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STUDY OF INTERNAL FLOW CHARACTERISTICS OF INJECTOR FUELLED WITH VARIOUS BLENDS OF DIETHYL ETHER AND DIESEL USING CFD

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ABSTRACT

Researchers across the world are exploring the potential of using diethyl ether as an alternate fuel to meet the stringent emission norms due to the high oxygen content in the fuel. The spray characteristics of any injected fuel are highly influenced by its physical properties. Due to high injection pressure in CI engines the fuel tends to cavitate inside the nozzle greatly. The change in fuel properties will affect the cavitating behavior of the fuel. In this paper computational technique is used to study and compare the internal flow characteristics of a fuel injector for different blends of diethyl ether and diesel fuel. Multi phase flow model considering the fuel as a mixture of vapor and liquid is adopted for the simulation study. The percentage volume of diethyl ether is varied from 0 to 100% and the flow characteristics are studied. Results indicate that as the percentage volume of diethyl ether increases in the fuel, the cavitating phenomenon also increases resulting in decrease in mass of fuel injected into the cylinder.

Keywords: *Cavitation, Diethyl ether, Diesel, Injector, fuel, CI engine*

1. INTRODUCTION

The major challenges faced by the developed nations today are: the economical use of the existing fossil fuels and the development of suitable alternative and renewable fuels considering their environmental impacts. The diesel engine, though provide high power output with better fuel economy, produce high NOx and smoke emissions. Reduction of emissions, to any great extent, without sacrificing fuel economy will be an enormous challenge. The emissions from the diesel engines can be reduced by treating the emissions before letting of to the atmosphere, by improving the combustion characteristics or by improving the fuel properties before inducting in to the cylinder. The diesel fuel properties can be improved by adding additives or blending with another fuel. Guru et al (2002, 2011) studied the effect of organic based metallic additives on the performance and emission characteristics of diesel engine. The authors reported that use of additives improved the specific fuel consumption by 2.5%. The authors also reported that CO and smoke emissions are reduced by around 20% with a marginal increase in the NOx emissions. Labeckas et al (2005) studied the effect of additives on the diesel engine fuelled with shale oil and reported that the NOx emissions are reduced by 23%. They also reported that CO and smoke emissions are increased by 15% and around 35% respectively. Cataluna et al (2006) studied the usage of ethers as an additive to the diesel fuel and reported that ter-amyl ethyl ether improved the diesel performance effectively.

Among all the ethers, diethyl ether has a greater potential to be used as diesel fuel additive. The effects of using diethyl ether and ethanol as additive to biodiesel and diesel blends were studied by Qi et al (2011). The authors reported that addition of 5% diethyl ether by volume reduces the smoke emission, due to its higher volatility. The authors also reported that the NOx emissions are slightly increased when 5% of ethanol was used as the additive. The use of diethyl ether along with diesel-water emulsion in direct injection diesel engine was studied by Ramesh et al (2002). The authors reported that NOx level at full load operation is reduced substantially.

The performance and emission characteristics of any engine are highly affected by the spray characteristics of the fuel. In diesel engine the fuel is injected at high pressure to overcome the air resistance (back pressure) to get penetrated into the chamber. High pressure is also needed to enhance the atomization and spray penetration of the injected fuel and also to improve the combustion efficiency. The high fuel pressure available at the nozzle seat (200 bar) is converted into kinetic energy at the loss of pressure energy as it passes through the nozzle orifice. The drop in pressure at the entry of the nozzle is very high, leading to cavitation, and it reduces as moving towards the nozzle exit. The fuel pressure available at the nozzle exit is little higher than the in-cylinder air pressure. Cavitation is the formation of vapor bubbles in the liquid fuel when the pressure rapidly drops below the saturation pressure of the liquid fuel. The nucleation process of cavitation and the formation of vapor bubbles are experimentally studied by Takenaka et al (2004) using neutron radiography. The effect of cavitation on the fuel spray characteristics is studied by Lee et al (2008) experimentally. He reported that the primary breakup regime of the fuel is highly influenced by the turbulence created inside the nozzle. J.M. Desantes et al (2010) also reported the cone angle of the fuel spray is increased due to the formation of vapor inside the nozzle.

