DESIGN AND FABRICATION OF A ROTOR-STATOR HOMOGENIZER

A Final Year Project Report

Presented to

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In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

by

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ABSTRACT

A rotor-stator homogenizer is a device used to generate a local shear rate significantly higher than that produced by typical radial agitators. It consists of a rotor, typically in a floating state with respect to the stator, and a cylindrical stator with a hollow and multiple flow passages. The rotor-stator homogenizer is designed to create stable emulsions and accelerate solid-liquid phase-transfer reactions by producing very small particles in the mixing tank, making it particularly effective for applications in the cosmetic, formulation, and dye industries.

This report explores the rotor-stator homogenizer, covering fundamental principles, design, fabrication, and performance testing. The first section delves into the working mechanisms, providing insight into its operation and applications, as well as its advantages over other types of homogenizers. The subsequent sections detail the design and fabrication processes, encompassing the approach taken and selection of subsequent parameters. Performance testing involves optimizing homogenization time and validating results through experimental testing.

The report concludes with key findings, recommendations for optimal use, and future development prospects, underscoring the rotor-stator homogenizer's significance in industrial processes and its potential for technological advancements.

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NOMENCLATURE

P	Transmitted power consumed in moving the rotor
T	Generated torque
ω	Angular velocity
V	Linear velocity
R_i	Radius of rotor
R_o	Radius of stator
Q	Volumetric flowrate
A	Area of rotor
μ	Fluid viscosity
V_r	Radial velocity
Q_r	Volumetric flowrate in radial direction
V_z	Axial velocity
Q_z	Volumetric flowrate in axial direction
l	Effective length of shearing between rotor and stator
ρ	Fluid density
$\partial p/\partial z$	Pressure gradient of the fluid about the z axis
r	Radial distance within the shear gap
τ_w	Wall shear stress
f_D	Darcy friction factor
$\bar{V}$	Effective velocity on the stator wall
Re	Reynolds number
d_s	Shear gap
ϕ_s	Stator hole diameter
l_{gv}	Guide vane length
t_{sb}	Shear blade thickness
η_h	Degree of homogenization
ρ_{exp}	Experimental density of emulsion
ρ_{th}	Theoretical density of emulsion
P_i	Parameter values
c_i	Coefficients governing parameters i
u	Emulsion net velocity
u_y	Velocity gradient
A_o	Stator hole area
F_s	Shear force induced during operation
F_o	Shear force induced due to shear blades

CHAPTER 1: INTRODUCTION

Homogenizers are high-shear mixers used in various industries to break down and mix substances, creating stable, uniform mixtures. Among them, rotor-stator homogenizers stand out as a type of mechanical homogenizer characterized by a fast-spinning inner rotor within a stationary outer sheath, known as the stator. The mechanism involves tangentially accelerating the fluid, causing it to flow towards the shear gap between the rotor tip and the stator. This design generates high-velocity differentials and turbulent fluid flow, resulting in elevated shear rates. Notably, rotor-stator homogenizers are recognized for their minimal heat generation during operation, making them particularly suitable for tasks such as plant and animal tissue homogenization.

The basic components of a rotor-stator homogenizer include a rapidly spinning inner rotor and a stationary stator. As the fluid is accelerated tangentially, it converges towards the shear gap between the rotor and stator, where turbulent fluid flow and high shear rates are generated. In comparison to blade-type homogenizers, rotor-stator types are more efficient, particularly when dealing with various sample sizes.

Rotor-stator homogenizers find extensive applications in the cosmetic industry due to their ability to homogenize products like creams and lotions effectively. These devices contribute to achieving a uniform and smooth texture in cosmetic formulations by breaking down and dispersing their components. The high shear rates generated by rotor-stator homogenizers are pivotal to produce stable and high-quality cosmetic products. Their adaptability to handle viscous materials and quick processing time make them indispensable in cosmetic manufacturing, ensuring the consistency and quality of the final products.

The benefits of utilizing rotor-stator homogenizers extend beyond the cosmetic industry. Their efficiency in reducing particle size, versatility in handling various sample sizes, minimal heat generation, and cost-effectiveness make them a preferred choice in many applications. These homogenizers also offer a wide volume range for processing, further enhancing their flexibility. Rotor-stator homogenizers play a vital role in diverse applications, providing efficient and reliable solutions for achieving uniform mixtures.

1.1 Problem Statement

The widespread adoption of rotor-stator homogenizers, known for their capacity to achieve stable and uniform mixtures through high-shear mixing, faces a significant impediment due to the absence of localized manufacturing dedicated to the design and manufacturing of these crucial devices.

Presently, industries reliant on homogenizers, particularly within sectors like cosmetics, grapple with challenges associated with importing these essential devices. The importation of rotor-stator homogenizers introduces additional costs, including transportation expenses, customs fees, and the impact of fluctuating currency exchange rates. Such financial burdens may hinder the adoption of this technology, particularly among small and medium enterprises, creating obstacles for businesses to capitalize on the benefits offered by rotor-stator homogenizers.

Beyond financial implications, the reliance on imported rotor-stator homogenizers exposes industries to the risk of supply chain disruptions. Potential delays in procurement, transportation-related issues, and unforeseen circumstances in the exporting country can result in production bottlenecks, impacting the timely delivery of products and diminishing the overall efficiency of manufacturing processes.

Moreover, it is crucial to highlight that maintenance and repair costs constitute a major challenge for imported homogenizers, as local support for this is inadequate and homogenizers have to be shipped overseas for repairs and routine maintenance, causing disruptions. The need for ongoing maintenance and potential repairs can add substantial operational costs over time, further accentuating the financial strain on businesses relying on these imported devices.

Given the pivotal role that rotor-stator homogenizers play in industries such as cosmetics, addressing the current lack of localized design and manufacturing capabilities is imperative. Initiating a project dedicated to the indigenous design and fabrication of these homogenizers holds the promise of not only reducing costs but also mitigating the risks associated with supply chain disruptions. This proactive effort is essential to enhance accessibility and affordability, allowing industries to consistently achieve the desired quality and uniformity in their mixtures while alleviating the financial and operational challenges posed by external dependencies.

1.2 Objective

The primary goal of this project is to initiate the local design and fabrication of rotor-stator homogenizers, addressing the current dependency on imports for these essential devices. By establishing indigenous manufacturing capabilities for rotor-stator homogenizers, the project aims to achieve multiple objectives, including cost reduction, shorter lead times, and the mitigation of supply chain risks for industries relying on these devices for high-shear mixing in various applications.

Specifically, the project aims to undertake the comprehensive design, development, and manufacturing of rotor-stator homogenizers that align with the exacting standards of quality, precision, and reliability demanded by industries, with a particular focus on the cosmetic sector. This involves meticulous efforts in identifying appropriate materials, selecting manufacturing processes that ensure optimal performance, and rigorous testing to verify compliance with performance requirements.

In addition to manufacturing, the project seeks to optimize mixing times for products produced using rotor-stator homogenizers, specifically targeting applications within the cosmetic industry. This optimization aims to enhance efficiency and efficacy in the homogenization process, ensuring the production of stable and high-quality cosmetic formulations.

Furthermore, the project emphasizes the establishment of a local supply chain for the production of rotor-stator homogenizers. This entails sourcing raw materials locally, fostering partnerships with nearby suppliers, and building a network of distributors to cater to end-users. By establishing a robust local supply chain, the project aims to reduce lead times and costs associated with importing these critical components from foreign sources.

