621. 436. 05 : 662. 612. 3

Study on the Burning of a Fuel Drop in Heated and Pressurized Air Stream*

(1st Report, Experiment)

By Hiroshi SAMI** and Mitsunobu OGASAWARA***

As a clue to elucidating the combustion process in diesel engines, the burning characteristics of a fuel drop in heated and pressurized air stream was studied experimentally. Its pressure was varied from 0.4 to 16 ata, its temperature, from the room temperature to 600°C, and its velocity, up to the transition velocity where the flame shape changes from envelope type to wake type. The fuel drops were simulated by porous spheres transpired liquid fuel. As the fuel, methanol, *n*-butanol and kerosene were used. Under these conditions, the flame shape, the burning rate $\dot{m}$, and the flame transition air velocity U_c were measured. Among the results of measurement, main ones concerning the influence of temperature and pressure are as follows. When the temperature is raised, U_c rapidly increases, but $\dot{m}$ scarcely changes. When the pressure is raised with the velocity, $\dot{m}$ increases remarkably. And when the temperature and the pressure are raised, flame becomes long and the soot formation increases.

1. Introduction

For diesel engines and oil-burning devices, spray combustion system has been broadly adopted. For the reason that the droplet combustion is an elementary phenomenon of spray combustion, and its knowledge will offer a clue to elucidating the mechanism of diffusion combustion between liquid phase and gas phase, many studies have been performed on the droplet combustion.

The authors' interest is in the combustion phenomena in a direct injection diesel engine, where droplets are injected intermittently into hot and highly pressed air. Paying attention to a single droplet in the spray, the following phenomena will occur. (i) It flies through hot and highly pressed air. (ii) Its temperature will rise toward the equilibrium temperature of evaporation. (iii) Evaporated fuel vapor and surrounding air will inter-diffuse, and ignition will take place near the point having a stoichiometric mixture ratio. (iv) In a moment, the droplet will be surrounded by flame, and its temperature will rise toward the equilibrium temperature of combustion. (v) Due to evaporation, the droplet decreases in diameter and finally burns

out.

In the above process, the following problems remain unclarified. (1) It has been generally supposed that, for a fine droplet, the effect of relative velocity between droplet and air on the combustion characteristics is negligible. But, there is no solid foundation for this fact. (2) It has been generally assumed that, up to the time of self-ignition, physical and chemical ignition lags appear in series. However, the mechanism of ignition lag remains not fully clarified. (3) When the air stream velocity (or the relative velocity between droplet and air) exceeds a critical value, the envelope flame suddenly changes to a wake flame, and the burning rate decreases abruptly. Reports on this transition air velocity are scarcely found. (4) It is well known that the droplet diameter decreases at such a rate as to keep the reduction rate of the surface area constant. This rule can be applied to the case of a relatively large droplet, where its burning can be considered as a quasi-steady process. For a fine droplet, such simple relation loses its validity, because the transient property becomes remarkable. (5) In the case of a diesel engine, fuel is injected into air whose pressure is exceeding the critical pressure of the fuel. Under such circumstances, the transient property will become more remarkable.

In this work, the authors took up the items concerning the burning rate, the flame shape and

* Received 17th September, 1968.

** Engineer, Toyota Motor Co., Ltd.

*** Professor, Faculty of Engineering, Osaka University, Suita.

the flame transition air velocity among the problems above mentioned, and studied the effect of temperature and pressure upon them. On the effect of air temperature under atmospheric pressure, some experiments have been reported already. But no experiment with various air temperatures and pressures has been conducted.

In this 1st Report, results of experiments, which were conducted with various temperatures (from the room temperature to 600°C) and pressures (0.4 ~ 16 ata) are shown. In the 2nd Report, empirical formulas having the theoretical basis are derived for the burning rate and the flame shape. In the 3rd Report, the condition determining the flame transition is considered theoretically and the experimental results of transition velocity are summarized into an empirical formula.

2. Experiments

In order to measure the burning rate, the flame shape and the flame transition air velocity for a fuel drop placed in heated and pressurized air stream, the experiments were carried out under the following air stream conditions.

Experiment I—

- ① Porous sphere
- ② Combustion chamber
- ③ Inlet duct
- ④ Surge tank
- ⑤ Rotary blower
- ⑥ Thin tube
- ⑦ Fuel tank
- ⑧ Float chamber
- ⑨ Glass tube for measuring the burning rate
- ⑩ Syringe
- ⑪ Anemometer
- ⑫ Wire gauze
- ⑬ Acrylite window
- ⑭ Camera
- ⑮ Thermocouple
- ⑯ Manometer
- ⑰ Cock

Fig. 1 Experimental apparatus (Experiment I, negative pressure experiment)

Temperature: the room temperature,

Pressure: 0.4 ~ 1.8 ata

Experiment II—

Temperature: the room temperature ~ 500°C,

Pressure: the atmospheric pressure

Experiment III—

Temperature: up to 600°C,

Pressure: up to 16 ata

The air velocity was varied up to the transition velocity. As fuels, methanol, *n*-butanol and kerosene were used, but, in Experiment II, kerosene was omitted.

