

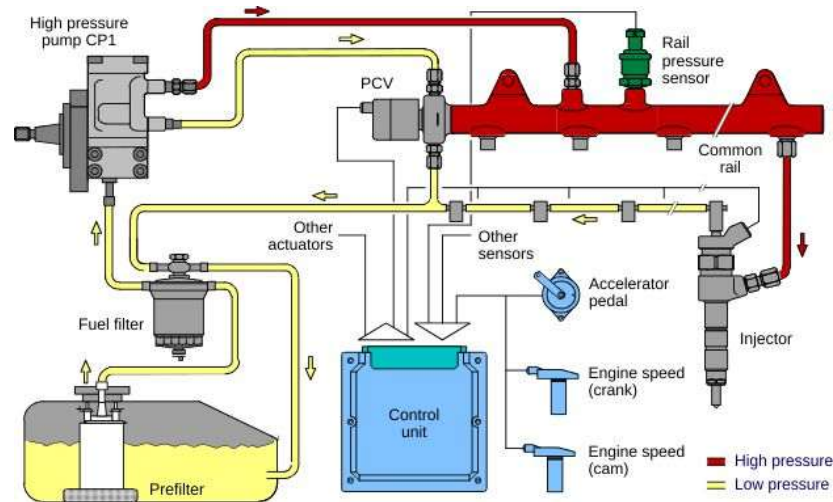
### 1.1 INTRODUCTION

The rapid growth in energy demands increases carbon emissions and leads to the risks of the global warming effect. According to the projection, about 40% of energy sources will come from liquid fuels by 2040<sup>[1]</sup>. A major portion of liquid fuel is used in the transportation sector with the Internal Combustion (IC) engine. Efficient fuel combustion is the prime requirement of both diesel & gasoline engines. Although, both engine technologies are evolving to satisfy two major requirements: Fuel efficiency, & Emission reduction. 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. Both engine technologies are rapidly advancing to meet the demands of lower emissions and higher energy efficiency. Enhancing fuel injector spray breakup is a key strategy for reducing emissions in diesel engines, resulting in finer and more dispersed droplets. The flow dynamics within the fuel injector nozzle significantly influence the spray characteristics <sup>[2]</sup>. While the hydrodynamic behaviour of diesel flow within the injector nozzle is well understood, comprehensive studies on injection and spray characteristics are less common in biodiesel literature. Biodiesel typically exhibits higher density and viscosity compared to petroleum diesel. With the growing use of biodiesel blends, there's a growing interest in developing engines that exclusively run on biodiesel. Consequently, there's an expanding scope for research into understanding spray breakup and flow behaviour of biodiesel within the fuel injector of internal combustion engines.

### 1.2 COMMON RAIL DIRECT INJECTION SYSTEM (CRDI)

The injection mechanism aims to provide high atomization for efficient evaporation and spray penetration, maximising the use of the air charge. The fuel injection system must accurately measure and inject fuel based on engine speed and load, at the proper rate and timing. In common rail injection systems, pressure generation and injection events are independent of engine speed. High-pressure fuel is stored inside the rail, which is typically a closed conduit with solid walls. A high-pressure fuel pump constantly supplies the rail. A pressure sensor adjusts rail pressure, while an auxiliary valve controls an excess fuel flow

