ISSN: 2278-5213

RESEARCH ARTICLE

Numerical analysis of droplet breakup in diesel engine

S. Nakkeeran
Dept. of Mechanical Engineering, Bharath University, Chennai-600073, India
naks_67@yahoo.co.in; +91 9445126016

Abstract

In diesel engines the fuel droplet breakup plays a vital role for better mixing of fuel and air inside the combustion chamber. The droplet breakup depends mainly upon the various aerodynamic factors such as flow of air, pressure inside the combustion chamber, and velocity of the fuel injected etc. The above factors decide the breakup types such as: (i) Vibrational breakup; (ii) Bag breakup; (iii) Shear breakup and (iv) Explosive breakup. In this work, we aim to simulate the breakup 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 constant at 23.62. A commercial CFD package FLUENT with volume of fluid formulation is used. A triangular cell with approximately 13500 cells is used for the simulation. The solution scheme is a standard k-ε. The pressure velocity coupling uses the SIMPLE algorithm and second order upwind scheme is used for both momentum and volume of fluid computations. Results obtained show the various methods with which a single droplet can break. Thus, numerical simulation helps in better understanding of the various aerodynamic interactions with the fuel droplet. This will help in better design of parameters like injection pressure, chamber pressure etc., without the need for an expensive experimental setup.

Keywords: Diesel engines, flow of air, pressure, triangular cell, combustion chamber, numerical simulation.

Introduction

The use of diesel engines has increased widely. Diesel engines are widely used for small and large-scale power generation and transportation. However, diesel engines cause serious environmental and human discomforts on global scale. The important pollutants from the diesel engine are NOx, HC, CO and PM. These pollutants are inhalable and capable of traveling deep in to the lungs and cause diseases. Thus, the diesel engine industry is under increased pressure worldwide to find methods to reduce these hazardous emissions. Atomisation 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 by Heywood (1988), the fuel jet usually forms a cone shaped spray at the nozzle exit. This type of behaviour is classified as the atomisation break up regime, and it produces droplets with sizes much less than the nozzle exit diameter. This behaviour 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 jet diameter. As jet velocity 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 jet diameter, this is called first wind induced break up regime, In second wind induced break up regime, the unstable growth short wavelength waves, 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 atomisation mechanism. Optimising the parameter 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 and Kenneth (1998), the theoretical problem of droplet vaporisation 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 heats transfer to be just equal to the energy needed to vaporise 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 µm in size compared with the 20-200 µm droplets. In general, the droplet surface moves because of vaporisation, and for rapid vaporisation 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 diesel 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 non ideal. Thus a detailed study to understand the physics behind the breakup of droplets needs to be carried out. Although, experimental investigating will provide better understanding numerical methods can be used to overcome expensive experimental setup. One of the methods used for analysing the breakup is Volume of fluid (VOF).

Volume of Fluid (VOF) technique was first reported by Hirt and Nichols (1981). The VOF method consists of three ingredients: a scheme to locate the surface, an algorithm to track the surface as a sharp interface moving through a computational grid, and a means of applying boundary conditions at the surface. In the past several years, a number of commercial CFD programs have claimed a VOF capability, when in reality they are only implementing 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 locate surfaces, but they then attempt to compute flow in both the liquid and gas regions instead of accounting for the gas by a boundary condition. This practice produces an incorrect motion of the surface since it is assumed to move with the average velocity of gas and liquid. In reality, the two fluids generally move independently of one another except for a thin viscous boundary layer.

In diesel engines the fuel droplet breakup plays a vital role for better mixing of fuel and air inside the combustion chamber. The droplet breakup 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 breakup types such as (i) Vibrational breakup (ii) Bag breakup (iii) Shear breakup (iv) Explosive breakup.

In this study, the aim is to simulate the breakup 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 performed 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 show the various methods with which a single droplet breakup thus, giving the better understanding on the various aerodynamic interactions with the fuel droplet.

Materials and methods

Numerical experiment: This work deals with simulation process using a commercial CFD package FLUENT. Modelling can be done with domain of 5 x 15 times the size of the fuel droplet. Cells with triangular in shape were generated and meshed. The experiments were conducted with different parameters given in Table 1.

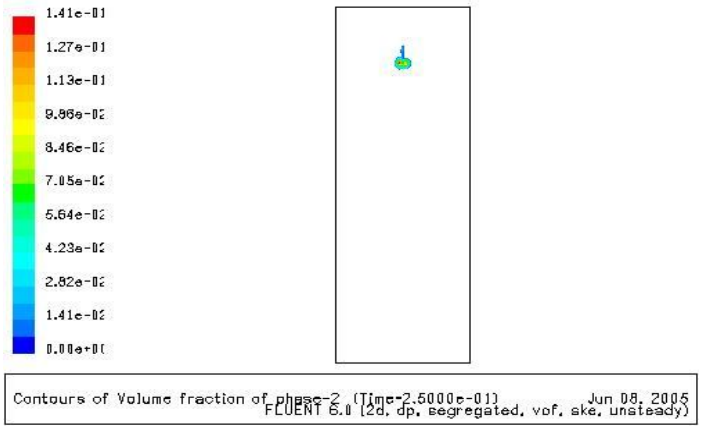
Table 1. Various injection velocities and chamber pressure.

