Modeling on Diesel Spray Impinging on Flat Wall

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ABSTRACT

This paper presents a model analysis on the dispersion process of a diesel spray impinging on a flat wall with high temperature to simulate the spray/wall interaction process inside diesel engines.The fuel spray was injected into high-pressure and high-temperature atmosphere,and impinged on the wall with elevated temperature of 550 K. Here, the temperature of the wall surface T_w was above the saturated temperature T_{sat} of the fuel droplet, then submodels concerning the heat transfer from the wall to the droplet, the breakup behavior of impinging droplets owing to the boiling at liquid-solid interface and a dispersion process of breakup droplets were considered. New submodels were incorporated into KIVA original code. Then, it was found that 2-dimensional calculated results by new submodels had qualitative correspondence with the experimental one, comparing with that by KIVA original code.

INTRODUCTION

In small type high-speed diesel engines, the injected fuel spray impinges on the piston cavity surface due to the short distance between an injection nozzle and cavity surface. The behavior of the impinging spray has a great influence on the dispersion of fuel, the evaporation and mixture formation process, and further on the combustion process.

The authors have presented spatial and temporal distributions of the fuel droplets density in a non-evaporative impinged spray on a flat wall, by use of a laser extinction method applying computed tomography(1)~(3). Here, the fuel spray was injected through a single hole nozzle into quiescent room-temperature atmosphere. The authors have also applied an exciplex fluorescence method to an evaporative impinged spray on a flat wall with high surface temperature , inside the quiescent atmosphere of nitrogen with high-pressure and high-temperature(4). Then, clear 2-dimensional images for vapor and liquid phases were obtained simultaneously, applying the naphthalene/N,N,N',N'tetramethyl-P-phenylene diamine (TMPD) exciplex system. Further, vapor concentration was assessed quantitatively by applying Lambert-Beer's law into measured fluorescence intensity in vapor phase(5).

In connection with the numerical analysis on the diesel spray, engine computer code, KIVA (6), was developed to simulate the combustion process. In the spray model of KIVA original code, actual phenomena of the dispersion process in impinging spray on the wall could not be assessed since all impinging droplets, called as parcel, stick on the wall. Therefore, Naber & Reitz(7) have proposed a new submodel on droplet/wall interaction at the impingement including a reflect model (droplets rebound) and liquid jet analogy mode (wall jet). However, when we calculate the behavior of the spray by this spray impingement model, impinging droplets almost disperse in radial direction on the wall as a wall jet owing to their higher Weber number. Thus, it has often been pointed out that calculated droplets distribution near the wall, especially the dispersion in upward direction on the wall, do not agree well with experimental results.

In this study, a new submodel describing the fuel dispersion process in the impinging diesel spray on the flat wall surface with high temperature was proposed by referring to the previous experimental study on the droplet impingement.

SPRAY/ WALL IMPINGEMENT MODEL

Spray Impingement Model by Naber & Reitz

Wachters et al.(8) have investigated on the behavior of a water drop impinging vertically on a flat wall with high surface temperature, and suggested that Weber number ($W_e=\rho_f \cdot v_i^2 \cdot d_i/\sigma$) of the impinging droplet had direct effect upon a drop reflection mode on the surface with the temperature range of film boiling state. And then, in the case of $We \geq 80$, the impinging droplet just spreads as a film flow on the wall surface, and it rebounds from the wall. Afterwards, Naber & Reitz(7) have formulated the relation between Weber number of the impinging droplet We_{in} and that of the rebounding droplet We_{out} , referring to the results by Wachters et al., then devised a spray impingement model including both the reflection and the wall jet mode. This model was incorporated into KIVA code, and the calculated results was compared with the experimental results(9). Figure 1 shows spray impingement model proposed by Naber & Reitz. In this study, this model was just applied to estimate the rebounding direction and velocity of droplets in the case of $We<80$ as mentioned later, thus the droplet dispersion process such as a reflect and a wall jet was not considered here.

