Investigation of Parameters Affecting the Efficiency of Hydrodynamic Cavitation: A Case Study on Heavy Fuel Oil Upgrading

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Abstract
Fuel oil (mazut) is one of the most important heavy fuels, commonly used as a combustion material in furnaces, marine diesel engines, and certain power plants. In recent decades, methods for improving the quality of heavy fuel oil and monitoring environmental requirements have gained increasing attention. In this study, hydrodynamic cavitation was investigated as a cost-effective and industrially scalable method for upgrading heavy fuel oil. Accordingly, experimental tests were conducted using a pilot-scale setup, and the cavitation behavior was analyzed through computational fluid dynamics (CFD). The results indicated that cavitation performance is significantly influenced by nozzle geometry and operating conditions such as fluid pressure and temperature. Proper control of these parameters led to effective cavity generation along the nozzle, allowing high-intensity energy release that induces structural changes in heavy hydrocarbon molecules and reduces fuel viscosity. The maximum cavitation efficiency occurred at an inlet pressure of 220 bar and a nozzle throat diameter of 1.5 mm, resulting in the formation of stable and extensive cavitation, a viscosity reduction of up to 170 units, and a total sulfur decrease to 1.1251. These conditions also enhanced the effective flow velocity and mixing uniformity between phases. The findings of this research demonstrate the feasibility of establishing heavy fuel oil upgrading units and highlight that optimizing nozzle geometry and inlet pressure provides an effective approach for improving the performance of cavitation-based systems.

Keywords: Hydrodynamic cavitation, Heavy fuel oil upgrading, Cavitating nozzle, Computational fluid dynamics (CFD)

Introduction
Heavy and residual crude oils, often referred to as heavy fuel oils due to their high molecular weight, density, and viscosity, present significant operational and economic challenges in the petroleum industry[1]. The high viscosity and complex molecular structure of these fractions increase the cost of transportation and handling, and conventional refining techniques such as catalytic cracking encounter limitations when applied to these heavy cuts. Consequently, developing cost-effective and scalable upgrading technologies for heavy residuals has been a central focus of research in petroleum processing and refining[2] .

Among the emerging techniques, hydrodynamic cavitation (HC) has attracted considerable interest as a promising intensification method for heavy oil upgrading. Cavitation refers to the formation, growth, and subsequent collapse of vapor-filled cavities or bubbles within a liquid under rapid changes in local pressure[3, 4]. The implosive collapse of these cavities generates localized hot spots with extremely high temperatures and pressures, while the bulk fluid conditions remain largely unchanged. These localized extreme conditions can facilitate the breakage of strong chemical bonds (e.g., C-C and C-S) in heavy oil molecules, leading to cracking reactions that reduce viscosity and improve the oil's physicochemical properties[5, 6] .The fundamental mechanisms of cavitation involve complex interactions between hydrodynamic flow, bubble nucleation, and energy dissipation, all of which are sensitive to fluid properties and flow conditions[7]. Hydrocarbon cracking and radical formation under cavitation have been identified as key phenomena in viscosity reduction and upgrading of heavy oils, with the potential to enhance yields of lighter fractions and lower the formation of coke compared to traditional processes[8] .

Existing literature on cavitation-assisted upgrading has explored various cavitation devices such as orifices, vortex diodes, and cavitation jets/nozzles. These studies have demonstrated that hydrodynamic cavitation can effectively lower viscosity and improve the rheological and compositional characteristics of heavy oils under suitable conditions. For example, cavitation-assisted treatment combined with hydrogen donors has been shown to significantly enhance viscosity reduction compared to cavitation alone. Moreover, hydrodynamic cavitation systems have shown cost and energy advantages over acoustic cavitation, particularly regarding scalability and operational efficiency[9].Despite these promising findings, the majority of studies to date have focused on qualitative assessments or limited parametric investigations, and comprehensive data detailing the effects of key operational and design parameters in hydrodynamic cavitation systems remain limited. In particular, the influence of nozzle geometry, inlet and outlet flow conditions, volumetric flow rate, and pressure differential on the intensity and efficiency of cavitation during heavy fuel oil upgrading has not been thoroughly quantified. Understanding how these parameters affect cavitation inception, bubble dynamics, and ultimately oil upgrading performance is critical for process optimization and scaling up to industrial applications[10].