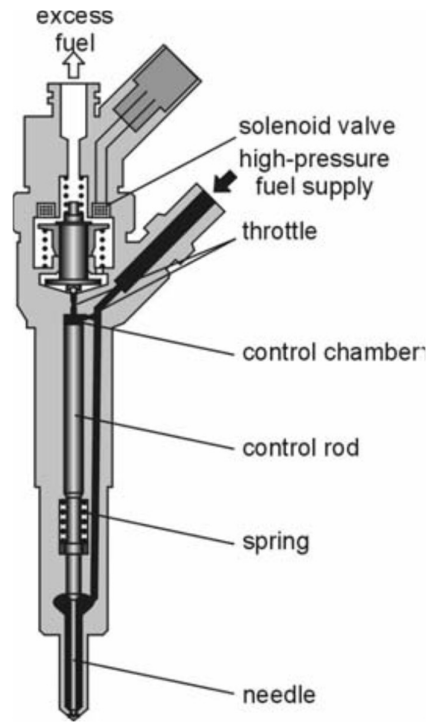
back to the tank. The rail pressure is independent of engine speed, allowing for suitable adjustment to the engine's operating point. Short pipes link the rail and injectors. The rail's capacity effectively reduces pressure changes caused by injection. Solenoid valves govern injection time and duration, independently of pressure generation. The common rail injection system can maintain the desired injection pressure and perform pre-injections (noise and nitric oxide reduction), main injections, and post-injections (soot raw emissions reduction and catalyst heating) with variable duration and timing based on operating conditions. There are low-pressure and high-pressure sides of the fuel injection system as shown in Fig. 1.1. The fuel tank, fuel delivery pump, and gasoline filter are examples of low-pressure components. A high-pressure pump, accumulator, fuel injector, and fuel injector nozzle are the parts of the high-pressure side. For use with various kinds of fuel injection systems, several injection nozzle designs and actuation techniques have been produced.



**Fig.1.1** Common Rail Diesel Fuel injection system [3]

### 1.2.1 Fuel Injector nozzle

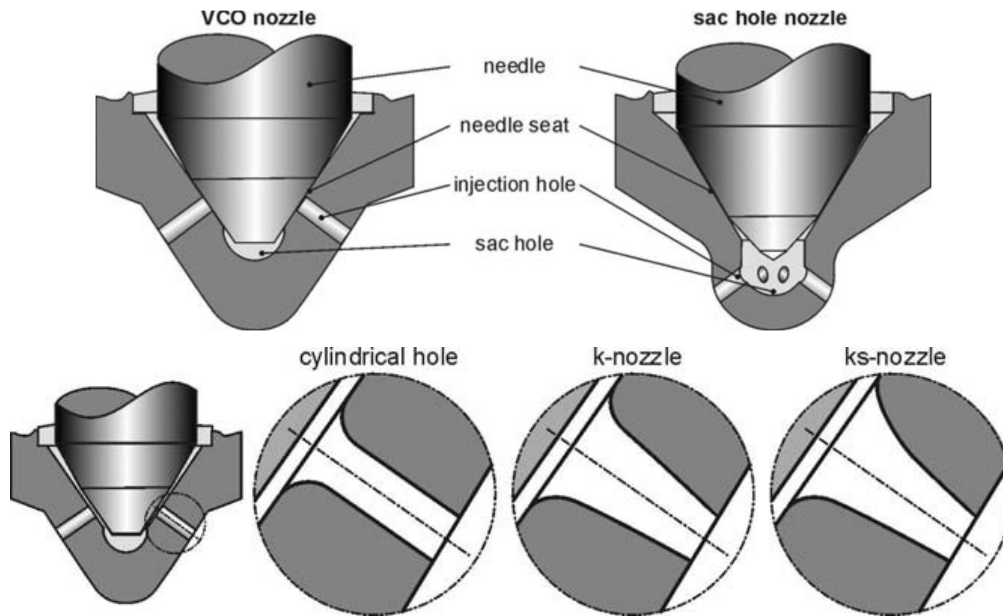
Fig.1.2 shows a typical common rail fuel injector. A solenoid valve controls the needle's movement. When the solenoid valve opens, the pressure in the control chamber lowers above the control rod, causing the needle to open. The inlet throttle, which connects the control chamber to the high-pressure fuel supply, is smaller than the output throttle. Excess fuel passes through the outlet. The fuel returns to the fuel tank after passing through the throttle. The needle's motion is hydraulically regulated. The timing and duration of the needle lift, as well as the pressure of the fuel in the rail, are precisely controlled by the engine management system to ensure that the correct amount of fuel is injected at the right moment during each engine cycle. This precise control helps to optimize fuel efficiency, reduce emissions, and enhance engine performance.



