COMPARISON OF VARIOUS DROPLET BREAKUP MODELS IN GAS-LIQUID FLOWS IN HIGH-PRESSURE ENVIRONMENTS

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Abstract– Droplet breakup affects spray penetration and evaporation, and plays a critical role in engine efficiency. The purpose of this research was to examine the rate of penetration and evaporation of droplets in a combustion chamber, and the efficiency of the engine when liquid jet is injected into the compressed gas chamber in an axisymmetrical fashion leading to a turbulent and unsteady flow. As a result of interaction with the highly compressed air in the chamber, the liquid jet breaks up and forms minute droplets. These particles will in turn breakup because of aerodynamic forces, producing even smaller droplets. A number of models are available for analyzing the breakup of droplets; however, each model is typically reliable only over a limited parameter range. In this research three well-known models are applied for droplet breakup modeling and their results are compared. To obtain the details of the flow field, the Eulerian gas phase mass, momentum and energy conservation equations, as well as equations governing the transport of turbulence and fuel vapor mass fraction are solved together with equations of trajectory, momentum, mass and energy conservation for liquid droplets in Lagrangian form. The numerical solution is performed using the finite volume method and EPISO (Engine-PISO) algorithm. The results obtained from the models show that the breakup process in a high pressure environment significantly affects the penetration and evaporation rates of the spray, and the droplet size is determined by the balance between breakup and coalescence processes. It is also shown that the details of atomization in the nozzle do not significantly influence the ultimate size of droplets. It should be mentioned that droplet collision modeling has been taken into account in the computer code and is activated wherever necessary.

Keywords– Spray penetration, evaporation, engine PISO algorithm, droplet–breakup

1. INTRODUCTION

In recent years, special attention has been paid to spray, with particular emphasis on its modeling in diesel engines. The restrictions on the rules of contaminators and also the high expense of laboratorial equipment and tools have caused scientists to focus much more attention on CFD computer codes. The effects of turbulence and various breakup models on penetration and evaporation of spray are the most recent subjects relating to spray current in two–phase flows. Droplet–breakup caused by symmetrical fuel injection into a cylindrical chamber containing compressed gas was first presented by Reitz and Diwakar [1]. The physical structure of spray was then studied at different pressures and temperatures by the mentioned scientists [2]. Spray calculations in which spray was considered a gaseous phase was quite popular [3]. Gas–liquid flow calculations were first organized in England and the U.S., resulting in different computer codes [4]. Researchers and scientists such as Watkins and Khaleghi were involved in designing some of these codes [5].

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Also, calculations related to the effect of temperature on dynamic properties of spray and the effect of the pressure difference around droplets on their breakup were completed by Feath [6] and Dwyer [7]. Further calculations of spray regarding heat and mass transfer sub-models [8], droplet surface temperature [9], spray wall impaction [10], the effect of liquid fuel droplet size on soot emissions [11], and spray modeling based on droplet size moment [12] have been reported in recent years.

The above mentioned works were also developed by Khaleghi et al. [13-15] in such a way that the codes written in Iran are identified as EPISO–II. This code is now able to study the 3D movement of laminar and turbulent flows accompanied by droplet breakup and collision processes, and to calculate the evaporation history of droplets in a two–phase flow fashion [16].

In this article, besides emphasizing the capabilities of the code, the effective factors on fuel droplets like droplet diameter, number of droplets added in each time step, and the rate of spray penetration in the chamber are considered using different models of breakup. The rate of droplet evaporation using different breakup models is also explained and the mutual impact of the liquid phase on the gas phase is further studied. In this research, three different models of droplet breakup are studied and the best model is presented.

2. ASSUMPTIONS

Calculations of droplet motion and evaporation history are made by solving Lagrangian liquid phase equations. The implemented model for two–phase flow is Discrete Droplet Model (DDM). In this model, droplets pass through the gas; exchange their mass and momentum with the gas and are influenced by drag force introduced by the gas. Also, droplets receive energy from the gaseous environment because the initial droplet temperature is much less than the gas phase temperature and they are also influenced by the turbulence of the environment.

