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Design, Construction and Performance Evaluation of a Horizontal Sand Screening and Heating Machine

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ABSTRACT

Quality sand of specific grain sizes and without contagious micro-organism is particularly needed for water bio-filters and other applications. Existing sand screening machines are large, expensive, and do not have capability to improve the quality of sand. The purpose of this work is to develop and evaluate the performance of a portable sand sieving and heating machine. The parts of the machine were designed based on standard equations in the literature. The machine was constructed and tested to evaluate its performance, and then modelled with SOLIDWORKS to determine the temperature distribution and Von-Mises stresses. The machine performed satisfactorily when tested showing a strong correlation between the sieving time and its effectiveness. The maximum Von-Mises stress (16 MN/m^2) is far lower than the yield strength of the used material (250 mN/m^2), indicating that it is unlikely to fail during operation. The maximum simulated temperature in the outer part of the heating chamber was found to be approximately 52°C which is low enough for human safety. Conclusively, the developed portable sand sieving machine has a good strength, operates at a safe temperature, and effective for producing high grade sand void of contagious micro-organism as needed particularly for water filters and other applications.

1. Introduction

There are numerous applications of sand: bricks making, fencing, water purification, paint making, abrasion and glass making. In its original form, sand comes in varying size and certain level of impurities thereby making them not suitable to be used directly from source. Sand screening is, thus, an important process in industries that utilize sand, and is achieved using various sieving techniques [1]. There is a general procedure adopted for sieve designs. According to Gupta and Yan [2], the surface, screen type and screen movement are the three main considerations for sieve designs, and the perforated sieve surfaces are commonly used for sand sieving compared to woven and grizzle types. These perforated sieves are square, circular or rectangular type, and the motion could be either an agitated, rotating or reciprocating motion. Additionally, the size of mesh needs be determined following some basic standards, namely, Tyler, USA, British, German, IP and the ISO standard sieve series which are listed in the literature [3, 4, 5]. Furthermore, several factors can affect the sieving efficiency. Whereas some factors are vital at the design stage, others may be considered during the sieve operation. Duration of sieving, for example, can affect the efficiency during operation because the more time spent on the screen machine, the more efficiently it would have separated the constituent [6, 7]. One factor that can be considered at design stage is the method of sieve, as the stack method, for instance, in which several screen sizes are mounted to separate sand into different sizes, has been found to be the best technique [8]. Additionally, the particle collision and vibration parameters which can also be altered at the design stage have been found to affect sieving efficiency [9]. Finally, screen blocking that can negatively affect sieve efficiency, can better be tackled using vibratory machines compared to rotary and drum types [10].

Notwithstanding, there are a number of sieving machines developed for various applications in recent time. Nwigbo et al. [11], developed a manually operated stacked sieve that can work without any power source. Moreso, there are some multi-staged sieving machines that were developed recently. There are the two-staged sieving machines: the "cam and follower" two-staged screen in which a prime mover is used to induce vibration for its sieving objective [12], and the two-level screen machine [13]. Also, there is the 4-stage vibration sieve applied to separate different sizes of shredded thermoplastics composites by Vincent et al., [14], and a three stack design developed by Alis et al., [15]. Some other recent sieve types are multi-purpose machine that combines other function to sieving with the same machine. A few examples are, the "mixing and sieving machine" [16] and the "slurring and sieving" [17]. Simolowo, [18] demonstrates that an entire production process that includes sieving can be improved when the machines are combined.

This work aims to develop a sand drying and sieving machine with intention to improve on existing designs of sieving machines and also solving the various challenges faced by previous designs especially in the area of sieving wet sand or sand with some form of moisture content. It is envisaged that heating sieved sand can improve its lustrous properties and destroy unwanted micro-organisms. Also, heat-drying sand before sieving can greatly reduce sieving time and improve sieve efficiency since sand particles will not bind together, thus, moving more freely relative to each other [19].

2.0 Methodology

In designing the sand sieving and drying machine, various factors (strength, reliability, weight, cost, material availability and maintenance) were put into consideration in the overall design of the machine.

2.1 Design concept

The sieving and drying machine consist of the following parts; the hopper, sieve tray, connecting rod/link, the crank arm, roller bearings, drying compartment, mesh and the frame. The hopper which is also called the feeder hopper is a conical shaped component through which the sand is fed into the system. As the sand is fed in, it gets to the sliding tray on which the mesh is installed. The sliding tray is connected to a motor via a mechanical link (connecting rod and crank arm) thereby producing a reciprocating motion that allows for the sieving process. However, during the sieving process, the heating compartment which is made up of an electric heater and is positioned just below the sieving trays, heats up the sand on the tray to remove any moisture present in the sand thereby loosening the sand further for proper separation to occur. The sieved sand enter into the heating chamber where the sand is further heated and stirred simultaneously to kill unwanted micro-organisms. The frame is made of mild steel and acts as a support for all component of the design.