In this study, a hydrodynamic cavitation system based on a cavitating nozzle was developed to investigate the effects of multiple operational and geometric parameters on heavy fuel oil upgrading. The main objectives of this work are to elucidate the relationships between nozzle geometry, flow conditions, and the resulting physicochemical improvements in heavy fuel oil, including viscosity reduction and changes in hydrocarbon distribution. The results presented here contribute to a deeper understanding of hydrodynamic cavitation mechanisms and provide practical insights for optimizing this technology for industrial heavy oil upgrading.

Computational Modeling

To analyze the flow characteristics and cavitation behavior inside the high-pressure nozzle, numerical simulations were carried out using computational fluid dynamics (CFD). Three nozzle geometries with different throat diameters were investigated to evaluate the effect of throat size on flow structure and cavitation development, while all other geometric parameters were kept constant (Table 1). As illustrated in Figure 1, each nozzle consists of convergent, throat, and divergent sections based on the dimensions of an actual industrial sample.

Table 1. Nozzle geometry parameters

Parameter	Nozzle throat diameter	Nozzle inlet diameter	Nozzle outlet diameter	Convergent angle	Divergent angle
Dimension (mm)	1.5, 2, 4	30	30	35°	15°

A structured mesh was generated for all geometries using identical meshing strategies to ensure consistent comparison. Local mesh refinement was applied near the nozzle walls and throat region to accurately capture high velocity and pressure gradients. A representative mesh configuration is shown in Figure 2. Grid-independence was verified for the nozzle with the intermediate throat diameter, confirming that the selected mesh resolution provided sufficient numerical accuracy.
The inlet boundary condition was defined as constant pressure corresponding to the experimental operating conditions, while ambient pressure was imposed at the outlet. No-slip conditions were applied at the walls. The flow was treated as incompressible due to negligible density variation within the investigated pressure and temperature ranges. Cavitation was modeled using a two-phase liquid–vapor approach, accounting for phase change in low-pressure regions. Turbulence effects were incorporated to ensure accurate prediction of flow behavior in regions with strong pressure gradients and possible flow separation. The governing equations were solved in an unsteady framework, and convergence was ensured by monitoring residual reduction below acceptable thresholds. The main governing equations and simulation parameters are summarized in Table 2.

(a) (b) (c)

Figure 1. Geometry of the nozzle: (a) 1.5 mm, (b) 2 mm, and (c) 4 mm.

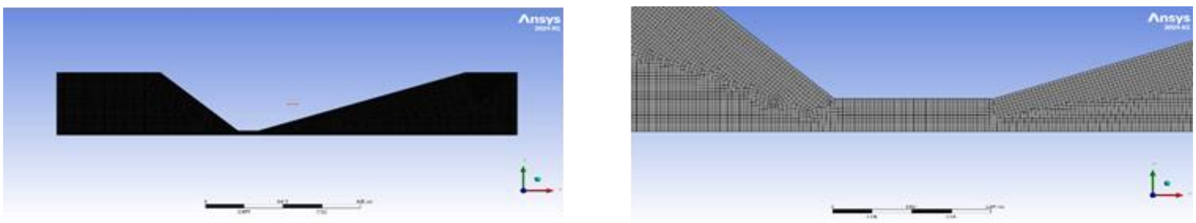

Figure 2. mesh element

Table 2. CFD modeling parameters

Type	Time	model	Cavitation model	Viscous Model
Pressure bace	Transient	Multiphase (Eulerian)	Schnerr - sauer	k-omega-SST