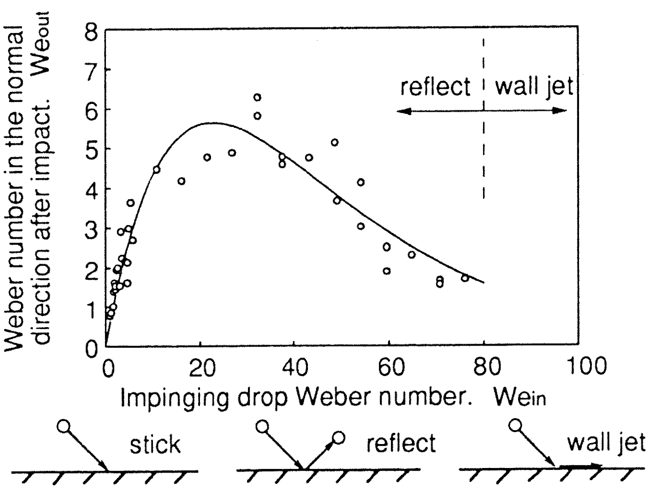


Fig.1 Spray impingement model by Naber & Reitz (7)

New Models on Spray Impingement

In this study, new models concerning the spray/wall interaction process were proposed by considering the change in the state at liquid-solid interface with surface temperature, on basis of several experimental results. Thus, in the analysis, the case that T_w was less than T_{sat} of the fuel droplet ($T_w<T_{sat}$), and the case where T_w was above T_{sat} ($T_w \geq T_{sat}$), were distinguished as summarized in Fig.2.

In the former case of $T_w<T_{sat}$, submodels on fuel film formation, film breakup process and dispersion of the breakup droplets were considered. We can estimate the spray dispersion process of non-vaporizing spray and of the case of T_w is relatively low such as the starting or light load operations in the engine, by use of this analytical model.

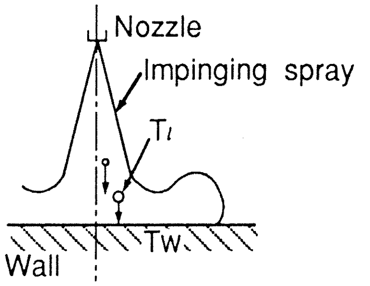
In the latter one of $T_w \geq T_{sat}$, submodels on heat transfer process from the wall surface to the droplets, breakup process of impinging droplets due to the boiling phenomena and dispersion process of breakup droplets were considered anew as shown in Fig.3,on the basis of previous experimental results by the authors(10)~(13). We can estimate the spray dispersion of vaporizing spray and of the case of T_w is high such as heavy load operation in engines, by this model.

In this paper, we present a model analysis on the dispersion process of a diesel spray impinging on a flat wall with high temperature.

SPRAY IMPINGEMENT MODEL ON HIGH - TEMPERATURE WALL

Heat Transfer Model

In the case that the droplet impinges on a dry hot surface, the impinged droplet spreads as a fuel film in radical direction on the wall for a certain period, and thereafter the film shrinks and it rebounds or it breaks up



Tw:Wall surface temperature

Tl : Temperature of impinging droplet

Tsat:Saturated temperature of fuel droplet

I $T_w<T_{sat}$: Nonvaporizing spray

(i) Model on fuel film formation on wall
(ii) Model on fuel film breakup due to impinging droplet after film formation
- Assumption on breakup droplets diameter and breakup volume

(iii) Model on dispersion process of breakup droplets

II $T_w \geq T_{sat}$: Vaporizing spray (In this paper)

(i) Model on heat transfer from wall to impinging droplet
- $Q=\alpha \cdot S \cdot \tau \cdot (T_w - T_l)$
- Assumption on droplet contact area S and residence time τ on wall

(ii) Model on breakup of impinging droplet due to boiling phenomena at liquid - solid interface
- Assumption on breakup droplets diameter

