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Studies on the Flame Structure of a Spray Burner (2nd
Report, Experimental Comparison with the Gas Diffusion
Flame and Discussion on the Behavior of Droplets) *

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It was conjectured in the first report that most of the droplets within the flame do not burn individually, but fuel vapor evaporated from them collects and burns like a gas diffusion flame. The main object of this study is to confirm this conjecture. First, various measurements were made on a spray combustion flame and a gas diffusion flame under the same conditions. Comparing the two sets of data, it was found that the flames are similar in structure. Experiments on five spray combustion flames having different sizes, produced by changing the flow rate of combustion air, were secondly conducted. From the results, the conjecture of the first report was confirmed and it was found that the turbulent diffusion process has much greater influence upon the shape of the flames used in this study than the evaporation process of droplets. Finally, assuming that the droplets simply evaporate within the flame, their behavior was analyzed by making use of the knowledge which has been obtained for a single droplet. The calculated results showed fairly close agreement with the measured results.

1. Introduction

Many experimental and theoretical investigations have been reported on a single droplet burning with an envelope flame or a wake flame and simply evaporating. However, it has not been known in which of the above three conditions droplets are within actual spray combustion flames.

In the previous report⁽¹⁾, the authors emphasized the possibility that most droplets within flames do not burn individually with envelope flames, but a cloud of vapor evaporated from droplets burns like a turbulent gas diffusion flame. The confirmation of this conjecture is the main objective in the present study.

If the above mentioned conjecture is true, the internal structure of spray combustion flames may be considered similar to that of turbulent gas diffusion flames. Then, experimental comparison was conducted between a spray combustion flame and a turbulent gas diffusion flame under the same condition. In the second step, the same measurement as in the previous report was conducted on five flames different in length, produced by changing the flow rate of combustion air, and the behavior of droplets within the flames and

the factors controlling the flame length and width were examined. Finally, the behavior of droplets flying within a flame was analyzed using the evaporation constant and the drag coefficient obtained for a single droplet, and the calculated result was compared with the experimental one.

2. Experimental apparatus

The experimental apparatus is the same as used in the previous study⁽¹⁾. The furnace is an upright one with a square cross section (43×43×114 cm). The slit on the wall is constructed such that the furnace can be closed after inserting various probes through it. An air atomizing type nozzle with a single hole is installed upward at the bottom center of the furnace, and combustion air is introduced through an annular slit around the nozzle in parallel with the spray jet.

3. Experimental comparison of spray combustion flame and turbulent gas diffusion flame

3.1. Experiments

A spray combustion flame and a turbulent gas diffusion flame were experimentally compared under the same conditions. The same apparatus was used and the flow rate of combustion air was the same in the two flames. The spray combustion flame tested is Flame B-3 shown in Table 1. Kerosene was used as fuel. For the gas diffusion flame, pure propane (propane; 99.76 %) was blown from the same nozzle as the above.

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Table 1 Flame condition

Flame		A	B-1	B-2	B-3	B-4	B-5
Flow rate of fuel	cc/s	0.48	0.51	0.51	0.51	0.51	0.51
Flow rate of atomizing air	cc/s	225	238	238	238	238	238
Flow rate of combustion air	l/s	30.6	38.59	21.03	14.11	10.20	8.23
Flow velocity of combustion air	m/s	8.5	10.0	5.5	3.7	2.6	2.2
Air-fuel equivalence ratio		5.81	6.90	3.78	2.55	1.85	1.51
Flame length	cm	53	46	51	55	59	65

The flow rate of propane was 197.6 cc/s and the burner thrust (the momentum of blowing fluid) was the same as for Flame B-3. The heat-release rate was 3.91 kcal/s in Flame B-3 and 4.67 kcal/s in the gas diffusion flame. The length of both flames was almost the same.

