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Numerical Modelling of Diesel Fuel Multiphase Evaporation in Heavy Duty Diesel Engine

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Abstract

Diesel engines are considered reliable and efficient in terms of their efficiency and working adaptability. Heavy duty diesel engines play an important role in the industrial as well commercial applications. These types of engines requires a large amount of torque than the speed. Efficiency of these engines depends upon many factors including complete combustion and evaporation of fuel droplets in the engine cylinder. Evaporation plays a very important role in the mixture formation, burning of fuel and exhaust gases. In present work evaporation of diesel fuel is modelled and investigated under high pressure conditions for a heavy duty engine. Computational fluid dynamics and an Eulerian-Lagrangian multiphase formulation are used to simulate the spray process. Modelling of overall evaporation process is done using the Ansys Fluent. Evaporation of diesel fuel is investigated using discrete phase model and species transport equations. A realizable k-epsilon turbulence model is used to consider the turbulence effects on evaporation of fuel droplets. Results are obtained using the practical engine conditions. The obtained results shows a generous effect on the evaporation rate of fuel droplets. Droplet diameter is plotted against different temperature. Droplet temperature is observed with respect to time and obtained results shows a good agreement with theoretical and experimental data. Mass fraction of fuel droplets is calculated using volume fraction. Heat flux to the droplet is also accounted for in this study. The results obtained are supportive in heavy duty engine design for better economy and controlled emission reduction.

Introduction

Engine power and efficiency depends upon many factors like air-fuel mixture ratio, spray breakup and evaporation of liquid fuel droplets inside the combustion chamber [1]. Among the above mentioned processes evaporation of fuel droplets is not a well resolved phenomenon for the preparation of air fuel mixture in heavy duty diesel engines [2]. A spray may be taken as a type of two phase flow in which liquid droplets are taken as dispersed phase and other one is continuous phase that is ambient gas present in the engine cylinder [3]. Accurate evaporation modelling of diesel fuel sprays in the DI engines is very important in commercial and industrial applications and is well known. Over the past few decades traditional evaporation modelling of diesel fuel droplets has been replaced by more new sophisticated methods by using high performance computational resources [4]. Much efforts have been made to visualize the spray pattern and droplet evaporation phenomenon numerically in parallel with experimental setups [5]. Many authors have studied the vaporization of diesel fuel droplets in high pressure atmosphere. Numerical techniques to model the evaporation of diesel fuel in the DI engines rely on the Eulerian gas phase governing equations and uses Lagrangian description for the liquid droplet [6-7]. In present work different governing equations are coupled and solved simultaneously to observe the evaporation process of fuel droplets. Evaporation rate of fuel droplet depends upon the diffusion of molecules into the hot chamber [8-10]. Generally, evaporation of liquid fuel droplet consists of two parts. The first part is the separation of molecules from the droplet surface to the hot air and second is vapour diffusion in the chamber [11]. The general method to model the evaporation of fuel droplets is to solve the mass, momentum, energy and species equation with the given operating conditions [12].In the DPM model calculations a discrete phase injection is created followed by initializing the flow field and then solution is advanced by taking the desired number of time steps. DPM model allows the unsteady particle tracking in the continuous phase when particles are dispersed in form of droplets or ligaments. It also allows to observe the particle trajectories at different operating conditions. Trajectories are calculated by using the particle force balance in Lagrangian frame of reference. Inertial force on the particle is balanced by the other forces acting upon it using the Cartesian coordinates. RANS turbulence model is applied to consider turbulence effects in the engine cylinder. A realizable k-Ɛ model is coupled with discrete phase model and species transport equation with scalable wall function. Reynold stresses that are present in the turbulent flows are modelled by this realizable k-Ɛ turbulence model. This turbulence predicts the behaviour of planar as well as well round jets in a more accurate manner than other models in the same category. LES turbulence model is also used for the same phenomena but in present work RANS model is used because of some fundamental reasons as the computational power required for LES is much high than RANS but the results obtained by RANS are in an acceptable range.