**Fig.1.2** Common Rail Diesel Fuel injector <sup>[4]</sup>

The most significant component of the injection system is the nozzle. Fuel enters the combustion chamber via nozzle holes. The number and size of holes in the cylinder are determined by the amount of fuel to be injected, combustion chamber geometry, and air velocity (swirl). Direct-injection diesel engines use two types of nozzles: sac holes and valve-covered orifice (VCO) showed in Fig.1.3. Modern injectors for passenger cars and heavy-duty engines are working at 2000 bar injection pressure and inject the liquid fuel through the orifice of diameter in the order of 100 to 300  $\mu\text{m}$ .

The inlet edges of nozzle holes are typically rounded using hydro-grinding to improve flow conditions and pre-emptively induce wear that would otherwise develop during operation, potentially changing spray characteristics. Various nozzle hole geometries are utilized depending on the specific application, as shown in Fig. 1.3. Cylindrical holes generate the most intense cavitation, leading to enhanced spray breakup and a wider spray angle near the nozzle. In contrast, axisymmetric conical geometries mitigate cavitation by gradually decreasing the effective cross-sectional area along the hole, resulting in increased spray penetration. Another category includes conical and flow-optimized geometries (ks nozzles, German: *konisch strömungsoptimiert*), where the cross-sectional reduction is tailored to mass flow distribution to completely suppress cavitation. These nozzles produce sprays with narrower cone angles near the nozzle and extended penetration lengths.



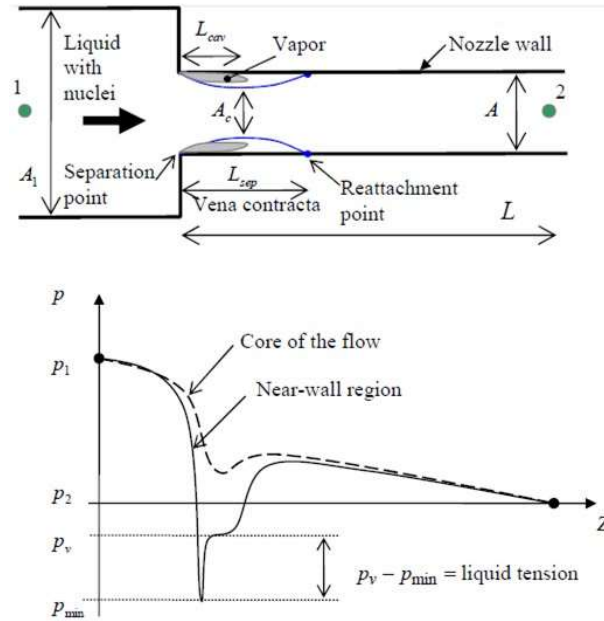
**Fig.1.3** Fuel injector nozzle types <sup>[4]</sup>

### 1.3 CAVITATION IN THE FUEL INJECTOR NOZZLE

Hydrodynamic cavitation can be defined as a phenomenon in which the formation of bubbles takes place in a liquid when the static pressure drops below the vapor pressure, it's due to the geometry through which liquid flows. The generation of cavitation bubbles starts from small nuclei which already present in the liquid in forms of micro-bubbles or from the wall which contains gas in the gap of surface roughness. Consider incompressible, frictionless, isothermal one-dimensional flow as shown in Fig. 1.4. Let's used the Bernoulli equation to explain the fact.

