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Design of a Screw Conveyor for Transporting and Cooling Plantain Flour in a Process Plant

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Abstract

This paper discusses the design, simulation and functional performance evaluation of an inclined screw conveyor with integrated system for cooling while conveying pulverized pulps from pulverizing unit to packaging unit of a plant that processes unripe plantain into flour. Hygiene, ergonomics, conveyance distance and height, thermal and mechanical properties of the materials selected, ease of fabrication and production cost were carefully considered. Model for the equipment was developed using SolidWorks application software, which was followed by design analysis of its components. Simulation of the developed model was done using ANSYS, SolidWorks and Autodesk Inventor application software packages, in order to predict the performance of its components and to ascertain its functionality before fabrication. The simulation results showed that the design of the equipment is adequate and safe for fabrication. The equipment was then fabricated and assembled using appropriate manufacturing techniques. The total fabrication cost is put at One Thousand, Three Hundred and Thirty dollars ($1,330) only. Its functional performance was evaluated; the throughput and thermal efficiencies obtained were 96.1% and 85.3% respectively. It can be said that the equipment has the capacity to serve its primary purpose as it was able to convey and cool the material poured into it from 82.2^{0}C to 29.2^{0}C.

Keywords: Screw Conveyor Design, Plantain Flour Cooling, Simulation, Evaluation, Process Plant;

Nomenclature

$\dot{m}$ *Mass flow rate*

Q_m *Mass throughput*

ρ_f *Flour's bulk density,*

w *Width of conveyor*

N *Angular speed of conveyor*

p *Pitch of conveyor auger*

f *Feed rate*

dH *Change in internal (heat) energy*

$\dot{m}_a$ *Mass flow rate of air*

k *Heat capacity of conveyor walls*

A *Surface area of conveyor walls*

C_P *Heat capacity of conveyor walls*

T_a *Ambient temperature*

T_{ain} *Inlet temperature of cooling air*

T_{aout} *Outlet temperature of cooling air*

T_{fin} *Inlet temperature of flour*

T_{fout} *Outlet temperature of the flour*

S_p *Screw pitch*

D_{screw} *Screw diameter*

P_f *Power required to overcome conveyor friction*

P_{cm} *Power required to transport the plantain flour*

P_L *Power required to lift the plantain flour*

g *Gravitational constant*

L_{sc} *Total length of the screw conveyor*

F_b *Hanger bearing factor*

F_m *Material factor*

Q_e *Equivalent capacity*

η_{drive} *Drive efficiency factor*

1. Introduction

Material handling is a science involving the moving, packaging and storing of materials [1]. Material handling is very crucial to food processing, which can either be manual, mechanized or pneumatic. According to Evstratov *et al*. [2], materials' conveyance is usually achieved by a combination

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of mechanical, inertial, pneumatic and gravity forces. Inclined simultaneous conveying and cooling of pulverized pulps in a plant that is meant for processing unripe plantain into flour require a material handling equipment that will be able to prevent air, dust and other foreign materials from interacting with the flour produced to avoid contamination and to ensure quality by making the equipment dust- and air-tight [3]. In view of this, Waje *et al.* [4], having established its advantages over other conveyors that are used as heat exchangers, the use of screw conveyor as heat exchanger is recommended whenever simultaneous conveying and cooling or heating are required during processing operations in addition to other factors. Because of its outstanding advantages over other conveyors, Kaplan and Celik [5, 6], Verchshagin et al. [7], Cucumo et al. [8] and Mustaffar et al. [9] also affirmed the use of screw conveyor as heat exchanger when faced with the challenge of simultaneous conveying and cooling or heating of materials during processing operations.

Screw conveyor is known to be cost-effective, easy to install, occupies less space, possesses excellent volumetric efficiency, requires low maintenance, gives good throughput control, provides environmentally clean solutions to process handling problems, and provides dust- and air-tight material handling [4, 10, 11]. It is interesting to know that belt, chain, bucket and pneumatic conveyors do not possess these aforementioned qualities to qualify them for use/consideration when pulverized materials are to be concurrently cooled and transported in an inclined position as in the case of a plant that processes unripe plantain into flour. Screw conveyor helps transport materials at controlled and steady rates, which makes it applicable for measuring materials' flow rates, which other conveyors (such as pneumatic, belt, chain and bucket conveyors) cannot do [2].

Screw conveyor can be designed to function as a dryer or heat exchanger by running hot or cold fluid through the jacket created around its trough. Screw conveyor is reported as one of the oldest, simplest, most efficient and economical methods of conveying materials from one location to another in processing operations [12]. Thus, screw conveyor is widely used in processing operations due to its inherent outstanding advantages over other conveyors [13]. Hence, a screw conveyor, with fully enclosed tubular type casing, was considered for this operation based on the recommendations of Waje *et al*. [6, 14] and because of its versatility and inherent ability to operate over a wide variety of speeds as well as angles of inclination up to vertical, which other conveyors cannot do [13, 15]. This will help the flour produced from the pulverizing unit retain its quality and moisture content since the screw conveyor is made dust- and air-tight to prevent interaction with the surrounding environment. It will also give room for controlled material flow/throughput into the packaging section of the plantain processing plant.

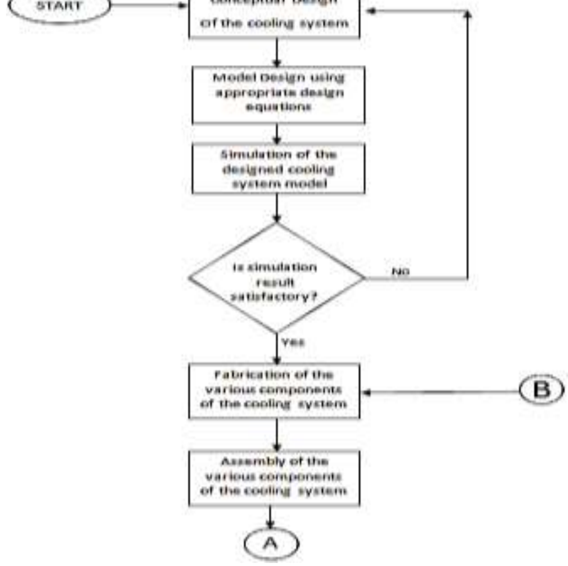
Plantain is from Musaceae plant family [3] and it is known to be cheap for the management of diabetes mellitus, a risk factor for COVID-19 [16, 17]. It is cultivated in humid tropical Africa, Asia, Latin America, Central and Southern America [18, 19]. It has also been reported that Nigeria is the largest producer of plantain in West Africa with huge percentage found in the Southern part of the country [20, 17]. Poor transportation and distribution facilities in the production areas, harvest at maturity close to fruit ripening, and poor storage conditions are factors likely to depreciate quality and provoke post-harvest losses of plantain. To minimize or eliminate these losses, to enhance and improve the value, plantain is usually processed into storable and value-added products [21, 17].

