

Effect of Spray/Wall Interaction on Diesel Combustion and Soot Formation in Two-Dimensional Piston Cavity

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ABSTRACT

The effects of spray/wall interaction on diesel combustion and soot formation in a two-dimensional piston cavity were studied with a high speed color video camera in a constant volume combustion vessel. The two-dimensional piston cavity was applied to generate the impinging spray flame. In the cavity, the flat surface which plays a role as the cylinder head has a 13.5 degree angle with the injector axis and the impinging point was located 30 mm away from the nozzle tip. Three injection pressures of 100, 150, and 200 MPa and a single hole diesel injector (hole diameter: 0.133mm) were selected. The flame structure and combustion process were examined by using the color luminosity images. Two-color pyrometry was used to measure the line-of sight soot temperature and concentration by using the R and B channels of the color images. The soot mass generated by impinging spray flame is higher than that of the free spray flame. As injection pressure increases to 200 MPa, the gap of soot levels between impinging spray flame and free spray flame becomes unobvious. In the impinging spray flame, the high soot concentration is observed in the head vortex region, whereas in the free spray flame, it was seen inside of and near the tip of the flame.

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INTRODUCTION

Spray wall interaction occurs in small-bore high speed diesel engines and has strong influences on mixture formation, combustion and emission processes inside the combustion chamber. In this case, the effects of spray wall interaction have become the subject of plenty of research works during the past decades [1, 2, 3, 4, 5]. For simplicity, the flat wall was always selected to form impinging spray and this kind of investigation conducted by previous researchers has produced lots of valuable information which could provide some basic theories of spray-wall interaction effects on diesel spray formation and combustion. However, the structure of impinging wall is complicated in a real engine and the spray often impinges on the piston crown and then

forms impinging spray, the mixture formation and combustion process are different with that of flat wall impinging spray. Thus it is worthwhile to investigate the combustion and soot formation characteristics by using two-dimensional piston cavity and forming an engine like impinging spray.

The combustion and soot formation characteristics of impinging spray could be analyzed by applying the optical methods both at modified engines and constant combustion vessels. The flame luminosity recording is one of the most widely used techniques for its simplicity and explicitness [3, 6, 7]. In a diesel flame, soot incandescence is the thermal radiation from soot particles and it is much stronger than chemiluminescence from other radicals [8]. The perceived

intensity reflects the flame characteristics and emission behavior because it depends on temperature and soot concentration [9]. This is also the basis for the two-color pyrometry which has been often used for the analysis diesel combustion. Two-color pyrometry could simultaneously obtain the temperature inside the flame and the quantized soot emission.

The aim of this study is to provide information on flame structure and soot formation characteristics of two-dimensional piston cavity impinging spray with single hole nozzle (0.133 mm) and three injection pressures (100 MPa, 150 MPa, 200 MPa). Flame luminosity recording is applied to analyze the combustion behavior and two-color pyrometry is used to obtain the line-of-sight temperature and soot concentration directly from the color images. Meanwhile, flame luminosity and soot concentration of impinging flame is also discussed in comparison with that of free flame.

EXPERIMENTAL APPARATUS AND CONDITIONS

The experiment was performed in a high-pressure, high-temperature constant volume combustion vessel as is shown in Fig. 1. A transparent quartz window was employed to make the inside observable and optically accessible. An electric heater installed in the bottom of the chamber was applied to produce an engine-like thermodynamic environment by filling the chamber with compressed air. The two-dimensional piston cavity was located inside the chamber to generate the impinging spray flame. In the cavity, the flat surface which plays a role as the cylinder head has a 13.5 degree angle with the injector axis and the impinging point was located 30mm away from the nozzle tip, detail is shown in Fig. 1.

A manually operated piston screw pump was used to suck the fuel from fuel reservoir and then to generate the fuel injection pressure up to 200 MPa. The injector was controlled by the injector ECU. Injection timing, injection mass and image taken timing were controlled by delay pulse generator DG535. The injector used in this study was a single-hole type one and the nozzle diameter is 0.133 mm. The injected fuel is JIS#2 diesel in this investigation. Injection rates are also shown in the Fig. 1 top left.

For natural flame luminosity and two-color perometry experiments, a high speed color camera (Nac Image Technology Inc. GX-8) was applied to record the images. The sensitivity of the camera is ISO 5,000. The camera setting for the experiments were the following: imaging speed of 10,000 fps, resolution of 576×576 , exposure time of $1/333,000$ s, and aperture of f22. A standard illuminant was applied in calibration system as is showed in the top right of Fig. 1; it will be introduced in the next section. A natural density filter with 5% transmittance was located before the lens to avoid image saturation result from diesel combustion and high camera sensitivity.