Materials and Methods

To experimentally investigate the effect of nozzle-induced flow phenomena on the physicochemical properties of heavy fuel oil, a laboratory-scale system was designed, as schematically shown in Figure 3. The setup consists of a fuel tank, a high-pressure pump, a pressure regulation unit, a nozzle holder, and a sampling section. In the experiments, water was pressurized to predetermined levels and injected through the nozzle, where a sharp pressure drop at the throat led to cavitation formation. The cavitating jet exiting the nozzle generates a complex two-phase flow characterized by vapor bubbles, fine droplets, and high-velocity liquid structures. Upon impingement on the fuel surface, this flow transfers high energy through intense mechanical stresses, micro-scale turbulence, and transient thermal effects. Fuel samples were collected after each experimental run and analyzed using standard methods, with kinematic viscosity and total sulfur content selected as key performance indicators. The fuel used in this study was commercial Fuel Oil 280, commonly applied in thermal power plants. The injected water-to-fuel ratio was maintained within 1–2 wt% to isolate cavitation effects while preserving conditions relevant to industrial applications. Due to experimental limitations, direct visualization of cavitation inside the nozzle was not feasible; therefore, cavitation behavior was evaluated based on complementary CFD results.

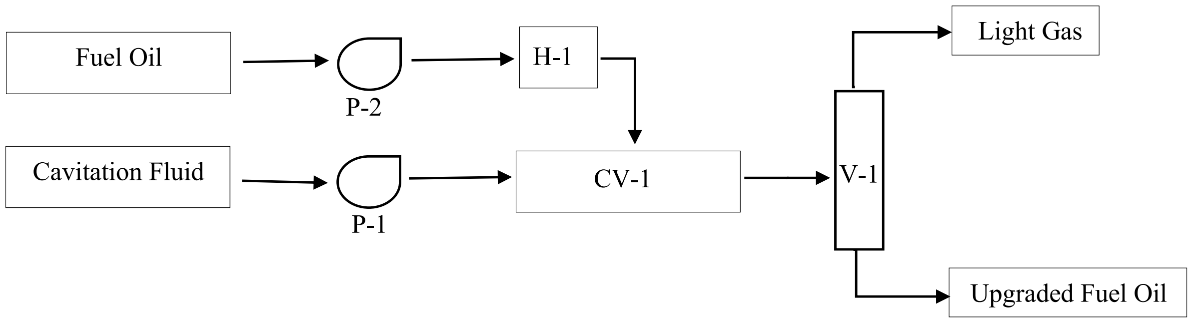

Figure 3. Cavitation performance test system for heavy fuel oil (P 1: high pressure pump; P 2: heavy fuel oil pump; H 1: heater; CV 1: cavitation device; V 1: separator)

Results and discussion

Figures 4 and 5, together with the axial pressure distribution shown in Figure 6, illustrate the variation of static pressure along the nozzle axis for different throat diameters. In all cases, the pressure remains nearly constant from the inlet to the throat entrance and then drops sharply at the throat due to flow acceleration and conversion of pressure energy into kinetic energy, marking the onset of cavitation. The magnitude and characteristics of the pressure drop strongly depend on the throat diameter. For the 1.5 mm throat nozzle, the pressure decreases abruptly to values close to or below the liquid vapor pressure, leading to extensive vapor formation and the development of strong and sustained cavitation. Under this condition, a significant portion of the pressure energy is consumed by phase change, resulting in a reduced effective liquid-phase velocity despite the smaller cross-sectional area. Pronounced pressure fluctuations downstream of the throat indicate rapid bubble collapse and flow instability, characteristic of a fully cavitating regime.

In contrast, nozzles with throat diameters of 2 mm and 4 mm exhibit less severe pressure drops, with minimum pressures approaching but not substantially falling below the vapor pressure. Cavitation in these cases is transient and localized, producing limited vapor regions. A pressure recovery peak downstream of the throat is observed, corresponding to bubble collapse, while the lower vapor fraction leads to higher effective density and improved kinetic energy of the flow. Consequently, these configurations demonstrate more stable operating conditions. Reducing the inlet pressure from 220 bar to 150 bar decreases both the intensity and spatial extent of cavitation zones; however, the relative performance of the nozzle geometries remains unchanged. The 1.5 mm throat consistently shows a tendency toward semi-stable or fully developed cavitation, whereas the 2 mm and 4 mm throats operate predominantly within the transient cavitation regime.