Injection velocity (m/s)	Levels	Chamber pressure (bar)
130	1	90
140	2	95
150	3	100
160	4	105
174	5	110

Results and discussion

Validation: The numerical experiment was conducted with density ratio of 1.15 as presented in Jaehoon *et al*. (1999) and the results were validated. The Shear breakup occurred for the above density ratio, and agreed with that published in the literature (Fig. 1). This section details the droplet breakup on atomization is presented. 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 23.62. The model is of two phases, phase1 being droplet and phase 2 the surrounding air.

Fig. 1. Shear breakup.



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 breakup for a given set of parameters. From Table 2, the Average (mean), Median and Mode are calculated.

1. *Vibrational breakup:* Where the droplet disintegrates into two or more equal sized smaller drops (arbitrary value assigned is 1).
2. *Bag breakup:* 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 breakup is 2 and for Backward bag breakup is 3).

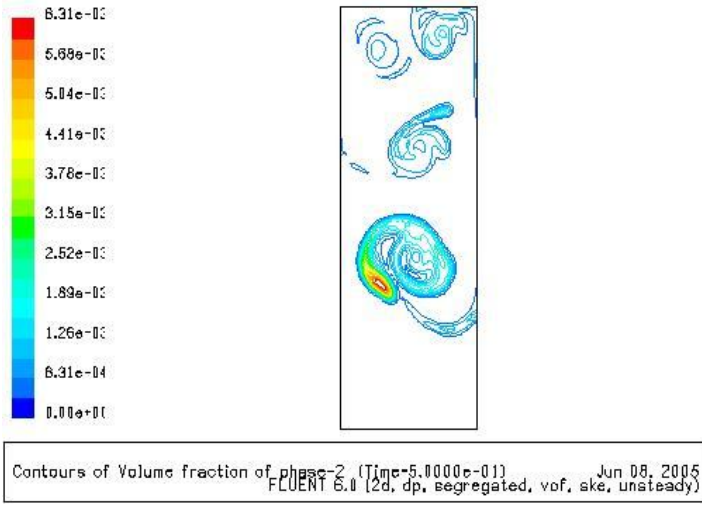
3. *Shear breakup:* Where the smaller drops are continuously stripped off the rim of the original droplet (arbitrary value assigned is 4).
4. *Explosive breakup:* Where strong surface waves disintegrate the drop in a violent manner (arbitrary value assigned is 5).

Table 2. Identification of breakups with assigned values.

Injection velocity (m/s)	Chamber pressure (bar)	Type of breakup	Assigned values
130	90	Vibrational	1
130	95	Forward bag	2
130	100	Forward bag	2
130	105	Forward bag	2
130	110	Forward bag	2
140	90	Forward bag	2
140	95	Forward bag	2
140	100	Forward bag	2
140	105	Forward bag	2
140	110	Forward bag	2
150	90	Forward bag	2
150	95	Forward bag	2
150	100	Forward bag	2
150	105	Forward bag	2
150	110	Shear	4
160	90	Forward bag	2
160	95	Forward bag	2
160	100	Forward bag	2
160	105	Forward bag	2
160	110	Shear	4
174	90	Backward Bag	3
174	95	Backward Bag	3
174	100	Backward Bag	3
174	105	Explosive	5
174	110	Explosive	5

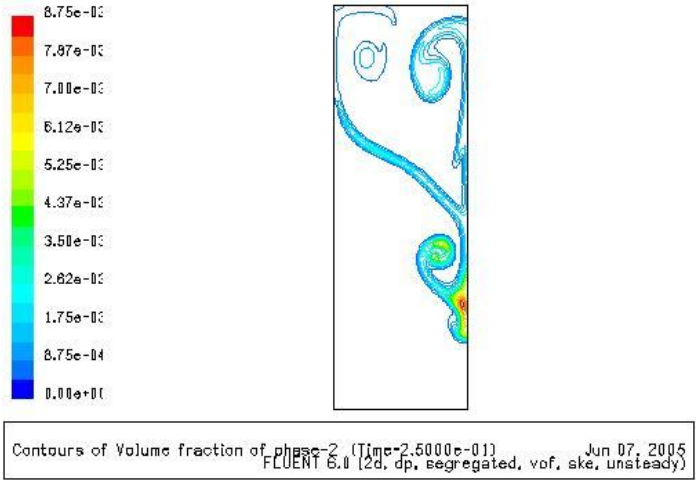
Vibrational breakup shows how a single droplet breaks into four parts this case is for injection velocity of 130m/s and chamber pressure of 90 bars (Fig. 2). This is the lowest level in the present experiment set. It is seen that the vibrational breakup occurs around 0.5 sec.

