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Evaluation of Statistical Study of Droplet Fragmentation In CI Engine Under Lower Injection Velocity

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Abstract

In CI Engines the fuel droplet fragmentation plays a vital role for better mixing of fuel and air inside the combustion chamber. The droplet split-up takes place under various aerodynamic factors such as flow of air, pressure inside the combustion chamber, and the speed of the fuel injected etc., The above factors decide the fragmentation types such as: (i) Vibrational fragmentation; (ii) Bag fragmentation; (iii) Shear fragmentation; and, (iv) Explosive fragmentation. In this work we aim to simulate the fragmentation of a single droplet due to a change in injection velocity and chamber pressure keeping the square root of ratio of density of fuel to that of air a fixed at 22.42. A CFD package of commercial fluent with volume of fluid formulation is used. For the simulation, a triangular cell with approximately 13500 cells is used. A standard k-ε is solution for the scheme. For both momentum and volume of fluid computations the pressure velocity coupling uses the SIMPLE algorithm and second order upwind scheme is used. Gathered results show the different methods to split a single droplet. To understand better the various aerodynamic interactions with the fuel droplet numerical simulation comes for help. In better designing of parameters like injection pressure, chamber pressure etc., without the need for an expensive experimental setup numerical simulation guides.

Keywords: Volume of Fluid, Droplet Liquid, Vibrational Fragmentation, Shear Fragmentation, Explosive Fragmentation

Introduction

A. Need for Reduced Emission

The use of diesel engines has increased widely. Diesel engines are widely used for small and large-scale power generation and transportation. However on global scale, compression Ignition Engines cause serious environmental and human discomforts. NOX, HC, CO and PM are the important pollutants from the compression Ignition Engine. These pollutants are inhalable and capable of traveling deep in to the lungs and cause diseases. Thus the compression Ignition Engine industry is under increased pressure worldwide to find methods to reduce these hazardous emissions.

B. Need for Atomization

Atomization is a process by which the sprayed fuel mixes with in cylinder air to attain combustion. It is an important factor to achieve complete combustion.

As presented in Heywood, J.B., [1], the fuel jet usually forms a cone shaped spray at the nozzle outlet. This phenomenon is defined as the atomization break up regime, and it produces droplets with sizes much less compression Ignition Engine than the diameter of the nozzle. This function is different from other modes of liquid jet break up. At low jet velocity, in the Raleigh regime, break up is due to other unstable growth of surface waves caused by surface tension and results in drops larger than the diameter of the jet. As the speed of jet is increased, forces due to the relative motion of the jet and surrounding air augment the surface tension force, and leads to drop in sizes of the order to diameter of the jet, then it is called as first wind induced break up regime. In second wind induced break up regime, the unstable growth short waves of short wavelength, induced by the relative motion between the liquid and surroundings air, produces droplets of average sizes much smaller than the jet diameter. Aerodynamic interactions at the liquid gas interface appear to be one major component in the atomization mechanism. Optimizing the parameters to improve aerodynamic interaction can be done using numerical computation.

It is proposed to study the different aerodynamic interactions to improve the performance of the engine and reduce the NOx emissions. As presented by Borman.G et.al.,[2] the theoretical problem of droplet vaporization is one of a sphere with a boundary layer in which vapour diffuses outward and from the surface. The simplest theoretical problem is in case of a wetted solid sphere surrounded by an infinite supply of hot gas (air) at conditions of zero gravity and no bulk gas flow (air stationary with respect to droplet). The idealized situation gives a spherically symmetric boundary layer. If steady state is assumed, then the liquid surface temperature is such that the heat transfers to be just equal to the energy needed to vaporize the liquid. The energy conservation equation gives the liquid temperature, and the conservation of mass and diffusion flux equations give the rate of vaporization. The problem is one of combined heat and mass transfer. In practical situations a number of complicating situations arise. First, the effects of free and forced convection are important. Small droplets may be moving with almost zero velocity relative to the flow velocity of the air, but they will be influenced by the turbulent eddies which are typically 2000-3000 micro meter in size compared with the

20-200 micro meter droplets. In general, the droplet surface moves because of vaporization, and for rapid vaporization this effect is significant. Second, the assumption of steady state is not realistic over a large portion of the droplet lifetime. For unsteady state, the some of the energy is spent in heating the droplet liquid, and heat transfer within the droplet is important. Third, the effects of high pressure (such as in compression Ignition Engines) cause changes in properties and may cause the droplet to approach a thermodynamic critical state where the latent heat goes to Zero. Fourth, for the practical case of high ambient temperature the properties in the boundary layer are functions of temperature and composition, and at high pressures they are not ideal. Thus a detailed study to understand the physics behind the fragmentation of droplets needs to be carried out. Although the experimental investigating will provide better understanding numerical methods can be used to overcome expensive experimental setup. One of the methods used for analyzing the fragmentation is Volume of fluid (VOF).