Each droplet is assumed as a parcel of smaller round–shape droplets that do not have any physical interactions among themselves. Temperature, velocity, size and other physical factors of the droplets in a parcel are uniform. By injecting a sufficient number of these parcels with different properties we can analyze the properties of the whole liquid spray injected. In this research, spray is injected into a chamber with an opening diameter of 7.5 cm, and a height of 11 cm is studied. The injector is located in the center of a cylinder with a diameter of 0.213 mm. The injector needle pressure is 220 bars and the ratio of length to the diameter of the injector is 3.6.

3. GOVERNING EQUATIONS

Equations used in this problem are generally divided into gas and liquid phase equations.

a) Gas phase equations

Equations governing the gas phase include the mass, momentum and energy conservation, turbulence quantities and fuel vapor mass fraction. The equations are written and solved using an Eulerian point of view which can generally be represented as:

$$
\frac{\partial}{\partial t} (\rho \phi) + \frac{\partial}{\partial x} (\rho u \phi) + \frac{1}{r} \frac{\partial}{\partial r} (r \rho u \phi) = \frac{\partial}{\partial x} \left( \Gamma_{\phi} \frac{\partial \phi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \Gamma_{\phi} \frac{\partial \phi}{\partial r} \right) + S_{\phi} + S_{\phi} \tag{1}
$$

In this equation, $\Gamma_{\phi}$ and $S_{\phi}$ are the diffusion coefficient and the source term for the transported property $\phi$, respectively, and are defined in Table 2. The parameter, $S_{\phi l}$, is the droplet source term, which is also shown in Table 2.
Equation (1), as noted earlier, represents turbulence transport as well. The turbulence model used in this research is the standard k-ε model, with the constant and variable quantities listed in Tables 1 and 2.

Table 1. Constant coefficients in standard $k-\varepsilon$ turbulence model

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>$C_\mu$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$\sigma_k$</th>
<th>$\sigma_\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantities</td>
<td>0.09</td>
<td>1.44</td>
<td>1.92</td>
<td>-0.373</td>
<td>1.0</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Table 2. Quantities of $\Gamma$, $S_\phi$, $S_{\phi t}$ for different quantities of $\phi$ (according to equation 1)

<table>
<thead>
<tr>
<th>Equation type</th>
<th>$\phi$</th>
<th>$\Gamma$</th>
<th>$S_\phi$</th>
<th>$S_{\phi t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>$S_{\phi t} = -\frac{\pi}{6\delta N_p} \sum_N d_k (</td>
</tr>
<tr>
<td>x-momentum</td>
<td>$\mu_{eff}$</td>
<td>$\varepsilon$</td>
<td>$\frac{\partial \rho}{\partial x} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0$</td>
<td></td>
</tr>
<tr>
<td>r-momentum</td>
<td>$\mu_{eff}$</td>
<td>$\varepsilon$</td>
<td>$\frac{\partial \rho}{\partial r} + \frac{\partial (\rho u)}{\partial r} + \frac{\partial (\rho v)}{\partial r} = 0$</td>
<td></td>
</tr>
<tr>
<td>K-Turbulence</td>
<td>$\mu_{eff} / \sigma_k$</td>
<td>$G - \rho e$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon$-Turbulence</td>
<td>$\mu_{eff} / \sigma_\varepsilon$</td>
<td>$\frac{k}{\varepsilon} (C_{\varepsilon} \rho e - C_{\varepsilon}^2 \rho e)$</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Energy Equation</td>
<td>$h$</td>
<td>$\mu_{eff} / \sigma_k$</td>
<td>0</td>
<td>$S_{\phi t} = -\frac{\pi}{6\delta N_p} \sum_N d_k {(D_{d,k}^{\phi t})^3 }$</td>
</tr>
<tr>
<td>Fuel Vapor Mass Fraction Equation</td>
<td>$f_{fuel}$</td>
<td>$\mu_{eff} / \sigma_k$</td>
<td>0</td>
<td>$S_{\phi t} = -\frac{\pi}{6\delta N_p} \sum_N d_k {(D_{d,k}^{\phi t})^3 }$</td>
</tr>
</tbody>
</table>

