets leave the forming die at temperature up to 95°C and 17.50% of moisture content on wet basis (**Leaver, 1988**). Pellets are cooled by using forced ambient air through the pellets bed for quick reduction in temperature and to remove a certain amount of the pellet moisture content. The pellets cooling process at high temperatures facilitates moisture removing without additional energy consumption and obviates the drying step. Thus, Pellet cooling is can be performed to remove both excessive heat and moisture (**Maier and Bakker-Arkema, 1992**). Cooling process contributes in enhancing the pellet quality, preventing sticking or caking in holding bins, breakage and crumbling during handling and transporting as well as protects the feed pellets from moldiness and the growth of bacteria and fungus that can spoil the pellets (**Brooker *et al.*, 1992**). To obtain high quality for the feed pellets, the temperature of existed pellets from the forming die should be reduced to be about 5°C above ambient temperature and their moisture content to 12% (**Mujumdar, 2007**). **Obernberger and Thek (2004)** recommended that, the moisture content of the feed pellets is between 8 and 12% on wet basis, wherein the water content either above or below this range can be led to poor pellets quality. In the same context, the desired final moisture content of the feed pellets should be less than 12–15% for long-term storage purpose (**Robinson, 1984**). Moreover, the lack of automatic control of the cooling process may lead to high energy consumption and cracks in the pellet surface which affect their durability (**Thomas *et al.*, 1997**). If the pellets are cooled too quickly, a dry crust layer will form on the surface of the pellet that will hamper the migration of water content from pellet core to the surface and leave the pellet core soft and moist. Once the pellet with this soft moist core is allowed to reach equilibrium, the pellet will become brittle and produce excessive fines (**Fowler, 2008**). Consequently, the large amount of fines in the pellet production is undesirable because it will increase the feeding wastage either for animals or aquaculture. Hence the improper cooling process can reduce the durability of feed pellets due to stresses in the pellet between the cooled outer layer and the warmer core (**Thomas and Van der Poel, 1996**), causing apparent cracks and higher energy consumption (**Thomas *et al.*, 1997**). Thus, the cooling process is a crucial stage in the feed pellet production. In general, the pellet cooler is considered as a weak link from viewpoint of the pellet quality (**McEllhiney, 1987**). Commercially, there are four major designs of feed pellets coolers include: vertical cooler, horizontal or belt style cooler, mixed rotary cooler, and counter flow cooler (**Maier, 1988**). There are several methods for exposing the hot pellets to the cooling air stream, where each design of pellet coolers uses one of the exposing methods represents in cross flow, concurrent flow, counter flow and mixed flow (**Brooker *et al.*, 1992**). The vertical and horizontal coolers are the most widespread designs in the feed pellet industry all over the world. The exposing method between the hot pellet and the cooling air is combination of the cross flow and counter flow which can help to achieve high efficiency of cooling and drying by controlling the speed of cooler belts, but this type is flawed by its high price, and energy consumption (**Fairfield, 2003**). Another major disadvantage of this design that it occupies a large space, even using the multiple decks to solve this problem, high energy consumption will be occurred resulting in high operational cost. On the other hand, the advantages of the vertical coolers comparing to other designs are the low energy consumption, less maintenance, small dimensions and it also gives good control of moisture content (**Maier and Bakker-Arkema, 1992).** The vertical pellet cooler at cross flow mode needs to a large airflow requirement which is the same for the cross flow horizontal cooler, but it gives high cooling efficiency for pellets. Regarding the counter flow cooler, the bed depth of pellets and residence time are the most significant design parameters, while the initial relative humidity of the cooling air has minor importance regarding this design (**Maier, 1988**). The counter flow pellet-cooler has several advantages included the low energy consumption comparing to the horizontal cooler, low maintenance cost, small dimensions, easy to operate and clean as well as excellent controlling for the pellet moisture content. Despite the cooling is not one of the most energy-consuming process in feed pellets production, the industrial investment has recently focused on the use of adjustable-speed drives to reduce fan energy consumption (**Lambert *et al.,* 2017**). The commercial widespread design of pellet cooler in Egyptian farms that represents in the vertical single-bed counter flow cooler is still suffering of the increase in energy consumption at the large scale of pellet production along to the high price of this cooler due exporting costs.

Hence, the aim of the present work is reporting a novel design of a local made vertical mixed flow cooler for feed pellets to exploit the advantages of counter and cross flow modes with low energy requirement and costs. This design is fabricated with advantages of simplicity in design, cheapness, easy to operate, easy to clean, small occupying space and precise control for the bed depth of pellets and residence time in purpose of high cooling efficiency. The performance of this design is evaluated experimentally in attempt to prove its capability to maintain the cooled pellets at desired high quality as well as reduce the consumed energy required to the cooling process, and then it can be adapted to the large scale production. The novel pellet cooler is compared to the commercial single-bed vertical cooler (SBVC) in counter flow mode from the performance and economic point of view. In this work, the novel design named as double separated-bed vertical cooler (DBVC) operated in mixed flow mode which used to cool down the temperature and moisture content of the hot fish feed pellets produced by a ring-die pelletizer.

MATERIALS AND METHODS

The Experimental Ration

The fish feed pellet was manufactured at animal feed factory located in Zagazig city, Egypt using ring-die pelletizer. The raw mash material of the experimental feed ration is prepared by a swinging hammer mill with three different diameters of screen holes to determine three categories of ration particles as 1, 2 and 3mm in average (**Abd El-Wahab *et al.,* 2011**). The ration formula was mixed in mixer with about 25% moisture of total mass moisture content using the standard method as wet basis. The ingredients of the used aquatic feed ration are shown in Table1.

The Ring-Die Pelletizer

A ring-die pelletizer (CPM Co., USA) is used in this investigation to produce sinking aquatic feed pellets (See Fig.1). The maximum machine productivity is 7 Mg/h using die speed of 350 rpm according to (Mohammad *et al.,* 2011). The pelletizer is operated by electric motor with rated power of 88.23 kW at rotational speed of 1400 rpm for the motor shaft.

The SBVC (Commercial Type)

It is a commercial single-bed counter flow vertical pellet cooler Changzhou Farthest Machinery Co., China) that used in the present work to be compared with the novel DBVC either from the performance and economic viewpoints. This pellet cooler is considered the most popular design in the Egyptian feed industry (see Fig.2). The commercial cooler has one cooling compartment with maximum capacity of 3 Mg/h in octagon design provided one vacuum fan fixed at the top with 7.50 kW, rotary airlock feeder operated by 1.5 kW electric motor, one level sensor, discharge sliding gate controlled by air piston powered by air compressor with 0.50 kW in power and air intake ports at cooler's bottom.