As presented by Liuzhengbai et.al.[3] developed a multizone mathematical model of film space atomization combustion in direct injection Compression Ignition Engines which consists of a sub model of atomization of the fuel sprayed in combustion chamber wall, divided into many sub zones. The fuel sprayed in the combustion chamber space is taken as one subzone. The sub models are joined through the conservation of the energy and mass in the full film space atomization combustion system by an overall system of differential equations. The authors compared the calculated results of the model with the experimental data. Uludogan.A et.al, [4] developed a computational model to increase the Compression Ignition Engine power by understanding the mechanisms of spray atomization, mixture formation and distribution. In spray atomization the authors concentrated on the effect of swirl. The swirling motion of the gas phase is an important role in mixing processes between the fuel and air and between partially oxidized products (Soot, Co, etc,). According to the authors, the spray atomization and dispersion can be described from two points by centrally mounted injector and centrifugal forces induced stratification. Though the injector is mounted centrally, the swirling motion drags fuel vapour and small droplets away from the spray centerline to the downstream volume. Centrifugal force induced stratification exists when high swirling motion, causes liquid fuel and fuel vapour in the core region of sprays to move from inner to the outer region. Authors used computational technique using KIVA II Code developed by Los Alamos National Laboratory. As presented by Takumi Ebara et.al [5] the high density zone around the spray tip was just apart from the wall surface and it is distributed various heights from the wall. It is meant that the spray which finished the fragmentation process did not make a high density layer on the impingement point. It was corresponding to a complex spray movement near the impinging center on the wall. Authors modified the elapsed time for impingement and plotted the results. Jirosenda and Tomoyuki Kanda et.al.,[6] assessed two-dimensional images of vapour and vapour concentration quantitatively by applying Lambert-Beer law to the measured fluorescence intensity in the vapour phase and modeled the vapour concentration analysis considering the adsorption of an incident laser light. There is a temporal change in fluorescence intensity with ambient temperature and fuel vapour-concentration.

As presented in Jaehoon Han et.al. [9] The secondary droplet fragmentation of liquid drops accelerated by a constant body force is examined for small density differences between the drops and the surrounding fluid. Two cases are examined in detail for a density ratio of 1.15 where the Boussinesq approximation is valid. The density ratio is ten. An ultimate difference tracking numerical technique is used to solve the unsteady Navier Stokes equations for both the drops and the surrounding fluid. An Eotvos number increases the drops fragmentation in a backward facing bag and forward facing bag mode.

Theory and Methodology

Volume of Fluid Method

Nichols and Hirt [11] first reported the Volume of Fluid (VOF) technique. The VOF method consists of three ingredients: a scheme to identify the surface, an algorithm to find the surface as a sharp interface moving through a computational grid, and a source of applying boundary conditions at the surface. In the past several years, a number of commercial CFD programs have claimed a VOF capability they are only implementing, actually one or two of the three VOF ingredients. This may be called as pseudo-VOF. Most pseudo-VOF methods use a fluid volume fraction to identify surfaces, but they then try to compute flow in both the liquid and gas regions instead of accounting for the gas by a of the boundary. This practice produces a faulty motion of the surface because it moves with the average velocity of gas and liquid. Actually, the two fluids generally move independently of one another except for a thin viscous boundary layer. In Compression Ignition Engines the fuel droplet fragmentation plays a vital role for better mixing of fuel and air inside the combustion chamber. The droplet fragmentation mainly depends upon the various aerodynamic factors such as flow of air, pressure inside the combustion chamber, velocity of the fuel injected etc., These above factors decide the fragmentation types such as (i) Vibrational fragmentation (ii) Bag fragmentation (iii) Shear fragmentation (iv) Explosive split up.