2.2 Design Calculation

Appropriate machine design principles for the design of the sand sieving and drying machine were adopted from standard mechanical engineering materials [20].

2.2.1. Crank mechanism

The slider crank mechanism is an assemblage that is interconnected to manage forces and transmit motion. It converts the rotational motion of the electric motor to the reciprocating motion. It utilizes four links connected to each other by four (4) joints as shown in Figures 2a and 2b.

In calculating the Degree of freedom (DoF) of the mechanism, the force and speed of motion transmitted were considered. Equation 1, the Grubler's criterion is employed for a two (2) bar linkage system [21].

$$DOF = 3(n-1) - 2j \quad (1)$$

$$DOF = 3(4-1) - 2(4)$$

$$DOF = 9 - 8 = 1$$

From Eq. 1 therefore, the degree of the mechanical linkage system of this machine is 1. where n and j are numbers of links (4) and numbers of lower pair or joints (4) respectively.

2.2.2 The stroke length of the connecting rod

The stroke length is the distance travelled by the tray in a revolution of the crank and it is obtained from Eq. 2, [21].

$$S = L_e - L_f \quad (2)$$

where S, L_e and L_f are the stroke length, length of extended dead center position and length of folded dead center position respectively. As shown in Figures (2a) and (2b), L_e and L_f are 259 mm and 142 mm respectively. Therefore, from Eq. 2,