The Components of the Novel Design DBVC

The DBVC is a vertical cooler for feed pellet cooling using the cross flow mode. The novel cooler is mainly consists of cooler frame, pellet feeding unit, double-vertical cooling chambers, cooling air system and pellets discharge unit. The components of the novel cooler can be described as follows:

Cooler's Frame

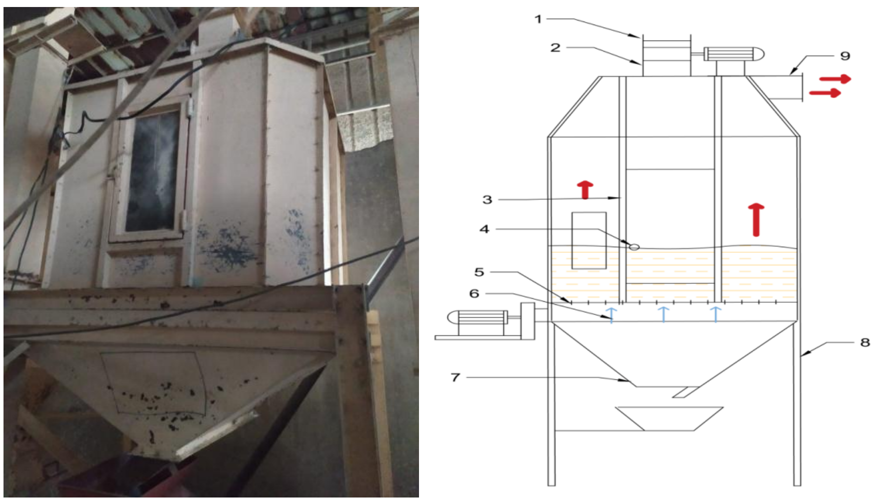
The frame of cooler is manufactured from iron sheets with a rectangular cooling bin and square base, as depicted in Figs. 3 and 4. The iron walls of the cooling bin were welded firmly and painted with anti-corrosion paint from inside and outside. A steel pallet was fixed at the top iron sheet cover of the frame to be the base of the cooler feeding unit. The frame is provided with indication board for observing the pellets in the bin during cooling process as well as ambient air inlet ports (slits) at the near the bottom edge of the cooling bin. The frame is fixed on four metal U shape trestles.

Table 1. The composition of aquatic feed ration*

Ingredients	Percentage (%)
Corn flour	23.00
Fish meal	8.00
Wheat bran	20
Soybean meal	43.5
Salt	0.20
Fish oil	1.50
Soybean oil	1.50
Agent bending (starch)	2.00
Vitamins+ Mineral pre-mix	0.30
Total	100

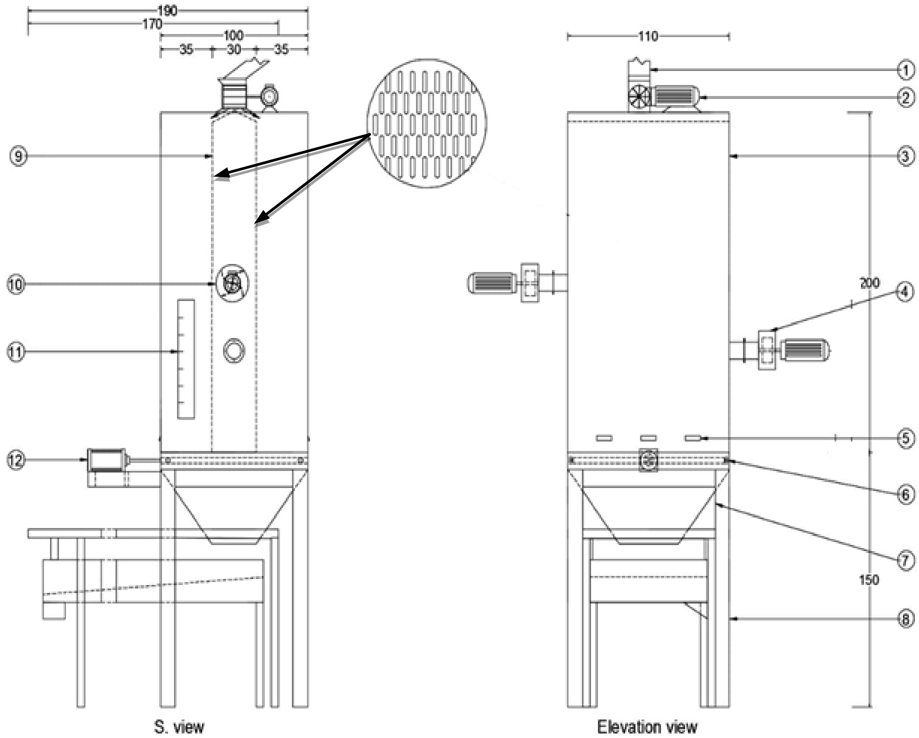
* According to the obtained knowledge from fish feeding research section, Central Laboratory for Aquaculture Research, Agriculture Research Center, Egypt

Fig. 1. Pictorial view of the ring-die pelletizer



No.	Part name
1	Feeding port
2	Rotary airlock
3	Frame of cooler
4	Level sensor
5	Air inlet openings
6	discharge gate
7	Collection hopper
8	Cooler's trestles
9	Exhausted air outle Dim in cm , Scale 1:1t

Fig. 2. The SBVC (commercial cooler) **Dim in cm , Scale 1:1**



No.	Part name
1	Feeding chute
2	Rotary airlock motor
3	Frame of cooler
4	Exhausted air damper
5	Air inlet openings
6	Pellets discharge gate
7	Collection hopper
8	Cooler's trestles
9	Double Sieves
10	Air vacuum fan
11	Indication board
12	Piston of exit gate

Dim in cm , Scale 1:1

Fig. 3. Schematic drawing of components of the novel design DBVC

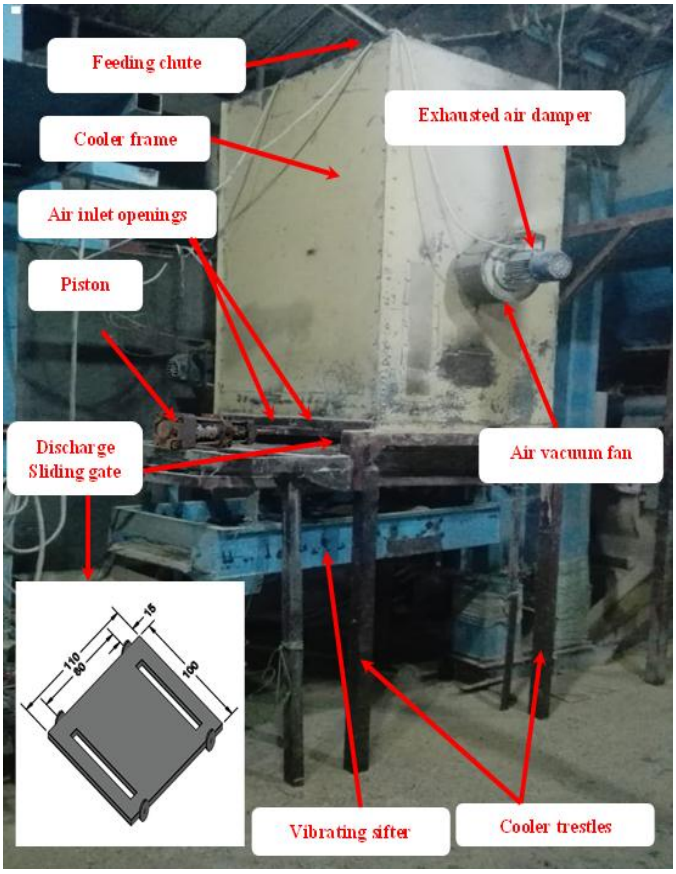


Fig. 4. Photo of the novel DBVC

Feeding Unit

After exist from the die of pelletizer, the hot feed pellets are transferred to feeding unit that consists of feeding chute and rotary airlock by conveying belt. The frame feed unit has a rectangular shape. The rotary airlock controls the hot pellets flow towards the cooling bin and distributes the pellets equally to the vertical cooling chambers without entering the ambient air with pellets.

