ABSTRACT The authors have proposed a spray model of fuel with multi-components and reported the successful model which has the capability of the expression of the batch-distillation in this kind of fuel by applying the chemical-thermodynamics analysis that includes the liquid-vapor equilibrium. The model considers the aerodynamic action as the breakup force by use of Taylor Analogy Breakup. However, it ignores the characteristics of internal flow in the nozzle in spite of their importance. This kind of flow is generally recognized as one of the major mechanism affecting the disintegration of liquid jet discharging through nozzle holes. In particular, the cavitation generating inside the injector nozzle causes the large disturbance that accelerates the disintegration.

The paper describes the new breakup model of fuel with multi-components spray from the standpoint mentioned above. The model takes account of the energy induced through collapse and shrinkage of cavitation bubbles. The model proposed is implemented into KIVA-3V code in order to validate the effect of energy generated by the cavitation on the primary breakup of the discharging jet.

Keywords: Breakup, Cavitation, Multi-Component Fuel, Diesel Spray

1. INTRODUCTION

The atomization of liquid fuel, which controls the evaporation rate and the mixing surrounding air with fuel, is one of the ultimate performing factors of diesel engine. The current CFD simulation is a powerful tool in order to investigate these phenomena and to provide guidelines for the design of spray-combustion systems. Despite of its importance, the development of atomization model is not always completed due to the limited quality of available data in diesel spray, since it is unable to apply the measurement technique such as laser diagnostics due to the very high droplets density at the initial part [1] of the diesel spray existing near the nozzle exit.

Several models were proposed as numerical approaches [2-5] until now. However, the complexity of diesel spray does not allow these kinds of model making the accurate prediction in the case of high injection pressure. In fact, the jet breakup mechanism is well understood the case of low and medium injection pressure and it is possible to follow the aerodynamic interaction [6]. However, injection pressure is over 100MPa in an actual diesel injector, so that the discharge velocity of fuel at the nozzle outlet is quite fast as several hundreds meters per second. In this case, the flow inside injection nozzle contributes the spray characteristics itself [7-9], which probably give a significant effect on the primary breakup, initiate the subsequent droplet breakup, that is the secondary breakup and play an important role in the spray behavior. The cavitation phenomena are the important matter relating to the atomization. They increase with increasing in the injection pressure. Experimental works have confirmed that the cavitation in the injector is usually dominant factor of the atomization [10-14].

The objective of this study is to construct a new breakup scheme which is taken into account of the effect of the energy induced by the cavitation on the primary breakup and to update the model of spray with multi-components proposed in the previous authors [15, 16]. Arcoumanis and Gavaises [17] introduced, as a similar approach, the breakup model based on the cavitation under the assumption that the breakup is dominated by the behavior of bubbles outside nozzle. Nishimura and Assanis [18] considered the effect of energy emitted during the shrinkage process of bubbles on the primary breakup. The model proposed here deals with bubble behavior inside the nozzle, namely, the process of the growth, the shrinkage and the collapse processes are taken into account by applying Rayleigh-Plesset equation. The assumptions are; (1) the resultant energy generating this kind of process contributes to the enhancement of initial perturbations on the spray surface, (2) the perturbations grow under the action of aerodynamic force until they detach as the atomized droplets according to the model proposed by Huh and Gosman [4] and (3) to obtain the better prediction of the movement of spray injected by the hybrid model coupled with two kinds of breakup model as applying in the current 3D codes [17, 19-21]. The hybrid model is composed of the breakup model induced by the cavitation to compute the primary breakup and the TAB (Taylor Analogy Breakup) model [2] calculates the secondary breakup under the condition of lower Weber number.

2. MODEL CONSTRUCTION

The schematic diagram of the model is illustrated in Fig.1. It is possible for this model to analyze not only the characteristics of the cavitation phenomena but also those of flashing spray because the model is based on the bubble dynamics and it is capable of applying the model to the simulation of the process of growth, collapse and shrinkage. The authors have already proposed the model of the latter case in detailed description and presented the simulated results [16]. Thus, this paper describes the construction of
the model of the former case.

The detailed description is mentioned below.

