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COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF A UNIQUE BIODIESEL PRODUCTION SYSTEM BASED ON HYDRODYNAMIC CAVITATIONS

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ABSTRACT

Purpose: The study aims to improve biodiesel production through hydrodynamic cavitation, focusing on increased energy efficiency, higher yields, and reduced production time. By optimising the production process, especially with the use of waste cooking oil.

Design/Methodology/Approach: A computational fluid dynamics (CFD) analysis was performed to model the flow of biodiesel within a multi-plate system featuring several orifices. Theoretical input and output velocities calculations were derived from experimental mass flow rates. The CFD analysis provided pressure distribution along the pipe walls, which was utilised to assess the lifespan and damage cycles of the cavitation pipe and to study the behaviour of fluid turbulence.

Research Limitation: The research focuses on simulating flow behaviour in acrylic pipes within designated boundary conditions.

Findings: The research showed that producing biodiesel through hydrodynamic cavitation markedly lowers production expenses and duration while enhancing energy efficiency and output. Computational fluid dynamics (CFD) analysis offered valuable information about the distribution of pressure, velocity, and turbulence, aiding in optimising the cavitation pipe design.

Practical Implication: An optimised design for cavitation chambers has the potential to enhance the cost-effectiveness and efficiency of biodiesel production, positioning it as a useful substitute for traditional fuels.

Social Implication: Embracing this technology can help mitigate environmental pollution by repurposing waste cooking oil and lessening reliance on non-renewable petroleum fuels, thereby supporting global sustainability objectives.

Originality/Value: This study introduces an innovative method for producing biodiesel using hydrodynamic cavitation and CFD analysis to improve pipe design and production parameters. It addresses a significant gap in boosting biodiesel's economic and environmental feasibility, offering a scalable and sustainable alternative for fuel production.
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Keywords: *Biodiesel. cavitation. damage cycle.* energy. *life cycle*

INTRODUCTION

The current upswing within the variety of automobiles has sparked an expanded hobby in fossil fuels (Halwe et al., 2023). Some international locations importing massive crude petroleum bring an enormous worldwide effective alternative. Consequently, there was a giant exploration for opportunity fuels and biodiesel to function as the proper diesel alternative for inner combustion engines (Halwe et al., 2022; Chatur et al., 2023).

Consequently, various vegetable oils, inedible plants, animal fat, and leftover cooking oil can all be used to make biodiesel. (Chatur et al., 2023). However, the preparation methods of biodiesel have drawbacks; the transesterification process is the most widely used. One of the significant drawbacks of the alkaline transesterification process is that it is unsuitable for higher free fatty acid-containing feedstock like waste cooking oil (WCO). Catalysts like sodium hydroxide (NaOH) and potassium methoxide (KOCH3), which are alkaline in nature, end up in saponification during a reaction with moisture (Halwe et al., 2021). Hence, conventional methods have failed to produce biodiesel from cost-effective feedstock like WCO.

This is why research should be encouraged toward intensification technologies for feedstock like WCO. Hydrodynamic cavitation is the intensification approach that yields the highest alkyl ester conversion in the shortest time among supercritical, microwave, and hydrodynamic cavitation. (Halwe et. al., 2021). As a result, it is regarded as one of the best technologies for producing WCO biodiesel.

In this discipline, modelling techniques based on CFD simulations are crucial for optimising complex systems in conjunction with actual experimental setup data and for examining the impact of several operating and geometrical variables. To ascertain the cavitation effect on the pipe for various configurations and items in the pipe, this research proposes a geometrical optimisation criterion by combining CFD simulations with an experimental setup. The current investigation presents the CFD study of multiple orifice holes in a pipe that replicates the marbles and pebbles in a real experimental setting.

LITERATURE REVIEW

The development of vapour bubbles within a liquid at low-pressure zones when the liquid has been driven to high speeds is known as cavitations (Franc et al., 2005; Gogate et al., 2006). Which ultimately causes the segmentation and enlarging of the bubble series that passes across higher-pressure regions (Halwe et al., 2021). These bubbles further collapse with a significant rise in pressure and temperature (Abdullah et al., 2012; Roa et al., 2015). Due to cavitations, there are various problems in turbomachinery like erosion of turbine blades and guide vanes (Roa et al., 2015), but it can also be used for process intensification in wastewater treatment plants (Musmarra et al., 2016; Capocelli et al., 2014), microorganism inactivation (Capocelli et al.,2014), emulsification processes (Pandit et al., 2007), and also be used in production of biodiesel (Abdullah et al.,2012), the potentiality of Christian Horst provides information about the use of ultrasonic cavitations in enhancing chemical-physical processes. Ozonek effectively summarised the application of cavitations (Ozonek, 2012) in more detail by Feng et al. (2015).

The primary features of cavitation in process intensification are the creation of multi phases and the giant tumults dominion that raises local heat and mass transfer coefficients and reaction rates. (Pandit et al., 2008). These characteristics give the biodiesel transesterification process a highly reactive system. (Ji et al., 2006). Triacylglycerides from a variety of feedstock can be permuted into fatty acids through a process called transesterification. Reaction times can be shortened, yields can be raised, operating conditions can be expanded, and thermic self-sustaining reactions can be produced.

Reactor size is smaller at higher rates. High concentrations of Free Fatty Acids (FFA), such as leftover cooking oil, can be used as a raw material by building an appropriate cavitation setup, which lowers energy usage (Gogate et al., 2008).

Biodiesel is the most widely utilised biofuel since it is the renewable counterpart to petro-diesel. It is frequently blended with petro-diesel to form BX (x% biodiesel, (100-x) % petro-diesel). Environmentally sustainable and economically competitive processes are required for production. [(Piemonte et al., 2014, Piemonte et al., 2015). To prepare feedstock for base-catalyzed biodiesel synthesis (Mahamuni et al., 2010), with shorter reaction times, less expensive reagents, less extreme physical conditions, and less expensive and smaller chemical plants, the feedstock price decreases. However, costs rise in this process (Boffito et al., 2015.).

