Investigation on the Characteristics of Biodiesel Droplets in the Engine Cylinder

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Abstract: The world is moving towards renewable energy sources rapidly and, at present, fossil fuels are reducing day by day. In this scenario, biofuels have become an attractive alternative to conventional diesel fuels. In the present work, the vaporization of Thumba biodiesel is numerically modeled using the finite volume-based approach in ANSYS Fluent and the results are compared with diesel fuel. Evaporation of fuels is governed by the conservation equations of energy, momentum, and mass. Owing to high temperature and pressure conditions, turbulence is present in the engine cylinder. To account for the turbulence effects, the Reynolds-averaged Navier–Stokes (RANS) turbulence model is used. Heat transfer to droplet and mass lost by the droplets is governed by the discrete phase model equations. The obtained results include the droplet lifetime, increase in temperature of a droplet, and velocity profiles. It is observed that the size and temperature of fuel droplets and ambient temperature have a significant effect on the evaporation time of fuel droplets in the engine cylinder. By reducing the droplet size, the complete evaporation of fuels can be achieved. Droplets having a high temperature have a short evaporation time and high evaporation rate. It is noted that, at a higher temperature, biodiesel evaporates more quickly than diesel fuel, thus producing complete combustion and hence giving maximum power output.

Keywords: biodiesel; numerical analysis; droplet size; fuel evaporation; turbulence effect

1. Introduction

The consumption of fossil fuels is increasing day by day throughout the world owing to the increase in the population of countries, which has ultimately increased the energy demand drastically [1]. To reduce the effects of greenhouse gas emissions, industries are trying to shift the burden of fuels from traditional fossil fuels towards renewable energy sources, which can be used for a longer period with less pollution to the environment [2,3]. The mixture of biofuels, when used in internal combustion engines with the fossil fuels, has the capacity to reduce greenhouse gas emissions and produce complete combustion in the engine cylinder, providing maximum thermal efficiency [4–6]. To reduce the pollution in the environment added by the exhaust from vehicles, many studies have been applied to alternate fuels such as butanol and ethanol instead of fossil fuels [7–9]. However microbial technologies for environmental pollutants and conversion of biomass into clean energy fuels are favorable approaches to a clean and green environment and in energy development [10]. In view of the recent advancement, biofuels have been developed as alternative fuels to be used in place of...
typical diesel fuels [11]. The basic definition of biodiesel is that ‘a fuel consists of mono-alkyl esters of long-chain fatty acids that are derived from animal fats or vegetable oils’ [12]. The process of getting biofuel from animal fat or vegetable oil is known as transesterification [13]. Most of the studies carried out in the recent past focused on palm oil, soybean, and rapeseed biodiesels. There is another term used in biodiesels known as second-generation biodiesels, used for the biodiesels derived from algae or inedible oil [14,15]. It is evident that compression ignition engines are highly efficient compared with spark-ignition engines owing to their high compression ratios. For this reason, compression ignition engines are preferred in heavy-duty works like transportation and in the propulsion systems. The study [16] of two alcohol fuels, butanol and ethanol, was conducted to observe the effects on the engine performance, combustion, and emissions in the compression ignition engines. The role of biodiesel was increased in the compression ignition engines owing to the ease of availability. There is no sulfur content in biodiesels, which makes it environmentally friendly in terms of exhaust gases. Biodiesel consists of up to 11% oxygen and a very small amount of aromatic hydrocarbons. Another characteristic that makes the biofuel attractive for compression ignition engines is a high cetane number, owing to which complete combustion takes place in the engine cylinder and emissions are reduced [17,18]. The presence of oxygen in biodiesel is up to 5%, which means ignition time is delayed as compared with the conventional diesel fuel used in the automobiles [19–21]. The studies presented above are the experimental studies that do not account for the detailed processes that occur in the engine cylinder before and after combustion, including the spray penetration, breakup, and evaporation of fuel droplets. In the current age, computational fluid dynamics has become a powerful tool to analyze the engine processes and other parameters in place of experimental work, which becomes cumbersome at high temperature and pressure conditions. Thus, computational fluid dynamics (CFD) modeling has been implemented to study the processes in detail numerically [22–28]. Heat release, spray characteristics, combustion, and emission are studied in detail in [29,30]. To study the in-cylinder processes, there are CFD codes and commercial softwares, but in practice, KIVA is used in academia owing to its ease of availability. However, a drawback in KIVA is found in that it cannot handle the complex geometries. This problem is solved in other commercial available soft wares like STAR-CD, VECTIS, FIRE, and ANSYS Fluent. In ANSYS Fluent, a high quality mesh generation and availability of user defined inputs make it very suitable for CFD analysis [23]. In [31,32], ANSYS Fluent is used to analyze the in-cylinder processes at high temperature and pressure conditions. Different in-cylinder processes like primary and secondary breakup and evaporation of diesel fuel droplets in conjunction with particle histories and temperature profiles were observed. In [28], it was observed that, as the injection time increased, the combustion phase also increased and resulted in a higher peak pressure. In the present work, evaporation of diesel fuel droplets is simulated and the results are compared with the evaporation histories of Thumba biodiesel. RANS turbulence model is used to account for the turbulence effects present in the combustion chamber of engine. A realizable k-ε model is used instead of standard k-ε model. This is because of the fact that the realizable k-ε model contains a new formulation to compute the turbulent eddy viscosity and a new transport equation for the dissipation rate. The relative Reynolds number confirms the presence of strong turbulence in the current spray evaporation process. Operating conditions are kept the same for both fuels, that is, high temperature and pressure. ANSYS Fluent is used to simulate the complete process in the engine cylinder.

