CHAPTER-6

CONCLUSIONS AND SCOPE OF FUTURE WORK

6.1 CONCLUSIONS

To address the dual issues of energy consumption and air pollution, researchers are becoming increasingly interested in alternative fuels such as biodiesel. Understanding the relationship between internal fuel injector flow and spray formation in the combustion chamber has become increasingly important, particularly with the use of alternative fuels. The current research aims to numerically model cavitation flow and its effect on spray properties for biodiesel. The work began with modelling cavitation flow, which was solved using an Eulerian frame of reference, and the findings were compared to experimental investigations. The work is expanded to investigate the effect of cavitation flow on spray properties using a novel two-step coupling approach. This is combined with the Eulerian-Lagrangian approaches. The proposed approach was tested in a real-size fuel injector, and the findings were compared to previous work published in partnership with the Engine Combustion Network (ECN). The experimental setup was designed to visualize the inner nozzle cavitation flow and its properties. The effect of operating and geometric characteristics on cavitation flow was calculated. The spray characteristics of diesel and different biodiesels were investigated experimentally, and the results were compared to those obtained using the two-step coupling approach. Finally, the effect of cavitation flow on spray properties was assessed using numerical and experimental methods.

6.1.1 Cavitation flow modelling

The ANSYS-Fluent CFD software has extensively investigated the internal nozzle flow parameters and cavitation phenomenon. A systematic study has been carried out with three different turbulence models, two cavitations models and two multiphase models. The combination of VOF+ZGB+k-ω SST has the lowest error in determining mass flow rate in cavitation flow. This combination accurately predicts the inception of cavitation and the choking condition. Both the VOF and Mixture models accurately capture the general structure of cavitation. However, the smaller structures like bubble formation and ligament breakup are only captured with the VOF sharp interface option. This is due to consideration of the effect of surface tension in the VOF model. Cavitation starts after 0.01 ms at the round corner of the throttle inlet. The cavitation zone progresses downstream and reaches full development at 0.1ms. The vapor fraction contour clearly shows bubble breakage and ligament development. Diesel cavitation occurs at a lower pressure differential ($\Delta P=60$ bar) than biodiesel (ΔP=67 bar). With higher liquid viscosity and lower saturation pressure, biodiesel lags in cavitation inception. Before cavitation, the divergent nozzle has a higher mass flow rate than the convergent nozzle. But this condition reverses after getting choked flow. As soon as the choking condition approaches, the area available to liquid is decreased in the divergent nozzle due to the thick cavitation layer.

6.1.2 Spray break-up modelling

In this study, ANSYS-FLUENT was used to investigate non-evaporating spray. ASNSYS-Fluent includes a discrete phase model (DPM) for simulating spray characteristics. In this study, ASNSYS-Fluent was used to investigate non-evaporating spray. A Fluent offers a discrete phase model (DPM) for simulating spray characteristics. Macroscopic spray properties, including (a) spray tip penetration (STP) and (b) Sauter mean diameter (SMD), have been estimated. The KHRT and the Wave model predict the penetration length reasonably good as compared to the SSD model.

6.1.3 Two-step coupling method

The two-step coupling method is a comprehensive computational approach that links the internal flow parameters of a fuel injector nozzle to its external spray formation and breakup. These parameters are calculated in each grid cell of the outlet cross-section and then stored in a *.inj file. In present method injection is assigned in terms of “file injection” type and *.inj file assigned as an initial condition for spray break-up. In our current research; we introduced a novel methodology- the Eulerian-Lagrangian two-step approach. This method was implemented in the ANSYS-Fluent for ECN spray-C injector nozzle and cavitation coupled spray calculation has been obtained. Notably, this approach offers enhanced accuracy, and the results align more consistently with the experimental data on spray cone angles provided by ECN. The current approach for measuring spray cone angle has a maximum error of ± 3.8%, while Payri et al.'s method has an error of ± 5.5% [110].

6.1.4 Experiments for cavitation flow

Three scaled up optical nozzles (CN 3, CN 4, and CN 5) were used to observe the cavitation flow with three different fluids i.e. water, diesel and WCO based biodiesel. The cavitation nozzles operate with injection pressure ranging from 0.5 bar to 8 bar, revealing a distinct stage of cavitation, i.e. inception of cavitation, growth of cavitation, super cavitation, and hydraulic flip.

- The cavitation begins when the cavitation number falls below unity, regardless of geometrical parameters or fluid properties. The spray cone angle increases with increasing injection pressure. The highest spray cone angle was observed during super cavitation. When injection pressure increases from 3 to 4 bar, super cavitation occurs, resulting in a 20% increase in spray cone angle. An increase in injection pressure from 4 bar to 5.4 bar generates a hydraulic flip, that reduces the spray cone angle to up to 40% in CN3. Super cavitation improves the spray angle of WCO-based bio-diesel by about 4˚ (5.7˚ to 9.8˚).