Compared to other technologies, such as ultrasound, the hydrodynamic cavitation method for producing biodiesel is more affordable, scalable, and energy efficient (Gogate et al., 2008), because it properly sets up the fluid flow restriction.

The experimental setup, modelling development, and computational fluid dynamics analysis on Ansys are the main areas of concentration for the academic community. More complicated geometries have not been the subject of much research (Pandit et al., 2011). Few models are available for CFD optimisation [(Pandit et al., 2011; Tarash et al., 2014).

METHODS

Computational Fluid Dynamics Analysis:

The study of forecasting fluid flow, heat and mass transfer, chemical reactions, and associated phenomena is known as computational fluid dynamics or CFD. CFD solves the Navier-Stokes equations for mass, momentum, and energy conservation to forecast these occurrences, as shown in equation 1.

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{\nabla P}{\rho} + v\nabla^2 \boldsymbol{u} \tag{1}$$

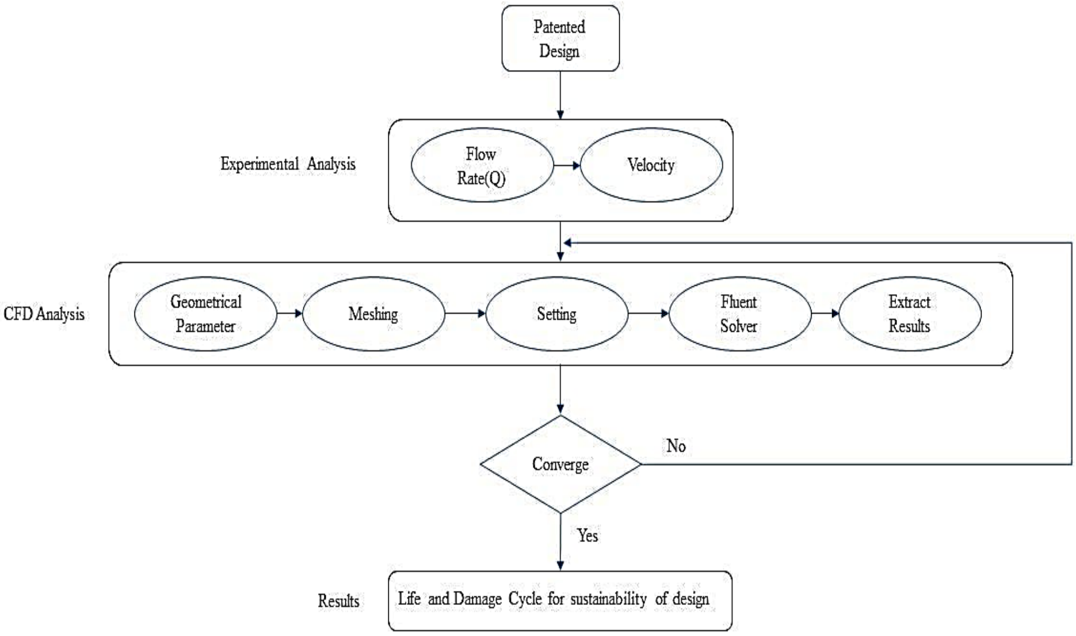

Figure 1: Flow chart of Numerical Simulation

By lowering the overall effort and expense needed for experimentation and data collection, CFD analysis enhances testing and experimentation. Using a CFD study, one can comprehend the flow and pressure creation during the design phase. Understanding flow models, flow separations, transient effects, physical interactions, proving assumed models, experimental results validation, parametric studies, structural simulations, oil and gas pipeline design for maintaining optimal pipe networks, etc., are some of the procedures that form the foundation of any engineering CFD analysis. Current analysis has produced visually represented data (Halwe-Pandharikar, 2021) for efficiently operating a patented machine. Figure 1 shows a detailed flow chart summarising the steps to be followed in the current analysis.

Experimental Design

A patented design (Halwe-Pandharikar, 2021) is used as a hydrodynamic cavitation (HC) reactor experimental assembly (Panda et al., 2020), as can be seen in Figure 2. The cavitation process is carried out. The cavitations reactor consists of a 30 L capacity storage vessel connected to a hydroelectric oil-sealed pump of 1 HP competence. The pump has a frequency of 50 Hz and runs at 2800 rpm, giving a discharge of 1200 LPH. Power consumption is 1.20 KW with head within the 6-40 meters range. The HC reactor pipe is made up of acrylic material. The HC reactor is kept running for 30 minutes for two input cases, as shown in Table 2, to get input and output boundary conditions. CFD analysis is carried out over the cavitation pipe's geometry to calculate the effect of the cavitation phenomenon.

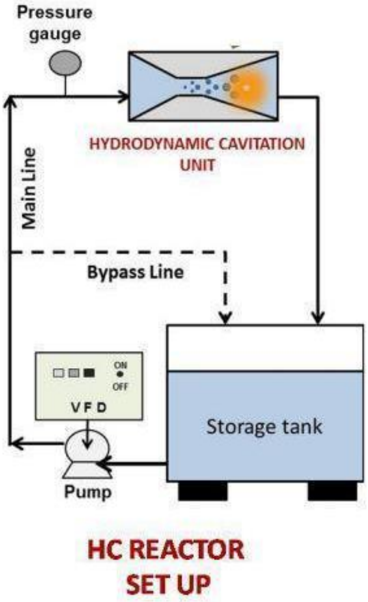

Figure 2 Hydrodynamic cavitation reactor (Reprinted with permission from Ref. Debabrata Panda, 2020[9], Copyright 2020 MDPI)

Physical Model:

Figure 3 represents a structural diagram simulated of a cavitation pipe with ‘d’ inner diameter, ‘D’ outer diameter, ‘H’ height, and multiple orifice plates attached up to length l. Table 1 provides details of the simulation's input parameters.