2. The Governing Equations

The process of evaporation is governed by the following conservation equations; these conservation equations are taken from [33] and particle equations are taken from the ANSYS Fluent Manual.

2.1. Continuity Equation

The general continuity equation can be written as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S_m$$  (1)
Mass of liquid fuel droplet is conserved by following the above equation. This equation is valid for both compressible and incompressible flows. Source term indicates that the mass is added by the discrete phase to the continuous phase.

2.2. Momentum Equation

The momentum of the droplet particle is conserved by the following momentum equation [33].

\[
\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \left( \rho \vec{v} \vec{v} \right) = -\nabla p + \nabla \left( \vec{T} \right) + \rho \vec{g} + \vec{F}
\] (2)

where \( p \) is the static pressure, \( \vec{T} \) is stress tensor, \( \rho \vec{g} \) is gravitational body force, and \( \vec{F} \) is external body force.

2.3. Energy Equation

The following energy equation is solved in ANSYS Fluent.

\[
\frac{\partial}{\partial t}(\rho E) + \nabla \left( \rho \vec{v} (\rho E + p) \right) = \nabla \left( k_{eff} \nabla T - \sum_j h_j \vec{J}_j + \left( \vec{T}_{\text{eff}} \cdot \vec{v} \right) \right) + \frac{1}{2} S_h
\] (3)

2.4. Species Transport Equation

Local mass fraction of species is conserved by the solution of following the convection-diffusion equation of species \( j \).

\[
\frac{\partial}{\partial t}(\rho Y_j) + \nabla \left( \rho \vec{v} Y_j \right) = -\nabla \vec{J}_j + R_j + S_j
\] (4)

2.5. Discrete Phase Model Equations

2.5.1. Particle Force Balance

The trajectory of the evaporating droplet is predicted by the integration of forces’ balance on the droplet in the Lagrangian frame of reference. The inertial force on the particle is balanced by the other forces on it, which are given in the following form.

\[
\frac{dv_p}{dt} = F_d(v - v_p) + \left( \rho_p - p \right) \frac{S_x}{\rho_p} + F_x
\] (5)

where \( F_d \) is particle drag force and is defined as follows:

\[
F_d = \frac{18 \mu C_D \text{Re}}{\rho_p d_p^2}
\] (6)

The particle relative Reynolds number \( \text{Re} \) is defined as follows:

\[
\text{Re} = \frac{\rho d_p}{\mu} |u_p - u| \] (7)

The drag coefficient is taken from [19] reference style.