The overarching objective of this project is to provide a comprehensive and locally-driven solution to the challenges posed by reliance on imports for rotor-stator homogenizers. Beyond the focus on indigenous manufacturing, the project also aims to optimize mixing times, particularly in the cosmetic industry, contributing to local economic growth, supporting industrial development, and meeting the specific needs of industries requiring high-shear mixing for their applications.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

According to Fig.1 a substantial increase in the research of different aspects of homogenizers has been observed over the last twenty years. Homogenizers are capapble of creating a single phase emulsion from two or more substances which may not be miscible. Classic emulsions have a droplet size greater than 1 μm[1], where the droplet size refers to the size of dispersed phase in an emulsion. The most common techniques used for homogenization include the use of high pressure[2], microfluidization[3], emulsification via phase inversion[4], milling techniques[5], ultrasonic emulsification[6], solvent displacement methods[7], and high speed stirring using rotor stator homogenizers[8].

Of all the techniques, the rotor stator homogenization is the only technique in which the governing principle of mixing is the generation of high shear force only. Other processes also use the impact between the moving parts as a means to produce emulsions. While these techniques do have the advantage of creating a relatively smaller particle size, however, the frequent impact between the moving components requires that the design be able to withstand the intermittent force that is applied as a result. Comparatively, the rotor stator homogenization is often used for making macro-emulsions[9]. These emulsions have various applications in manufacturing such as petrochemical industry[10], food sector[11], and cosmetics[12]. A more extensive review of applications of emulsions used in cosmetics is provided by Calvo et al[13].

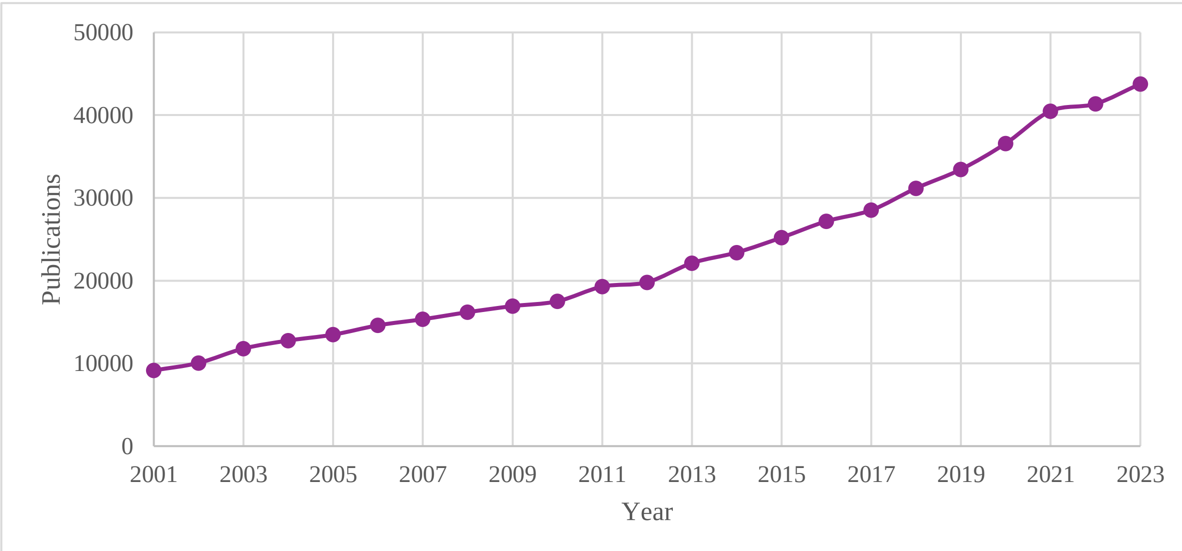

Figure 1 Trend in research in homogenization techniques over the last 20 years

In chapter two the review of literature is presented. It summarizes the existing knowledge in the area of the project while referring to significant publications (books, research papers) in the area of the research work. This chapter should be no more than 10-15 pages long and should explain the necessity of the project in the context of previous works.

2.2 Parameter Considerations

The homogenizer primarily comprises of two components – the rotor which will rotate via connecting rod attached to the motor, and the stator that is to remain stationary at all times while ensuring a consistent shear gap for uniform and effective emulsification. According to Floyd[14] the most crucial parameters to consider for an experimental setting of the homogenizer include the vessel temperature prior to the emulsification process, the time taken for the homogenization to complete, the rotor speed, rate of oil addition, temperature and pressure at which the process is to take place, and the number of passes through the homogenizer. The experimental account provided by Hanna et al.[15] indicates that an experimental setup can be an impactful means to observe the parameters pertaining to homogenization, and had concluded that the model created was sufficient to studying the droplet size within their scope of research.

The most prevalent experimental analysis observed from the literature is in the modification of the rotor blade geometry. For example, Yang et al.[16] analyzed the turbulent power consumption of the homogenization process by modifying the rotor blade curvature. Similarly, Rai[17] studied the performance of rotor blade for different twist angles. Another approach taken by Kumaresan[18] considers the existing rotor designs obtained from the standardized catalogues, while Rane et al.[19] have customized a set of rotor blade designs for analysis.

The design of the stator profiles provided by Vashisth et al.[20] compare the circular and square slots with regards to their homogenization efficiency based on the overall uniformity of emulsion density. The work of Henrik[21] provides more clarity regarding the need for different stator slot profiles. Wider slots give rise to re-circulation while narrower and smaller slots facilitate a more uniform turbulence. As such, narrower slots are suitable for dispersion and mixing of low viscosity products.

The dimensionless parameters provided by Bates et al.[22] were studied for vertical cylindrical vessels, and use dimensionless geometric relations to analyze the impeller power and the homogenization efficiency. Since the study is independent of dimensions, it may provide a suitable validation case to compare experimental results against.

2.3 Theoretical Analysis

The Reynold number is evaluated first in order to ensure whether the fluid domain is in the laminar or turbulent region. The shear rate could be found using the Hagen-Poiseuille equation in laminar regime. However, since most of the region in the homogenizer is aimed to be turbulent, a different set of equations must be used in order to obtain the shear rate. The transmitted power P consumed in moving the rotor is given as the product of the generated torque T and the angular velocity ω.

$$P = T\omega$$

The angular velocity can be related to the linear velocity V using the radius of the rotor R_i and radius of stator R_o. This can in turn be used to evaluate the volumetric flowrate Q within the shear gap in both the radial and axial directions.

$$V_r = R_i\omega \qquad\qquad Q_r = AR_i\omega$$

$$V_z = \frac{1}{4\mu}\left(-\frac{\partial p}{\partial z}\right)\left[\frac{\ln(r/R_i)}{\ln(R_o/R_i)}(R_o^2 - R_i^2) - (r^2 - R_i^2)\right]$$

$$Q_z = \frac{\pi(R_o^2 - R_i^2)}{8\mu}\left[R_o^2 + R_i^2 - \frac{R_o^2 - R_i^2}{\ln(R_o/R_i)}\right]$$

The expression for the torque generated due to the fluid can be expressed in terms of the radii of rotor and stator, the effective length in which the shearing occurs between the two entities l, and the fluid viscosity μ.

$$T = \frac{2\pi\mu\omega l R_i^3}{R_o - R_i}$$

Since the shear gap regime can be approximated as a short annular pipe for simplicity, the Darcy factors can be used in order to evaluate the wall shear stress τ_w.

$$\tau_w = \frac{1}{8} f_D \rho \bar{V}^2$$

In the above expression $\bar{V}^2$ indicates the effective velocity on the wall of the stator, since the effect of shear would be observed due to the fluid motion along both the radial as well as the transverse axes. The Darcy factor f_D is an empirical value that is to be consulted from the tables based on different values of the Reynold number.

