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Development and Design of a Centrifuge Separation Chamber for Natural Rubber Latex Concentration

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Abstract

This paper focuses on the design and fabrication of a separation chamber which is part of a centrifuge for natural rubber latex concentration. The design and fabrication of the separation chamber is based on the centrifugation principle where the centrifugal acceleration causes the more dense substances to separate along the radial direction. The separation chamber allows a continuous flow process which has two outlets designed to expel the heavier liquid (water) at the top of the cover and the lighter liquid (rubber particles) at the top of the plate holder. An electric motor of two horse power was used to drive the separation chamber with a speed of 4,800 rpm to achieve separation. The throughput of the chamber is 95 litres per hour running at 7200rpm with a horse power of 7.5hp electric motor. With this operation, the separation chamber gives about 60% rubber latex concentrate of dry rubber content (DRC).

1. Introduction

Natural rubber latex is a white or slightly yellowish opaque liquid obtained from tapping the rubber trees (Hevea brasiliensis). It is a colloidal dispersion of minute particles of rubber in an aqueous medium. The rubber latex from the rubber tree contains between 30-40% rubber particles while the remaining 60-70% is mainly water. The latex on collection from the field can either be processed to obtain dry rubber or the concentrate. The concentrate is an important raw material with a wide range of application such as in the manufacture of carpet, underlay, balloons, hand gloves, rubber bands, condom and so on [1].

There are various methods used in the production of the latex concentrate but the two most common ones are creaming and centrifugation [1]. Creaming involves mixing a creaming agent such as ammonium alginate and allowing the latex to separate into two layers; an upper layer of concentrated latex (having 50-55% dry rubber content, DRC) and lower layer of serum containing very little rubber. The centrifugation process involves the use of machine where the rubber latex is fed into a separation chamber to obtain two fractions with one fraction having concentrated latex of about 60% DRC and the other part containing 4-8% DRC with the serum. The specific gravity is the ratio of the weight of the molded piece as compared to the weight of an equal volume of water ASTM D792 which means that the specific gravity of natural rubber latex is 0.91 and that of serum is 1.021 [2].

There are two separation chambers commercially available with respect to the disk type and they are the two-phase and three-phase separation chambers. The basic design of a separation chamber consists of a rotating drum that has an enclosed set of stacked metallic separator disc. Rubber latex enters the drum through an axial feed tube and flows to the bottom of the drum through a distributor. A series of small holes on the separator discs, positioned at definite distance from the axis of rotation allow the rubber latex to get distributed and broken up into a number of thin conical shells within the drum which rotates at high speed. When the centrifuge is running at steady state, the DRC of the rubber latex at the periphery of the drum will be much lower than that of the rubber latex at the axis of rotation. The rubber latex concentrate which has above 60% DRC passes towards the centre and is collected through a gallery at the top. The skim rubber latex which contains about 6 to 10% rubber is collected through a separate gallery. The DRC of the rubber latex concentrate and that of the skim rubber depends on so many factors like the diameter of feed tube, length and diameter of the skim screw, DRC of the feed latex, pressure head in the feed cup and speed of rotation of the drum. Higher DRC of field rubber latex, shorter skim screw and low feed rate of the rubber latex favours a higher DRC for the concentrate. Several conditions influencing efficiency of different types of centrifuges have been studied in detail and operating conditions to get the maximum drum efficiency have been worked out [3, 4].

2. Methodology

The separation chamber was fabricated using locally source materials. The materials used in the construction of the separation chamber were mainly stainless steel. Some parts were drilled, threaded, brazed, machined, arc welded and bolted to form main components like the plate holder, drum plates, separating plate and cover. The separation chamber is mounted through a vertical hollow shaft and driven by an inverted vertically mounted motor via a belt drive. Natural rubber latex was fed at the top of the hollow shaft and got separated into phases in the separation chamber.

2.1 Conceptual Design

When using the centrifugation method in the commercial production of rubber latex concentrate, there are two concepts in mind. These concepts are based on how the mixture separates into two or three outlets in the separation chamber. The concepts are two-phase and three-phase continuous flow system. In the course of manufacturing this chamber, a two-phase centrifuge was chosen because of ease of manufacture. Figure 1 and Figure 2 show the schematic diagram of a two and three-phase separation chamber.