(iii) Model on dispersion process of breakup droplets

Fig.2 New models on spray impingement in this study

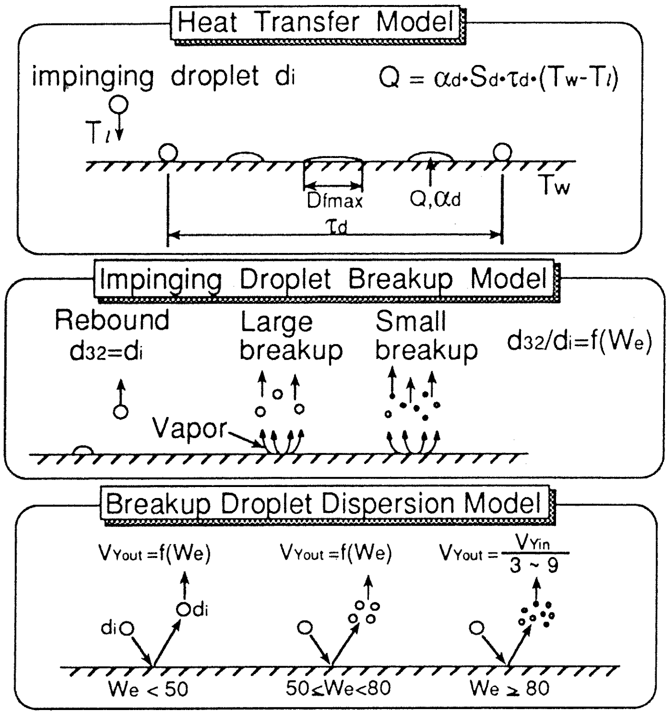


Fig.3 Spray impingement model on high - temperature wall

into small droplets as shown in Fig.3, since vapor blows through the film (10)~(12). And in this analysis case, temperature T_l of the impinging droplet is lower than that of wall surface T_w, then heat is transferred from the surface to the film formed on the surface during the residence time τ_d of the film. This heat transfer Q per a droplet is given by the following equation.

$$Q = \alpha_d \cdot S_d \cdot \tau_d \cdot \Delta T \qquad (1)$$

Assuming the heat is supplied for just heating the droplet, the increase in droplet temperature ΔT_l is shown in the following equation.

$$\Delta T_l = \frac{Q}{M \cdot C_p} = \frac{\alpha_d \cdot S_d \cdot \Delta T}{M \cdot C_p} \qquad (2)$$

Here, unknown quantities such as α_d, S_d and τ_d are estimated as follows.

Averaged heat transfer coefficient α_d The authors (13) have previously reported on the heat transfer characteristics of impinging water drops upon a hot surface. Now in this analysis condition, the superheating degree ΔT_{sat} is 41[K] for the surface temperature of T_w=550 [K] and the saturated temperature T_{sat}=509 [K] of n-Tridecane. Therefore, α_d is approximated to 10 [kw/(m^2 · K)] from the results.

Averaged contact area S_d The authors have also investigated (12) on the deformation process of the impinged droplet, and summarized that the maximum diameter D_{fmax} of the film flow spread in the radical direction could be indicated by the following equation as a function of Weber number We_{in} of the impinging droplet, in the case of ΔT_{sat}=100 [K].

$$D_{fmax} = (1 + 0.463 \cdot We_{in}^{0.345}) \cdot d_i \qquad (3)$$

Then, the averaged contact area S_d is assessed approximately by the relation of $S_d = (\pi/4) \cdot D_{fmax}^2$.

Residence time τ_d The residence time τ_d of the droplet as a film state on the wall surface could be estimated by the first-order vibration period τ_r of a free oscillating droplet proposed by Rayleigh as follows (12),(13).

$$\tau_r = \pi \cdot \sqrt{\rho_f \cdot d_i^3 / (16 \cdot \sigma)} \qquad (4)$$

However, in the case of higher Weber number, τ_d obtained by experiments (12) became shorter than the calculated value of τ_r attributed to the film breakup, though the experimental result of τ_d was consistent well with τ_r in the case of We<80. Then, in this analysis, the time of τ_d is given by following equations from the experimental results (12).

$$\left.\begin{aligned} W_e < 80 &: \tau_d = \tau_r = \pi \cdot \sqrt{\rho_f \cdot d_i^3 / (16 \cdot \sigma)} \\ W_e \geq 80 &: \tau_d = \frac{\tau_r}{2} = \pi \cdot \sqrt{\rho_f \cdot d_i^3 / (64 \cdot \sigma)} \end{aligned}\right\} \qquad (5)$$

This residence time τ_d is just considered in heat transfer calculation. And in the droplet breakup model, the time of τ_d is not considered exactly to simplify the calculation, on the assumption that τ_d is equivalent to one time step in calculation.

