



INVESTIGATION ON THE EFFECT OF INJECTION PRESSURES ON THE SPRAY CHARACTERISTICS FOR DIETHYL ETHER AND DIESEL FUEL AT DIFFERENT CHAMBER TEMPERATURES

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ABSTRACT

Diethyl ether is one of the potential alternative fuels for the high speed compression ignition engines that can replace the existing neat diesel fuel. It is well known that the combustion characteristic of a compression ignition engine is highly influenced by the fuel spray structure formed during the injection process. In this paper the spray structure formation for the diethyl ether fuel is studied numerically, using the discrete phase model and it is compared with the neat diesel fuel. The spray is investigated in a constant volume chamber maintained at 30 bar pressure. The fuel is injected into the chamber at an injection pressure of 200 bar and 400 bar. The chamber temperatures are maintained at 500 K and 800 K to simulate the vaporizing and non-vaporizing conditions for the spray. The injection duration is for 3 milliseconds. The depth of penetration, the liquid length formed, the Sauter Mean Diameter of the droplets and the distribution of droplets across the spray are studied and compared for the diethyl ether and diesel fuels. The simulated results have shown that the spray penetration and liquid length for the diethyl ether fuel is reduced when compared to diesel fuel at all injection pressures and chamber temperatures. The Sauter Mean Diameter of the ether fuel is found to be decreasing as the injection pressure is increased which is in the similar trend as that of the diesel fuel.

Keywords: *Diethyl ether; spray characteristics; liquid length; penetration; discrete phase model; atomization*

1. INTRODUCTION

In high speed diesel engines the combustion, emission and performance characteristics are greatly influenced by the fuel injection process. The injection process is characterized by the structure of the fuel spray formed during this process. Generally the fuel sprays are characterized both at the macroscopic level and at the microscopic level. At the macroscopic level the interaction of the spray with the air chamber is studied and it is characterized by the terms spray tip penetration, spray cone angle and liquid length. At the microscopic level the formation of fuel droplet is studied and it is characterized by the terms atomization and droplet distribution. Spray tip penetration and spray cone angle characterize the depth and width of the fuel being injected in the combustion chamber. The distance from the nozzle tip at which the first droplet formed is obtained from primary breakup or liquid length characteristics. The fuel spray structures are greatly influenced by many parameters such as injection pressure, fuel temperature, chamber conditions, and more dominantly by fuel properties.

The spray penetration characteristics studies of diesel fuel at different injection pressures and air chamber density had shown the existence of linearity between the spray tip penetration and the time after injection (Hay and Jones, 1972). The initial fuel droplet that emerges from the injector tip experiences more aerodynamic resistance from the air in the combustion chamber and gradually loses its momentum and its velocity (Ahmadi et al., 1991). This aids the successive fuel droplets to have lesser aerodynamic resistance that helps to penetrate little deeper into the chamber. Studies on the effect of the injection parameters on spray characteristics had shown that during the

initial stages of injection the spray angle formed was large and then it converges after the breakup period (Song et al., 2005).

The primary breakup of fuel spray influences the quality of the combustible mixture formation in diesel engines. The primary breakup affects the fuel spray characteristics such as fuel penetration, distribution and atomization. Study on the transient behavior of the diesel spray by Eagle et al. (2014) shows that the earlier spray tip penetration, before the breakup, is not sensitive to the orifice sizes but with the injection pressures. The size of orifice greatly influences the spray characteristics only beyond the break up period. Wang et al. (2016) studied the effect of fuel temperature on the diesel fuel spray at the macroscopic and microscopic level. Experiments were carried out by maintaining the fuel temperature well below the atmospheric temperature. Low fuel temperatures resulted in increased fuel viscosity which reduces the mass of fuel injected at the set injection pressure. Low temperature of fuel also results in larger droplets due to poor dispersion.

Experiments conducted by Huang et al. (2015) revealed that the spray spreading angle and the spray area were greatly influenced by the evaporation and combustion process in an engine. Studies on the effect of fuel properties on spray formation by Zigan et al. (2010) shown that the primary breakup and the spray tip penetration were greatly affected by the fuel temperature, the injection pressure and the fuel properties.

Park et.al (2010) studied the spray characteristics of dimethyl ether both experimentally and numerically. They had reported that at ambient conditions the spray angle for dimethyl ether was larger than that of diesel due to occurrence of flash boiling. Similar kind of spray behavior was reported by Suh et al. (2009) during the study on the effect of injection pressure on the atomization characteristics of dimethyl ether

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sprays. Dimethyl ether fuel showed better atomization characteristics compared to diesel fuel. Cipolat and Valentim (2013) studied the spray characteristics of dimethyl ether and diesel experimentally and reported that the penetration depth of dimethyl ether was consistently lesser compared to diesel at all injection conditions.

Lee et.al (2013) had numerically studied using the KIVA-3V code the behaviour of spray penetration at different compression ratios. The results had shown that the spray penetration length was decreasing when the compression ratio increases. M.R.Turner et.al (2012) had studied numerically the transient behavior of the fuel spray and developed a model to characterize the breakup regime of the spray. The authors had adopted the hydrodynamic stability theory to develop a composite model that defines the breakup and the droplets formation separately. The primary jet breakup and the spray development process, for an injector sac-nozzle flow, were simulated by Befrui et.al.(2015). The nozzle flow and the primary breakup were simulated using the VOF-LES (Volume of Fluid Large Eddy Simulation) model and the spray development process was studied using the standard Lagrangian discrete droplet model. The simulated results for the penetration, spread angle and the distribution of droplets were in good agreement with the experimental results. Vujanovic et.al (2015) adopted Eulerian-Eulerian multiphase approach to simulate the high pressure diesel injection. The authors had used nine Eulerian phases to perform the spray simulation – one gaseous phase, seven droplet phases with different droplet diameters and one bulk liquid phase. The results had clearly shown the dependency of injection pressure on spray development. Torelli et.al (2015) along with the Sandia Engine Combustion Network characterized the diesel spray behavior numerically using Discrete Droplet Model (DDM) method where each parcel was assumed to be surrounded by sphere of ambient gas.