3.2. Results and discussion

Figs. 1 and 2 are axial profiles of various measured values in Flame B-3 and in the gas diffusion flame respectively. The ordinate N indicates the number of droplets collected in one operation (diameter of collecting area; 2 mm, shutter opening period; 9.96 ms). The notation HC indicates lower hydrocarbons, having less carbon number than 4, formed by thermal decomposition of fuel. In the gas diffusion flame, the burning reaction occurs a little downstream as compared with the spray combustion flame, because the initial flow velocity of propane is greater than that of kerosene. In the spray combustion flame, the temperature drop downstream is steeper than in the gas diffusion flame, because the emissivity and the radiation cooling rate are higher. The distribution of oxygen concentrations near the nozzle differs, because droplets in the spray combustion flame have not yet vaporized. Though the above differences exist between both flames, it will be seen that the distributions shown in Figs. 1 and 2 are very similar.

The observed length of both flames was almost the same and about 55 cm, which is indicated also by the location where CO comes to extinction in Figs 1 and 2. These two figures show that, though the burning reaction occurs a little farther downstream in the gas diffusion flame, the flame length becomes the same because the decreasing rate of CO concentration is larger in the gas diffusion flame than in the spray combustion flame. The spray combustion flame forms much more soot particles than the gas diffusion flame. It may be considered that CO formed by the combustion of soot reduces the decreasing rate of CO concentration because the reaction rate of soot particles is low.

Figs. 3, 4 and 5 show radial profiles of various values in the P2, P4 and P6 cross sections of the spray combustion flame respectively. Notations P2, P4 and P6 indicate the positions of 10, 20 and 30 cm from the nozzle. Figs. 6 and 7 show radial profiles in the P4 and P6 cross

sections of the gas diffusion flame respectively. It will be seen in these figures that the similarity discussed above holds also for the horizontal cross sections, that is, Figs. 3 and 7 indicate that the tendency of the various profiles is not different and Figs. 3-7 indicate that the

Fig. 1. Various distributions on the flame axis (Flame B-3)

Fig. 2. Various distributions on the flame axis (the gas diffusion flame)

Fig. 3. Various distributions in P2 cross section (Flame B-3)

Fig. 6. Various distributions in P4 cross section (the gas diffusion flame)

Fig. 4. Various distributions in P4 cross section (Flame B-3)

Fig. 7. Various distributions in P6 cross section (the gas diffusion flame)

Fig. 5. Various distributions in P6 cross section (Flame B-3)

changing process of radial profiles is also similar in the two flames. The gas diffusion flame is broader than the spray combustion flame. It may be because the diffusion rate of fuel gas is higher than that of spray droplets.

The above results revealed that axial and radial profiles of various measured values are not different in tendency between the two flames. Then, the inside structure of the spray combustion flame may be considered very similar to that of the turbulent gas diffusion flame.

4. Influence of the flow rate of combustion air on the state within flames

4.1. Experiments

Various measurements were conducted

on five flames different in size, produced by changing only the flow rate of combustion air. The flow rate of fuel oil (kerosene) is 0.51 cc/s and the flow rate of atomizing air is 238 cc/s in all flames. The flames are Flames B-1-B-5 shown in Table 1. It is difficult to measure the flame length because flames constantly fluctuate. The length shown in Table 1 is a length at which it looks to the naked eye as if the flame were always present.

Fig. 8 shows the size distribution of droplets collected on the axis of 25 cm from the nozzle tip for the non-burning spray. Fig. 9 shows the velocity distribution of combustion air at the entrance of the furnace.

4.2. Results and discussion

4.2.1. Droplet behavior in flames

A large flame under comparatively low

Fig. 8. Initial size distribution of droplets in non-burning spray

Fig. 9. Flow velocity of combustion air at the entrance of the furnace

turbulent condition is advantageous for examining the correlation between various distributions within the flame. Then, droplet behavior within a flame was examined using the experimental results on Flame B-5.