CHAPTER 3: METHODOLOGY

A homogenizer is a type of mixing equipment used to create a uniform and consistent mixture by breaking the components and evenly distributing them throughout the solution. It is a common industrial practice that is used readily to create stable emulsions for various use cases. In the cosmetic industry, for example, high-shear homogenizers in cosmetics facilitate the formation of kinetically stable emulsions with finely dispersed droplets through mechanical and pressure-driven disruption, enhancing active ingredient penetration and optimizing formulation scalability from R&D to manufacturing volumes. For the scope of our project, we decided to focus on cosmetic industry application based on market analysis.

3.1 Preliminary Design Considerations:

Within the cosmetic industry, achieving uniform and stable emulsions with targeted particle sizes is paramount. This is where high-shear rotor-stator homogenizers excel, offering advantages over their ultrasonic counterparts for large-scale production. Both homogenizer types utilize distinct mechanisms to achieve dispersion:

3.1.1 Rotor-stator homogenizers:

They employ a rapidly rotating inner rotor within a stationary outer stator. The narrow gap between them generates intense shear forces and turbulence, disrupting and dispersing components in the mixture. This approach excels at handling large volumes and diverse viscosities, common characteristics of cosmetic formulations.

3.1.2 Ultrasonic homogenizers:

These devices leverage high-frequency sound waves transmitted through a probe immersed in the sample. These waves create cavitation bubbles that collapse rapidly, inducing intense shear forces and micromechanical mixing. While ideal for achieving extremely fine dispersions, their effectiveness diminishes with increasing sample volume and viscosity.

3.1.3 Justification for rotor-stator choice in cosmetics:

Despite the prospects of extremely fine dispersions offered by ultrasonic homogenizers, their limitations in scalability, cost, and viscosity compatibility render them less suitable for the diverse demands of high-volume cosmetic production. In contrast, rotor-stators excel in these crucial areas, efficiently handling large batches, offering a spectrum of affordable options, and adeptly processing various viscosities while achieving desirable particle sizes for most cosmetic applications. Their practicality and cost-effectiveness outweigh the marginal benefit of ultra-fine dispersions, making them the clear choice for the homogenization needs of the cosmetic industry.

3.2 Selection of the type of Rotor-Stator Homogenizer:

Rotor-stator homogenizers may be classified further into two categories:

3.2.1 Batch Homogenizers:

Batch homogenizers operate on a discrete volume basis, processing entire batches within a closed vessel before moving on to the next. They employ various mechanisms, including high-pressure pumps, rotor-stator shearing, and ultrasonic cavitation, to disrupt and disperse components, creating uniform mixtures. Their versatility allows for handling diverse viscosities and volumes, making them ideal for laboratory experimentation and small-scale production.

3.2.2 In-Line Homogenizers:

In-line homogenizers integrate directly into production lines, continuously processing flowing streams of material. They often rely on high-shear rotor-stator designs to achieve homogenization and are well-suited for large-scale, high-throughput applications. While offering efficient continuous processing, they necessitate higher initial investment and are less adaptable to diverse viscosities and small batch sizes.

3.2.3 Justification for Batch Homogenizers:

For the sake of our project where we aim to work with small batches, batch homogenizers excel in both technical and economic suitability. Their closed vessels provide precise control over homogenization parameters and easy cleaning between experiments, perfect for iterative development. Additionally, their diverse processing options and configurability allow exploration of various homogenization mechanisms and optimization for specific formulations and viscosities, crucial for achieving desired results. Finally, compared to the higher initial investment of in-line homogenizers, batch homogenizers offer a more cost-effective solution for our current project scope. Therefore, given the project's focus and resource constraints, batch homogenizers represent the optimal choice for achieving efficient and adaptable homogenization.

3.3 Component Design, Selection & Analysis

3.3.1 Motor Selection

To initiate the design process efficiently, we prioritized motor selection from readily available local options. Due to budget constraints, a custom motor exceeding predefined specifications was not pursued. Selecting the motor upfront established crucial design constraints, guiding the subsequent physical design decisions. Two readily available options were considered: a blender motor and a food processor motor. The higher torque output of the food processor motor deemed it excessive for our application's requirements. Consequently, we opted for a 500W blender motor, aligning perfectly with the required performance parameters, and offering an optimal balance of power and cost-effectiveness.

3.3.2 Rotor design

The rotor acts as the key component responsible for generating the high shear forces that disrupt and disperse the sample. It's a rapidly rotating component, typically constructed from robust and corrosion-resistant materials like stainless steel or aluminum. Its design varies depending on the desired homogenization intensity and sample characteristics. Some rotors feature blades or other geometric features that enhance turbulence and shearing within the narrow gap between the rotor and its stationary counterpart, the stator.

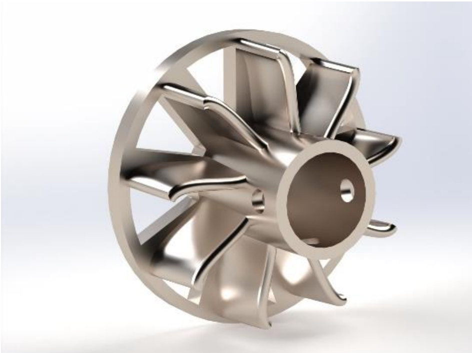

Figure 2 CAD Rendering of the final rotor design (front)

The rotational speed of the rotor, combined with its geometry and the gap size, directly impacts the shear forces generated, allowing for targeted control over the homogenization process.

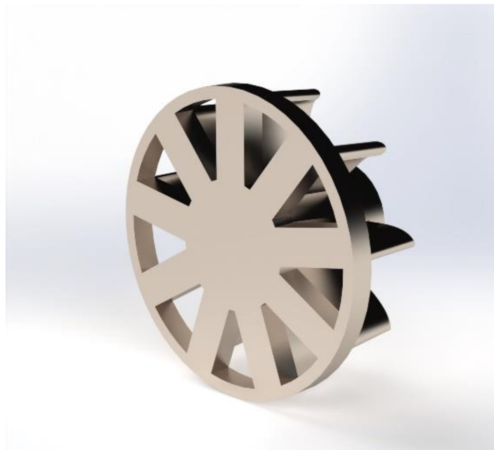

Figure 3 CAD Rendering of the final rotor design (rear)

Our rotor design draws inspiration from existing literature and incorporates specific features to achieve its function. It comprises two key elements:

i. **Shear Blades:** These blades are responsible for imparting the high shear forces required for particle disruption and dispersion within the sample. Their geometry and thickness directly influence the intensity of the shearing action. In our design, the blades have a thickness of 8 mm, optimized based on our specific homogenization requirements and manufacturability constraints.

ii. **Guide Vanes:** These vanes serve the dual purpose of directing the axial flow of the liquid through the homogenization zone and enhancing mixing within the chamber. Their height of 13 mm was determined based on their intended function and available space within the homogenizer chamber.

The overall size and dimensions of the rotor were carefully chosen to be compatible with our target batch size of 2-3 liters, as identified through literature review. Based on the dimensions of the chosen beaker and desired liquid volume, we opted for an outer diameter of 49.8 mm. Additionally, the total thickness of the rotor was chosen proportionally to the stator dimensions to ensure proper fit and maintain the critical gap necessary for shearing.

3.3.3 Stator Design

The stator acts as the stationary counterpart to the rapidly spinning rotor. Typically crafted from robust and corrosion-resistant materials like stainless steel or aluminum, it forms a fixed housing that surrounds the gap through which the sample flows. This crucial gap, meticulously controlled in size, facilitates the intense shear forces generated by the rotating rotor. The stator's internal geometry plays a crucial role in guiding the sample flow and enhancing the shearing action. Features like grooves, channels, and baffles can be incorporated to create turbulence and promote efficient interaction between the sample and the rotor blades.