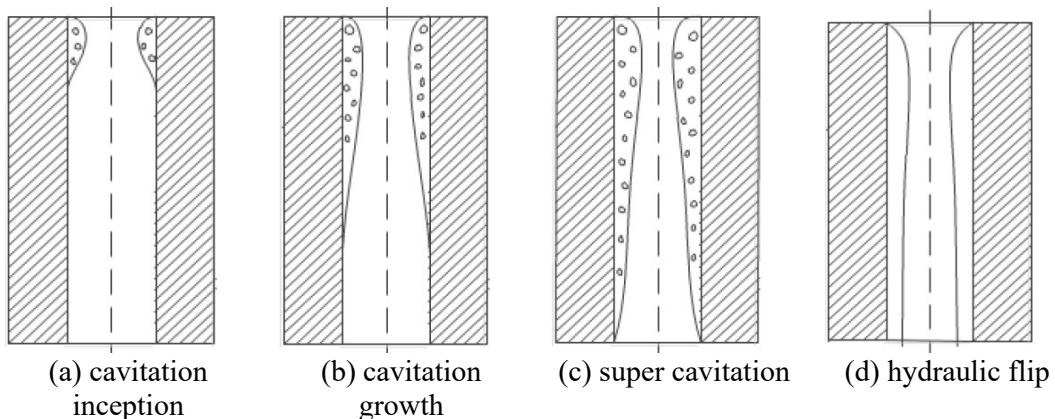
$$p_1 + \frac{\rho u_1^2}{2} = p_2 + \frac{\rho u_2^2}{2} \quad (1.1)$$

When the fluid flow through the nozzle from point 1 to point 2, the flow velocity ( $u$ ) increases, as well as static pressure ( $p$ ) decreases along the length. At the inlet edge (vena-contracta) the minimum static pressure has been reached, which creates a recirculation zone. The recirculation zone is filled with vapor bubbles when the local pressure reaches below vapor pressure. An additional effect enhancing the inception of cavitation in this low-pressure zone is the high shear flow generated by the large velocity gradients in the region between the recirculation zone and the main flow. This shear flow generates a high level of turbulence. The cavitation area that forms at the nozzle wall eventually splits away from the wall and decomposes into bubble clusters. As soon as the local pressure exceeds the vapour pressure, the bubbles will begin to collapse downstream.



**Fig.1.4.** Sketch of nozzle entrance that shows the cavitation inception [5]

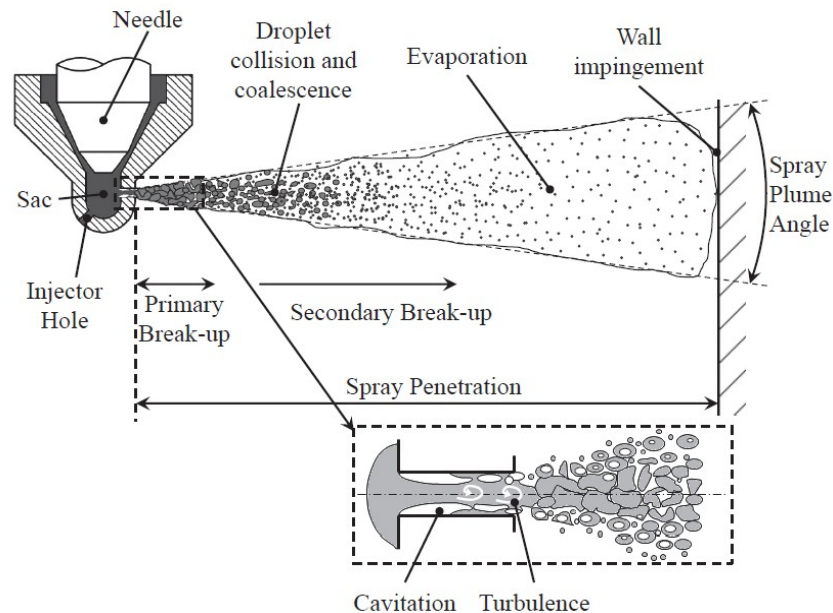
The rise in the injection pressure increases the intensity of the cavitation. Based on the injection pressure the inner nozzle flow can be classified into different flow regimes: no cavitation or turbulent flow, cavitation inception flow, cavitation growth flow, super-cavitation flow, and hydraulic flip flow. Fig.1.5 is a schematic of the evolution of cavitation flow. The cavitation bubbles start to generate at the nozzle entrance when the local pressure reaches the critical value, as shown in Fig.1.5(a); the cavitation region developed with pressure refers to cavitation growth, as shown in Fig 1.5 (b). When cavitation bubbles reach the outlet of the nozzle, this is known as super cavitation, as shown in Fig. 1.5(c). The cavitation bubbles collapse as they come out of the nozzle, increasing the turbulence within the liquid jet. The further rise in injection pressure leads to gas entrainment into the nozzle creating a thin layer of gas attached to the wall and cavitation disappears immediately. This is known as hydraulic flip, as shown in Fig. 1.5(d).