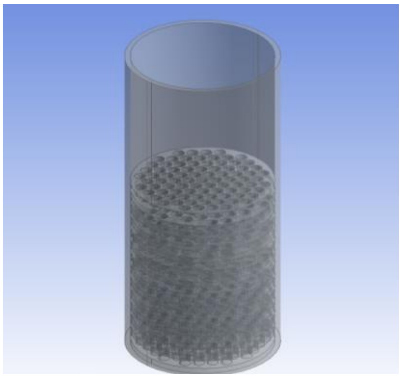

Figure 3: Structural geometry of cavitation pipe

Table 1 Details of simulation input parameters

Name of Material of Pipe	Acrylic Pipe	**Name of Fluid**	Waste Cooking Oil
Mechanical Properties		**Mechanical Properties**	
Young’s Modulus	3170 N/m2	**Density**	875 kg/m^3
Density	1.81e-06 kg/m^3	**Kinematic Viscosity**	4.07 C. St.
Poisson’s Ratio	0.4	**Dynamic Viscosity**	3.57 C. Poise

Generation of mesh:

ANSYS Parametric Design Language (APDL) is used to generate computational domains for the grid, as shown in Figure 4 (a), representing the meshing of flow inside the pipe, and Figure 4 (b), representing the meshing of the outer pipe. The accuracy of simulation results is directly influenced by the quality of the meshing. Also, high-quality meshes can reduce computational time. The current simulation geometry is complex, so unstructured tetrahedral meshing is used to discretise the computational domain.

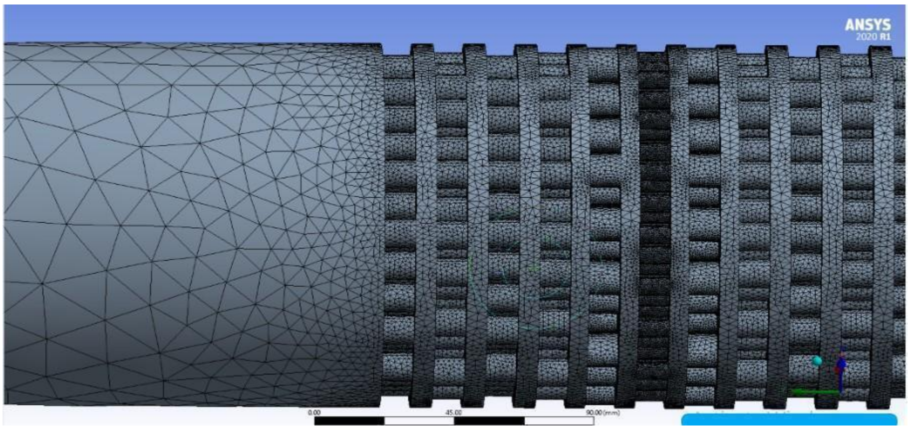

Figure 4 (a) Meshing of flow inside the pipe

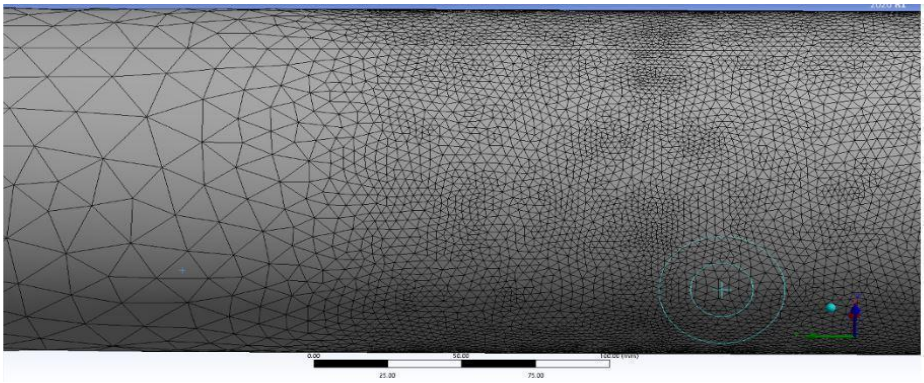

Figure 4 (b) Meshing of outer pipe

Boundary Conditions and Solver

Boundary conditions at Inlet

As shown in Table 2, boundary conditions are given by considering two different experimental inputs. In the first case, the bypass valve for a given patented design (Halwe-Pandharikar, 2021) is kept fully open. As per-flow rate calculations, velocity is taken as the y velocity component as the direction of the cavitations pipe is vertical. As per the inlet boundary condition, the velocity at the pipe inlet is 0.6904 cm/sec. The fluid is assumed to enter with negligible horizontal velocity. In the second case, the bypass valve for a given patented design (Halwe-Pandharikar, 2021) is kept half open and as per flow rate calculations, velocity is taken as y velocity component as 0.27989 cm/sec.

Boundary conditions at Outlet

For outlet boundary conditions, in the first case of the bypass valve fully open, as per flow rate calculations, the outlet velocity is taken as 0.4227 cm/sec. In the second case of the bypass valve half open, as per flow rate calculations, velocity is taken as 0.2196 cm/sec. The assumption for flow is a fully developed, steady, turbulent flow.