Figure 4 CAD Rendering of stator design (View 1)

Figure 5 CAD Rendering of stator design (View 2)

Our initial stator design is informed by research and subject to future optimization. We currently favor a circular profile, acknowledging the presence of other shapes in available literature and reserving the right to adapt based on testing results. The chosen profile features small, 5 mm diameter holes, aligning with established standards in the cosmetics industry. Both the geometry and size of these features will be iteratively refined through testing to achieve optimal performance. In terms of dimensions, the stator boasts an inner diameter of 51.8 mm, an outer diameter of 57.8 mm, and a thickness of 3 mm. These dimensions ensure compatibility with the chosen rotor design and maintain the critical gap size essential for effective shearing.

3.3.4 Shaft:

A shaft was designed for transfer of torque from the motor to the rotor. The diameter was selected to be 15 mm, in proportion to the diameter of the rotor.

Figure 6 Shaft Design

A coupling had to be designed to connect the shaft to the motor attachment. The motor side of the coupling has an inner diameter of 8 mm, and the shaft side is at an internal diameter of 15 mm.

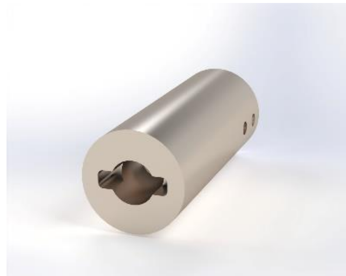

Figure 7 Motor-shaft coupling design (View 1)

Figure 8 Motor-shaft coupling design (View 2)

3.3.5 Bearing

An off the shelf bearing of 15 mm internal diameter was selected, along with its housing.

Figure 9 Bearing & bearing housing

The bearing is the SKF UC YAR 202. From the information in its catalogue, its maximum axial load bearing capacity is 1.1875 kN, while the applied load doesn't exceed 3 N.

3.3.6 Support Structure

The support rods are crucial components in our homogenizer assembly, responsible for:

i. **Minimizing vibrations:** Their strategic placement, determined by the pre-existing holes in the bearing housings, ensures rigidity and dampens vibrations during operation. These vibrations could negatively impact the homogenization process, particularly affecting the sensitive shear gap (distance between rotor and stator) crucial for efficient particle disruption.

ii. **Maintaining shear gap:** The rods directly connect to the stator at its base, where precisely designed grooves act as seats for securing the rods with nuts. This robust connection ensures the optimal and consistent positioning of the stator, guaranteeing the critical shear gap of 0.8 mm remains uncompromised during operation.

iii. **Structural integrity:** The four support rods extend downwards to connect to the base plate, forming a stable configuration. This configuration effectively transfers forces and minimizes stresses within the assembly, preventing unwanted movement and maintaining the integrity of the shear gap.\

Figure 10 Support Rod

The base plate serves as the foundation of the entire assembly, acting as the primary load-bearing member.

Figure 11 Mounting Plate

To improve stability and prevent a cantilevered design (which is prone to tipping), the base plate is connected to commercially available aluminum extrusions at its bottom. These extrusions, specifically assembled such that they provide a for wide base and robust profile to the assembly, contribute to:

i. **Enhanced stability**: The wide base area of the extrusions distributes the weight of the assembly more evenly, increasing its overall stability and resistance to tipping.

ii. **Low center of gravity:** By strategically designing the extrusions, thecenter of gravity of the entire assembly can be kept within the base area. This further enhances stability and minimizes the risk of tipping, especially during operation when vibrations are present.

Figure 12 Exploded view of rotor-stator assembly

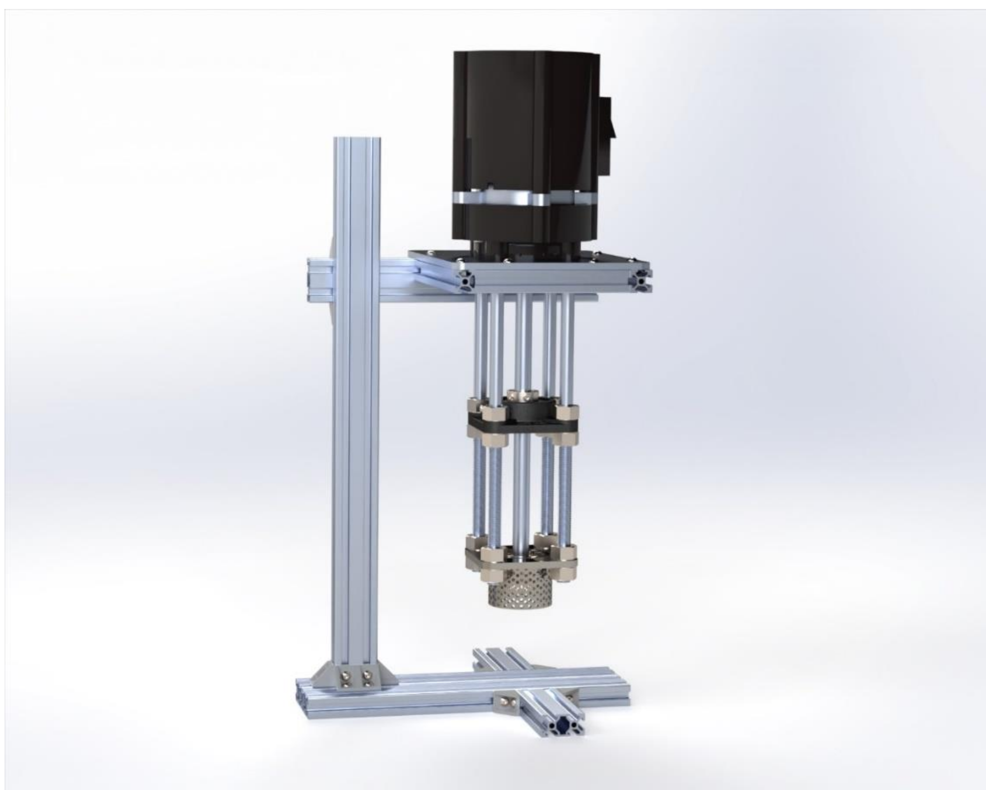

Figure 13 CAD rendering of final assembly

It is important to note that the motor housing, which is custom-designed, and 3D printed, also mounts onto the base plate. While contributing to the overall aesthetics of the assembly, its primary function is to stabilize the motor and integrate the speed control knob for convenient operation.