In a plantain processing plant, several materials are moved within the production floor, ranging from washed plantain pulps to dry pulverized plantain pulps. This research investigated the simultaneous transfer and cooling of flour from pulverizing unit to the packaging unit of a plant that processes unripe plantain into flour that is being developed in Mechanical Engineering Department of the Federal University of Technology, Akure, Ondo State, Nigeria. The packaging, however, must be done only after the plantain flour is cooled as stated by Olutomilola [3]. Cooling to storage temperature is necessary to prevent the flour produced from clumping after packaging due to temperature induced heating of its particles, which can adversely affect its quality, shelf life and esteem value. Cooling while conveying the flour, using enclosed screw conveyor, will bring reduction in production cost (in terms of processing time), improvement in hygiene, quality and esteem value of the product [22]. Hence, there exists a need to develop an adequate cooling system alongside the conveyance of plantain flour before packaging.

2. MATERIALS AND METHODS

2.1. Flowchart and Model Development for the Screw Conveyor

In actualizing the aim of this study, a flowchart, depicting the flow of activities involved in developing a screw conveyor for simultaneous conveyance and cooling of flour in a plantain processing plant, was developed as shown in Figure 1. Model for the screw conveyor was developed using solidworks computer aided design (CAD) application software (see Figures 2 to 5). Design calculation of all its component parts was done after they were identified. Before fabrication, a simulation study was also conducted on the model developed for the screw conveyor in order to ascertain the adequacy of its design.



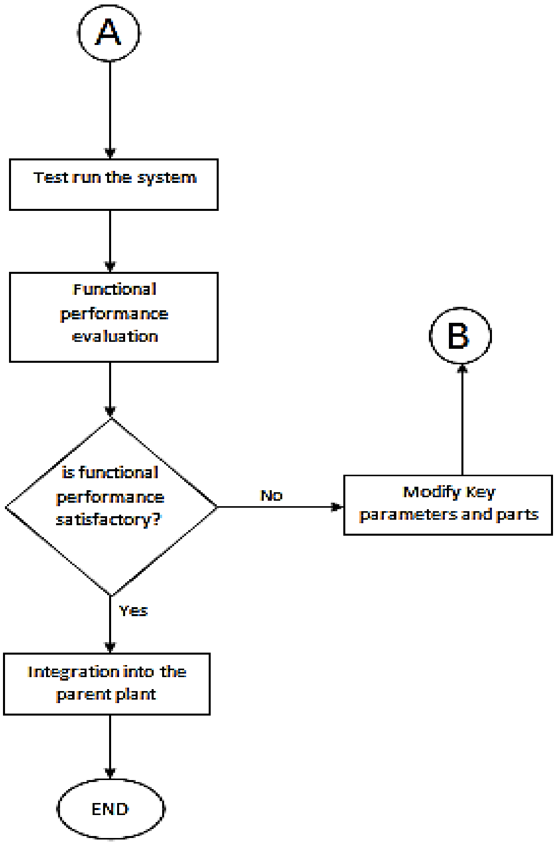


Figure 1. Process flow chart for the research methodology

2.2. Design Consideration

The materials and methods adopted in this research were appropriated in consideration of the following factors in order to produce an efficient and reliable equipment that will ensure techno-economic status of the intended users: availability of material, mechanical properties of the materials selected (such as rigidity, corrosion and wear resistance), hygiene, fabrication cost and overall weight of the machine.

2.3. Design Concept of the Screw Conveyor System

The screw conveyor, which is expected to convey 500 kg of plantain flour per hour, consists of a worm screw in a cylindrical housing with aluminum heat sink arranged around its periphery (Figures 2 to 4). Another tube (known as cooling chamber) houses the heat sink. The screw works by using the internal friction within the flour (bulk solid) to transfer forward motion to the flour in contact with the spiral and to the whole tube contents. With the inclination of the system, a dynamic equilibrium is set up with the spiral action moving some particles upward, the rate of volume transfer being proportional to the shaft's speed. When the screw moves, the hot flour from the hopper contacts the screw housing, through which heat is absorbed from it to the heat sink. The heat sink absorbs the heat and transfers it through convection currents to the cooling air medium. The blower (rating: 0.375 kW; 1400 rpm), which is attached close to the flour exit end of the conveyor, countercurrently blows cool atmospheric air into the cooling chamber against the flour's direction of flow. Heat is removed from the heat-sink and released through an outlet that is attached to the cooling chamber near the conveyor's hopper. A speed reducing gear system helps to stepdown the motor's speed from 1400 rpm to the screw's speed (42 rpm). The motor (1hp) is connected to the reducing gear via shaft and pulley system, which are connected to the screw shaft through a belt drive system. The cooled flour pours out of the conveyor through a tubular outlet, near the motor. Figures 2 and 3 show the isometric and exploded views of the screw conveyor respectively. Its orthographic projection, showing the side, front and plan views in third angle projection, is presented in Figure 4. The sectional view of the screw conveyor was also generated through the mid-plane of the set up to facilitate access to the hidden components of the machine as shown in Figure 5. It is to be noted that: all the materials selected for the fabrication of the screw conveyor were sourced/obtained locally in/within Nigeria; all the components in contact with the flour (i.e. the screw, end plates, screw housing, hopper, flour inlet and outlet) were made of stainless steel in compliance with international food safety policies, while others were made of mild steel.

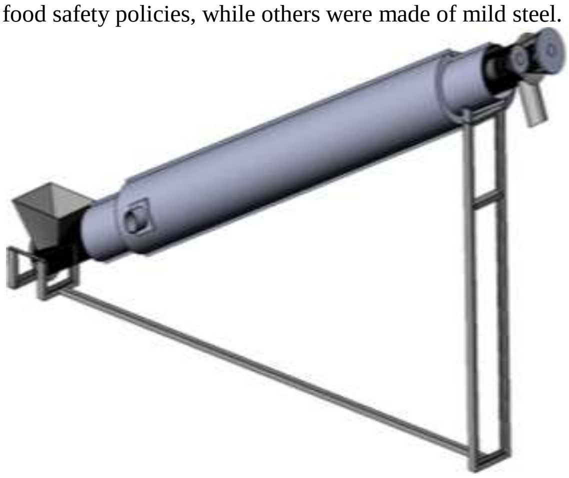
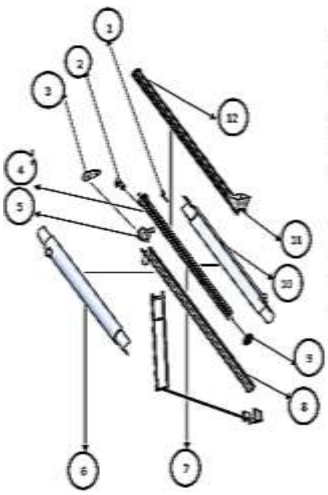


