

Executive summary of PhD thesis entitled

**Numerical modelling of cavitation and its effect on
spray characteristics in the fuel injector for bio-
diesel**

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INDEX

ACKNOWLEDGEMENT	III
ABSTRACT	IV
CONTENTS	II
LIST OF FIGURES	X
LIST OF TABLES	XV
NOMANCLATURE	XVI

CONTENT

Chapter No.	Content	Page No.
1.	INTRODUCTION	1-10
	1.1 Introduction	1
	1.2 Common Rail Direct Injection System (CRDI)	1
	1.2.1 Fuel Injector nozzle	2
	1.3 Cavitation in the Fuel injector nozzle	3
	1.4 Fundamental of Spray break-up	5
	1.5 Cavitation induced spray breakup	7
	1.6 Bio-diesel	7
	1.6.1 Cavitation assisted Bio-diesel production	8
	1.7 Organization of thesis	9
2.	LITERATURE REVIEW	11-32
	2.1 Introduction	11
	2.2 Experimental study on cavitation flow	11
	2.3 Computational study on cavitation flow	17
	2.3.1 One-dimensional modelling of cavitation flow	17
	2.3.2 Multi-dimensional modelling of cavitation flow	18
	2.3.2.1. <i>Bubble Dynamics</i>	19
	2.3.2.2 <i>Cavitation modelling</i>	20
	2.4 Influence of cavitation flow on spray characteristics	24
	2.4.1 Cavitation coupled spray model	26

	2.4.2 Experimental study on cavitation-induced spray breakup	27
	2.5 Vortex induced cavitation	28
	2.6 Research gap	31
	2.7 Research objective	31
	2.8 Expected outcomes	32
3.	NUMERICAL AND EXPERIMENTAL METHODOLOGY	33-50
	3.1 Numerical modelling of cavitation	33
	3.2 Numerical modelling of spray breakup	35
	3.2.1 Discrete phase model (DPM)	35
	3.2.2 Spray breakup model	36
	3.3 Two-step coupling method	38
	3.4 Experimental apparatus for cavitation	40
	3.4.1 Development of nozzle	41
	3.4.2 Experimental conditions	46
	3.5 Experimental apparatus for spray characteristics	47
	3.5.1 Image processing methods	47
	3.6 Biodiesel production from Waste cooking Oil	49
	3.7 Closer	50
4.	VALIDATION OF NUMERICAL AND EXPERIMENTAL WORK	51-86
	4.1 Validation of cavitation model	51
	4.1.1 Winklhofer geometry detail	51
	4.1.2 Grid Generation	52
	4.1.3 Numerical setup	53
	4.1.4 Initial validation	54
	4.1.5 Assessment of Turbulence model	56
	4.1.6 Assessment of Cavitation Model	57
	4.1.7 Assessment of Multi-phase model & Interface modelling	58
	4.1.8 Summary of numerical modelling of cavitation flow	60
	4.1.9 Transient Simulation	61
	4.2 Validation of spray model	61
	4.2.1 Computational domain & Boundary condition	62