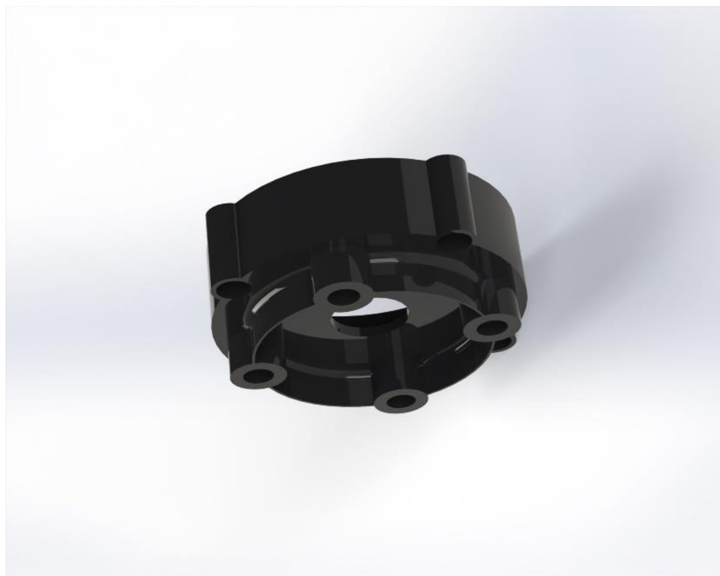

Figure 14 Motor housing

3.3.6 Structural Analysis of the Homogenizer

This analysis investigated the structural integrity of the homogenizer under applied loads. The individual components and their respective masses are listed in the table below:

Table 1 Mass breakdown of the assembly

Components	**Quantity**	**Individual mass (grams)**	**Total mass (grams)**
M12 Nuts	28	28.53	798.84
Bearing	1	572.92	572.92
Slot Nuts	33	1.17	38.61
Head cap screw	37	2.2	81.4
Corner bracket	14	23.37	327.18
Motor housing	2	317.95	635.9
Aluminum extrusions	4	442.24	1768.96
Motor	1	2000	2000
Base Plate	1	903.93	903.93
Connecting rods	4	83.48	333.92
Main shaft	1	143.14	143.14
Stator	1	366.15	366.15
Rotor	1	86.38	86.38

Coupling	1	94.99	94.99

The total mass of the homogenizer is approximately 8.15 kg.

The loading on the base plate is divided into two distinct regions:

1. **Middle holes:** These holes carry the load of the bearing, rods, rotor, and stator.
2. **Outer holes:** These holes carry the load of the motor and its housing.

This type of loading can induce bending stresses and potentially reduce the factor of safety (FOS).

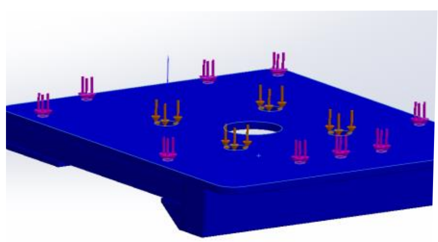

Figure 15 Stress Analysis on bolt holes

A static analysis of the aluminum extrusion using SolidWorks Motion Study revealed that it exceeded the minimum FOS of 5. The base plate, with an FOS of 7.44, demonstrated sufficient strength. All bolts also exhibited FOS values exceeding the minimum requirement of 2. The base rod had a minimum FOS of 6.5, indicating its ability to withstand the applied loads.

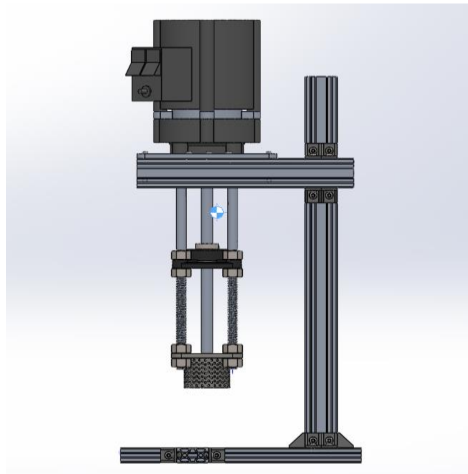

Figure 16 COG Analysis for final assembly

Additionally, the center of gravity analysis confirmed the design's stability. The center of gravity is positioned well within the base area, ensuring the homogenizer's resistance to tipping over during operation.

This structural analysis indicates that the homogenizer design is capable of withstanding the applied loads with sufficient factors of safety. The center of gravity analysis further confirms the design's stability, mitigating the risk of tipping over during operation.

3.4 Prototyping & Fabrication

In order to study the general trend of the selected design parameters on the emulsion formation and homogenization efficiency in general, the prototypes are developed in advance to study the trend, based on which the data sets are obtained to be studied. The results of the study are then compiled in order to decide upon the final design, which is then implemented on the rotor stator homogenizer.

The prototyping mainly comprises of the rotor and stator fabricated using 3D printing technology. The material used for the printing is PLA, which is durable and proved to be sturdy enough to withstand the stresses impeded upon operation. The 3D printed designs were then incorporated with the assembly, and the trial was run in accordance with the procedure discussed in the previous sections. This is to ensure that the experimentation is fair and that the analysis of the parameters fairly reflect upon the concept design proposed in the scope of the project.

Once the prototyping phase is completed and the desired results are accomplished, a mathematical model is used to identify the key parameters required for optimal performance, which are then implemented in the final design. During the fabrication process of the final design the manufacturing constraints were also taken into account, which had set the upper and lower bounds on the design parameters considered for our study in order to retain the practicality of our study.

Figure 17 Final Homogenizer Assembly (View 1)

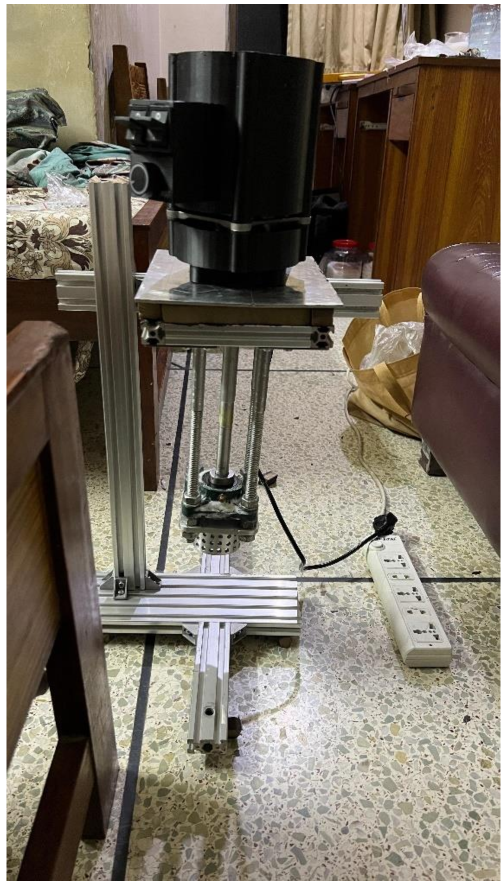

Figure 18   Final Homogenizer Assembly (View 2)

Figure 19 Close-up picture of stator

Figure 20 Close-up picture of rotor-stator shear gap

3.5 Bill of Materials

Present below is a detailed breakdown of all of the materials that went into the fabrication of the final design.

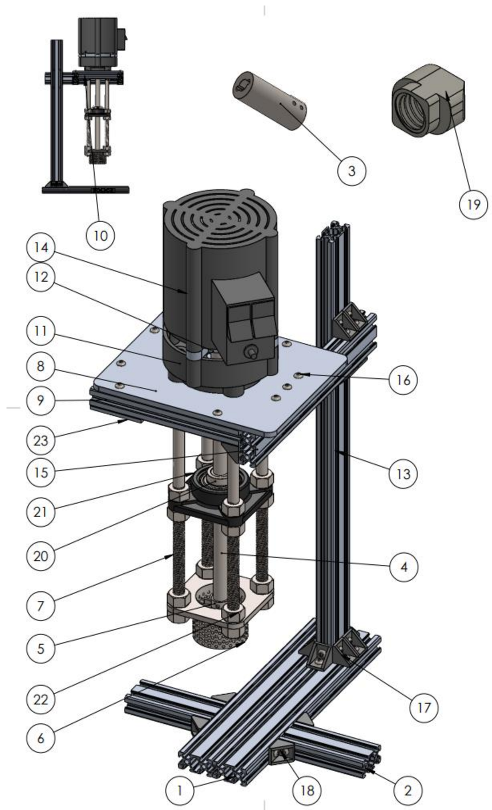

Figure 21 Assembly labelled for BOM

Table 2 Bill of Materials

ITEM NO.	PART Name	QTY.	Price
1	2040 Aluminum Extrusion Profile 300mm	2	4000

2	2040 Aluminum Extrusion Profile 100mm	2	
13	2040 Aluminum Extrusion Profile 500mm	1	
15	2040 Aluminum Extrusion Profile 270mm	1	
9	2020 extrusion 175mm	2	1660
10	2020 extrusion 134.5mm	1	
3	Coupling	1	5000
4	Center rod	1	220
5	Rotor (50mm)	1	15,000
6	Stator	1	11,000