Figure 2. Isometric view of the screw conveyor



Part Number	Part Description	Quantity
1	Motor Bracket	1
2	Drive Motor	1
3	Belt-Drive Mechanism	1
4	Auger Conveyor	1
5	Cooling Fan	1
6	Left Hand Casing	1
7	Frame	1
8	Lower Conveyor Channel	1
9	Conveyor Chamber Seal	1
10	Right Hand Casing	1
11	Conveyor Inlet Hopper	1
12	Upper Conveyor Channel/Cover	1

Figure 3. Exploded view of the screw conveyor

Figure 4. Orthographic view of the screw conveyor

Figure 5. Sectional view of the screw conveyor

2.4. Design Calculation of the Screw Conveyor

2.4.1. Classification of the design model

Design calculation of the screw conveyor system began with classification of the design model, which involved the adoption of appropriate design method/approach to describe and evaluate problem domains under consideration. The design of the screw conveyor system has two major aspects, namely: material flow and material cooling. Material flow is primarily governed by the width (w) of the screw conveyor, rotational speed (N) of the conveyor shaft, pitch (p) of the screw and the flour feed rate (f). Modeling a dependence expression, with the mass flowrate ($\dot{m}$) of the flour as the dependent variable, gave rise to equation (1).

$$\dot{m} = \emptyset(w, N, p, f) \quad (1)$$

Material cooling is primarily determined by: mass flow rate of the cooling air ($\dot{m}_a$) circulated by the blower around the chamber, thermal conductivity (k) of the chamber material, surface area (A) and thickness (t) of the chamber, heat capacity (C_p) of the flour, ambient temperature (T_a), and rotational speed (N) of the screw shaft. Similarly, a dependence equation with the rate of heat removal (dH) as the dependent variable is given in equation (2).

$$dH = \emptyset(\dot{m}_a, k, A, t, C_p, T_a, N) \quad (2)$$

2.4.2. Frame of the screw conveyor system

The frame, which supports the screw conveyor assembly, must be rigid enough to withstand the weight of the whole assembly without buckling in order to prevent vibration or collapse of the equipment. The height of the frame is a function of the conveying height, which was obtained from the configuration and arrangement of the machines in the process plant. In essence, it is necessary to determine the load that the frame can withstand without crippling or buckling. Mild steel angle bar having L-shaped cross-section (welded together at ends) was selected for the frame. There are different types of end connections used in holding frames together and the type of end connection used usually affects the performance of supporting frames. Hence, the frame members were welded together at the ends since fixed-type end connection was selected for the frame. The Euler's theory for crippling and buckling load 'W_{cr}' under various end conditions is represented in equation (3) [23].

$$W_{cr} = {[C\,\pi^2 E\,A]}\big/{[L_{col}/k]^2} \quad (3)$$

$$k = \sqrt{\frac{I}{A}} \quad (4)$$

where: C is the constant representing the end conditions of the column or end fixity coefficient, which is 4 for welded and bolted joints; E is the modulus of elasticity for the column material; A is the cross-section area; L_{col} is the column's length (1500mm); k is the least radius of gyration of the cross section; and I is the polar moment of area.

Since the frame which supports the screw conveyor system is made from angle iron with L- shaped cross section, it is important to know that the value of the crippling load must be far greater than the total weight of the whole assembly supported by the frame. To achieve this, various dimensions of angle iron from manufacturers' specification were used until the desired crippling load was obtained [24]. A dimension that produced a crippling load far greater than the weight of the screw conveyor assembly was a 75 mm angle iron, whose dimensions are presented in Figure 6. The polar moment of area of the section is a factor that contributes to the strength of the column. This was obtained from equations (5) and (6) to be 635885.41 mm^4. Since I_{YY} is equal to I_{XX}, the section will tend to buckle along Y-Y axis and X-X axis [24].

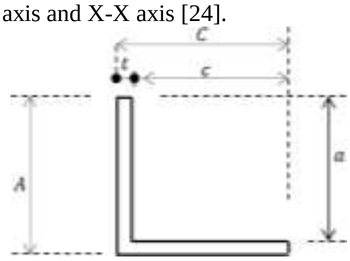


Figure 6. Cross section of the Frame

$$I_{XX} = \frac{1}{12}(AC^3 - ac^3) \quad (5)$$

$$I_{YY} = \frac{1}{12}(A^3C - ca^3) \quad (6)$$

Where: A = 75 mm; C = 75 mm; a = 70 mm; t = 5 mm; and c = 70 mm.

The area of the column A_c was obtained to be 725 mm^2 from equation (7). Hence, the least radius of gyration of the cross section (k) was obtained to be 877.08 mm using equation (4). According to Khurmi and Gupta [24], the young's modulus of elasticity for mild steel is 2.1×105 N/mm^2. Since the length of the column supporting the screw conveyor system is 1500mm, the buckling load on the column was obtained as 2.05 GN from equation (3). The angle of elevation of the system was obtained as 30° from equation (8) [25].

$$A_c = (a + C)t \quad (7)$$

$$\theta_{con} = \sin^{-1}\left[{L_{col}}/{L_{con}}\right] \quad (8)$$

Where: θ_{con} is the angle of elevation of the conveying medium; and L_{con} is the screw conveyor length, which is 3 m.

2.4.3. Determination of the screw conveyor's throughput and speed

The volumetric throughput (Q_v) and rotational speed of the screw conveyor (N_{sc}) were determined from equations (9) and (10) to be 2.495 m^3/hr (or 88.111 ft^3/hr) and 100rpm respectively [15, 12]. A trough loading and screw diameter of 30%A and 150 mm were respectively selected based on the material characteristics of plantain flour. Hence, the screw pitch was determined as 75 mm using equation (11).

$$Q_v = \frac{Q_m}{\rho_f} \quad (9)$$

$$N_{sc} = \frac{Q_v \times CF_0 \times CF_1 \times CF_2 \times CF_3}{C_{1rpm}} \quad (10)$$

$$S_p = 0.5 \times D_{screw} \quad (11)$$

Where: Q_m is the mass throughput, which is 500 kg/h; ρ_f is the flour's bulk density, which is 200 kg/m^3 [26]; CF_0, CF_1, CF_2 *and* CF_3 are constants related to the conveyor configuration, which are 1.11, 2, 1 and 1 respectively; C_{1rpm} is the conveyor's capacity at 1 rpm, which is 2; S_p is the screw pitch and D_{screw} is the screw diameter.

2.4.4. Design of hopper for the screw conveyor

The function of the hopper in the conveying machine is to ensure that plantain flour enters the screw conveyor's trough at a consistent rate in order to prevent the whole flour from getting stuck at the entrance of the conveyor. Basically, conical and pyramidal shaped hoppers are common. The choice of selection depends on the nature of material to be conveyed and physical configuration of the machine. In practice, flour or powdery materials are suitable with pyramidal shaped hopper because it reduces material's flowrate into the conveyor by virtue of its sharp edge restrictions. Thus, a stainless steel square pyramidal shaped hopper was considered for the design. The volume of the hopper is a function of the total volume of plantain flour to be conveyed in the process plant, while its dimensions were obtained from the volume of plantain flour to be contained by it. The volume of the hopper was a section of a complete square pyramid cut away at some point along its vertical height as shown in Figures 7 and 8. Hence, the volume of the hopper was obtained as 90863000 mm^3 using equation (13).