2.5.2. Heat Transfer to the Droplet

After the injection in the engine cylinder, fuel droplets disperse into the continuous phase and heat transfer between droplets and the air present in the chamber takes place by the following equation.
\begin{equation}
m_p c_p \frac{dT_p}{dt} = h A_p (T_\infty - T_p) + \frac{dm_p}{dt} h f_g \tag{8}
\end{equation}

2.5.3. Mass Transfer Equation

When the droplet is placed in the hot environment, the mass of the droplet is reduced according to the following mass transfer equation.

\begin{equation}
m_p(t + \Delta t) = m_p(t) - N_j A_p \dot{m}_{inj} \Delta t \tag{9}
\end{equation}

2.6. Turbulence Model

A realizable k-epsilon turbulence model is used in the calculation to account for the turbulence effects generated in the engine cylinder owing to high operating conditions. The high temperature and pressure present in the cylinder generate turbulence. When droplets are injected into this hot environment with high injection pressure, the effects of turbulence on the particle trajectory become vital. These turbulence effects are taken into account by the following equations of the realizable k-\(\varepsilon\) turbulence model.

\begin{equation}
\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 \tag{10}
\end{equation}

\begin{equation}
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial X_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial X_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial X_j} \right] + \rho C_1 S \varepsilon - \rho C_2 \varepsilon \frac{\dot{\varepsilon}^2}{k + \sqrt{\dot{\varepsilon}}} + C_1 \dot{\varepsilon} C_3 G_b + S_\varepsilon \tag{11}
\end{equation}

3. Numerical Modelling

The finite volume approach is used to calculate the solution of equations at each time interval. The model presented above is applied to model the evaporation of droplets of Thumba biodiesel and n-decane diesel fuels in ANSYS Fluent. Conservation equations of mass, momentum, and energy are coupled with the realizable k-\(\varepsilon\) turbulence model and species transport equation to model the evaporation of fuel droplets in high temperature and pressure conditions. Discrete phase model (DPM) is applied to solve the discrete phase that is, fuel droplet into the continuous phase present in the combustion chamber. In the coupled calculation, the continuous phase is solved before the introduction of a discrete phase injection. Then, the discrete phase is introduced by calculating the particle trajectories for discrete phase injection. Then continuous flow phase is recalculated after the injection of the discrete phase using the interphase exchange of mass, momentum, and heat determined by the previous calculation. Finally, the discrete phase is recalculated using the modified continuous phase flow field. The present model is applied to the engine specifications, as mentioned in Table 1.

| Engine Specifications | Values | Injection Specifications | Values |
|-----------------------|--------|--------------------------|--------|
| Bore                  | 150 mm | Injection type           | single |
| Stroke                | 180 mm | Droplet velocity         | 35 m/s |
| Max Torque            | 295 kg-m| Droplet temperature      | 300 K  |
| Ambient Pressure      | 4 MPa  | Flow rate                | 0.003 kg/s |
| Nozzle Diameter       | 0.29 mm| Injection duration       | 4 ms   |

3.1. Geometry and Meshing

Modeling in computational fluid dynamics starts with the geometry of the computational domain. In the present work, the original geometry of the piston is taken for calculations. Symmetry feature is applied to the whole domain to achieve the same boundary conditions for it. A 2D geometry of piston
is used to carry out the simulation. Mesh of the one-sixth sector of the engine cylinder is shown in Figure 1.

**Figure 1.** Mesh of one-sixth sector of cylinder and injection position.

### 3.2. Boundary Conditions

The velocity of the droplet is taken as 35 m/s. Primary and secondary breakup effects are ignored to visualize the evaporation of fuel droplets. The temperature of the droplet is taken as 300 K. Three different ambient temperatures of 623, 823, and 973 K are taken for analysis. The flow rate of spray is set as 0.003 kg/s and spherical drag law is applied to the droplet. Diameters of 20 and 25 microns are taken to model the evaporation of fuel droplets. The temperature of the cylinder is taken accordingly as discussed above. The injection location \((x, y) = (0, 0.005)\) m is also shown in Figure 1.