The objective of present work is to model the evaporation of diesel fuel droplet in a heavy duty diesel engine working at high pressure and temperatures. Analysis is focussed on the droplet evaporation rate, droplet diameter, increase in droplet temperature change in cylinder temperature and mass fraction of liquid and vapour phase. We are focussing the heavy duty diesel engine and work on this type of engine is not much found

Methodology

Mass Conservation Equation

Fuel droplet follows the following equation for the mass conservation.

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \vec{v}\right) = S_m \tag{1}$$

In above equation source S_m is a source term from which mass is added to the continuous phase.

Momentum Conservation Equation

Momentum of moving droplet coming out from the nozzle is conserved by the following conservation equation.

$$\frac{\partial}{\partial t}\left(\rho \vec{v}\right) + \nabla \bullet \left(\rho \vec{v}\vec{v}\right) = -\nabla p + \nabla.\left(\bar{\bar{\tau}}\right) + \rho \vec{g} + \vec{F} \tag{2}$$

In above equation p is the static pressure, $\overline{\overline{\tau}}$ is the stress tensor.

Energy Conservation Equation

Energy equation is used in calculating the solution of problem is given below.

$$\frac{\partial}{\partial t}\left(\rho E\right)+\nabla\bullet\left(\vec{v}\left(\rho E+p\right)\right)=\nabla\bullet\left(k_{eff}\nabla T-\sum_{j}h_{j}\vec{j}_{j}+\overline{\overline{(\tau_{eff}}}\bullet\vec{v})\right)+S_{h} \quad (3)$$

Species Transport Equation

Local mass fraction of species is predicted by the following equation.

$$\frac{\partial}{\partial t}\left(\rho Y_i\right)+\nabla\bullet\left(\rho\vec{v}Y_i\right)=-\nabla\bullet\vec{J}_i+R_i+S_i \qquad (4)$$

DPM model equations

1) Particle Force Balance

The following particle force balance is applied in the DPM model to the evaporating droplet.

$$\frac{du_p}{dt}=F_d\left(u-u_p\right)+\left(\rho_p-p\right)\frac{g_x}{\rho_p}+F_x \qquad (5)$$

And relative Reynolds number is given by

$$R_e=d_p\left(u_p-u\right)\frac{\rho}{\mu} \qquad (6)$$

2) Heat Transfer to Droplet

After injection into the combustion chamber the heat transfer between droplet and continuous phase takes place according the following equation.

$$m_p c_p\frac{dT_p}{dt}=hA_p(T_\infty-T_p)+\frac{dm_p}{dt}h_{fg} \qquad (7)$$

3) Mass Transfer Equation

When droplet is injected into the combustion chamber heat is transferred to the droplet and mass transfer takes place by the equation below.

$$m_p\left(t+\Delta t\right)=m_p\left(t\right)-N_i A_p M_{\omega,i}\Delta t \qquad (8)$$

Transport Equations for the Realizable k-ε Model

The realizable k-ε model uses the following transport equations to take into account the turbulence effects.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial X_j}(\rho k u_j)=\frac{\partial}{\partial X_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial X_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \qquad (9)$$

$$\frac{\partial}{\partial t}\left(\rho\varepsilon\right)+\frac{\partial}{\partial X_j}\left(\rho\varepsilon u_j\right)=\frac{\partial}{\partial X_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial X_j}\right]+ \qquad (10)$$

$$\rho C_1 S\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_3 G_b+S_\varepsilon$$

Engine specification

Droplet of liquid diesel fuel is evaporated in a hot gas environment. Initially a droplet of diameter d_0 is injected into the hot air with temperature T_0 and ambient pressure and temperatures are given also. The diesel fuel used for the present model is n-decane ($C_{10}H_{22}$). The simulation is done for the following engine specifications.

Engine Specifications		Injection specifications	
Bore	150 mm	Injection type	single
Stroke	180 mm	Droplet velocity	35 m/s
Max Torque	295 kg-m	Droplet temperature	293 K
Ambient Pressure	4 MPa	Fuel type	Diesel n-decane
Nozzle Diameter	0.29 mm	Flow rate	0.003 kg/s
Injection pressure	20 MPa	Injection duration	3 ms

Table 1. Engine Specifications

All the work is done using the Ansys Fluent 19.0. A 2D geometry is used and mesh independence is studied. The CPU time for a single test case is 3 hours. Total number of nodes for the meshing geometry were 250,000 approximately.