**Bubble nucleation**

\[ N = C \cdot \exp(-\Delta t/k \Delta T) \]

**Nuclei number distribution**

\[ N(R) = C_n \cdot \log_e \left( \frac{R}{\sigma} \right)^{\frac{3}{2}} \cdot \exp \left( \frac{\left( \log R - \log \sigma \right)^2}{2 \lambda^2} \right) \]

**Bubble growth and shrinkage**

\[ R^2 + \frac{3}{2} R^2 = \frac{1}{\rho_1} \left( p_v - p_r \right) \]

\[ p_w = p_v + \left( \frac{2 \sigma}{R_0} \right) \left( R_0 \right)^{3n} - \frac{2 \sigma}{R} \cdot \frac{4 \mu R}{R} \]

**Due to shock pressure**

\[ E_{\text{collapse}} = 4/3 \pi \left( R_{\max} \right)^{\frac{3}{2}} \cdot p_{\max} \cdot N \]

where

\[ p_{\max} = p_{\gamma R_{\max}} \left( R_{\max} / R_0 \right)^{3n} - \frac{2 \sigma}{R_0} \]

**Due to bubble shrinkage**

\[ E_{\text{shrink}} = \frac{1}{2} \int_{R_{\max}}^{R_{\min}} N(R) \int_{R_{\max}}^{R_{\min}} \left( \frac{R}{R_{\max}} \right)^{\frac{3}{2} \lambda} \left( R_{\max} / R \right)^2 \cdot 4 \pi R^2 dR \]

**Criterion for primary breakup regimes**

\[ \alpha > \alpha_{\text{crit}} \quad \Rightarrow \quad \text{Flash boiling (1)} \]

\[ \alpha < \alpha_{\text{crit}} \quad \Rightarrow \quad \text{K-H instability (2)} \]

**Flash boiling**

- Model proposed by Kawano et al. \(^{16}\)
- Determination of dominant atomization scale by comparing the scale induced by nozzle flow \( L_n / \tau_n \) and cavitation bubble behavior \( L_{\text{av}} / \tau_{\text{av}} \)

**Primary breakup**

- Surface wave growth according to K-H instability theory proposed by Huh and Gosman \(^{4}\)

**Secondary breakup**

- TAB model \( (\phi=2, K=8/9) \)

**Fig.1 Schematic diagram of present model**

**Fig.2 Pressure-temperature diagram of pure substances and mixed fuel consisting of n-tridecane and n-pentane**

### 2.1 Cavitation Modeling

**Bubble growth model**

It is able to describe the growth process of spherical bubble having the infinite volume by Rayleigh-Plesset equation shown as eq. (1).

\[ \frac{R^2 + \frac{3}{2} R^2}{\rho_1} = \frac{1}{\rho_1} \left( p_v - p_r \right) \]

where \( R \) is the bubble radius, \( \rho_1 \) is the density of surrounding fluid, \( p_v \) is the pressure of fluid at the bubble surface and \( p_r \) is expressed by the following equation, respectively.

\[ p_w = p_r + \left( \frac{2 \sigma}{R_0} \right) \left( R_0 \right)^{3n} - \frac{2 \sigma}{R} \cdot \frac{4 \mu R}{R} \]

where \( p_r \) is the vapor pressure, \( p_{\gamma} \) is the initial pressure of fluid surrounding a bubble, \( R_0 \) is the initial bubble radius and \( \sigma \) is the surface tension, therefore, the term \( \left( \frac{p_r + 2 \sigma}{R_0} \right) \) expresses the pressure inside a bubble, \( n \) is polytrope index and \( \mu \) is the viscosity of surrounding fluid, respectively.

Since the present model has the capability of taking into account the vapor-liquid equilibrium of the fuel with multiple components, it connects the model of this kind of fuel previously \(^{15}\). Figure 2 shows the pressure-temperature diagram of pure substance of n-tridecan (C\(_{13}\)H\(_{28}\)) and n-pentane(C\(_{5}\)H\(_{12}\)), and the fuel mixed with both fuels. Hereinafter, the mixed fuel is called C\(_{13}/C_{5}\). The molar fraction of n-pentane in mixed fuel is selected 0.4, 0.6 and 0.8. As found in the diagram, the saturated vapor pressure line of pure substance is represented by single line, while that of mixed fuel forms two-phase region where exists liquid phase and vapor phase of both components. The pressure on the saturated liquid line is defined as a saturated vapor pressure \( p_v \) for the mixed fuel in this model.