The fuel injection process is greatly influenced by the cavitation phenomenon happening inside the injector due to large pressure differential available across the orifice during the injection (Sou, 2007; Park 2007; Payri 2004; Vijayakumar 2013). The turbulence induced inside the nozzle due to cavitation enhances the primary breakup of the fuel (Suh et al., 2008). The formation of vapor bubbles, due to cavitation (Desantes et al., 2010), inside the nozzle increases the cone angle of the fuel being sprayed. The presence of cavitation bubbles at the nozzle exits slightly increases the spray angle. The internal geometry of the holes has significant effect on the exit flow and the primary breakup of the spray and this influences the injection rate and the degree of atomization (Han et al., 2002).

The properties of the fuel play an important role in the formation of fuel spray in a compression ignition engine which in turn affects the performance and the emission characteristics. A good amount of work has already been carried out by various researchers across the globe to meet the emission requirements by controlling the diesel spray characteristics. Currently the emission norms are becoming so stringent that in order to meet the norms, modifications in the fuel injection alone will not be sufficient but modification in the properties of the fuel is also becoming the need of the hour. Researchers across the world are working on various alternative fuels with good fuel properties that are similar to neat diesel fuel that can produce lower combustion emissions and reduced greenhouse gas emissions. The usage of ethers as an additive to the diesel fuel was studied by Cataluna et al. (2006) and they reported that ter-amyl ethyl ether improved the diesel performance effectively.

Oxygenated fuel like Diethyl Ether (DEE) can be a potential alternative in replacing the diesel fuel. Subramaniam and Ramesh (2002) studied the use of diethyl ether along with diesel-water emulsion in direct injection diesel engine and reported that NOx level at full load operation is reduced substantially. Qi et al. (2011) reported that addition of 5% diethyl ether by volume to conventional diesel greatly reduces the smoke emission, due to its higher volatility. Thus from the various literatures cited, it can be said that diethyl ether may be a potential alternative for the neat diesel fuels in the near future, though it is not currently used as practical fuel in the transportation sector.

Fuel injection process is greatly influenced by the flow dynamics happening inside the injector and by the aerodynamic disturbances caused by the air on the spray inside the chamber. Studying the complex injector flows and the atomization process experimentally is a challenging one. Several visualization and image capturing techniques have been used to characterize the sprays inside the engines by various researchers. Owing to the difficulty in experimental methods, numerical simulation techniques can be an alternative tool for studying and analysing the fuel spray characteristics in extensive manner. Also, though a good amount of research has been carried out on the usage of diethyl ether as a fuel for diesel engines, the detailed study on its spray characteristics both experimentally and numerically have been missing in the technical literature as of the authors' knowledge. Hence in this study, an extensive numerical work on spray characteristics of diethyl ether under non-reacting or non-combusting condition in a constant volume chamber is studied and the results are compared with neat diesel when injected at two different pressures of 200 and 400 bar.

2. NUMERICAL MODELLING

The fuel spray characteristics such as mean droplet diameter, droplet distribution, penetration length are determined by solving the general governing equations namely mass, momentum and energy along with discrete phase model using the computational fluid dynamics commercial codes. The detailed working mechanism of the spray model is explained as follows.

2.1 Computational Spray Model

Diesel spray injection involves complex heat and fluid flow interaction between the air and the fuel inside the chamber. The spray characteristics are best studied in a high pressure constant volume chamber under evaporating and non-reacting conditions (Lucchini et al., 2009). Due to the wide range of spatial and temporal scales associated with the fuel spray, numerical modelling of the spray characteristics posts a high challenge to the researchers. In order to characterize the sprays numerically, the help of CFD code ANSYS Fluent 15.0 is used to solve the transport equations for the given realistic boundary and initial conditions. ANSYS Fluent15.0 provides a separate model called Discrete Phase Model (DPM) to study the spray simulations. DPM deals with two phases: air is considered as the continuous phase and the fuel particles as the discrete phase.

The DPM model is based on the Lagrangian Drop Eulerian Fluid (LDEF) method, where the atomized fuel droplets (discrete phase) are tracked in the Lagrangian frame of reference and the continuous gas phase is tracked with respect to the Eulerian frame of reference (Dukowicz, 1980; Rourke and Bracco, 1980). The transport equations [25], given below, are solved for the continuous phase only and the discrete phase are dealt with the calculation of trajectory path using different drag models. The generic mass conservation equation is given in equation (1) as below.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = S_{md} \quad (1)$$

Where S_{md} is mass source due to the evaporation of fuel particles originating from discrete phase.

The momentum equation is solved for the continuous phase by considering the static pressure, p , the stress tensor, τ , and the body force, F_b , due to the interaction between the discrete and the continuous phase. The momentum equation in vectorial form is given below as in equation (2).

$$\frac{\partial}{\partial t} (\rho \vec{V}) + \nabla \cdot (\rho \vec{V} \vec{V}) = -\nabla p + \nabla \cdot \tau + F_b \quad (2)$$

The energy equation required to obtain the thermal effects and vaporization phenomenon for the current study is given by equation (3).

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot [\vec{V}(\rho E + p)] = \nabla \cdot [(k + k_t)\nabla T - \sum_j h_j \theta_j + (\vec{\tau} \cdot \vec{V})] \quad (3)$$

The terms on the right hand side includes the energy transfer due to conduction, species transport and the viscous dissipation effects.