Table 2: Input and Output Boundary Condition

1. Case 1: Flow through full open bypass valve	
Mass flow rate	333.33cm3/sec
Inlet Velocity	0.6904 cm/sec
Outlet Velocity	0.4227 cm/sec
2. Case 2: Flow through half open bypass valve	
Mass flow rate	135.135 cm3/sec
Inlet Velocity	0.27989 cm/sec
Outlet Velocity	0.2196 cm/sec

Initialization

In solution initialisation, Fluent was prompted to compute from the inlet. Iterations are done until the convergence is achieved for the current solution. Using the waste cooking oil properties for two cases (Table 2), turbulent intensity and Reynolds number are calculated using eq. 2 and 3. (Where ρ =875 kg/m^3, $\mu = 0.0000936$, D = 12.4 cm and only velocity is varying in both cases as shown in Table 2). Since Re in both cases is greater than 4000, flow is fully developed turbulent flow (Schlichting et al., 1979)

$$Turbulentintensity \ = \ (\frac{\rho VD}{\mu})^{-1/7} = Re^{-1/7} \tag{2}$$

$$Re = \frac{\rho VD}{\mu} \tag{3}$$

Reynolds's number and turbulent intensity calculation for first case:

$$Re1 = \frac{0.875*0.6904*12.4}{0.0000936}$$

Re1 = 80030.34188

$$Turbulentintensity = \ 80030.34188^{-1/7}$$

$Turbulentintensity$ = 0.1993, (for case 1.)

Reynolds's number and turbulent intensity calculation for second case:

$$Re2 = \frac{0.875* \ 0.27989 \ *12.4}{0.0000936}$$

Re2 = 32444.51389

$$Turbulentintensity = 32444.51389^{-1/7}$$

$Turbulentintensity$ = 0.2267, (for case 2).

RESULTS AND DISCUSSION

The computational analysis performed in this research provides a valuable perspective on cavitation behaviour in biodiesel flows through an acrylic pipe under different conditions. The velocity streamlines and pressure contours (Figures 5–12) present a comprehensive visualisation of fluid dynamics in two scenarios, emphasising the contrasts between fully opened and half-opened bypass valve states. The velocity ranges from 4.587×10^{-2}m/s to 8.520×10^{-6} m/s, illustrating a gradual dissipation of energy as the fluid passes through the orifices, aligning with findings from studies like those of (Pandit et al., 2008), which highlights the energy transfer and pressure fluctuations resulting from cavitation.

The observed pressure range of 4.389×10^{0} Pa to -3.061×10^{-1} Pa is essential for understanding the effects of turbulence on cavitation zones, supporting previous research (Capocelli et al., 2014) that such fluctuations can affect material fatigue and deformation. The static structural analysis (Figures 7–12) reveals minimal deformation 7.136×10^{-8} mm and elemental stress 1.934×10^{-5} Pa, confirming the durability of the acrylic material against stress induced by cavitation.

The results of the CFD analysis strongly agree with existing literature that emphasises the significance of cavitation in causing localised pressure reductions and fluctuations in velocity. Research conducted by (Mahamuni & Adewuyi, 2010) examines how the interaction between pressure and velocity can lead to cyclic stress, which may affect the lifespan of materials. The contour plots depicting damage and life cycles (Figures 13–16) further illustrate this phenomenon, revealing substantial variability in maximum and minimum values based on differing flow and pressure conditions. This analysis reflects the findings of (Franc & Michel, 2005), who demonstrated the effects of cavitation-induced pressures on material performance over time.