Fig. 10 shows various distributions measured in the P2 cross section. Droplet collection in the cross section was not conducted in this experiment, but it is supposed from the experimental result of the previous report that the spatial density profile of droplets in the flame is shown by such a curve as the broken line in Fig. 10, which is similar to a Gaussian distribution having the flame axis as its center. In contrast to the spatial density profile of droplets, the concentration profiles of lower hydrocarbons (HC), CO and CO₂ have two peak points symmetrical to the flame axis and similar to the temperature profile. The peak points of HC, CO and CO₂ are arranged outwardly in this order within the flame. This phenomenon was dimly observed in the flame used in the previous study, and that was slightly mentioned in the previous report. It is considered that the phenomenon became clear in Flame B-5 because the turbulence was low.

Such correlation between various distributions means that most of the fuel vapor from the droplets forms a cloud that diffuses toward the high temperature zone near the outer boundary of the flame, and that this vapor is decomposed into lower hydrocarbons and then oxidized to CO and CO₂. Based on this, it may be concluded that most droplets do not burn individually, but that the vapor cloud evaporated from the droplets burns like a turbulent diffusion flame.

4.2.2. Comparison of the five flames

Fig. 11 shows the number of droplets caught on the axis for the five flames. It

Fig. 10. Various distributions in P2 cross section (Flame B-5)

Fig. 11. Spatial density distribution of droplets on the flame axis

Fig. 12. Temperature distributions on the flame axis

Fig. 13. Flow velocity distributions on the flame axis

is seen that the location where most droplets evaporate is not different for the five flames though the flame length changes from 46 cm to 65 cm. Each point shows the average value taken from a number of operations.

Fig. 12 shows the axial profiles of gas temperature for the five flames. The mark (+) indicates the point of the flame tip shown in Table 1, and the region A indicates the location where most droplets have finished their evaporation. Fig. 13 shows the axial profiles of gas flow velocity. Though the temperature profiles up to the region A were different for the five flames in Fig. 12, the location where most droplets had evaporated was almost the same. It may be because gas flow velocity was different as shown in Fig. 13 and then the flying velocity of droplets was different by the flames. Fig. 14 shows the concentration profiles of various chemical species on the flame axis, only about Flames B-1, B-3 and B-5 for reasons of clarity. The change of flame length is observed in the change of the concentration profiles.

Fig. 14. Concentration distributions of various chemical species on the flame axis

As mentioned above, the experimental result revealed that droplets within the flames only evaporate and a cloud of vapor formed by the droplets burns like a gas diffusion flame. So, it is considered that the spray combustion flames are formed mainly by the droplet evaporation process

Fig. 15. Temperature distributions in P2 cross section

Fig. 16. Concentration distributions of various chemical species in P2 cross section

and the diffusion combustion process of fuel vapor. Though the axial profiles of chemical species concentrations and gas temperature change according to the change of flame length, the spatial density profile of droplets is considered not to change from Fig. 11. In addition, Fig. 11 and the spatial density profiles of droplets in the previous report indicate that the region where droplets exist in considerable spatial density is limited to a small area near the axis up to about 10 cm above the nozzle tip. It is supposed from these two facts that the flames used in this experiment are controlled more strongly by the diffusion combustion process of fuel vapor than by the droplet evaporation process. This conclusion may be applicable to the flames generally used.

Fig. 15 shows radial profiles of gas temperature in the P2 cross section. The hollows on the top of the profiles become deeper and wider with a decrease of the flow rate of combustion air. Figs. 16 and 17 show the concentration profiles of various chemical species in the P2 and P4 cross sections respectively. The flame width could not be measured because of its violent fluctuation, but it is observed from Figs. 16 and 17 that the flame also

Fig. 17. Concentration distributions of various chemical species in P4 cross section

becomes wider with a decrease of the flow rate of combustion air and its changing rate is much larger than that of the flame length. The concentration profiles of chemical species for Flame B-1 are different from the others. It is because the flow velocity of combustion air was much larger in Flame B-1 than in the other flames and high turbulence due to that raised the temperature near the flame axis in the upstream (Fig. 15).