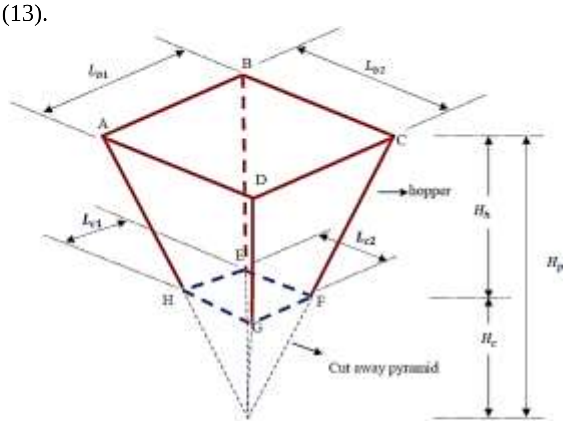


Figure 7. Schematic diagram of the hopper

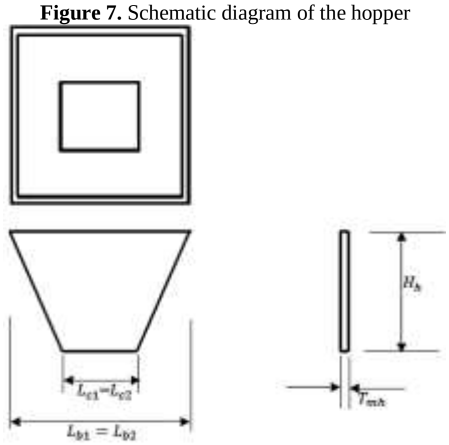


Figure 8. Orthographic projection of the hopper

According to Olowofeso *et al.* [25], the volume of a pyramid with square base is given as

$$V_{pd} = \frac{(area\ of\ base \times height\ of\ the\ pyramid)}{2} \quad (12)$$

$$V_{hp} = V_{wpd} - V_{capd} = \left\{\frac{1}{2} \times L_{b1} \times L_{b2} \times H_p\right\} - \left\{\frac{1}{2} \times L_{c1} \times L_{c2} \times H_c\right\} \quad (13)$$

Note that $L_{b1} = L_{b2}$ and $L_{c1} = L_{c2}$ for a square pyramid.

Moreover, the weight of the hopper was obtained as 102.11 N from equation (14).

$$W_{hopper} = \rho_{hm} \times V_{hm} \times g = \rho_{hm} \times (2H_h T_{mh}[L_{b1} + L_{c1}]) \times g \quad (14)$$

Where: V_{pd} is the volume of a pyramid; V_{hp} is the hopper's volume; V_{wpd} is the volume of the whole pyramid's; V_{capd} is the volume of cutaway pyramid; L_b is the length of the top shape of the hopper, which is 470 mm; L_c is the length of the base of the hopper, which is 240 mm; H_p is the vertical height of the pyramid, which is 940 mm; H_c is the vertical height of the cut away pyramid, which is 450 mm; H_h is the vertical height of the hopper, which is 490 mm; W_{hopper} is the weight of the hopper when empty; ρ_{hm} is the density of the material from which the hopper was made, which is 7480 kg/m^3 [24]; V_{hm} is the Volume of the material from which he hopper was made; and T_{mh} is the thickness of the stainless steel sheet (2 mm).

2.4.5. Power requirement for the conveying and cooling system

The power required by the screw conveyor was computed using equations (15) to (19) [12, 3, 27]. Hence, 1 horsepower or 0.746 kW motor was selected to drive the screw conveyor and its components as recommended by CEMC [12] and Daniyan [28].

$$P_{ST} = P_f + P_{cm} + P_L \approx 0.023\ kW \quad (15)$$

$$P_f = \frac{g \times L_{sc} \times F_b \times N_{sc}}{30300} \approx 0.016\ kW \quad (16)$$

$$P_{cm} = \frac{g \times L_{sc} \times Q_e \times F_m}{30300} \approx 0.004\ kW \quad (17)$$

$$P_L = \frac{g \times Q_e \times h}{1000} \approx 0.003\ kW \quad (18)$$

The required motor power P_{motor} was calculated to be 0.031 kW using equation (19).

$$P_{motor} = \frac{P_{ST}}{\eta_{drive}} \quad (19)$$

Where: P_f is the power required to overcome the friction of the conveyor components (which is the power needed to drive the empty conveyor) in kW; P_{cm} is the power required to transport the plantain flour in kW; P_L is the power required to lift or elevate the plantain flour up vertical height "h" in kW; g is gravitational constant, which is 9.81 m/s^2; L_{sc} is the total length of the screw conveyor, which is 3 m; F_b is the Hanger bearing factor, which is 0.14; F_m is the Material factor, which is 24; Q_e is equivalent capacity, which is 0.139 kg/s; h is the vertical height to which the flour is to be lifted, which is 2.5 m; and η_{drive} is the drive efficiency factor, which is 0.75.

2.4.6. Design of shaft for the screw conveyor

The assembly of the screw (or screw shaft), drive and tail shafts, which are supported by flange bearings, is as presented in Figure 9. The vertical and horizontal loadings of the assembly are as presented in Figures 10 and 11 respectively. It is to be noted that R_A and R_B are reactions at the bearings that are supporting the drive and tail shafts; D_p is the diameter of the pulley that is transmitting power to the drive shaft, which is 100 mm; T_3 *and* T_4 are the tensions in the tight and slack sides of the belt transmitting power to the drive shaft respectively; W_{ap} *and* W_P are the weights (200 N each) of the pulleys receiving power from the electric motor and transmitting power to the drive shaft respectively; L_{CS} is the total length of the screw conveyor, which is 3500 mm; L_{p3} is the length of the screw conveyor assembly (after incorporating shafts) from end of tail shaft to the midpoint of power transmitting pulley, which is 3600 mm; L_S is the distance between the ends of drive and tail shafts, which is 3650 mm; W_{flight} is the weight of the screw's standard length, which is 334 N [12]; R_{AV} and R_{BV} are vertical components while R_{AH} and R_{BH} are horizontal components of reactions at the bearings.