S = 259 – 142 = 117 mm

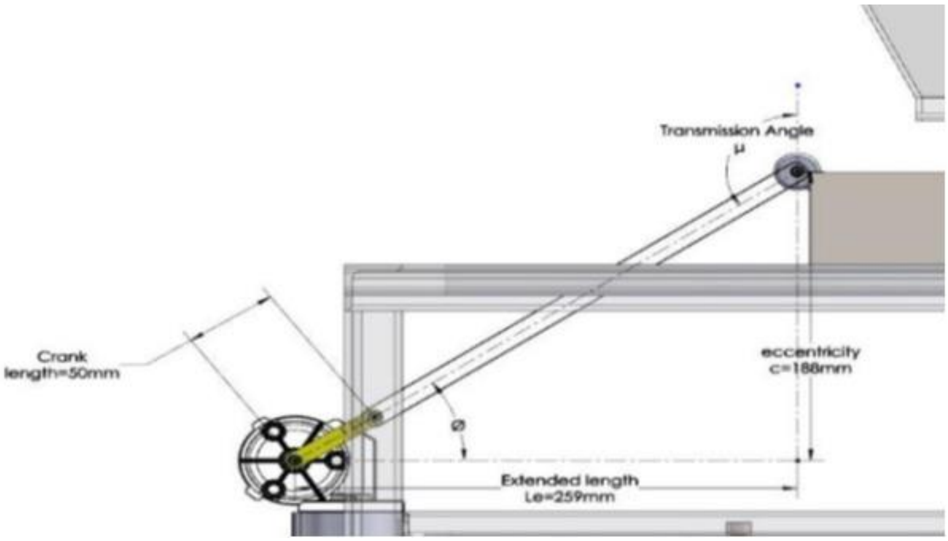


Figure 2a: An extended dead center position of the connecting rod

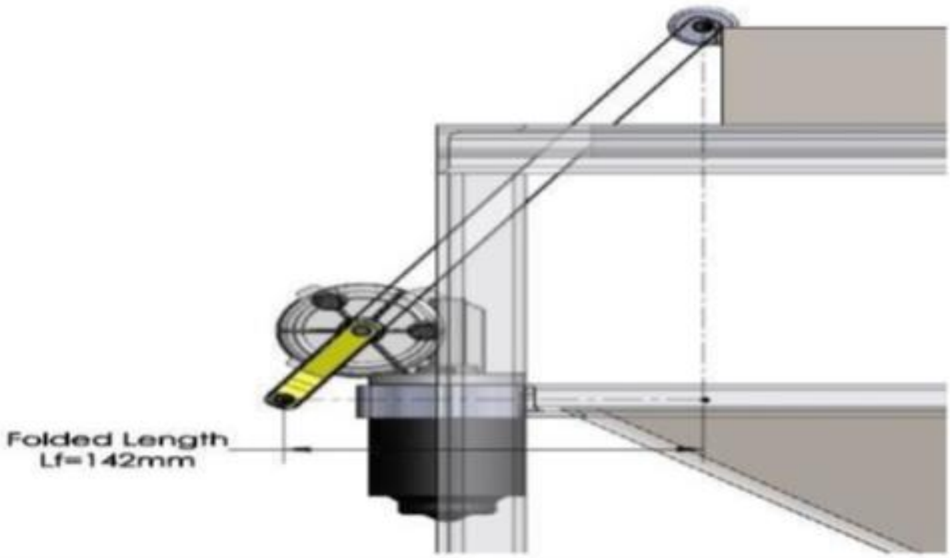


Figure 2b: The folded Dead center position with the connecting rod

2.2.3 Length of the connecting rod

The connecting rod length (L_c) of the machine can be determined from Eq. 3 and 4 [21]. Where L_e is length of extended dead center position (259 mm), L_r is crank length (50 mm) and c is eccentricity (188 mm) as shown in Figures 2a and 2b.

$$(L_c + L_r)^2 = {L_e}^2 + c^2 \quad (3)$$

$$L_c = \sqrt{L_e^2 + c^2} - L_r \quad (4)$$

$$L_c = \sqrt{259^2 + 188^2} - 50$$

$$L_c = 270.0391\, mm \ \approx 270\, mm$$

2.2.4 Sieve tray

Two sieve trays of mesh sizes 2mm and 3.35 mm, US sieve number 10 and 6 respectively, were first constructed using mild steel metal sheet purchased locally. The tray was a square shape of 40 mm side. The sieve tray area is thus calculated from Eq. 4.

$$Area\ (A) = length\ (L) * breadth\ (b) \quad (4)$$

$$A = 40 * 40 = 1600\, mm^2$$

where l and b are length (40 mm) and Breadth (40 mm), respectively.

2.2.5 Hopper design

In the design of the hopper, consideration was given to the mass of sand to be sieved, size of sliding tray and mesh, and density of sand. Thus, a 2 mm thick mild steel sheet was selected for use in the designing of the hoppers.

The volume of the hopper (V_o) is derived by employing Eq. 5 [22].

$$V_o = \frac{H_o}{3}\left[\frac{D^2B - D_d^2B_d}{D - D_d}\right] \quad (5)$$

where H_o is the height of the hopper, D = B (200 mm) top side of the hopper, and $D_d = B_d$ (0.044 m) base of feeder hopper

Computing for the hopper height (H_o) using concise assumptions and principles as obtained from Greg et al. [22], and as shown in Eq. 6.

$$H_o = \frac{D/2}{\tan\theta} \quad (6)$$

where D (200 mm) is inlet length, θ (30°) is the end angle taken and H_o is the height of the feeder hopper.

$$H_o = 0.173\ m$$

Therefore, the volume of hopper is obtained using Eq. 5 as follows:

$$V_o = \frac{0.173}{3}[0.2^2 * 0.2 - 0.044^2 * 0.44]/(0.2 - 0.44)$$

$$V_o = 0.00292\ m^3$$

2.2.6 Frame

A mild steel 50.8 mm angle bar was selected for the design of the frame and stand of the machine. The frame was constructed to support and withstand static and operational loads produced by all components of the design.

$$Area\ (A) = length\ (l) * breadth\ (b) \quad (7)$$

The area of frame was calculated using Eq. 7, where the length of the frame is 640 mm and breadth is 440 mm. Therefore, the area of the frame is obtained as follows:

$$A = 640 * 440 = 281600\ mm^2$$

2.2.7 Speed and power of the sieve motor

In calculating the speed of the sieve motor, Eq. 8 derived in the literature [20] was employed;

$$V_s = \omega r$$

Where V_s is the speed of the sieve motor, ω is angular velocity (2π rad/s) and r is radius of the motor shaft (0.119 m).

$$V_s = 2 * 3.142 * 0.119$$

$$V_s = 0.747\ m/s$$

The minimum power of the sieve motor can be calculated from Eq. 9 and 10, [20], where P, F_s, V_s, M and α are power of sieve motor, motor force, motor speed, mass of sand (4.67 kg) and centripetal acceleration of the motor, respectively.

$$P = F_s * V_s \quad (9)$$

$$F_s = m * a \quad (10a)$$

$$a = \frac{V_s^2}{r} \quad (10b)$$

$$a = \frac{0.747^2}{0.119} = 4.689\ m/s^2$$

Therefore, $F_s = 4.67 * 4.689 = 21.89\ N$

Using Eq. 9 therefore, the minimum power Ps of the motor can be calculated as

$$P_s = 21.89 * 0.747 = 16.36\ watt$$

As a result, a motor of 50 watt power capacity was thus selected for the work, providing a factor of safety of 3.05.