The non-evaporation images is taken by using the same setting with the luminosity experiments, however a xenon lamp and two reflection mirrors are applied to form the source of scattering light.

Each case of the experiments was taken at least 3 times. Before the experiment, a scale ruler was inserted into the chamber and taken a scale image by the high speed color camera at the same camera settings with experiments. All the backgrounds of the images in this paper have been removed.

Table1. Experimental conditions

Ambient Gas	Air	
Ambient Temperature T_a	873 K	300 K
Ambient Pressure P_a	4.1 MPa	1.5 MPa
Ambient Density ρ_a	16 kg/m ³	
Piston Cavity	With / Without	
Injector Type	Piezo Actuator Type	
Nozzle Hole Number/ Diameter	1/ 0.133 mm	
Injection Pressure P_{inj}	100/ 150/ 200 MPa	
Injection Quantity M_f	2.97 mg	
Injection Duration	0.91/ 0.77/ 0.69 ms	

CALIBRATION OF TWO COLOR PYROMETRY

Two-color pyrometry was wide adopted to analyze the temperature and soot concentration of diesel flame. Detail discussion of the principle of two-color pyrometry can be found in [9].

The precision of two-color method seriously depends on the accuracy of calibration. The basic principle of calibration of this study could be found in [10]. The details of the calibration are different from Ahn's to some extent because high speed color camera is used in this study. It will be introduced in detail.

In this experiment, when doing the calibration experiment, black body radiation is replaced by standard light as the calibration source. The standard light is placed at the same distance with the flame to the camera. Eight neutral density filters with different transmittance are rotating before the standard illuminant as Fig.1 top right shows.

According to the Wien's equation, the monochromatic emissive power of a black body $N(\lambda, T)$ could be expressed as:

$$N(\lambda, T) = C_1 \lambda^{-5} \exp(-C_2 / \lambda T_a) \quad (1)$$

Where C_1 and C_2 are the first Planck's constant and the second Planck's constant respectively; λ is the wavelength and T_a is the temperature of the black body.

