Measurements of Droplet Size and Gas Temperature in Spray Combustion Flames

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Introduction

THE evaporation of droplets is one of the most important factors controlling spray combustion mechanism. Thus, it is very important in the study of that mechanism to obtain experimental knowledge on droplets within the flames. A photographic method may be considered first for the technique to detect droplets.[1] But, since the droplets are very small and moving with high speed in the flame, which has high temperature and high luminosity, the device becomes complex. So it is difficult to apply this technique to such flames as are being used in actual combustion equipment. Meanwhile, the thermocouple may be a good means to measure the temperature within flames because of its reliability and handiness. But, for spray combustion flames, it is unavailable for the region where droplets and soot exist in high concentration, because they adhere to it. In this Note, two techniques for detecting droplets and for measuring temperature under the foregoing circumstances will be proposed.

Measurement of Number and Size of Droplets

The magnesium-oxide method, which has been used widely for noncombustion sprays, is applied also in this study to detect droplets within flames. The probe for collecting droplets is shown in Fig. 1 (a). This is a kind of shutter mechanism. The outer cylinder ① slides on the inner one ② along their axis, and they are coupled by a coil spring. A copper plate having a small hole (2 mm diam) and a glass plate coated with magnesium oxide are set in slots ③ and ④, respectively. The copper plate limits the droplet collection area and prevents the magnesium-oxide coating from damage caused by the blowing of hot gas.

By operating the shutter after the probe is introduced into a flame, droplets passing through the hole of the copper plate impinge on the glass plate by their own inertia and put their marks on the magnesium-oxide coating. The diameter of these marks is measured on the microphotographs of the glass plate. Then the actual droplet diameter can be converted.[2] The spatial density of droplets also can be obtained by counting the number of the marks. This probe is not cooled, because a cooling system makes it bulky and disturbs the flow in flames. So, the device must be operated rapidly within a flame. Shutter speed can be varied by changing the spring, and the shutter opening periods used in the present measurement were measured as 9.96 and 5.23 msec.

Figure 2 is a microphotograph of droplets collected in a flame by the foregoing procedure. The measurements were conducted on a flame formed by a spray injected upward in parallel with surrounding air flow. A single-hole nozzle was used as an air-atomizer, and kerosine was used as fuel. Some examples of the measured results on this flame have been reported elsewhere.[3] The smallest droplet perceived, limited by the distinctness of marks on the magnesium-oxide coating, was about 4 μm diam in this measurement.

To find the spatial density of droplets by means of the inertia method, collection efficiency must be considered. The calculated results on the collection efficiency shown in Ref. 3 indicate that the droplets larger than 10 μm diam are collected completely when the flow velocity exceeds 10 m/sec, but the efficiency is poor for those smaller than 10 μm and particularly, it becomes very low when the gas becomes hotter, because the viscosity increases. The gas entering the probe impinges on the glass plate and then flows upward to the opening. Observing many microphotographs of the plates, it can be seen that the droplets smaller than 10 μm tend to be conveyed by this flow and gathered in the downstream part of the plate. This fact shows that the fine droplets are easy to flow with gas and difficult to be caught.

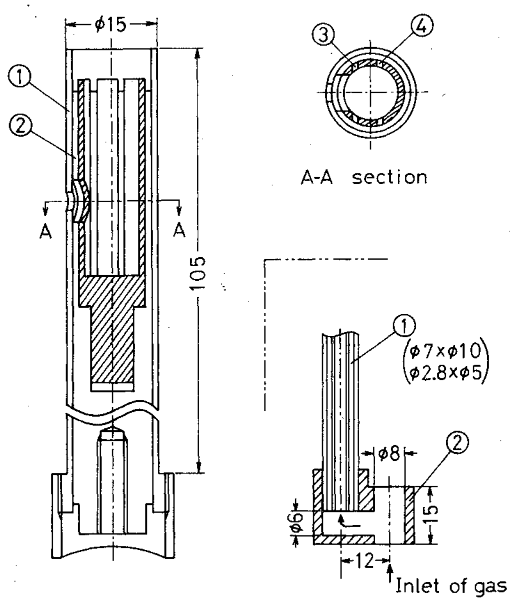

Fig. 1 Measuring devices (dimensions in millimeters).