**Bubble nucleation model**

The number, \( N \), of nuclei bubble caused by the generation of cavitation due to the sudden pressure decrease is described by the nuclei formation theory. It is expressed by the following equations:

\[ N = C \cdot \exp(-\Delta t / k \Delta T) \]

where \( C \) is the model constant, \( k \) is Boltzmann constant and \( \Delta T \) is the degree of superheat, respectively.

\[ \Delta t = 4 / 3 \pi R^2 \cdot \sigma \] \n
Referring to the constants of previous work \(^{16, 22}\), eq.(3) is rewritten as follows:

\[ N = 9.0 \times 10^{11} \exp(-5.28 / \Delta T) \]

To extend the equations to the fuel with multicomponents whose state is inside two-phase region, the number of nuclei is reduced by the following manner. When the equations mentioned above are applied to the fuel with multiple components it must consider the existence of the two-phase region. Thus, when the mole number of vapor is \( X \) in the two-phase region, it assumes that the molar fraction of the liquid phase is \( x_i \) and that of the vapor phase is \( y_i \) for each specie \( i \) at given pressure and temperature. As a result, the total number of mole containing both phases is written as \( \sum_{i=1}^{n} \left( y_i + x_i \right) \).

NIST program \(^{23}\) installed into the model of multicomponents spray calculates \( K \) factor \( K_{vap} \) regarding vapor-liquid equilibria. Consequently, the correlation factor, \( C_{vap} \), for the nuclei number is given by
\[ C_{np} = X \sum_{i=1}^{n} (v_i + y_i / K_i) \]  

(6)

The nuclei number is given by multiplying eq.(5) by \( C_{np} \).

The distribution function of nuclei number distribution function, \( N(R) \), proposed by Liu et al. [24] is as follows

\[ N(R) = C_n \frac{\log e}{(2\pi)^{3/2}} \exp \left( -\frac{(\log R - \log \xi)^2}{2\lambda^2} \right) \]  

(7)

where \( C_n \) is the nuclei concentration found from eq.(5) and eq.(6) for a given bubble radius. By adjusting the value of \( \xi \) and that of \( \lambda \), it is possible for the distribution function to be most suitable form. In this model, \( \xi \) and \( \lambda \) are adjusted to 5.0e-4 and 0.5, respectively. These give the well-known distribution function of nuclei number distribution, which is used in Blasius equation, it is possible to predict the nuclei number increases exponentially.

Consequently, the nuclei number increases exponentially with decrease in the radii of nuclei bubbles. Consequently, the discharge coefficient, \( C_d \), at vena contracta is assumed to be 0.62 since the shape of the orifice is the sharp edge [29]. Thus, it is capable of obtaining the static pressure, \( p_s \), there by solving simultaneously both the equations of the continuity and the Bernoulli equation. However, the solution of \( p_s \) often results less than 0 [Pa] for the high pressure injection, thus, \( P_c \) is assumed to be zero in this case. The pressure increases due to the decrease in the flow velocity at the end of vena contracta. The static pressure at the end of vena contracta is defined by applying the Blasius equation relating to the wall friction from the nozzle exit to the location mentioned above. Then, the pressure falls off linearly with the distance from the end of vena contracta to the nozzle exit. Additionally, it is assumed that bubbles travel according to the liquid velocity and have the pressure defined as shown above. The bubbles stay several times longer than the surrounding flow at the contraction region when the recirculation flow is assumed.