### 3.3. Mesh Independence Analysis

Mesh plays an important role in achieving the best results. Different types of meshes are available in ANSYS Fluent. Coarse mesh gives poor results of calculations, while a high-quality fine mesh generates the best results that are close to real ones. Increasing the number of cells in a mesh increases the computational time and, to resolve high-quality mesh, very high computing sources are required. In the current work, three different meshes are created and analyzed and are shown in Figure 2. Finally, a mesh of 0.63 million elements is selected for performing the numerical calculations.

**Figure 2.** Mesh Independence Analysis.

### 3.4. Fuel Composition

In the present work, two different fuels are used to model the evaporation of fuel droplets. Fuels used in this work are diesel (n-decane D100) and a blend of biodiesel from Thumba oil with diesel. Biodiesel is a composition of methyl palmitate, methyl linoleate, and methyl oleate. All these species of biodiesel contain long chains of methyl esters that cause the disturbance in calculation time owing to impractical reactions. Therefore, these species are not suitable to represent the biodiesel.
To overcome this problem, a new species is developed in the form of a hydrocarbon containing hydrogen, carbon, and oxygen as basic constituents to represent the biodiesel of Thumba oil [19]. The molecular formula of pure Thumba biodiesel is C_{5.96}H_{11.71}O_{0.81} and the molecular formula of diesel is C_{10}H_{22}. The properties of both fuels are given in Table 2.

Table 2. Properties of fuel droplets.

| Droplet Properties             | Diesel         | Thumba Biodiesel [19] |
|--------------------------------|----------------|-----------------------|
| Density (kg/m³)                | 835            | 880                   |
| Specific heat capacity (J/kg K)| 2090           | 1774                  |
| Thermal conductivity (W/m K)   | 0.149          | 0.158                 |
| Viscosity (kg/m s)             | 0.004          | 0.00466               |
| Latent heat (J/kg)             | 277,000        | 229,327               |
| Vaporization temperature (K)   | 341            | 341                   |
| Boiling point (K)              | 447            | 691.69                |
| Volatile component fraction (%)| 100            | 100                   |
| Binary diffusivity (m²/s)      | 3.79 × 10⁻⁶    | 7.42 × 10⁻⁶           |
| Saturation vapor pressure (Pascal) | 1329          | 1329                  |
| Droplet surface tension (N/m)  | 0.02521        | 0.02715               |

4. Model Validation

The droplet evaporation model presented in this work is implemented in the ANSYS Fluent and obtained numerical results are compared with the most accurate vaporization experiments [34] and numerical model of Abramzon and Sirignano [35]. In their experiment [34], the effect of the droplet suspending technique is eliminated by using a novel cross micro-fiber system, as compared with most of the studies where larger fiber diameters are used. This technique enables them to preserve the spherical shape of the droplet throughout the vaporization process in a normal gravity atmosphere. The present model of evaporation is compared with the experiment of Chauveau et al. [34] owing to the fact that the temperature of the cylinder is kept at 623 K in both studies.

As shown in Figure 3, the results include the droplet lifetime with respect to the normalized time. The profile of regression in the droplet lifetime of diesel fuel is compared with the available experimental and numerical data.

![Figure 3. Comparison of n-decane droplet vaporization with the experiments of Chauveau et al. [34] and the model of Abramzon and Sirignano [35].](image-url)
The result of the present model is close to the experimental work in Chauveau et al. [34] as compared with the numerical model of Abramzon and Sirignano [35]. This may be because of the fact that, in the present model, turbulence effects are taken into account by applying a realizable k-epsilon model, and this is the reason for obtaining the results closer to the experimental work. Another reason is, in the experiment of Chauveau et al. [34], the droplet was at room temperature initially and droplet regression was recorded when the droplet was already heated in the furnace. For this reason, the heat-up period of droplet was ignored and only the evaporation characteristic was recorded. The difference between the present model and the experiment of Chauveau et al. [34] is also owing to this heat-up period. Furthermore, all experimental measurements are subject to some uncertainty. Therefore, the numerical results are not expected to exactly match the experimental results. The absolute error was calculated for the present model when compared with the experimental model [34]. The absolute error was found to be 0.9238, which is acceptable as the error is less than 1.

