Study of Fuel Adhesion Behavior during Spray-wall Impingement in PFI Engine

Authors: Takashi Yonezawa* and Kazuhiko Kawajiri*

A new method has been proposed and experimentally verified for evaluating the amount of adhered fuel when the fuel spray is injected from an automotive injector and impinges on the wall surface. It has been confirmed that the proposed method can describe the relationship between the incident angle of the spray droplet and the amount of adhered fuel on the wall, which is not possible by the conventional simulation.

1. Introduction

In recent years, with growing awareness of energy saving and global environmental conservation, it is increasingly important to improve automobile fuel economy and reduce exhaust gas emissions. In the port fuel injection (PFI) engine, a fuel spray is injected into the intake port and a part of that spray impinges on the wall surface, where complex phenomena are taking place such as adhesion and flow with evaporation. The behavior of the fuel adhered on the wall significantly affects the fuel economy and exhaust gas characteristics, and thus it is important to understand the adhesion behavior.

This paper presents our new numerical simulation method and its verification for evaluating the adhesion behavior of the fuel spray when it is injected from an automotive injector and impinges on the wall surface. The verification was performed by fundamental experiments involving injecting fuel sprays onto a flat plate (1).


When fuel sprays impinge on the wall surface, various adhesion behaviors take place depending on the velocity and diameter of the droplets and other impingement conditions. The types of behavior range from all adhered to all reflected, including partially adhered and re-dispersed otherwise (referred to as "splashing"). In the conventional simulations of spray–wall impingement, the ratio between the adhered and re-dispersed fuel of splashing is assumed to be constant regardless of the impingement conditions (2), or the fraction of re-dispersed fuel is assumed to increase with the increase in impact velocity of the droplet normal to the wall surface (3). In the case of splashing, the mass and kinetic energy of the impinging droplet are first absorbed into the liquid film on the wall surface. Subsequently, a part of the absorbed energy is consumed and some droplets are re-dispersed (Fig. 1). Therefore, the ratio between the adhered and re-dispersed fuel is thought to depend on the incident angle and energy of the droplet. According to the conventional simulations, however, the amount of re-dispersion droplets remains unchanged regardless of the incident angle of the spray droplets, or oblique impingement reduces the normal component of the droplet velocity and hence the amount of re-dispersed fuel. As such, if the incident angle of the impinging droplet varies, it was impossible to accurately evaluate the amount of fuel adhered on the wall surface. This paper proposes a method to evaluate the amount of adhesion during splashing at different incident angles of the fuel spray.

The wall adhesion behavior in the splashing process is thought to be affected not only by the normal component of the droplet velocity but also by the tangential component. Therefore, the proposed method takes into consideration the droplet velocity tangential to the wall surface, which was previously not considered. The re-dispersed fraction of impinging droplets is expressed by Eq. (1), in terms of the normal Weber number, $W_{e,n}$, based on the incident droplet velocity normal to the wall, $V_{n}$, and the tangential Weber number, $W_{e,t}$, based on the tangential velocity, $V_{t}$ (Fig. 2).

$$ \frac{M_{out}}{M_{in}} = C \times \left\{ C_n \times W_{e,n} + (1-C_n) \times W_{e,t} \right\} $$

(1)
where, $W_{e_{in-n}} = \rho d V_{in-n}^2 / \sigma$, and $W_{e_{in-t}} = \rho d V_{in-t}^2 / \sigma$. $\rho$: density, $d$: droplet diameter, $V$: droplet velocity, and $\sigma$: surface tension. $C$ and $C_n$ are the coefficients and $C_n$ ranges from 0 to 1.

3. Verification by Spray - Plate Impingement and Adhesion Experiment

3.1 Method of experiment

To verify the proposed method for evaluating the adhesion characteristics of the splash behavior, the fuel sprays were injected onto a wall surface and the amount of adhered fuel was measured. Figure 3 illustrates the outline of the experimental apparatus, where a dual spray injector with 10 holes is installed and a low-volatility dry solvent is used as the fuel (Table 1).

