Characteristics of Flat-Wall Impinging Spray Flame and Its Heat Transfer under Small Diesel Engine-Like Condition. 3\textsuperscript{th} Report: Effect of Oxygen Concentration

R Mahmud\textsuperscript{1}, T Kurisu\textsuperscript{1}, K Nishida\textsuperscript{1}, Y Ogata\textsuperscript{1} and O Akgol\textsuperscript{1}

\textsuperscript{1}Department of Mechanical System Engineering, University of Hiroshima, 1-4-1 Kagamiyama, Higashi-Hiroshima, Japan

Abstract. To investigated heat transfer phenomena inside the combustion chamber wall in diesel engines, we investigated the effects of spray/flame impingement on transient heat flux to the wall. By using a constant volume vessel under engine-like condition, surface heat flux of the wall at spray/flame impingement was measured with three thin film thermocouple heat flux sensors. Fuel was injected using a single-hole injector with a 0.133 mm diameter nozzle. Under these conditions, spray evaporates, then burns near the wall. In order to investigate the relation between diesel flame and wall heat loss, two colour-method was applied to observe local flame temperature distribution. The effect of oxygen concentration on the heat transfer was investigated parametrically. The results showed that the ratio of oxygen concentration influenced the combustion behaviour, which has significant effect on flame temperature and flame contact area that gave rise to further heat loss on the wall.

1. Introduction

Heat transfer losses are one of the largest factor loss of engine thermal efficiency, especially in small-size diesel engines. More than half of total heat energy in the internal-combustion engine is lost by cooling through the cylinder wall to the atmosphere and the exhaust gas. Heat loss through combustion chamber wall largely determines cooling loss. For this reason, fully understanding of heat transfer mechanism from combustion gas to cylinder wall is required for maximizing the thermal efficiency.

In general, heat loss (q) from the combustion gas to cylinder wall in internal combustion engine as shown in formula (1). Considering the decreasing value of surface area (A), temporal changes in the heat transfer coefficient (h) and temperature difference between gas temperature and wall temperature (T\textsubscript{gas}-T\textsubscript{wall}) are required for decreasing heat loss (q).

\[ q = A . h . (T\textsubscript{gas} - T\textsubscript{wall}) \] (1)

Some studies showed that minimizing temperature difference between in-cylinder gas and combustion chamber wall surface was possible by applying insulation material such as ceramic coating on the surface [1-3]. As a result, the heat loss was reduced. Thus, both exhaust energy and piston work increased which, in turn, led to improved thermal efficiency.

Another simulation study, applying the Exhaust Gas Recirculation (EGR) rate also become considering to decreasing flame temperature distribution on heat loss. Comparing the single injection results at different EGR rate, it was confirmed that the heat flux was decrease at higher EGR rate [4]. With increasing EGR rate, the oxygen concentration in the fuel/gas mixture decreases and the
The specific heat of the cylinder increases and leads reaction rate decrease. Further, in-cylinder pressure and combustion decrease [5].

As described by the previous researchers, oxygen concentration has an effect on combustion behavior, which closely relates with lower temperature combustion. Therefore, it is important to clarify an effect of oxygen concentration on decreasing heat loss. For this reason, this paper aims to investigate the oxygen concentration effect on the transient local heat flux of combustion. In order to investigate the relation between diesel flame and wall heat loss, two colour-method [4][6-7] was applied to observe local flame temperature distribution. Instantaneous temperature was detected by three Thin Film Thermocouple Heat Flux Sensors (TFTHFSs) which were mounted on the wall surface. By using the measured temperatures as boundary condition, we computed non-steady heat flux through the surface with finite difference method.

2. Experimental Apparatus and Method

2.1 High-Pressure and High-Temperature Chamber Vessel

The experiment was previously conducted by the authors [8] using high-pressure and high-temperature chamber vessel. Pressurized hot air was supplied through an electric muffle furnace and heated with an electric heater mounted at the bottom of the chamber in order to simulate an engine-like thermodynamic environment. The chamber pressure was manually operated, whereas the chamber temperature was controlled by a volt slider for the heater. Four K-type thermocouples were installed around the combustion area. Diesel fuel from a common rail system was injected into the chamber when temperature difference of the thermocouples was within range of 5 K. Injection quantity and timing was controlled by a delay pulse generator (Stanford Research Systems DG645). Injection pulse had been calibrated by the injection rate measurement previously.