Species Equation: The conservation of various species dealing with the interaction of discrete and continuous phase of the fuel air mixture is obtained by solving the corresponding species transport equation (4) as given below

$$\frac{\partial}{\partial t}(\rho \theta_i) + \nabla \cdot (\rho \vec{V} \theta_i) = -\nabla \cdot J_i + S_i \quad (4)$$

Where J_i is the species diffusion flux and S_i is the source term due to evaporation

The turbulent kinetic energy k' and the turbulent dissipation rate ϵ are solved for capturing the fluctuating velocity components and in the current study the realizable $k - \epsilon$ model [26] is employed to obtain the same as given by the equations (5) and (6) respectively.

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho \vec{V} k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + \mu_t S^2 - \rho \epsilon \quad (5)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \nabla \cdot (\rho \vec{V} \epsilon) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \nabla \epsilon \right] + \rho C_{1\epsilon} S \epsilon - \rho C_{2\epsilon} \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} \quad (6)$$

In the discrete phase model, the sprays are introduced into the continuous phase using the plain orifice atomizer model (Bekdemir et al., 2008). The two way interaction of the discrete phase and the continuous phase is enabled during the simulation. In order to capture the droplets breakup phenomenon, the CFD code ANSYS Fluent 15.0 is provided with two models namely the Taylor Break-up Model (TAB) (Rourke and Amsden, 1987) and Kelvin-Helmholtz Rayleigh-Taylor model. The former is mainly used for the lower Weber number injections and the Kelvin-Helmholtz Rayleigh-Taylor model also known as wave model is preferred for higher Weber number injections. In this study the Wave breakup model, proposed by Reitz (1987), is used as it considers the relative velocity between the droplets and the air chamber.

3. MODEL VALIDATION

A 3D mesh of size 20 X 20 X 120 mm with symmetric boundary conditions and 48000 cells representing one fourth of the chamber, is constructed to define the constant volume environment wherein the spray is simulated.

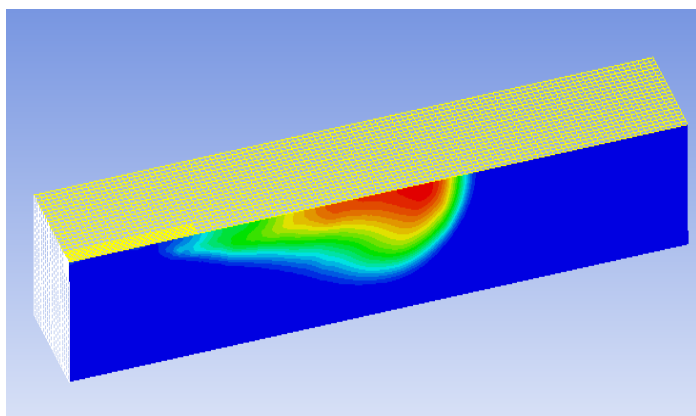


Fig. 1 Computational Mesh representing one fourth of the Constant Volume Chamber

The mesh, shown in Fig 1, is created using Gambit and it is discretized in such a way that sufficient volume is available in each cell for the continuous phase to hold the discrete phase particles during the

penetration (Stiesch, 2013). The DPM model is validated by comparing the numerically simulated results with the measurement data available with the Engine Combustion Network (ECN), Sandia National Laboratories, USA. These measurement data includes spray length, liquid length and the spray angle needed for spray validation. Experiment conducted with the n-heptane fuel, a surrogate for diesel fuel, under controlled condition, as given in Table 1, is considered for validation (Sandia ECN, 2016).

Table 1. Test and Simulation Conditions for heptane ECN – Sandia

Parameter	Value
Fuel name	Heptane
Nozzle diameter, μm	100
Nozzle length, μm	400
Mass flow per nozzle, kg/s	0.0028
Fuel temperature, K	373
Chamber pressure, MPa	4.33
Chamber temperature, K	1000
Oxygen percentage in chamber	0

The spray lengths obtained from the experiments are compared with the simulated results. In order to ensure that the DPM model is grid independent, shown in Fig. 2, different mesh sizes are used and the mesh with minimum cell size of 1 mm^3 gave comparable results with the experimental values. The model is also validated for time-step independent by simulating the spray at time steps of 10^{-5} , 5×10^{-6} and 10^{-6} seconds. Lower time-step of 10^{-6} seconds is able to predict the spray length that is closer to experimental data. Hence a time-step of 10^{-6} seconds with mesh size of 1 mm^3 along the axis direction is chosen for the DPM spray model. The DPM model constants used for both the fuel is shown in Table 2.

Table 2: Model Constants for Discrete Phase Model

Parameter	Value
Drag Law	Dynamic Drag
Breakup constant B0	0.61
Breakup constant B1	1.71
No of Parcels	1000