The example of the temporal change in bubble radii whose initial values are 1, 3, 6, 9, 12 and 15[\( \mu m \)], respectively, for the mixed fuel of C13/C5 of which the molar fraction of n-pentane, \( X_{C5} \), is 0.8 is shown in Fig.3 (a). The pressure distribution of each mixing fraction is also depicted in Fig.3 (c). The logarithmic axis indicates the velocity reaches the maximum locally. The vena contracta is assumed to be located at the one-half of the orifice diameter from the nozzle inlet. The contraction coefficient, \( C_d \), at vena contracta is assumed to be 0.62 since the shape of the orifice is the sharp edge [29]. Thus, it is capable of obtaining the static pressure, \( p_s \), there by solving simultaneously both the equations of the continuity and the Bernoulli equation. However, the solution of \( p_s \) often results less than 0 [Pa] for the high pressure injection, thus, \( P_c \) is assumed to be zero in this case. The pressure increases due to the decrease in the flow velocity at the end of vena contracta. The static pressure at the end of vena contracta is defined by applying the Blasius equation relating to the wall friction from the nozzle exit to the location mentioned above. Then, the pressure falls off linearly with the distance from the end of vena contracta to the nozzle exit. Additionally, it is assumed that bubbles travel according to the liquid velocity and have the pressure defined as shown above. The bubbles stay several times longer than the surrounding flow at the contraction region when the recirculation flow is assumed.

The other purpose of nozzle flow model is to provide the pressure distribution inside the nozzle. Nevertheless, the details are unknown. Therefore, the assumption relating to this kind of model is set for simplification as described below. At the vena contracta of the nozzle, the pressure drops shows the local minimum, at the same time, the velocity reaches the maximum locally. The vena contracta is assumed to be located at the one-half of the orifice diameter from the nozzle inlet. The contraction coefficient, \( C_d \), at vena contracta is assumed to be 0.62 since the shape of the orifice is the sharp edge [29]. Thus, it is capable of obtaining the static pressure, \( p_s \), there by solving simultaneously both the equations of the continuity and the Bernoulli equation. However, the solution of \( p_s \) often results less than 0 [Pa] for the high pressure injection, thus, \( P_c \) is assumed to be zero in this case. The pressure increases due to the decrease in the flow velocity at the end of vena contracta. The static pressure at the end of vena contracta is defined by applying the Blasius equation relating to the wall friction from the nozzle exit to the location mentioned above. Then, the pressure falls off linearly with the distance from the end of vena contracta to the nozzle exit. Additionally, it is assumed that bubbles travel according to the liquid velocity and have the pressure defined as shown above. The bubbles stay several times longer than the surrounding flow at the contraction region when the recirculation flow is assumed.
surface tension acting at the bubble wall and the balance of the difference between the internal pressure of the bubble and the surrounding fluid pressure are considered it is clear that the smaller nuclei grow and shrink faster. Fig.3 (b) demonstrates the comparison of the calculated result in the case of change in the fuel compositions. The higher molar fraction of n-pentane is, higher vapor pressure is, hence bubbles grow rapidly. The reason is why the saturated vapor pressure of n-pentane is higher than that of n-tridecane. In addition, the mixing n-Pentane causes the decrease in the surface tension and the viscosity as shown in Table2 (listed later), which acts on the inhibition of the bubble growth and its shrinkage, as a result, the bubble growth is promoted.

Due to lack of the accurate information on $R_{brk}$, the present study defined it as $1 \text{ [um]}$. The effect of the nucleus radius on the bubble collapse energy is shown in Fig.5. All the data are normalized by the energy at the molar fraction of n-pentane, $X_{c5}$, equal to 0.8 whose nucleus radius is $1 \text{ [um]}$. The fuel containing the higher concentration of n-pentane generates the higher energy because of its higher saturated vapor pressure that causes much number of nuclei bubbles and the rapid growth of them. The trend is different when the fuel composition is varied. In the case of $X_{c5}$=0.8, the higher saturated vapor pressure makes bubbles grow rapidly even in the case of the smaller nuclei bubble. As a result, the smaller bubbles contribute to the total energy emerged. In the case of $X_{c5}$=0.4, the energy is mainly dominated by larger one. It is noticed that the collapse energy emerged by $X_{c5}$=0.0 is not appeared in Fig.5 since the value is negligibly small due to its poor volatility.