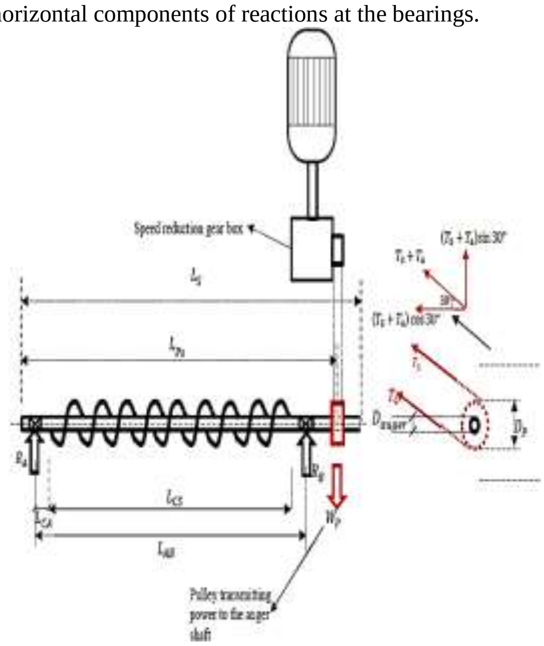


Figure 9. Drive and tail shafts assembly for the screw conveyor

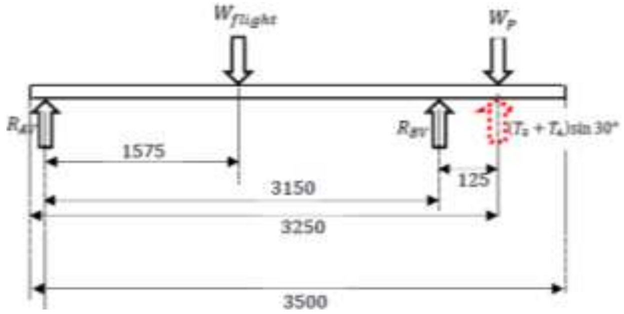


Figure 10. Vertical loading of the screw shaft

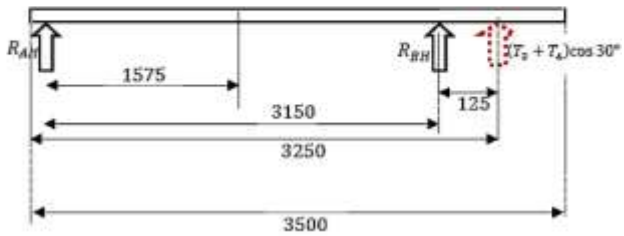


Figure 11. Horizontal Loading of the Screw shaft

It is necessary to determine the shaft diameter and angle of twist of the shaft between the bearings. According to Khurmi and Gupta [24], the ASME code equation for a solid shaft under little or no axial loading is given by equation (20), while the torsional moment M_t and bending moment M_b are given by equations (21) and (24) respectively.

$$D_{dts} = \sqrt[3]{\frac{16}{\pi S_{as}}\sqrt{\{(K_b M_b)^2 + (K_t M_t)^2\}}} \quad (20)$$

$$M_t = M_{tap} + M_{tp} = 81.4\ Nm \quad (21)$$

$$M_{tp} = (T_3 - T_4)\frac{D_P}{2} = 10.2\ Nm \quad (22)$$

$$M_{tap} = (60P_{Tds})/(2\pi N_{sc}) = 71.2\ Nm \quad (23)$$

$$M_b = \sqrt{V_{BM}^2 + H_{BM}^2} \quad (24)$$

Where: D_{dts} is the diameter of the drive or tail (m); S_{as} is the allowable shear stress, which is 55 MN/m^2 for shafts without keyways; K_b is the combined shock and fatigue factor for bending, which is 1.5; K_t is the combined shock and fatigue factor for torsion, which is 1.0; M_b is the bending moment of the shaft (Nm); M_t is the torsional moment of the shaft (Nm); M_{tap} is the torsional moment for the pulley receiving power from the electric motor; M_{tp} is the torsional moment for the pulley connected to the screw shaft; T_3 and T_4 are tensions in the tight and slack sides of the belt, which are 374 N and 171 N respectively; P_{Tds} is the power transmitted to the drive shaft, which is 0.746 kW; V_{BM} and H_{BM} are the maximum vertical and horizontal bending moments respectively.

From Figure 10,

$(T_3 + T_4)\sin 30° = (374 + 171)\sin 30 = 272.5\ N$

Summing all the vertical forces in Figure 10 gives

$$R_{AV} + R_{BV} \approx 262\ N \quad (25)$$

Taking moment about R_{BV} gives

$$\sum MR_{BV} = 0 \quad (26)$$

$\therefore\ R_{AV} \approx 484\ N$

Hence, from equation (25), R_{BV} was obtained as -222 N.

From Figure 11,

$(T_3 + T_4)\cos 30° = (374 + 171)\cos 30 = 472\ N$

$\therefore R_{AH} + R_{BH} = -472N$ (27)

Taking moment about R_{BH} gives

$\sum MR_{BH} = 0; \quad \therefore R_{AH} = 974\ N$

From equation (27), R_{BH} was obtained as -1446 N. The maximum resultant bending moment M_b obtained from equation (24) is 1958 Nm, as shown in Figure 12. According to equation (20), CEMC [12], Khurmi and Gupta [24], a shaft diameter of 40 mm was selected for the drive and tail shafts of the screw conveyor.

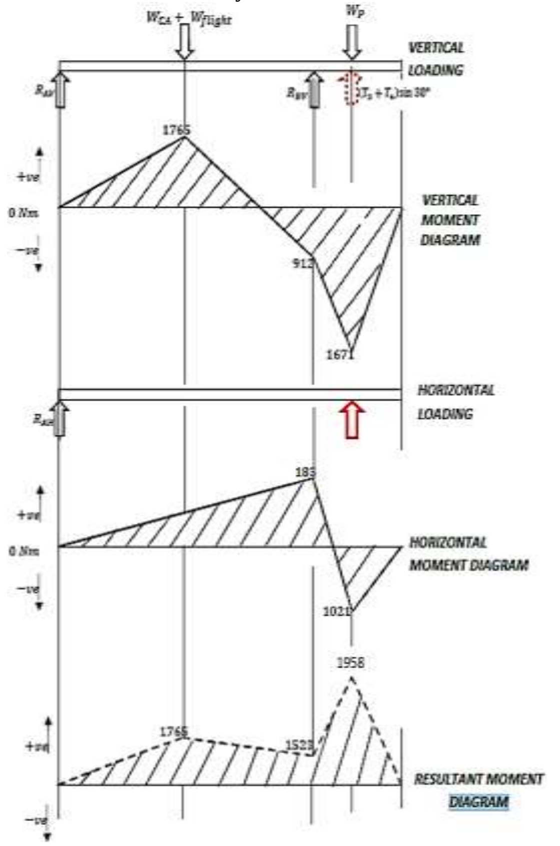


Figure 12. Bending moment diagram for the conveyor

2.4.7. Cooling system and screw housing

The function of cooling in the plantain flour processing plant is to ensure that the flour is maintained at a temperature that will prevent it from clumping and loss of nutritional qualities due to temperature induced reactions after packaging. There are several methods in existence for cooling food materials, but the choice of a method depends on the nature of substance to be cooled and the intended temperature difference that is to be achieved. In this study, since the material to be cooled is powdery in nature, it is then required that it must be enclosed while cooling it to prevent spillage or loss of the product. Furthermore, in order to reduce the processing time, the cooling process has been designed to be done alongside the conveying process. In view of this, the conveying length was carefully selected so that the cooling would have been achieved before the product exits the screw conveyor. The need to enclose the product in the screw housing during conveyance prompted the use of a double pipe type of heat removal process. A counter-flow arrangement was chosen because of its efficiency in terms of large temperature difference compared to parallel- and cross-flow arrangements [29, 30, 31]. Hence, Figure 13 shows a cross section of the cooling and conveying system assembly, from which the mass flow rate of air entering the system, heat removed from the flour, outlet temperature of air exiting the system and the overall heat transfer coefficient were determined.