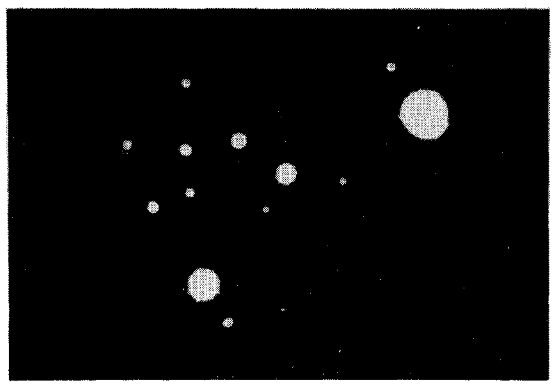

Fig. 2 A microphotograph of collected droplets.

Measurement of Gas Temperature

When the thermocouple is used in high-temperature gas flow, conduction and radiation errors must be considered. However, they may be reduced by using an appropriate suction pyrometer. To measure the temperature within spray combustion flames, the following two causes for error must be added to those just mentioned: 1) Droplets adhering to the thermocouple wire may cool the hot junction. 2) Soot coating the thermocouple wire may hinder the heat convection from gas flow.

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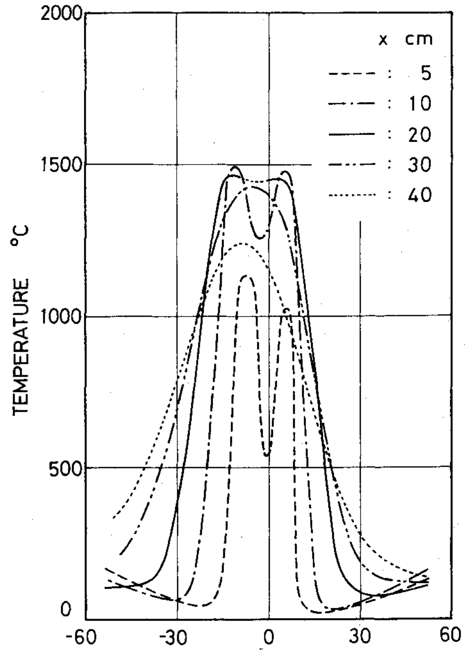

Fig. 3 Temperature distribution.

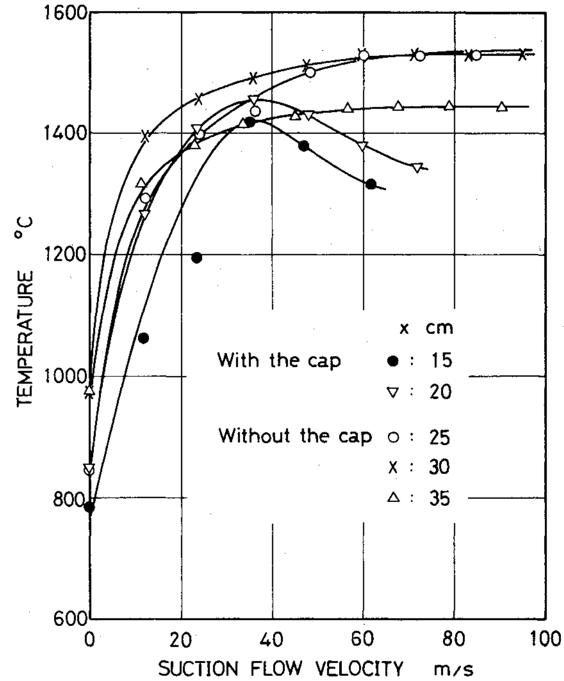

Fig. 4 Correlation between suction velocity and reading of the suction pyrometer.

Figure 1 (b) shows the suction end of the suction pyrometer used in this measurement. A Pt-PtRh (13%) thermocouple of 0.1 mm diam is set along the center of a porcelain double tube ①, and its hot junction is fixed at 3 mm above the bottom end of the double tube. To measure gas temperature, the double tube is held in parallel with the flame axis, and gas is drawn from its bottom end. When the temperature in the region having high concentrations of droplets and soot is to be measured, a cap ② is used. The cap serves to separate droplets and soot from gas by their own inertia and to reduce the errors due to causes 1 and 2.