* In these relations, $G$, $\mu_{eff}$, $\mu_t$ are respectively defined as follows:

\[
G = \mu \left[ \frac{1}{2} \left( \frac{\partial u}{\partial x} \right)^2 + \frac{1}{2} \left( \frac{\partial v}{\partial r} \right)^2 + \frac{1}{2} \left( \frac{\partial v}{\partial \theta} \right)^2 \right] + \frac{1}{2} \left( \frac{\partial u}{\partial r} \right)^2 + \frac{1}{2} \left( \frac{\partial v}{\partial \theta} \right)^2 - \frac{2}{3} \left( \mu \nabla \cdot \mathbf{u} + \rho k \right) \nabla \cdot \mathbf{u}
\]

\[
\mu_t = c \mu \rho \kappa^2 / \varepsilon
\]

\[
\mu_{eff} = \mu_{mol} + \mu_t
\]

b) Liquid phase equations

The Lagrangian equations for each droplet parcel include the trajectory and momentum equations in both radial and axial directions:

\[
\frac{dx_d}{dt} = u_d \quad \text{(2)}
\]

\[
\frac{dy_d}{dt} = v_d \quad \text{(3)}
\]

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In the above equations, the effect of shear force on the droplets is shown by $k_d$, which is defined as:

$$k_d = \frac{3}{4} C_{D_r} \frac{\rho}{\rho_d} \frac{1}{D_d} |\overline{V}_{rel}|$$

(6)

where $\overline{V}_{rel}$ is the relative velocity between the gas and liquid phases.

$$\sqrt{[(\overline{u} + u') - u_d]^2 + [(\overline{v} + v') - v_d]^2}$$

(7)

In these equations, and elsewhere in this paper, the primed quantities represent fluctuation components caused by flow turbulence, and barred quantities represent the mean values. Droplet mass and energy changes are calculated from Borman–Johnson equations [17]:

$$\frac{d m_d}{dt} = -\pi D_d D_p \ln \left( \frac{P_i - P_{rel}}{(P_i - P_{rel})/P_{rel}} \right) \frac{Sh}{RT_m}$$

(8)

$$\frac{d (mC_p T)_d}{dt} = \pi D_d k(T - T_j) \left[ Z (\epsilon - 1) \right] \frac{\delta}{Nu} + \frac{Q}{dt}$$

(9)

In these equations, $Z$ is heat transfer correction coefficient when mass transfer is simultaneously taking place and is obtained from

$$Z = \frac{-C_{mV} d m_d / dt}{\pi D_d k N u}$$

(10)

c) Droplet breakup equations

In this research three droplet breakup models, each based on different breakup mechanisms, have been considered [18]. These breakup mechanisms are:

1) Parachute type (Bag type)
2) Claviform type (Engle type)
3) Oblate type (Stripping type)

1) Parachute method (Bag type): In this mechanism, gas flow from the external area is blown towards the center of the droplet. This will cause a pressure difference between the droplet center and the surrounding environment and leads to breakup when the inertial force overcomes the surface tensile force. The process of this breakup is illustrated in Fig. 1. The relative magnitudes of the inertial and surface tension forces can be represented by Webber number and breakup occurs when:

$$We = \frac{\rho V_{rel}^2 D_d}{2\sigma} > 6.0$$

(11)
In this equation (*We*) is the Weber number, *ρ* is the gas density, *V_{rel}*, is the relative velocity between the gas and the droplet, *D_d* is the diameter of the droplet and *σ* is the liquid surface tension. Breakup takes place over a very short period of time (instability time of the droplets) which can be estimated from

\[ t_i = \pi \left[ \frac{\rho_d D_d^3}{16\sigma} \right]^{1/2} \]  \hspace{1cm} (12)

2) **Claviform method (Engle type):** This breakup mechanism resembles the aforementioned bag type mechanism; with the difference that the forces here are directed toward the upper and lower parts of the center so that the droplet looks like a claviform. The breakup here is caused by the pressure difference between the inside and outside of the droplet as well as the inertial forces, which overcome the surface tension forces. The droplet will breakup as shown in Fig. 2.