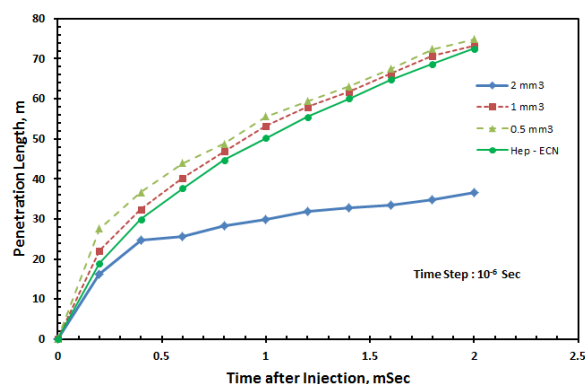


Fig. 2 Spray Penetration length of Heptane fuel for various mesh configurations

Figure 3 shows the simulated spray penetration contour of heptane fuel (shown in the upper half) compared with the Schlieren image (shown in the lower half), obtained from Engine Combustion Network-Sandia, at 1 millisecond and 2 milliseconds after the start of injection. The spray penetration length of the fuel is obtained by plotting the contours for the zero fuel vapor fraction value. The maximum axial

penetration length is then measured from the contour. The contour is then compared with the Schlieren image at the specified timeframe as shown in Fig. 3. The simulation is able to predict the spray length closer to the experimental values and the maximum deviation is less than 6 % at the time duration of 1 millisecond and it is found that the variation is negligible around 2 milliseconds. The experimental liquid length for heptane is reported to be 9.2 mm and the simulated value is 10.4 mm. Figure 4 shows the penetration length for heptane fuel obtained by simulation and through experiment. In order to validate the diethyl ether the fuel is injected under the conditions given in Table 3. The simulated results shown in Fig. 5, are compared with the empirical relations provided by Dent (1971) and Wakuri et.al (1960) for spray tip penetration with respect to time. Discrete phase simulation model is able to predict the spray length more closely with experimental values and hence this model is used with confidence to simulate the spray characteristics of diethyl ether and diesel fuel in this current research work.

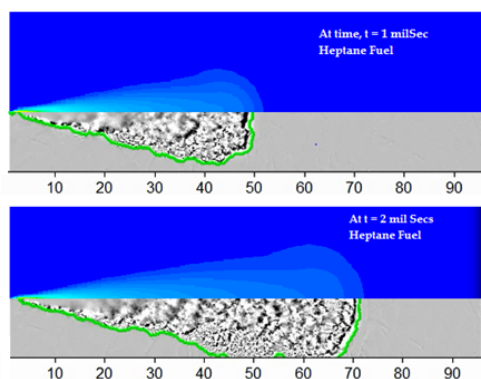


Fig. 3 Spray penetration comparison for heptane at 2 milliseconds

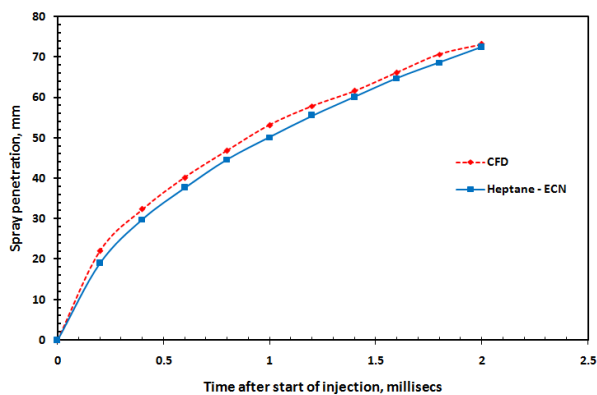


Fig. 4 Spray penetration versus time comparison for Sandia ECN heptane fuel

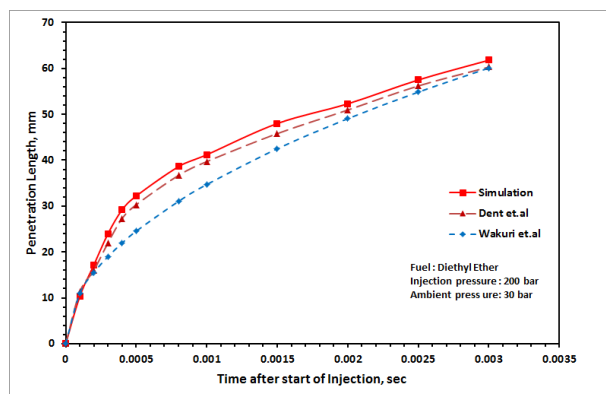


Fig. 5 Spray Penetration vs time comparison for DEE fuel with empirical equations

3.1 Simulation Conditions for Fuels

The validated DPM model is used to simulate the spray characteristics of diethyl ether and diesel fuel at injection pressures of 200 bar and 400 bar. The fuel is injected into the chamber containing air maintained at a pressure of 30 bar through an injector with an orifice diameter of 196 μm . The inlet fuel temperature to the nozzle is maintained at 300 K for both the fuels. The chamber temperature is maintained at 500 K and 800 K for the injection pressures of 200 bar and 400 bar in order to simulate the non-vaporizing and vaporizing nature of the diesel fuel respectively and to compare the spray characteristics with diethyl ether fuel. The simulation is run for injection duration of 3 milliseconds. The constant volume chamber conditions and the fuel properties are provided in the Tables 3 and 4 respectively.

Table 3. Constant volume air chamber conditions

Parameter	Values
Nozzle diameter, μm	196
Nozzle length, μm	784
Injection pressures, MPa	20 / 40
Fuel temperature, K	300
Chamber pressure, MPa	3
Chamber temperature, K	500 / 800
Oxygen percentage in chamber	0

Table 4. Fuel properties of diesel and diethyl ether

Fuel property	DEE	Diesel
Carbon weight %	64.7	83
Hydrogen weight %	13.5	17
Oxygen weight %	21.6	0
Density @ 25°C (kg/m^3)	713.4	822
Viscosity @ 25°C ($\text{kg}\cdot\text{m}/\text{s}$)	0.0002448	0.00224
Surface tension @ 25°C (N/m)	0.017	0.020
Vapor pressure @ 25°C (Pa)	58660	1280

4. RESULTS AND DISCUSSIONS

4.1 Spray Penetration

The spray tip penetration is one of the important parameter that characterises the fuel spray. It is defined as the axial distance measured from the tip of the nozzle exit to the far end of the spray. Figure 6 compares the simulated spray structure for diesel and diethylether fuels, at the end of 2 milliseconds from the start of injection for an injection pressure of 200 bar. The penetration lengths of both the fuels vary by a difference of around 8 mm and its higher for diesel fuel.