And monochromatic emissive power of non-black body follows that

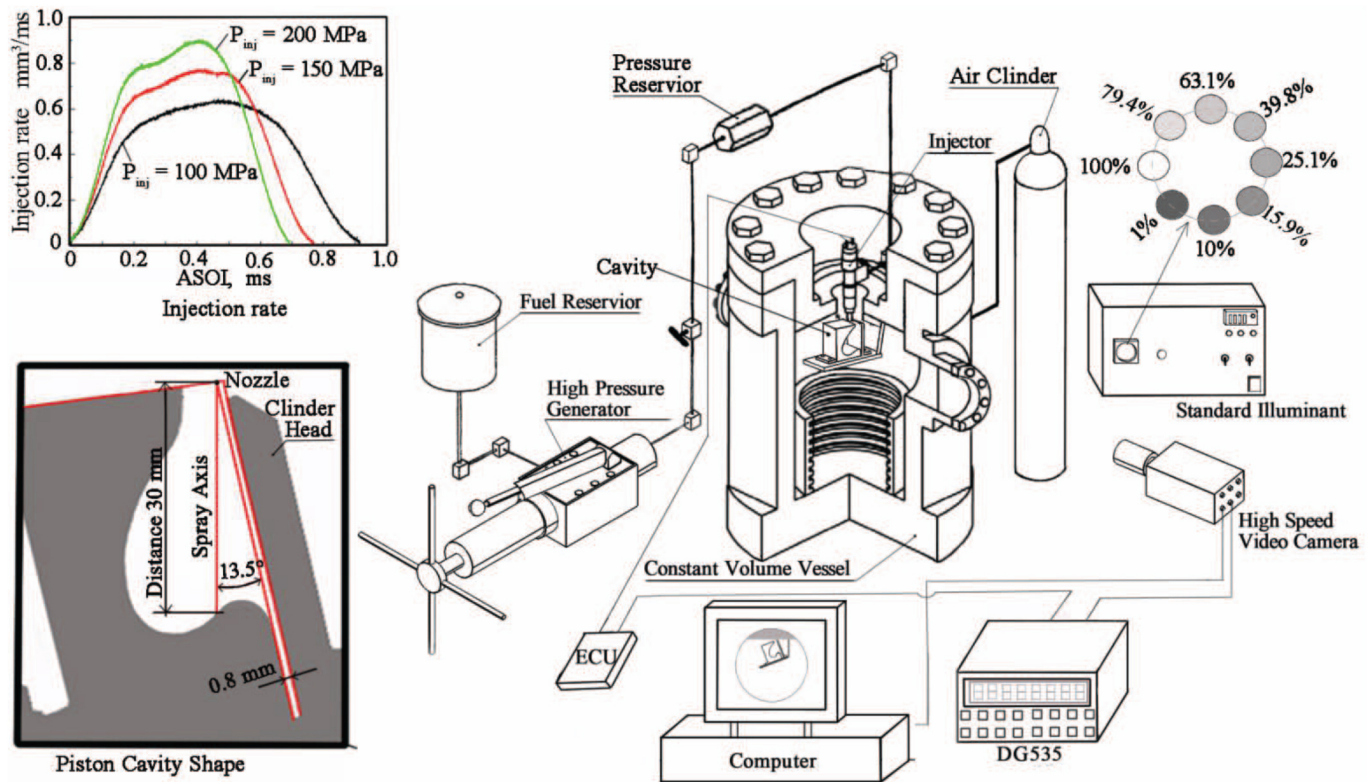


Figure 1. Experimental apparatus

$$N(\lambda, T) = \tau_i \varepsilon_\lambda C_1 \lambda^{-5} \exp(-C_2/\lambda T) \quad (2)$$

Where T is the surface temperature of the non-black body; τ_i is the transmittance of the neutral filter; ε_λ is the monochromatic emissivity of a non-black body. Combining Eqs (1) and (2) gives:

$$1/T - 1/T_a = \lambda/C_2 \cdot \ln(\tau_i \varepsilon_\lambda) \quad (3)$$

When the transmittance is 1, the temperature T will be received by using a thermodetector and then T_a will be calculated through equation 1. The empirical correlation of $\varepsilon_\lambda = a_0 + a_1 \lambda + a_2 T + a_3 \lambda T$ is used in this calculation.

The luminous intensity I perceived by camera sensor could be defined as:

$$I = a \varepsilon_\lambda C_1 \lambda^{-5} \exp(-C_2/\lambda T) + b \quad (4)$$

Where a and b are constants which depend on the camera sensor. Taking the logarithm at both sides of equation 4 gives

$$\ln(I - b) = -C_2/\lambda T + \ln(a \varepsilon_\lambda C_1 \lambda^{-5}) \quad (5)$$

According to this equation, the relationship between $\ln(I - b)$ and $1/T$ follow linearity when the illuminant happens. The slope equals to $-C_2/\lambda$, in reverse, the effective wavelength of this system could be defined as follows:

$$\lambda_{\text{effective}} = -C_2/\text{slope} \quad (6)$$

In this investigation, a high speed video color camera is used and the intensity of Red, Green and Blue channels could be obtained. Three effective wavelengths could be acquired:

$$\lambda_{\text{red}} = 577.38\text{nm}, \lambda_{\text{green}} = 541.12\text{nm}, \lambda_{\text{blue}} = 517.82\text{nm}$$

Only the red and blue channels are selected for our two-color calculation because these two channels have spectral responses with insignificant overlap [11].

When the source of the light is a standard illuminant, the ε_λ will becomes the value of 1, and the T will be replaced by T_a . After the camera recorded eight kinds of luminous intensity and calculate those data by using the equation 5 then the calibration line like Fig.2 will be obtained.

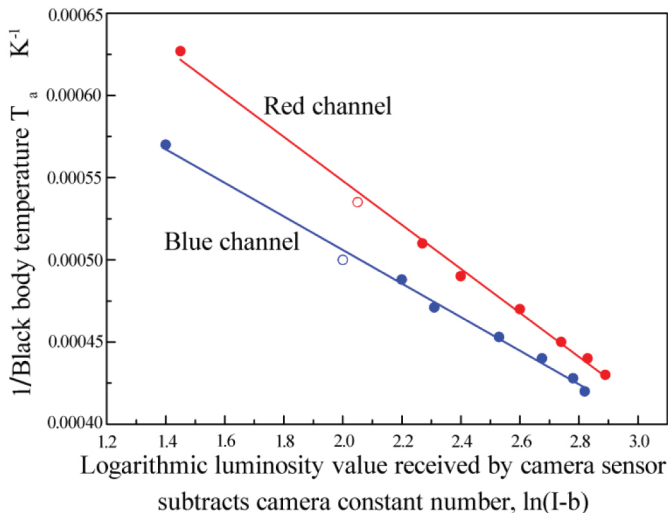


Figure 2. Calibration graph sample.