The droplet breakup in this method depends not only on the Weber number, but also on the dynamic viscosity of the droplets. If the dynamic viscosity of the droplets is assumed to be \( \mu_d = 5.95 \times 10^{-3} \text{ (Pascal seconds)} \), the critical Weber number varies in the range of 4.5 to 21. The critical *We* is therefore calculated as follows:

I. When the relative velocity decreases:

\[
\begin{align*}
We &= 14.5 \quad & \text{if} \quad \sqrt[1/3]{L_p} < 0.12 \\
We &= 36.5L_p^{-0.14} \quad & \text{if} \quad 0.12 < \sqrt[1/3]{L_p} < 0.7
\end{align*}
\]  \hspace{1cm} (13)

II. When the relative velocity increases:

\[
\begin{align*}
We &= 21.0 \quad & \text{if} \quad \sqrt[1/3]{L_p} < 0.12 \\
We &= 43.0L_p^{-0.14} \quad & \text{if} \quad 0.12 < \sqrt[1/3]{L_p} < 0.7
\end{align*}
\]  \hspace{1cm} (14)

The parameter *L_p* is the Laplace number.
Instability time of the droplets ($t_2$) in this breakup mechanism can be estimated from:

$$t_2 = 2.8 \frac{D_d}{V_{rel}} \left[ \frac{\rho_d}{\rho} \right]^{0.5}$$  \hspace{1cm} (16)

3) **Oblate method (Stripping type):** In this mechanism, the droplets are stripped from their edges. The droplet fragmentation basically occurs by cutting droplets from their corners or poles. In this mechanism, aerodynamic forces overcome the surface tension force and droplets are stripped from the corners toward the centers, as shown in Fig. 3.

![Fig. 3. Droplet breakup model in stripping type (Oblate)](image)

In this model, it is assumed that droplets in a parcel become unstable and breakup occurs when:

$$\left( \frac{We}{\sqrt{Re}} \right) > 0.5$$  \hspace{1cm} (17)

Where $Re$ is the droplet Reynolds number which is defined as:

$$Re = \frac{\rho V_{rel} D_d}{\mu}$$  \hspace{1cm} (18)

The droplet instability time, $t_3$, for this mechanism can be estimated by:

$$t_3 = D_2 \frac{D_d}{2 V_{rel}} \left[ \frac{\rho_d}{\rho} \right]^{0.5}$$  \hspace{1cm} (19)

Where $D_2$ is a constant. If droplet parcels remain in conditions where Eq. (17) is satisfied for a time period longer than $t_3$, all of the droplets will break into smaller ones. The diameter of the droplets, $D_{stab.}$, and the number of newly formed droplets, $N_d'$, can be obtained from:

$$D_{stab.} = \frac{\sigma^2}{\rho V_{rel}^3 \mu}$$  \hspace{1cm} (20)

$$N_d' = \frac{N_d D_d^3}{D_{stab.}^3}$$  \hspace{1cm} (21)

It should be mentioned that energy is conserved before and after the breakup, so the crucial factor of $\Delta V$ can be found:
\[ \Delta V = 1 - \left( \frac{D_d}{D_{d,stab}} - 1 \right) \left( \frac{3\sigma}{2\rho_d D_d u_d^2} \right) \] (22)

In this expression, \( D_{d,stab}, u_d \) are the diameter of droplets after breakup and their velocity before breakup, respectively. The velocity of droplets after breakup \( (u_d) \) is obtained using momentum conservation equation:

\[ u_{di} = u_d \Delta V \] (23)

Since \( \Delta V \) is smaller than unity, the velocity and the momentum of the droplets are reduced after the breakup. As a consequence, the droplet penetration decreases. Also, after breakup, the surface of the droplets exposed to the hot gas of the combustion chamber will increase, so the rate of droplet evaporation will increase as a result.

d) Droplet collision

The Collision model used in the present study follows that of O'Rourke and Bracco [19] in which droplet collision and coalescence are modeled using a statistical approach. This is because the outcome of collision in practice can lead to the formation of many new droplet parcels, causing rapid exhaustion of the computer storage capacity.

In the statistical approach used here, collision only occurs between a pair of droplet parcels provided they are in the same computational cell in which the droplets are also assumed to be uniformly distributed. The EPISO computational code does include collision modeling, but in the present calculations, in order to consider the isolated effects of different breakup models, the collision sub model has been switched off off.

4. SOLUTION METHOD

Numerical methods are applied to solve the governing equations. In order to find the answer to these equations, we can use various methods to discrete them and use different algorithms to solve the discretized sets of equations. In this paper, the finite volume method (FVM) is applied to discretize the equations. Discretization of the general transport equation, Eq. (1), is explained in [4], but discretized terms relating to droplets which are of great importance are mentioned in Table 2. After discretization of the equations using the finite volume approach, the implicit non-iterative Engine PISO algorithm [5, 20] has been applied to solve the set of equations.

