

Design and Development of an Industrial Centrifuge for Small and Medium Scaled Industries

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Abstract
A centrifuge for separating industrial mixtures was designed, developed and evaluated. The major components of the centrifuge include: an electric motor, a rigid frame, rotating wheel, three sedimentation vessels and a centrally mounted shaft. Stress analysis of the centrifuge wheel, which is the major load carrying member of the machine was done using Solidworks SimulationXpress and a factor of safety of 5.12815 was obtained for an estimated load of 331.5N. The centrifuge was designed to withstand vibration caused by the rotating masses and fabricated using locally sourced standard materials. Performance test analysis gave a specific energy consumption and optimal separation time of 206.5KJ/Kg and 30 minutes respectively. Thus, the centrifuge constitute a veritable option for production of pure and quality industrial products in small and medium scaled industries.
Keywords: Centrifuge, Stress analysis, Specific energy consumption, Optimal separation time

1. Introduction

A centrifuge is a piece of equipment that puts an object in rotation around a fixed axis (spins it in a circle), applying a potentially strong force perpendicular to the axis of spin (outward). The centrifuge works using the sedimentation principle, where the centripetal acceleration causes denser substances and particles to move outward in the radial direction. At the same time, objects that are less dense are displaced and move to the center. Hence, a centrifuge uses centrifugal force to separate two or more substances of different densities or masses from each other (Susan et al, 2004).

Effective separation of mixtures is a common challenge experienced in many industrial processes. These mixtures could be two immiscible liquids or solid suspension in liquid. The oldest and easiest way of separating such mixture is by allowing it to settle into two distinct layers with the denser liquid/solid at the bottom while the lighter liquid stays on top (sedimentation) before decanting. Unfortunately, this sedimentation process for most mixtures is time consuming (consuming several hours and in some cases, may run into days) causing a consequent stagnation in production. To achieve continuous production for such systems and reduce overall production time, there is need for a faster means of separating such mixtures.

Centrifuges achieve separation by means of accelerated gravitational force achieved by a rapid rotation (Salim et al, 2013). This replaces the normal gravitational force required for settling. Hence, sedimentation can be achieved in less time by replacing the sedimentation tank/vessel with a centrifuge.

Centrifuges are used in a variety of medical and industrial applications (Piero, 1997). There are 4 basic types of centrifuges designed for different applications: Industrial scale centrifuges, very high speed centrifuges (ultracentrifuges), large centrifuges and gas centrifuges.

Although different centrifuge designs and capacities are already in existence, most of these centrifuges are complex to operate and costly to maintain by small and medium scale producers, especially in developing countries. Hence, the need to develop a simple and cost effective centrifuge for small and medium scaled industries using locally sourced materials.

1.1 Objectives and Scope of Study

Specific objectives of this study are;

i. To design and fabricate a centrifuge for separating industrial mixtures using locally sourced materials.
ii. Performance evaluation of the centrifuge.

1.2 Justification

Development of the centrifuge will reduce the time consumed by process industries in production of chemical products, as well as improve the quality and homogeneity of chemical products. This will also provide employment for the populace and increase the external trade potential of Nigeria, as pure substances especially liquids can easily be produced in industries

2. Design Analysis and Specifications of the Centrifuge

2.1 Design Concepts and Considerations

The design, material selection and development of the centrifuge were based on the following concepts and considerations:

i. 80mm thick mild steel U-channel was used to fabricate the centrifuge frame in order to withstand vibrations that may arise from its operation.
ii. Three 10 liter aspirator bottles balanced symmetrically on the rotating disc of the centrifuge were used as the centrifuge vessel. These vessels were inclined at 45^0 for faster sedimentation.
iii. The design of the centrifuge shaft was based on stiffness and rigidity instead of the more conventional design for strength because vibration of the centrifuge will be very hazardous.