5. Calculation of droplet behavior

As mentioned above, most droplets within the flames are considered only to evaporate. Then, the behavior of the droplets flying with evaporation in the hot flame zone is analyzed using the experimental results obtained for a single droplet. The measured values are used for the gas flow velocity, gas temperature and initial droplet size distribution.

5.1. Calculation procedure

It is assumed that the initial velocity of the droplets is equal to the discharge velocity of kerosene from the nozzle and that the droplets begin to evaporate when their temperature reaches the boiling point. Calculation was carried out on Flame A of the previous report shown in Table 1. Fig. 18 shows the profiles of gas temperature and gas flow velocity on the flame axis with others. Fig. 19 is the initial droplet size distribution obtained from Fig. 12 of the previous report. The ordinate N^* indicates the ratio of the droplets number of each size range to that of 0-10 μm range. In the calculation, the measured droplet size of 0-10 μm , 10-20 μm ... diameter were replaced, respectively, by 5 μm , 15 μm ... diameter.

Fig. 18. Various distributions on the flame axis (Flame A)

The following equations are used:
Motion of droplets:

$$m(dv/dt) = F - mg \quad (1)$$

where m and v are the droplet mass and velocity, t is the elapsed time, F is the drag force and g is the gravitational acceleration.

Drag force:

$$F = \bar{C}_d \{ \rho_g (U - v) |U - v| / 2 \} A \quad (2)$$

where $\bar{C}_d$ is the drag coefficient of an evaporating droplet, U is the gas flow velocity, A is the projected droplet area and ρ_g is the density of the gas.

Change of droplet diameter D :

$$-d(D^2)/dt = k \quad (3)$$

where k is the evaporation constant in forced convection.

Evaporation constant in a stagnant atmosphere⁽²⁾:

$$k_0 = (8\lambda / \gamma_\ell c_p) \ln(1+B) \quad (4)$$

where λ and c_p are the thermal conductivity and the specific heat of the gas, γ_ℓ is the specific gravity of fuel and B is the Transfer Number.

Transfer Number:

$$B = c_p (T_\infty - T_\ell) / L \quad (5)$$

where T_∞ and T_ℓ are the temperature of the environmental gas and the droplet and L is the latent heat of evaporation of fuel.

Evaporation constant in forced convection k ⁽³⁾:

$$k = k_0 (1 + 0.276 Re^{1/2} Sc^{1/3}) \quad (6)$$

where Re is the Reynolds number and Sc is the Schmidt number.

Drag coefficient of a sphere C_d ⁽⁴⁾:

$$C_d = (24/Re) (1 + 0.15 Re^{0.687}) \quad (7)$$

Drag coefficient of an evaporating droplet $\bar{C}_d$ ⁽⁵⁾:

$$\bar{C}_d / C_d = 1 / (1+B) \quad (8)$$

Nusselt number for a droplet in non-evaporating period:

$$Nu = 2 + 0.6 Pr^{1/3} Re^{1/2} \quad (9)$$

Fig. 19. Initial size distribution of droplets (Flame A)

where P_r is the Prandtl number.

The values of air at the arithmetical mean of the temperatures of droplet and environmental gas were used for the physical properties such as λ , c_p and ρ_g .

Calculation was conducted also on the droplet burning with an envelope flame. In this case, the Transfer Number is given as follows(2):

$$B = \{c_p(T_\infty - T_d) + y_{ox}Q/\epsilon\}/L \quad (10)$$

where y_{ox} is the mass fraction of oxygen and ϵ is the stoichiometric oxygen-fuel ratio and Q is the heat of combustion of fuel. The measured value (Fig. 18) was used for the mass fraction within the flame. Several workers have proposed different ways to decide physical properties in the case of a single droplet burning in an envelope flame, and it is an open question how to take the temperature of the envelope flame (T_f) in the present case. However, after trying various methods, it was known that the calculated results are almost the same in all methods. Then, a value of 1700 °C was taken as the temperature of the envelope flame and the values of air at the temperature of $(T_\infty + T_f)/2$ were used for the physical properties.