Impinging Droplet Breakup Model

The authors have previously reported on breakup behavior of impinging water droplet on the heated hot surface above the liquid saturated temperature T_{sat}, on the variation of droplet Weber number and the surface temperature T_w (10)~(13). In those studies, it was revealed that the breakup form due to the boiling phenomena and Sauter mean diameter of breakup droplets were dependent upon both Weber number and the surface temperature T_w.

Figure 4 shows the relation between Weber number of the impinging droplet and diameter ratio d_{32}/d_i, in the case of T_w=473 [K].In the result in Fig.4, the superheating degree ΔT_{sat} of the wall surface for the droplet saturated temperature T_{sat} is 100 [K], while the degree of ΔT_{sat} in this analysis corresponds to 41 [K]. Though there is some difference in the value of ΔT_{sat}, let us now assume that the breakup process could be estimated by the relation shown in Fig.4 , since the

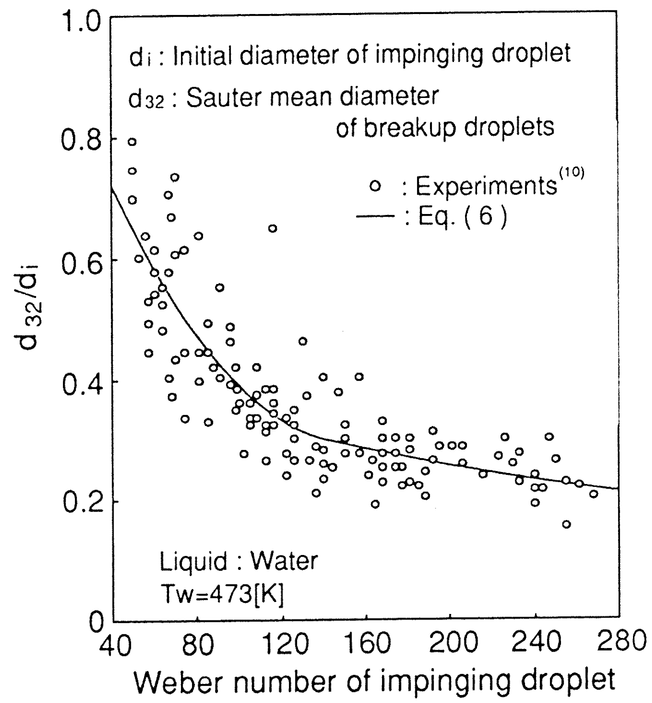


Fig.4 Relation between Weber number of impinging droplet and diameter ratio of d32 / di (10)

phenomena under both temperature ranges correspond to nucleate boiling.

From the relation in Fig.4, Sauter mean diameter d_{32} of droplets can be approximately expressed by following equations as function of Weber number.

$$\left.\begin{array}{l} \bullet\ W_e < 50 : d_{32} = d_i \\ \bullet\ 50 \leq W_e < 140 : \\ d_{32} = (1.07 - 1.01 \times 10^{-2} \times W_e + 3.29 \times 10^{-5} \times W_e{}^2) \cdot d_i \\ \bullet\ 140 \leq W_e < 300 : \\ d_{32} = 0.416 \times 10^{(-1.02\,\text{¥}\,10^{-3}\text{¥}\,W_e)} \times d_i \\ \bullet\ W_e \geq 300 : 0.2 \times d_i \end{array}\right\} \quad (6)$$

Breakup Droplet Dispersion Model

From the relation in Fig.1, W_{eout} of rebounding droplet can be approximated by following equation as a function of W_{ein} of impinging droplet.

$$\left.\begin{array}{l} W_{eout} = 0.678 \cdot W_{ein} \cdot \exp(-4.415 \times 10^{-2} \cdot W_{ein}) \\ W_{ein} = \dfrac{\rho_f \cdot V_{Yin}{}^2 \cdot d_i}{\sigma} \end{array}\right\} \quad (7)$$

Where, V_{Yin} is the velocity component of impinging droplet in perpendicular direction against the wall. Accordingly, the rebounding velocity V_{Yout} of the droplet in vertical direction is expressed as follows from spray impingement model by Naber&Reitz (7).

$$\left.\begin{array}{l} W_{ein} < 80 : V_{Yout} = -\left(W_{eout} \cdot \dfrac{\sigma}{\rho_f \cdot d_i}\right)^{1/2} \\ W_{ein} \geq 80 : V_{Yout} = 0 \end{array}\right\} \quad (8)$$

Here, a mass and a momentum of the droplet are conserved during the process of droplet impingement and its reflection.