![Diagram](image)

**Figure 1.** Thin Film Thermocouple Heat Flux Sensor arrangement and optical set-up of high-speed video camera observation for spray/flame
2.2 Heat Flux Measurement and High-Speed Video Camera Photography

Figure 1 (a) shows Thin Film Thermocouple Heat Flux Sensor (TFTHFSs) arrangement. Three Alumel/Chromel TFTHFSs (Medtherm 10702B) were applied to obtain the instantaneous surface heat flux on the wall. The diameter of the sensors is ø 1.55 mm, and distance between their thermal contacts (surface and inside) is 3.30 mm. The sensors were radially located on the wall surface with a 10 mm distance each other. Positions of the sensors are designated as Position1 (centre of wall impingement), Position2 (10 mm from centre) and Position3 (20 mm from centre). The flat wall was made of stainless steel which has a thickness of 7.3 mm. The back side of the wall plate was cooled by oil in order to form one-directional heat flow across the wall. The cooling oil temperature was kept constant by a thermostatic oil bath.

Instantaneous local heat flux was computed by applying one-dimensional non-steady heat conduction equation using two measured temperatures by the identical sensor as boundary conditions. The equation was explained in the previous report [8]. Total heat loss was calculated by integrating the heat flux with concentric area and time. In area integration, heat flux affected areas were defined as concentric circles of 0-5 mm for Position1, 5-15 mm for Position2, and 15-25 mm for Position3, respectively.

Figure 1 (b) shows optical set-up of high-speed video camera observation. Spray and flame behaviour were recorded by high speed video camera (Nac Image Technology Inc, HX-3) with an imaging speed of 20,000 fps and resolution of 320 x 448 pixels. To observe the spray behaviour, Mie scattering method was adopted to support the spray impingement illumination photography. Light from Xenon lamp illuminated the spray in the chamber through the sideward transparent quartz window to provide observation at non-evaporating and evaporating conditions. Observation of flame was conducted with natural flame luminosity. In order to acquire high quality spray images, image processing was employed in this study. To clarify the flame temperature distribution, two-colour method was applied. We used a two-colour pyrometry software named “Thermias” of Nac Company for analysing the natural flame colour images. A standard light was used as an illumination source for calibration.

3. Test Conditions

Measurement conditions are listed in Table 1. It was decided based on actual operation of small size diesel engines. Injection quantity was 5 mm$^3$ with injection pressure 120 MPa using a nozzle of 0.133 mm hole diameter. The impinging distance between the nozzle tip to the impingement wall was set at 40 mm as shown in Figure 2. Oxygen concentrations were conducted at 21% and 16% as experimental parameters to investigate the effect of the heat transfer characteristics on the impinging flame on the wall. The conditions were “non-evaporating spray” at room temperature with N$_2$ gas, “evaporating spray” at high temperature with N$_2$ gas, and “combusting spray” at high temperature with air. To keep the gas density same for all of the conditions, which is 16 kg/m$^3$, ambient pressures was set at 1.4 MPa for non-evaporation and 4.1 MPa for others.

![Figure 2. Spray impinging distance](image-url)
### Table 1. Experimental conditions

|                      | Non-Evaporation | Evaporation | Combustion |
|----------------------|-----------------|-------------|------------|
| **Fuel**             | Diesel fuel     |             |            |
| **Ambient Condition**|                 |             |            |
| Ambient gas          | N₂              | Air (N₂:79%, O₂:21%) |            |
| Ambient pressure (MPa) | 1.4          | 4.1         |            |
| Ambient temperature (K) | 300           | 873         |            |
| Ambient density (kg/m³) | 16             |             |            |
| **Injector and Injection Condition** |                 |             |            |
| Injector type        | Piezo actuator type |             |            |
| Number of nozzle holes | 1              |             |            |
| Injection quantity (mm³) | 5             |             |            |
| Diameter of nozzle holes (mm) | 0.133 |             |            |
| Injection pressure (MPa) | 120           |             |            |
| **Impingement Wall** | Flat plate, Stainless steel |             |            |
| Impingement distance (mm) | 40             |             |            |
| Wall temperature (K)  | 300            | 460 ±10      |            |
| Cooling method        | -              | Oil cooling  |            |