The other energy, $E_{shrink}$, generated by the movement of surrounding fluid during the shrinkage process is taken into account. The energy is shown in the following eq.(13):

$$E_{shrink} = \frac{1}{2} \rho V \int N(R) \sum_{i} \int_{R_{rlshrink}}^{R_{max}} R^{5/4} \left( \frac{R_{brk}}{r} \right)^{2} \cdot 4\pi r^{2} dr ,$$

(13)

where $i$ indicates the time when a bubble reaches the maximum radius, $j$ is the time when it collapses and $r$ shows the bubble radius. Since shrinkage velocity of bubbles, $V$, the velocity, $v$, of surrounding fluid are in inverse proportion to their surface area, $v$ was given as follows:

$$v/V = \frac{R_{max}^{2}}{r^{2}} .$$

(14)

By substituting $\rho$ into eq.(14) into eq.(13), the result is

$$E_{shrink} = \frac{1}{2} \rho \int N(R) \sum_{i} \int_{R_{rlshrink}}^{R_{max}} \left( \frac{R_{brk}}{r} \right)^{2} \cdot 4\pi r^{2} dr .$$

(15)

2.2 Spray Modeling

The numerical calculations were performed using the JIWA-3V code [32] which was upgraded by Kawano et al. [15] with modifications to the breakup model.

**Primary breakup**

To account for the effect of the liquid jet turbulence on the primary breakup, the phenomenological model is
constructed based on the approach proposed by Huh and Gosman [4]. They assume that the turbulence fluctuation in the liquid discharging from the nozzle is drawn from the initial surface perturbation that grows exponentially by Kelvin-Helmholtz instability due to the interaction with surrounding gas.

The effect of turbulence is supposed that the atomization length scale, $L_{At}$, is proportional to the turbulence length scale, $L_{Tt}$. The former and the wavelength of surface perturbation, $L_m$, are expressed by the following function of one of turbulence.

$$L_{At} = C_2L_{Tt}, \quad L_{Wf} = C_3L_{Tt},$$  \hspace{1cm} (16)

where $C_2$ is 2.2 in this model.

From the hypothesis that a half of the surface wave is detached as a secondary droplet [33], the relation between both constants is expressed by follows:

$$C_2 / C_3 = 0.5.$$  \hspace{1cm} (17)

Due to the lack of turbulence information in the injector nozzle, $L_{Tt}$ and the turbulence time scale, $\tau_{Tt}$, are obtained from the following equations:

$$L_{Tt} = C_{k} \varepsilon_{\text{inlet}}^{3/2} \varepsilon^1,$$  \hspace{1cm} (18)

$$\tau_{Tt} = C_{\mu} \varepsilon_{\text{inlet}}^{-1},$$  \hspace{1cm} (19)

$$k_f = u_{\text{m}}^2 \frac{1}{8 \nu / \mu_{L}} \frac{1}{C_{\mu}^2 - \varepsilon^1},$$  \hspace{1cm} (20)

$$\varepsilon_{\text{inlet}} = \frac{C_{\alpha} u_{\text{m}}}{2 C_{\alpha} L_{Tt}^2 - \varepsilon_{\text{inlet}}^1},$$  \hspace{1cm} (21)

where $C_{k}$ is the constant of 0.09 given by $k-\varepsilon$ model, $C_{\mu}$ is 0.27. $u_{\text{m}}$ is the mean effective velocity predicted by $u_{\text{a}}$ and $C_{\alpha}$. $C_{\alpha}$ is found from eq.(10). $C_{\alpha}$ includes a cavitation effect on the turbulent flow except for the energy induced by the bubble shrinkage and collapse.

The atomization time scale, $\tau_{At}$, is the linear combination of the turbulence time scale, $\tau_{Tt}$, and wave growth time scale, $\tau_{Wf}$, such as

$$\tau_{At} = C_1 \tau_{Tt} + C_4 \tau_{Wf}.$$  \hspace{1cm} (22)

The constants $C_1$ and $C_4$ are set equal to 1.7 and 0.4, respectively. $\tau_{Wf}$ is calculated from following K-H instability theory.

$$\tau_{Wf} = \sqrt{\frac{\sigma}{\rho_L - \rho_g}} \left( \frac{u}{L_{Wf}} \right)^2 \left( \frac{C_{\mu}^2}{C_{\mu}^2 - \varepsilon_{\text{inlet}}^1} \right)^{0.5},$$  \hspace{1cm} (23)

where $\rho_L$ and $\rho_g$ indicate the density of liquid and gas. And $u$ is relative velocity between the spray and the surrounding gas.