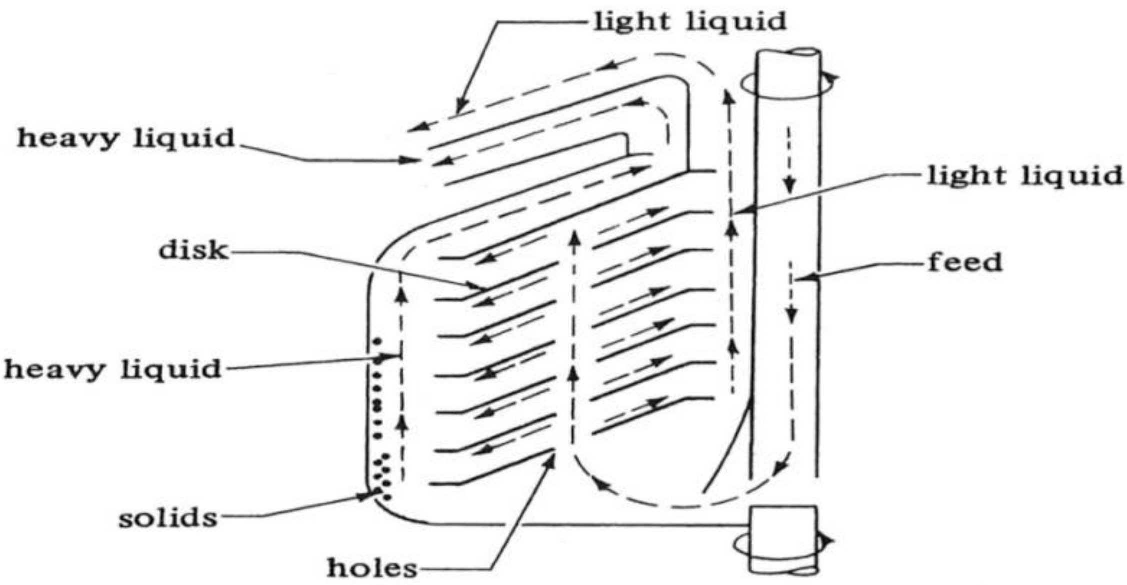


Figure 1 Two-phase centrifuge

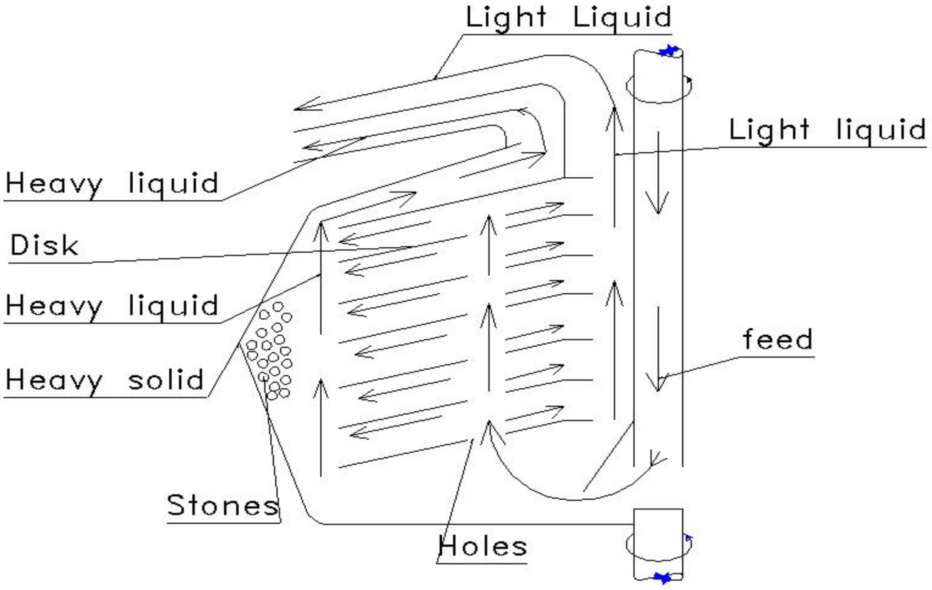


Figure 2 Three-phase centrifuge

2.2 Design Details

Relative centrifugal force (RCF) is the measurement of the force applied to a sample within a centrifuge. This can be calculated from the speed (revolution per minute, rev/min) and the rotational radius (m) using the following calculation.

$$G = RCF = 0.00001118 * r * N^2 \quad (1)$$

The centrifugal force on a particle that is constrained to rotate in a circular path is given as;

$$F_c = mr\omega^2 \quad (2)$$

But $\omega = \frac{v}{r}$, (where $v = the\ tangetial\ velocity\ of\ the\ particle$), therefore,

$$F_c = \frac{(mv^2)}{r} \quad (3)$$

Rotational speeds are normally expressed in revolutions per minute, where $\omega = \frac{2\pi N}{60}$ therefore Equation (2) becomes:

$$F_c = mr\left((\frac{2\pi N}{60})^2\right) = 0.011mrN^2 \quad (4)$$

If Equation (4) is compared with the force of gravity (F_g) on the particle, which is $F_g = mg$ it can be seen that the centrifugal acceleration is equal to $0.011rN^2$. The centrifugal force is often expressed for comparative purposes as so many "g". With reference to Equation (2), the centrifugal force depends upon the radius (r) and speed of rotation (estimated as v) and upon the mass of the particle (m). If the radius and the speed of rotation are constant, then the controlling condition is the weight of the particle so that the heavier the particle the greater is the centrifugal force acting on it. As a result, if two liquids, one of which is twice as dense as the other, are placed in a drum and the drum is rotated about a vertical axis at high speed, the centrifugal force per unit volume will be twice as great for the denser liquid as for the less dense liquid. The denser liquid will therefore move to occupy the outer part of the drum and it will displace the less dense liquid towards the centre [5; 6].

Rate of separation (V_m)

$$V_m = \frac{d^2N^2r(\rho_s - \rho_l)}{160m} \quad (5)$$

Time taken to precipitate all suspended particles

$$T = \frac{9l\eta}{\pi r^2(\rho_s - \rho_l)\omega^2 R} \quad (6)$$

Volume of fluid in the separating chamber

$$V = \pi(R^2 - r^2)\, h \quad (7)$$

Time in seconds for a particle to be in a separating chamber

$$t = \frac{18n}{D^2(F - P)\omega^2} \ln\frac{R}{r} \quad (8)$$

Volumetric flow rate, Q

Throughput or Volumetric flow rate or Feed flow rate Q, (m^3/s) can be calculated when the separation chamber runs at a speed of about 7200 rpm.