Measurements were conducted on the aforementioned flame. In this flame, the spatial density profile of droplets in the horizontal cross section is similar to the Gaussian distribution having the flame axis as center, and most droplets vaporize up to 25 cm above the nozzle tip.[3] The outline of the temperature profiles within the flame is shown in Fig. 3, which was measured by a bare Pt-PtRh (13%) thermocouple of 0.3 mm diam. The notation x indicates the distance from the nozzle tip. Figure 4 shows the temperature readings along the flame axis, which was obtained by the preceding suction pyrometer for various suction gas flow rates. This shows that, for the suction gas velocity above 60 m/sec, the measured value becomes nearly constant at the points of $x=25$, 30, and 35 cm, where only few droplets exist in the gas. Since the velocities of surrounding gas are 14-17 m/sec at these points, surrounding gas may be drawn together into the probe at high suction velocity. However, since the temperature distribution around there is flat, this may not cause any large error. Figure 5 shows the comparison of these experimental values with those measured by a bare thermocouple. The maximum difference between them is about 100°C, and it occurs at the point where the temperature is maximum throughout the flame, and the error due to radiation will be maximum when the bare thermocouple is used.

As shown in Fig. 4, the results measured by the suction pyrometer with the cap at points of $x=15$ and 20 cm, where droplets exist, give a maximum value at about 35 m/sec, and then decrease with increasing suction flow rate. It may be considered as the reason that the increased suction flow rate draws more cold gas from upstream, where the temperature gradient is steep (Fig. 5). However, if the temperature gradient were not so steep, those temperature changes would

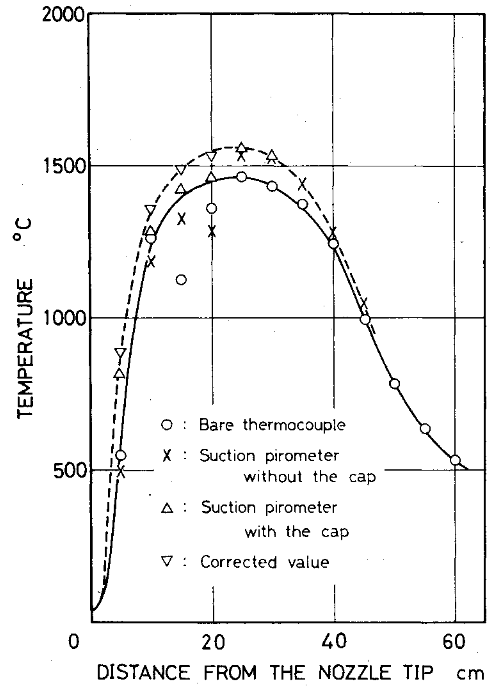

Fig. 5 Comparison of the temperature measured with various methods along the flame axis.

give the same tendency as those at the points of $x=25$, 30, and 35 cm. So, by reforming the curves of $x=15$ and 20 cm so as to be parallel with those of $x=25$, 30, and 35 cm, the temperatures at the points of $x=15$ and 20 cm may be estimated about 70°C higher than the maximums of each measured temperature, respectively.

The results measured by various methods are shown in Fig. 5. "Corrected value" written in the figure means the values of 70°C added to the maximum temperature measured by the suction pyrometer for the range of $x<20$ cm. Then a smooth curve, such as shown by the broken line, is obtained.

The solid line is the result obtained by the bare thermocouple. Readings are very low at the points of $x=15$ and

20 cm, where soot concentration is highest throughout the flame. It was observed that, with droplets acting as paste, thermocouple wire is covered with a thick soot layer soon after it is introduced into such a region. Values shown by circles at $x = 15$ and 20 cm are those read while the indicator was at rest for a moment just after the thermocouple was introduced into the flame. After that, the readings decrease as the coating of soot grows thicker. Similar effect by soot and droplets was seen also in the case of the suction pyrometer if the cap was removed.

When the suction pyrometer is used, the data at the points lower than 25 cm above the nozzle tip differ, depending on whether the cap is used or not, because soot and/or droplets adhere to the thermocouple when using the suction pyrometer without the cap. Especially at the points of $x = 5$ and 10 cm, where many droplets exist, the difference is remarkable. The large hollows seen in the temperature profiles of the cross sections of $x = 5$ and 10 cm (Fig. 3) may be explained by this fact. Such an apparent temperature drop on the center of the cross section of $x = 5$ cm is evaluated from Fig. 5 as about 350°C.