The present model, additionally, assumes that the cavitation bubbles also cause the turbulent flow as described above. The schematic diagram of the length scale, $L_{Bk}$, induced by the cavitation bubbles is illustrated in Fig.6. Supposing that the bubbles are gathered along the wall of nozzle, $L_{Bk}$ is defined as the difference between the maximum thickness of bubbles and that just before their collapse. Thus, $L_{Bk}$ is expressed as

$$L_{Bk} = 1/2 d_{Bk} \left( 1 - \sqrt{1 - \alpha_{\text{max}}} \right),$$  \hspace{1cm} (24)

where $\alpha_{\text{max}}$ is the void fraction when it reaches the maximum. The atomization length scale induced by the cavitation bubbles, $L_{Atr}$, is also obtained by eq.(16). The two kinds of energy calculated by eq.(12) and (15) model transformed into those of turbulent kinetic energy, $E_{\text{collapse}}$ and $E_{\text{shrink}}$ as follows:

$$k_{\text{collapse}} = E_{\text{collapse}} / Q, \quad k_{\text{shrink}} = E_{\text{shrink}} / Q,$$  \hspace{1cm} (25)

where $Q$ is the injected quantity in terms of a time step. Assuming isotropic turbulence, the turbulent fluctuation at the nozzle exit, $u_{\text{e}}$, can be estimated by the following equation:

$$u_{\text{e}} = \sqrt{2/3 (k_{\text{collapse}} + k_{\text{shrink}})}.$$  \hspace{1cm} (26)

The turbulence time scale, $\tau_{At}$, induced by the collapse and the shrinkage of bubble is obtained from the following eq.(27):

$$\tau_{At} = L_{Bk} / u_{\text{e}}.$$  \hspace{1cm} (27)

The present model hypothesizes that both kinds of the fluctuation induced by the internal flow and the cavitation derive the primary breakup. During this event, the child droplets are flying from a parent droplet as implemented by Reitz [34]. A random number is applied to determine the radii of child droplets under the assumption that the radius of spray droplets shows the distribution. The Sauter mean diameter, SMD, of child droplets is assumed to be in proportion to the wavelength of liquid core surface wavelength. The temporal change in the radius, $r_{\text{sd}}$, of parent droplets is given as follows:

$$dr_{\text{sd}} / dt = -C_r L_A / t_{\tau},$$  \hspace{1cm} (28)

where $t$ is the time, $C_r$ is the constant taken equal to 0.02. The number of new parent droplets is as same as that before the generation of child droplets. The radius of new parent droplet and number of the child droplets are found by solving simultaneously the equation of mass conservation equation and the conservation of SMD calculated from eq.(28) as the similar way of Su et al. [35]. New child droplets are created and counted to the succeeding equation and the conservation of SMD calculated from eq.(28) as the similar way of Su et al. [35]. New child droplets are created and counted to the succeeding computation when they have the sufficient mass. The threshold is that the mass of child droplets reach or exceed 3% of that of the parent droplet. The trajectory of each child droplet generated is estimated by adding the turbulent fluctuation $L_{L} / \tau_{At}$ orthogonally to that of parent droplet.

Secondary breakup

TAB model is employed as the model of secondary breakup. This method solves the oscillation and the distorting motion of fuel droplets as the displacement of droplet surface from its sphere. Sauter mean radius of atomized particles, $r_{32}$, is evaluated through the energy conservation of particle before and after the disintegration process. The ratio of the total energy in distortion and oscillation to that in the fundamental mode is denoted $K$. It
is justified to be \( K = 11/12 \). And the degree of freedom for the size distribution function is set to be 6 by referring the previous study [36]. Weber number \( (We = \rho_d a^2 / \sigma, d_c \) droplet diameter) is used as the criterion to distinguish the atomization regime and the critical Weber number, \( We_{cr} \), is set equal to 1000 according to the references [19] and [21].