2.2.8 Static analysis of the frame

Due to availability and ease of use, SolidWorks software was used to analyze the static stress of the entire frame. ASTM A36 Mild Steel, which was used for the body of the machine, was selected for the analysis. A mesh model was generated with maximum aspect ratio of 341.9. A total of 44669 solid triangular elements was generated and used for the analysis as shown in Figure (3).

Figure 3: Mesh model of the frame structure of the sand sieving and heating machine

The total volume of sand at maximum capacity for the hopper and heating chamber determined in sections 2.2.5 and 2.2.9, respectively, were used to calculate the weight of sand by multiplying the volume with density and gravitational acceleration. Detachable components viz: electric motor, mesh, sieve tray and connecting rods were measured using a weighing scale. Thus, the weight of hopper used for the analysis was 41.306N, heating compartment: 26.196N, sieve motor: 10.104N, sieve tray: 3.237N, mesh: 0.981N, and connecting rod: 2.256N.

2.2.9 Thermal analysis of the heating compartment

The heating chamber is a 210mm x 230mm x 195mm compartment. It is made up of double wall Mild steel material with a lagging material (Rockwool) in-built for heat loss prevention. Considering that the recommended temperature for the complete destruction of micro-organism is 100^{o} Celsius [23], the heating time per batch of sieved sand was estimated using Eq. 11 which is derived in the literature [24].

$$M * C * \Delta T = P * t \quad (11)$$

Where M is the mass of sand to be stirred inside the combustion chamber, C is the specific heat capacity of sand (840 J/kgK), and ΔT is the difference in final temperature to be attained (100^{o}) and the initial temperature of sand to be heated (ambient temperature = 25^{o}), P is the power of heater (5000 watts for available sizable heating element) and t is the total heating time per batch of sand to be determined with Eq. 11.

Mass of sand in chamber equal to the product of the chamber volume and the density of sand.

$$Chamber\ volume = 0.21 * 0.195 * 0.23 = 0.009419\ m^3$$

$$Density\ of\ sand = 1442\ kg/m^3$$

$$So\ maximum\ mass\ of\ sand\ inside\ chamber = 1442 * 0.0483 = 13.58\ kg$$

Then the steady state thermal analysis of the machine was investigated with SOLIDWORKS to ascertain the temperature distribution around the outer parts of the machine. The modelled machine was meshed with solid triangular element with a minimum and maximum aspect ratio of 1.129 and 1749.2, respectively. A total of 26255 mesh element and 55059 nodes were formed. Figure 4 shows the meshed model for the steady state thermal analysis of the machine. Emissivity of the frame and drying compartment were taken as 0.4, while that of the lagging material was 0.9. A maximum heater temperature of 160^{o}C was used. This value corresponds to the internal temperature calculated for an estimated heating time of 5 minutes, using Eq. 11. 5 minutes was chosen to allow for human errors, should the machine be allowed to continue heating beyond the prescribed 3 minutes, with the assumption that maximum quantity of heat generated would be transmitted to the stirred sand.

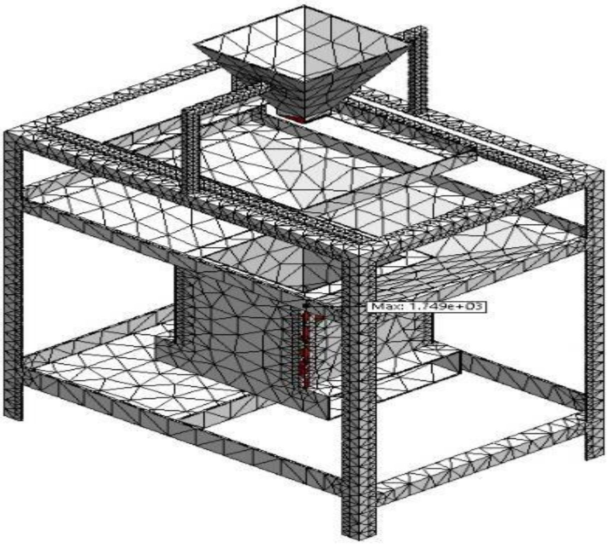
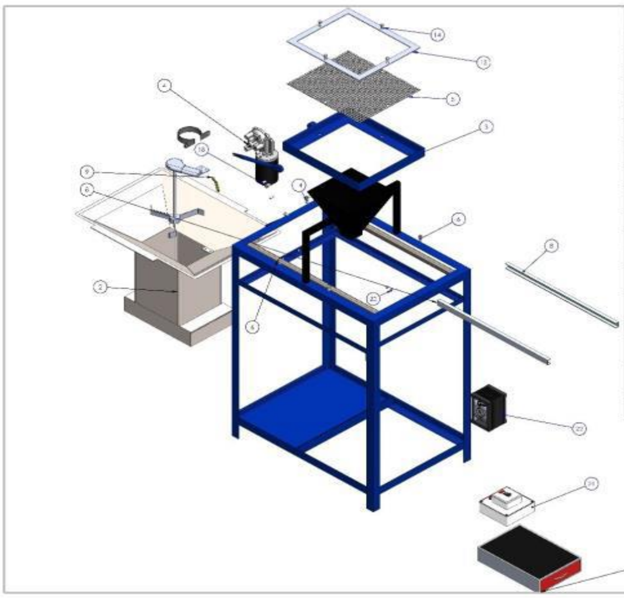