7	Support rod 12mm	4	880
8	Base plate	1	3000
11	Motor housing 2	1	0
12	Motor	1	10,000
14	Motor housing	1	0
16	M5 x 12 Bolts	9	90
17	2020CornerBracket	16	640
18	M5 x 8 bolts	42	420
19	M5_T_Slot nut	35	1000
20	UC 202-bearing	1	1100
21	Bearing holder	1	
22	M12 nuts	20	300
23	2020 corner plates	2	240
			Total
			PKR 59,550

**Prices as of May 2024*

3.6 Testing & Parameter Optimization

After the fabrication and assembly of the basic structure, an experimental setup was designed in order to select the rotor-stator configuration with the best homogenization performance, characterized by the homogenization efficiency discussed later in the report. Extensive testing was conducted for various combinations and data was collected at different timestamps. This gave a diverse data set which was analyzed to select the most suitable parameters in keeping with manufacturability constraints.

3.6.1 Experimental Setup

A precisely controlled heating and mixing system was utilized to prepare the mixture for homogenization. This system consisted of a hot plate equipped with magnetic stirring capabilities, as well as a precise weighing balance accurate up to 3 decimal places. The magnetic stirrer ensured homogenous mixing of the fluid phases within the beakers while the hot plate provided precise temperature control.

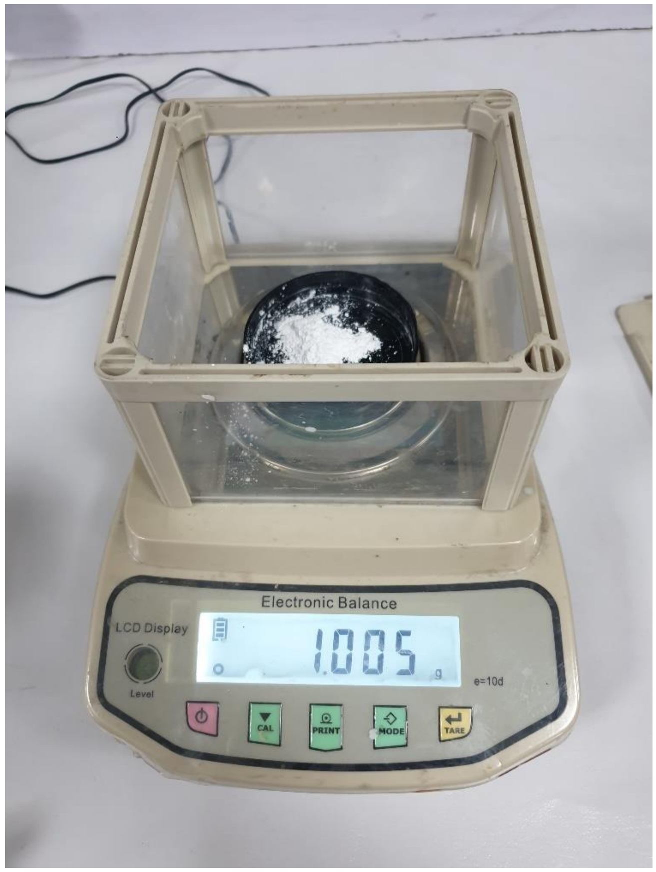

Figure 22 Weighing balance

A thermometer was continuously used to monitor the temperature of the agitated mixture in the beakers. Finally, a larger vessel was employed to perform the homogenization process itself.

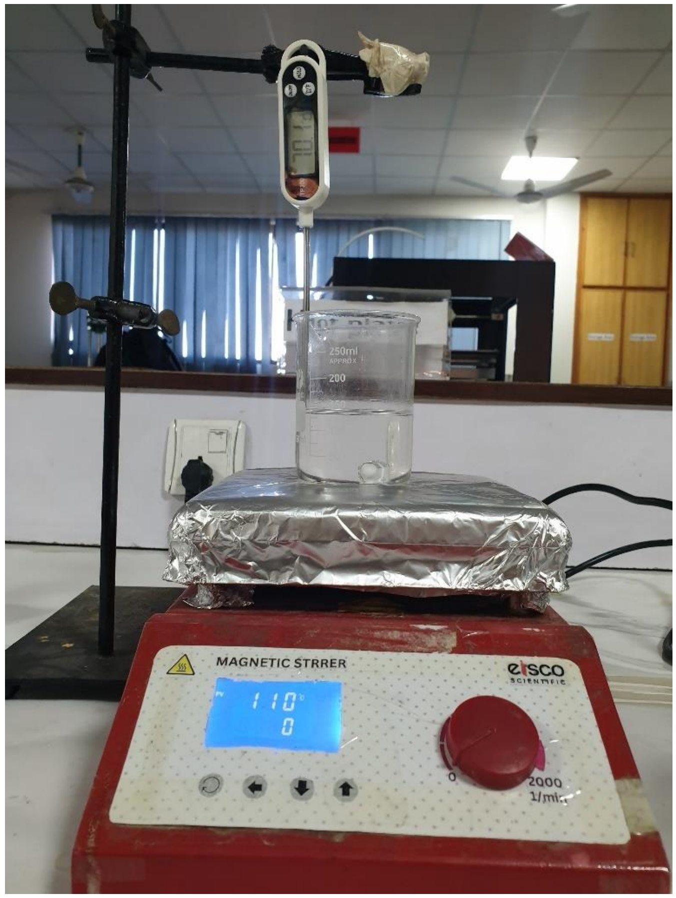

Figure 23 Hot plate setup

3.6.2 Composition

The composition of the emulsion is indicated in the table below. The “phase” column signifies the solubility of the particular component. The total sample size is 1 kilogram. This is the standard local industrial composition for a simple lotion base which is used in many cosmetic products:

Table 3 Emulsion composition for trials

Component	**Quantity (g)**	**Phase**
Water	842	-
White Mineral Oil	102	-
Glycerol monostearate (GMS)	15	Mineral Oil
Crodafos CES	20	Mineral Oil
Cetyl Alcohol	20	Mineral Oil
Carbopol 940	1	Water

This composition is adequate to study the textural properties and homogeneity of the emulsion.