(a) (b) (c)

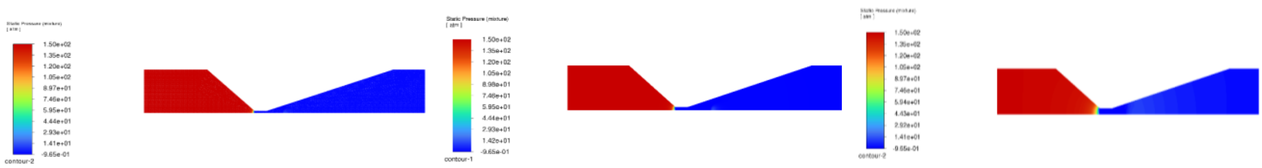

Figure 4. Figure 4 Static pressure profiles at an inlet pressure of 150 bar: (a) nozzle with a 1.5 mm throat, (b) nozzle with a 2 mm throat, (c) nozzle with a 4 mm throat.

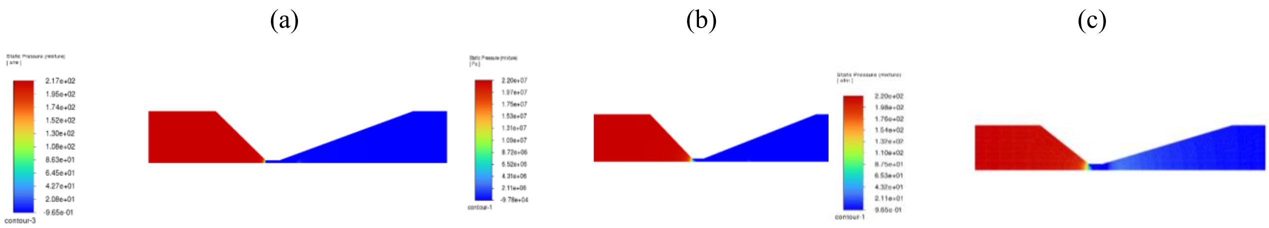

Figure 5. Static pressure profiles at an inlet pressure of 220 bar: (a) nozzle with a 1.5 mm throat, (b) nozzle with a 2 mm throat, (c) nozzle with a 4 mm throat.

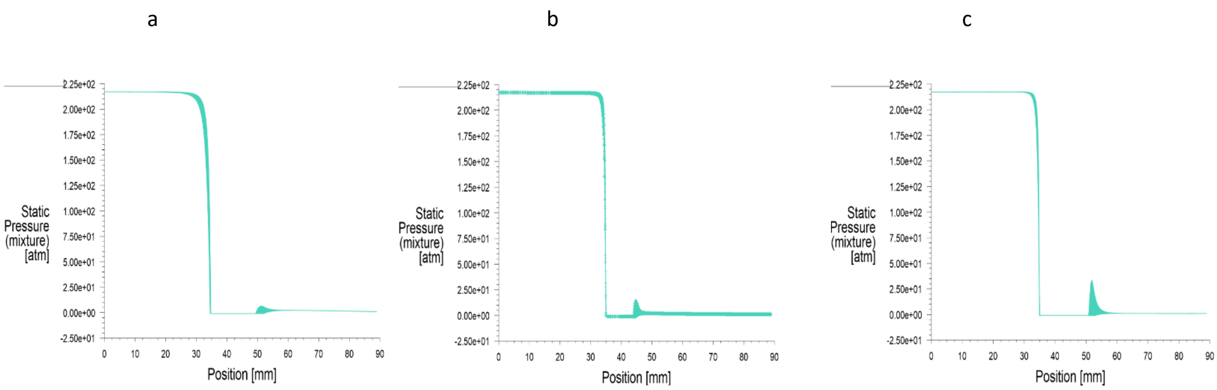

Figure 6. Static pressure diagram at 220 bar: (a) nozzle with a 1.5 mm throat, (b) nozzle with a 2 mm throat, (c) nozzle with a 4 mm throat