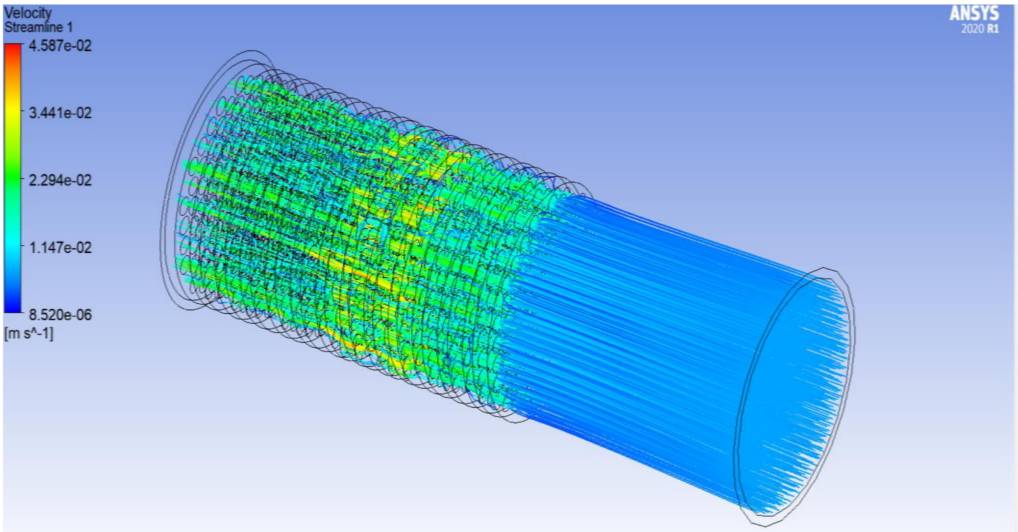

Figure 5: Velocity streamline for Case 1

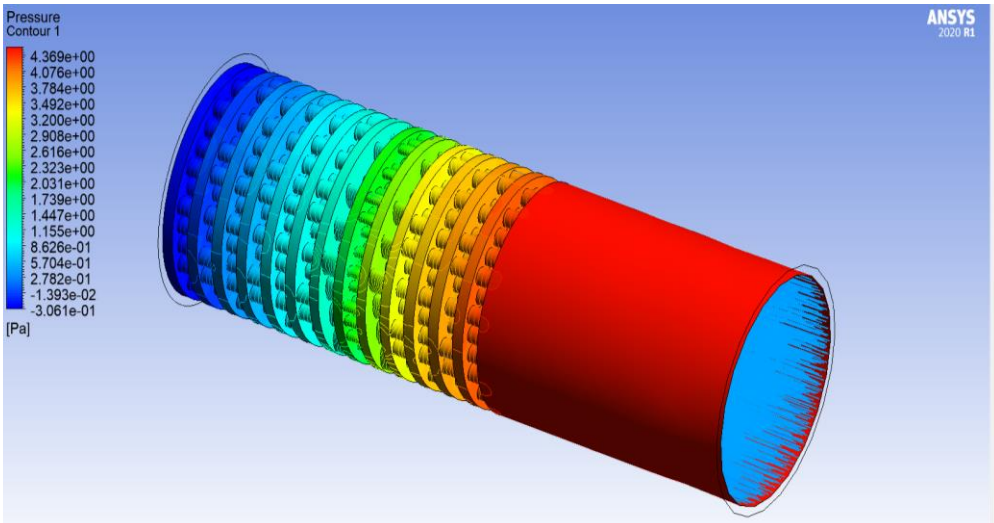

Figure 6: Pressure streamline for Case 1

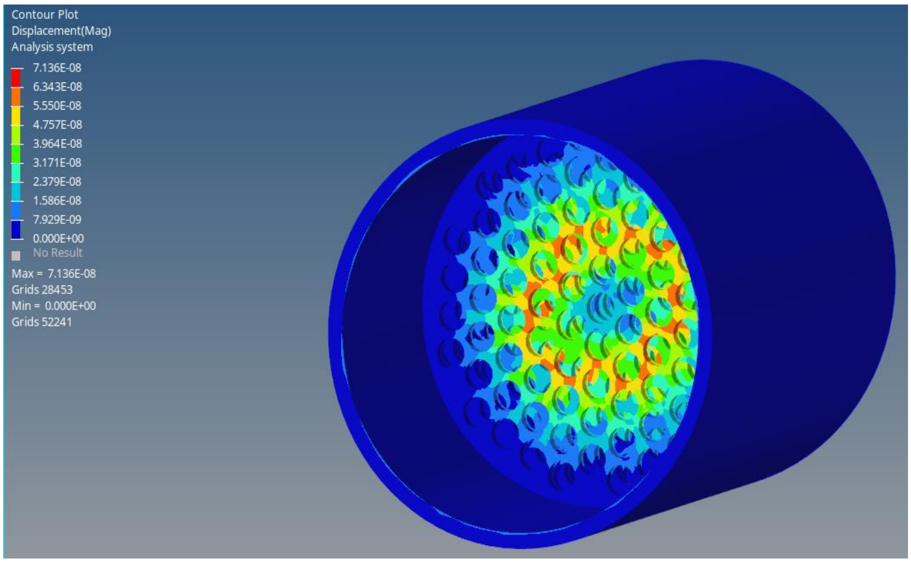

Figure 7: Total Deformation for Case 1

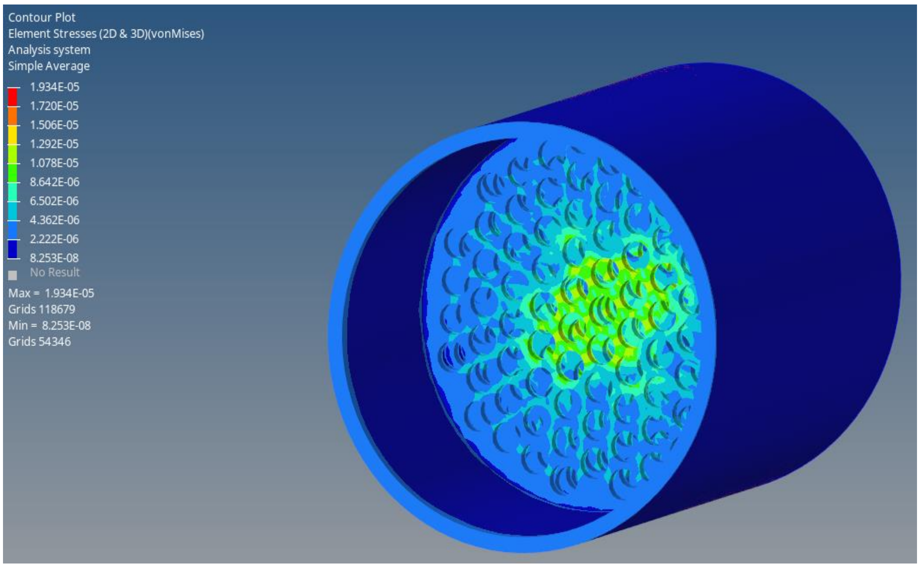

Figure 8: Elemental Stresses for Case 1

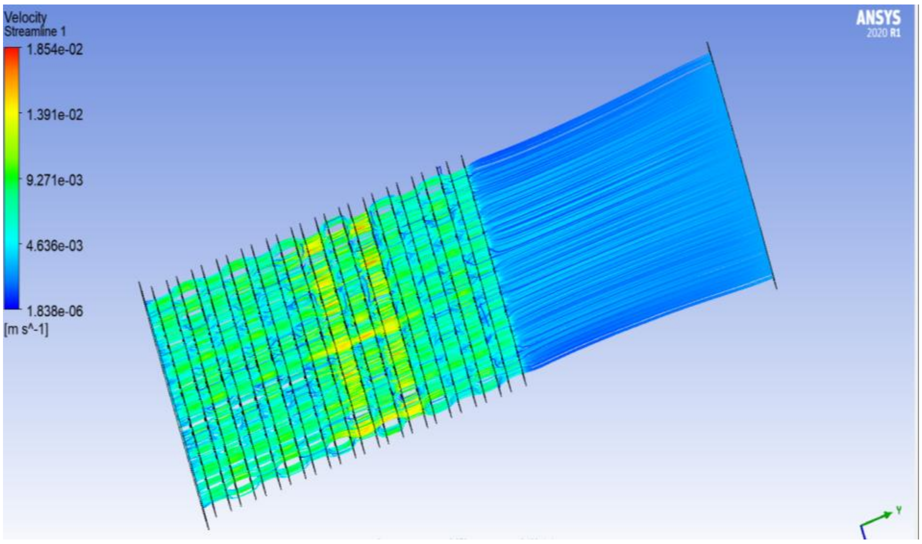

Figure 9: Velocity streamline for Case 2