The injection flow characteristics of the fuel are greatly affected by the fuel density, vapor pressure and surface tension. Hosny et al (1996) studied that the cavitation phenomenon are more sensitive to the changes in fuel properties and developed correlation between cavitation and fuel properties. The thermophysical and transport properties of diethyl ether are different from diesel; hence different injection flow characteristics can be expected. Vijayakumar et al (2011) studied the cavitating phenomenon of diethyl ether, dimethyl ether and diesel fuel

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numerically and reported that the fuel velocity at the nozzle exit for ether fuels is greater than for the diesel fuel. They also reported that the mass flow rates for the ether fuels are substantially reduced when compared with diesel fuel at same injection pressure. It can be said that the rate of injection of the fuel, cavitation and the turbulence at the nozzle exit are affected by the injector flow characteristics, which in turn affects the spray atomization and penetration and hence the performance.

In the present study, the injector flow characteristics for different blends of diethyl ether and diesel fuel are studied numerically using Computational Fluid Dynamics. The effects of physical properties on the cavitation, injection velocity, coefficient of discharge and mass flow rate at the nozzle exit are simulated for different blends (0 – 100 % by volume in steps of 10) of diethyl ether and diesel fuel. The fuel injection pressure is taken as 200 bar and the pressure inside the combustion chamber (back pressure) is taken as 30 bar and a comparative study of flow characteristics is done for all the blends.

2. INJECTOR FLOW MODEL

The nozzle flow simulations were performed using ANSYS Fluent. The fluid is assumed to be a mixture comprising of liquid fuel (diesel and diethyl ether) and its vapor. Multi phase flow analysis using Schnerr and Sauer cavitation model is performed with no-slip condition between the liquid and vapor. The Schnerr and Sauer model can be used for both mixture and Eulerian multiphase models. Schnerr and Sauer model can also be used well along with all turbulence models available in Fluent, but this model doesn’t takes into account the effect of non condensable gases present in the mixture.

RNG k-ε model derived using a rigorous statistical technique called renormalization group theory, with non-equilibrium wall conditions is used in order to account for the large pressure differential across the nozzle. This model takes into account the effect of swirl well also it is capable of predicting the effective viscosity of the mixture even at low Reynolds number flow.

The vapor formation, the bubble growth and condensation are solved by considering Rayleigh-Plesset equation (2006). A three-hole injector with an orifice diameter of 184 µm and an included angle of 90° is considered for the analysis. The flow is considered to be symmetrical across all the nozzles and hence only one nozzle is considered for analysis as shown in Fig 1. The fluid domain is characterized by 441787 tetrahedral cells with 84878 nodes. The inlet and outlet conditions are provided with pressure values and symmetry conditions are employed to demarcate the 120° sector mesh. Wall boundary conditions, with no slip between the fuel-vapor mixture and the wall surface, are adopted for all the other surfaces. The flow simulation is performed at the full needle lift condition of 0.2 mm

2.1 Validation of computational model

The experimental data from Som et.al (2010) for a nozzle orifice of diameter 169µm with an included angle of 120° fuelled with diesel was used to validate the computational flow model. Fuel is injected at pressures of 1100 bar and 1300 bar for 3 ms. The back pressure is taken as 30 bar. The comparison of the mass of the fuel injected per nozzle and discharge coefficient between the experimental values and simulation values are shown in Table 1.

Table 1 Comparison of experimental and simulation values

Property	**Injection Pressure, (bar)**	**Exp.**	**Sim.**	**% error**
Mass flow rate, kg/s	1100	0.00621	0.0067	-7.89
	1300	0.00693	0.0073	-5.34
Coefficient of Discharge	1100	0.64	0.69	-7.81
	1300	0.64	0.693	-8.28

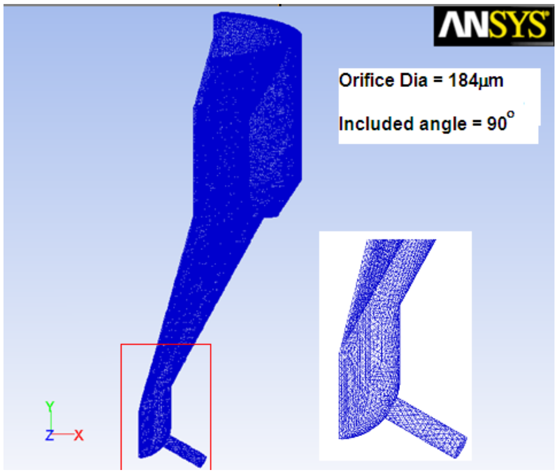

Fig. 1 Injector model

It is observed that the deviations of simulation data are well within the acceptable limits from the experimental values. It can be said that the computational model is able to capture the inner flow characteristics of the injector well and hence can be used for comprehensive parametric study of the injector flow.