The development of spray inside the chamber along the axial direction with reference to the time for both diesel and diethyl ether fuels at an injection pressure of 200 bar and for various chamber temperatures is shown in the Fig. 7. The chamber temperature is maintained at 500 K and 800 K for non-vaporizing and vaporizing conditions respectively. The rate of penetration of the both the fuel during the early stage of injection, upto 0.1 milliseconds, is very high as expected due to higher momentum available for the fuel particle. This is called the primary breakup period. More fuel particles are available nearer to the nozzle exit with higher axial velocity and hence they are

able to easily overcome the air resistance and penetrate much deeper into the chamber. As it gets into the chamber, the fuel particle loses its momentum and after that the motion of the particle is defined by the motion of air inside the chamber and hence the gradient of the penetration is less after the primary breakup. At 800 K chamber temperature, the sprays of both fuels are able to penetrate deeper than at 500 K as expected and similar results have been reported by Park et al (2010).

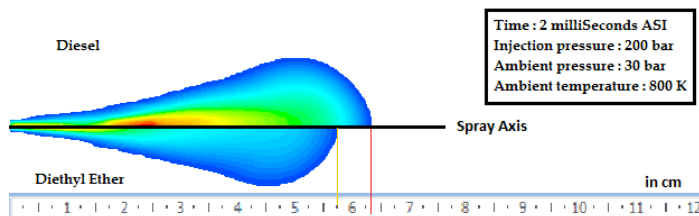


Fig. 6 Contours of fuel sprays for diesel and diethyl ether compared at 200 bar and 800 K

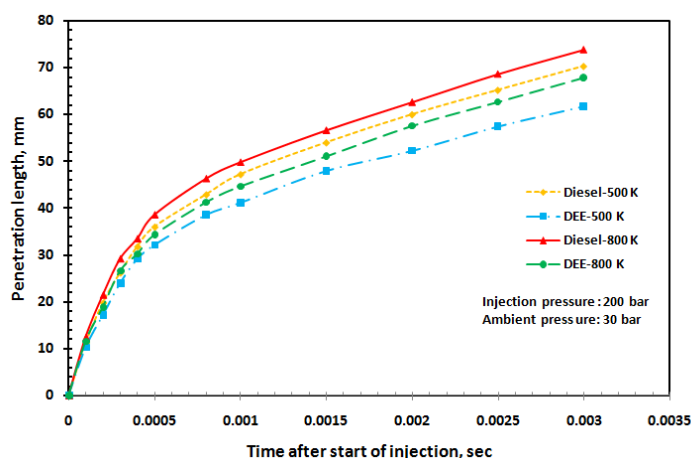


Fig. 7 Spray penetration versus time at 200 bar

The reduced density of the chamber at 800 K decreases the resistance offered by the chamber for the incoming fuel particles and hence allows the fuel particles to penetrate little deeper. Diethyl ether is able to penetrate less due to its decreased density when compared to diesel fuel. As the density of the fuel decreases, the momentum of the fuel particle also decreases hence the penetration of the particle. The decrement in the penetration length for diethyl ether compared with diesel fuel at 500 K is little more when compared at 800 K.

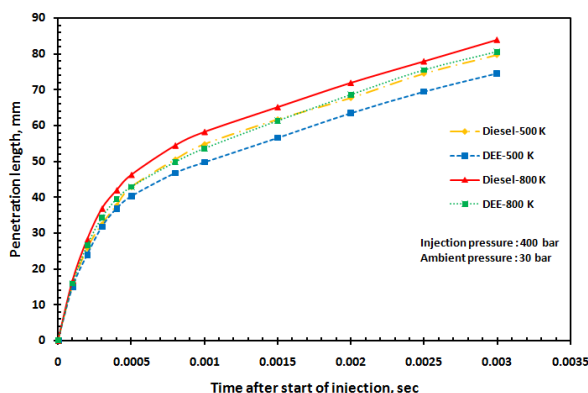


Fig. 8 Spray penetration versus time at 400 bar

Figure 8 shows the spray penetration for injection pressure of 400 bar for both the fuels. Similar kind of trend as that of 200 bar is observed for both the fuels. The penetration lengths are increased for both the fuels when compared to 200 bar. Increase in injection pressure with the same chamber pressure, increases the kinetic energy of the fuel particles emerging from the nozzle orifice hence the momentum of the particles. This gives the fuel particles sufficient energy to penetrate more into the chamber. The difference in the penetration levels between the diesel and the diethyl ether is reduced at 400 bar when compared with 200 bar injection pressure due to the higher saturation pressure of the diethyl ether fuel. Formation of cavitation inside the injector for diethyl ether is much higher at high injection pressures when compared with diesel fuels as reported by Vijayakumar et al (2011). Due to this, effective area of the nozzle reduces and hence increasing the fuel velocity slightly for diethyl ethers. Increased fuel velocity results in increased penetration.

4.2 Liquid Length

Liquid length is the axial distance from the tip of the nozzle to the point where the separation of the fuel droplets from the bulk liquid core occurs. Liquid length is experimentally determined by studying the dense region of the spray using back illumination technique. In CFD simulation, the liquid length is determined by plotting the densely liquid droplets and measuring the axial distance from the tip of the nozzle to the point where the droplet separate from the liquid core. Figure 9 shows the liquid length obtained for the diethyl ether and the diesel fuels. The liquid length for the diethyl ether is lower than diesel fuel at both injection pressures due to the lesser density and lesser viscosity of the diethyl ether fuel.