From Fig.2 the temperatures of black body at two effective wavelengths are received. And the surfaced temperature could be calculated by using the traditional two color equation:

$$\{1 - \exp[-\frac{C_2}{\lambda_1} \cdot (\frac{1}{T_{a1}} - \frac{1}{T})]\}^{\lambda_1^\alpha} = \{1 - \exp[-\frac{C_2}{\lambda_2} \cdot (\frac{1}{T_{a2}} - \frac{1}{T})]\}^{\lambda_2^\alpha} \quad (7)$$

Where λ_1 , λ_2 , T_{a1} and T_{a2} are the known parameters through calibration method.

RESULTS AND DISCUSSION

Flame Natural Luminosity and Structure

The flame characteristics are analyzed by the flame luminosity at three injection pressures. Flame natural luminosity comes primarily from incandescence and chemiluminescence. In diesel flames, the soot incandescence is the largest source of flame luminosity; the chemiluminescence typically comes from the OH, CH, and C2 radicals and is very weak [8]. In this study, although a 5% transmittance neutral density filter was located to avoid the saturation, the chemiluminescence also could be faintly detected by the high sensitivity camera system.

Fig.4 shows the process of the converting original color image to the colorful luminosity image. For the original color images acquired directly from the high speed video camera, it is difficult to recognize the gradient of the natural luminosity as the left image of Fig.3 shows. In order to resolve this problem, a special processing method was adopted: Firstly, the well-known NTSC transmission standard [12] was applied to convert the images from RGB to YIQ color-space and the luminosity channel (Y) was selected as the gray value. Secondly, those grayscale images were painted by colorized paint, in this way, each value of the grayscale image could have its own color.

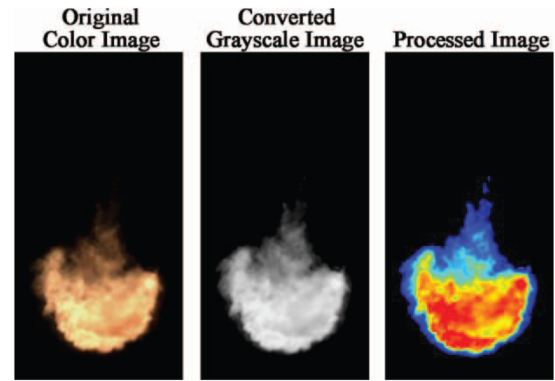


Figure 3. Image converting process.

Flame structure is also one parameter of combustion characteristics. The definition of flame structure is shown in Fig.4.

The 5% threshold is chosen to remove the image noise. Figs.5 and 6 show the representative luminosity images of impinging spray and free spray under three injection pressures respectively. Fig.7 shows the temporal integrated flame natural luminosity of free flame and impinging flame at three injection pressures. The integrated flame luminosity is obtained by summing up all pixels inside the flame region.

The impinging flame luminosities show that under all the three injection pressures, there is first a thin flame layer close to the wall and then a big head vortex flame region at the flame tip.

This flame structure is similar with that of the flat wall impinging flame [1, 5], however, because of the influence of the curved surface, the vortex region becomes larger and the wall flame region becomes thinner. The large intensity region can be observed mostly in the head vortex region.

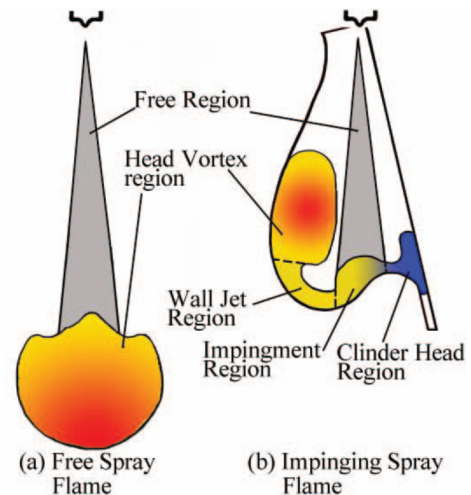


Figure.4. Definition of spray flame region.