From Figure 13, T_{ain} is the inlet temperature of cooling air (28°C); T_{aout} is the outlet temperature of cooling air; T_{fin} is the inlet temperature of flour (65°C); T_{fout} is the outlet temperature of the flour, which is desired to have a value closer to the value of the ambient temperature (27°C) [3]; L_{CM} is the length of the cooling Chamber, which is 3500mm; L_{PS} is the length of the flour conveying medium (3250mm); D_{PS} is the diameter of the flour conveying medium (156 mm); and D_{CM} is the diameter of the cooling chamber (320mm). Since the process plant is set to an output of 500 kg/hr, it can be stated that the mass flow rate ($\dot{M}_f$) of plantain flour in the plant is 0.139kg/s. Moreover, Figure 14 depicts the temperature exchange in a counter flow heat exchanging system.

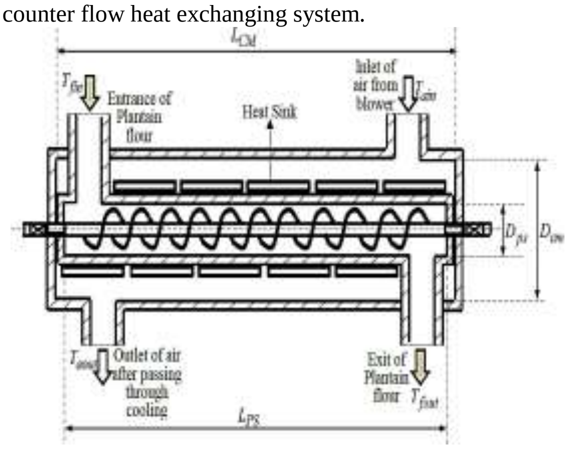


Figure 13. Schematic Diagram of the screw conveyor

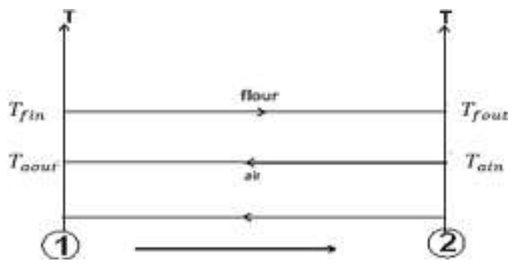


Figure 14. Cooling diagram of the conveyor set up

The heat removed from the flour (Q_f) was obtained from equation (28) as 8.895 kJ. The temperature of the air exiting the system (T_{aout}) was obtained from equation (29) as 40.67°C, while the mass flow rate of air ($\dot{M}_{air}$) entering the system was obtained from equation (31) as 0.699 kg/s by assuming that the heat lost by the flour is equal to the heat gained by the cooling air.

$$Q_f = \dot{M}_f C_{pf}(T_{fin} - T_{fout}) \quad (28)$$

$$Q_f = h_{air}A_{ch}\Delta T_a = h_{air} \times A_{ch}(T_{ain} - T_{aout}) \quad (29)$$

$$A_{ch} = \pi D_{cm} L_{CM} \quad (30)$$

$$\dot{M}_{air} = \frac{Q_f}{C_{air}(T_{ain} - T_{aout})} \quad (31)$$

Where: C_{pf} is the Specific heat capacity of plantain (*Agbagba Species*), which is 1.684 kJ/kg K [26]; h_{air} is the convective heat transfer coefficient of air (200 W/m^{2}K); A_{ch} is the surface area over which cooling air travels, which was obtained as 3.51 m^2 using equation (30); and C_{air} is the specific heat capacity of air at constant pressure (1.005 kJ/kg K).

3. 3. RESULTS AND DISCUSSION

3.1. Simulation of the Screw Conveyor System

The screw conveyor was simulated, using ANSYS, SolidWorks and Autodesk Inventor application software packages in order to predict the performance of its designed components and to ascertain its functionality in the process plant before fabrication [32, 33, 34].

3.1.1. Simulation of the screw conveyor's frame

The primary stresses induced in the frame are normal and axial stresses as shown in Figures 15 and 16. The maximum normal stress induced is 17.44 MPa, a value below the yield stress of mild steel which is about 250 MPa [24]. This leaves ample room for optimizing the design with enough factor of safety (FOS) to spare. Most of the points where this stress is induced are located around the base of the frame and this may be attributed to the interaction of reaction forces and the concentration of body forces. In the case of the axial stress shown in Figure 16, the maximum value is 0.036 MPa. This is obviously below the breaking limit, which tends to occur in long members of the frame assembly. This happens because the axial load is compressive in nature and the greater the length, the greater the chances of having compression occur due to buckling.

Another primary parameter that ascertains the viability of the design is the displacement as shown in Figure 17. The displacement is the geometric deformation of members in the frame assembly. This is an important consideration because of the space constraints imposed by the plant arrangement and operator safety. A maximum displacement of 3.649 mm is seen in Figure 17 and it occurs along the midpoint of the member at center, which also happens to be the longest. This agrees with the principles of structural mechanics where the maximum deflection is at the midpoint of the primary loaded member.

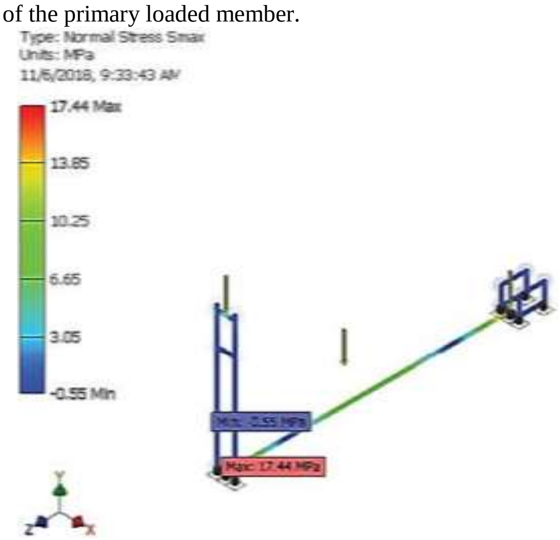


Figure 15. Normal Stress induced in the Frame.