Double- Vertical Cooling Chambers

The interior enclosure of the feed pellets cooling bin is divide into two cooling chambers separated by a vacuumed air chamber. The vacuumed air vertical chamber allocated in the middle of the inwards of cooling bin provided with two vertical sieves wherein, each sieve has slits smaller than the diameter of the hot pellets that being cooled.

Air Cooling System

It consists of two vacuum fans to suck the ambient air to cool down the hot pellet within the two vertical cooling chambers. Each fan had attached to an electric motor. One fan is installed at one of side wall of the vacuumed air chamber from outside, while the other fan is installed at the opposite side wall of the same chamber, as displayed in Figs. 3 and 4. In the present study, each fan is provided with air damper to rid of the hot air used in cooling pellets outside the cooler. The opposite vacuum fans are installed at different height from the bottom of the vacuumed air chamber to make together different operating positions (as will be explained later).

Pellets Discharge Unit

This unit is responsible to deliver the cooled pellet from the two vertical cooling chambers outwards the cooler. This unit consists of 2 level sensors located inside the two cooling chambers to maintain the vertical column of the hot pellets at certain height within these chambers. A sliding gate is constructed below the cooling bin wherein, its horizontal movement allows opening or closing the openings at the bottom of the two vertical cooling chambers. The movement of sliding gate is controlled by a horizontal piston that receives signals from the level sensors. The piston is powered by air compressor. An inverted cone hopper is fixed beneath the sliding gate to collect and deliver the cooled pellets towards the vibrating sifter as a last step before packing the pellets within plastic sacks.

The Performance Evaluation of Coolers

In the present work, the commercial SBVC was operated for cooling feed pellet .The diameter, length and bulk density of produced fish pellets were 4 mm, 8 mm and 950 $kg/m^{3,}$ respectively at the standard adjusted parameters by the manufacturer using cooler's capacity of 2 Mg/h. For comparing purpose with SBVC, the performance of the DBVC was evaluated experimentally for optimizing some operational parameters affecting the cooling performance using the same fish feed pellets and cooler capacity of 2 Mg/h. These parameters can be briefed as follows:

- Three positions of the two opposite vacuum fans were tested including different heights from the vacuumed air chamber bottom.
- Three heights for feed pellets within the cooling chamber of 25, 50 and 75 cm are used as bed depths of the hot pellets.
- Three values for the sieve slit width of 1, 2 and 3 mm are tested.

The positions of vacuum fans were position1 (30 cm- 60 cm), position 2 (30 cm- 90 cm) and position 3 (60 cm- 90 cm), as shown in Fig.5. The heights of pellets (Bed depths of pellets) were determined as follows:

$$\mathrm{H\ (m)} = \frac{\mathrm{T} \times R}{P \times C} \quad (1)$$

Where H is height of pellet (Bed depth) (m) ,T is throughput (kg/min), R is required retention (min), p is pellet bulk density (Kg/m^3), C cooler bed area(m^2)

Accordingly, the heights of pellets 25, 50 and 75 cm ware corresponding to retention times of 5 min, 10 min and 15 min , respectively on basis of throughput of 2 Mg/h, pellet bulk density of 950 kg/m^3 and 0.70 as total bed area for both cooling chambers.

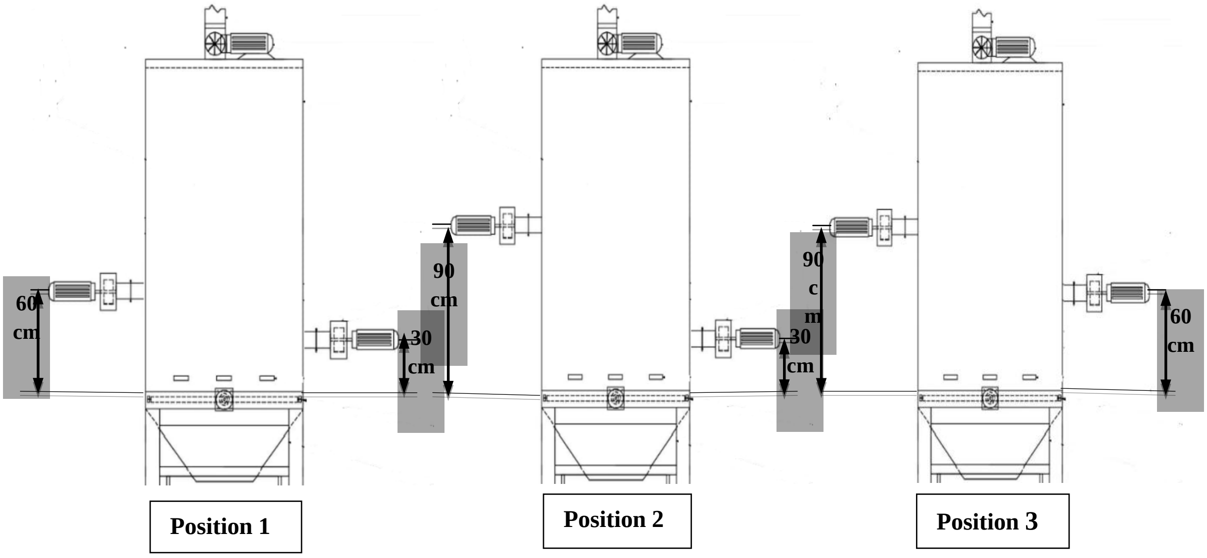


Fig. 5. Schematic sketch of the different positions of vacuum fans.

In the present experiments, 6 K-type thermocouples were used to measure the input pellets temperature, output pellets and pellet temperature inside the two cooling chambers. The moisture content (M.C) of input pellets (after pelleting process and before cooling) and output pellets (cooled pellets) were measured. Additionally, the relative humidity (R.H) and temperature of ambient air as well as R.H of the exhausted air at the fan damper exit were measured. The specifications of the equipment used in the experimental measurements are declared in Table 2. The comparison between SBVC and the novel DBVC was addressed based on the performance indications including productivity, cooling efficiency, pellets durability, power and energy requirement as well as cost analysis.

Productivity (Q) of the cooler is determined by the following relation given by **Abdel Wahab *et al.* (2011)**:

$$Q(Mg/h) = \frac{W_P}{T} \times 3.6 \quad (2)$$

Where *Q* is the cooler's productivity (Mg/h), W_p was the mass of cooled pellets (kg), *T* is the consumed time (s).