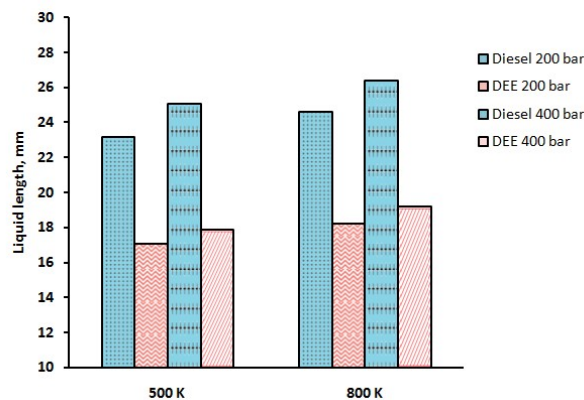


Fig. 9 Liquid length comparison for diesel and diethyl ether

The liquid length is slightly increasing for both the fuels when the chamber temperature is increased from 500 K to 800 K. Increased chamber temperature enhances the heat transfer between the fuel and the air and hence reduces the fuel viscosity inside the chamber. This reduces the internal resistance and tends the fuel droplets to separate from the liquid core more early. At the same time when the chamber temperature is raised to 800 K, the density of the chamber reduces which makes the liquid to penetrate easily hence overall the effect of the density is predominant and hence the liquid length slightly increases (Fisher and Mueller, 2012). The increased injection pressure slightly increases the liquid length of the fuel due to increased kinetic energy of the fluid particle.

4.3 Droplet Distribution

After the primary breakup the fuel droplets further divides into smaller droplets due to the aerodynamic interaction of the air and the fuels. This process is called atomization. During this process droplets of different diameters are formed and it gets distributed along the spray.

Figure 10 shows the comparison of fuel droplets formed for diesel and diethyl ether fuels at an injection pressure of 200 bar with a chamber temperature of 500 K. More droplets are seen for diesel fuel when compared to the diethyl ether fuel, this is due to the lesser boiling temperature of diethyl ether. Most of the droplets formed for diethyl ether fuels were evaporated in the given time. Figure 11 shows the distribution pattern of the fuel droplets at regular intervals along the axial distance when the injection pressure is maintained at 200 bar and the chamber temperature is at 500 K. The droplet distribution is studied after 3 milliseconds of fuel injection. For diesel fuel majority of the droplets are in the diameter range of 4-10 microns and these droplets are spread in the axial distance between 20 – 50 mm from the nozzle tip. The majority of the droplet diameters in the case of diethyl ether are in the range of 2-4 micron, much lesser than that of diesel fuel.

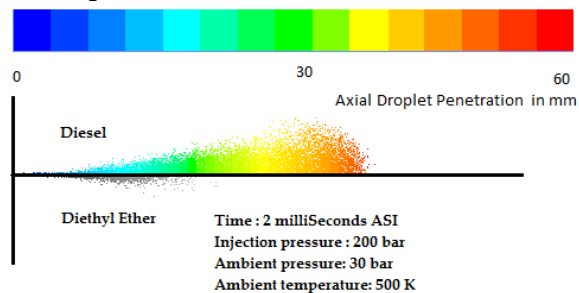


Fig. 10 Spray profile showing fuel droplets for diethyl ether and diesel at 200 bar

The droplet diameter highly depends on the surface tension of the fuel. Since the surface tension of the ether fuel is less than the diesel fuel, the droplet diameter is reduced (Ashgriz, 2011). These droplets are distributed closer to the nozzle tip less than 30 mm. Beyond the axial distance of 30 mm majority of the ether droplets have been converted into vapor due to the faster evaporation of ether droplets when compared to the diesel droplets. The ether droplets have lower boiling point compared to diesel hence it gets converted into vapor quickly for the same injection pressure and duration. In case of diesel more droplets are found even after the axial distance of 50 mm.

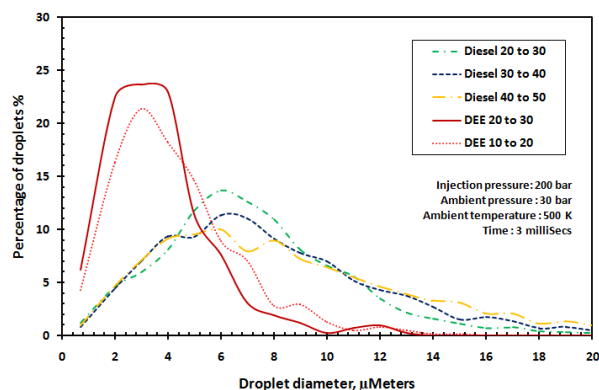


Fig. 11 Distribution of droplets along the axial direction at 200 bar

The effect of injection pressure on atomization is quite significant when the injection pressure of the fuel is increased to 400 bar. Figure 12 shows the distribution of droplets along the axial direction at an injection pressure of 400 bar and chamber temperature of 500 K. As the injection pressure increases, the fuel injection velocity also increases. This increases the relative velocity between the fuel droplets and the air chamber and hence the aerodynamic interaction of air on the fuels. This reduces the diameter of the fuel droplets. This is evident from the distribution of fuel droplets as seen in Fig. 12. More percentage of fuel droplets of smaller droplet diameter at 400 bar are formed when compared with 200 bar at the same axial distance. Due to reduced

physical properties of ether, finer droplets are formed at 400 bar pressure compared to earlier injection pressure of 200 bar.