4.2.2	Effect of mesh size	62
4.2.3	Effect of the Spray breakup model	63
4.3	Validation of Two-step coupling method	64
4.3.1	ECN Spray C Fuel Injector nozzle	64
4.3.2	Geometry and Mesh for internal nozzle flow	66
4.3.3	Geometry and Mesh for spray formation	68
4.3.4	Initial and boundary condition	68
4.3.5	Validation for ECN spray-C results	70
4.4	Experimental work for cavitation	70
4.4.1	Validation of results	72
4.4.2	Observation table	73
4.4.3	Uncertainty analysis	79
4.5	Experimental work for Spray	82
4.5.1	Validation of spray tip penetration	83
4.6	WCO Biodiesel production	84
4.6.1	Cavitation reactor	84
4.6.2	Biodiesel Yield	84
5.	RESULTS AND DISCUSSION	87-136
5.1	Results of Winklhofer nozzle	87
5.1.1	Effect of Pressure difference	87
5.1.2	Effect of nozzle geometry	90
5.1.3	Effect of fuel properties	91
5.2	Results of ECN spray c injector	92
5.2.1	CASE-1 (ECN Spray 210037 C)	93
5.2.2	CASE-2 (ECN Spray 210003 C)	99
5.3	Experimental Results of Scaled-up Nozzle	112
5.3.1	Results of cavitation nozzle 3 (CN 3)	112
5.3.2	Results of cavitation nozzle 4 (CN 4)	119
5.3.3	Results of cavitation nozzle 5 (CN 5)	122
5.4	Experimental Results of spray characteristics	130
5.4.1	Spray development	131
5.4.2	Spray tip penetration (STP)	131
5.4.4	Spray cone angle (SCA)	135

5.5	Cavitation induced spray breakup- A Solution	136
6.	CONCLUSIONS AND SCOPE OF FUTURE WORK	137-140
6.1	Conclusions	137
6.1.1	Cavitation flow modelling	137
6.1.2	Spray break-up modelling	138
6.1.3	Two-step coupling method	138
6.1.4	Experiments for cavitation flow	138
6.1.5	Experiments for spray characteristics	139
6.1.6	Cavitation induced spray breakup	140
6.2	Scope of Future work	140
	REFERENCES	141
	Annexure-I: List of Publication	151
	Annexure-II: Dimension details of cavitation nozzle-3 (CN 3)	153
	Annexure-III: Experiment Data for Various Nozzles	156
	Annexure-IV: Bio-Diesel (WCO) Laboratory Test Report	171

LIST OF FIGURES

Figure No.	Title	Page
1.1	Common Rail Diesel Fuel injection system	2
1.2	Common Rail Diesel Fuel injector	3
1.3	Fuel injector nozzle types	3
1.4.	Sketch of nozzle entrance that shows the cavitation inception	4
1.5	Evolution of cavitation flow inside fuel injector nozzle	5
1.6	Primary and secondary spray breakup	6
1.7	Governing mechanism for primary spray break-up	7
2.1	Cavitation observed by Nurik ^[9] in the transparent nozzle	12
2.2	Comparison of hole cavitation for the enlarged (left with CN=5.5) and the real size (right with CN=5.4) nozzle, Arcoumanis et al. ^[13]	13
2.3	Two-dimensional throttle geometry and cavitation field using interferometry imaging (a, b) Winklhofer et al. ^[14] and (c, d) Mauger et al. ^[17]	14
2.4	Real size single hole transparent cylindrical nozzle (d=0.51mm, L=1mm) used by Payri et al. ^[15]	15
2.5	Transparent nozzle (d=0.3 mm, L=1 mm) fabricated by Selective Laser Etching (SLE) method to withstand 250 bar of pressure used by Kirsch et al. ^[19]	16
2.6	Compilation of experimental nozzle discharge coefficient. Data are plotted on loglog axes. Schmidt and Corradini ^[5]	18
2.7	Sketch of the atomization processes of liquid fuel injected from a nozzle, Reitz ^[64]	24