For a disc bowl separation system, we have

$$Q = V_g \times \sum$$

Where V_g = Particle velocity = $\frac{D^2\times(F-P)\times g}{18\times n}$ and

$$\sum = f(R, r, h, \omega) = \text{Cross sectional area} = \frac{2\times\pi\times\omega^2\times N\times(R^3-r^3)}{3\times g\times\tan\theta}$$

$$Q = V_g \times \sum = \frac{2\times D^2\times \pi\times\omega^2\times N\times(F-P)\times(R^3-r^3)}{18\times n\times 3\times\tan\theta} \text{ [7]} \quad (9)$$

Where D = Diameter of a rubber latex particle = 0.5×10^{-6}m
P = Rubber latex particle density = 910kg/m^3
F = Rubber latex fluid density = 1021kg/m^3
R = radius of bottom bowl = 0.14m
N = number of drum plate = 12
r = radius of top bowl = 0.07m
n = viscosity of rubber latex medium = 0.002kg/m/s
g = acceleration due to gravity = 9.8 m/s^2
θ = angle of inclination of drum plate = 45°

$$\omega = \frac{2\times\pi\times n}{60} = \frac{2\times\pi\times 7200}{60} = 240\pi$$

$$Q = \frac{2\times D^2\times \pi\times\omega^2\times N\times(F-P)\times(R^3-r^3)}{18\times n\times 3\times\tan\theta}$$

$$Q = \frac{2\times(0.5\times10^{-6})^2\times\pi\times(240\pi)^2\times12\times(1021-910)\times(0.14^3-0.07^3)}{18\times0.002\times3\times\tan 45}$$

Q = 2.644×10^{-5} m^3/s = 0.0952m^3/hr. = 95.2 litres/hr.

Torque developed is given by:

$$M_t = \frac{159\times P_d}{n} \quad (10)$$

Where n is the centrifuge rotation in revolution per second = 7200 rpm = $\frac{7200}{60} = 120$ rps

$M_t = \frac{159 \times 9.056}{120} = 12$ Nm,

$M_t = 12\text{Nm}$

Relating the torque with the tensions in the belt, we have

$$T_R = M_t = (T_1 - T_2)\frac{d}{2} \quad (11)$$

$(T_1 - T_2) = \frac{M_t}{d} \times 2 = \frac{12}{40 \times 10^{-3}} \times 2 = 600\text{N}$

Where d = 40mm.

$(T_1 - T_2) = 600\text{N}$. And $T_2 = T_1 - 600$

Power developed by the belt is given as;

$$P = (T_1 - T_2)\, v \quad (12)$$

Where v = velocity of the belt.

Belt Speed, v

$$v = \frac{\pi \times d \times N}{60} \quad (13)$$

$v = \frac{\pi \times 40 \times 10^{-3} \times 7200}{60} = 15.08\ ^{m}/_{s}.$

$P = (T_1 - T_2)\, v = 600 \times 15.08 = 7.24\text{kW}$

Tension in the belt of both pulleys;

$$\frac{T_1 - mv^2}{T_2 - mv^2} = e^{\alpha\mu} \quad (14)$$

Where T_1 = tension in the tight side(N), T_2 = tension in the slack side(N)

α = wrap angle on the pulley, μ = coefficient of friction between the belt and pulley.

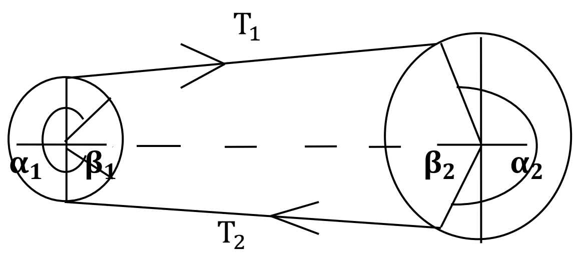


Figure 3 Tension in the belt

$$\alpha_1 = (180 - 2\beta);\ 180 - 2\sin^{-1}\left(\frac{R - r}{c}\right) \quad (15)$$

$$\alpha_2 = (180 - 2\beta); 180 + 2\sin^{-1}(\frac{R-r}{c}) \qquad (16)$$

Where α_1 and α_2 are angle of wrap of small and big pulley respectively.

Where $R = 50mm$, $r = 20mm$, $c = 440mm$

$\beta = \sin^{-1}\frac{(R-r)}{c}$, $\beta = 4^0$,

$\alpha_1 = (180 - 2\beta) = 180 - 2 \times 4 = 172°$

$\alpha_2 = (180 + 2\beta) = 180 + 2 \times 4 = 188°$

The load carrying capacity of a pair of pulleys is determined by the one which has the smaller $e^{\alpha\mu}$. Also $\mu = 0.35$

α in radian $= 172 \times \frac{\pi}{180} = 3rad$,

For centrifuge Pulley = $e^{\alpha\mu} = 2.86$

α in radian $= 188 \times \frac{\pi}{180} = 3.28rad$,

For Motor Pulley = $e^{\alpha\mu} = 3.15$

Here the smaller pulley which is the centrifuge pulley governs the design. That is the smaller pulley is transmitting its maximum power with the belt on the point of slip while the larger pulley is not developing its maximum capacity.