2.2 Selection of Pulleys and Belt

Two mild steel pulleys of diameters 159mm and 115mm respectively were used for the centrifuge power transmission. These diameters were obtained using Equation (1) (Khurmi and Gupta, 2005; Sharma and Aggarwal, 2006).

$$\frac{N_2}{N_1} = \frac{d_1}{d_2} \quad (1)$$

Where:

N_1 = Speed of the driving pulley in r.p.m
N_2 = speed of the driven pulley in r.p.m
d_1 = diameter of the driving pulley
d_2 = diameter of the driven pulley
The design center distance between the two pulleys was calculated as 146.7mm using Equation (2)

$$c = \frac{1.5D_2}{(VR)^{1/3}} \quad (2)$$

The minimum length of the belt required to transmit motion between the two pulleys was obtained as 726.9mm using Equation (3) (Khurmi and Gupta, 2005; Sharma and Aggarwal, 2006).

$$L = 2C + 1.57(D_2 + D_1) + \frac{(D_2 - D_1)^2}{4C} \quad (3)$$

By assumption, the power transmitted by the drive should exceed 3.75KW. Hence, a "type B" V-belt with standard pitch length of 747mm (IS: 2494 – 1974 standard) was selected. The actual center distance between the two pulleys was then obtained as 146.5mm using Equations (4), (5) and (6) (Khurmi and Gupta, 2005; Sharma and Aggarwal, 2006).

$$C = p + \sqrt{p^2 - q} \quad (4)$$

$$p = \frac{L}{4} - \frac{\pi}{8}(D_2 + D_1) \quad (5)$$

$$q = \frac{(D_2 - D_1)^2}{8} \quad (6)$$

Coefficient of friction μ between the pulley and the belt, maximum safe stress σ, cross sectional area 'a' and weight per meter length of the belt were also determined from standard tables (IS: 2494 – 1974 standard) as 0.3, $2.1N/mm^2$, $81mm^2$ and 1.06N respectively (Khurmi and Gupta, 2005; Sharma and Aggarwal, 2006). Pulleys with groove angle (2β) of 38^0 were selected for the drive due to its availability and cost effectiveness. The angle of contact of the driven pulley Θ is 167^0 as shown in Equation (7)

$$\theta = 180 - 2\left[sin^{-1}\left(\frac{D_2 - D_1}{2C}\right)\right] \quad \textbf{(7)}$$

Tensions in tight and slack sides of the belt (T_1 and T_2) were determined as 162.13N and 8.967N respectively using Equations (8) to (12) (Burr and Cheathan, 2002, Khurmi and Gupta, 2005; Sharma and Aggarwal, 2006).

$$T_1 = T_{max} - T_c \quad \textbf{(8)}$$

$$T_{max} = \sigma \times a \quad \textbf{(9)}$$

$$T_c = mv^2 \quad \textbf{(10)}$$

$$\frac{T_1}{T_2} = e^{\mu e \theta} \quad \textbf{(11)}$$

$$\mu e = \frac{\mu}{sin^{\beta}/_2} \quad \textbf{(12)}$$

Where:
T_{max} = maximum tension on the belt
T_c = centrifugal tension on the belt

2.3 *Shaft Design*

The centrifuge shaft was designed on the basis of rigidity and stiffness because vibration of the shaft would be hazardous. The diameter of the shaft (d) was determined as 36.5mm using Equation (13) – (15) (Khurmi and Gupta, 2005; Sharma and Aggarwal, 2006). This shows a higher value when compared to the value for "d" obtained as 29.3mm from the combined bending and twisting moment equation which is used while designing for strength. Hence a standard 40mm diameter shaft was used for the drive.

$$d = \left(\frac{32J}{\pi}\right)^{\frac{1}{4}} \quad (13)$$

Where:
J = polar moment of inertia of the cross-sectional area about the axis of rotation
J can be obtained using the torsion equation;

$$J = \frac{TL}{G\theta} \quad (14)$$

$$T = \frac{P \times 60}{2\pi N} \quad \mathbf{(15)}$$

Where:

L = length of shaft = 2763mm
G = modulus of rigidity for the shaft material = 77.2GPa
Θ = torsional deflection or angle of twist in radians

The torsional deflection is limited to 0.25^0 per meter length (Khurmi and Gupta, 2005; Sharma and Aggarwal, 2006).