Figure 4: Mesh model for thermal analysis of the sand sieving and drying machine

3.0 Results and Discussion

An exploded view of the sand sieving and drying machine with all its parts indicated is shown in Figure 5 while Figure 6 shows the isometric view of the design.



ITEM NO.	PART NUMBER	QTY.
1	Frame	1
2	Stiring and Drying Unit	1
3	Seive	1
4	Drive Motor	1
5	mesh	1
6	ISO 4762 M8 x 12 - 12N	4
7	Heater	1
8	Slider	2
9	Crank arm	1
10	Link/connecting rod	1
11	motor clip	1
12	Stirer unit	1
13	AM -- M6 x 16 N	1
14	B18.6.7M - M6 x 1.0 x 10 Indented HHMS --10N	6
15	Mesh Guide	1
16	B18.6.7M - M6 x 1.0 x 40 Indented HFMS --40N	1
17	B18.2.4.5M - Hex jam nut, M6 x 1 --D-N	1
18	pin	1
19	B18.6.7M - M8 x 1.25 x 10 Indented HHMS --10N	1
20	B18.6.7M - M4 x 0.7 x 5 Indented HHMS --5N	2
21	Contol Box	1
22	transformer	1

Figure 5: An exploded view of the sand sieving and drying machine

Figure 6: An isometric view of the sand sieving and drying machine

3.1 Performance evaluation of the design

At loading condition, the machine was tested with different weights of sand (1.89 kg, 3.71 kg, 5.67 kg, 7.26 kg and 8.7 kg) which was fed through the hopper and onto the sieving tray. The avearage time of 4 trials that it took the machine to sieve each portion of the sand fed into it was recorded as shown in Table 1.

Table 1: Results of the test carried out.

S/N	$\mathbf{M_b}$ (kg)	$\mathbf{M_o}$ (kg)	$\mathbf{M_i}$ (kg) ($\mathbf{M_o - M_b}$)	$\mathbf{M_r}$ (kg)	$\mathbf{M_s}$ (kg) $\mathbf{M_i - M_r}$	Average $\mathbf{T_r}$ (
1	0.14	1.89	1.75	0.20	1.55	1.89
2	0.14	3.71	3.57	0.30	3.37	4.51
3	0.14	5.67	5.51	0.37	5.12	6.57
4	0.14	7.26	7.12	0.45	6.67	8.81
5	0.14	8.70	8.56	0.52	8.04	10.68

where M_o, M_b, M_i, M_s, M_r and T_f are original mass of sand, mass of bucket, mass of sand before sieving, mass of sand after sieving, mass of sand (impurities) remaining on sieve and time taken to sieve respectively.