3. FLOW CHARACTERIZATION

The injector flow characteristics are studied by the cavitation number (K), discharge coefficient (C_d), velocity coefficient (C_v), area coefficient (C_a), and Reynolds number (Re) as described below: Singhal et.al (2002). The cavitation number, K is calculated from

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$$K = \frac{2(P_i - P_v)}{\rho_f V^2} \qquad (1)$$

where P_i is the injection pressure (Pa), P_v is the saturation vapor pressure of the fuel (Pa), ρ_f is fuel density (kg/m^3) and V is the characteristic velocity of the fuel (m/s). The discharge coefficient, C_d is calculated using the following equation

$$C_d = \frac{M_{act}}{A_{th} \cdot \sqrt{2 . \rho_f . \Delta P}} \qquad (2)$$

where M_{act} is the actual mass flow rate (kg/s) which is obtained from the simulation, A_{th} is the nozzle exit area (m^2), ρ_f is the fuel density (kg/m^3) and ΔP is the pressure differential across the nozzle orifice.

The velocity coefficient, C_v is calculated from the following equation

$$C_v = \frac{V_{act}}{\sqrt{2 . \Delta P / \rho_f}} \qquad (3)$$

where V_{act} is the actual velocity at the nozzle exit (m/s).

The area coefficient is calculated as

$$C_a = \frac{C_d}{C_v} \qquad (4)$$

The Reynolds number, Re is calculated from the following equation

$$R_e = \frac{\rho_f.V.D_{ex}}{\mu_f} \qquad (5)$$

where V is the average flow velocity (m/s) along the nozzle orifice, D_{ex} is the nozzle exit diameter (m), μ_f is the fuel viscosity (kg-m/s).

4. RESULTS AND DISCUSSION

The thermo physical and transport properties of the fuels: diesel and diethyl ether are listed in Table 2. The fuel properties of diethyl ether are taken from CRC handbook of chemistry and physics: Lide (2003).

Table 2 Fuel properties

Fuel property	DEE	Diesel
Carbon weight %	64.7	83
Hydrogen weight %	13.5	17
Oxygen weight %	21.6	0
Density @ 25°C (kg/m3)	713.4	822
Viscosity @ 25°C (kg-m/s)	0.0002448	0.00224
Surface tension @ 25°C (N/m)	0.017	0.0020
Vapor pressure @ 25°C (Pa)	58660	1280

The injector flow simulation is performed for 120° sector mesh for an injection pressure of 200 bar with a back pressure of 30 bar. The fuel temperature is taken as 298 K for all the fuel blends.

4.1 Cavitation

Figures 2 and 3 show the vapor fractions of diesel and diethyl ether fuel. The cavitation inception is found in all the blends. It is observed that the vapor volume fraction of diethyl ether is more than the diesel due to the higher saturation pressure.

The vapor that is formed at the nozzle entry for diesel fuel is found to be collapsed immediately inside the orifice itself before reaching the nozzle exit, whereas for diethyl ether it is found that some small amount of vapor is carried along the orifice to the nozzle exit at 100% blend. Higher viscosity and lower saturation pressure of the diesel fuel helps in collapsing the vapor formed immediately. The similar kind of observation was made by Shi and Arafin (2010). The authors reported the cavitation phenomenon is highly influenced by the fluid viscosity.

