NUMERICAL INVESTIGATION ON THE EFFECT OF INJECTION PRESSURE ON THE INTERNAL FLOW CHARACTERISTICS FOR DIETHYL ETHER, DIMETHYL ETHER AND DIESEL FUEL INJECTORS USING CFD

by

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The spray characteristics of the diesel fuel are greatly affected by the cavitation formed inside the injector due to the high pressure differential across the nozzle. Many researchers across the globe are exploring the potential of using diethyl ether and dimethyl ether as an alternate for diesel fuel to meet the strict emission norms. Due to the variation in the fuel properties the internal flow characteristics in injectors for ether fuels are expected to be different from that of the diesel fuel. In this paper computational technique is used to study and compare the internal flow characteristics of diethyl ether, dimethyl ether and diesel fuel. The two phase flow model considering the fuel as a mixture of liquid and vapor is adopted for the simulation study. The injection pressure is varied from 100 to 400 bar and the flow characteristics of all three fuels are simulated and compared. Results indicate that all three fuels have distinct cavitating patterns owing to different property values. The dimethyl ether is found to be more cavitating than diesel and diethyl ether fuels as expected. The mass of fuel injected are found to be decreasing for the ether fuels when compared with diesel fuel at all injection pressures.

Key words: *Cavitation, Diethyl ether, Dimethyl ether, Injector*

1. Introduction

In diesel engine the fuel is injected into the cylinder through the fuel injector at high pressure, to enhance the atomization and spray characteristics of the injected fuel and to improve the combustion efficiency. High fuel pressure is needed to overcome the air resistance (back pressure) to get penetrated into the chamber. The high fuel pressure available at the nozzle seat (100 – 400 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 voids in the liquid fuel when the pressure rapidly drops below the saturation pressure of the liquid fuel. Cavitation affects the performance of the injector and also damages the inner surfaces of the nozzle. Takenaka et al [1] experimentally studied the nucleation process of the cavitation using neutron radiography and reported the formation of vapor bubbles in the nozzle hole. Lee et al [2] experimentally studied and reported that cavitation enhances the fuel spray characteristics and the primary fuel breakup due to the turbulence created inside the nozzle. J.M. Desantes et al [3] also reported the cone angle of the fuel spray is found to be increased due to the formation of vapor inside the nozzle.

The diesel engine, though provide high power output with better fuel economy, produce high NOx and smoke emissions. With the strict emission standards set by the environmental protection agencies across the world, it makes necessary to look for alternate fuels to meet the requirement. Researchers have reported that oxygenated fuels like Dimethyl Ether (DME) and Diethyl Ether (DEE) can be potential candidates in replacing the diesel fuel. Kapus et al [4] and Kajitani et al [5] reported that the NOx emission with DME is lower than the diesel fuel when the injection is retarded and optimized and Miyamoto et al [6] studied that the presence of oxygen in the fuel reduces the smoke emission.

The injection flow characteristics of the fuel are greatly affected by the fuel density, vapor pressure and surface tension. Hosny et al [7] studied that the cavitating phenomenon are more sensitive to the changes in fuel properties and developed correlation between cavitation and fuel properties. The thermophysical and transport properties of dimethyl ether and diethyl ether are different from diesel; hence different injection flow characteristics can be expected. 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 diethyl ether, dimethyl ether and diesel fuel are studied 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 injection pressure. The fuel injection pressure is varied from 100 bar to 400 bar and a comparative study of flow characteristics is done for all three fuels.

2. Injector flow computational model

The nozzle flow simulations were performed using ANSYS Fluent. The fluid is assumed to be a mixture comprising liquid fuel and vapor. Two phase flow analysis using Schnerr and Sauer model is performed with no-slip condition between the liquid and vapor. RNG k-ε model with non-equilibrium wall conditions is used in order to account for the large pressure differential across the nozzle. The vapor formation and condensation are solved by considering Rayleigh-Plesset equation [8]. A three-hole injector with an orifice diameter of 196µm and an included angle of 120° 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 (fig 1). The fluid domain is characterized by 443637 tetrahedral cells with 85228 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. The back pressure at the nozzle exit is taken as 30 bar to simulate the in-cylinder pressure condition at the time of injection.

The injection pressure is varied from 100 to 400 bar and the simulation is performed for a injection duration of 3 ms for all three fuels.