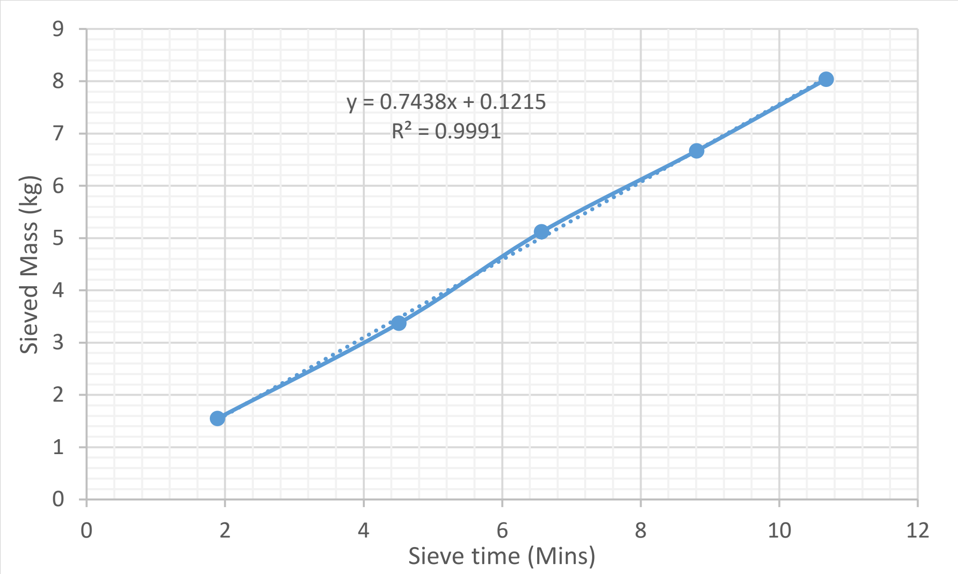


Figure 8: Mass of sieved sand against time of filtration

As observed, the average time of sieve and mass of remnant increased with the quantity of sand sieved. This is expected, as previous works reported a similar trend [6, 7]. There is a linear relationship between sieve time (Tr) and the quantity of sieved sand (Ms), having R-square value of 0.9991 when modelled with a linear equation as shown in Figure 8. Thus, the machine has a constant sieve rate of about 0.7438 which is the slope of the model. More so, it was observed that the more the weight of sand the higher the impurities left after filtration. Overall, an average of 0.42kg of impurities was recorded from the five (5) different samples of sand filtered.

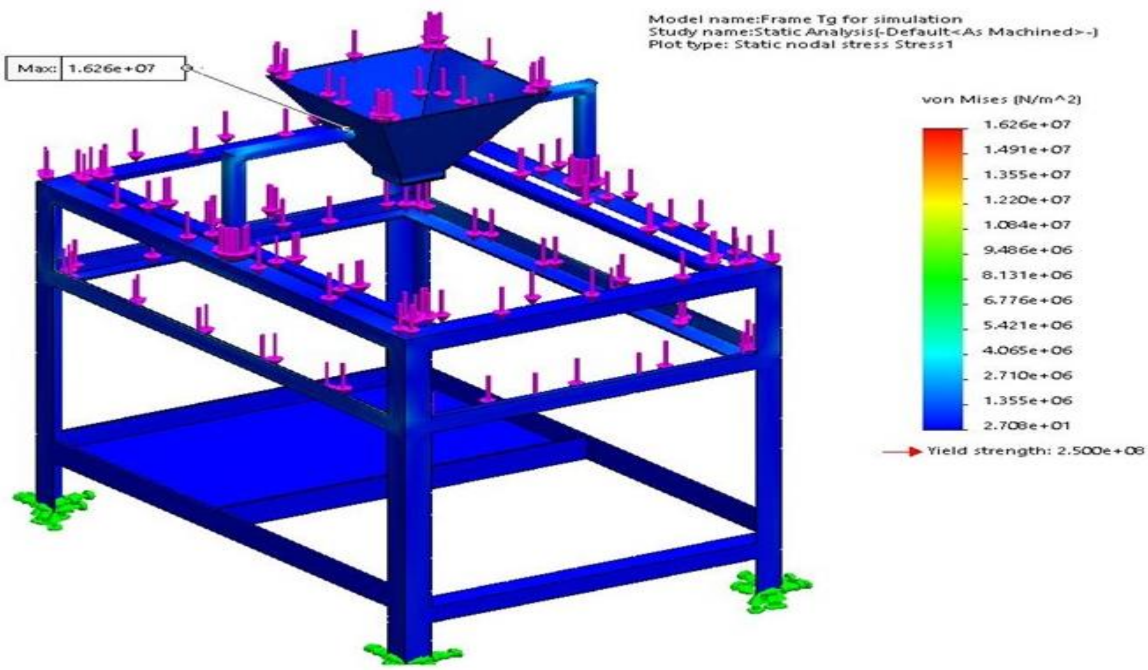


Figure 9: Simulation for static modal stress distribution

The Von-Mises stress distribution on the machine obtained from statics structural analysis using SolidWorks is shown in Figure 9. The value of Von-Mises stress is highest in the handle that carries the hopper, indicating that it is the position that is mostly stressed in the machine and can be considered to be the most critical point. The frame is the least stressed part of the machine, showing blue coloration which has the least Von-Mises stress values on the color plot. This is so because the load the frame bears are uniformly distributed around its members. However, the maximum Von-Misses stress (16.26 MPa) is less than the yield stress of the material which is 250 MPa, implying that the machine is not likely to undergo structural failure as discussed in the literature [25].