For a leather belt of 6mm thickness, the allowable stress on the belt is 2.5MPa, so we have

$T_1 = \sigma \times b \times t = 2.5 \times 10^6 \times b \times 6 \times 10^{-6} = 15b$ N

Therefore; $\frac{T_1 - mv2}{T_2 - mv2} = e^{\alpha\mu} = 2.86$

$$m = b \times t \times \rho \qquad (17)$$

Where m = mass of the belt, t = thickness of the belt and ρ = density of belt

$m = b \times 0.006 \times 970 = 5.82b$ Kg/m

Therefore; $\frac{T_1 - mv2}{T_2 - mv2} = \frac{15b - 5.82b \times 15.08^2}{(15b - 600) - 5.82b \times 15.08^2} = 2.86$

Therefore; $\frac{15b - 1.323b}{15b - 1.323b - 600} = 2.86$;

$13.677b = 39.116b - 1716$

Therefore; $b = 1716 \div (39.116 - 13.677) = 67.46mm$

Therefore; the belt width b = 70mm

T_1 = 15b = 15×70 = 1050N, T_2 = T_1−600 = 1050 – 600 = 450N

T_1 = 1050N and T_2 = 450N

2.1.1 Shaft Design

Owing to the toughness, strength, reliability on resistance to shock and repeated loading, stainless steel material was chosen for the shaft to accommodate the loads that would be impacted on it and also to handle corrosion. In shaft design calculation, the parameters to look out for are; maximum shear stress (τ), density of steel (ρ), combine shock and fatigue factor as applied to bending (k_b), maximum allowable stress for shaft, combine shock and fatigue factor as applied to torsion (k_t) **[8].** The following loads are expected to be acting on the shaft for centrifugal operation: pulleys, bearing, and the separating system. Therefore, all the forces acting on the shaft need to be resolved separately.

Force exerted by the pulley(F_p)

$$\mathbf{F_p} = T_1 + T_2 \quad (18)$$

$$\mathbf{F_p} = 1050 + 450 = 1500\text{N}$$

Force exerted by separation system(F_s)

$$\mathbf{F_s} = F_1 + F_2 \quad (19)$$

Where F_1 = Force exerted by the separator, F_2= Force exerted by the volume of rubber latex in the separator

Force exerted by the separator (F_1)

$$F_1 = \rho_s \times V_s \times w^2 R \quad (20)$$

Where ρ_s = density of stainless steel bowl = 1.81kg, V_s = Volume of Separator

$w^2 R$ = Centrifugal force acting on the separation system

$$\text{Centrifugal force} = w^2 R = \left(\frac{2\times\pi\times N}{60}\right)^2 \times R \quad (21)$$

$$w^2 R = \left(\frac{2\times\pi\times 7200}{60}\right)^2 \times 0.14 = 79588.49$$

Force exerted by the Separator, $F_1 = 1.81 \times 8.621 \times 10^{-3} \times 79588.49 = 1242.90\text{N}$

Force exerted by the volume of rubber latex in the separator (F_2)

$$F_2 = \rho_r \times V_r \times w^2 R$$

Where ρ_r = Density of rubber (1.52kg), V_r = Volume of rubber latex in the separator

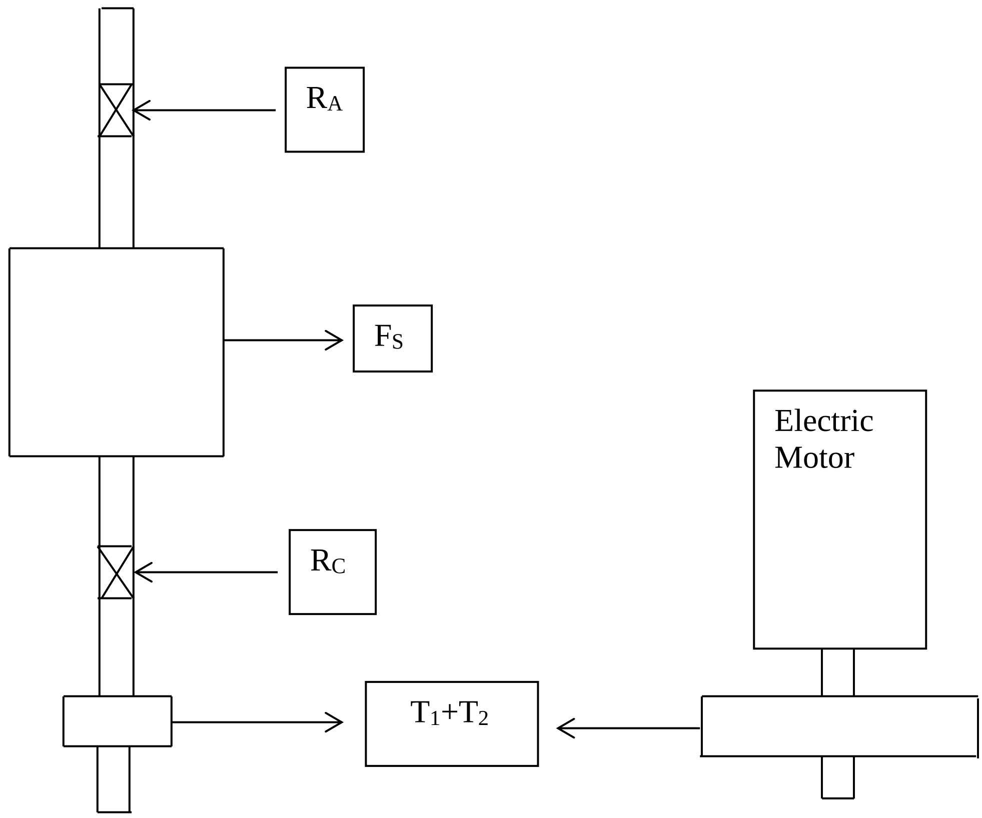
$V_r = \pi \times (R^2 - r^2) \times H$ (22)