Model validation

The numerically calculated droplet diameter and temperature profiles are compared with the experimental and theoretical work of different authors [13, 14]. The temperature and droplet diameter profiles for 10 μm are compared with [14] and found a good agreement. Obtained numerical results for all cases predict the similar droplet evaporation rates as in [1, 12]. Maximum rise in droplet temperature in all cases is 447K that shows the accuracy of present model. Droplet of small diameter evaporates quickly as predicted in the [12]. Temperature profiles are in a good agreement with predicted in [14].

Results and Discussion

Test Case 01

For test case-01 droplet diameter is taken 10 μm. Droplet diameter and different temperatures are plotted against the time. Three different temperatures are used for calculation.it is observed that when temperature is increased from 750K to 973K droplet evaporates more quickly. An appreciable reduction in evaporation duration of droplet is predicted at high temperatures. Similar trend is observed in droplet temperature vs time graph. At high temperatures droplet absorbs heat more quickly than lower ones. Figures 1 and 2 shows the results of test case 1. In figures 3 and 4 DPM contours of temperatures are shown. It is observed that if the cylinder temperature is high droplets reach to evaporation temperature more quickly.

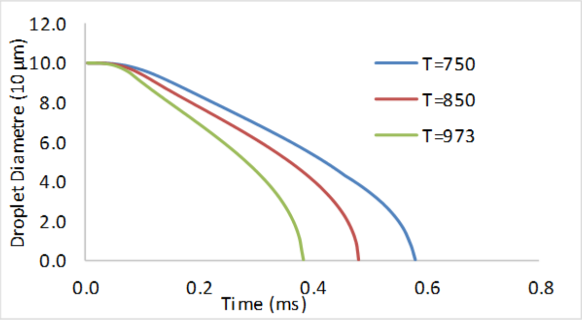

Figure 1. Plot of droplet diameter and time at various ambient temperatures

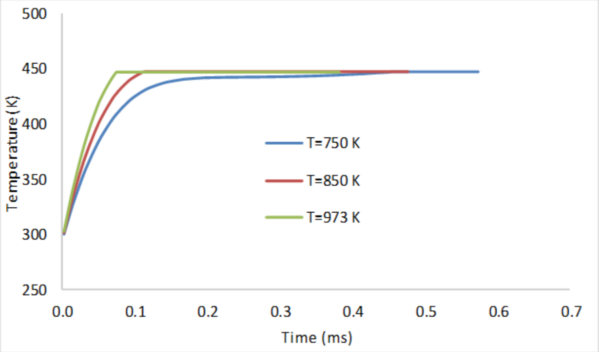

Figure 2. Plot of droplet temperature at different ambient temperatures

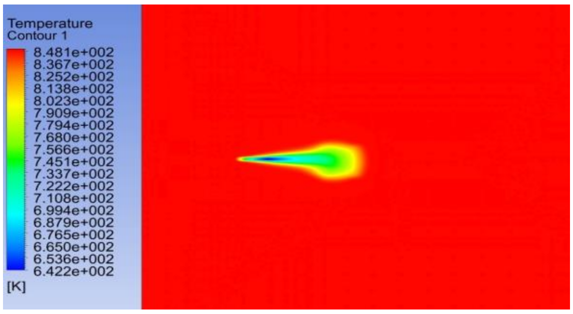

Figure 3. DPM contour of temperature at 850 K and 10 µs

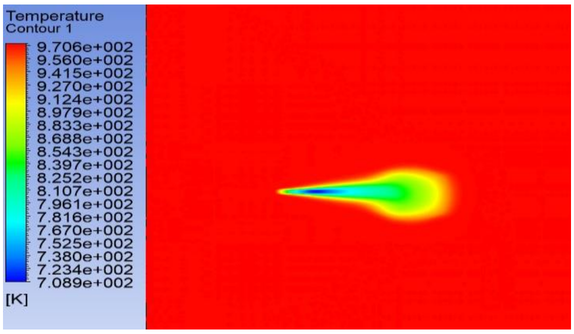