2.8	Spray cone angle with different cavitation flow pattern map, Abbasiasl T. et al. ^[94]	28
2.9	Two types of cavitation patterns obtained by shadow photography Cao T et al. ^[97]	29
2.10	String cavitation at selected needle lift during the SOI Gavaises et al ^[103]	30
3.1	Spray breakup mechanism with KHRT instability ^[104]	36
3.2	Conceptual diagram of the Two-step cavitation coupled spray breakup method	40
3.3	Schematic diagram for test set up to visualization of cavitation flow	41
3.4	Actual image of test set up to visualization of cavitation flow	42
3.5	Details of cavitation nozzle-1 (CN1), L= 10 mm, W _n =8mm, t=8mm	42
3.6	Details of cavitation nozzle-2 (CN2), L= 10mm, W _n =5mm, t=2mm	43
3.7	Schematic diagram of cavitation nozzle 3 (CN3)	44
3.8	Development stages of the cavitation nozzle-3 (CN3)	44
3.9	Microscopic image of the cavitation nozzle-3(CN3)	44
3.10	Details of cavitation nozzle-4(CN4)	45
3.11	Details of cavitation nozzle-5(CN5)	45
3.12	Schematic diagram of test set up to visualization of spray characteristics	47
3.13	Actual image of test set up to visualization of spray characteristics	48
3.14	Image processing method	48
3.15	Schematic diagram of experimental setup for biodiesel production using hydrodynamic cavitation	49
3.16	Actual image of experimental setup for biodiesel production using hydrodynamic cavitation	49

4.1	Two-dimensional throttle (transparent rectangular cross-section) geometry ^[14]	51
4.2	Cavitation field capture using interferometry imaging technique ^[14]	52
4.3	Computational domain with its dimension	52
4.4	Grid generation with refinement at throttle inlet	53
4.5	Effect of number of mesh elements on the mass flow rate of fuel	53
4.6	Quantitative comparison of fuel mass flow rate with experimental results	54
4.7	Comparison of the velocity profiles at 53 μm from the nozzle inlet	55
4.8	Qualitative comparison of Liquid volume fraction with experimental results ^[14]	56
4.9	Volume fraction of vapor at with different of turbulence model	56
4.10	Comparison of turbulence model based on the mass flow rate of fuel	57
4.11	Comparison of the SS and the ZGB cavitation model based on the volume fraction of vapor	58
4.12	Comparison of the predicted mass flow rate with the Mixture and VOF multiphase model in the SS & ZGB cavitation model combination at different pressure differentials	58
4.13	Comparison of vapor fraction contour between the mixture and VOF model in conjunction with dispersed and sharp interface option at $\Delta P=85$ bar.	59
4.14	Percentage error mass flow rate of the fuel with different combinations of numerical models	60
4.15	Vapour bubble formation and its development inside the throttle at $\Delta P=85$ bar	61
4.16	Boundary condition with detail mesh geometry	62

4.17	Effect of mesh elements on spray penetration length	62
4.18	Spray developments compared with the experimental work	63
4.19	Comparison of Spray tip penetration of different spray breakup models with experimental data	64
4.20	X-ray CT image at the injector's central cross section ^[106,107]	66
4.22	Mesh generation for internal flow	67
4.23	Mesh sensitivity study for internal flow	67
4.24	Geometry and mesh quality for spray simulation	68
4.25	Comparison and validation of Two-step coupled method with experimental and numerical work of Payri et al ^[109]	71
4.26	Comparison of theoretical and actual mass flow rate of water at different injection pressure.	72
4.27	Macroscopic spray characteristics (a) spray tip penetration (b) spray cone angle (c) spray area ^[111]	82
4.28	Development of spray after start of injection (SOI)	83
4.29	Comparison of STP with empirical model	83
4.30	Orifice plates with different slit cross section	84
4.31	Temperature rise with respect to time for different orifice	85
	Fig 4.31 Temperature rise with respect to time for different orifice	
4.32	Sample collected at every five minutes of time interval	85
5.1	Velocity profile at a location $x=0.053\text{mm}$ from the nozzle inlet	87
5.2	Pressure distribution along with the axial distance	87
5.3	Comparison of Discharge coefficient vs. Cavitation parameter with Nurik's theoretical model ^[9]	88