The stiffness S_S was also determined as $7.02 \times 10^6 N/mm$ using Equation (16)

$$S_S = \frac{G}{L} \times \frac{\pi}{32} \times \square^4 \quad (16)$$

2.4 *Selection of Prime Mover (Electric Motor)*

The power (p) required to drive the centrifuge was determined as 3.728kw (≈5hp) using Equation (17) (Khurmi and Gupta, 2005; Sharma and Aggarwal, 2006).

$$p = \frac{(T_1 - T_2)v}{1000}, kw \quad (17)$$

2.5 *Description of the Developed Centrifuge*

The developed centrifuge is shown in Figure 1. It is divided into three major parts: the stationary part, the rotating part and the prime mover.

The stationary part consists of the centrifuge frame and two bearing housings. The centrifuge frame is a welded section constructed from 80mm×80mm×8mm mild steel U-channel, with 8 holes of diameter 10mm each drilled around its axis (4 holes on top and 4 directly below) for bolting the two bearing housings. Every other part of the centrifuge, both stationary and rotating is mounted on the frame.

The rotating parts of the centrifuge include: wheel, sedimentation vessels, shaft, pulleys and bearings. The wheel is a circular mild steel sheet of diameter 950mm and 5mm thickness with three tangential holes of diameter 210mm arrayed symmetrically round its axis. Mild steel sheet of 3mm thickness was used to form "semi-cylinder" and welded to the inner half of each hole at an angle of 45^0 towards the center. This arrangement holds the sedimentation vessel firmly and rigidly as the centrifuge rotates at high speed. Provision for mounting the centrifuge shaft was made by drilling a hole of diameter 40mm in the center of the wheel. The centrifuge shaft is a 40mm diameter solid stainless steel shaft of 1020mm length, mounted vertically on two roller bearings (1000mm apart). A 5mm diameter steel rod was welded round the shaft at a distance of 155mm from the bottom, to support the wheel. Three aspirator bottles where used as sedimentation vessels because of its lightweight, transparent appearance and high fatigue strength. Cast iron pulleys with groove angle of 38^0 were used to transfer motion from the prime mover to the shaft through a flat belt drive.

The prime mover is an electric motor whose power rating was derived in previous section to be 5hp. After centrifugation, the glycerol which settles at the bottom of the sedimentation vessel is run off while the methyl ester (biodiesel) is pumped into an evaporation tank.