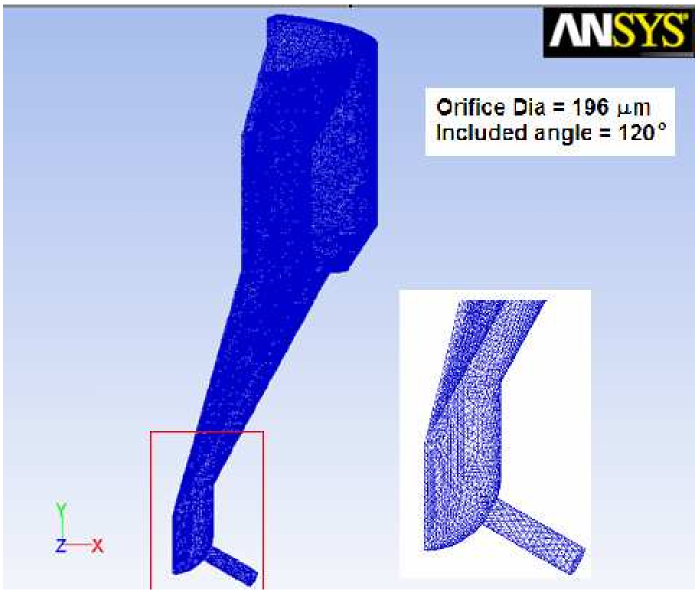

Fig 1 Mesh generated for the 120° sector of the injector

3. Injector 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), Reynolds number (Re) and Weber number (We) as described below [9,10]. The cavitation number, K is calculated from

$$K = \frac{P_i - P_v}{P_i - P_b} \tag{1}$$

where P_i is the injection pressure, P_v is the saturation vapor pressure of the fuel and P_b is the back pressure at the nozzle exit. The discharge coefficient, C_d is calculated using the following equation

$$C_d = \frac{M_{act}}{A_{th}.\sqrt{2.\rho_f.\Delta P}} \tag{2}$$

where M_{act} is the actual mass flow rate which is obtained from the simulation, A_{th} is the nozzle exit area, ρ_f is the fuel density and ΔP is the pressure differential across the nozzle orifice.
The velocity coefficient, C_v is calculated from the following equation

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

where V_{act} is the actual velocity at the nozzle exit.

The area coefficient is calculated as

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

The Reynolds number, R_e and the Weber number, W_e are calculated from the following equations

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

$$W_e = \frac{\rho_f . V^2 . D_{ex}}{\sigma_f} \quad (6)$$

where V is the average flow velocity along the nozzle orifice, D_{ex} is the nozzle exit diameter, μ_f is the fuel viscosity and σ_f is the surface tension of the fuel.

4. Results and discussion

The thermo physical and transport properties of the three fuels: diesel, diethyl ether and dimethyl ether are listed in tab 1. The fuel properties reported by Arcoumanis et al [11] for dimethyl ether are used for the simulation and the properties of diethyl ether are taken from CRC handbook of chemistry and physics [12].

Table 1 Fuel properties

Fuel property	DEE	DME	Diesel
Carbon weight %	64.7	52.2	83
Hydrogen weight %	13.5	13	17
Oxygen weight %	21.6	34.8	0
Density @ 25°C (kg/m^3)	713.4	667	822
Viscosity @ 25°C (kg-m/s)	0.0002448	6.67E-5	0.00224
Surface tension @ 25°C (N/m)	0.017	0.012	0.0020
Vapor pressure @ 25°C (Pa)	58660	530000	1280

The injector flow simulation is performed for 120° sector mesh for injection pressures of 100, 200, 300 and 400 bar with a fixed back pressure of 30 bar. The fuel temperature is taken as 298K for all the three fuels.

4.1 Cavitation

Figure 2 shows the vapor fraction at the orifice nozzle for all the three fuels for an injection pressure of 100 bar. The cavitation inception is found in all the three fuels. The cavitation region is found to be almost same for all the three fuels. However, the vapor volume fraction of DME is found to be more than that of the other two fuels due to the high saturation pressure. The vapors formed are collapsed immediately near the entry of the orifice itself and the liquid fuel is reached at the nozzle exit.