Figure 4. DPM contour of temperature at 973 K and 10 µs

Test Case 02

In test case-02 droplet diameter is doubled that is 20 μm. In this case it is shown that evaporation time is increased more than two times for all temperatures. Droplet temperatures and diameter profiles are same but evaporation time is increased. Figures 5 and 6 shows the results of test case 2. In figure 7 and 8 DPM contours of temperatures are shown. Contours show the range of maximum and minimum temperature of engine cylinder from where the droplet is passing through. It is observed again that if the cylinder temperature is high droplets reach to evaporation temperature more quickly. At higher temperature droplet absorbs temperature in a quick way due to diffusion of molecules from the droplet surface.

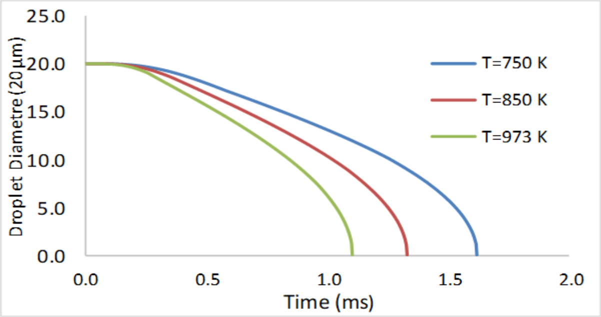

Figure 5. Plot of droplet diameter and time at various ambient temperatures

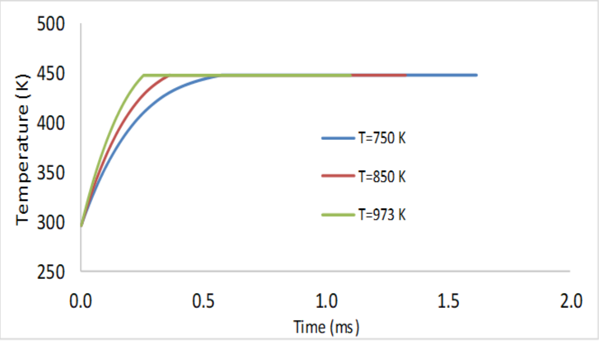

Figure 6. Plot of droplet temperature at different ambient temperatures

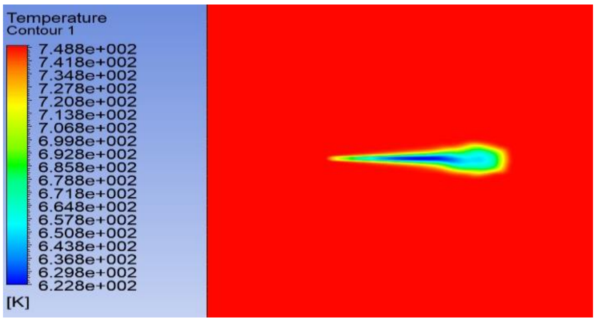

Figure 7. DPM contour of temperature at 750 K and 20µs

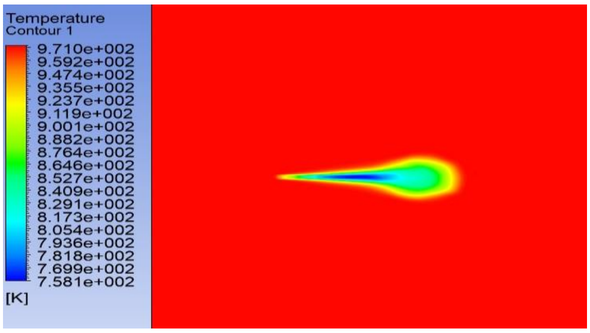

Figure 8. DPM contour of temperature at 973 K and 20 µs

Test Case 03

In test case-03 droplet diameter is increased to 30 μm. Due to increase in droplet size evaporation time is also increased. But both droplet diameter and temperature profiles are same as in previous cases.it is observed for all three cases at different droplet dimeters droplet evaporates quickly at high ambient temperature of 973K and slowly at low ambient temperature of 750K. Evaporation of larger droplets take longer than the smaller ones. Figures 9 and 10 shows the results of test case 3.