- When cavitation occurs inside the nozzle, the discharge coefficient begins to decline due to reduction in the effective area. The discharge coefficient reduces from 0.95 to 0.9 during no-cavitation to super cavitation for CN3 using diesel fuel. The cavitation flip causes a dramatic fall in the discharge coefficient from 0.9 to 0.7. The magnitude of the discharge coefficient in the case of water is much lower than that of diesel fuel. The void generated inside the water flow had a bigger cross-sectional area than the diesel flow during cavitation
- The cavitation number decreases with increasing Reynolds number. The rate of cavitation number reduction changes after cavitation begins, and the cavitation number curve becomes asymptotic when the hydraulic flip occurs.
- As L/W decreases the onset of cavitation, super cavitation occurs at a lower Reynolds number. A lower Reynolds number indicates lower exit velocity and injection pressure. It is concluded that reducing the L/W ratio demands less pressure to produce super cavitation. The cavitation begins when the cavitation number falls below unity, regardless of geometrical parameters or fluid properties.

6.1.5 Experiments for spray characteristics

In order to optimize the performance and efficiency of diesel engines running on biodiesel, it is crucial to understand the fuel spray characteristics of both diesel and biodiesel fuels. The spray characteristics, such as spray penetration and spray cone angle are experimentally investigated. The fuel injection is filmed with a high-speed camera (1000 frames per second) and then slowed down with an image processing program (ADOBE Pro). The still image was recorded every 0.2 ms, and additional image processing was performed to determine spray tip penetration (STP) and spray cone angle.

- Initial fuel penetrates quickly; after the spray breakup starts, the rate of penetration decreases. Spray tip penetration increases with injection pressure. As injection pressure increases, the spray border becomes unstable, and ligament breakage is easily visible.

- At the start of injection, all fuels have similar penetration lengths, but as time progresses, it can be observed that the tallow biodiesel spray has a shorter penetration length compared to diesel fuel. Although the WCO-based biodiesel shows greater spray tip penetration as compared to diesel fuel.
- The spray cone angle is measured using the image capture after 1.2 ms SOI at the injection pressure of 500 bar. The average values of are considered as a final spray cone angle. The spray cone angle of diesel, tallow biodiesel and WCO biodiesel are 17˚, 15.4˚ and 15.6˚ respectively. Biodiesel is projected a lower spray cone angle than diesel spray. Spray characteristics are essentially identical in tallow and WCO biodiesel.

6.2 MAJOR OUTCOMES

1. Development of a Two-Step Coupled Method for Cavitation-Spray Interaction: A significant outcome of this research is the formulation of a two-step coupled computational methodology capable of accurately predicting the influence of internal nozzle cavitation on external spray characteristics. Unlike conventional modelling approaches that rely on predefined mass flow inputs and fail to capture the complex interaction between cavitation and spray formation, the proposed method uses only injection pressure as input. This allows for the dynamic evaluation of cavitation-induced flow behaviour and its effect on spray dispersion. The two-step approach demonstrates strong agreement with experimental spray cone angle results while substantially reducing computational effort, thereby offering a reliable and efficient tool for injector design and optimization.

2. Development of a Cavitation Map and Empirical Model for Cavitation Onset and Super cavitation:

Another key contribution is the development of a cavitation regime map based on a systematic investigation of internal flow across various nozzle L/D ratios. Using dimensionless parameters such as the cavitation number (CN) and L/D ratio, this map delineates the onset, development, and super cavitation zones within the nozzle. From this, empirical equations have been derived that can predict the cavitation inception and super cavitation thresholds based on geometrical and operating parameters. These models are particularly valuable for biodiesel fuel applications, where promoting super cavitation can lead to enhanced atomization, improved spray breakup, and superior combustion characteristics. The developed framework provides both theoretical insight and practical guidelines for designing fuel injectors tailored to alternative fuels like biodiesel.

6.3 SCOPE OF FUTURE WORK

- A single fluid approach does not consider the relative motion between the two-phase. The two-step method can be used to predict cavitation accurately.
- In current research the compressibility effect is not considered. One can include the effect of compressibility in the existing cavitation model.
- The present work considered only liquid and vapour phase of fluid. The model did not consider non-condensable gas.
- The current method considered steady cavitation flow with full needle lifted. The effect of needle movement can be incorporate using dynamic mesh.
- The study can be extended to evaluate the effect of cavitation on nozzle wall in terms of erosion.
- Here, all phenomenon taking place isothermally. Temperature effects can be included in the presents work.
- Two-step coupling method is implemented in two-dimensional geometry, this can be used with three-dimensional geometry of fuel injector.
- The experimental work for inner nozzle can be carried out using real size nozzle with high injection pressure.