Whereas, the cooling efficiency (η_{col}) was calculated using the following relation (**Kadduor and Alvi, 2010**):

$$\eta_{col}(\%) = \frac{T_1 - T_2}{T_1} x100 \quad (3)$$

Where T_1 and T_2 are temperatures of the feed pellets before and after cooling, respectively.

Pellet durability (D_U) as an important indicator for the pellet quality was determined according to ASAE Standards S269.4 (**ASAE, 1997**). The pellet durability tumbler consists of three dust tight tumbling boxes to obtain three replicates for this test. After tumbling, the pellet sample is screened and the retained pellets on sieve are weighted. D_U is calculated using the following relation (**Colley *et al.*, 2006**)

$$D_U = \left(\frac{M_{pa}}{M_{pb}}\right) \times 100 \quad (4)$$

Mpa: Pellets mass after tumbling, g. *pb:* Pellets mass before tumbling, g.

The net electric power consumption (P_n) was calculated according to Eq.5 (**Kurt, 1979**) as:

$$P_n(kW) = \frac{\sqrt{3}\,.\ I.\ V.\varepsilon.\ \cos\theta}{1000} \quad (5)$$

Where $\sqrt{3}$ is coefficient current for three phase AC circuits, *V* is Voltage that being equal to 380 V, ε represents the mechanical efficiency of cooler which assumed to be 90 % and $Cos\ \theta$ is power factor being equal to 0.84 according to **Umran (2015)**.

Accordingly, the specific energy requirement (S) is calculated as follows:

$$S\,(kW/kg.h) = \frac{P_n}{Q} \quad (6)$$

Table 2.The equipment measuring range, resolution and accuracy of parameters.

Parameter	Equipment	Measuring range	Resolution	Accuracy
Pellet temperature	Digital thermometer− 4 channels (TENMARS,TM747DU,Taiwan) using K-type thermocouples	−200 - +1372 °C for K-type	0.1 °C	± 0.1% rdg + 0.7 °C*
	Digital thermometer− 2 channels (TENMARS,TM82N,Taiwan)	−200 - +1370 °C for K-type	0.1 °C	± 0.05% rdg + 0.7 °C*
$M.C_p$	Pellet moisture meter (Pochun,PC-16A,China)	0%~ 100%	0.02%~0.1%(sample≥2g)	±0.5% (sample≥2g)
Pellet height	Level sensor(M18 inductive proximity sensor, China YUMO Electric Co. LTD, China)	Detection distance 8 mm		
Ambient temp. & R.H	Digital temperature-humidity meter with probe (Pros'Kit-N312, Taiwan) • (Pro'sKit, NT-312, Taiwan).	–50 – +70 °C (outdoor)	0.1 °C	±1%
R.H of exhausted air and velocity of inlet air	Digital hot-wire anemometer (TENMARS,TM-4002, Taiwan)	< 20% >80% R.H	0.1% R.H	±5% R.H
Electric power (for 3 phases motors)	Digital Clamp meter (Mastech ,MS2001, USA)	2A- 200A (AC current)	0.1A	±(2.0%+5)

* Accuracy is specified for ambient temperatures between 18 to 28 °C

Cost Analysis

The life cycle cost (LCC) analysis is used to report a detailed economic analysis by assuming the useful life of 6 years for frame system and 3 years life for air suction fan and sieve for both the novel DBVC and the SBVC.

The cost analysis for DBVC and the SBVC is performed according to the following equations of LCC method given by **Dhillon (2009)**:

Present Maintenance Cost

$$P_m = C_m \left[\frac{1-(1+i)^{-k}}{i}\right] \quad (7)$$

Where *Pm* present maintenance cost (USD), Cm annual maintenance and repairs cost (taken 10% of capital cost),*i* interest rate (taken 17%), *K* machining equipment's expected useful life in years.

Net Present Cost

$$P_{Net} = P_i + p_m + \left[\frac{cR+V}{(1+i)^f}\right] - \left[\frac{z}{(1+i)^k}\right] \quad (8)$$

Where *PNe*t net present cost for cooler (USD), *Pi* capital cost (USD), *k* machining equipment's expected useful life in years (6 years), *f* useful life of replaceable parts (3 years),*(R+V)* air suction fan and Sieve cost (USD), *z* salvage value of system at the end 6 years(taken 25% of capital cost) (USD).

Annualized Cost

$$A_A = P_{Net}\left[\frac{i\times(1+i)^k}{(1+i)^k-1}\right] \quad (9)$$

Where AA annualized cost of cooler (USD/year).

Cost of Cooling Unit of Production Based on Cooler Value

$$C = \frac{A_A}{Q\times h} \quad (10)$$

Where *C* the cost consumed of the cooler value per ton (USD/Mg),Q machinery line productivity (Mg/h), *h* total number of working hours per year=1250 (h\year).

Total Cost of Pellets Cooling Process

$$T_{cost} = C + (S\times E) \quad (11)$$

Where (*S*×*E*) is the cost of the consumed electric power per unit of production (USD/Mg), noting that cost of consumption of the electric power unit *(E)* is 0.05 USD/kW.h according to the **Egyptian Ministry of Energy and Electricity (2017).**

RESULTS AND DISCUSSIONS

Performance of the SBVC (Commercial Type)

In the present paper, the performance of the most popular type of vertical coolers in Egypt represents in the single-bed vertical cooler (SBVC) was evaluated. This design was operated under the recommended standard operational parameters by the manufacturer for cooling fish feed pellets with constant bed depth of 40 cm. The SBVC performance was evaluated to be compared to the novel DBVC under the same environmental conditions (*i.e.* the ambient temperature and relative humidity).The results revealed that, the fish feed pellets temperature (T_p) and moisture content ($M.C_p$) were reduced from 91°C to 36°C and from 18% to 13.2%, respectively using the SBVC under ambient air temperature (T_a) of 30°C±1 and air relative humidity (RH%) of ~35% by using the SBVC. It was clear that the temperature difference of 6°C between the ambient temperature and the lowest temperature of pellets hasn't achieved the recommended difference range (3-5°C) and the same was occurred with pellet $M.C_p$ (recommended range is 8-12%). Furthermore, the cooling efficiency and pellet durability were 60.53% and 93.50%, respectively with productivity of (~1890 kg/h) and specific energy consumption of 3.73 kW.h/ kg.