5.4	Effect of k-factor on the mass flow rate of fuel at a variable pressure difference	89
5.5	Comparison of the vapor fraction contour at different k-factor values	90
5.6	Effect of cavitation parameter on discharge coefficient for diesel and bio-diesel	91
5.7	Details of various simulation case for Spray C injector	91
5.8	Quantitative comparison of the simulation result with Tahmasebi et al. [110]	93
5.9	Results contour for ECN spray C injector (Case-1)	94
5.10	DPM concentration and velocity of spray	96
5.11	Steps for image processing and spray cone angle	97
5.12	Vapor fraction contour with different pressure and turbulent mode	98
5.13	Outlet velocity at different combination of inlet and back pressure	99
5.14	Mass flow rate at different combination of inlet and back pressure	100
5.15	Effective outlet diameter at different combination of inlet and back pressure	101
5.16	Corrected mass flow rate at different combination of inlet and back pressure	101
5.17	Static pressure distribution along the nozzle length	102
5.18	Liquid volume of fraction profile at nozzle outlet	104
5.19	Velocity profile at different inlet and outlet pressure	106
5.20	Turbulent kinetic energy profile at different inlet and outlet pressure	107
5.21	Spray shape at different inlet and outlet pressure	108
5.22	Cavitation coupled spray breakup	110

5.23	MPD and SMD at different inlet and outlet pressure	111
5.24	Different cavitation stages coupled with spray results with scaled up nozzle (CN 3)	112
5.25	Actual image of cavitation bubbles and sheet cavitation inside the nozzle	113
5.26	Spray cone angle vs. Injection pressure (CN 3W)	114
5.27	Injection pressure vs. Cavitation number (CN 3W)	115
5.28	Reynolds number vs. Cavitation number (CN 3W)	115
5.29	Cavitation number vs Characteristics length (L_c/L)	116
5.30	Reynolds number vs Coefficient of discharge (CN 3W)	117
5.31	Reynolds number vs Spay cone angle (CN 3W)	117
5.32	Different stages of the cavitation for diesel fuel	118
5.33	Pressure vs volume flow rate for water and diesel (CN 3WD)	119
5.34	Reynolds number vs Cavitation number for Water and diesel (CN 3WD)	119
5.35	Geometry, boundary condition and mesh details.	120
5.36	Pressure, velocity and vapour fraction contour for CN 4	121
5.37	Experimental results for CN 4 using water and diesel	121
5.38	Acrylic nozzle with its dimension and mesh details	122
5.39	Different cavitation stages coupled with spray results with scaled up nozzle	123
5.40	Effect of pressure on (a) Volume flow rate (b) Spray cone angle (c) L_{cav}/L (d) C_d	125
5.41	Reynolds number vs Spray cone angle (CN 5WDB)	126
5.42	Reynolds number vs Cavitation number (CN 3WD & CN 5WDB)	127

5.43	Comparison of CFD results with experimental image for diesel fuel	128
5.44	Pressure distribution along the axis	129
5.45	Velocity profile at (a) Inlet of the nozzle (b) Outlet of the nozzle	129
5.46	Image processing steps	130
5.47	Spray development at different injection pressure (a) 100 bar (b) 300 bar (c) 500 bar	131
5.48	Spray development for different fuels (a) Diesel (b) B20 (Tallow) (c) B20 (WCO)	132
5.49	Spray tip penetration of diesel fuels at different injection pressure	133
5.50	Spray tip penetration foe diesel, tallow & WCO (a) 150 bar (b) 300 bar (c) 500 bar	135
5.51	Spray cone angle at different time interval	135
5.52	Effect of cavitation on spray cone angle	136