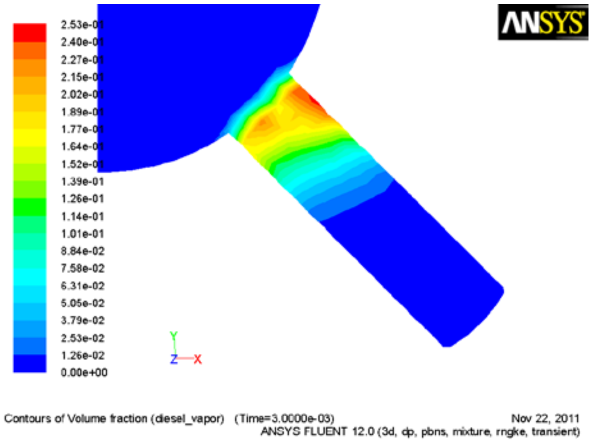

Fig. 2 Diesel vapor volume fraction at 0% blend

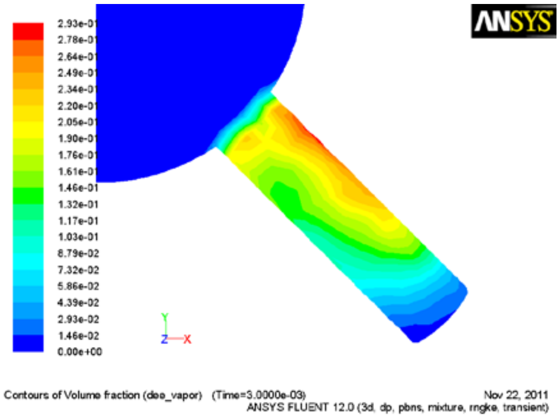

Fig. 3 Diethyl ether vapor volume fraction at 100% blend

Figure 4 shows the variation of vapor volume fraction for diesel and diethyl ether inside the injector at different blends of the fuel. It is observed that at higher blends of diethyl ether the vapor volume fraction of diethyl ether increases at little higher rate than the rate at which the diesel vapor decreases. As the percentage of the diethyl ether increases in the fuel the saturation pressure and viscosity of the fuel is also changes.

The variation of cavitations number for different blends of the fuel is shown in Fig 5. It is observed that as the percentage volume of diethyl ether increases the cavitating behavior of the fuel increases. It is also observed that the cavitation number decreases gradually up to 90% of blend. The presence of diesel fuel up to 90% blend controls the cavitating behavior to some extent. At 100% diethyl ether the cavitation number decreases sharply.

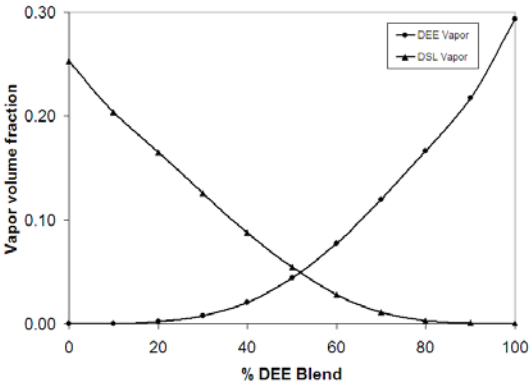

Fig. 4 Vapor volume fraction of diesel and diethyl ether

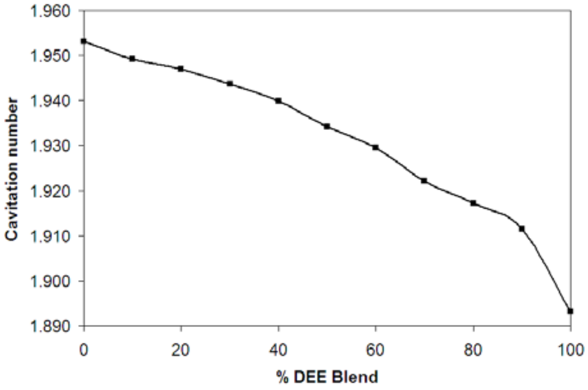

Fig. 5 Variation of cavitation number with blends

Figure 6 shows the variation of Reynolds number with cavitation number. Higher the cavitation number lesser is the Reynolds number.

At lower cavitation number more amount of vapor is formed which increases the turbulent behavior of the fuel inside the orifice. It can be said that diethyl ether creates more turbulence inside the orifice than the diesel fuel due to lower viscosity

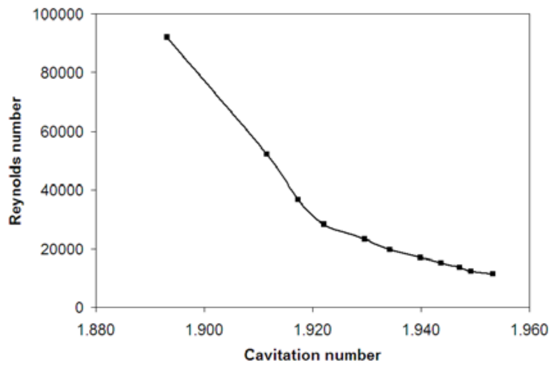

Fig. 6 Variation of Reynolds number with cavitation number

4.2 Nozzle exit parameters

The variation of coefficient of discharge with different blends is shown in Fig. 7. It is observed that as the volume percentage of diethyl ether increases the fuel viscosity and fuel density gradually decreases. Due to this the total vapor (diesel + diethyl ether) formed at the nozzle entry increases, which reduces the area (Fig. 8) available for liquid fuel to pass through: Park et.al (2010). This increases the fuel velocity at the nozzle exit. This is evident from Fig 9 which shows the variation of exit velocity with blends. Fig 10 shows the variation of mass flow rate with blends.