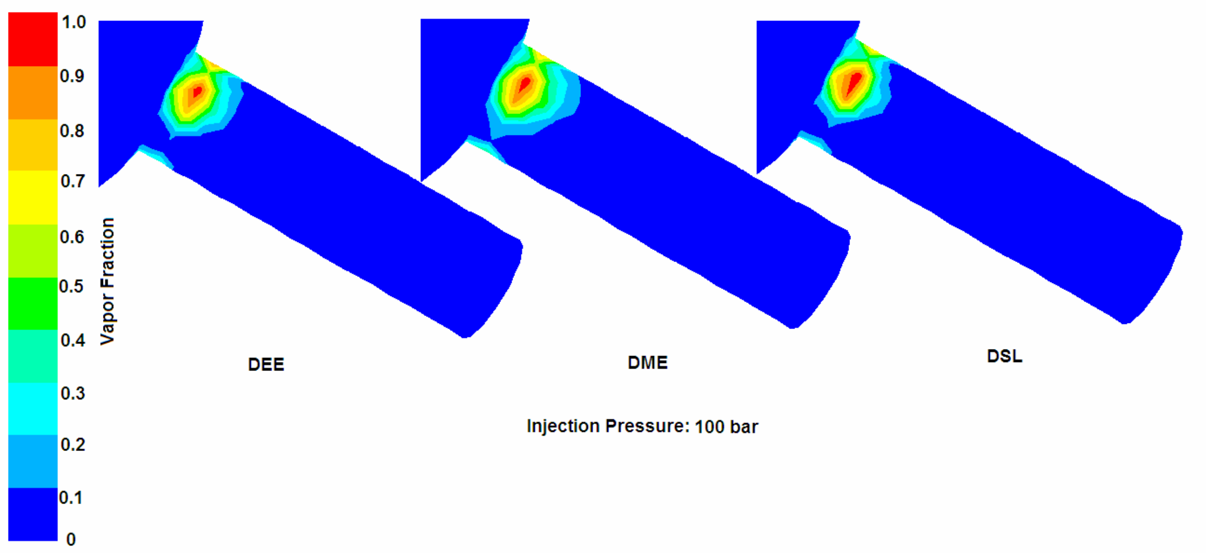

Fig 2 Vapor fraction at injection pressure of 100 bar

Figure 3 shows the vapor fraction for 200 bar at the nozzle. Distinct cavitation region is formed for all the three fuels. For DME more volume of vapor is formed due to the higher saturation pressure and lower viscosity and the vapor formed is convected along the nozzle wall. The vapor volume fraction formed is lesser for the diesel fuel than the DEE due to the lower saturation pressure and higher liquid viscosity. This is in accordance with the result of Jun-Mei Shi and Mohammad Shamsul Arafin [13]. The authors reported that the reduction of fuel viscosity enhances the cavitation. Figure 4 shows the vapor volume fraction at the nozzle outlet for 300 and 400 bar for all the three fuels. It is found that as the injection pressure is increased; more vapor bubbles are convected along with the fluid for DME than other fuels and sprayed at the outlet as mixture of vapor and liquid.