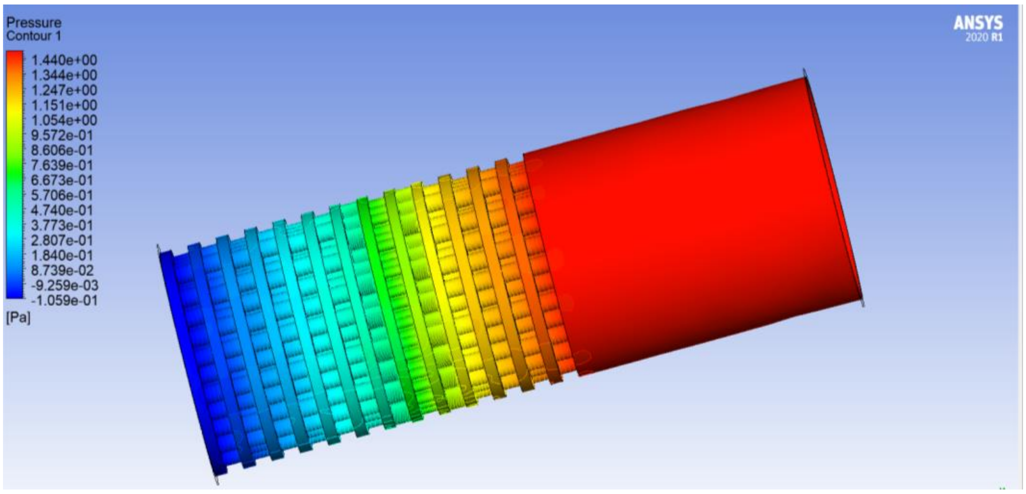

Figure 10: Pressure streamline for Case 2

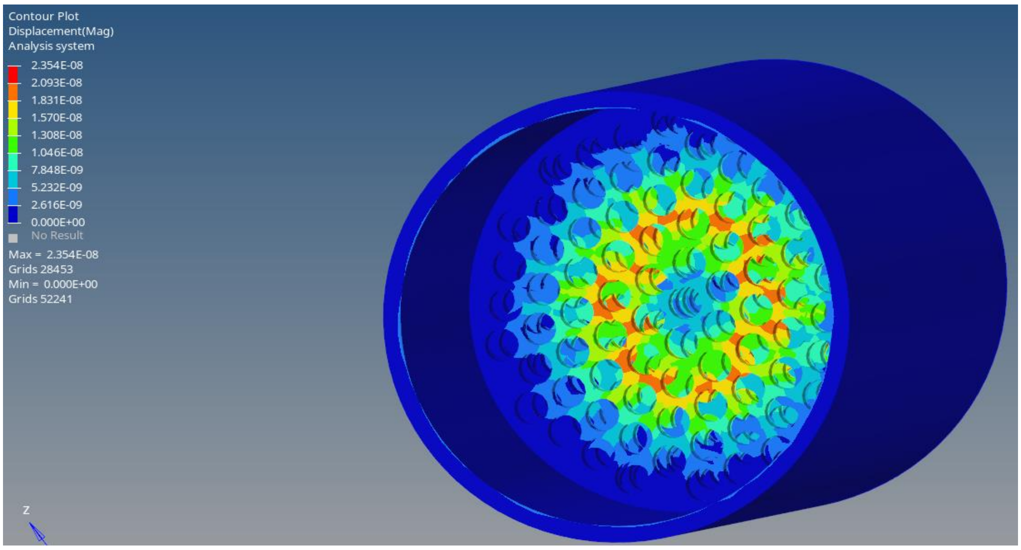

Figure 11: Total Deformation for Case 2

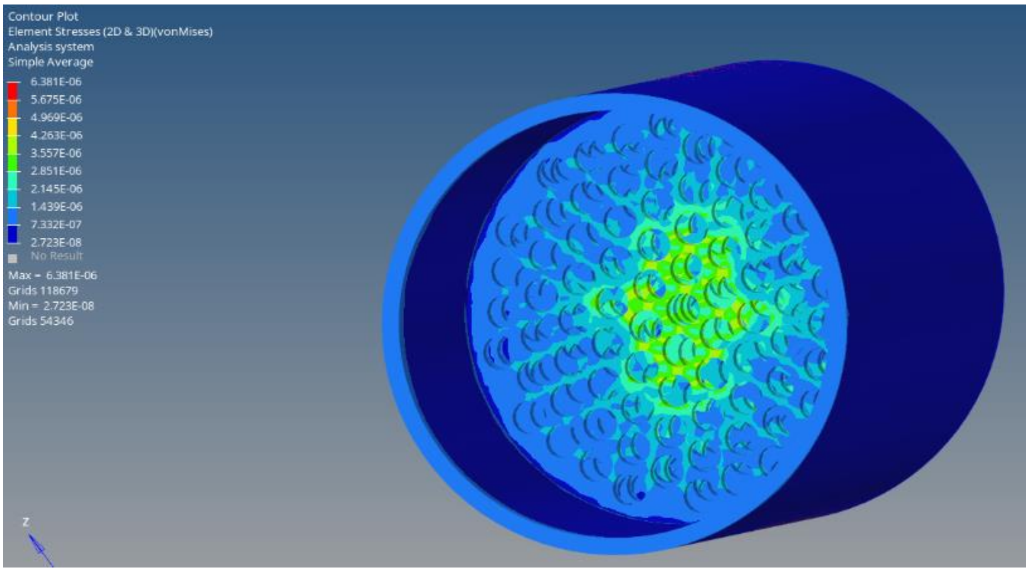

Figure 12: Elemental Stresses for Case 2

Table 3: Results output for Maximum and Minimum

Sr. No	**Velocity**	**Maximum Pressure**	**Minimum Pressure**
1	0.006904 m/s	4.389e+00 Pa	-3.06e-01 Pa
2	0.002789 m/s	1.440e+00 Pa	-1.059e-01 Pa