In this work the aim is to simulate the fragmentation of a single droplet due to a change in injection velocity and combustion chamber pressure keeping the square root of the ratio of Density of fuel to Density of air equal to a constant value of 23.62. Since the density would vary with pressure, simulation was also done by taking the densities to vary with pressure. A commercial CFD package FLUENT with volume of fluid formulation is used. Numerical results obtained above are showing the various methods with which a single droplet fragmentation. Thus gives better understanding on the various aerodynamic interactions with the fuel droplet.

Numerical Experiment

1. Modelling of domain with 5 x 15 times the size of the fuel droplet.
2. Generating the surface mesh in Fluent with triangular cells.

3. The following parameter were used to carry out the experiments and given in Table1**.**

Table .1. Various Injection Velocities and Chamber Pressure

INJECTION VELOCITY (m/s)	**LEVELS**	**CHAMBER PRESSURE (bar)**
100	LEVEL 1	**60**
110	LEVEL 2	**75**
120	LEVEL 3	**85**
130	LEVEL 4	**90**
140	**LEVEL 5**	**95**

Result and Discussions

Validation

The numerical experiment was conducted with density ratio of 1.25 as presented in [9] and the results are validated. The Shear fragmentation occurred for the above density ratio, and agreed with that published in the literature (Figure 1).

The simulation is done by creating a mesh 5 x 15 times of the size of a droplet. The simulation is performed for square root of large density ratio of 22.42. The model is of two phases, phase1 being droplet and phase 2 the surrounding air.

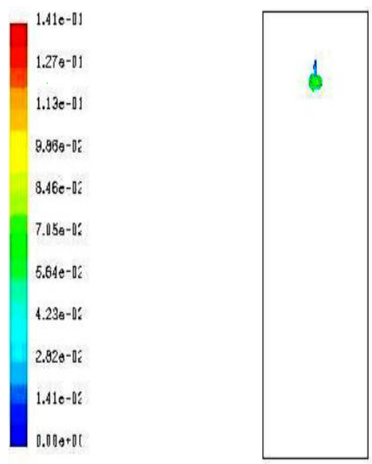

Figure 1: Shear Fragmentation

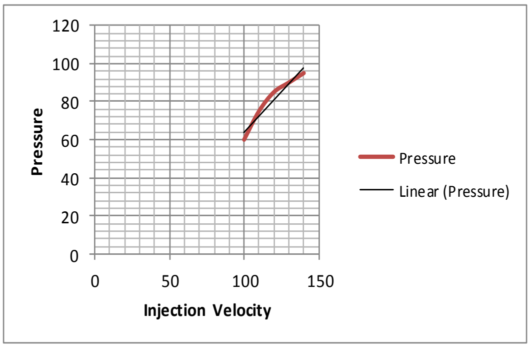

Figure 2: Various Injection Velocities with Chamber Pressure

Parametric Analysis

Simulation was performed for the various combinations of injection velocity and chamber pressure totaling 25 runs. Table 2 lists the various modes of fragmentation for a given set of parameters with arbitrary assigned values. It is in Annexture-1.

Vibrational Fragmentation

Where the droplet disintegrates into two or more equal sized smaller drops. (Arbitrary value assigned is 1). Figure 3 shows how a single droplet breaks into four parts. This case is for injection velocity of 130m/s and chamber pressure of 90 bars. This is the lowest level in the present experiment setup. It is seen that the vibrational breakup occurs around 0.5 seconds.

Figure 4 shows how a single droplet breaks as Forward bag. It can be seen that the original droplet deforms into a torus-shaped rim ahead of the droplet spanned by a thin fluid film that ruptures in to a tiny droplets followed by disintegration of the rim in to largest droplets. This Forward bag breakup happens around 0.25 seconds.