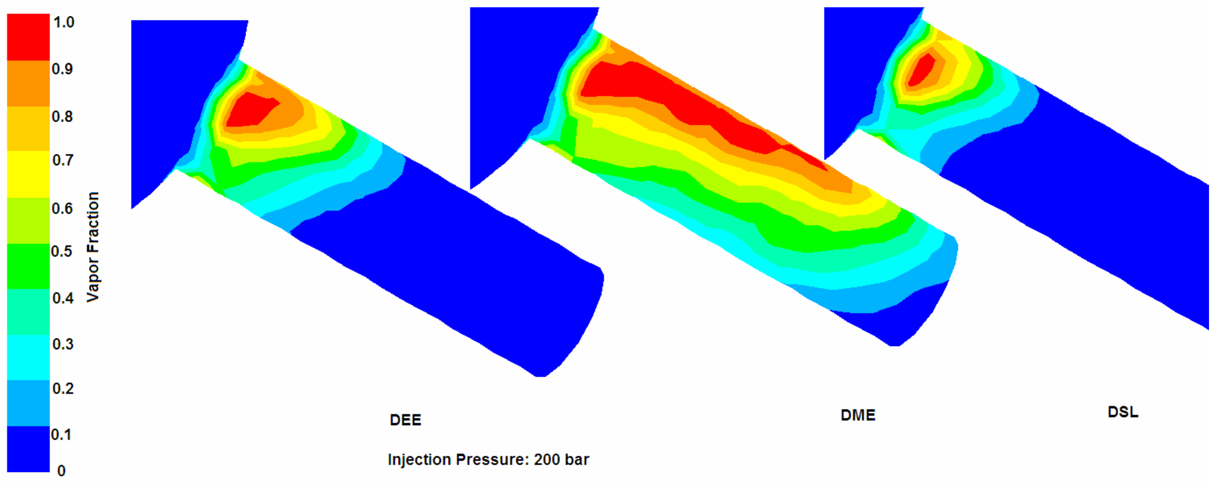

Fig 3 Vapor fraction at injection pressure of 200 bar

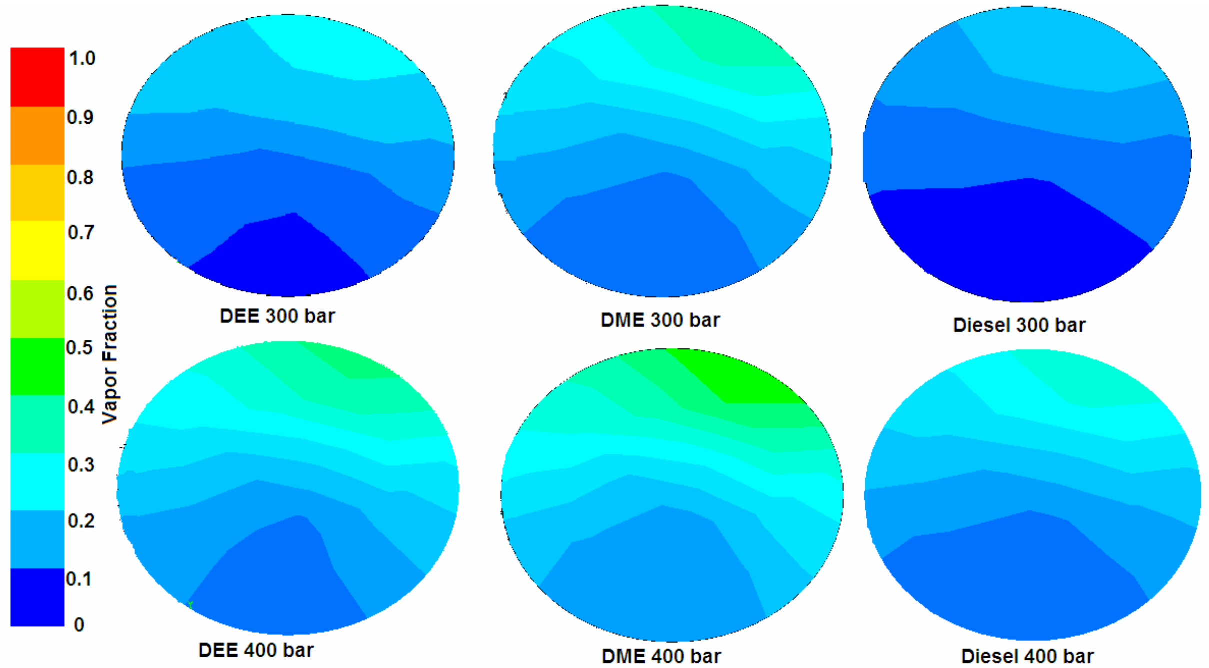

Fig 4 Vapor fraction at the nozzle outlet for injection pressures of 300 and 400 bar

Figure 5 shows the variation of cavitation number for different injection pressures. The cavitation number DME for all injection pressures is lesser than diesel and DEE due to the higher saturation vapor pressure and the lesser fuel viscosity. The cavitation number for DEE is almost similar to that of the diesel fuel across all injection pressures. Figure 6 and 7 compares the cavitation number with Reynolds number and Weber number for all the fuels. It is found that the Reynolds number and Weber number for DME are higher by an order of magnitude when compared to diesel. Though the density of DME is lesser than the diesel fuel, the lesser viscosity of DME increases the Reynolds number and Weber number and increasing the cavitating phenomenon. The same reason can be attributed to DEE for its increased Reynolds number and Weber number.