LIST OF TABLES

Table No.	Title	Page No.
2.1	Summary of Experimental work for cavitation flow with real-size nozzle	16
2.2	Different Forms of Bubble dynamic equation	19
2.3	Different mass transfer source terms for condensation and evaporation	23
2.4	Summary of the work carried out in different CFD tool by the various researchers	25
3.1	Different mass transfer source terms for condensation and evaporation	34
3.2	Liquid properties	46
3.3	Experimental conditions	46
4.1	Particle summary for Diesel	64
4.2	Nominal specifications of ECN spray C injector	65
4.3	Thermo-physical properties of n-dodecane and diesel fuel	69
4.4	Boundary conditions for nozzle flow and spray simulation	69
4.5	Observation table for cavitation nozzle-3 (CN 3W) using Water	73
4.6	Observation table for cavitation nozzle-3 (CN 3D) using Diesel	74
4.7	Observation table for cavitation nozzle-3 (CN 3B) using Bio-diesel	74
4.8	Observation table for cavitation nozzle-4 (CN 4W) using Water	75
4.9	Observation table for cavitation nozzle-5 (CN 5W) using Water	76
4.10	Observation table for cavitation nozzle-5 (CN 5D) using Diesel	77
4.11	Observation table for cavitation nozzle-5 (CN 5D) using Bio-diesel	78

4.12	The parameters used for Reynolds number	79
4.13	The parameters used for Cavitation number	80
4.14	The parameters used for discharge coefficient	81
4.15	Accuracy of Measurements and Uncertainty of the calculated results	82
5.1	Quantitative comparison of mass flow rate m (g/s)	92
5.2	Quantitative comparison of spray cone angle	96
5.3	Quantitative comparison of present results with experimental data of Payri et al. ^[109]	99
5.4	Mean particle diameter (MPD) and Sauter mean diameter (SMD)	110

1. Identification of the research problem

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. 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. There is a substantial body of literature on the cavitation phenomenon in fuel injector nozzles. However, relatively little research has been published on cavitation-induced primary breakup. A lot has been learned from experimental experiments, but the pattern of the two-phase mixture remains unclear. It is also identified that the fuel jet break-up process during the early phases of droplet generation in injectors is still not fully understood. The cavitation phenomena are still being studied for diesel fuel in fuel injectors, with the goal of better understanding what happens when biodiesel is used as fuel in an internal combustion engine. The current research aims to investigate the effect of various factors on the internal flow of a fuel injector nozzle and its spray characteristics using diesel and blends of biodiesel. The research also aims to developed a two-step coupling method to include the effect of cavitation on primary liquid spray breakup, which leads to spray atomization in secondary breakup utilising numerical techniques.

2. Research Objective

- This research proposes the detailed assessment of an existing two-phase numerical model to study the cavitation phenomena inside the fuel injector nozzle.
- It is proposed to validate the results with existing experimental data available in the literature for diesel as fuel and explore the limitations of the numerical model.
- It is proposed to calculate the flow parameter at the outlet of the nozzle in both cavitation and non-cavitation conditions. These results are used to assign the initial condition for spray simulations as a part of the two-step coupling method.
- The hydrodynamic behaviour and size of cavitation bubbles will be investigated under different operating conditions to develop a cavitation map using experimentation.

- To investigate the spray characteristics of diesel, tallow biodiesel and WCO biodiesel, including the effect of cavitation.
- The results are assessed and based on that the recommendation for the new fuel injector nozzle design can be proposed for biodiesel.

3. Research Methodology

Current research has been conducted by using numerical and experimental methodology. The commercial computational fluid dynamic tool has been used for numerical modelling of the cavitation and spray characteristics. 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 using three different turbulence models ($k-\epsilon$ RNG, $k-\epsilon$ Realizable, $k-\omega$ SST), two cavitation models (SS, ZGB), and two multiphase models (Mixture, VOF), in the framework of ANSYS-Fluent platform. The non-evaporating spray has been numerically studied using the Discrete phase model (DPM) which is based on the Lagrangian drop Eulerian fluid method. It allows for tracking the fuel droplets (discrete phase) in the Lagrangian frame of reference and the continuous gas phase in the Eulerian frame of reference. Furthermore, the Wave breakup model has been used to capture droplet breakup phenomena. The Wave model is suitable for high Weber numbers ($We > 100$) and high-pressure spray. When the fuel droplets travel in the chamber, they experience the turbulent vortex, which causes the motion of the particles to shift from straight lines to non-smooth curves. The interaction between the droplet and discrete vortex is taken into account by the discrete random walk (DRW) model. The discrete random walk model was used to simulate the turbulent diffusion of the spray droplets. Finally, a two-step coupling method has been developed to understand the effect of cavitation on spray characteristics.