Effect of Studied Operational Parameters of the DBVC on Temperature and Moisture Content of the Outlet Cooled Pellets

In this work, the performance of the new design of DBVC was assessed under the same environmental conditions (T_a=30°C±1 and RH%= ~35%) and the type of fish feed pellets that used in the practical experiments of SBVC. For more reliability, samples of the outcome hot pellets from the forming die of pelletizer were immediately collected to measure the initial temperature and moisture content of the outlet pellets prior entering the DBVC. Ten runs were performed on the samples of hot pellet and the average initial temperature and moisture content were found to be 91.2°C and 18.10%. Figs. 6 and 7 showed the effect of height of pellets, slit width and vacuum fan position on the initial temperature and moisture content of outlet hot pellets which were considered crucial parameters affecting the cooling performance of pellet cooler. It can be seen that the DBVC reduced the T_p from 91.2° to ranges of 34- 45°C, 36-54°C and 40-58°C for vacuum fans positions No. 1, 2 and 3, respectively, meanwhile the $M.C_P$ reduced from 18.10% to ranges of 11.80-13.80 %, 12.30-15.3% and 13.70-15.60% for the mentioned fan positions, respectively. As general trend, it was found that the increase of pellets height from 25 to 75 cm and slit width from 1 to 3 mm led to an explicit decrease in T_p and $M.C_P$ under all positions of vacuum fans. The lowest values of T_p (34 °C) and $M.C_p$ and (11.80%) were achieved by operating DBVC at position No.1 for vacuum fans compared to corresponding values at positions No. 2 and 3 at the same optimum operating conditions represent in the pellet height of 75 cm (retention time 15 min) and slit width of 3 mm, as depicted in Figs.6 and 7. This can be attributed to the increase in residence time of pellet within DBVC by using the larger bed depth of pellets, simultaneously the combination of low position of vacuum fans and large slit width may accelerate the removal rate of heat and moisture content from hot pellets by the vacuumed ambient air stream with minimal resistance through the pellets bed. In the light of above, it can be summarized that the final T_p and MC_p after cooling process using DBVC under the mentioned appropriate operating conditions were lesser than those of SBVC by about 5.55 % and 10.60%, respectively.

Effect of the Studied Operational Parameters on the Productivity of DBVC

The effect of height of feed pellets, slit width and vacuum fan position on the productivity of DBVC was illustrated in Fig. 8. The obtained results showed that the increase of sieve slit width and height of feed pellet caused noticeable decrease the productivity of DBVC under all positions of the vacuum fans. It can be seen that using the increase of slit width from 1mm to 3mm and height of feed pellet from 25 cm to 75 cm the productivity decreased in ranges from 1916 to 1876 kg/h, 1946 to 1886 kg/h and 1952 to 1914 kg/h for vacuum fans positions No. 1, 2

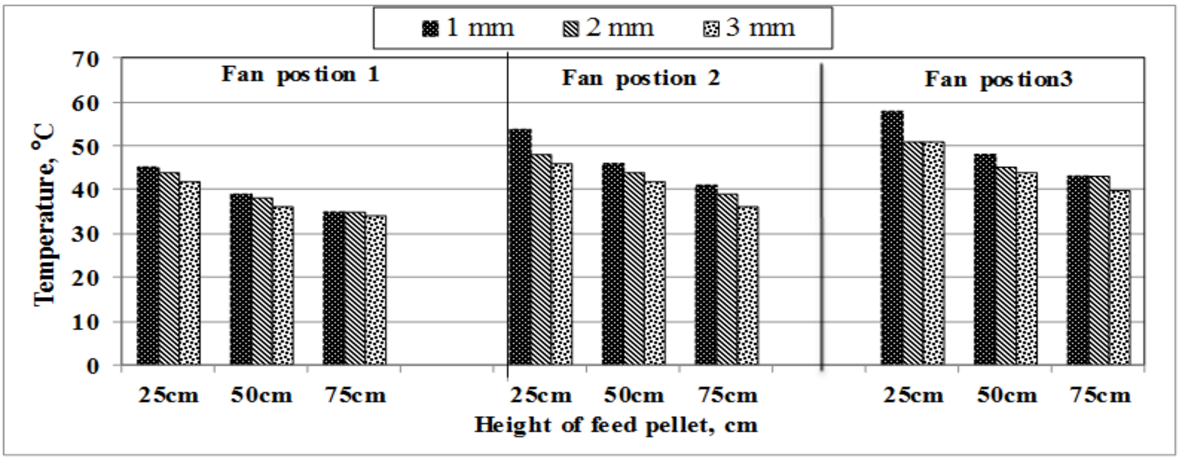


Fig. 6. Effect of vacuum fan position, sieve slit width and height of pellets on the temperature of the outlet cooled pellets from DBVC

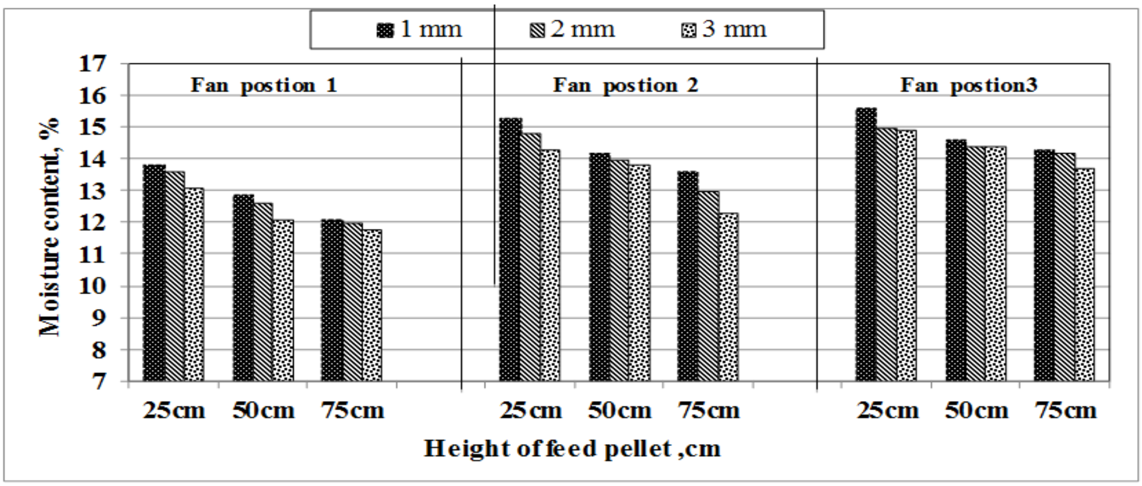


Fig. 7. Effect of vacuum fan position, sieve slit width and height of pellets on the moisture content of the outlet cooled pellets from DBVC

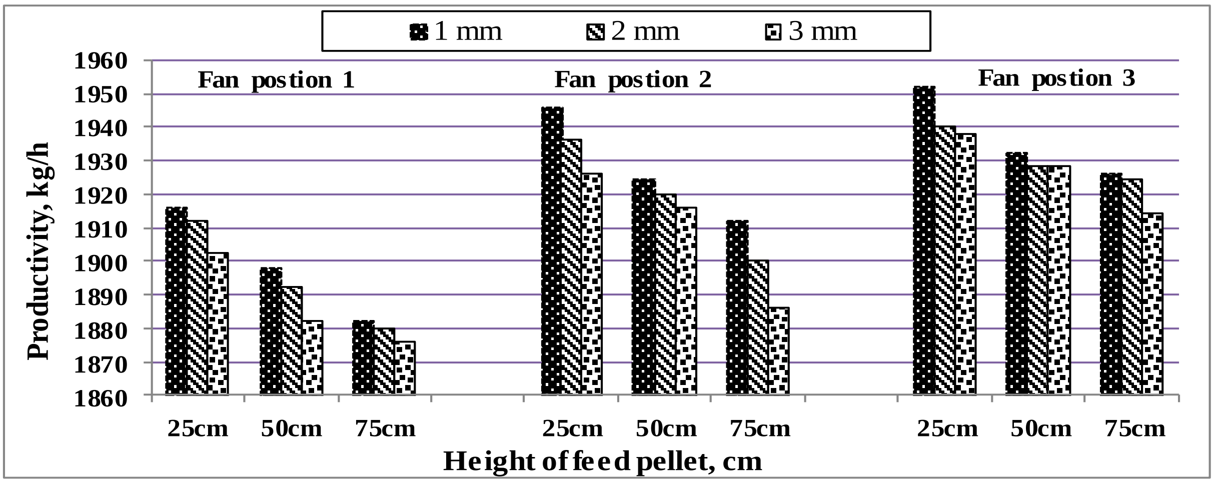


Fig. 8. Effect of vacuum fan position, sieve slit width and height of pellets on the productivity of DBVC

Effect of the Studied Operational Parameters on the Cooling Efficiency of DBVC

Cooling efficiency was a very important parameter to evaluate the cooling effectiveness of the proposed new design of pellet cooler which was greatly influenced by the inlet and outlet temperatures of the feed pellets that corresponding to pellets temperatures before entering the cooler and after coming out from cooler, respectively.