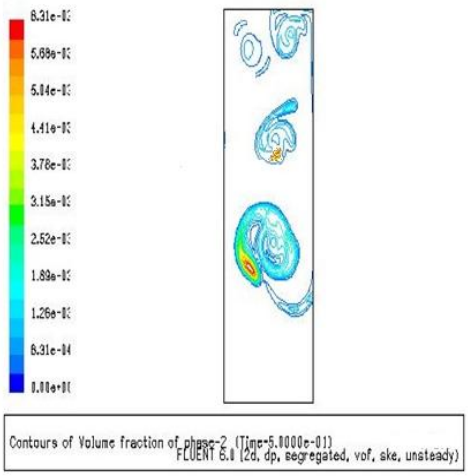

Figure 3: Vibrational Fragmentation

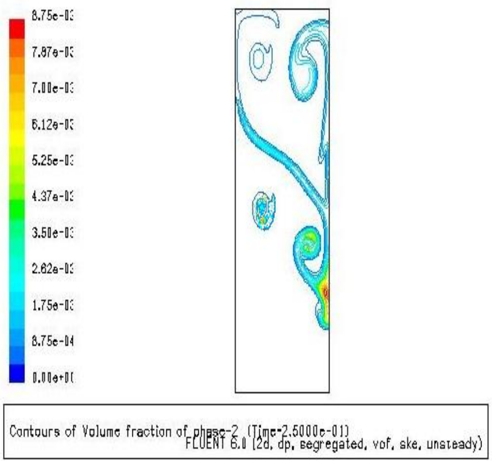

Figure 4: Forward Bag Fragmentation

Bag Fragmentation

Where the original droplet deforms into a torus-shaped rim spanned by a thin fluid film that ruptures in to a tiny droplets followed by disintegration of the rim in to largest droplets. (Arbitrary value assigned for forward bag fragmentation is 2, and for backward bag fragmentation is 3) Figure 5 shows how a single droplet breaks as backward bag. It can be seen that the original droplet deforms into a torus-shaped rim behind the droplet spanned by a thin fluid film that ruptures in to a tiny droplets followed by disintegration of the rim in to largest droplets. This Backward bag breakup happens much earlier around 0.05 sec, for an injection velocity of 174m/s and chamber pressure of 90 bars.

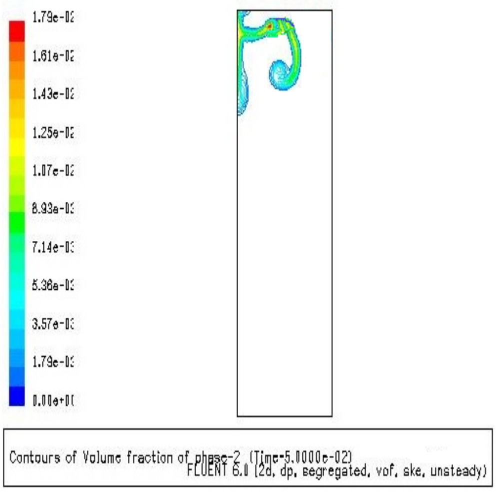

Figure 5: Backward Bag Fragmentation

Shear Fragmentation

Where the smaller drops are continuously stripped off the rim of the original droplet. (Arbitrary value assigned is 4). Figure 6 shows the Shear breakup where the smaller drops are continuously stripped off the rim of the original droplet. This case is for Injection velocity of 160m/s and chamber pressure 110 bar. This Shear breakup happens around 0.25 seconds.

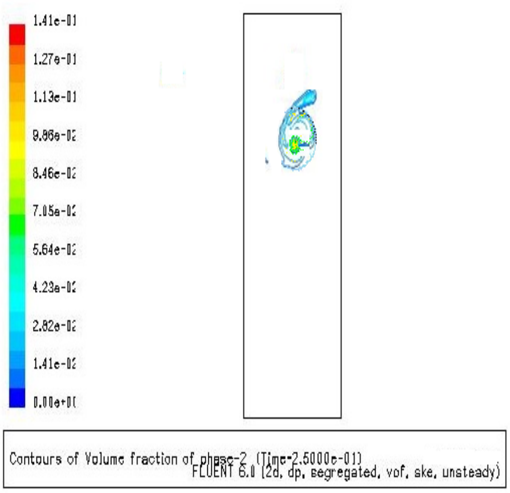

Figure 6: Shear Fragmentation

Explosive Fragmentation

Where strong surface waves disintegrates the drop in a violent manner. (Arbitrary value assigned is 5). Figure 7 shows how a single droplet breaks in a violent manner. This case is for an injection velocity of 174m/s and chamber pressure of 110 bars. This Explosive breakup happens around 0.15 seconds. The experiment was conducted in such a way that by keeping the velocity level constant and the pressure is varied and Table.3 presents the frequency of the various droplets by assigning arbitrary values between 1 and 5 for the various breakup regimes.