## 4. Results and Discussion

### 4.1. Injection Rate

According to Wakisaka and Azetsu [9], shapes of fuel injection rate influences the combustion and emission formation. As Bower and Foster [10] performed and confirmed that the Zeuch method is more accurate for measuring injected volume. Injected fuel quantity was calibrated by Zeuch method injection ratemeter (Ono Sokki Co. Ltd, FJ-7000). Figure 3 shows an averaged result of a ten times injection rate measurement with a single hole injector at 120 MPa. In all experiments, injected quantity was kept at 5mm³, with 1.2 ms injection duration.

![Figure 3. Injection rates](image)

### 4.2 Spray Behavior at Non-evaporation and Evaporation

In this section, the impinging spray behaviour under non-evaporation and evaporation conditions was studied.
4.2.1 Spray Behaviors. Figure 4 shows comparison between non-evaporating and evaporating wall impinging spray images. Spray travel from the top to the bottom at each photo and impinges on the wall. Non-evaporating spray images were observed at room temperature (300 K), while the evaporating spray at high temperature (873 K). In the case of evaporating spray, intensity of white colour shows liquid spray concentration. The images revealed that non-evaporating spray led to shorter impingement timing and larger spray spreading to the circumferential area of the flat wall. On the other hand, in the case of evaporation, the spray almost evaporated completely before impinging to the wall. As it can be seen at 0.9 ms After Start of Injection (ASOI), there is some fuel droplets spread on the wall.

Figure 4. High-speed video camera images of wall impinging spray at non-evaporating and evaporating

Spray tip penetration lengths, which are obtained from the non-evaporating and liquid lengths from evaporation images are plotted in the Figure 5. Spray tip penetration length is defined as a summation of axial and radial penetration distances as shown in Figure 2. The liquid length, which was defined similar to the non-evaporating spray, were obtained by the image processing as the maximum liquid penetration during the injection using a pre-determined threshold intensity. We used a threshold intensity of 10% on the 0 to 255 intensity scale of the image.

Figure 5. Non-evaporating and liquid lengths of evaporating spray
Closed and open triangles show before and after the spray impingement on the wall, respectively. Figure shows that the length of evaporating was rapidly declined at ASOI 1.2 ms and reached zero, while the length of non-evaporating spray steadily grew. As can be seen in the figure, liquid penetration length rapidly decreases after the end of injection compared with non-evaporation state.

4.3 Combustion Flame Behavior and Wall Heat Transfer under Oxygen Concentrations

In this section, impinging flame behaviour and combustion effect on the wall heat transfer under oxygen concentration are studied. Effects of the oxygen concentrations, which were 21 and 16% were investigated at impingement distance of 40 mm.

4.3.1 Combustion Flame Behavior. Figure 6 shows images of impinging flame at different oxygen concentrations (O\textsubscript{2}). Comparing with non-evaporating spray photographs in Figure 4 (a), luminous flames occur a few deci-seconds after the spray impingement. In the Figure 6, the luminous flame appeared earlier with O\textsubscript{2} of 21%. It had started at 0.9 ms ASOI before the end of the fuel injection and at 1.25 ms ASOI just after the end of the fuel injection for O\textsubscript{2} of 16%. It is found that the reduction of the oxygen concentration in the enclosure mainly affects the reactions in the gas phase and results in changes of the combustion behaviour such as ignition timing and flame development. Furthermore, comparing the photographs of evaporation in Figure 4 (b) and combustion in Figure 6, it can be seen that the luminous part, which is product of combustion, existed in the vapor area.