Figures 7 and 8 show that the maximum flow velocity occurs in the throat region, consistent with Bernoulli’s principle and the conversion of pressure energy into kinetic energy. However, the velocity distribution indicates that increasing the throat diameter leads to a higher effective outlet velocity. Although this trend may appear counterintuitive, it can be explained by the cavitating and two-phase nature of the flow. In nozzles with smaller throat diameters, the pronounced pressure drop causes the local pressure to reach saturated or sub-vapor conditions, resulting in extensive vapor formation. Under these conditions, a significant portion of the pressure energy is consumed by phase change processes, reducing the effective liquid-phase velocity despite the large pressure gradient. In contrast, larger throat diameters exhibit a more uniform pressure distribution with either non-cavitating or transient cavitation regimes, allowing a more efficient conversion of pressure energy into kinetic energy and extending the high-velocity region along the flow path.
As summarized in Table 3, increasing the inlet pressure and decreasing the throat diameter reduce the cavitation number and intensify cavitation. At an inlet pressure of 220 bar, the 1.5 mm throat nozzle exhibits the highest cavitation intensity, whereas the 4 mm throat nozzle shows greater resistance to cavitation formation. This behavior is consistent with hydrodynamic principles, as smaller throat areas promote higher velocities and lower local pressures, facilitating cavitation inception. Experimental results confirm that higher inlet pressures enhance the upgrading performance of heavy fuel oil by accelerating molecular decomposition reactions. This effect leads to a reduction in viscosity, disruption of asphaltene structures, and improved desulfurization efficiency. The lowest sulfur content achieved was 1.1251%, accompanied by a kinematic viscosity of approximately 170 cSt. The consistency of these results across experimental replicates demonstrates that nozzle-induced cavitation plays

a decisive role in improving reaction kinetics and upgrading efficiency, in agreement with previous studies.

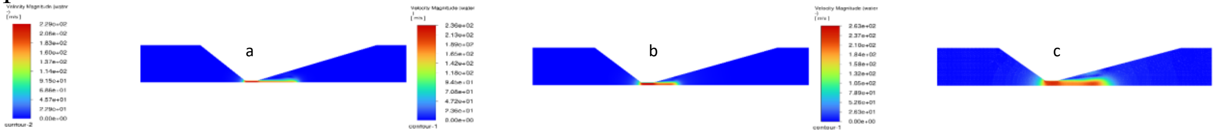

Figure 7. Velocity profiles at an inlet pressure of 150 bar: (a) nozzle with a 1.5 mm throat, (b) nozzle with a 2 mm throat, (c) nozzle with a 4 mm throat

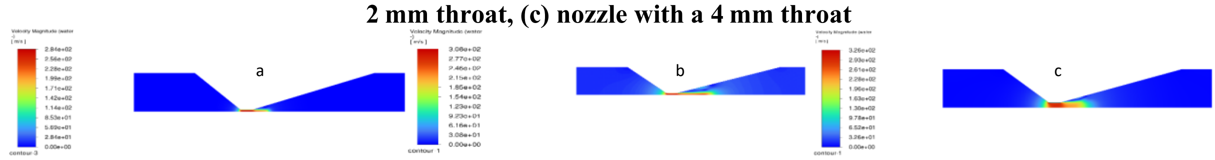

Figure 8. Velocity profiles at an inlet pressure of 220 bar: (a) nozzle with a 1.5 mm throat, (b) nozzle with a 2 mm throat, (c) nozzle with a 4 mm throat

Table 3. Effect of inlet pressure and throat diameter on cavitation number

Inlet Pressure (bar)	150	150	150	220	220	220
Nozzle Throat Diameter (mm)	1.5	2.0	4.0	1.5	2.0	4.0
Cavitation Number	0.123	0.116	0.1392	0.070	0.0681	0.1153

Conclusion

The results of this study demonstrate that the cavitation intensity and pressure drop inside the nozzle are strongly governed by the inlet pressure and throat diameter. Increasing the inlet pressure from 150 to 220 bar significantly intensified cavitation, leading to stable cavitation in the 1.5 mm throat nozzle, while larger throats (2 and 4 mm) mainly operated under transient cavitation conditions.

Both numerical simulations and experimental measurements identified an inlet pressure of approximately 220 bar as the optimal operating condition. At this pressure, the system exhibited the highest kinetic efficiency, accompanied by a minimum total sulfur content of 1.1251 and a kinematic viscosity of about 170 cSt. The close agreement between CFD predictions and experimental data confirms that enhanced nozzle-induced cavitation improves interfacial interactions, flow uniformity, and overall upgrading efficiency. Although further molecular-scale investigations are required, the findings clearly indicate that operating near 220 bar provides the best compromise between dynamic stability and chemical performance for heavy fuel oil upgrading.

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