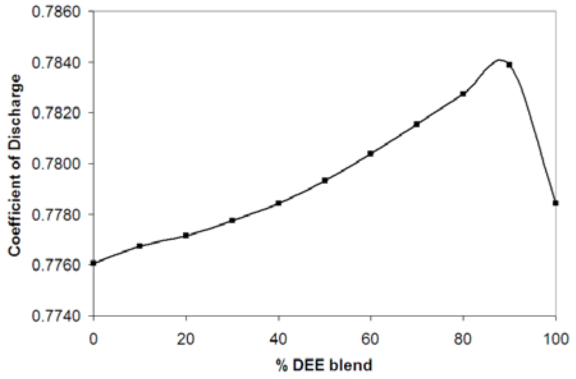

Fig. 7 Variation of coefficient of discharge

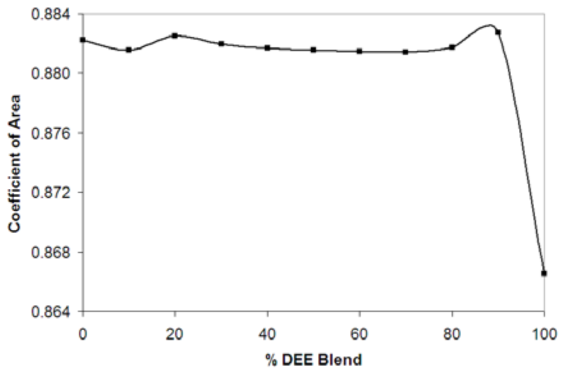

Fig. 8 Variation of coefficient of area

The mass flow rate is observed to be reducing due to the decrease in fuel density. Though the mass flow rate decreases with increasing blends, the coefficient of discharge is found to increase up to 90% of blend. At 100 % diethyl ether due to some vapors are convected along the flow up to the nozzle exit thereby reducing the mass flow rate and also the coefficient of discharge and area decreases appreciably.

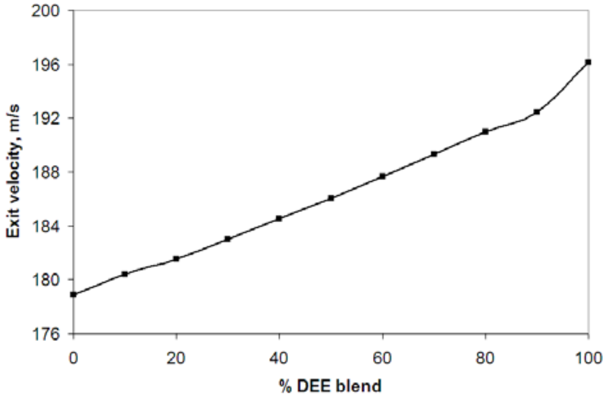

Fig. 9 Variation of exit velocity with blends

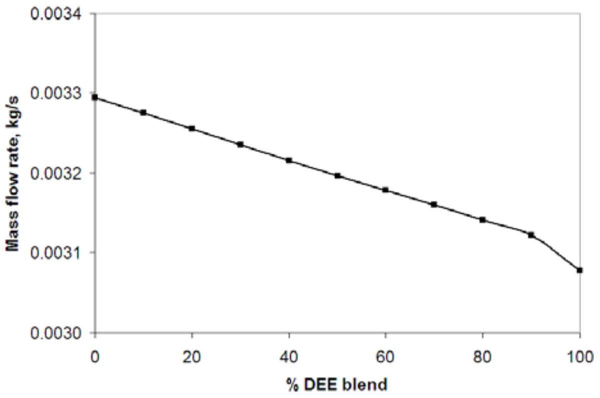

Fig. 10 Variation of mass flow rate with blends

5. CONCLUSION

The cavitation behavior and the nozzle exit parameters for different blends of diethyl ether and diesel are studied using the computational technique. The major conclusions are as follows.

- The cavitating behavior of the fuel increases with increasing percentage of diethyl ether
- The exit velocity of the fuel increases with increase in blends
- The mass flow rate of the fuel is found to be decreasing with increasing diethyl ether volume in fuel

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