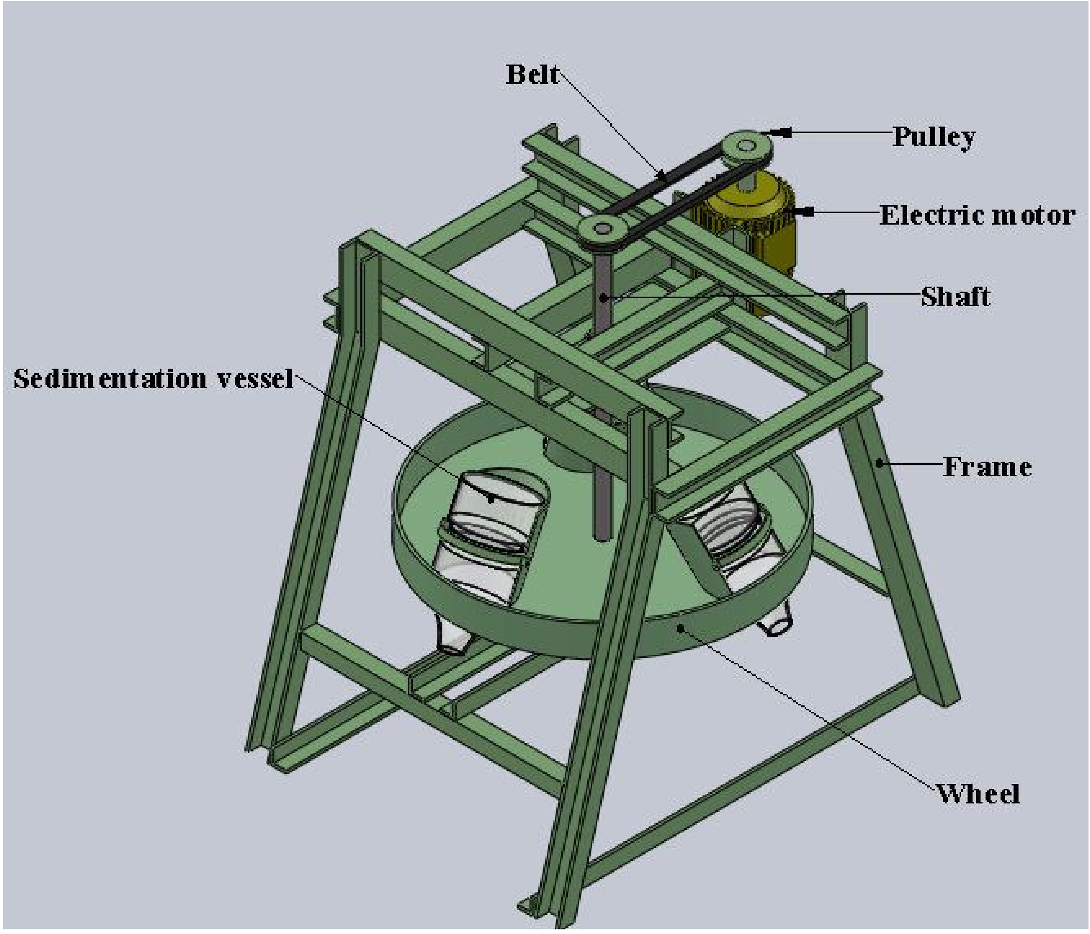

Figure 1: The Centrifuge

2.6 Stress Analysis of the Centrifuge Wheel

Stress analysis was done on the designed rotating wheel of the centrifuge using "SolidWorks SimulationXpress" to determine its factor of safety (FOS). Factor of safety is a term describing the structural capacity of a system beyond the expected loads or actual loads. Essentially, how much stronger the system is than it actually needs to be for an intended load. FOS is usually calculated using detailed analysis because comprehensive testing is impractical on many projects. Figure 2 shows the procedure followed in performing the stress analysis of the centrifuge wheel using Solidworks SimulationXpress.