Where r = 0.07m is radius at top, and R = 0.14m is radius at bottom

$F_2 = 1.52 \times \pi \times (0.14^2 - 0.07^2) \times 0.14 \times 79588.49 = 783.18N$

Total force on the Separator System($\mathbf{F_s}$) = F_1+F_2

$\mathbf{F_s} = 1242.90 + 783.18 = 2025.08N$

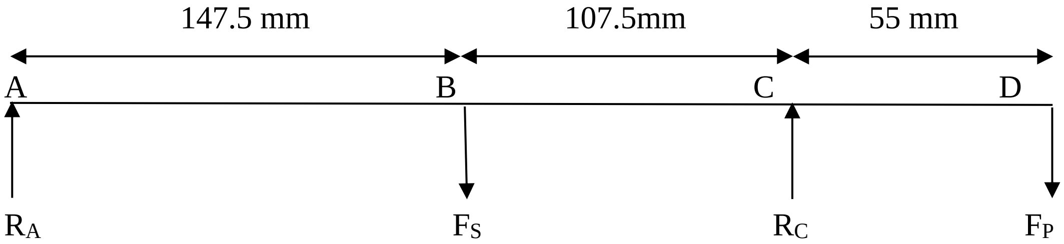


Where R_A = Bearing reaction at point A and R_C = Bearing reaction at point C

Figure 4 Force analysis of the system

Horizontal loading consideration

Horizontal loading is produced owing to the pull (tension) of the belt on the pulley against the shaft and the centrifugal force against the rubber latex in the separating system.



$[F_S = 2025.08N,\ F_P = 1500N]$

Taking moment about A, we have

$R_C = 2994.9N$

Total upward forces $=$ total downward forces

$R_A = 530.18N$

Table 1: shear force and the bending moment for horizontal loading consideration.

S/N	FORCES (N)	POINT (mm)	SHEAR FORCE (N)	BENDING MOMENT (Nm)
1	530.18	A	530.18	0
2	2025.08	B from A	1495.00	78.20
3	2994.90	C from D	1499.00	-82.50
4	1500.00	D	0	0

Max. Vertical Bending Moment $M_V = 0Nm$ (No vertical force consideration because of the setup of the machine)

Max. Horizontal Bending Moment $M_H = 82.5Nm$

Max. Bending Moment $M_b = [M_V^2 + M_H^2]^{\frac{1}{2}}$ (23)

$M_b = [0^2 + 82.5^2]^{\frac{1}{2}} = 82.5Nm$

2.1.2 Determination of hollow shaft diameter

$$d_o^3 = \frac{16}{\pi s_s(1-k^4)} \sqrt[2]{\left[(K_b M_b + \frac{\alpha F_a d_o(1+k^2)}{8})^2 + (K_t M_t)^2\right]} \text{ [8]} \quad (24)$$

Where S_s= torsional shear stress, $\alpha =$, $F_a =$ axial load, $K = \frac{d_i}{d_o}$, d_i = Internal diameter of shaft and d_o= outer diameter of shaft.

ASME codes states for commercial steel shafting.

S_s (allowable) = 8000 psi for shafting without keyway = (55MN/m^2)

S_s (allowable) = 6000 psi for shafting with keyway = (40MN/m^2)

Assuming no axial force on the shaft, that is $F_a = 0$, then Equation (24) becomes

$$d_o^3 = \frac{16}{\pi s_s(1-k^4)} \sqrt[2]{[(K_b M_b)^2 + (K_t M_t)^2]} \quad (25)$$

Also let the thickness in the hollow shaft be 3mm, then $d_o - d_i = 2 \times 3\text{mm} = 6\text{mm}$

$$\text{Then } k = \frac{d_o - 6}{d_o} \quad (26)$$

$$[1 - (\frac{d_o-6}{d_o})^4] \times d_o^3 = \frac{16}{\pi s_s} \sqrt[2]{[(K_b M_b)^2 + (K_t M_t)^2]} \quad (27)$$

Expanding the left hand side of the equation, and equating to the left side of the equation, we have

$$24d_o^3 - 216d_o + 864d_o - 1296 = \frac{16}{\pi s_s} \sqrt[2]{[(K_b M_b)^2 + (K_t M_t)^2]} \times d_o \quad (28)$$

For rotating shaft, load gradually applied

$[K_t = 1.0$ selected, $K_b = 1.5 =$ selected, $S_s =$ Shear Stress (constant with keyway) $= 40\text{MPa}]$ [8].