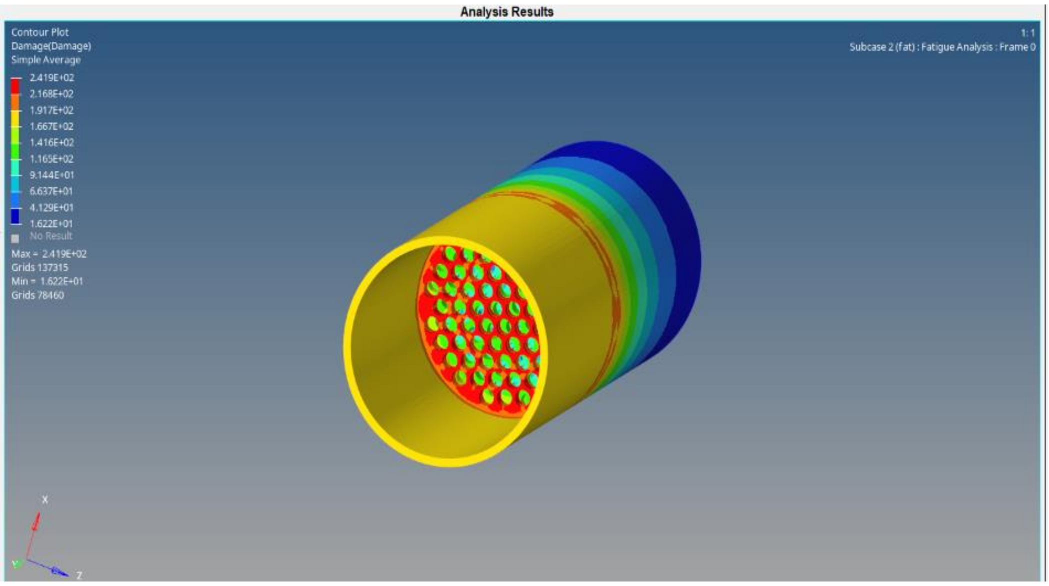

Figure 13: Contour Plot of Damage for Case 1

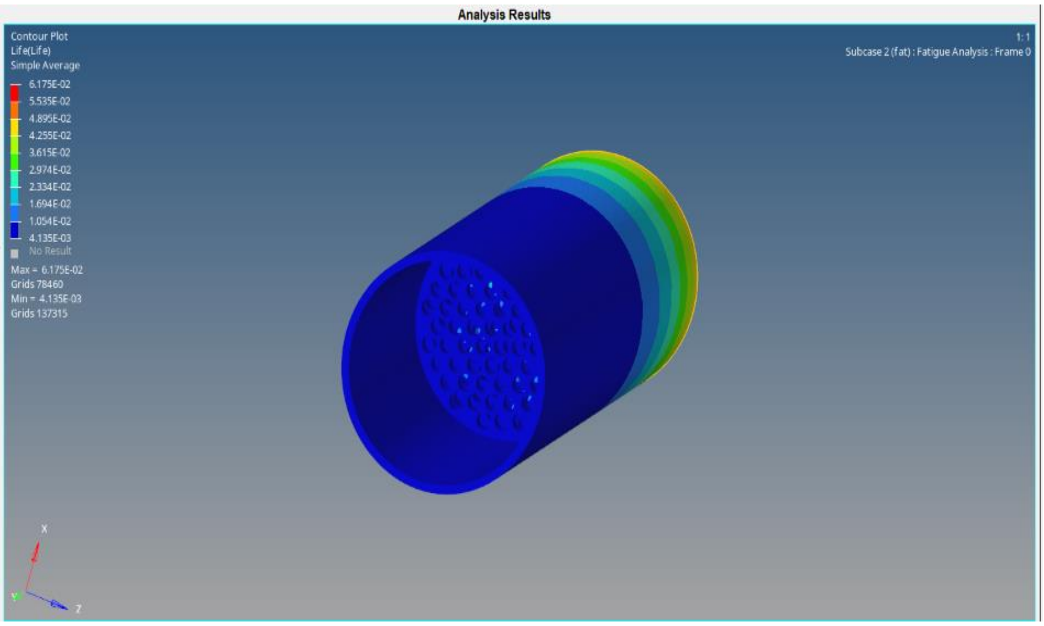

Figure 14: Contour Plot Life for Case 1

Table 3 illustrates the correlation between velocity and pressure in both scenarios, highlighting the significant influence of valve positioning on flow dynamics. In Case 1, which experiences a higher maximum pressure (4.389 Pa), the turbulence effect is more pronounced compared to Case 2, where the lower maximum pressure (1.440 Pa) indicates a milder level of cavitation. These observations are consistent with the research conducted by (Gogate & Pandit, 2008) regarding pressure fluctuations in cavitation reactors.

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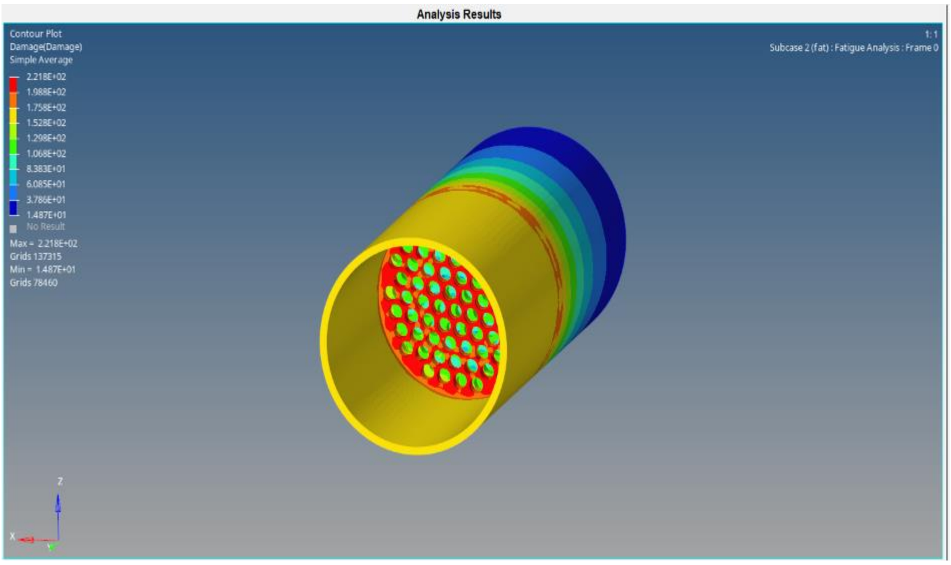