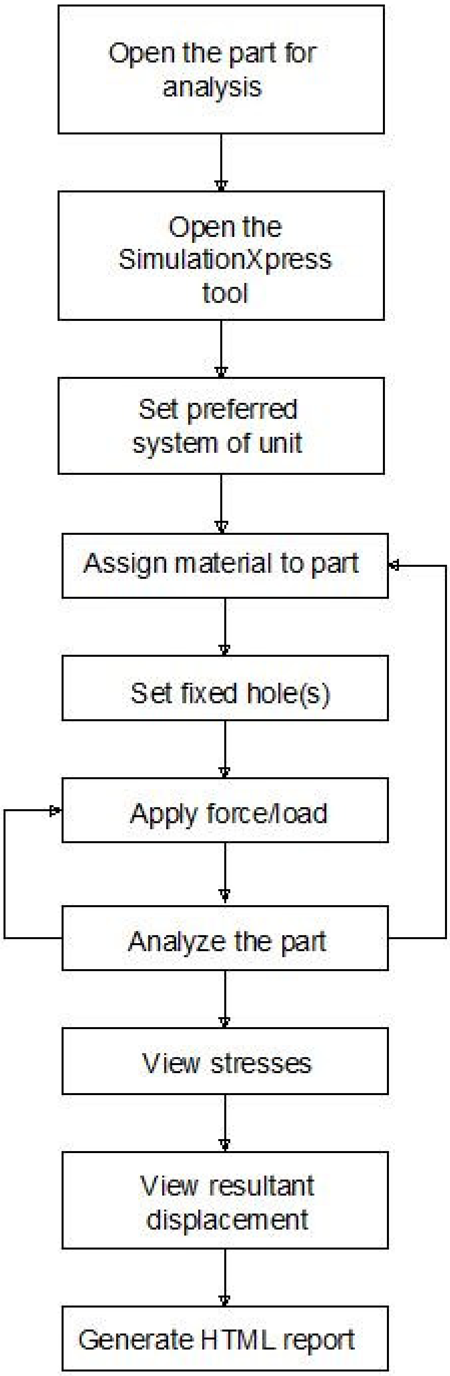

Figure 2: Solidworks SimulationXpress Flow Chart

Components whose failure could result in substantial financial loss, serious injuries, or death may use FOS of four or higher (up to ten). Non-critical components generally might have FOS of two, automobiles use 3.0 and aircrafts use 1.2 to 3.0. The program uses the maximum von Mises stress criterion to calculate the factors of safety. This criterion states that a ductile material starts to yield when the equivalent stress (von Mises stress) reaches the yield strength of the material. The yield strength (SIGYLD) is a material property which is defined as stress at which a material begins to deform plastically. SimulationXpress calculates the factor of safety at a point by dividing the yield strength by the equivalent stress at that point. A factor of safety less than 1.0 at a location indicates that the material at that location has yielded and that the design is not safe. A factor of safety of 1.0 at a location indicates that the material at that location has just started to yield. A factor of safety larger than 1.0 at a location indicates that the material at that location has not yielded. The material at a location will start to yield if you apply new loads equal to the current loads multiplied by the resulting factor of safety.

When loads are applied to a body, the body tries to absorb its effects by developing internal forces that, in general, vary from one point to another. The intensity of these internal forces is called stress. The units of stress are force per unit area. In SimulationXpress, a stress quantity called the equivalent (or von Mises) stress is viewed. While the equivalent stress at a point does not uniquely define the state of stress at that point, it provides adequate information to assess the safety of the design for many ductile materials. Unlike stress components, the equivalent stress has no direction.

The analysis gave a factor of safety (FOS) value of 5.12815 (Figure 3) for an estimated load of 331.5N, determined by adding the weights of the three sedimentation vessels and the weight of the liquid they contain.

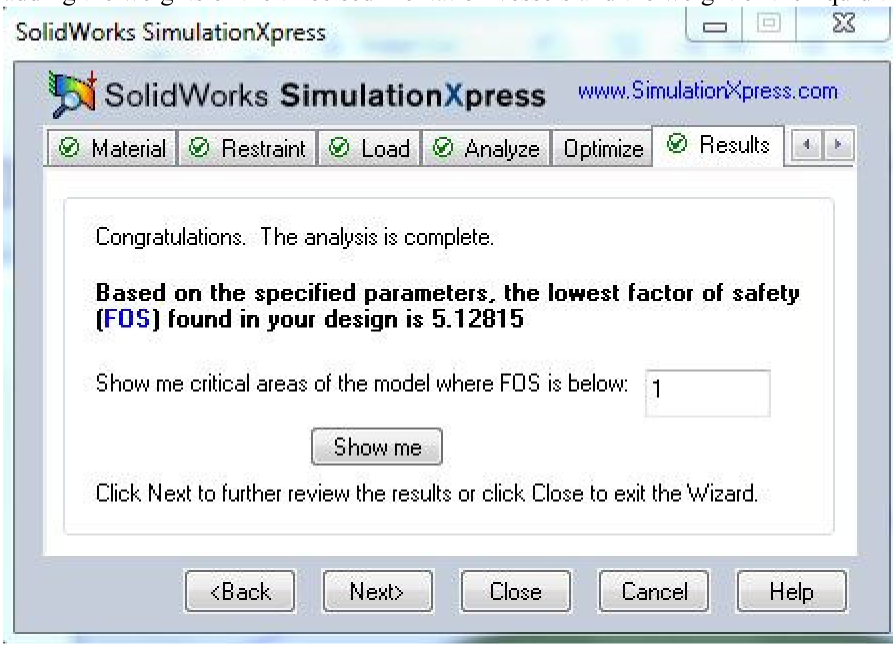

Figure 3: Design Factor of Safety for the centrifuge wheel

The result of the nodal stress analysis is shown in Figures 4 and 5. Figure 4 is the nodal stress plot, which shows the stress distribution on the component for a FOS with value less than 1. Regions with maximum stress concentration are shown in red while regions with minimum stress concentration are shown in blue. Figure 5 is the static displacement plot showing regions of maximum displacement (red) and regions of minimum displacement (blue).