5. EPISO ALGORITHM FOR ENGINE MULTI-PHASE FLOWS

The Engine Pressure Implicit by Splitting of Operators (EPISO) algorithm has been proposed by Ahmadi and Gosman [20]. This algorithm was then tested on a number of flow cases in order to (i) assess its performance in comparison with earlier iterative methods, (ii) examine the temporal accuracy of the operator splitting technique, and (iii) illustrate the capability of the method to handle complex geometries and turbulent flow situations.

The method is found to produce time step independent solutions at the same time step as fully implicit iterative schemes, but it is nearly an order of magnitude faster than the procedures based on the SIMPLE algorithm. The algorithm is also shown to be capable of calculating complex turbulent flows in engines.

Given the engine specifications, including the combustion chamber geometry, and piston and valve motions, the prediction method starts from initially prescribed conditions and marches forward in finite time increments. At each time step the following sequence of computations are made:
o Prediction of the velocity field: The predicted velocity field \((V^*)\) is obtained by solving momentum equations using boundary conditions and given pressure \(P^*\).

o First correction of velocity and pressure fields: by solving momentum equations with coefficients derived from predicted fields, a new velocity field \(V^{**}\) and pressure \(P^{**}\) are attained. The new corrected velocity field satisfies the continuity equation.

o Second correction of velocity and pressure field: like the previous stage and by applying the velocity and pressure fields of the first stage, velocity field \(V^{***}\) and pressure filled \(P^{***}\) are calculated.

Now by considering the above stages, we can write the details of the equations concerned:

a) In the prediction stage, the position of all droplets are obtained from Eqs. (2) and (3), as follows:

\[
x_{d} = x_{d}^{o} + \delta t u_{d}^{o}
\]

\[
r_{d} = r_{d}^{o} + \delta t v_{d}^{o}
\]

Also, the velocity components of all the droplets are obtained from Eqs. (4) and (5), as follows:

\[
u_{d}^{o} = \frac{u_{d}^{o} + k_{d}^{o} \delta t (u^{o} + u^{o}) + \delta t S_{ud}^{o}}{\delta t k_{d}^{o} + 1}
\]

\[
v_{d}^{o} = \frac{v_{d}^{o} + k_{d}^{o} \delta t (v^{o} + v^{o}) + \delta t S_{vd}^{o}}{\delta t k_{d}^{o} + 1}
\]

b) Calculating the velocity of the droplets and substituting them into momentum equations, the final gas phase velocity equations in the prediction stage are obtained:

\[
A_{u}^{p} = \Sigma_{c} A_{u}^{c} + (P_{p}^{c} + P_{w}^{c})a_{ud} + S_{u}^{u} + A_{u}
\]

\[
A_{v}^{p} = \Sigma_{c} A_{v}^{c} + (P_{p}^{c} + P_{w}^{c})a_{vd} + S_{v}^{v} + A_{v}
\]

c) In the first stage of correction the position and velocity of the droplets are written as:

\[
x_{d}^{**} = x_{d}^{o} + \delta t u_{d}^{o}
\]

\[
r_{d}^{**} = r_{d}^{o} + \delta t v_{d}^{o}
\]

\[
u_{d}^{**} = \frac{u_{d}^{o} + k_{d}^{o} \delta t (u^{o} + u^{o}) + \delta t S_{ud}^{o}}{\delta t k_{d}^{o} + 1}
\]

\[
v_{d}^{**} = \frac{v_{d}^{o} + k_{d}^{o} \delta t (v^{o} + v^{o}) + \delta t S_{vd}^{o}}{\delta t k_{d}^{o} + 1}
\]

In the preceding equations, \(u'\) and \(v'\) are velocity fluctuations which are evaluated by Dukowicz statistical distribution [21].

The first pressure correction equation is given as:

\[
A_{p}^{p}P_{p}^{c} = \Sigma_{c} A_{p}^{c} + S_{u}^{u} + S_{m}^{m}
\]
By substituting new density and pressure values in the momentum equation we can correct the new velocity fields \((u^*, v^*)\).

d) The position and velocity of the droplets are corrected by substituting \(*^*\) by \(*^***\) in the second stage (similar to former one).