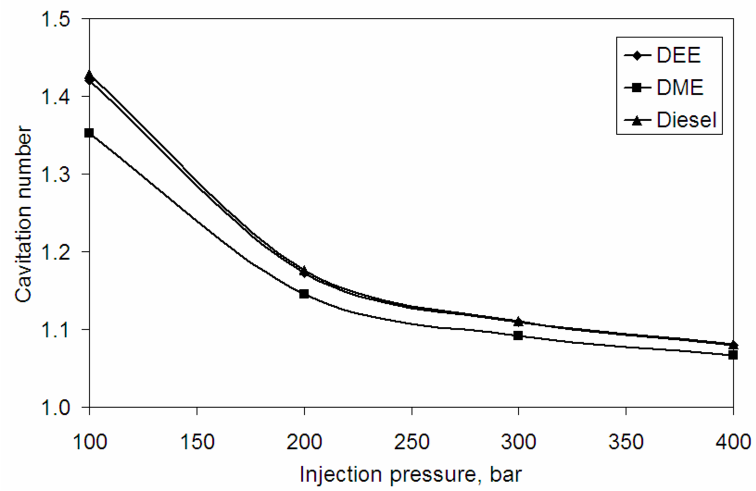

Fig 5 Variation of cavitation number with injection pressures

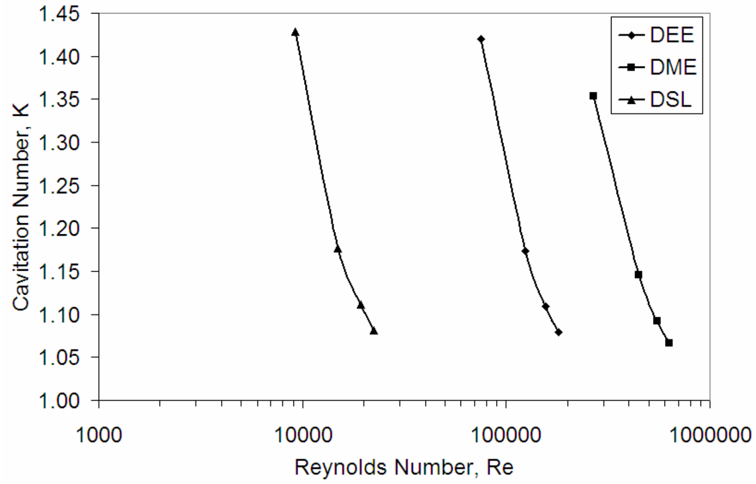

Fig 6 Variation of cavitation number with Reynolds number

4.2 Nozzle exit parameters

Figure 8 shows the variation of discharge coefficient for different injection pressures for all the three fuels. It is observed that the coefficient of discharge for ether fuels is higher than the diesel fuel up to 200 bar. Vapors formed near the inlet of the orifice reduce the available flow area [14] and hence increasing the flow velocity and the mass flow rate of the fuel. For ether fuels the volume of vapor formed is higher than the diesel fuel and hence the area reduction is more and so the coefficient of discharge is slightly increased (Fig 9). As the injection pressure increases, for ether fuels the vapors are convected along the flow up to the exit stream thereby reducing the mass flow rate. For diesel fuel though the vapors are convected along the flow they collapse before reaching the exit. Due to this the discharge coefficient of ether fuels is lesser than the diesel fuel at injection pressures of 300 and 400 bar. Figure 10 shows the variation of discharge coefficient with cavitation number. It is observed that for all the fuels the discharge coefficient initially increases with cavitation number and almost constant at higher cavitation numbers.