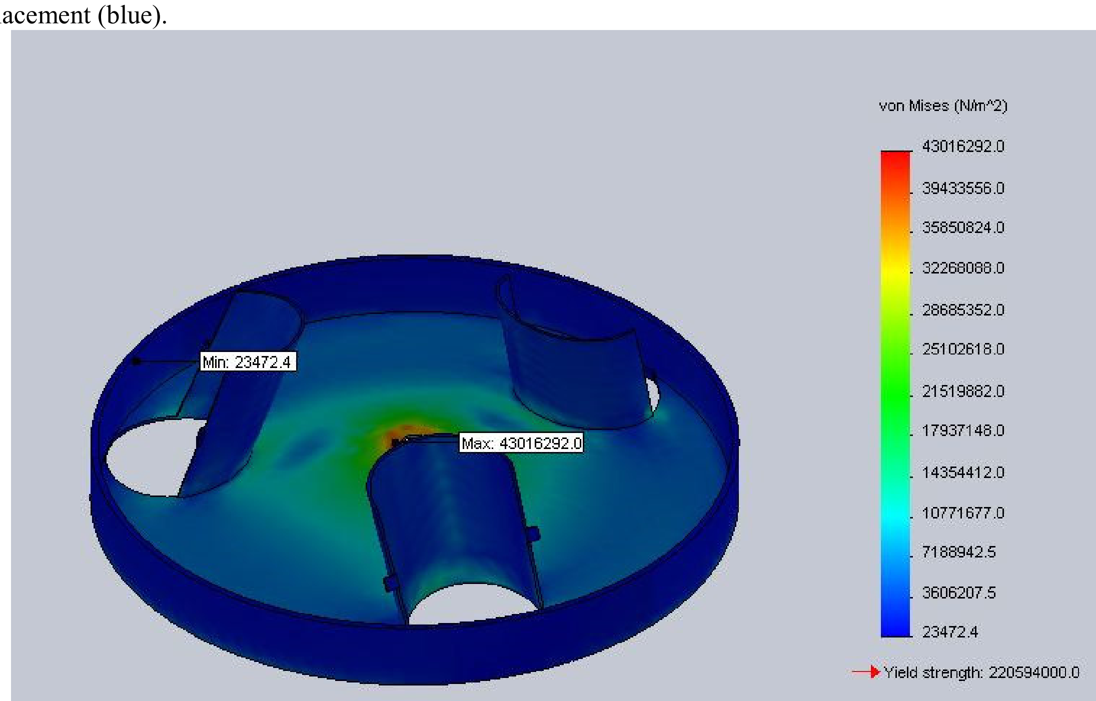

Figure 4: Nodal stress plot showing areas with maximum stress concentration on the centrifuge wheel