We also apply this model to dispersing velocity in the case of We<80. However, in this analysis here, impinging droplet breaks up into small droplets in higher W_e number region and they must be dispersed in both upward and radial direction, being different from the wall jet model with $V_{Yout} = 0$. Then, the dispersing velocity of breakup droplets was measured from our previous experimental results (11),(12), as a result, it was revealed that the dispersing velocity V_{Yout} in upward direction lies in the range from one-third to one-ninth of the impinging velocity V_{Yin}. Therefore, in the range of $W_{ein} \geq 80$, the velocity of V_{Yout} is given as follows.

$$W_{ein} \geq 80 \ : \ V_{Yout} = V_{Yin} / \gamma \quad (9)$$

Where, γ is the constant ranged from 3 to 9.Here, the constant γ is provided arbitrarily for individual parcel including the breakup droplets.

COMPUTATIONAL RESULTS AND DISCUSSION

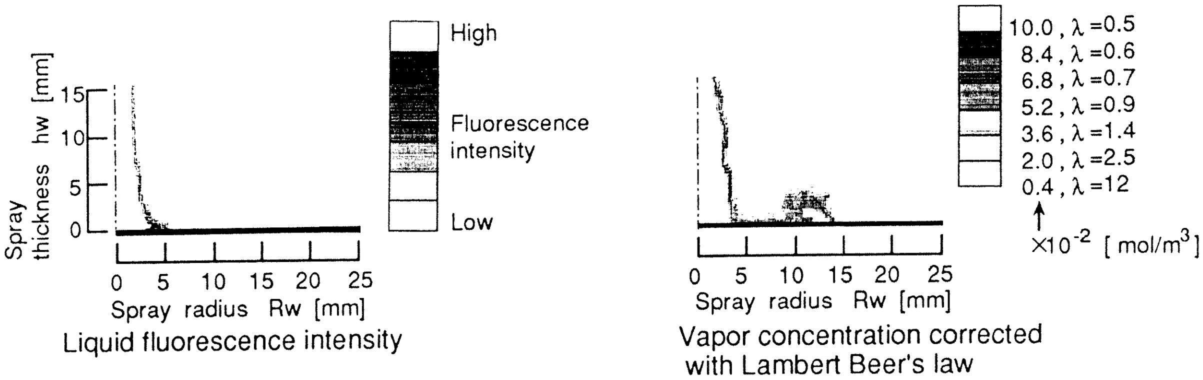
In the analysis of the spray impingement on the high-temperature wall, we considered correspondingly the evaporative spray under high-temperature and high-pressure field of nitrogen. Thus, a transient spray of n-Tridecane was injected from a hole nozzle, and impinged vertically on the flat wall with 550 [K] in surface temperature Tw. In this experiment, the vapor and the liquid phases inside the spray were separated by naphthalene/TMPD exciplex system, and further vapor concentration was assessed quantitatively by applying Lambert-Beer's law(4),(5). Here, the thickness of the laser light sheet was about 0.2 [mm]. The analytical calculation was performed using the new model, under the conditions shown in Table 1.

Figure 5 shows the calculation results on spatial distributions of a droplet parcel and excess air ratio in vapor phase in the case of elapsed time from injection start t=1.2 [ms]. Experimental results on liquid fluorescence intensity and the vapor concentration represented with excess air ratio λ inside the cross section of the spray containing its central axis are shown in Fig.5 (a).In the results by KIVA original code of Fig.5 (b), impinged droplets almost stick to the wall surface in the same manner as the impingement on the low-temperature wall, and the existence of vapor is confirmed merely in the region of apparently close to the wall surface. And in the case of the model by Naber & Reitz of Fig.5 (c), the distribution of droplet parcel, being analogous to the case of the non-evaporative spray, differs remarkably from the experimental data. On the other hand, the dispersion of the parcel in radial direction seems to be most reasonable, and the vapor also disperses upward in the results of Fig.5 (d). Thus, calculated results of the droplet parcel and vapor by new model make an accurate estimate of the actual phenomena in the evaporative spray comparing with another models.