In the present work effects of droplet size and cylinder temperature on droplet evaporation rate are modelled numerically. Obtained results show that rate of evaporation of droplet is highly affected by the droplet size and cylinder temperature.

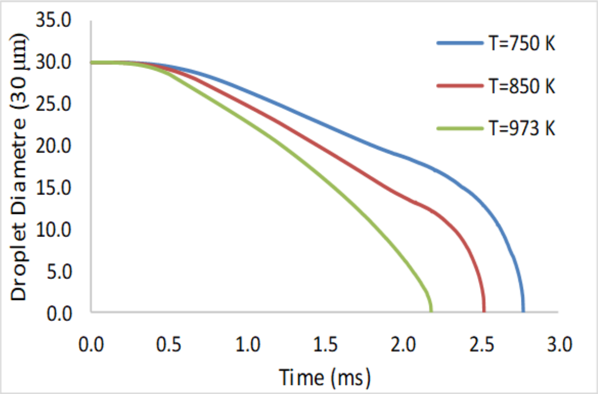

Figure 9. Plot of droplet diameter and time at various ambient temperatures

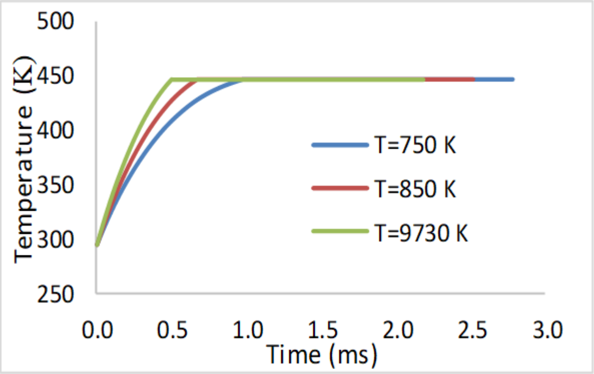

Figure 10. Plot of droplet temperature at different ambient temperatures

As seen in case 1 droplet of small size 10 μm evaporates quickly at high temperature of 973K but slower at 750K. But in cases 2 and 3 where the temperature is kept same but size of droplet is varied up to 20 and 30 μm.In these cases it can be seen clearly that even at high temperature of 973K droplet evaporation time is increased appreciably as compared to small droplets of 10 μm. Contours of temperatures inside the chamber are shown for different droplet temperatures and diameters.

In all cases it is observed that size of droplet is an important parameter to control the evaporation rate. Small droplets evaporates quickly than larger ones. One thing similar found in all cases is that maximum temperature of droplet is 447K. This shows that final temperature of droplets of all sizes in this work is the same. Evaporation of droplets starts after the secondary breakup in the in the engine cylinder. To ensure the high evaporation rate of diesel fuel droplets it is recommended that breakup of droplets must be as finer to reach the very small size of droplets that are to be evaporated. This means breakup also affects the evaporation rate of liquid fuel droplets. Further, droplet size affects the rate of evaporation in the engine cylinder as small droplets evaporates quickly than the larger ones.

Conclusion

In this work evaporation of diesel fuel droplets is carried using the DPM model coupled with species transport and energy equations. The results show that droplets of small diameters evaporate quickly than the larger ones. The effect of ambient temperature is also a vital parameter in the evaporation of fuel droplets.it is shown that droplet evaporation rate is high for the high ambient temperatures. At high ambient temperature droplets absorb more heat in a short period of time. Larger droplets takes more time to evaporate as they need more time to absorb the heat and decay into the hot air. Heating of large droplets takes more time even at higher temperature of 973K. There is a need to control the size of droplets in the combustion chamber to make the evaporation process fast. It is recommended that droplet size should be small enough after the secondary breakup so that evaporation takes place effectively.

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