### 3. NUMERICAL CONDITION

The computation results are compared the experimental ones. The experimental condition and numerical condition are summarized in Table 1.

#### Table 1 Experimental and numerical condition

<table>
<thead>
<tr>
<th></th>
<th>Exp.</th>
<th>Pred.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient gas [Vol.%]</td>
<td>( \text{N}_2: 100 )</td>
<td>He: 76.3 Ar: 23.7</td>
</tr>
<tr>
<td>Compression ratio [-]</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>Initial cylinder pressure [MPa]</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>Start of injection [deg. C.A. BTDC]</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Ambient temperature [K]</td>
<td>666</td>
<td>293</td>
</tr>
<tr>
<td>Ambient pressure [MPa]</td>
<td>1.88</td>
<td>1.88</td>
</tr>
<tr>
<td>Ambient density [kg/m³]</td>
<td>9.66</td>
<td>9.66</td>
</tr>
<tr>
<td>Hole diameter [mm]</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Hole length [mm]</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Injection pressure [MPa]</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Fuel temperature [K]</td>
<td>333</td>
<td>333</td>
</tr>
</tbody>
</table>

#### Table 2 Fuel Properties

<table>
<thead>
<tr>
<th></th>
<th>( X_{CS} = 0 )</th>
<th>( X_{CS} = 0.4 )</th>
<th>( X_{CS} = 0.6 )</th>
<th>( X_{CS} = 0.8 )</th>
<th>( X_{CS} = 1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density* [kg/m³]</td>
<td>766</td>
<td>740</td>
<td>718</td>
<td>683</td>
<td>626</td>
</tr>
<tr>
<td>Viscosity* [μPa s]</td>
<td>1794</td>
<td>908</td>
<td>617</td>
<td>398</td>
<td>228</td>
</tr>
<tr>
<td>Surface tension* [N/m]</td>
<td>0.0277</td>
<td>0.0256</td>
<td>0.0237</td>
<td>0.0207</td>
<td>0.0162</td>
</tr>
<tr>
<td>Saturated vapor pressure** [MPa]</td>
<td>0.0001</td>
<td>0.075</td>
<td>0.118</td>
<td>0.165</td>
<td>0.215</td>
</tr>
</tbody>
</table>

* at 293K, 0.101 MPa ** at 333K

The experiments are conducted in the rapid compression and expansion machine having 100 [mm] bore. The temperature of cylinder wall is kept at 353 [K]. To avoid ignition of the fuel injected, the combustion chamber was filled with nitrogen gas. On the other hand, the prediction is performed under the condition of room temperature. The ambient gas in the computation is the mixture of the argon gas and the helium gas whose pressure and density are the same as those in the experiments. However, the viscosity is different each other.

The injection timing is 25 [deg. BTDC]. The electrically controlled common-rail injection system is used in the experiments. The fuel in it was pressurized up to 70 [MPa]. The injection nozzle has a single-hole. Its diameter is 0.15 [mm] and the length is 0.8 [mm], respectively. The fuel tested is C13/C5 composed of n-pentane and n-tridecane. The molar fraction, \( X_{CS} \), of the former fuel is set to be 0.0, 0.4, 0.6 and 0.8 as described in Fig.2. Their physical properties are listed in Table 2.

### 4. RESULTS AND DISCUSSION

KIVA-3V code with the breakup model induced by the cavitation is employed to simulate a fuel spray for several kinds of mixed fuel.

![Fig.7 Comparison of spray images measured and predicted](image)

The spray images measured and predicted at the end of injection are compared in Fig.7. The measured ones are taken by the shadowgraph photography. By evaluating the region with higher contrast region existing near the nozzle exit in shadowgraph images, the higher the molar fraction, \( X_{CS} \), of n-pentane is, the shorter the liquid area where the liquid phase is dominant is. The image of \( X_{CS} = 0.8 \) shows the trend clearly. It is marked that it is capable of predicting the overall shape of the fuel spray.