Fig. 2. Vibrational breakup.



Forward bag breakup: Figure 3 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 sec.

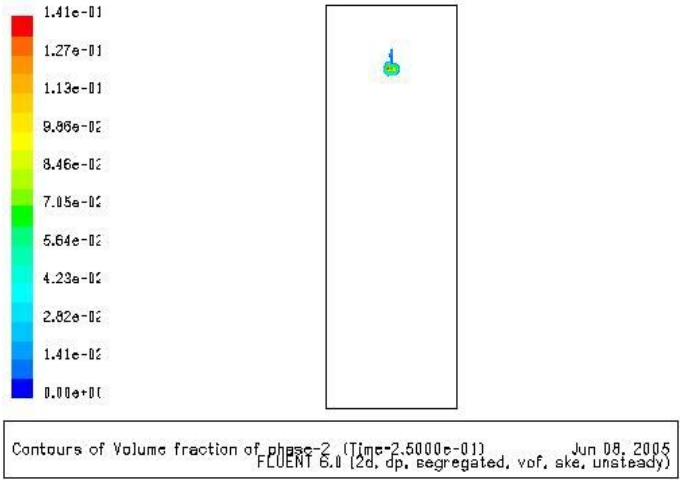
Fig. 3. Forward bag breakup.



Backward bag breakup: 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 bar.

Shear breakup: Figure 4 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 sec.

Fig. 4. Shear breakup.



Explosive breakup: Figure 5 shows how a single droplet breaks in a violent manner. This case is for an injection velocity of 174 m/s and chamber pressure of 110 bar. This Explosive breakup happens around 0.15 sec. 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. From Table 3, the Average (mean), Median and Mode are calculated (Table 4). It can be seen that for a wide range of pressure and velocity the bag breakup is the preferred form of breakup by the droplet.

Fig. 5. Explosive breakup.

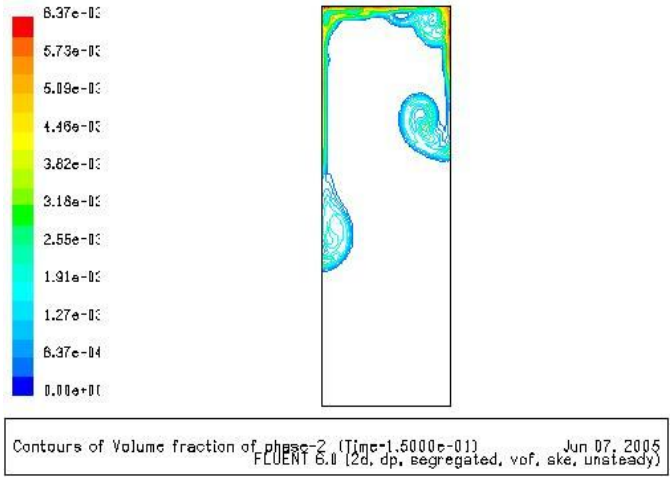


Table 3. Frequency of various droplet breakups.

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

Table 4. Mean, median, mode and standard deviation values.

Mean	2.48
Median	2
Mode	2
Standard deviation	1.0048
Variance	1.0100

Table 5. Breakup mode assigned values.

Velocity (m/s)/ Pressure (bar)	130	140	150	160
90	1	2	2	3
110	2	2	4	5

Table 6. Mean median, mode values.

Mean	2
Median	3.25
Mode	2

From the present numerical experiments it can be said that the optimum levels for getting the explosive breakup is very high injection velocity of 174 m/s and a combustion chamber pressure of 105 to 110 bar. 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 bar the change in velocity caused the breakup change from vibrational to forward and forward to backward. This is summarized in Table 5. From Table 5, the Mean, Median and Mode are calculated and confirm the bag breakup is the preferred 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

The following conclusions can be made out of this study.

1. It is seen that the bag breakup is the preferred form of breakup. That droplet breakup due to aerodynamics forces occurs by bag or stripping breakup.
2. From the 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 increasing 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 taken into account (i) droplet to droplet interaction (ii) droplet wall interaction and (iii) droplet mass transfer to better understand the breakup physics under actual conditions.

References

1. Borman G.L. and Kenneth W.R. 1998. Combustion engineering. WCB McGraw-Hill, Boston, pp.289-334.
2. Heywood, J.B. 1998. Internal combustion engines. McGraw Hill, New York, p.522.
3. Hirt and Nichols. 1981. Volume of fluid techniques. McGraw Hill, New York, pp.315-348.
4. Jaehoon, S., Han, R. and Gretar, T. 1999. Secondary breakup of axisymetric liquid drops acceleration by a constant body force. *Physics Fluids*. 11: 3650-3667.