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. The current study considers the effect of geometry in the form of the nozzle's length to diameter (L/W) ratio. The operating conditions vary with injection pressure. The atmospheric pressure is considered as 1.013 bar. The entire experimental work was conducted using three different liquids: water, diesel, and biodiesel (tallow biodiesel and WCO biodiesel). Second experimental setup has been designed to investigate the spray characteristics. The experiment used a Delphi make

single-hole injector with a 0.2mm nozzle diameter. The injector operated at a maximum working pressure of 500 bar. To regulate injection pressure, a motor-driven fuel pump was used. The spray parameters of diesel and biodiesel fuels were investigated, including penetration length and spray cone angle. Third experimental setup has been designed to produce biodiesel using hydrodynamic cavitation. A slit type orifice-based cavitation reactor has been designed to produce the bio-diesel from the waste cooking oil. The biodiesel produced from the inhouse test setup are then used for the experimentation.

4. Key Findings

(1) Cavitation modelling:

A systematic study has been carried out with three different turbulence models, two cavitations models and two multiphase models. The results of the mass flow rate of fuel were compared to experimental data. Typically, all combinations overstate the mass flow rate to experimental data. The simulation results calculate the mass flow rate based on the nozzle's exit area. However, the reduction in the effective area during the cavitation flow is not considered using CFD calculation. This is why all models projected a higher mass flow rate than the actual mass flow rate. The maximum error with different combinations of the model has been calculated and reported in Fig. 1. The combination of the VOF+ZGB+ k- ω SST exhibits the least error among all cases.

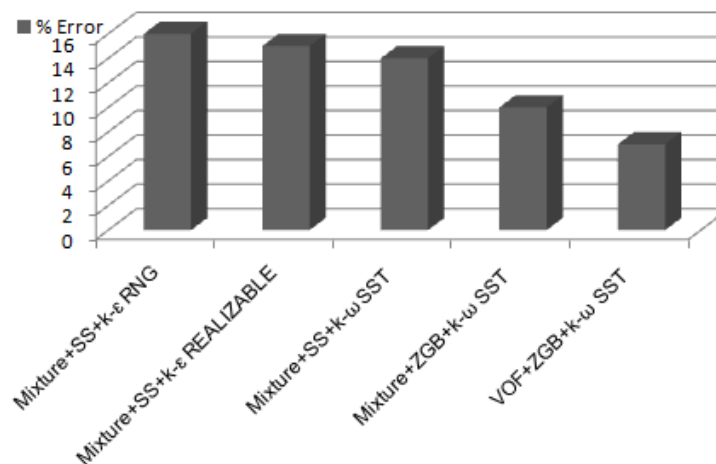


Fig. 1 Percentage error mass flow rate of the fuel with different combinations of numerical models

(2) ECN Spray-C results:

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, as shown in Fig. 2. Present method shows clear boundary of the spray after image procession. Moreover, calculation of spray is done by using file injection method which creates the exact condition for the cavitation assisted spray breakup. The developed spray patterns with proposed method exhibit a higher level of accuracy.