In the real phenomena, turbulence effects are present and cannot be ignored while performing CFD computations. The model validation shown in Figure 3 is for the diesel fuel. The model predicts the evaporation rate in a good agreement with the experimental and numerical results. As the current model predicts the correct evaporation rate of diesel fuel droplet, it can be applied to the biodiesel fuel because the properties of both fuels are similar in a number of ways. For example, properties like vaporization temperature, volatile component fraction, and saturation vapor pressure are exactly the same. Some other properties of both fuels differ that make the composition of fuels different and their behavior under the same operating conditions. Thus, we can extend the model validation to both fuels.

5. Results and Discussion

In the section below, the results of biodiesel and diesel fuel droplets are presented. Three different ambient temperatures are chosen to perform the analysis. At the end of the compression stroke in diesel engines, the nominal temperature reaches from 623 K up to 973 K, depending upon the compression ratio of the engine. For the engine designed for heavy-duty work and high torque, the temperature ranges up to 973 K in the compression stroke. The current work represents the results of a high torque engine and its specification are given in Table 1. Three different results are analyzed for a moving droplet in the engine cylinder. When the spray is atomized in the engine cylinder, it breaks into droplet particles. These are known as primary and secondary breakups. For the current calculation, these breakup effects are ignored as primary breakup effects are negligible at high operating conditions and can be ignored.

5.1. Effect of Droplet Size on Evaporation at Different Ambient Temperatures

In Figure 4, the profiles of reduction in diameter of 20-micron droplets of diesel and biodiesel are plotted at three different temperatures. Regression in diameter is plotted using the classical D^2 law. Normalized diameter is plotted against the normalized time. At an ambient temperature of 623 K, biodiesel droplets take the maximum time to evaporate completely. The life of the droplet is extended owing to low ambient temperature. Another reason the biodiesel droplet takes longer to fully evaporate is that the boiling point of biodiesel is much higher than that of the n-decane diesel fuel. As stated in Table 2, the boiling point of biodiesel is 669.91 K and that of diesel is 477.10 K. Thus, at the low ambient temperature of 623 K, biodiesel droplets take more time to evaporate than the diesel fuel droplet. At the temperature of 823 K, both biodiesel and diesel fuel droplets fully evaporate earlier than the droplet temperature of 623 K. The effect of increasing temperature has shortened the lifetime of diesel fuel droplet more than as compared with the biodiesel that is evident from Figure 4. Finally, at the temperature of 973 K, the droplet lifetime becomes smaller as compared with previous cases. At this high temperature of 973 K, the lifetime of both diesel fuel and biodiesel droplets is too short as compared with the lower temperatures of 623 and 823 K.
The evaporation of droplet increases with the increase in surface area and the rate of evaporation is directly proportional to the surface area. In the case of the fuel droplet, however, it should not be so large that the time of evaporation increases and creates problems in the complete combustion. Therefore, an appropriate droplet size is selected so that it produces complete combustion in the engine cylinder by evaporating completely. In Figure 5, the vaporization of the 25-micron droplet of both diesel and biodiesel is shown at three different temperatures. It is observed that, at a lower temperature of 623 K, the same behavior of droplet is predicted as in the case of a 20-micron droplet. At the temperature of 823 K, droplet evaporates rapidly compared with at the lower temperature of 623 K. Similarly, at a higher temperature of 973 K, both fuels exhibit faster evaporation, as predicted in the previous case. One interesting observation is that, at the lower temperature of 623 K, the difference in evaporation histories of both fuels is very large, as shown in Figure 5. Nevertheless, as the temperature is increased from 623 K to 823 K and 973 K, this difference is reduced sharply. At the temperature of 823 K, both fuels almost take an equal time for complete vaporization. For biodiesel, evaporation starts at a faster pace than diesel fuel at 823 K, but the complete evaporation takes place at the interval of time equal to diesel fuel droplet. The vaporization temperature of both fuels is the same as indicated by Table 2, but the difference lies in the boiling point. Owing to the high boiling point of biodiesel, it has a longer heat-up period than the diesel fuel. At the size of 25-micron droplet diameter, when the temperature is increased to 973 K, the difference in evaporation characteristic between the droplets of both fuels becomes very small as compared with the 20-micron droplet.