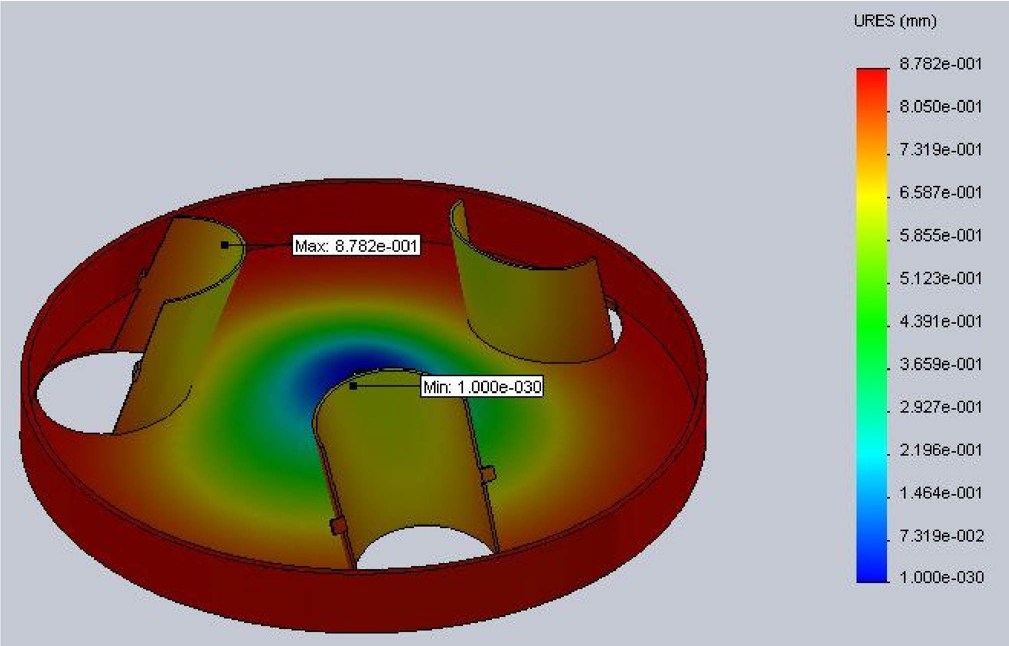

Figure 5: Static displacement plot showing areas of maximum displacement

The analysis also showed the number of nodes, elements and degree of freedom (DOF) of the component as 16582, 7960 and 49584 respectively.

2.7 Performance Evaluation Procedure of the Developed Centrifuge

The centrifuge was tested after fabrication to evaluate its performance. The test performance indicators include; optimal speed and specific energy consumption. The optimal speed of the centrifuge is the safest speed required to separate a given mixture in the shortest possible time while the specific energy consumption, SE is defined as the ratio of the total energy consumed by the centrifuge to the mass of the mixture separated in one operational cycle.

Experiment was carried out to determine the effect of centrifuge speed on separation time using "methyl ester-glycerol" mixture produced from the transesterification of vegetable oil and methanol. This was done by operating the centrifuge after fabrication (with full load) at different speeds until complete separation of the methyl ester-glycerol mixture was achieved. The centrifuge was stopped at intervals of 10 minutes to check if complete separation/sedimentation has occurred. Variations in the speed of the centrifuge was achieved by changing the diameters of the driving and driven pulleys to obtain speed ratios of 1:2, 2:3, 1:1, 1.3:1 and 1.5:1 respectively.

3. Results and Discussion

The results of the experimental investigation of the developed centrifuge as per each experimental procedure described in the previous section are presented and discussed in this section.

3.1 Determination of Optimal Separation Time

Optimal separation time of the centrifuge was determined from the result of five experimental runs at speeds of 720rpm, 960rpm, 1440rpm, 1990rpm and 2160rpm respectively tabulated in Table 1.

Table 1: Result of variation of centrifuge speed.

Parameters	**1st run**	**2nd run**	**3rd run**	**4th run**	**5th run**
Centrifuge speed (rpm)	720	960	1440	1990	2160
Velocity ratio	1:2	2:3	1:1	1.3:1	1.5:1
Separation time (mins)	90	70	40	30	30
Vibration (pulse/s)	368	411	750	1250	1663

At speeds of 720rpm, 960rpm, 1440rpm, 1990rpm and 2160rpm the "methyl ester-glycerol" mixture separated completely in 90 minutes, 70 minutes, 40 minutes, 30 minutes and 30 minutes respectively. Separation was fastest at speeds of 1990rpm and 2160rpm, with vibrations of 1250pulse/s and 1663pulse/s recorded respectively. Lower vibration value means higher operational safety. Hence, 1990rpm was selected as the optimal speed for operating the developed centrifuge since there was no reduction in separation time beyond this point. Plots of centrifuge speed against separation time and centrifuge speed against vibration are shown in Figures 6 and 7 respectively.