5.2. Calculated results and discussion

Fig. 20 shows the calculated flying velocity of droplets and the gas velocity measured on the axis. As mentioned in the previous report, the experimental measurements revealed that most droplets vaporize up to 25 cm above the nozzle tip (Fig. 9 of the previous report). Fig. 20 shows that the droplets with an initial diameter of 115 μ m just vaporize at that position. This appears reasonable based on the initial size distribution shown in Fig. 19.

Fig. 21 shows the calculated evaporation rate. In this calculation, the droplets reaching 10 μ m in diameter were regarded as fuel vapor because it has been reported(6)(7) that droplets smaller than about 10 μ m burn like fuel vapor. The

Fig. 20. Calculated flying velocity of droplets in the flame; $\downarrow$ Point where droplet begins to evaporate; $\uparrow$ Point where droplet diameter becomes 10 μ m

solid line in Fig. 22 shows the integrated quantity of evaporated fuel vapor calculated from Fig. 21. It is seen in this figure that evaporation of the spray is almost complete up to 30 cm from the nozzle tip, though the flame extends to 53 cm. The calculated results shown in Figs. 21 and 22 indicate good agreement with the measured axial profile of lower hydrocarbons concentration in Fig. 18. The broken line in Fig. 22 shows the result calculated under the assumption that droplets burn with envelope flames. It is seen that the broken line is not so different from the solid line.

Fig. 23 shows the evaporation constant and the burning constant of the droplets flying within the flame. The two constants are different from each other in the upstream where gas temperature is low and oxygen concentration is high, and they are not so different in the downstream where gas temperature is high and oxygen concentration is low. As shown in Fig. 20, comparatively large droplets do not reach the boiling point in their temperature in the upstream and begin to evaporate in the downstream. This may be the reason why the calculated result for burning droplets is not so different from that for evaporating droplets in Fig. 22.

Fig. 21. Evaporation rate of fuel calculated on the spray in the flame

Fig. 22. Integrated quantity of evaporated fuel vapor

Fig. 23. Evaporation and burning constants calculated on the droplets flying in the flame

Fig. 24. Reynolds number calculated on the droplets evaporating in the flame ; ↓ Point where droplet begins to evaporate; ○ Point where droplet diameter becomes 10 μm

Fig. 24 shows the Reynolds number for the droplets flying with evaporation. It is seen that even a small droplet has a considerable Reynolds number.

6. Conclusions

It was supposed from the result shown in the previous report that droplets only evaporate within flames and a cloud of fuel vapor formed by the droplets burns like a diffusion flame. To confirm this supposition, experiments and an analysis on droplet behavior were carried out in this study. The conclusions are as follows:

(1) Since the various distributions measured in the spray combustion flame and

the turbulent gas diffusion flame under the same conditions are very similar, it may be considered that the internal structures of both flames are very similar. This result appears to support the above mentioned supposition.

(2) The correlation between the various distributions in the cross section were examined on the flame which is mildest in turbulent mixing. As the result, the supposition of the previous report that most droplets only evaporate and evaporated vapor burns like a turbulent diffusion flame was almost confirmed.

(3) Therefore, it seems that the spray combustion flame is formed mainly by the evaporation process of droplets and the diffusion combustion process of fuel vapor.

(4) In the experiment on the five flames different in length, produced by changing the flow rate of combustion air, though the profiles of chemical species concentrations and gas temperature changed according to the change of flame length, the spatial density profile of droplets scarcely changed. Considering this fact and that the region where droplets considerably exist is limited to a small area above the nozzle tip, the flames used in this study appear to be controlled more strongly by the diffusion combustion process of fuel vapor than by the droplet evaporation process.

(5) Assuming that droplets fly with evaporation in a flame, their behavior was analyzed using the information obtained for a single droplet and the measured gas temperature and velocity. The calculated and experimental results were in good agreement.

The above conclusions suggest that it may be possible to treat the spray combustion flame theoretically by applying the information for a single droplet and for the turbulent gas diffusion flame.

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