**Figure 4.** Variation of 20-micron droplet’s dimensionless diameter at various ambient temperatures.

**Figure 5.** Variation of 25-micron droplet’s dimensionless diameter at various ambient temperatures.
The droplets of the same size evaporate more quickly at a high temperature. As the temperature increases, vaporization time decreases, and vice versa. When fuel is atomized in the engine cylinder in the form of a spray, it breaks into a form of fine droplets and travels along the combustion chamber. The velocity of spray decreases owing to drag and turbulence present in the engine cylinder under high operating conditions. It is observed that the same velocity droplets with large diameters take more time to evaporate completely in the engine cylinder and droplets having small diameters take much less time to evaporate and their velocity decreases in a much shorter interval of time.

5.2. Effect of Temperature on Evaporation

In Figure 6, the temperature profiles of both fuels are plotted at various ambient temperatures at 20-micron diameter. It is observed that, at the temperature of 623 K, the droplet has a longer lifetime. In Figure 6, the increase in droplet temperature is plotted by keeping the droplet temperature at 300 K. Droplets are evaporated in a short time and vanish in a small period at a high ambient temperature, while at a lower ambient temperature, droplets take more time to evaporate completely. An increase in droplet temperature of different sizes is observed at various ambient temperatures. Temperature profiles of droplet temperature obtained are in good agreement with the experimental and numerical data.

The maximum temperature attained by the diesel fuel droplets is 447 K, because this is the boiling point of diesel. At all ambient temperatures, the maximum temperature reaches up to 447 K. However, one thing that is noticed is that, as the ambient temperature increases, the droplet life decreases. When the ambient temperature is 973 K, the droplet attains the value of 447 K in a very short interval of time as compared with 623 K and 823 K.

In the case of biodiesel, the behavior of droplets is different from the diesel fuel droplets. At the ambient temperature of 623 K, droplets do not attain the temperature of more than 460 K, thus leading to poor evaporation of fuel. However, as the temperature increases, droplets readily attain the boiling temperature of 691 K. At 823 K, biodiesel droplets evaporate more rapidly and need less time to evaporate completely, but diesel fuel droplets reach the maximum temperature in a shorter time than biodiesel droplets.

Droplets of small size evaporate completely in a short interval of time, but droplets having larger diameters take more time to evaporate fully at the same operating conditions. Small diameters absorb
heat quickly as the heat-up period is low for small droplets and is greater for the large size droplets. Hence, small droplets are heated up in a small amount of time and vaporization starts right after the heat-up period. The heat-up period of large droplets is more as compared with the small droplets, and hence these droplets take more time to evaporate at the same ambient temperatures.

In Figure 7, the temperature profiles of 25-micron droplets are plotted against the normalized time. The same trend is observed for the different ambient temperatures. For a lower temperature, the droplet of larger diameter evaporates in a large time as compared with the higher temperatures. The residence time of biodiesel droplets is lower than the residence time of diesel fuel droplets, thus leading to the complete evaporation of fuel and, ultimately, complete combustion to produce more power and high thermal efficiency.