**Fig. 1.5** Evolution of cavitation flow inside fuel injector nozzle [6]

## 1.4 FUNDAMENTAL OF SPRAY CHARACTERISTICS

The spray breakup or fuel atomization process refers to the disintegration of a liquid jet or sheet into smaller droplets or ligaments due to the interaction of various physical processes. These processes can be broadly categorized into primary breakup, secondary breakup, and tertiary breakup. Primary breakup occurs at the nozzle exit or immediately downstream, where the liquid jet undergoes instability due to disturbances such as aerodynamic forces, surface tension, and turbulence within the flow. These disturbances cause the liquid to break up into ligaments or droplets of varying sizes. Secondary breakup involves the further disintegration of these ligaments or large droplets into smaller droplets through mechanisms such as surface erosion, turbulence-induced breakup, and collision-induced breakup. Secondary breakup is influenced by factors such as the velocity gradient within the spray, turbulence intensity, and droplet interaction. Tertiary breakup occurs at smaller length scales and involves the breakup of individual droplets into even smaller droplets or mist. This process is driven by phenomena such as droplet deformation, surface instabilities, and interactions with surrounding gas flow. Several factors influence the breakup behaviour of liquid sprays, including the properties of the liquid (e.g., viscosity, surface tension, density), the operating conditions (e.g., injection pressure, ambient pressure, temperature), and the geometric characteristics of the nozzle (e.g., orifice size, shape, and configuration). The spray characteristics can be understood by the macroscopic parameter like the Spray cone angle and Spray tip penetration as well as the microscopic parameter like droplet size distribution and velocity distribution as shown in Fig. 1.6.