![Figure 6](image6.jpg)

**Figure 6.** High-speed video camera images of impinging flame at different oxygen concentration

![Figure 7](image7.jpg)

**Figure 7.** Flame temperature distribution at different oxygen concentration
Figure 7 shows flame temperature distributions at different oxygen concentrations obtained from two-colour method analysis, which was performed with flame natural luminosity images. The temperature distribution shapes were similar to those of flame, because they were obtained from the flame luminosity. The colour distribution scale varying from dark to bright indicates temperature.

By comparing the temperature distributions with different oxygen concentrations, it can be seen that the $O_2$ of 16% had the lowest temperature. It can be inferred from Figure 8 that burned gas temperature decreases with decreasing volume fraction of oxygen because the heat capacity of ambient gas increase with decreasing the volume oxygen concentration [11].

![Figure 8. Mean temperature at different oxygen concentration](image1)

![Figure 9. Temporal variation of local heat flux, integrated flame luminosity, and total heat flux at combustion](image2)
4.3.2 Heat Flux on the Wall Surface. Figure 9 (a-b) show non-steady local heat fluxes with flame impinging on the wall and integrated luminosity from flame images at different oxygen concentration. Timings of the spray impinging and ignition, which were obtained from the video images, are also plotted. The luminosity increased from near-the ignition timings at all oxygen concentrations. Local heat flux at Position1 started to increase earlier than Position2 and 3 at each oxygen concentration. This increase in local heat flux at Position1 was followed by ignition at O₂ of 21% and after Position2 for O₂ of 16%, which had the minimum value. The low temperature due to decreasing oxygen concentration causes unsuitable equivalence ratio for ignition. As a result, ignition takes time to start after spray impinging on the wall.

Regarding the effect of oxygen concentration on the heat flux, it could be found from the graphs as follows: (1) earlier start of local heat flux increase was observed at all positions with the O₂ of 21%, except Position3 was similar (2) higher peak value was observed at Position1 and 2 with the O₂ of 21%.

Figure 9 (c) shows temporal variation of the total heat flux at different oxygen concentrations. It can be seen in the graph, O₂ of 21% had two peaks waves i.e. there were two stages for the local heat transfer. At first, the local heat flux was increased by turbulence of impingement spray. Then, heat transfer by flow along the wall, which started after impingement, took place. While O₂ of 16% accumulated at the second stage for local heat transfer due to significant ignition delay.

![Figure 10](image)

**Figure 10.** Comparison of the areal transferred heat and ratio of heat loss to total combustion heat at different oxygen concentration

A comparison of the transferred heat at each area under different oxygen concentrations are shown in Figure 10. Transferred heat value was decreased with lower oxygen concentration. This effect is mainly due to the decrease in the burned gas temperature with decreasing the volume fraction of oxygen concentration [11]. Ratios of heat lost through the wall to total combustion heat are also shown in the graph. It is about 11 to 14 % of total combustion energy.
Effect of flame contact to the wall at different oxygen concentrations as shown in Figure 11. Figure 11 (a) is definition of flame contact area. Figure 11 (b) shows that O₂ of 16% had smaller contact area than that 21%. It means with oxygen concentration of 21%, leads to flame contact significantly to spread wide into circumferential area of flat wall. This flame contact area contributes to the heat transfer by conduction. Time integration of the flame contact area can be seen in Figure 11 (c), which shows that flame traveling distance was shorter as the oxygen concentration is decreased.

5. Conclusion
Effects of oxygen concentration on the combustion wall heat transfer under diesel engine-like conditions were investigated. The main conclusions are summarized as follows. By using the two-colour pyrometry analysis, we found that the combustion distribution was low temperature at oxygen concentration of 16%. The low temperature due to decreasing oxygen concentration delays start of ignition. As a result, total heat flux accumulated at the peak of second waveform stage. Comparing different oxygen concentration, O₂ of 16% showed the lower transferred heat to the wall. This was caused by decrease in burned gas temperature and small flame contact area.

Nomenclatures
q : Heat Loss
A : Surface Area
h : Heat Transfer Coefficient
EGR : Exhaust Gas Circulation
TFTHFS : Thin Film Thermocouple Heat Flux Sensor
ASOI : After Start of Injection
O₂ : Oxygen Concentration
a.u. : arbitrary units

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