Working on the right hand side of the equation we have

$M_b = 82.5\text{Nm} = 82.5 \times 10^3\text{Nmm}$, $M_t = 12\text{Nm} = 12 \times 10^3\text{Nmm}$,

$S_s = 40\text{MN/m}^2 = 40\text{N/mm}^2$

Then we have $\frac{16}{\pi \times 40} \sqrt[2]{[(1.5 \times 82.5 \times 10^3)^2 + (1 \times 12 \times 10^3)^2]} \times d_o = 15830.25 \times d_o$

$$24d_o^3 - 216d_o - 14966.25d_o - 1296 = 0 \quad (29)$$

Then $d_o = 29.91$mm, -2.08mm.-0.0867mm,

Note: The negative values are disregarded. So $d_o = 29.91$mm is taken as the outside diameter of the shaft.

Diameter (d) of Centrifuging Machine Shaft:

$d_o = 35$mm is selected for safety, factor of safety is $= \frac{35}{29.91} = 1.17$

Then $d_o = 35$mm so the inside diameter $d_i = 35 - 6 = 29$mm.

2.2. Separation Chamber Description: The separation chamber consists of the following components; (a) Plate holder (b) Drum plates (c) Separating plate (d) Cover

2.3. The Plate Holder

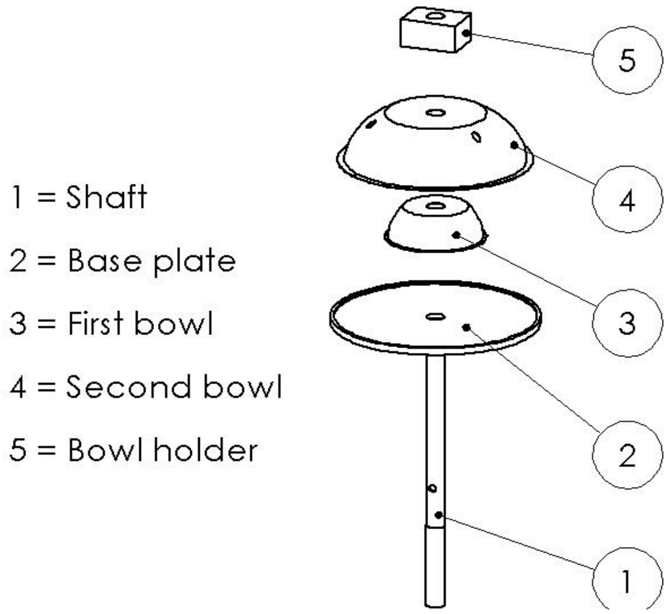


Figure 5 The assembled plate holder

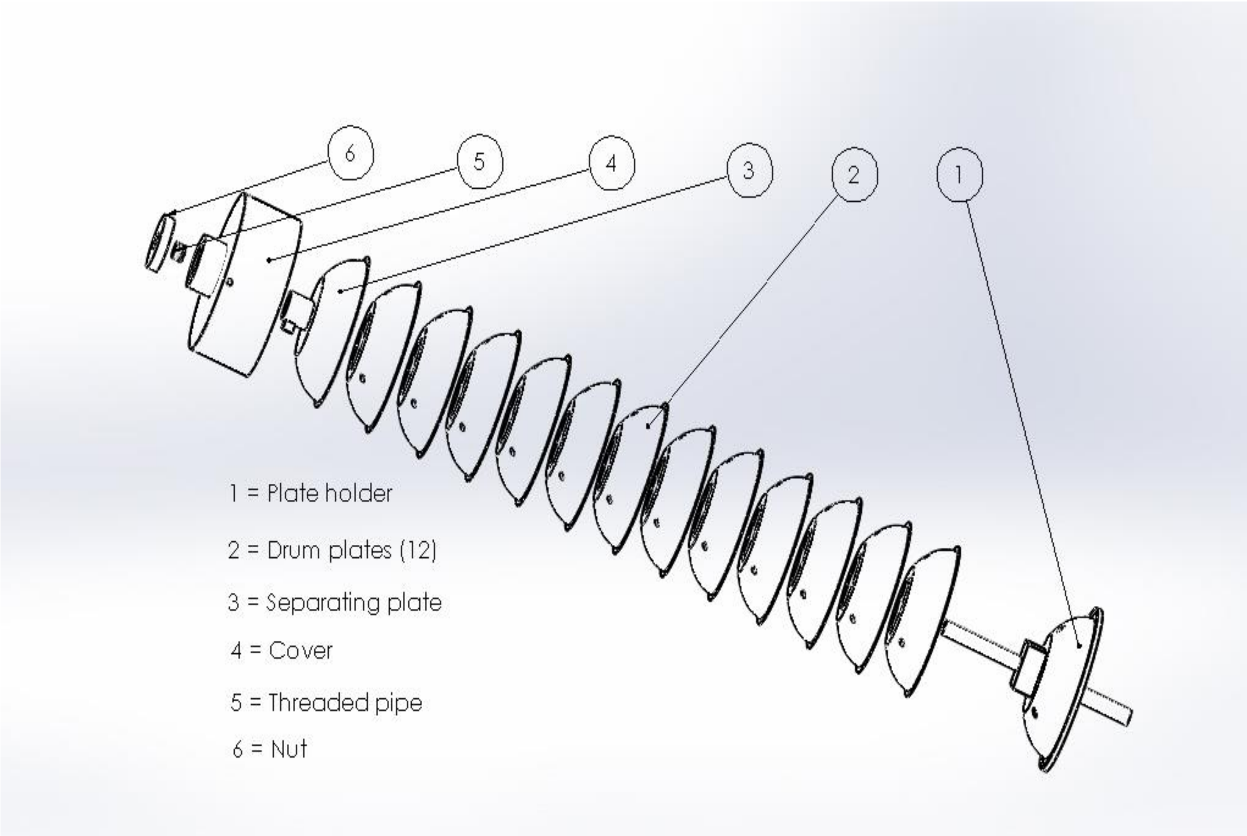