Fig. 9 showed the influence of feed pellets height, sieve slit width and vacuum fan position on the cooling efficiency of DBVC. The obtained data indicated that the increase of sieve slit width and height of feed pellets was accompanied with explicit increase in the cooling efficiency of the proposed cooler regardless of the vacuum fans position. The obtained result revealed that the increase of sieve slit width from 1mm to 3mm and height of feed pellets from 25 cm to 75 cm increases the cooling efficiency from 50 to 62.63%, 42.55 to 60% and 38.29 to 55.55% for vacuum fan positions No. 1, 2 and 3, respectively. This is because the large sieve slit width and low position of vacuum fans allows to large amount of cold air to penetrate the bed of hot pellet due to the close distance between the vacuum fans and the air intake holes allocated near the bottom of the cooling chamber. In the same time, increasing the pellet height means increasing of the residence time of hot pellet inside the cooling chamber that allows to gradual removing of both heat and moisture content from the hot pellets. Accordingly, it can be observed that highest cooling efficiency of 62.63% was higher than the cooling efficiency of the SBVC (60.53%) that achieved by using sieve slit width of 1 mm and feed pellets height of 75 cm (retention time 15 min) under vacuum fan position No.1 as shown in Fig. 9.

Effect of Operational Parameters of the DBVC on Pellet Durability

Pellets durability was considered one of the most important indicators of pellets quality, therefore in the feed industry, the high durability means high quality (**Mohammad *et al.*, 2010; Abd El-Wahab *et al.*, 2011**). The effect of feed pellets height, sieve slit width and vacuum fan position on the durability of the cooled feed pellets using the proposed DBVC was illustrated in Fig.10. The obtained data showed that the increase of sieve slit width and height of feed pellets causes an increase in the durability of the cooled pellets using proposed cooler of DBVC at any position of the vacuum fans. The results showed that the increase of sieve slit width from 1mm to 3mm and height of feed pellets from 25 cm to 75 cm increases the durability of cooled pellets from 91.50 to 98%, 89.50 to 92.50 % and 88 to 95.50 % for vacuum fan positions No. 1, 2 and 3, respectively. Fig. 10 showed that the highest durability of 98% for the cooled pellet was achieved under the optimum operating conditions including sieve slit width of 3 mm and of feed pellets height of 75 cm (retention time 15 min) at lowest position of the vacuum fans No.1. This is because the mentioned optimum operating conditions offers good penetration of the cold stream of the ambient air through the pores between the hot pellets with high retention time. So, a gradual removing of heat would be occurred which can prevent the forming of a surface crusted layer that may be formed by the shock of fast cooling, subsequently the moisture content of hot pellets can be removed easily and high durable cooled pellets would be obtained. It can be concluded that, the highest durability of cooled pellets using DBVC (98%) was higher than the durability of cooled pellets using the SBVC (93.50%) by about 4.60%.

Effect of Operational Parameters of the DBVC on the Specific Energy Requirement during Pellets Cooling Process

The specific energy requirement depends theoretically upon the consumed power in the pellets cooling process and the productivity of the feed pellets cooler. The effect of feed pellets height, sieve slit width and vacuum fan position on the consumed specific energy in the cooling process for the feed pellets using the DBVC was depicted in Fig.11.

It can be seen that the increase of sieve slit width followed by a clear decrease in the consumed specific energy; meanwhile the contrary was occurred by increasing the feed pellets height inside the cooling chamber.

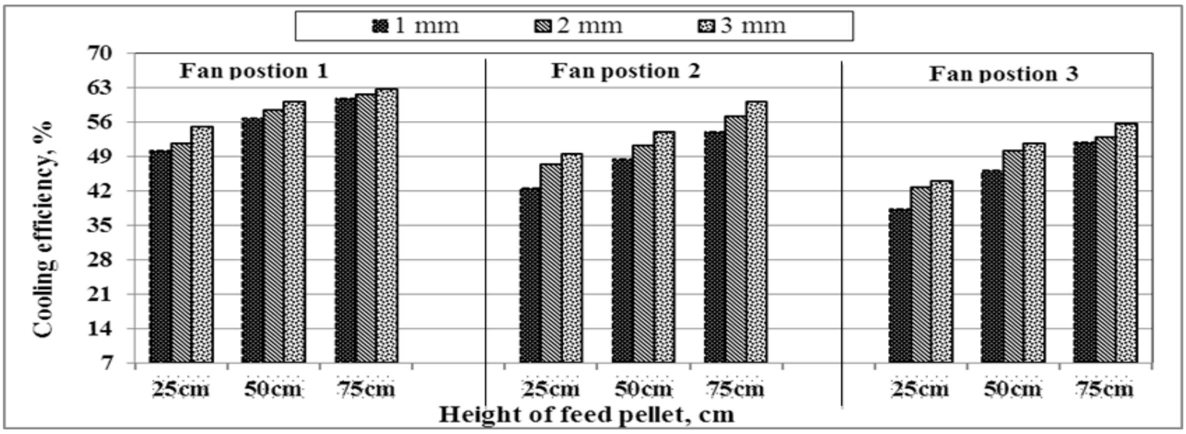


Fig. 9. Effect of vacuum fan position, sieve slit width and height of pellets on cooling efficiency of DBVC