Conclusion

A technique was developed for detecting droplets within spray combustion flames. Although this technique is inferior to a photographic one in the respect that droplet velocity cannot be measured, it show sufficient reliability on the data giving number and size of droplets, and the device and operation are much simpler. Thus, this technique has the merit that it can be applied directly to the combustion equipment actually used.

The error in temperature measurement due to droplets and soot adhering to themocouple wire is removed by using a suction pyrometer with a small cap. But a suction pyrometer should be applied carefully to the temperature field where the gradient is steep, because it needs a large suction gas flow rate.

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Axisymmetric Vibrations of Polar Orthotropic Circular Plates

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Nomenclature

A_1, A_2	= undetermined constants
a	= radius of plate
$D_r, D_\theta, D_{r\theta}$	$= E_r h^3/12, E_\theta h^3/12, E_{r\theta} h^3/12$
$E_r, E_\theta, E_{r\theta}$	= elastic constants of the plate material
h	= thickness
r, θ	= polar coordinates
W	= lateral deflection
ρ	= mass per unit area
ϕ^2	$= D_\theta / D_r$
μ^2	$= D_{r\theta} / D_r$
λ^2	$= \rho\omega^2 a^4 / D_r$
ω	= circular frequency
σ_r, σ_θ	= stresses in r, θ directions, respectively
$\epsilon_r, \epsilon_\theta$	= strains in r, θ directions, respectively

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I. Introduction

THE axisymmetric vibration of polar orthotropic circular plates has been studied by several authors, namely, Akasaka and Takagishi,[1] Borsuk,[2] and Pandalai and Patel.[3] However, several inconsistencies appear in the literature cited above, as has been pointed out by Leissa.[4] The purpose of this Note is to expose the crux of the problem. The governing equation of motion and boundary conditions are identified from variational principles, and it is seen that there are four boundary conditions. The problem arises because some authors choose to ignore certain boundary conditions or treat them incorrectly. The problem is worked out using the Lagrangian and the Galerkin approach, and this reveals that an error of qualitative nature can arise in the latter case due to violation of a boundary condition at the origin.

II. Theory

The expression given in Ref. 3 for the lowest cyclic frequency of axisymmetric vibration of clamped orthotropic circular plate indicates that this frequency decreases with increase in the value of ϕ^2. Reference 2 also shows a similar behavior in an example for $\phi = 1.4$, where the frequency is lower than that for the isotropic case ($\phi = 1$). However, the expression for frequency given in Ref. 1 shows that the frequency increases with increase in the value of ϕ^2 as is to be physically expected. In all these references, a series solution was used.

In the present investigation, the axisymmetric vibration of a clamped orthotropic circular plate is considered. The stress-strain relations for the case of polar orthotropic material are

$$\sigma_r = E_r \epsilon_r + E_{r\theta} \epsilon_\theta$$

$$\sigma_\theta = E_{r\theta} \epsilon_r + E_\theta \epsilon_\theta$$

$$\tau_{r\theta} = G \gamma_{r\theta}$$

The Lagrangian function is

$$L = \pi D_r \int_0^a \left(\frac{\rho r W^2{}_{,t}}{D_r} - r W_{,rr}^2 - \frac{\phi^2}{r} W_{,r}^2 - 2\mu^2 W_{,r} W_{,rr} \right) dr$$

Using the Hamilton's principle and assuming $W(x,t) = W(x)\, e^{i\omega t}$, the equation of motion and the boundary conditions are, respectively,

$$W_{,rrrr} + \frac{2}{r} W_{,rrr} - \frac{\phi^2}{r} \left(\frac{W_{,rr}}{r} - \frac{W_{,r}}{r^2} \right) - \lambda^2 W = 0$$

$$r W_{,rr} + \mu^2 W_{,r} = 0 \quad \text{or} \quad W_{,r} = 0 \quad \text{at } r = 0, a$$

$$r W_{,rrr} + W_{,rr} - \frac{\phi^2}{r} W_{,r} = 0 \quad \text{or} \quad W = 0 \quad \text{at } r = 0, a$$

For a clamped circular plate, the usual assumed geometric conditions are

$$W = W_{,r} = 0 \quad \text{at } r = a \tag{1}$$