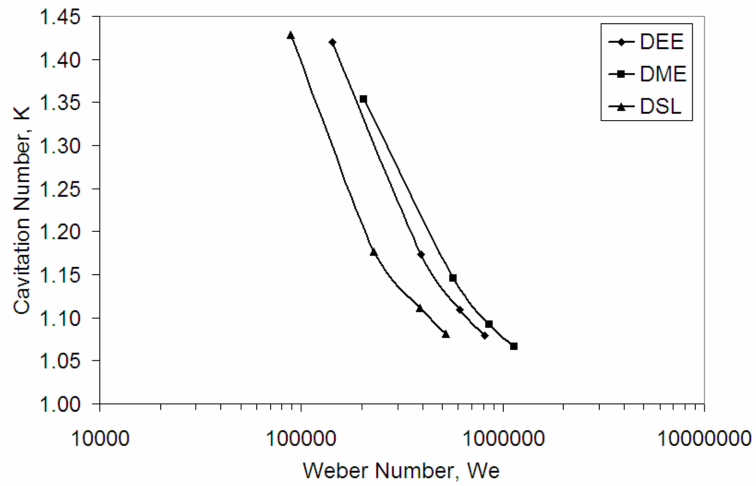

Fig 7 Variation of cavitation number with Weber number

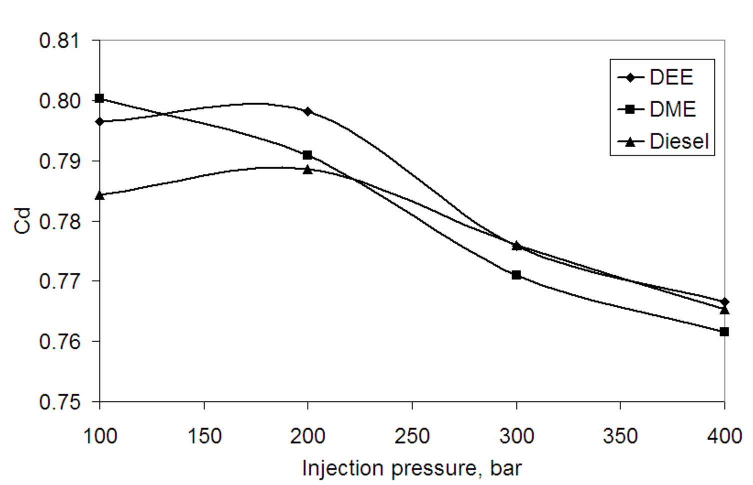

Fig 8 Variation of discharge coefficient with injection pressure

The variation of fuel velocity and mass flow rate at the nozzle exit is shown in Fig 11 and 12. It is observed that the nozzle exit velocity is higher for DME and DEE than diesel fuel for all injection pressures due to the lesser fuel density and lesser fuel viscosity. However the mass flow rate for the ether fuels is lower than the diesel fuel due to the lesser fuel density.

Table 2 Percentage reduction of mass flow rate

Inj pressure , bar	DEE	DME
100	5.4	8.1
200	5.7	9.7
300	6.9	10.5
400	6.7	10.4

Table 2 shows the percentage of reduction in the mass flow rate of ether fuels compared to the diesel fuel. It is observed that the reduction percentage is more for the DME fuel than the DEE fuel due to the formation of more vapor and lesser density.