Table 1 Experimental conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient pressure</td>
<td>0.1 MPa</td>
</tr>
<tr>
<td>Injected pressure</td>
<td>0.37 MPa</td>
</tr>
<tr>
<td>Fuel</td>
<td>Drysolvent</td>
</tr>
<tr>
<td>Ambient &amp; Wall temperature $T$</td>
<td>296 K</td>
</tr>
<tr>
<td>Plate surface roughness $R$</td>
<td>Ra 10 $\mu$m</td>
</tr>
<tr>
<td>Injector-wall distance $H$</td>
<td>50, 75, 100 mm</td>
</tr>
<tr>
<td>Wall inclination angle $\theta$</td>
<td>0, 45 deg</td>
</tr>
</tbody>
</table>

3.2 Results of experiment

Figure 4 shows the measurement result when varying the injector-wall distance, $H$, and the wall inclination angle, $\theta$. The vertical axis shows the fraction of adhered fuel (= mass of adhered fuel/mass of all injected fuel). When $H$ is changed, the behavior at $\theta = 0$ deg differs from that at $\theta = 45$ deg. When $\theta = 0$ deg, as $H$ increases the amount of adhesion monotonously decreases. With the increase in $H$, more and more spray droplets float in the air and less fuel reaches the wall surface, and thus the amount of adhesion decreases. In contrast, when $\theta = 45$ deg, the amount of adhesion at $H = 75$ mm is greater than that at $H = 50$ mm, showing a trend opposite to the case when $\theta = 0$ deg. It is thought that the impact velocity of spray droplets impinging on the wall at $H = 50$ mm is greater than that at $H = 75$ mm, and the amount of re-dispersed droplets increases in excess of the amount of adhered droplets, resulting in the decrease of adhered fuel.

3.3 Numerical simulation method

The wall impingement behavior of the spray droplets was simulated using the spray impingement model of Bai et al.(2), and Eq. (1) was used to calculate the mass fraction of the re-dispersed droplets. For comparison, the conventional calculation was also performed based on the impingement velocity normal to the wall surface(3). The coefficients $C$ and $C_n$ in Eq. (1) were determined as $C = 0.0015$ and $C_n = 0.13$ so that the proposed method and the conventional evaluation agreed in terms of the mass fraction of the re-dispersed droplets when the spray droplets impinge normal to the wall surface. The spray droplet behaviors were calculated in a Lagrangian manner using the discrete droplet model (DDM). Breakup of the droplet was simulated by the bag and stripping breakup model of Reitz et al., but droplet recombination was not considered. In this simulation, the diameter, velocity and direction of the spray droplets were predetermined so that the simulation results of the spray shape formed by the injector, spray distribution, spray penetration, and Sauter mean diameter matched those of the experiment.
3.4 Verification of numerical simulation

Figure 5 shows the comparison of the experimental and calculation results. According to the conventional evaluation method, when the wall inclination angle $\theta = 0$ deg, the calculation and experimental results agree with each other, but when $\theta = 45$ deg, they do not agree at the injector-wall distance of $H = 75$ mm or less. In contrast, according to the proposed Equation (1), which takes into consideration that the amount of re-dispersion varies depending on the incident angle of the impinging droplet, the calculation results are in good agreement with the experimental results of the fuel adhesion during the spray-wall impingement. Note that the splash behavior rarely occurs at $H = 100$ mm or greater, and thus no difference is observed between the two evaluation methods.

![Figure 5 Comparison of adhesion mass fraction](image)

4. Conclusion

In this paper, a new method has been proposed for evaluating the amount of adhered fuel when fuel spray is injected from an automotive injector and impinges on the wall surface. The new method was verified by a fundamental experiment of injecting fuel sprays onto a flat plate. As a result, it was verified that the proposed method is able to describe the relationship between the incident angle of the spray droplet and the amount of fuel adhered on the wall, which is not possible by the conventional simulation.

By fully utilizing this numerical evaluation method, we will contribute to the development of next-generation engines and components that will improve fuel economy and lower exhaust gas emissions.

References