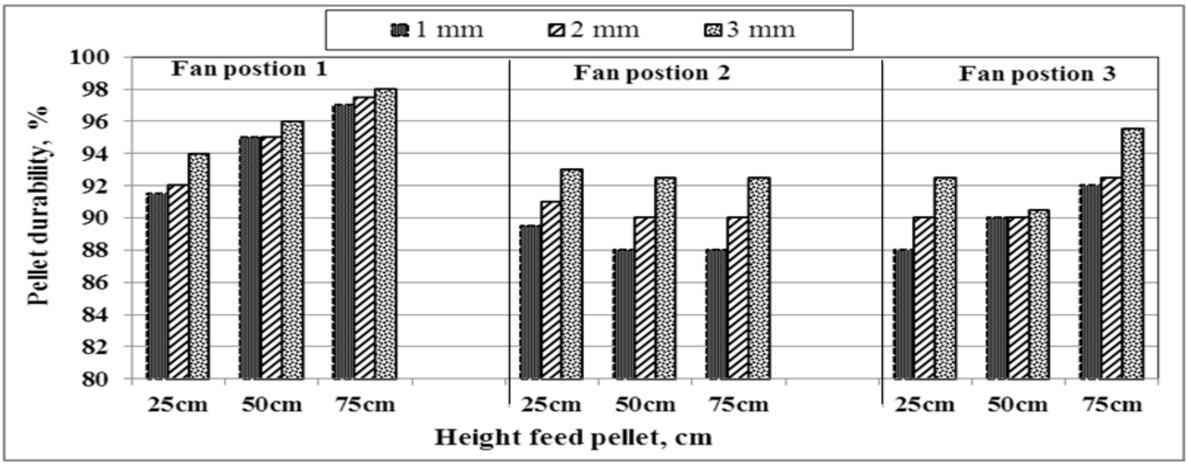


Fig. 10. Effect of vacuum fan position, sieve slit width and height of pellets on pellet durability using DBVC

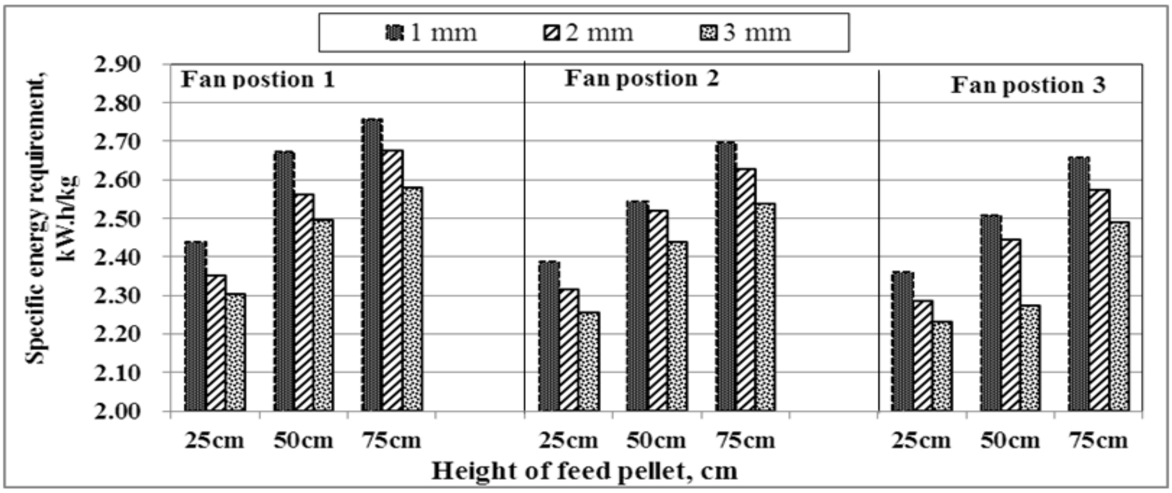


Fig.11. Effect of vacuum fan position, sieve slit width and height of pellets on the energy requirement for cooling hot pellets using DBVC

Hence, the low position (No.1) of the vacuum fans was the best position comparing to the other positions No. 2 and 3 under any width of the sieve slit because the lowest values of the consumed specific energy for cooling the hot pellets were achieved at this position. This because the penetration resistance against the stream of the cold ambient temperature by the feed pellets bed would be low at lower height of pellets resulting in low consumed power and energy. On the other hand, the same reason led to decrease the required energy for cooling by increasing the sieve slit width. At best position of vacuum fans No.1, the increase of sieve slit width from 1 mm to 3 mm followed by an explicit decrease in the consumption of specific energy required for cooling the hot pellets from 2.44 to 2.30 kW.h/kg, 2.67 to 2.50 kW.h/kg and 2.76 to 2.58 kW.h/kg for pellets heights of 25, 50 and 75 cm, respectively. At the same position, the increase of pellets height from 25 cm to 75 cm was led to increase in the consumption of specific energy required for cooling from 2.44 to 2.76 kW.h/kg, 2.35 to 2.68 kW.h/kg and 2.30 to 2.58 kW.h/kg for sieve slit width of 1, 2 and 3 mm, respectively. In the present work, the appropriate consumption of the specific energy for cooling the hot pellet would be 2.58 kW.h/kg. This value of the specific energy consumption was recorded under the optimum operating conditions of DBVC that achieved the highest quality for the cooled pellets including the sieve slits width of 3 mm, pellets height of 75 cm (retention time 15 min) and the lowest vacuum fan position No.1. In summary, using DBVC under the optimum operating conditions reduces the specific energy consumption for cooling the hot pellets by about ~30.83% comparing to the SBVC that operated under the recommended conditions by the manufacturer.

Cost of the Feed Pellet Cooling Process

Decreasing the processing cost was considered one of the most important goals for any industry. Regarding the feed pellets industry, the balance between producing high quality of feed pellets and reducing the cost of manufacturing processes is a difficult question that needs to be answered. Therefore, this work may be considered as an attempt to answer this question by using a new, simple and economical technique to achieve this desirable balance for one of the most effective process on the feed pellet quality that represented in cooling process.

Table 3 showed the cost of the proposed DBVC including cost of each component as well as the total cost of SBVC (commercial cooler). It was clear that there was huge difference in the cost of both coolers. It can be seen that using the proposed DBVC reduces the capital cost of the cooling process by about 73.91% lower than the cost when using the SBVC. According to the presented data in Table 4, it was obvious that the use of DBVC led to decrease net present cost annualized cost and cooling cost based on cooler value by 72.08%, 72.11% and 67.28%, respectively lower than SBVC. Additionally, the DBVC reduces the total cost of cooling process per unit of production by about 61.26% compared to SBVC. Ultimately, it was clear that the proposed new design of feed pellets cooler of DBVC proved a potential performance to produce a high quality of pellets with massive save in the cost of cooling process compared to the common commercial feed pellet cooler of SBVC.

Conclusions

The present work aims to fabricate and evaluate the performance of a novel design of feed pellets cooler provided with a vacuum chamber and double vacuum fans named as double bed vertical cooler (DBVC). The performance of the proposed cooler is compared to the performance of the commercial pellet cooler named as single bed vertical pellet cooler (SBVC) that exist already in the local markets and used widely in the Egyptian feed pellets industry. The performance evaluation of DBVC was performed in terms of the output pellets temperature and moisture content, productivity of cooler, cooling efficiency, pellets durability and required specific energy for cooling process. Furthermore, both types of feed pellets coolers are investigated from the economic point of view. The DBVC was evaluated using three heights for feed pellets within the cooling chamber of 25, 50 and 75 cm, which corresponding to pellets retention time of 5, 10 and 15 min, respectively, three values for the sieve slit width of 1, 2 and 3 mm and three positions

Table 3. Cost of the novel DBVC and SBVC (commercial cooler)