Figure 15: Contour Plot of Damage for Case 2

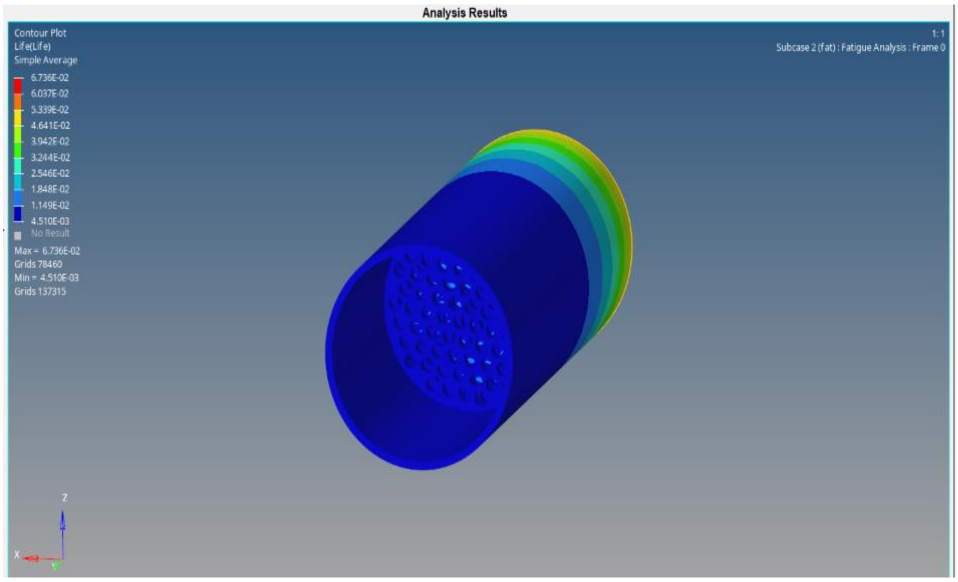

Figure 16: Contour Plot Life for Case 2

Table 4: Result of Life and Damage Cycle

Sr.No	**Pressure**	**Maximum Life Cycle**	**Minimum Life Cycle**	**Maximum Damage Cycle**	**Minimum Damage Cycle**
1	4.389e+00 Pa	6.175e-02	4.135e-03	2.419e+02	1.622e+01
2	1.440e+00 Pa	6.735e-02	4.510e-03	2.218e+02	1.1487-01

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Table 4 quantitatively analyses material lifespan and damage cycles under varying pressure conditions. In Case 1, where the pressure is higher, the life cycles are shorter (6.175×10^{-2} to 4.135×10^{-3} cycles), and the damage cycles are more pronounced (2.419×10^{2} to 1.622×10^{1} cycles). Conversely, Case 2, which operates under lower pressures, exhibits longer life cycles and reduced damage. This pattern aligns with the Goodman theory as it pertains to brittle materials, as noted in the research conducted by (Boffito et al., 2015).

CONCLUSION

In the current research simulation, the design of the cavitation pipe is validated for two different cases of flows flowing through the pipe, which consist of a bypass valve fully opened (case 1) and half opened (case 2) conditions. Initially, CFD analysis is performed over the parameters, which consist of a type of fluid flow and material used as a pipe, which is biodiesel and acrylic pipe, respectively. In addition, the pipe's inlet, outlet and wall are defined with the help of Fluent Solver in ANSYS. Furthermore, 200 iterations are done for setup, and the solution converges at the 37th iteration.

From the result, the maximum pressure obtained for the two cases is 4.389e+00 Pa and 1.440e+00 Pa, respectively, for cases 1 and 2. Considering results from Static Structural analysis, the life and damage cycle caused by pressure acting upon the pipe were calculated as 6.175e-02 to 4.135e-03 cycle and 2.419e+02 to 1.622e+01 cycle, respectively. Considering Fatigue properties, ultimate tensile strength (UTS) of acrylic pipe, Goodman theory (brittle material), and Correction theory as negative signed Von-mises.

The suggested standard appears to be a beneficial device for the theoretical enhancement of recent geometries explaining the severity of cavitation and different method factors indicating the size and effectiveness of the chamber for a particular flow charge. In addition, it can be extended to attain precise models, including compressibility outcomes and section mass distribution of the biodiesel production process. These upgrades may additionally encompass the assessment of bubble reciprocity.

The practical outcomes of this research contribute to the optimisation of cavitation chamber designs, leading to improved efficiency and durability of pipes utilised in biodiesel production while offering a scalable framework for the analysis of complex flow dynamics. From a social perspective, the study advances sustainable energy initiatives by enhancing biodiesel production technologies, fostering environmental conservation, and decreasing reliance on fossil fuels. Economically, the results can potentially reduce production costs, positioning biodiesel as a more viable alternative fuel. A novelty of this study is the integration of CFD analysis, fatigue characteristics, Goodman theory, and Von-Mises correction, which collectively assess cavitation behaviour in brittle materials such as acrylic, delivering a precise and scalable methodology for refining biodiesel production techniques and tackling issues related to flow management and cavitation intensity.

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