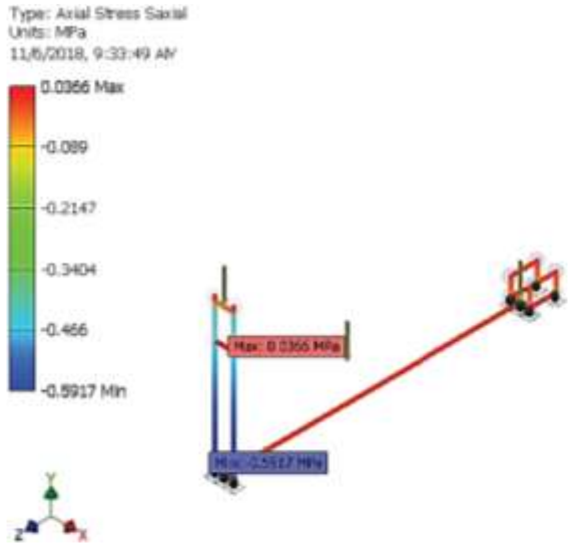


Figure 16. Axial Stress induced in the frame

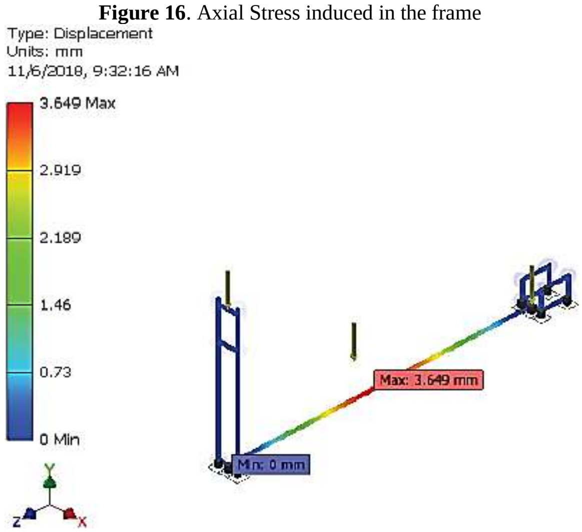


Figure 17. Displacement of frame members

3.1.2. Simulation of the screw conveyor's shaft

It is seen from Figure 18 that stresses are concentrated at the bearing surfaces of the two edges of the conveyor due to the high torsional forces induced at rotation. There is a similar situation at the root of the screw surface which can be attributed to centrifugal effect and reaction forces as they convey the flour along the conveyor's trough. From displacement diagram shown in Figure 19, the displacement is maximum at the very tips of the conveying screw surface. Two things can be said to be responsible for this condition; one is the reverse effect of centrifugal forces with the flour making maximum contact at the tips of the screw. This is as a result of the fact that the screw is partially immersed in the flour (fill ratio, $\lambda = 0.45$ or 45% of the outer edge of the surface). For this same reason, the displacement is minimum at the root of the screw shaft. Figure 20 shows the equivalent strain induced in the screw shaft. This is seen to be concentrated at the ends of the shaft, which may be, mostly, due to the bearing loads. Hence, Table 1 presents the maximum values of the stress, displacement and strain obtained from the simulation.

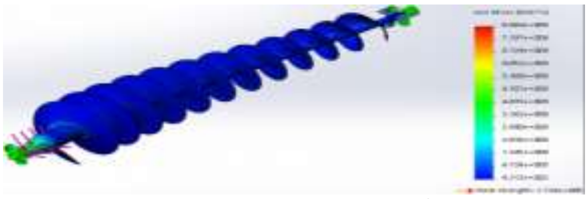


Figure 18. Von Mises stress induced in the shaft under applied loads

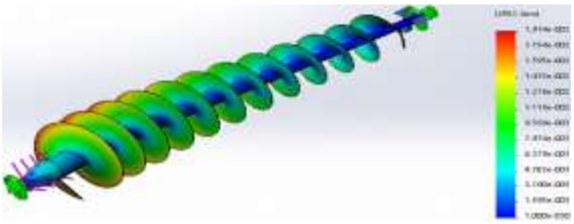


Figure 19. Displacement of the various nodes of the shaft under applied loads

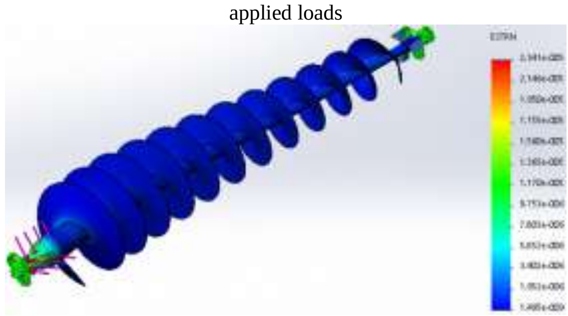


Figure 20. Equivalent Strain of the shaft under loads

Table 1. Comparison and validation of static stress values for screw shaft

Parameter	Maximum Simulated Value	Safety Limit	Remark
Von Mises Stress	8.069 MPa	172.4 MPa	Safe
Displacement	1.914×10^{-2}mm	Not Applicable	-
Equivalent Strain	2.341×10^{-5}	Not Applicable	Safe

3.1.3. Simulation of the screw conveyor system

Figures 21 to 23 show the results of the heat transferred across the two domains of the simplified model of the heat exchanging system as executed in ANSYS. The boundary conditions were set at air mass flow rate of 0.139 kg/s at temperature of 65°C for the main inlet, and set at mass flow rate of 0.699 kg/s at 27°C at the small outlet of the top all at atmospheric air pressure of 101325 N/m^2.

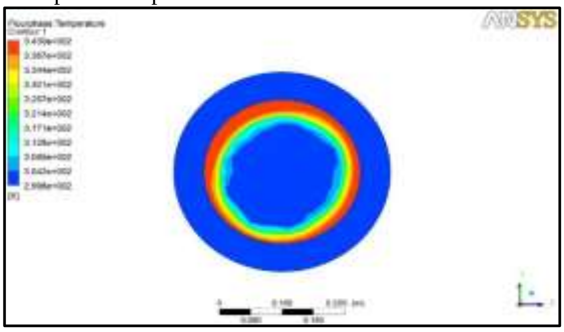


Figure 22. Temperature contour in the radial direction at air and flour inlets

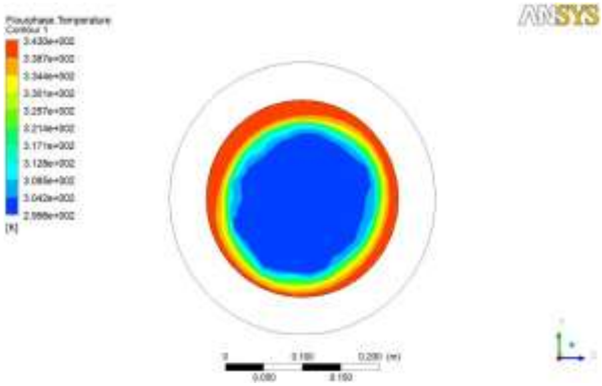


Figure 23. Contour showing flour outlet temperature distribution in the radial direction

