

## **ABSTRACT**

To address the dual challenges of energy consumption and air pollution, there's increasing interest in alternative fuels like biodiesel within the research community. 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. Due to high pressure fuel injection; the cavitation bubbles start to generate at the nozzle entrance when the local pressure reaches the critical value. Cavitation is one of the important phenomena happening inside the fuel injector nozzle, leading to a primary breakup. The various parameters affecting the cavitation flow inside the fuel injector nozzle, and its consequent effect on the spray characteristics have been studied.

The numerical solution's accuracy for cavitation flow and spray breakup depends on the appropriate section of the model and sub-model. A systematic study has been carried out with three different turbulence models ( $k-\epsilon$  RNG,  $k-\epsilon$  Realizable,  $k-\omega$  SST), two cavitation models (SS, ZGB), and two multiphase models (Mixture, VOF). The results of the mass flow rate of fuel were compared to the published experimental data. Among all cases, the combination of the VOF+ZGB+ $k-\omega$  SST exhibits the least error. The VOF sharp interface option captures smaller structures such as bubble formation and ligament breakup. This is due to a consideration of the effect of surface tension in the VOF model. A discrete phase model (DPM) is used to calculate the spray characteristics. Compared to the SSD model, the KHRT and Wave models predict penetration length reasonably well. A two-step coupling method is proposed to induce the effect of cavitation on spray characteristics. This novel 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. Then the \*.inj file was used to define the initial condition in the discrete phase model to simulate the spray breakup. This method was implemented in the ANSYS-Fluent platform for the 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 experimental setup was designed to visualize the inner nozzle cavitation flow and its properties. The effect of operating and geometric parameters on the cavitation flow was investigated. 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 distinct stages 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 highest spray cone angle was observed during super cavitation stage for water, diesel and WCO biodiesel. When cavitation occurs inside the nozzle, the discharge coefficient begins to decline due to a reduction in the effective area. The cavitation flip causes a dramatic reduction in the discharge coefficient for water and diesel. 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 with a real-size fuel injector. The spray characteristics, such as spray penetration and spray cone angle, are experimentally investigated with injection pressures ranging from 100 bar to 500 bar. 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. Biodiesel projected a lower spray cone angle than diesel spray.

Finally, based on experimental and numerical work, a two-step coupling method was used to compare spray characteristics between diesel and WCO-biodiesel fuel. 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. A cavitation regime map has been developed 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.