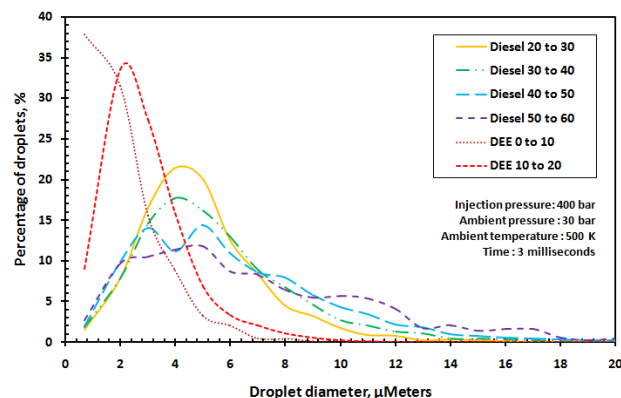


Fig. 12 Distribution of droplets along the axial direction at 400 bar

Figure 13 shows the Sauter Mean Diameter obtained for both the diesel and diethyl ether fuels for all tested conditions. At low pressure and temperature the SMD is lower for both the fuels. As the pressure increased, the SMD of both the fuels decreased, due to better atomization. The mean diameter of the diethyl ether fuel was comparatively lower than the diesel fuel due to the lower surface tension and viscosity properties. The SMD decreases with increase in both chamber temperature and fuel injection pressure and the effect of temperature is more prominent compared to increase in pressure.

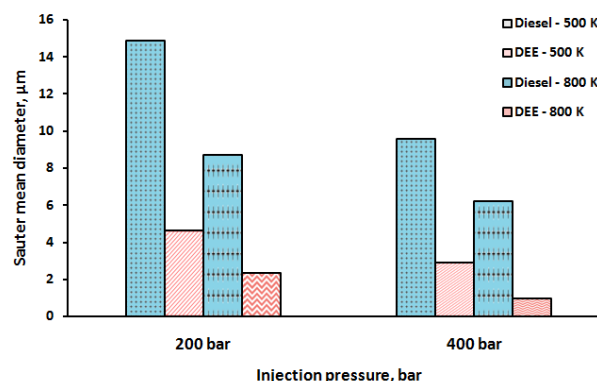


Fig. 13 Sauter Mean Diameter for diethyl ether and diesel fuels

4.4 Vapor Fraction Formed

Figure 14 and 15 shows the vapor mass fraction formed along the radial direction at a distance of 30 mm and 50 mm respectively from the nozzle tip for an injection pressure of 400 bar. At 500 K only a little quantity of diesel vapors are formed when compared to diethyl ether fuel due to the higher boiling point of the diesel fuel. The diesel vapors are spread by around 10 mm radially into the chamber at an axial distance of 30 mm from the nozzle tip for diesel fuel and it is 6 mm for diethyl ether fuel. This is mainly due to the lower density of the diethyl ether fuels. When the temperature of the chamber is increased to 800 K more vapor formation takes place for both the fuels and the spread of diethyl ether along the radial directions for diethyl ether increases whereas diesel vapor spread almost remains the same.

From Fig. 15, the mass concentration of vapors for both the fuels is comparatively lesser at 50 mm to that of 30 mm location. Even though the mass fraction of both the fuels gets decreased at 50 mm axial location their spread and radial distribution increases. The radial distribution of diesel fuel at 800 K at an axial location of 50 mm is 17.5 mm whereas it is 10 mm at 30 mm axial location. Similar trend is obtained for both the fuels. The spread of diethyl ether radially at an

axial location of 50 mm with respect to temperature is also investigated. The spread of diethyl ether fuel radially is only 7 mm at 500 K whereas it increases to 16 mm when the temperature is increased to 800 K. This may be due to the lesser resistance faced by the fuel due to reduced gas density.

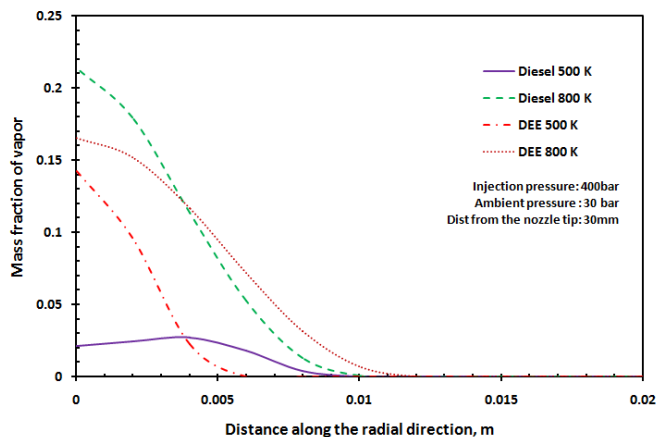


Fig. 14 Vapor mass fraction along the radial direction at 400 bar and at 30 mm along the axis

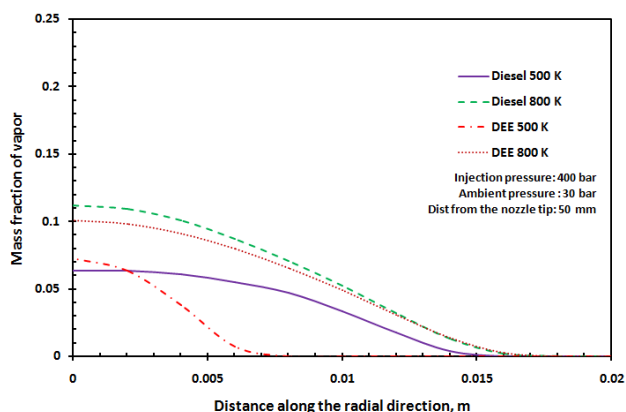


Fig. 15 Vapor mass fraction along the radial direction at 400 bar at 50 mm along the axis

4.5 Turbulent Kinetic Energy

During the fuel injection process, the fuel is sprayed into a quiescent chamber. The liquid droplets entering the chamber displace the air available inside the chamber thereby disturbing the flow field. The disturbed flow field creates velocity gradient inside the chamber due to which turbulence is created in the chamber. These turbulence are characterized either by the length scale of the vortices or the energy possessed by the vortices. The energy possessed by these formed vortices is termed as turbulent kinetic energy. Higher the turbulent kinetic energy higher the fluctuation in the velocity of the field.