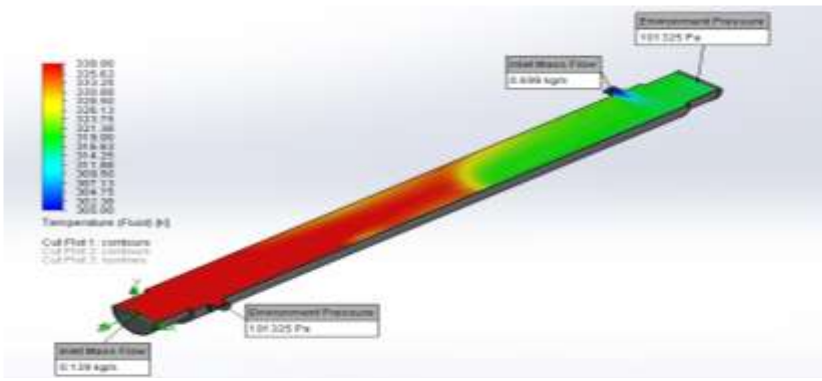


Figure 21. Computed temperatures from simulation

3.1.4. Functional test of the fabricated screw conveyor

The functional performance of the fabricated screw conveyor system was evaluated: to ensure that it serves its intended purpose when incorporated into the plantain process plant, and to ensure that the values arrived at fall within the projected limits, as obtained from its design analysis. 4.5 kg of the food material to be cooled was then used for the test. The evaluation parameters imputed, instruments used in achieving this purpose and the results obtained, with the conditions under which the test was done are as presented in Table 2. A significant cooling effect, a throughput of 2.4 kg/min or 144 kg/h, a travel time of 2.43 minutes and an efficiency (based on the ratio of the output to the input) of 96.1% were obtained. The outlet temperature of the cooled material as measured at the conveyor outlet was found to be 29.2^{0}C (compared to 27^{0}C obtained from the design analysis). It is believed that the outlet temperature of any food material under consideration can be influenced by influencing inlet temperature of the cooling air. It can be inferred that the lower the temperature of incoming cooling air, the lower would be the temperature of exiting cooled material. This can be expressed by equation (32), which is a linear relationship.

$$T_{ain} \propto T_{fout} \quad (32)$$

The heat removed from the food material (Q_{hrff}) was calculated to be 2.4 kW using equation (33) in conjunction with equations (34) and (35). In order to determine the efficiency of the machine, the analysis results were compared with the actual evaluation results. The cooling factor percentage was then obtained to be 64.48% from equation (36).

$$Q_{hrff} = \dot{m} C_{pf} \Delta T \quad (33)$$

$$\dot{m} = \frac{Weight\ of\ flour}{Time\ of\ travel} = 0.0276\ Kg/s \quad (34)$$

$$\Delta \mathrm{T} = T_{fin} - T_{fout} = 53°\mathrm{C} \quad (35)$$

$$\text{Cooling Factor Percentage} = \frac{T_{fin} - T_{fout}}{T_{fin}} \times 100\% \quad (36)$$

According to Olanrewaju *et al*. [11], the throughput efficiency of the screw conveyor system was calculated using equation (36) as 96.1%, while its thermal efficiency was calculated as 85.3% using equation (37). Hence, it can be inferred (based on the results obtained from its simulation and functional performance) that the screw conveyor system is capable serving its intended primary functions, which are to convey and cool flour in a plant for processing unripe plantain into packaged flour.

$$\text{Throughput Efficiency} = \frac{Output\ weight\ of\ cooled\ flour}{Input\ Weight\ of\ hot\ flour} \times 100 \quad (36)$$

$$\eta_{thsc} = \frac{measure\ temperature\ of\ cooled\ flour}{Cal.\ temp.\ air\ emerging\ from\ chamber} \quad (37)$$

Where: $\dot{m}$ is the mass flow rate of the flour**;** C_{pf} is the specific heat capacity of plantain flour (1.684 kJ/kgK); ΔT is the difference between the inlet and outlet temperatures of the flour; and η_{thsc} is the thermal efficiency of the screw conveyor system.

Table 2. Input parameters and their measurement

Parameter	Initial Value	Final Value
Ambient temperature	28.1 ^{0}C	28.1 ^{0}C
Outlet Air Velocity	8.2 m/s	8.2 m/s
Weight of Flour	4.5 Kg	4.33 Kg
Time of travel		163 sec
Inlet temperature of flour	82.2 ^{0}C	29.2 ^{0}C
Relative Humidity	68.1%	
Moisture content of flour		≤10%
Throughput		144 kg/h
Average Time of Travel of Flour Through the Screw.	-	2.33 min

4. Conclusions

The performance, reliability and service life of any equipment or machine depends, to a large extent, on the care taken in assembling, installing and preparing it for its intended use [12]. While other researchers considered the screw conveyor as a heat exchanger for horizontal applications, in this study, an inclined screw conveyor heat exchanger, that is capable of simultaneously conveying and cooling flour from the pulverizing unit to the packaging unit of a plant that processes unripe plantain into flour has been developed. This study has been able to establish the advantages and use of screw conveyor as a heat exchanger, over other conveyors, when faced with the challenge of inclined simultaneous conveying and cooling/heating of materials during processing. The development was achieved through the application of suitable design analysis principles and manufacturing techniques.

A throughput of 144 kg/h and an efficiency of 96.1% were respectively recorded during its preliminary test. It was observed that the throughput was low because there was no continuous supply of material while conducting the test. A throughput that is as high as the designed throughput can be obtained if material is continuously fed into the screw conveyor. Being an ongoing research, a comprehensive/detail performance evaluation of the conveyor is under consideration, during which it will be evaluated with different food materials in order to establish its capability of handling any pulverized farm produce. Some factors or parameters would also be varied during the evaluation, and their effect(s) would be investigated, documented and reported.

Moreover, it was observed that the material's inlet temperature was 82.2^{o}C while its outlet temperature was 29.2^{o}C. It can be inferred from this observation that the temperature of incoming cooling air is directly proportional to the temperature of outgoing flour or food material under consideration. The quantity of heat thus removed was observed to be 2.4 kW, while the total cost of fabricating the screw conveyor is put at One Thousand Three Hundred and Thirty dollar ($1,330). The components of the costing include; bought out parts at $617; cost of fabricated parts was estimated at $340; and cost of labour plus other variables were computed at $373. This research has been able to establish a basis for the expansion of economic potential associated with the processing of plantain and a pioneering effort in developing more efficient systems for simultaneous conveying and cooling of plantain flour and other similar food materials. It is hoped that this research will be found effective for process theory development or industrial applications.

Future work on this study will be to look at the adaptability and reconfigurability of the design for other agrarian allied flour processing plant.

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