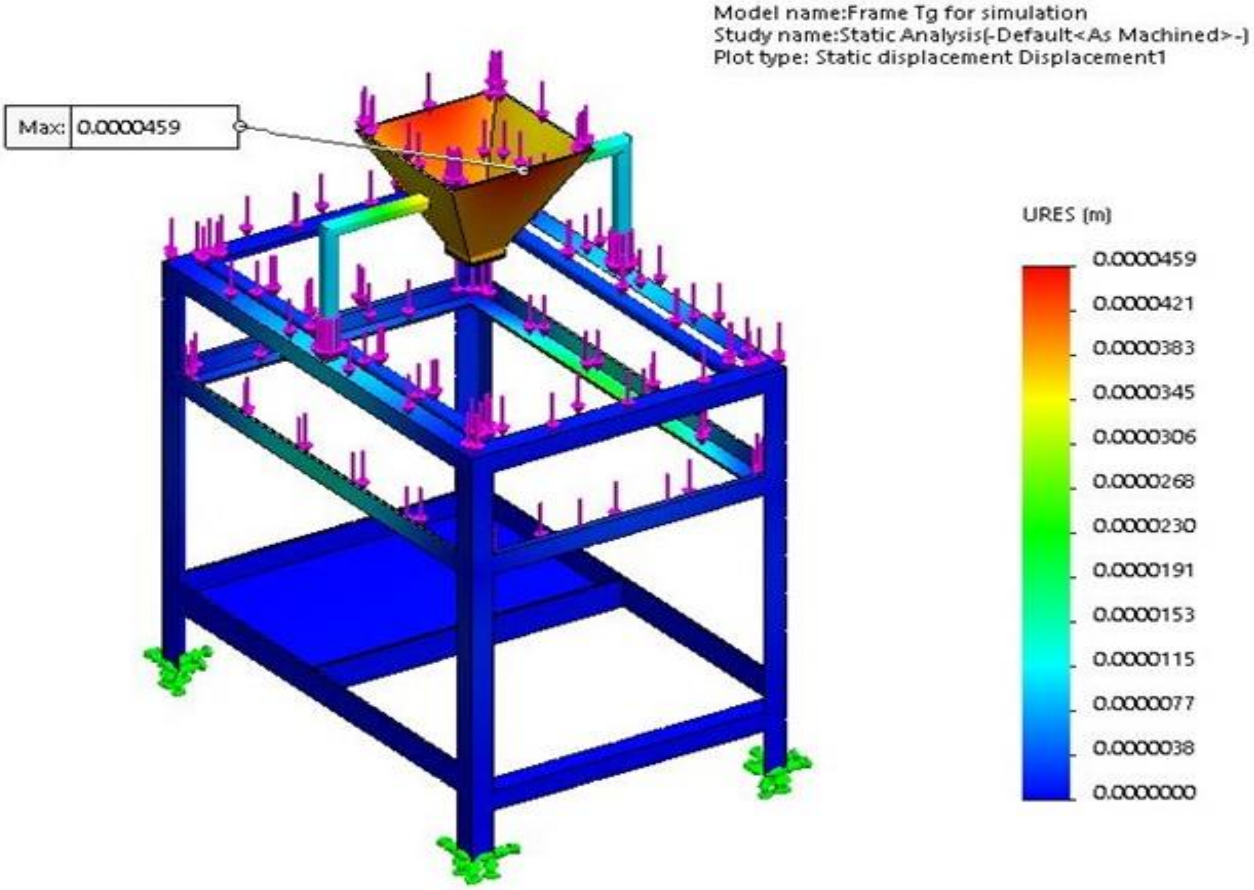


Figure 10: Simulation for static displacement

The displacements obtained via the static structural analysis with SolidWorks is shown in Figure 10. Although there is not much one can deduce from the obtained distribution of displacements, the maximum displacements (0.000459mm) which is significantly low informs that the structural deformations would not likely affect the operation of the machine. Hence, the system can operate and withstand the maximum load working condition without yielding and significant vibration. The hopper has the highest displacements as can be observed. This is due to the large mass it may contain during the operation of the machine. The side frame also has significantly high displacement, as it bears the load of the sieve tray.