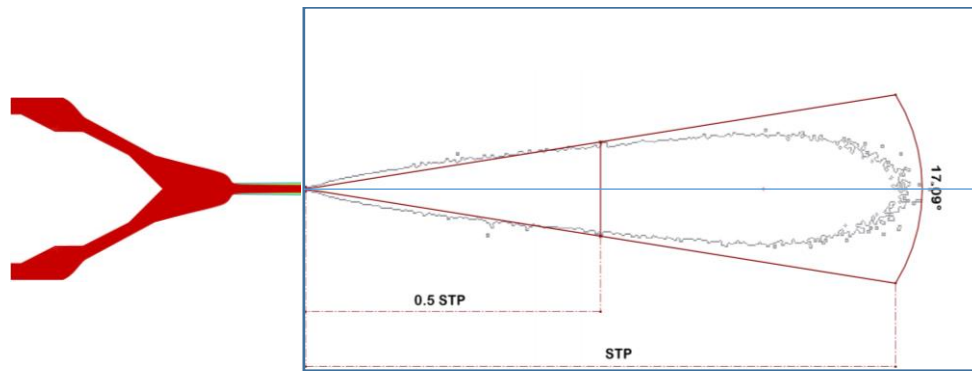


Fig.2 Spray angle calculation by using the Eulerian-Lagrangian coupling approach

(3) Cavitation induced spray break-up:

The primary goal of the current research is to investigate cavitation flow and its effect on spray characteristics. The cavitation flow, among other spray properties, has a considerable effect on the spray cone angle. The spray cone angle is estimated based on the liquid edge's divergence from the vertical line. The spray cone angle increases with increasing injection pressure.

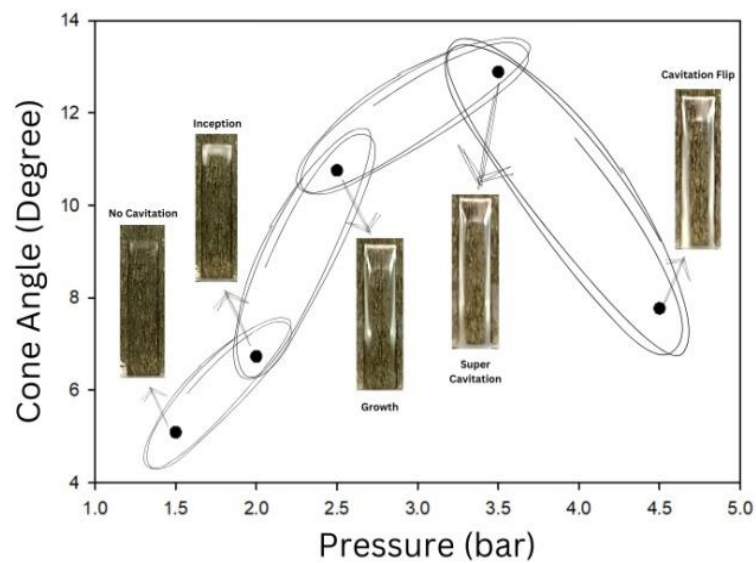


Fig. 3 Spray cone angle vs. Injection pressure

The highest spray cone angle was observed during super cavitation, as shown in Fig. 3. During super cavitation, vapor bubbles collapse at the nozzle output. The liquid jet will encounter turbulence as a result, which will improve the breakup mechanism. Hydraulic flip occurs when there is an additional increase in injection pressure, which causes air entrainment inside the nozzle and flow separation from the nozzle surface. Hydraulic flip reduces the spray cone angle.

The cavitation begins when the cavitation number falls below unity, regardless of geometrical parameters or fluid properties. Although vapor pressure affects the inception of cavitation and it starts at lower cavitation number. The fluid viscosity has a significant effect on the Reynolds number and cavitation number. As viscosity increased, curves moved inwards. The higher viscosity delayed the inception of cavitation, resulting in bubbles appearing at relatively lower cavitation numbers shown in Fig.4.