Following two stages of correcting different parameters and factors, the mass fraction of the evaporated fuel are determined as follows:

\[
A_p^f f_p^* = \Sigma f_c^* A_c^f + \Sigma f_p^* + \Sigma f^* + \Sigma f^*
\]  

(34)

In this calculation, the gas phase energy equation together with the turbulence equations of \(k\) and \(\varepsilon\) are solved before going on to the next time step.

It can also be proved that, after two stages of corrections, the calculated results are obtained with a convenient level of accuracy [6].

### 6. RESULTS AND DISCUSSION

In this research, spray is injected in a 1.4 millisecond period of time, and calculation is made using the time step of \(DT = 0.25CA = 1.4 \times 10^{-5}\) Sec for calculations.

The droplet breakup process, according to the bag breakup mechanism, is illustrated in Fig. 1. In this model, force is directed toward the center of the droplet by the external fluid flow. Furthermore, because of the pressure difference between the droplet rear and front, the droplet (plane A) is first deformed into a curved shape (plane B) and then into a bag or parachute like configuration (plane C). Eventually, the droplet is divided into two separate parts (plane D) as the gas flows through the bag and shatters it.

The droplet breakup process according to the Engel (Claviform) model is demonstrated in Fig. 2. In this model, forces are directed toward the sides of the droplet. Due to the pressure gradients, the droplet first deformed into an ellipse having a longer axis perpendicular to the flow (plane B), and then into a Claviform (plane C). Finally, together with the shear forces, the hydrodynamic forces manage to divide the droplet into three separate fragments (plane D).

Figure 3 displays the droplet breakup process according to the stripping droplet breakup mechanism. In this case, the external forces are directed toward the poles of the droplet by fluid (gas) flow. As a consequence of this force (commonly known as aerodynamic force), small liquid fragments are stripped from the vicinity of the droplet’s poles. Once stripped the liquid fragments are entrained in the vortex behind the droplet, collide and coalesce (plane C), eventually forming a secondary droplet (plane D). The process depicted in (plane B) is sometimes referred to as droplet scissoring.

The physical structures of the spray, predicted by applying different breakup models, and assuming no breakup at all, are demonstrated in Fig. 4. As noted in these illustrations, in the bag model there are more wandering droplets than in other models. In the stripping model these droplets are scarcely seen since they quickly evaporate. This implies that in the stripping model evaporation takes place faster than in the other models.

The spray physical structure predicted by the EPISO-II and SPICE [7] computer codes are depicted in Fig. 5, where an experimentally obtained picture is also shown for comparison. As noted in the figure, the predictions of the EPISO-II code are in better agreement with the experiment than the SPICE code [7]. Furthermore, as will be shown, the EPISO-II code predicts more acceptable results than the SPICE code.

An illustration of the movement of the spray in the combustion chamber and its effect on the stream lines is demonstrated in Fig. 6. The conditions of this figure are identical to those for Fig. 5. Clearly, the deeper the spray penetration into the chamber, the more are the stream lines are influenced, and the more intense the generated turbulence.
Figure 7 depicts the droplet transient time as a function of droplet density, as predicted by various droplet breakup models. As noted, the droplet transient age predicted by the bag breakup model is consistently longer than the other models. The stripping model predicts the shortest droplet transient age. The droplets in this model are broken up more rapidly and the smaller droplets that result from the shattering of the original droplet undergo rapid evaporation. This also contributes to a faster evaporation rate in the stripping model than the other models. These observations are evidently consistent with the trends in Fig. 4.
The predictions of the different droplet breakup models, based on total evaporated mass, are compared in Fig. 8. The trends in this figure confirm the arguments that were made in the discussion of Figs. 4 and 7: the rate of evaporation in the stripping model is greater than in the others as claimed in the recently mentioned figures.