Figure 6 shows comparison of experimental data with calculated results in the temporal change in spray radius on the wall. It seems that the spray radius in liquid and vapor phase obtained by new model coincide qualitatively with the experimental data.

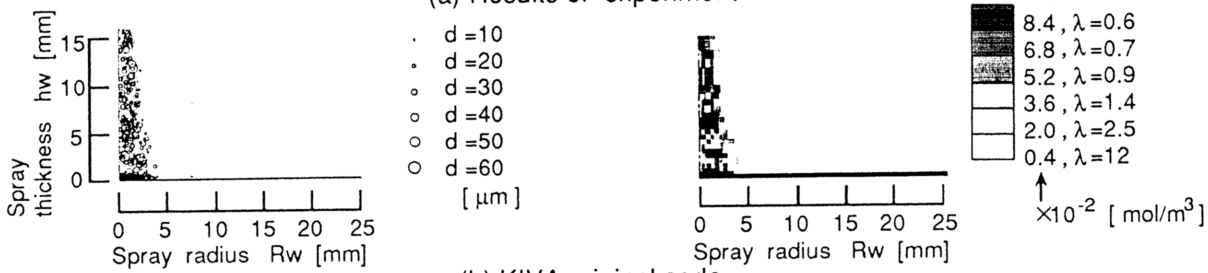
CONCLUSIONS

In this study, new submodels on the dispersion process of the spray impinged on the flat wall with high temperature was proposed to simulate the spray / wall interaction process inside the diesel combustion chamber. The evaporative spray which impinged on the surface with high-temperature above the spray saturated temperature could be treated by these models. And, these models were incorporated into KIVA code to calculate the dispersion process.

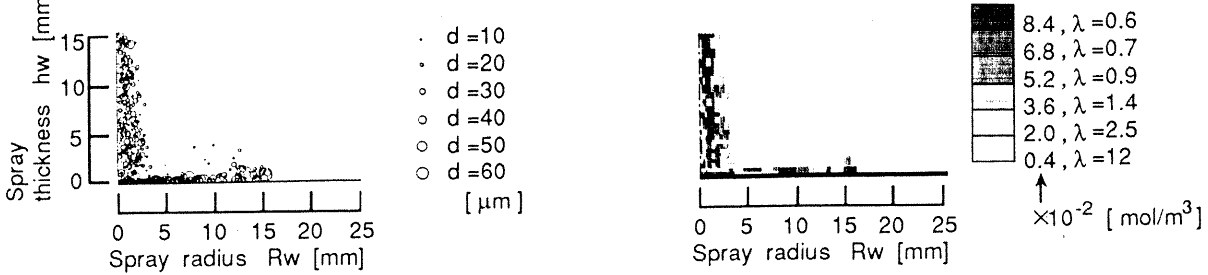


Liquid fluorescence intensity
Vapor concentration corrected with Lambert Beer's law