The temporal change in the spray tip penetrations measured and calculated for each \( X_{CS} \) is shown in Fig.8. The experimental results indicate the difference in the spray tip penetration due to \( X_{CS} \). The numerical results show the trend of the experimental data. The spray in the case of higher \( X_{CS} \) tip penetration is the slightly short length although the prediction is performed under the room temperature. The fact is almost the same so that of the experimental results. Figure 9 is the distribution SMD distributions derived from Fig.7 as a function of the distance from nozzle exit. SMD is decreases when the
location is further from the nozzle outlet. $X_{C5}$ significantly affects on SMD near the nozzle outlet. The differences in SMD become relatively smaller despite of kinds of $X_{C5}$ when the location is over around 40 [mm], that is, it corresponds to the mid region of spray. The secondary breakup is dominant there. When the location is over about 60 [mm], in other words, the location reaches the spray tip region, SMD increases in spite of $X_{C5}$. The trend at the mid region and the spray tip region is caused by the fact that the density of n-tridecane is larger than that of n-pentane, as a result, the former droplet has the larger diameter and momentum and it goes farther from the nozzle outlet.

![Fig.8 Comparison of measured spray tip penetration to spray tip penetration predicted by present model for each mixing fraction](image1)

![Fig.9 Effect of molar fraction of n-pentane on distribution of local SMD as a function of distance from nozzle exit](image2)

Figure 10 compares the effect of molar fraction, $X_{C5}$, of n-pentane on the droplets number distribution. The peak appears at the smaller diameter as the increase in $X_{C5}$. Due to lack of the experimental data, the accuracy of the droplet number distributions is not known well. However, the trends predicted by the present model might be reasonable. Because the facts that high number of smaller droplets yields much fuel vapor than low number of larger ones. Generally speaking, the number density is affected by $X_{C5}$ due to the existence of the cavitation phenomena.

5. CONCLUSION

The following conclusions are drawn from this work:
(1) The two kinds of breakup model are proposed by considering the existence of cavitation bubble.
(2) It is able to solve the shrinkage and collapse of bubbles by use of Rayleigh-Plesset equation.
(3) The cavitation bubble doesn’t grow inside nozzle in the case of pure substance of n-tridecane due to its low volatility. It is likely that the cavitation phenomena don’t occur in the case of using gas oil with low volatility.
(4) It is possible to simulate the spray growth by the combination of this equation and KIVA-3V.
(5) It is capable of predicting the spray growth, in other words, the spray tip penetrations, SMD and the droplets number density of mixed fuel composed of n-pentane with high volatility and n-tridecane with low one.
(6) The cavitation bubble collapsed affects the atomization itself. The phenomena are affected by the molar fraction of n-pentane. Thus, the atomization of pure substance of n-tridecane is not enhanced by its energy.
(7) The scheme proposed is the first step. Thus, it is required the further validation and optimization.

6. NOMENCLATURE

- $A$ area
- $C$ constants or coefficient
- $C_{\mu}$ constant in $k-\varepsilon$ model (=0.09)
- $d$ diameter
- $E$ energy
- $k$ kinetic energy
- $K$ energy ratio in TAB model
- $K_{inlet}$ inlet loss coefficient
- $K_{\varepsilon}$ constant in primary breakup model (=0.27)
- $l$ length
- $L$ length scale in primary breakup model
- $N$ number of bubbles
- $p$ pressure
- $p_v$ saturated vapor pressure
- $r, R$ radius
- $Q$ injected mass per a time step
- $t$ time
- $u$ velocity
- $u'$ turbulent fluctuation
\( x_i \) mole fraction of \( i \) component in liquid phase

\( y_i \) mole fraction of \( i \) component in vapor phase

**GREEK SYMBOLS**

\( \alpha \) void fraction

\( \varepsilon \) dispersion rate

\( \rho \) density

\( \sigma \) surface tension

\( \tau \) time scale in primary breakup model

**SUBSCRIPTS**

\( b \) bubble

\( c \) cavitation

\( d \) droplet

\( g \) gas

\( l \) liquid

\( m \) mean

\( n \) nozzle

\( t \) turbulence

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8. REFERENCES