Components of DBVC	Cost (USD)
Frame	275.86
Rotary airlock distributer electric motors	273.56
Sieves	51.72
Discharge sliding gate	42.52
Piston & compressor air	215.51
Sensors (thermocouples +level sensor)	36.2
Vacuum fans+ electric motors	275.86
Electric control panel	229.90
Labor wage for components assembly	323
Total cost of DBVC	$ 1724.13
Total cost of SBVC (Average price in the local market)	$ 6610.00

Table 4. Total cost of the pellet cooling process according to LCC method

Costs	DBVC	SBVC
Present maintenance cost [USD]	618.85	2418.16
Net present cost [USD]	2379.54	8524.03
Annualized cost [USD/year]	662.9	2374.7
Cooling cost per unit of production based on cooler value [USD/Mg]	0.28	0.98
Cost of consumed electric power per unit of production [USD/Mg]	0.13	0.19
Total cost of cooling per unit of production [USD/Mg]	0.41	1.18

of the double vacuum fans including position1 (30 cm- 60 cm), position 2 (30 cm- 90 cm) and position 3 (60 cm- 90 cm), which represent the height of double vacuum fans from the bottom of pellet bed. The best performance of DBVC was achieved at pellet height of 75 cm (pellet retention time 15 min), sieve slit width of 3 mm and vacuum fans height of 30 cm- 60 cm. Under the optimum operating conditions for both cooler, the results of this investigation can be enlisted as follows:

i) The temperature and moisture content of outlet pellets reduced to from ~91ºC to 34ºC and 18.10% to 11.80%, respectively by using DBVC, whilst from~91ºC to 36ºC and ~18% to 13.2%, respectively for SBVC.

ii) The productivity of DBVC was 1.876 Mg/h, but it was to be 1.900 Mg/h for SBVC.

iii) The cooling efficiency and pellet durability were 62.63% and 98%, respectively by using DBVC and 60.53% and 93.50%, respectively for SBVC.

iv) Using DBVC led to decrease the capital cost of cooler, net present cost annualized cost cooling cost based on cooler value and total cost of cooling per unit of production by 73.91 %, 72.08%, 72.11% ,67.28% and 61.60%, respectively.

v) The new design of feed pellets cooler of DBVC produced a high quality of pellets with high save in the cost of cooling process compared to the SBVC and it is recommended to use the new cooler for cooling another types and sizes of pellets in future works.

Nomenclature

A_A Annualized cost of the pellet cooler [USD /year]

C Cooling cost of the production unit of based on cooler value [USD/Mg]

C_m Annual maintenance and repairs cost [USD /Mg]

C_R Cost of air vacuum fan [USD]

D_u Pellet durability [-]

E Cost of consumption of the electric power unit [USD /kW.h]

F Useful life of replaceable parts [years].

h Total number of working hours per year [h/ year]

i Interest rate [%]

I Line current strength in amperes [A]

k Machining equipment's expected useful life [years]

M_a Mass of pellets sample after tumbling (mass of remained pellets on sieve) [g]

M_b Mass of pellets sample before treating [g]

P Consumed power by the pellet cooler [kW]

$M.C_p$ Pellet moisture content [%]

P_i Capital cost [USD]

P_m Present maintenance cost [USD]

P_{Net} Net present cost for cooler [USD]

Q Cooler productivity [Mg/h]

R.H Relative humidity [%]

S Specific energy requirement for pellets cooling [kW.h/Mg]

T Consumed time [s]

T_a Ambient air temperature [°C]

T_{cost} The total cost of cooling process per unit of production [USD/Mg]

T_P Pellet temperature [°C]

V Potential difference/Voltage [V]

v Sieve cost [USD]

W_P Pellets mass after cooling [g]

Z Salvage value of cooler [USD]

ε Mechanical efficiency of the pellet cooler [%]

DBVC Double separated-bed vertical cooler

SBVC Single bed vertical cooler

LCC Life cycle cost

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تقـــييم أداء تصـــميم جـــديد لمبـــرد أعـــلاف مصبعة رأســـي

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يهدف هذة البحث إلي دراسة تصميم جديد لمبرد رأسي للأعلاف المصبعة تحت مسمي المبرد الرأسي ذو المرقد المزودج. تم تقييم أداء هذا المبرد عملياّ لتبريد أعلاف الأسماك المصبعة الغاطسة و المنتجة بواسطة آلة تصبيع الأعلاف الحلقية و ذلك تحت ظروف تشغيلية شملت وضعية مراوح سحب الهواء البارد ، إرتفاع عمود العلف كدالة لزمن الإبقاء للعلف داخل المبرد ،قيم مختلفة لعرض فتحات دخول هواء التبريد. تم تقييم أداء المبرد المقترح و مقارنته بأداء مبرد الأعلاف المصبعة ذو المرقد الأحادي (المبرد التجاري) و الذي يستخدم علي نطاق واسع في صناعة الأعلاف المصبعة في مصر عند سعة تبريد 2 طن/ساعة لكلا المبردين. تم إجراء المقارنة مع الأخذ في الأعتبار مؤشرات الأداء مثل درجة حرارة ،رطوبة الأعلاف المصبعة الخارجة من المبرد، إنتاجية المبرد، كفاءة التبريد، الطاقة النوعية المستهلكة في عملية التبريد. تم إستخدام طريقة تكاليف دورة الحياة لإجراء التحليل الإقتصادي لكلا النوعين من المبردات. أوضحت النتائج المتحصل عليها أن أفضل أداء للمبرد الجديد قد تحقق عند تشغيله تحت الظروف التشغيلية المثلي و التي تشمل أرتفاع 15 سم لإصبعيات الأعلاف داخل غرفة التبريد (تناظر 15 دقيقة كزمن إبقاء)، 3 مم عرض لفتحات دخول الهواء وإرتفاع 30 سم- 60سم لمروحتي السحب تحت أفضل الظروف التشغيلية لكلا المبردين كذلك أظهرت النتائج أن درجة الحرارة و المحتوي الرطوبي للأعلاف المصبعة بعد التبريد قد أنخفضت بحوالي 5,55% و 10,60% علي التوالي وذلك بإستخدام المبرد الجديد و الذي حقق أيضاّ زيادة طفيفة عن المبرد الرأسي ذو المرقد الأحادي تقدر بحوالي 3,35% و 4,60% لكل من كفاءة التبريد و متانة الأعلاف علي التوالي ولكن مع إنخفاض واضح للطاقة النوعية المستهلكة لتبريد الأعلاف تصل إلي 30,83% أقل منه في حال إستخدام المبرد الرأسي ذو المرقد الأحادي (المبرد التجاري) من الناحية الإقتصادية وجد أن التكلفة الإجمالية لرأس المال وتكلفة التبريد الإجمالية لكل وحدة إنتاج للمبرد الجديد الرأسي مزدوج المرقد أقل من المبرد الرأسي ذو المرقد الأحادي بنسبة 73,91٪ (فرق السعر بين المبرد التجارى والمبرد الجديد توفير يعادل 4885.87 دولارأمريكي) و 61.26٪ (توفير يعادل 0,77 دولارأمريكي / طن) على التوالي .أخيراّ فأنه من الواضح أن المبرد الجديد الرأسي مزدوج المرقد أثبت أداءً عاليًا ووفر تكاليف عملية تبريد الأعلاف المصبعة.

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