![Figure 7. Effect of ambient gas temperature on the evaporation of 25-micron droplet.](image)

5.3. Analysis of Velocity at the Same Temperature for Different Droplets’ Size

In this section, the velocity profiles of droplets of different sizes are plotted at the same ambient temperature. It is observed that, at the same velocity and the same ambient temperature, the residence time of small droplets is short and, for large droplets, it is longer. Drag force plays an important role in the residence time of droplets. Large size droplets face a lower drag force as compared with smaller ones, and hence their residence time is greater than the smaller ones. When the droplet is injected through the nozzle after the injection, the velocity of droplet decreases because it faces the drag, and because of the gravity force that acts downward. Thus, the velocity of the droplet is not increasing while traveling through the engine cylinder. In the current study, primary and secondary breakups are ignored. After injection, the droplet attains a maximum velocity. Then, the velocity of the droplet starts decreasing. In the present study, the maximum velocity of the droplet is taken and, owing to the absence of breakup effects, the velocity will not increase. Thus, the evaporation time of larger droplets is greater than the smaller ones at the same temperature and velocity.

In Figure 8, velocity profiles of 20-micron droplets are shown at different ambient temperatures. The initial velocity of the droplet is taken 35 m/s in all cases. Almost all the profiles are the same in the initial 0.5 ms except the velocity profile of biodiesel fuel droplet at 973 K. At this temperature, after decreasing velocity up to 32 m/s, it remains constant for a while and then decreases suddenly to the lowest value. In other cases, the velocity decreases gradually.
Further, it is noted for both fuels that, as the temperature increased, the residence time of fuel droplets decreased, irrespective of the final velocity of the droplet. In Figure 8, velocity profiles of 20-micron droplet are plotted at various ambient temperatures. It is observed that the behavior of species present in biodiesel fuel is not in a continuous manner, as indicated by Figure 8, but diesel fuel droplets behave continuously whether the temperature is increased or decreased. It is noted for both fuels that, as the temperature increased, the residence time of fuel droplets decreased, irrespective of the final velocity of the droplet.

In Figure 9, the velocity profiles of the 25-micron diameter are plotted at various ambient temperatures. Velocity decreases in the same way as for the 20-micron droplet. However, one noticeable thing is that, for 823 K, the velocity of the biodiesel fuel droplet has become almost zero, which might be owing to the kinetic energy force of the particle being balanced with the drag force. The velocity is also decreased for 623 K and 973 K as compared with the 20-micron droplet. In the case of the diesel fuel droplet, the velocity profiles exhibit almost the same trend for both 20 and 25-micron droplets. One important thing that is observed is that as the size of the droplet is increased and its residence time is also increased. Larger droplets need more time to evaporate completely and smaller droplets need a short amount of time.

**Figure 8.** Variation in velocity of 20-micron droplet at different ambient temperatures.

Minimum velocity is achieved by the biodiesel fuel droplet at 823 K. The minimum velocity achieved by the diesel fuel droplets is about 10 m/s at all given temperatures subjected to the longer residence time at a lower temperature. It is observed that the behavior of species present in biodiesel fuel is not in a continuous manner, as indicated by Figure 8, but diesel fuel droplets behave continuously whether the temperature is increased or decreased. It is noted for both fuels that, as the temperature increased, the residence time of fuel droplets decreased, irrespective of the final velocity of the droplet.

In Figure 9, the velocity profiles of the 25-micron diameter are plotted at various ambient temperatures. Velocity decreases in the same way as for the 20-micron droplet. However, one noticeable thing is that, for 823 K, the velocity of the biodiesel fuel droplet has become almost zero, which might be owing to the kinetic energy force of the particle being balanced with the drag force. The velocity is also decreased for 623 K and 973 K as compared with the 20-micron droplet. In the case of the diesel fuel droplet, the velocity profiles exhibit almost the same trend for both 20 and 25-micron droplets. One important thing that is observed is that as the size of the droplet is increased and its residence time is also increased. Larger droplets need more time to evaporate completely and smaller droplets need a short amount of time.