Figure 11 shows the temperature distribution of the sand sieving and heating machine obtained from the SolidWorks steady state thermal modelling of the machine. As observed, the temperature of the frame is close to the ambient temperature used for the simulation (25^{o}C), so the frame remains safe enough for handling during operation of the device. The maximum temperature of the heating chamber was found to be greater than 100° Celsius which is high enough to destroy unwanted micro-organisms that may be found in sieved sand (World health Organization, 2015). External temperature in the heating chamber region is shown to be high (greater than 100°), and as thus, not safe enough for touch during operation. It is important that the machine be heated not more than 3 minutes heating time to avoid excessive rise in temperature, as the difference in external and internal temperature of the heating chamber is not sufficient for human safety.

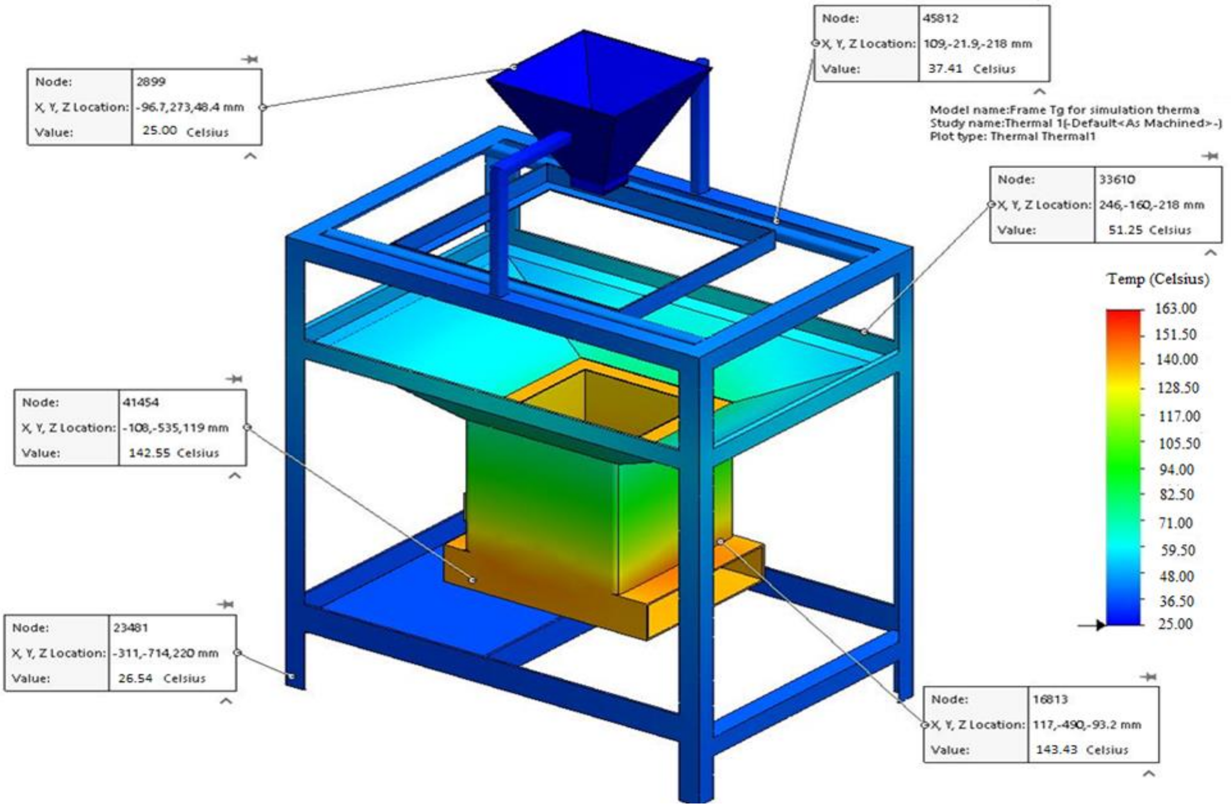


Figure 11: Simulation result for steady state heat transfer analysis of the sand sieving and heating machine

4.0 Conclusion

Conclusively, the sand sieving and drying machine was fabricated and operated successfully and was able to produce fine and dry sand with negligible vibrations. The design incorporated components like the sieve tray, the hopper, connecting rods, sieve motor, and the drying compartment to achieve its set objectives. It is capable of sieving sand at a rate of 0.7438, and the heating temperature of about 100° Celsius can be obtained within 3 minutes of heating. The machine at full capacity is capable of producing approximately 8kg of pure and dry sand under 11 minutes. Finally, the fabricated machine is safe, easy to operate and can be used to produce non-contagious sand of desired specifications.

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