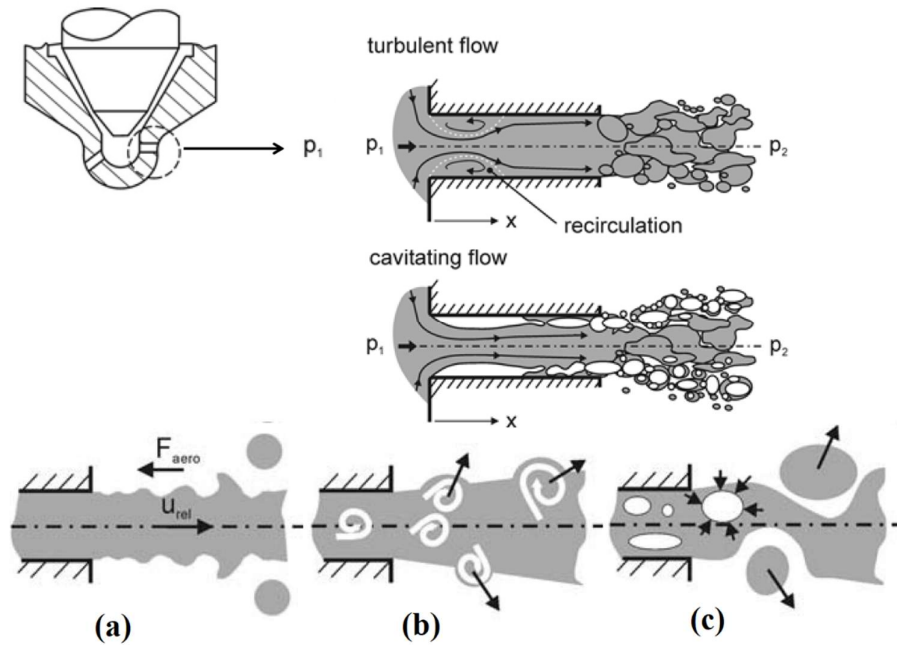


**Fig 1.6** Primary and secondary spray breakup <sup>[7]</sup>

- **Spray Cone Angle:** The angle formed by the outer boundaries of the spray cone, which represents the spatial extent of the spray. The spray cone angle influences the distribution and coverage of the sprayed material
- **Spray Penetration:** The distance travelled by the spray from the nozzle exit to a defined location downstream. Spray penetration is indicative of the reach and effectiveness of the spray in reaching its intended target.
- **Droplet Size Distribution:** The distribution of droplet sizes within the spray, typically represented as a histogram or cumulative distribution function. Droplet size distribution affects various spray properties, including droplet evaporation rate, surface area-to-volume ratio, and spray dispersion.
- **Spray Droplet Velocity:** The velocity at which individual droplets within the spray travel. Droplet velocity determines the momentum and kinetic energy of the spray, influencing its ability to penetrate and interact with the surrounding medium

### **1.5 CAVITATION INDUCED SPRAY BREAK-UP**

There is debate on whether cavitation has a positive or negative impact on engine performance and emissions. Cavitation reduces effective cross-sectional flow area and complicates injecting large fuel masses through small nozzle holes. Cavitation improves mixture formation and removes carbonisation deposits from nozzle holes, reducing injector fouling. Cavitation is one of the important phenomena happening inside the fuel injector nozzle which significantly effects on primary break-up. The primary breakup governs the quality of the atomization and combustion of fuel inside the combustion chamber of an IC engine. It is widely accepted that there is a close relationship between spray formation and primary breakup. The combination of three mechanisms controls the primary breakup of the liquid jet (a) Aerodynamic forces experienced by the liquid jet (b) Turbulence within the liquid phase (c) Cavitation bubbles shown in Fig.1.7. The collapse of cavitation bubbles generates high-speed micro-jets, which can break up the fuel into smaller droplets, leading to improved atomization and mixing with air. Cavitation-turbulence induced breakup can lead to the formation of a wider spray cone angle, resulting in better spray dispersion and coverage. This can be useful with fuels such as biodiesel, which has high viscosity and poor spray characteristics.



**Fig 1.7** Governing mechanism for primary spray break-up <sup>[4]</sup>

## 1.6 BIO-DIESEL

Biodiesel, an alternative fuel, has gained global interest for its potential to partially replace mineral diesel in recent decades. Biodiesel is now available in various regions of the world. Transesterification is used to produce this product from vegetable or animal fats or waste cooking oil (WCO). Biodiesel's high oxygen content reduces particulate matter emissions from engine exhaust. Biodiesel contains minimal amounts of sulphur and aromatics. However, because of its high viscosity, fuel injection equipment may experience lower flow rates at the nozzle exit. Biodiesel's higher viscosity and glycerol content might lead to increased wear on injector nozzles. Biodiesel is typically made from organic oils such as sunflower, soybean, and canola. However, the production of biodiesel from edible oil is unsustainable due to food versus fuel issues. Biodiesel is a fuel derived from long-chain mono-alkyl esters of vegetable or animal lipids. Biodiesel is chemically manufactured from waste or organic sources, including food oils, animal fats, and leftover frying oils. Biodiesel fuel is clean, renewable, and can be utilised in compressor combustion engines without compromising performance.

- Tallow Bio-diesel: Tallow biodiesel, derived from animal fats, holds great promise as an alternative fuel for diesel engines. Its unique composition, characterized by high fatty acid methyl ester (FAME) content and a blend of saturated and unsaturated fatty acids, presents distinct fuel properties that can significantly influence spray characteristics. Investigating the spray characteristics of tallow biodiesel is of utmost

importance due to its potential to contribute to a sustainable and renewable energy landscape. Moreover, tallow biodiesel offers a viable solution for utilizing animal fat by-products, reducing waste, and mitigating environmental concerns.