Figures 16 and 17 shows the turbulence kinetic energy along the axial direction inside the spray for both the fuels at chamber temperatures of 500 K and 800 K respectively. In general for diesel sprays the turbulent kinetic energy is found to be higher compared to diethyl ether fuel spray at all injection and temperature conditions. The disturbance caused by the diesel droplets are higher due to its bigger droplets and hence higher fluctuation in the flow field causing higher turbulence level inside the chamber. As the temperature is increased to 800 K, the turbulence level is decreased for both the fuels due to the reduced droplet sizes and faster evaporation of droplets causing lesser disturbance on the air. Increase in viscosity of air at higher temperatures also reduce the turbulence level inside the chamber.

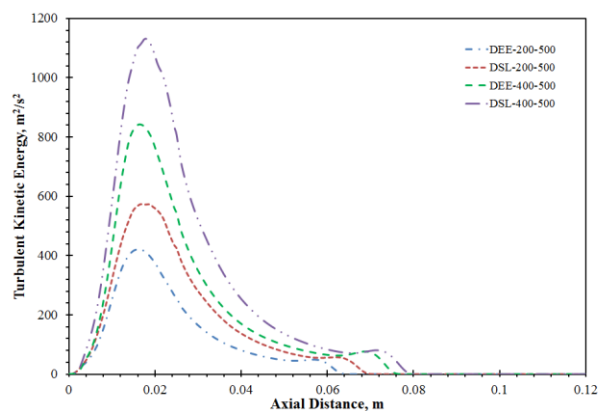


Fig. 16 Turbulent Kinetic Energy along the Axial Direction at 500 K

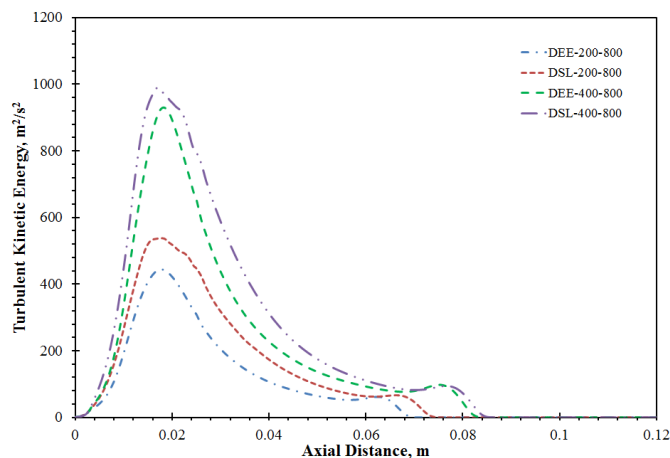


Fig. 17 Turbulent Kinetic Energy along the Axial Direction at 800 K

5. CONCLUSIONS

The numerical investigation of the non-reacting diethyl ether and the diesel fuel sprays have been studied in a constant volume air chamber. The spray tip penetration, liquid length, droplet distribution and the vapor formation are studied at an injection pressure of 200 bar and 400 bar with chamber temperature maintained at 500 K and 800 K. The major conclusions are as follows:

- The diethyl ether fuel is penetrating lesser when compared with diesel fuel at all injection pressures, 200 bar and 400 bar, and chamber temperatures, 500 K and 800 K, due to its lesser physical properties like density and viscosity compared to diesel fuel.
- The liquid length of the diethyl ether is in the range of 12-14 mm, whereas the diesel fuel had liquid lengths of 22-26mm at all simulated conditions due to lesser viscosity of the diethyl ether fuel.
- The Sauter Mean Diameter of the diethyl ether fuel spray is smaller, due to lesser surface tension, when compared to the diesel fuel at both the injection pressures. The SMD for the diesel fuel at 500 and 800 K temperatures for 200 bar injection pressure was around 14 and 8 μm respectively, whereas for the diethyl ether it was only 4 and 2 μm . Similarly for 400 bar pressure, the SMD was reduced to 8 and 6 μm for diesel and 2 and 1 μm for diethyl ether.
- The vapor formation of diethyl ether is more along the axial direction compared to diesel fuel at 500 K due to its lower boiling point. When the temperature is increased to 800 K the diesel fuel vapor is increased compared to diethyl ether as more diesel fuel gets into evaporation process.

- The diethyl ether, due to its lesser density, is able to penetrate lesser along the radial direction compared to diesel fuel at all temperatures. When the chamber temperature is increased to 800 K, due to reduced gas density, both the fuel face lesser resistance and hence they penetrate little deeper along the radial direction.

NOMENCLATURE

Symbol	Description	Units
ρ	Density	kg/m ³
\vec{v}	Velocity Vector	m/s
S_{md}	Mass source due to evaporation	kg/m ³ s
τ	Stress tensor	N/m ²
F_b	Body force	N
E	Energy	J
k	Turbulent kinetic energy	m ² /s ²
T	Temperature	K
h	Enthalpy of species	J/kg
ϕ	Species concentration	
J	Species diffusion flux	
S	Source term due to evaporation	
μ	Dynamic viscosity	kg/ms
ϵ	Turbulent kinetic energy dissipation rate	m ² /s ³
SMD	Sauter Mean Diameter	m
DPM	Discrete Phase Model	
ECN	Engine Combustion Network	

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