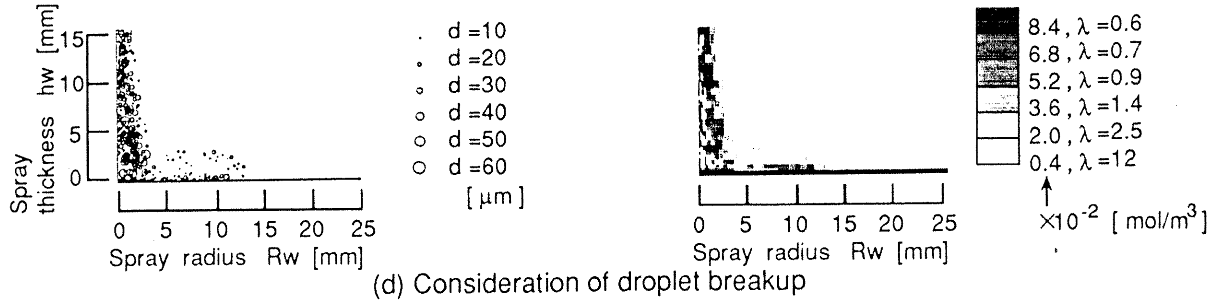
(a) Results of experiment



(b) KIVA original code



(c) Consideration of liquid jet model by Naber and Reitz



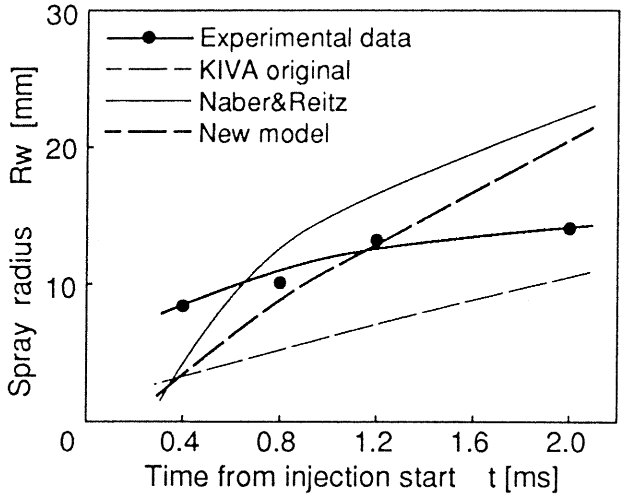
(d) Consideration of droplet breakup model and heat transfer model

Distribution of drop parcel Distribution of excess air ratio

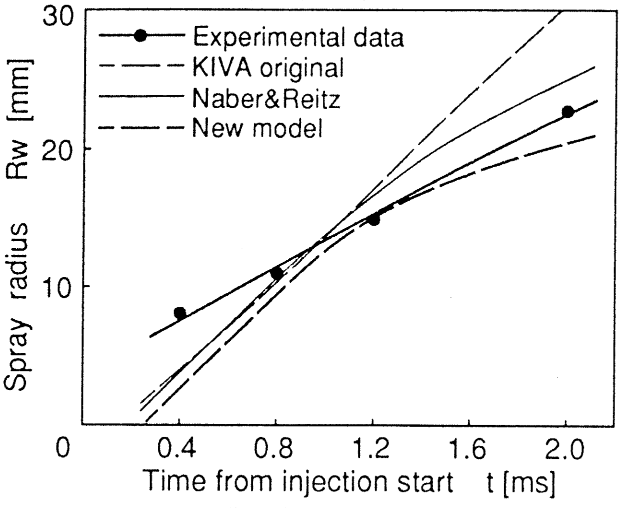
Fig.5 Spatial distribution of droplet parcel and excess air ratio at t=1.2 [ms]

Table 1 Calculation conditions

Ambient temperature	T_a [K]	700
Ambient density	ρ_a [kg/m^3]	12.3
Wall temperature	T_w [K]	550
Injection duration	t_{inj} [ms]	1.9
Injection fuel amount	Q_{inj} [mg]	7.2
Injection velocity	V_{inj} [m/s]	154
Diameter of injection nozzle	d_n [mm]	0.2
Spray cone angle	2θ [deg.]	16
Impingement distance	Z_w [mm]	24
Inclination angle of wall	α_w [deg.]	0
Number of parcel	N_p	2400
Minimum timestep	dt_{min} [sec.]	1.0×10^{-6}
Number of mesh		$52 \times 1 \times 40$
Initial mean diameter	d_{i32} [mm]	3.0×10^{-3}
Initial droplet temperature	T_{pi} [K]	323
Fuel	n - tridecan	



(a) Liquid phase



(b) Vapor phase

Fig.6 Comparison of experimental data with calculated results in spray radius on the wall

Nomenclature

C_p : Specific heat of the droplet [J/(kg•K)]
D_{fmax} : Maximum diameter of the film flow [mm]
d_i : Diameter of impinging droplet [mm]
d_{32} : Sauter mean diameter [mm]
M : Mass of the droplet [kg]
Q : Heat transfer [J]
S_d : Averaged contact area of impinged droplet during τ_d [m^2]
T_l : Temperature of impinging droplet [K]
T_{sat} : Saturated temperature of fuel droplet [K]
T_w : Temperature of wall surface [K]
ΔT : Temperature difference given by $(T_w - T_l)$ [K]
ΔT_{sat} : Superheating degree [K]
V_i : Impinging velocity of droplet [m/s]
We : Weber number
Z_w : Impinging distance from the nozzle to the wall [mm]
α_d : Averaged heat transfer coefficient [kw / (m^2• K)]
ρ_f : Liquid fuel density [kg/m^3]
σ : Surface tension [N/m]
τ_d : Residence time [s]

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