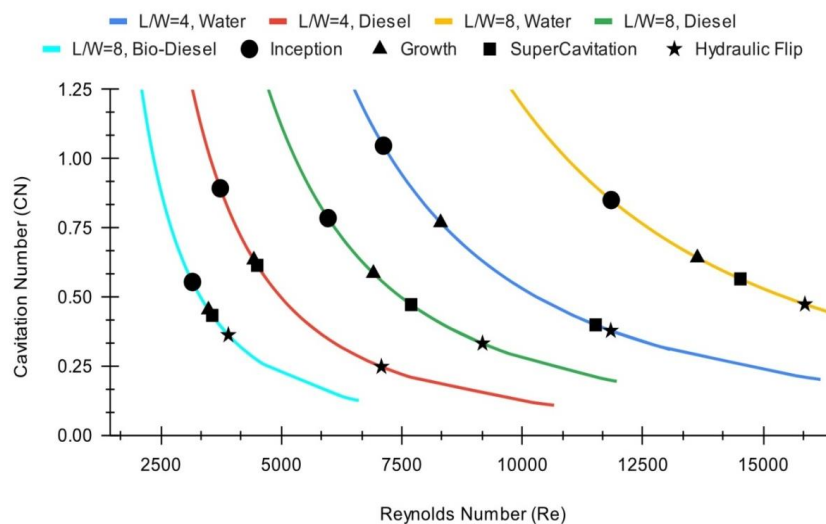


Fig. 4 Reynolds number vs Cavitation number

(4) Spray development of Biodiesel

The spray development of diesel spray under different injection pressures. As injection pressure increases, the spray border becomes unstable, and ligament breakage is readily visible. Figure 5 depicts spray formation for diesel, tallow biodiesel, and WCO-biodiesel at a pressure of 500 bar. Due to its high viscosity, biodiesel produces narrow spray. 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.

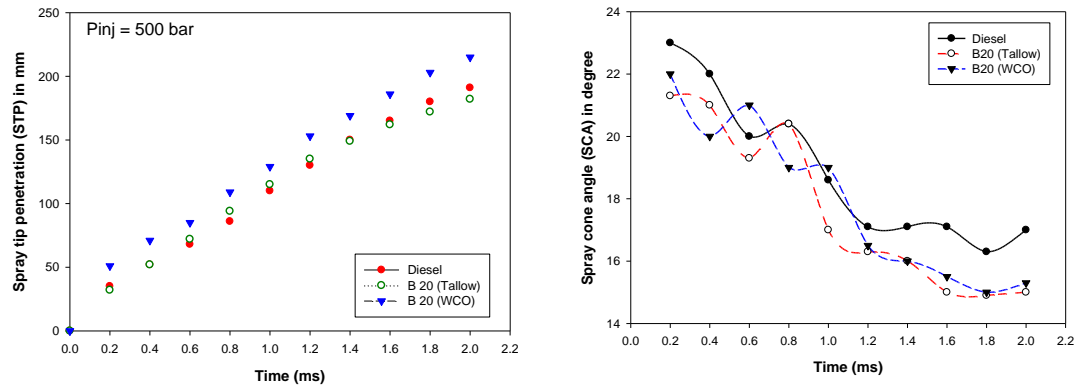


Fig. 5 Spray tip penetration and spray cone angle for diesel and bio-diesel fuels

5. Conclusions

- 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 cavitation occurs inside the nozzle, the discharge coefficient begins to decline due to reduction in the effective area. The cavitation flip causes a dramatic fall in the discharge coefficient for CN3 from 0.95 to 0.7.
- 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.
- 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. Recommendations

The current research work finds effect of inner nozzle cavitation flow on the spray characteristics. The two-step coupling method developed in the current work can be applied to assess the impact of inner nozzle cavitation on spray breakup. It was discovered that the inner nozzle cavitation has a substantial effect on the spray's primary breakup. A specific cavitation condition results in a wider spray cone angle due to improved spray atomization. The current research suggests that super cavitation conditions can result in significant improvements in spray characteristics. Furthermore, this can help to mitigate the drawbacks connected with the biodiesel. The super cavitation assisted fuel injector can work quite effectively with both diesel and biodiesel fuels.

7. Scope of future work

- 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.
- Two-step coupling method is implemented in two-dimensional geometry, this can be used with three-dimensional geometry of fuel injector.

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