The predictions of various breakup models are compared with the experimental data and the results obtained from the KIVA-II code [22] as shown in Figs. 9 and 10. These comparisons are made for tetradecane fuel spray at two different ambient gas pressures and temperatures; namely, atmospheric pressure and room temperature (Fig. 9) and 17 bar pressure and 480 K (Fig. 10). It has to be mentioned that the KIVA-II calculations were made using a Taylor Analogy Breakup (TAB) model [22]. As can be seen from Fig. 9 the KIVA-II results are in agreement with the experimental data only during the initial stage of injection, and as time goes on the tip penetration is highly under-predicted, whereas in Fig. 10 the spray tip penetration is continuously underestimated throughout the injection period. As shown in Figs. 9 and 10, there is a better agreement between the results of the present work and the experimental data reported in [22].
In a separate study, the results of the present work have been compared with the reported experimental data in [23] for dodecane fuel spray at 25 bar and 573K, the results of which is shown in Fig. 11. It is observed from this figure that during the first half of the injection period the penetration rate obtained from the present study follows more or less the experimental results but in the second half, a 4 to 10 percent over prediction is made for various breakup models. It can easily be seen that a faster evaporation rate is accompanied by a shorter penetration length, and this is an expected trend. Accordingly, the bag model, which provides the slowest evaporation rate, also predicts the deepest penetration.

The variations of the droplet Sauter Mean Diameter (SMD) with time are depicted in Figs. 12 and 13 for stripping and bag models, respectively. In these figures, model predictions are presented and compared for several initial droplet diameters. Both figures indicate that the effect of the initial droplet diameter is only important during the very early stages of the injection process and diminishes with time.

Figure 14 depicts the influence of the surrounding pressure on the temporal change of the droplet SMD in the spray. Higher pressure evidently leads to a slightly larger SMD.
Fig. 11. Comparison of different breakup models in penetration with experimental data (P=25 bar, T=573K).

Fig. 12. Variation of Sauter Mean Diameter with time (Stripping Model) (P=25 bar, T=573K).

Fig. 13. Variation of Sauter Mean Diameter with time (Bag Model) (P=25 bar, T=573K).
7. CONCLUSION

The results obtained in this study show the following trends in the predictions of the EPISO-II computer code:

1. The movements and performance of droplets are relatively insensitive to how they are produced and distributed in the nozzle.

2. In numerical modeling, greater droplets are barely seen as time passes.

3. The EPISO-II code predictions are consistently in very good agreement with the experimental data. This code has sometimes been even better than has the SPICE code.

4. In the absence of droplet breakup, droplets penetration is greater than that with breakup models.

5. When droplet breakup occurs, the evaporation rate is greater than when no breakup is assumed.

6. The mean droplet diameter of spray decreases as the spray penetrates into the chamber. However, sufficiently away from the injection point, the spray mean diameter is relatively independent of the initial diameter of droplets.

7. The Stripping model of droplet breakup illustrates a greater rate of evaporation than the other models.

The Stripping model also predicts a more reasonable rate of penetration compared with the other models, and is in better agreement with the experimental data in high pressure ambient such as diesel engine chambers.

NOMENCLATURE

- \( C_D \): drag Coefficient
- \( C_b \): breakup Model Constant
- \( C_p \): specific Heat
- \( D \): diffusivity, Diameter
- \( D_d \): droplet Diameter
- \( DT \): time Step
- \( k \): thermal Conductivity
- \( m \): mass
- \( Nu \): Nusselt Number
- \( P \): pressure
- \( Q \): heat, Latent Heat of Evaporation
- \( R \): radius
- \( Re \): Reynolds Number
- \( S \): source Term
- \( S_w \): source Term in Gas Phase Equations
- \( t \): time
- \( U_u \): radial Velocity
- \( V \): volume
- \( V_{rel} \): relative Velocity
- \( We \): Webber Number

Greek Symbols

- \( \Gamma \): diffusivity
- \( \rho \): density

Fig. 14. The Effect of environmental pressure on the changes of Sauter mean diameter versus time (\( P=25 \) bar, \( T=573K \))
Comparison of various droplet breakup models in...

\[ \Delta \text{ increment} \]
\[ \theta \text{ void fraction} \]
\[ \mu \text{ viscosity} \]

\[ \sigma \text{ surface Tension} \]
\[ \Phi \text{ dependent Variable} \]

**Subscripts**

- bag breakup
- stripping Breakup
- droplet
- effective
- liquid
- mean

**Superscripts**

- fluctuating components, post breakup
- predicted value
- first corrected value
- second corrected value

**REFERENCES**