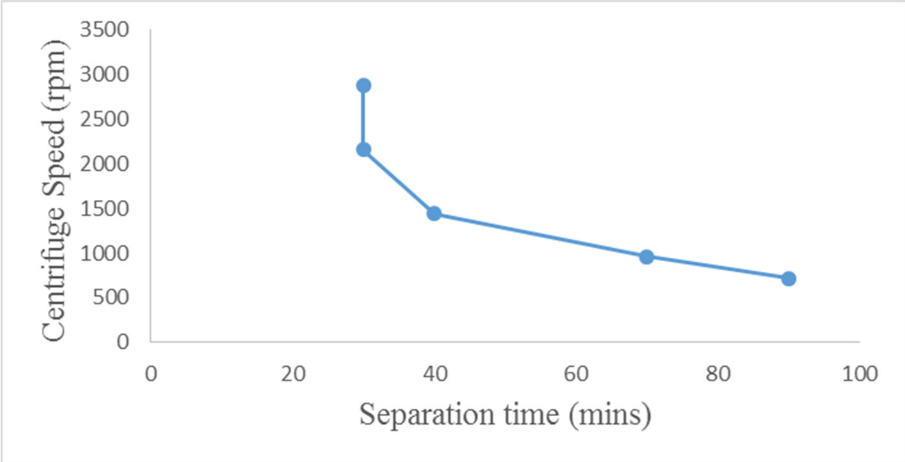

Figure 6: Variation of separation time with centrifuge speed

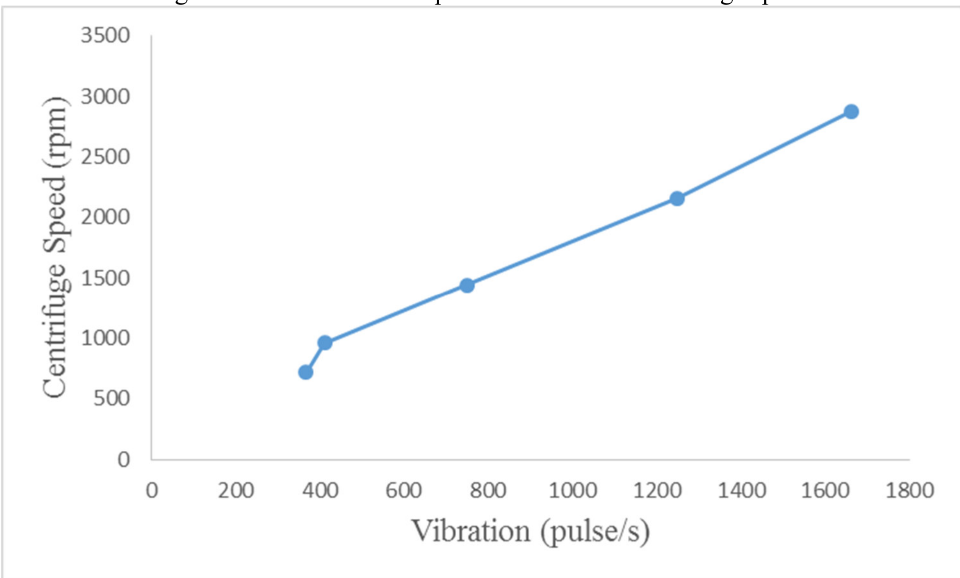

Figure 7: Shaft vibration recorded at different centrifuge speeds

Figure 6 above shows a maximum separation time of 90minutes for centrifuge speed of 720rpm and minimum separation time of 30minutes for centrifuge speeds of 2160rpm and 2880rpm. The plot shows a reduction in separation time from right to left, with increase in centrifuge speed until the speed of 2160rpm is reached after which separation time stays constant at 30minutes with increase in centrifugation speed up to 2880rpm.

In figure 7, vibration (in pulse/s) of the centrifuge shaft increases with increase in centrifuge speed. Maximum vibration of 1663pulse/s was recorded at speed of 2880rpm while minimum vibration of 368pulse/s was recorded at speed of 720rpm.

3.2 Specific Energy Consumption

The specific energy consumption (SE) of the centrifuge was determined as 206.5KJ/Kg using the relation in Equation (18).

$$SE = \frac{PT}{M} \tag{18}$$

Where:
P = Power input to the plant
T = Separation time obtained from table 1
M = mass of mixture

5. Conclusion

A centrifuge was designed and developed for separating industrial mixtures. The performance test of the developed centrifuge showed that the plant has a specific energy consumption of 206.5KJ/Kg. The optimal separation time, required to completely separate a given mass of a mixture is 30 minutes. Also, vibration of the centrifuge should not exceed 1250 pulse/sec for safe operation of the centrifuge. The developed machine will bring relief to chemical industries since mixtures produced from various industrial processes can easily be separated into its constituent substances. This innovation is expected to encourage faster and easier production of substances like drugs, chemicals etc.

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