Figure 6 Exploded view of the separation unit

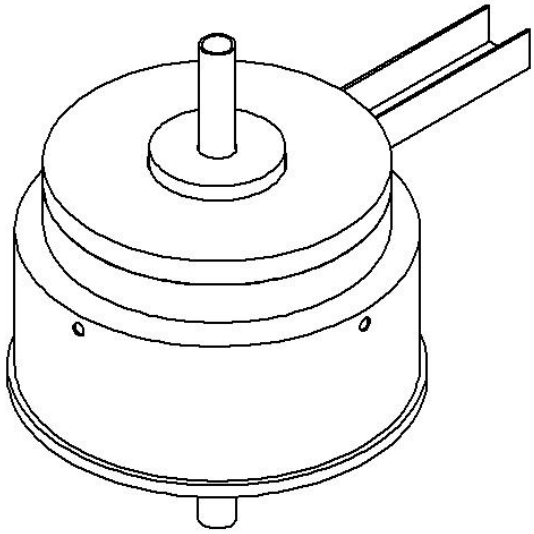


Figure 7 Assembly of the separation and collection unit

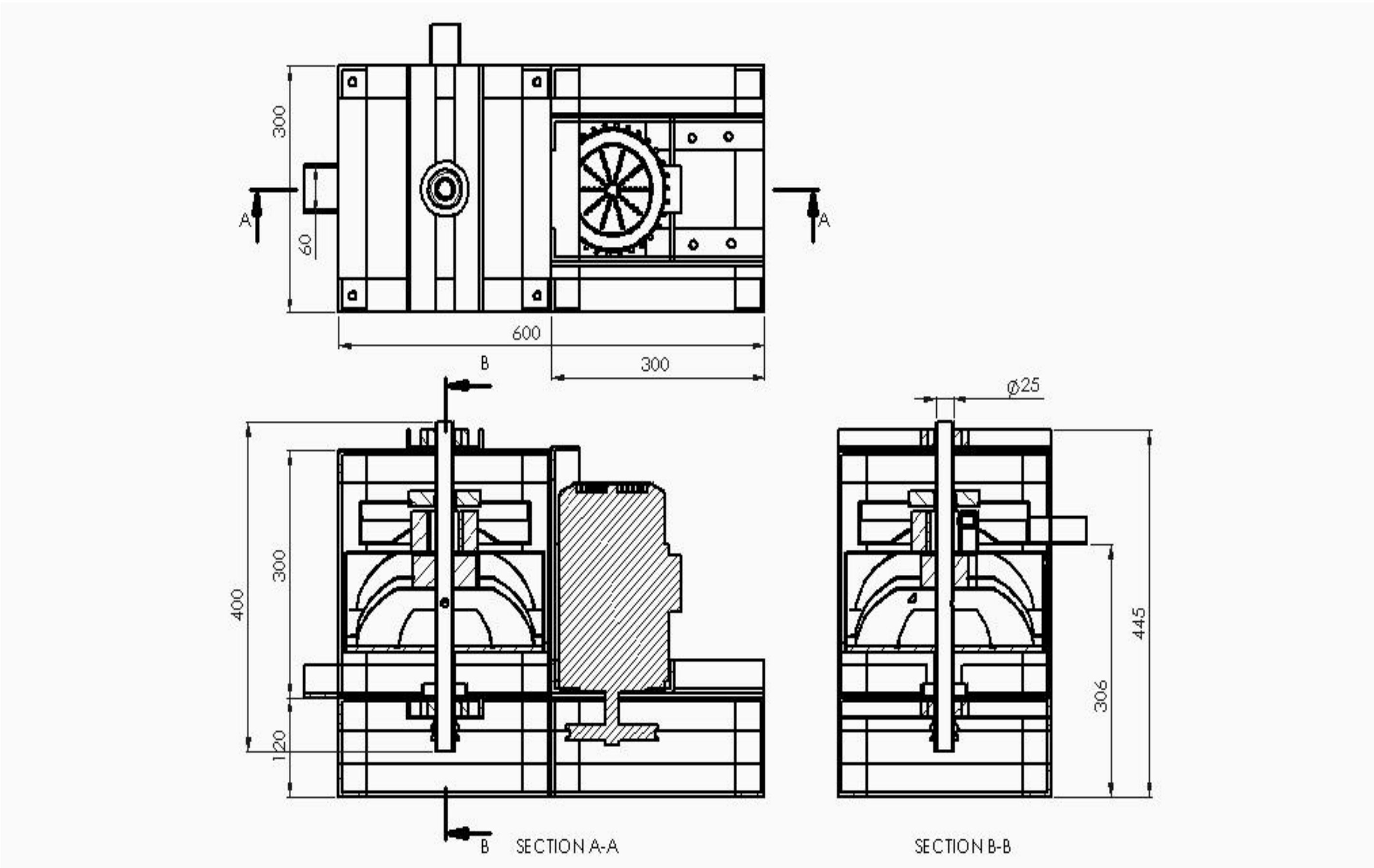


Figure 8 Sectional view of the centrifuge

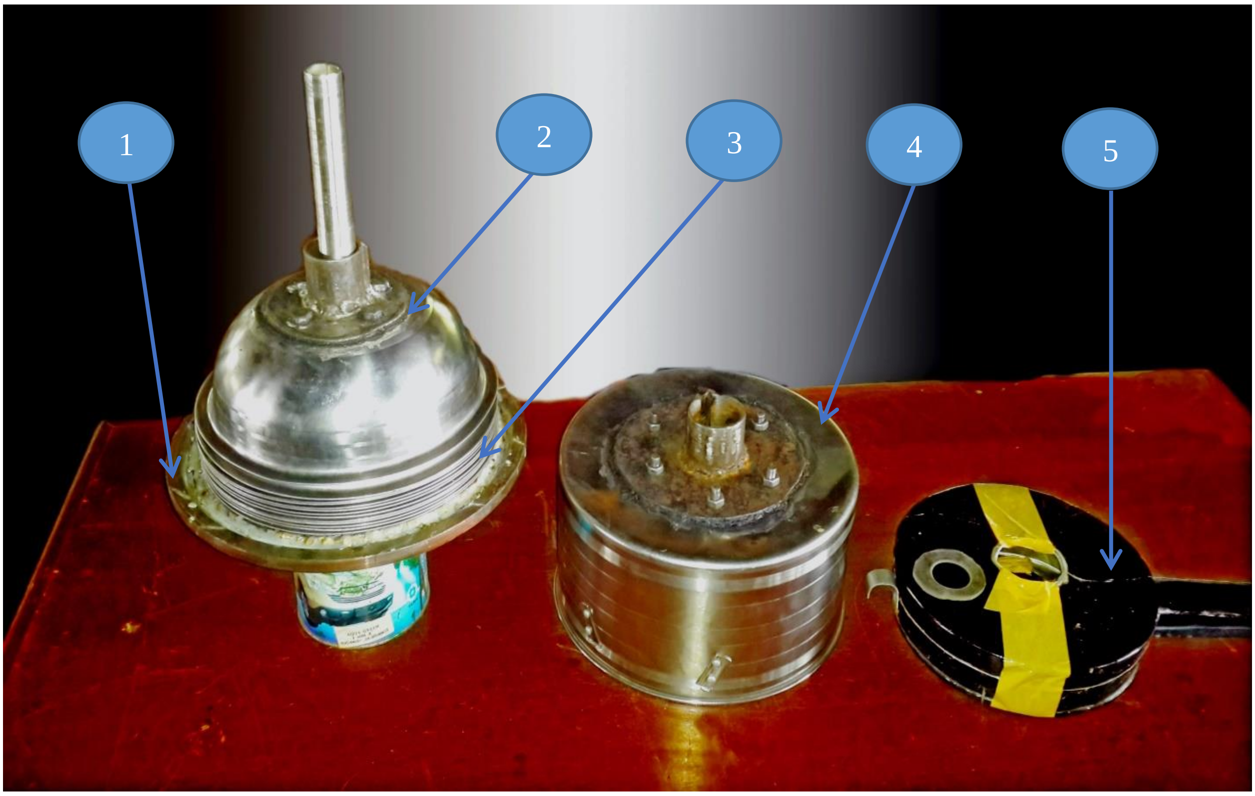


Figure 9 Shows the fabricated plate holder (1), separating plate (2), 12 drum plates (3), cover (4) and latex collector (5)

3. Conclusion

In the course of manufacturing the separation chamber, the drum plates were meant to be conical in shape to give the desired angle of inclination of a range of 30^0 to 50^0 [7] but this could not be achieved. So already shaped stainless steel bowls were gotten and the desired patterns were cut on them. The separator head was meant to slide up unto the cover head, so fabricating these parts and the joining method used were not conventional, some areas were putty filled to seal up some spaces, some were joined using bolts and nuts while other spaces were closed using araldite (a special gum). Fabricating the plate holder was the greatest challenge as it was difficult getting a professional to braze stainless steel materials of different thickness together. However, with an electric motor attached to the separation chamber, the machine can generate a high separating force enough to course separation of the rubber latex to give rubber latex concentrate of about 60% dry rubber content. The components of the separation chamber are strong to withstand pressure developed within the system. The materials used are stainless steel which is readily available. Also, the separation chamber is designed in a way that it can be easily manufactured and maintained with less complexity of operation making it easily used by natural rubber farmers to enhance the value of rubber products in economic development. Hence, we can infer that the outcome of the design of the separation chamber shows much promise to the rubber industries in the production of rubber goods like balloons, foam, hand gloves, condom which use rubber latex concentrate as raw material.

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