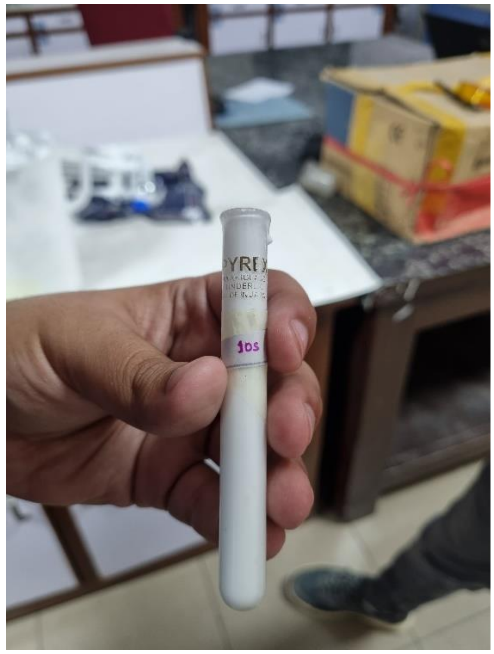

Figure 24 Sample drawn at 10 seconds

3.6.3 Procedure

The following procedure was followed for experimental testing:

i. All oil/water soluble components were weighed and arranged for easy access.

ii. The oil phase was heated to 80 °C.

iii. The stirrer was turned on and the oil soluble components were added. This resulted in a sharp decrease in the oil phase temperature, indicating an endothermic reaction. The oil was allowed to heat upto 75 °C. The oil phase appeared clear again at this temperature, while it appeared waxy for lower temperatures.

iv. While maintaining the oil at a temperature of over 70 °C, water was heated to around 80 °C as well.

v. The only water soluble component, Carbopol 940, was added gradually while the stirrer was turned on. The constant stirring was necessary in order to avoid the formation of clumps, which adversely affects the emulsion's texture. The water temperature was then allowed to rise to 70 degrees again.

vi. Upon ensuring that both phases were at the requisite temperature of 70 degrees, the water phase was added to the larger vessel.

vii. The rotor-stator end of the homogenizer was submersed in the water phase. The homogenizer was then turned on and the oil phase was gradually added. The process was allowed to proceed for intervals of 5, 10 and 15 seconds measured from the time of complete oil addition.

viii. Samples were also drawn and collected at the timestamps indicated above. This was necessary to compare and quantify the impact of the rotor-stator geometry, shear gap, and homogenization time on the homogenization efficiency.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 Experimental Results

The samples obtained from the homogenization of oil and water phases were based on the variations in different design parameters. These parameters were modified for each iteration in order to obtain a basis for the mathematical model. These parameters are as listed below:

- Shear gap d_s
- Stator holes diameter ϕ_s
- Guide vane length l_{gv}
- Shear blade thickness t_{sb}

The samples considered for the model are obtained at time steps of $5\ s$ up to $15\ s$. The densities of the samples are considered in order to represent the effect of homogenization time on the sample, along with the respective design parameters.

Table 4 Densities at different homogenization times for all samples

	$\mathbf{5\ s}$	$\mathbf{10\ s}$	$\mathbf{15\ s}$
Sample 01	0.500	0.631	0.871
Sample02	0.533	0.571	0.756

Sample 03	0.420	0.522	0.842
Sample 04	0.430	0.665	0.775

**All readings are in g/mL*

The basis of study of homogenization is considered to be the degree of homogenization η_h, which is given as the ratio of the obtained density values to the theoretical density values for a typical oil water emulsion.

$$\eta_h = \frac{\rho_{exp}}{\rho_{th}}$$

The value of theoretical density obtained is $\rho_{th} = 0.9 \text{ g/mL}$. The industrial standard range is between 0.8 g/mL and 1.03 g/mL for oil-water based emulsions. Thus, the degree of homogenization for the above data set can be represented as follows.

Table 5 Degree of homogenization for all samples

	$\mathbf{5\ s}$	$\mathbf{10\ s}$	$\mathbf{15\ s}$
Sample 01	0.556	0.701	0.967
Sample 02	0.592	0.634	0.840
Sample 03	0.467	0.580	0.936
Sample 04	0.478	0.739	0.861

The details of variations of the design parameters considered are as follows.

Table 6 Variation of parameters

Design Parameter	**Parameter Value 01**	**Parameter Value 02**
Shear gap d_s	0.8 mm	1 mm
Stator holes diameter ϕ_s	3 mm	5 mm
Guide vane length l_{gw}	13 mm	20 mm
Shear blade thickness t_{sb}	4 mm	8 mm

4.1.2 Plotted Results

The experimental results have been scatter plotted, as shown below. An approximate function defined curve has been added to predict the trend change.

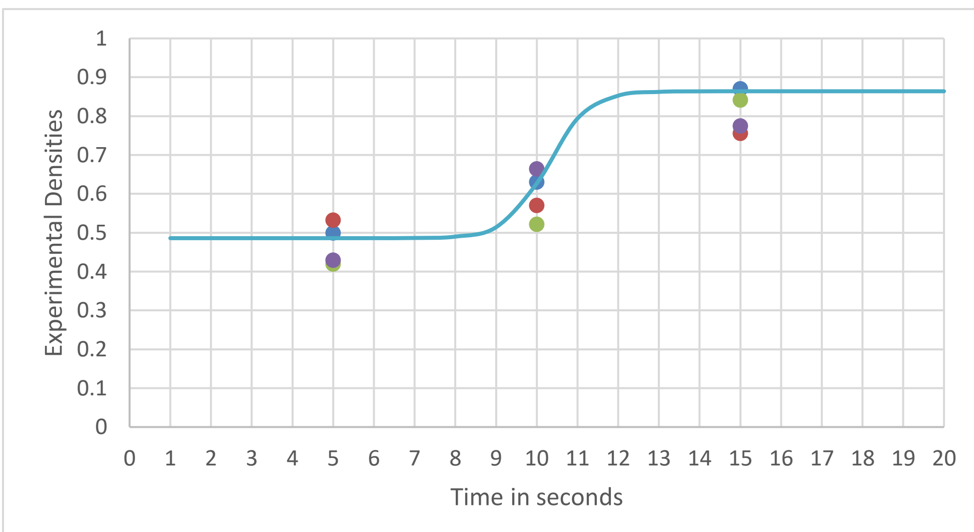

Figure 25 Experimental densities vs homogenization time

The function is given as followed, and the subsequent curve is plotted above:

$$0.18902 \times tanh(C_{12} - 10.259675) + 0.675$$

4.2 Optimization

4.2.1 Mathematical Modelling

The model for a single sample is represented by the expression:

$$-\sum_{i=1}^{n} P_i c_i = \eta_h$$

In the above expression P_i and c_i correspond to the parameter values and coefficient governing design parameter i. The homogenization is considered at $15\ s$ for all of the cases. The same applies for all samples, and thus the mathematical model can be represented as:

$$1c_1 + 3c_2 + 13c_3 + 4c_4 = -0.967$$

$$0.8c_1 + 5c_2 + 20c_3 + 4c_4 = -0.840$$

$$0.8c_1 + 5c_2 + 13c_3 + 4c_4 = -0.936$$

$$0.8c_1 + 5c_2 + 13c_3 + 8c_4 = -0.861$$

$$c_1 \approx -0.974451 \qquad c_2 \approx -0.081945 \qquad c_3 \approx 0.013714 \qquad c_4 \approx 0.018750$$

4.2.2 Discussion of optimization coefficients

The above coefficients represent the correlation of the design parameters with the degree of homogenization. A negative value represents that η_h value increases with a decrease in the parameter corresponding to the coefficient, and vice vera for a positive coefficient. Based on the results obtained the following observations can be made:

The negative value of c_1 represents a negative correlation between the shear gap and the degree of homogenization. This indicates that the homogenization is relatively better for smaller shear gap values. This is because the mixing mechanism for a homogenizer is through the high shear forces that are induced in the fluid as it passes through the shear gap and expelled from the stator orifices. The shear force induced in the fluid during the operation is represented as

$$F_s = \mu A u_y = \mu A \frac{du}{dy}$$

Where μ represents the dynamic viscosity, A is the effective contact area, and the u_y term represents the velocity gradient. As the shear gap reduces for constant rotational velocity, even though the velocity u remains unaffected, the shear gap y affects the overall velocity gradient. As such, the gradient increases with the decrement in shear gap values, which effectively raises the shear forces induced in the fluid during the operation.