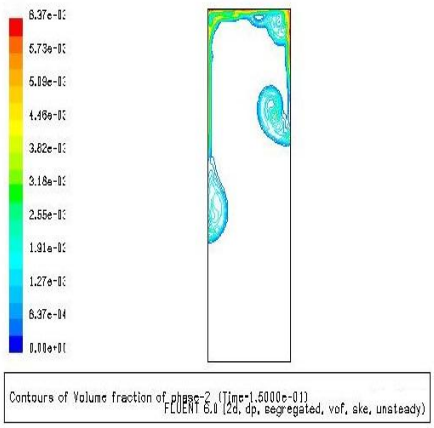

Figure 7: Explosive Fragmentation

Experiments show that the optimum levels for getting the explosive breakup is a very high injection velocity of 174 m/s and a combustion chamber pressure of 105 to 110 bars. It was observed in the present experiment that for a given velocity the change in pressure did not change the mode of breakup drastically. However at a constant pressure of 110 bar and an increase in velocity from 130 m/s to 174 m/s the breakup regime changed from forward to shear and finally to explosive breakup.

A similar trend is found when the chamber pressure is fixed at lower level of 90 bars the change in velocity caused the breakup change from vibrational to forward and forward to backward.

Table 3: Frequency of Various Droplet Breakups

Type of Breakups	Assigned values.	Frequency
Vibrational breakup	1	1
Forward bag breakup	2	17
Backward bag breakup	3	3
Shear breakup	4	2
Explosive breakup	5	2

This is summarized in Table 5.

Table 4: Mean, Median, Mode and Standard Deviation

Mean	**2.48**
Median	**2**
Mode	**2**
Standard deviation	**1.0048**
Variance	**1.0100**

Table 5: Breakup Mode in Assigned Values

	Velocity (m/s)			
Pressure (bar)	100	110	120	130
90	1	2	2	3
110	2	2	4	5

From the table 4, the mean, median and mode are Calculated and confirm that the bag breakup is the predominant mode. Thus it can be concluded that Injection velocity plays a major role in deciding the breakup mode and therefore a more significant factor compared to chamber pressure. Simulations were also carried by letting the density to vary with pressure. It was found that in these cases too, Bag breakup was the preferred mode.

Conclusion

1. This paper present the results based on Nakkeeran.s [12]. But in this paper analyzed the droplet breakup trend at low chamber pressure. Whether the injection velocity is low or high, seen that the bag breakup is the preferred form of breakup. This also confirms the theoretical study of Reitz-Diwakar [Star-CD Methodology, 2002] that droplet breakup due to aerodynamic forces occurs by bag or stripping breakup.
2. From the present study it can be seen that the injection velocity decides the mode of breakup and the chamber pressure is second to it. Thus better atomization can be obtained by various ranges of the injection velocity rather than chamber pressure.
3. It is seen that numerical simulation helps in better understanding and the various aerodynamic interactions with the fuel droplet. This will help in better design of parameters like injection velocity, chamber pressure etc., without the need for an expensive experimental setup.
4. However the following should take into account: i) droplet to droplet interaction; ii) droplet wall interaction; and, iii) droplet mass transfer, in order to better understand the breakup physics under actual conditions.

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Annexure-1

Table 2 : Identification of Breakups with Assigned Values

Velocity (m/s)	**PR (bar)**	**MODE**	**Assigned Values**
100	90	Vibrational	**1**
100	95	Forward bag	**2**
100	100	Forward bag	**2**
100	105	Forward bag	**2**
100	110	Forward bag	**2**
110	90	Forward bag	**2**
110	100	Forward bag	**2**
110	105	Forward bag	**2**
110	110	Forward bag	**2**
1 120	90	Forward bag	**2**
120	95	Forward bag	**2**
120	100	Forward bag	**2**
120	105	Forward bag	**2**
120	110	Shear	**4**
130	90	Forward bag	**2**
130	100	Forward bag	**2**
130	105	Forward bag	**2**
130	110	Shear	**4**
142	90	Backward Bag	**3**
142	95	Backward Bag	**3**
142	100	Backward Bag	**3**
142	105	Explosive	**5**
142	**110**	**Explosive**	**5**