**Figure 9.** Variation in velocity of 25-micron droplet at different ambient temperatures.
The current evaporation model is applied to the real high torque heavy-duty diesel engine. Certain things need to be addressed, such as the fact that the diameter of the evaporating droplet should be as small as possible to completely vaporize the droplet. In diesel, the spray is atomized from the injector nozzle having fixed diameter holes. After ejecting from the nozzle, spray breaks up into the droplets. In the present study, the diameter of the nozzle taken is 290 micron and, after the penetration length and secondary breakup, the droplet diameter reaches up to 25 micron. Thus, the nozzle should be designed in such a way that, after penetration length and primary and secondary breakup, the droplet should achieve the minimum. Moreover, there are a large number of droplets formed after the injection, and it is not necessary to evaporate each droplet. The radiation effects are ignored in the present calculation because, at the present engine conditions, these effects are negligible.

6. Conclusions

In the present study, the evaporation characteristics of Thumba biodiesel and n-decane diesel fuel are modeled numerically by applying the realizable k-epsilon turbulence model and the results are compared with the available experimental and numerical data. The results show that the droplets having a large diameter take more time to evaporate completely as compared with the smaller ones. Small droplets evaporate more quickly owing to a shorter heat-up period than the larger ones. Droplets of the same size behave differently at different ambient temperatures. Furthermore, temperature profiles of both biodiesel and diesel are plotted against the normalized time. It is observed that, when the temperature is increased or decreased, evaporation of diesel fuel follows a similar pattern, but this is not the same for the biodiesel. It is noted for both fuels that, as the temperature increased, the residence time of fuel droplets decreased, irrespective of the final velocity of the droplet. It is worth noting that, at higher temperatures, biodiesel evaporates faster than the diesel fuel and complete evaporation is achieved, resulting in the complete combustion, hence giving the maximum thermal efficiency. Moreover, if the bore size of the cylinder is increased, droplets of a large size can give a better evaporation rate owing to increased vapor distribution.

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Nomenclature

\[
\begin{align*}
\rho & \quad \text{Density of air (m}^3/\text{kg)} \\
\kappa & \quad \text{Mass transfer coefficient (m/s)} \\
\rho_p & \quad \text{Density of particle (m}^3/\text{kg)} \\
C_i,s & \quad \text{Vapor concentration at droplet surface (kg-mol/m}^3) \\
v & \quad \text{Velocity of air (m/s)} \\
C_i,\infty & \quad \text{Vapor concentration in bulk gas (kg-mol/m}^3) \\
v_p & \quad \text{Velocity of droplet (m/s)} \\
S_m & \quad \text{Source term} \\
p & \quad \text{Static pressure (N/m}^2) \\
\tau & \quad \text{Stress tensor (N/m}^2) \\
F & \quad \text{External body force (N/m}^2) \\
\mu & \quad \text{Molecular viscosity (kg/ms)} \\
l & \quad \text{Unit tensor} \\
k_{\text{eff}} & \quad \text{Effective thermal conductivity (W/m-K)} \\
j_j & \quad \text{Diffusion flux of species j (kg/s-m}^2) \\
S_h & \quad \text{Heat of chemical reaction} \\
Y_j & \quad \text{Mass fraction of species j}
\end{align*}
\]
\( R_j \) Net rate of production of species \( j \)
\( S_j \) Rate of creation by addition from disperse phase
\( D_{j,m} \) Mass diffusion coefficient of species \( j \) \((m^2/s)\)
\( D_{T,m} \) Thermal diffusion coefficient of species \( j \) \((m^2/s)\)
\( Sc_t \) Turbulent Schmidt number
\( \mu_t \) Turbulent viscosity \((m^2/s)\)
\( d_p \) Droplet diameter (m)
\( Re \) Relative Reynolds number
\( C_d \) Drag coefficient
\( m_p \) Mass of particle (kg)
\( C_p \) Droplet heat capacity \((J/kg-K)\)
\( h \) Convective heat transfer \((W/m^2-K)\)
\( T_\infty \) Temperature of continuous phase (K)
\( h_{fg} \) Latent heat of vaporization \((j/kg)\)
\( A_p \) Surface area of particle \((m^2)\)
\( M_{w,j} \) Molecular weight of species \( j \) \((kg/kmol)\)
\( N_j \) Molar flux of vapor \((kgmol/m^2-s)\)

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