The negative value of c_2 represents a negative correlation between the stator hole diameter and the degree of homogenization. This indicates that the homogenizations is relatively better for smaller stator holes, as compared to larger orifices. This can be attributed the the concept of volumetric flowrate Q, which relates the velocity u and orifice area A_o as

$$Q = uA_o$$

Thus, as the orifice area A_o is reduced for the same volumetric flowrates, the velocity of the fluid will increase in order to sustain the equation. As such, the fluid velocity will increase. This will effectively increase the resulting velocity gradient u_y discussed above, and eventually lead to an increase in the fluid shear.

The positive value of c_3 represents a positive correlation between the guide vane length and the degree of homogenization. This indicates that the longer guide vanes lead to better homogenization, because the purpose of the vanes is to direct the fluid out through the stator orifices while increasing the fluid entering the shear gap by creating pressure difference. By doing so, the guide vanes effectively increase the volumetric flowrate through the stator. Since the flowrate has a direct proportion with flow velocity, considering that the orifice dimension is constant, the flow velocity is also increased, which subsequently increases the shear force that acts upon the fluid. The guide vanes also ensure axial flow is maintained in the vessel, which allows the unhomogenized fluid to enter the shear gap while simultaneously discharging the homogenized fluid. The positive value of c_4 represents a positive correlation between the shear blade thickness and the degree of homogenization. This indicates that the shear blades pose a positive impact on the quality of homogenization. This is because the blade profile is such that when the fluid impacts on the surface, it is pushed into the shear gap, which effectively imposes additional shear force on the fluid. Thus the cumulative shear force on the fluid can be represented as

$$F_s = \mu A \frac{du}{dy} + F_o$$

Where F_o is the additional shear force due to the shear blade which is imparted in the radial direction.

4.3 Basic 2 Degree of Freedom Vibration Model

The vibration model for the homogenizer can be assumed as a dual mass spring-damper system, with the masses of homogenizer body and the support structure considered as individual entities, each with their own spring constant and damping coefficients. The purpose of this is to study the vibrational behavior of the homogenizer under operation, and to identify possible causes for it along with the corresponding mitigation strategies. The equations obtained can be expressed as

$$m_h\ddot{x}_h + c_h(\dot{x}_h - \dot{x}_s) + k_h(x_h - x_s) = 0$$

$$m_s\ddot{x}_s + c_h(\dot{x}_s - \dot{x}_h) + c_s\dot{x}_s + k_h(x_s - x_h) + k_s x_s = 0$$

The system is considered to be homogenous since the vibration occurs due to the motor action, and the corresponding assembly action, which are part of the masses considered. Thus, no external forces are considered in the analysis of the homogenizer assembly. The above equations can be compiled into an equivalent matrix form as follows

$$\begin{bmatrix} m_h & 0 \\ 0 & m_s \end{bmatrix}\begin{bmatrix} \ddot{x}_h \\ \ddot{x}_s \end{bmatrix} + \begin{bmatrix} c_h & -c_h \\ -c_h & c_h + c_s \end{bmatrix}\begin{bmatrix} \dot{x}_h \\ \dot{x}_s \end{bmatrix} + \begin{bmatrix} k_h & -k_h \\ -k_h & k_h + k_s \end{bmatrix}\begin{bmatrix} x_h \\ x_s \end{bmatrix} = 0$$

The structural analysis as shown above suggest the structural stability of the homogenizer components based on the different loading conditions that may act on the components. As such, the material selection conducted so far satisfies the needs of the product. The aluminum support rods ensure that the assembly does not get too bulky, and the multitude distributes the overall load as well as create some notion of symmetry to minimize vibrations due to misalignment. The material for the rotor and stator is, however, considered to be aluminum since the high shearing and the corresponding dynamics demand that the material should not only be able to withstand the stresses and forces developed due to the fluid, but also do so without deformation and compromising the overall durability of the product. The target capacity for homogenization per batch is at an estimate of three kilograms.

The mode of study of performance optimization of the homogenizer is mainly experimental, as found in the available literature. The theoretical analysis of a simplified model can be performed using the concepts of fluid shear, turbulence, and generalizations made to the Navier Stokes equations. One of the simplifications made is to consider the shear gap between the rotor and stator to be an annular domain, and the regions surrounding it to be simple cylindrical domains of the dimensions as per the component features. The mass transfer is subject to deliberation as of yet, and no substantial progress has been made in the regard due to its sheer complexity. The dimensions may also be modified based on the results obtained, however, that aspect seems unlikely.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Discussion & Conclusion

The design and fabrication of the rotor-stator homogenizer acknowledges the issue of lack of proper channels of procurement of locally manufactured equipment, due to which the emphasis of industrial requirements is diverted towards imported machineries. The project aims to provide a homogenizer capable of competing with the demands dictated by the manufacturers. Other categories of homogenizers such as the bead homogenizer work on the principle of imparting energy to the composition via impact, which further leads to diffusion phases within the regime. While this technique serves the purpose of homogenizing the mixture, impact is not generally preferred for the mixing phenomenon, as it might damage the components to be homogenized themselves. This issue is most prevalent in the pharmaceutical manufacturing, as the impacts can cause damage to the cell walls or break the bonds between compounds during homogenization[23].

The fabrication process involved careful consideration of different design parameters, as discussed in the previous sections, based on which the appropriate manufacturing techniques were deployed to generate a finished product that not only accomplishes the deliverables it had set out to achieve, but exceeds them – both when it comes to cost effectiveness, as well as performance and durability. The overall design is not too complex, and can be easily manufactured, which supports the cause that this equipment could be manufactured locally.

The performance of the rotor-stator homogenizer had been consistently aligned with the theorized model, which had further been validated using the literature survey conducted. Furthermore, the motor was made capable of supplying a variable power to increase the subsequent shaft speed or the developed torque at the expense of variable power.

5.2 Limitations

Despite the simplicity of the design, owing to the few key components that play a pivotal role in the performance of the assembly, the main issue arose with the manufacturability constraints pertaining to the stringent design requirements. The most prevalent issue that arose was the maintaining of the shear gap not during the manufacturing process, but also during the operation as well as afterwards in order to ensure design safety and repeatability of the operation using the same design. This problem had to be extensively studied in order to fabricate a functional design, and despite the parameter having the greatest impact on the degree of homogenization, it is governed not only by the requirements of the end product, but also the manufacturing capabilities available.

Another design constraints lies within the stator profile. The profile must be uniform in order to ensure adequate degree of homogenization, while also ensuring that the volumetric flowrate is optimized in order to avoid choking within the shear gap. A possible remedy to the issue could have been to take the surface roughness into account, however, it would require further study in order to establish the trend between the two parameters, if any are discovered at all.

The shear gap also significantly limits the nature of the substances that can be homogenized in the assembly. For example, colloidal particles or agglomerates cannot be treated in the device, since they can lead to issues of clogging or uneven pressure and velocity gradients. These can further lead to complications of unnecessarily high torque demands or uneven stress profile generation at the rotor and stator features. Solids impart generally greater force upon impact, which is prevalent in turbulence. This can lead to erosive wear in the design and subsequently damage the features that have a direct relation with the degree of homogenization.

5.3 Recommendations

Taking the aforementioned risks and mitigation strategies into account, the most reasonable approach would be to correlate more design parameters in order to create a holistic review of the entire process, along with the adequate correlation of each variable. This can further be treated as an optimization problem constrained with the desired outcomes and solved accordingly. The mathematical model obtained can then be used to study the affects of different design criterion, and how the parameters correlate to each other as well.

The study of vibration model can also be refined to incorporate the performance curves of the individual components, and how each of them are integrated to create a more comprehensive review of the overall design.

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