- **Waste cooking oil base Bio-diesel:**

Waste cooking oil (WCO) is a useful feedstock for biodiesel production. The majority of the WCO is disposed of in a dustbin, drainage system, or on the soil. Their disposal generates numerous environmental difficulties. Instead of being disposed of, WCO can be used to produce biodiesel. Because WCO is a low-cost feedstock, using it in biodiesel manufacturing makes the process relatively cheap. In comparison to edible oils, WCO does not produce a food-versus-fuel crisis, is readily available, and has no negative environmental impact. The only concern with WCO is that it contains a high concentration of FFA and water, making transesterification difficult.

### **1.6.1 Cavitation assisted Bio-diesel production**

Hydrodynamic cavitation is one of the most promising technologies for the replacement of conventional reactors. During biodiesel production with HC, cavitation occurs when the oil-alcohol mixture passes through a orifice plate or venturi tubes, resulting in pressure expansion. Cavities emerge when local pressure drops below the vapour pressure of an oil-alcohol mixture, resulting in boundary layer separation and wake production. Cavities expand and compress, releasing tremendous amounts of energy as shock waves. When the holes close, shear stresses are generated in the adjacent bulk fluids, which disrupt molecular bonds. Hydrodynamic cavitation (HC) is a very energy-efficient technique to produce biodiesel, treat wastewater, and synthesising chemicals. Hydrodynamic cavitation can increase biodiesel yields by up to 90% in just 15-60 minutes.

## **1.7 ORGANIZATION OF THE THESIS**

The thesis is organized in seven chapters.

**Chapter1:** This chapter includes a fundamental introduction to the common rail direct injection system, fuel injector and fuel injector nozzle. Introduction of cavitation inside the fuel nozzle, spray characteristics and effect of cavitation on spray breakup. Finally, discuss biodiesel and the role of cavitation in biodiesel production.

**Chapter 2:** This chapter presents a comprehensive review of the influence of cavitation flow on spray formation and examines the effects of geometric and operational factors. The experimental techniques used to generate a cavitation map and the mathematical models have been discussed. Finally, the research gap and problem have been identified based on this literature review.

**Chapter 3:** This chapter discusses the numerical and experimental methodologies used in this research work. Numerical methodology includes multiphase, turbulent, cavitation (Eulerian) modelling and spray breakup (Lagrangian) modelling. Finally, two-step Eulerian-Lagrangian coupled method has been proposed. Experimental methodology includes the design of an experimental setup to visualize cavitation flow and spray characteristics. It also includes the method for image processing and non-dimensional numbers used in this research work. Finally, an experimental set-up for waste cooking oil (WCO) - based biodiesel production has been discussed.

**Chapter 4:** This chapter provides validation of cavitation flow modelling, spray breakup modelling and the two-step coupled method. It also shows the validation of experimental data on cavitation flow and spray visualization with an empirical co-relation. The uncertainty analysis of the results has been calculated. It also includes the results obtained for biodiesel production from waste cooking oil.

**Chapter 5:**

This chapter summarizes the computational and experimental findings for cavitation flow and water, diesel, and biodiesel spray characteristics. The numerical effort began with a parametric analysis of Winklhofer et al.'s [14] nozzle geometry. The Spray C injector's cavitation and spray characteristics were investigated using the two-step coupled approach under different operating conditions. The experimental findings for rectangular and cylindrical nozzles were reviewed utilizing water, diesel, and waste cooking oil (WCO)-based biodiesel. The impact of various cavitation stages on spray break-up has been investigated. Finally, the experimental and numerical findings of spray properties for diesel, tallow biodiesel, and WCO-based biodiesel are compared.

**Chapter 6:** Finally based on current research work summarizes the key findings and recommendation that have been suggested for the fuel injector using biodiesel.

**Chapter 7:** The future work has been suggested based on the recommendation of the current work.