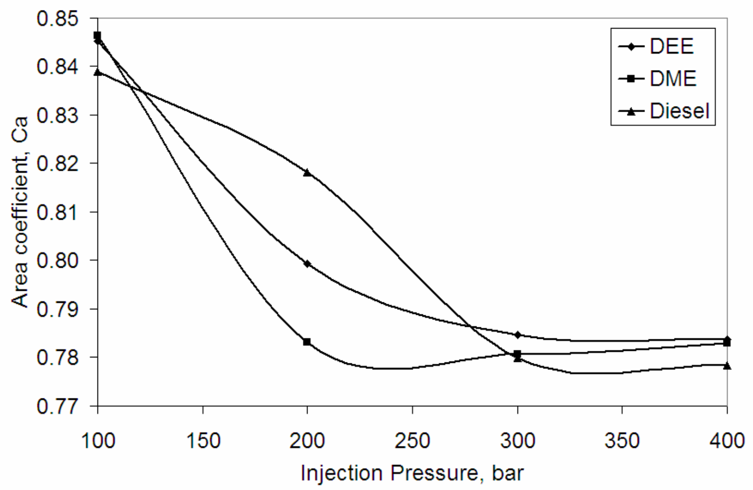

Fig 9 Variation of Area coefficient with injection pressure

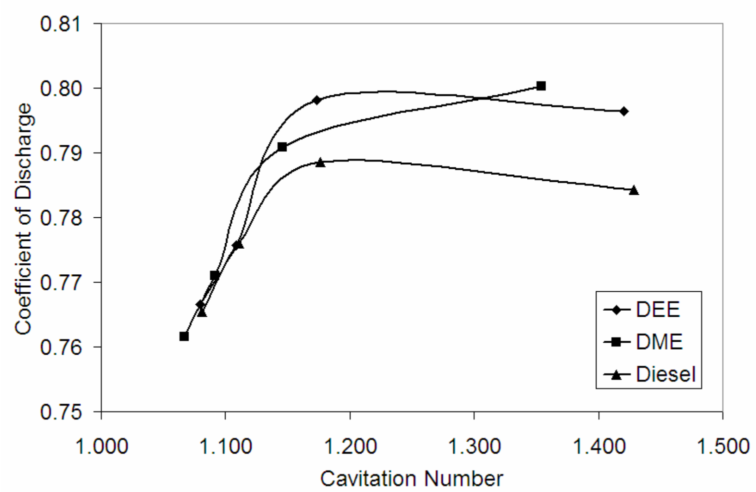

Fig 10 Variation of discharge coefficient with cavitation number

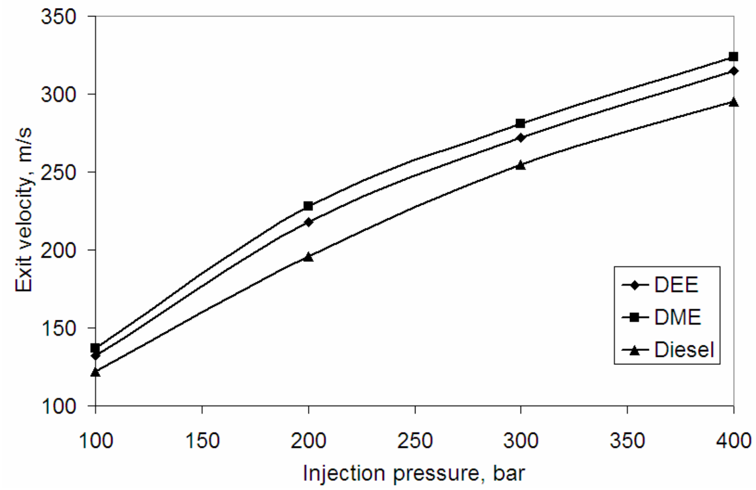

Fig 11 Variation of exit velocity with injection pressure

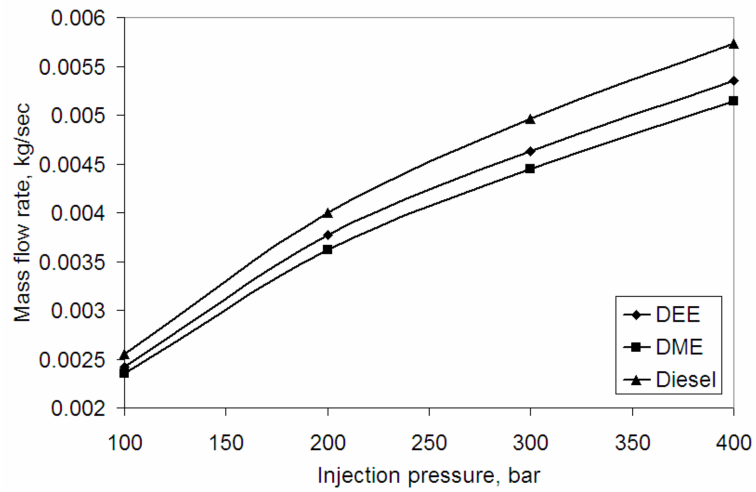

Fig 12 Variation of mass flow rate with injection pressure

5. Conclusions

The injector flow characteristics for three different fuels: Diethyl ether, Dimethyl ether and Diesel have been studied using computational technique. The cavitation behavior and the flow properties at the exit of the nozzle for all three fuels at different injection pressures were studied and compared. The major conclusions are as follows:

- Dimethyl ether is found to be cavitating more compared to diesel and diethyl ether due to its lesser viscosity and density
- Cavitation pattern for all three fuels are found almost the same at injection pressure of 400 bar
- The fuel velocity at the nozzle exit are higher for the ether fuels when compared with the diesel fuel
- The percentage reduction of mass flow rate for diethyl ether is around 6 to 7% when compared with diesel at same injection pressures and for dimethyl ether the reduction is around 9-10%

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