2.1 Experimental apparatus

[Experiment I] Figure 1 shows the apparatus used for the negative pressure experiment. Following Agoston et al.⁽¹⁾, porous alundum sphere ① was used as the kernel for a fuel drop. It was set at the center of the combustion chamber ②. Fuel was fed from the tank ⑦ to ①, passing through the float chamber ⑧ and the glass tube ⑨. Fuel flow was controlled by changing the level of ⑧. Its flow quantity was measured from the time required for a bubble to travel between two indices on the glass tube ⑨. The bubble can be inserted into ⑨ at any time. On the relation between the flow quantity and the time required, calibration has been conducted. A thin stainless steel tube was inserted into the alundum sphere and bound together by the dental cement. In Table 1, dimensions of these tubes are shown corresponding to those of spheres. Air stream velocity in the combustion chamber was calculated from the air quantity flowing through the inlet duct ③, in which the thermometer ⑮ and the anemometer ⑪ were installed. The flame shape and its transition were observed through acrylite windows.

In the positive pressure experiment, the above apparatus was reconstructed as follows. To the lower and upper ends of combustion chamber, the outlet of the surge tank ④ and the outlet duct similar to ③ were connected, respectively. Thus, air from the blower ⑤ flowed through the surge tank, the combustion chamber and the outlet duct. In this case, air flow quantity was found by measuring the temperature and velocity of air in the outlet duct, neglecting the volume occupied by evaporated vapor and the change of mole quantity due to combustion.

Table 1

Sphere diameter	Outer diameter of thin tube
2.5 mm	0.4 mm
5	0.6
7~10	0.8~1

[Experiment II] One part of the apparatus is shown in Fig. 2. This was reconstructed from the apparatus shown in Fig. 1, by reconnecting the blower to the right of (3), through the surge tank. The other modifications are as follows. (1) Between surge tank and combustion chamber, the air heaters (19) and (20) were provided. (2) The duct between (20) and combustion chamber was made of stainless steel, preparing for the Experiment III. (3) To prevent the boiling, a thin fuel tube (6) was cooled by water. (4) As the porous sphere, a spherical copper shell with many fine holes was used, with the intention of examining the effect of kernel material on the burning rate. (5) Ignition device made of nichrome wire was provided.

The temperature of air stream at the outlet of

①~⑦ Same as Fig. 1
⑧ Nozzle
⑨ Air heater
⑩ Air heater
⑪ Air heater
⑫ Air heater
⑬ Nozzle
⑭ Ignition device
⑮ Air heater
⑯ Ignition device
⑰ Air heater
⑱ Ignition device
⑲ Air heater
⑳ Ignition device
㉑ Air heater

Fig. 2 Experimental apparatus (Experiment II)

nozzle was measured by chromel-alumel thermocouple and its velocity was calculated from the flow quantity measured by the anemometer (14). Two nozzles of 33 and 70 mm caliber were used.

The experiments were conducted by varying air velocity under each constant air temperature. The air temperature was controlled by the air heater (20).

[Experiment III] Apparatus shown in Fig. 2 was modified as follows. To the right of the heater (20), a reducing valve, a surge tank and air bottles were joined. The bottles (47 l x 7), filled with 100 at. air initially, were made to serve as the air source. The air, adjusted to a desired pressure by means of the reducing valve, flows into the heater. Though the pressure in the air bottles decreases with the flow, an air stream having the flame transition air velocity under 16 ata was maintained stationary during 10 minutes by this apparatus. During this period, all the readings must be obtained. After that, the bottles must be refilled with air. Fuel flow was varied by controlling the pressure acting in the fuel tank. By changing the fuel path from the tank to the inclined bypath, the flow rate was measured from the falling speed of level in it. The flow rate of burned gas was measured in a duct, similar to the duct (3) shown in Fig. 2, which was joined to the cooler set up at the outlet of combustion chamber.

2.2 Preliminary tests

Prior to the experiments, (1) the velocity distribution, (2) the temperature distribution, (3) the variation of temperature with air velocity and (4) the variation of pressure with air velocity,

	1	2	3	4	1'	2'
d mm	5.0				2.5	
U m/sec	0.25	0.70	1.11	3.49	0.44	0.80
p_a ata	Atmospheric pressure				0.5	
t_a °C	Room temp.				Room temp.	
R_{ea}	89	256	407	1238	38	68

d : sphere diameter
 U : air velocity
 p_a : ambient pressure
 t_a : ambient temperature
 R_{ea} : R_e defined under the ambient condition

Fig. 3 Flame photographs (Experiment I, methanol)

	1	2	1'
d	10.0		2.5
U	0.24	1.18	0.35
p_a	1.35	1.33	Atmospheric pressure
t_a	Room temp.		Room temp.
Re_a	226	1066	63

Fig. 4 Flame photographs (Experiment I, *n*-butanol)

were measured and tested at the test section where the porous sphere is to be placed. Of these items, (1) and (2) were measured by an anemometer and a $50\mu\phi$ platinum-platinum rhodium thermocouple, respectively. By these tests, both distributions were confirmed to be nearly constant. As for the items (3) and (4), although the temperature and pressure were slightly decreased with the increase of air velocity, it was confirmed that this apparatus would be available for the experiment, if these results were used as the calibration curves.

	1	2	1'	2'
d	5.0		2.1	
U	0.21	1.22	0.42	2.49
p_a	Atmospheric pressure		Atmospheric pressure	
t_a	300		422	428
Re_a	21	127	13	77

Fig. 6 Flame photographs (Experiment II, methanol)

	1	2	1'
d	4.9		2.5
U	0.29	0.56	0.17
p_a	1.74	1.67	Atmospheric pressure
t_a	Room temp.		Room temp.
Re_a	175	308	30

Fig. 5 Flame photographs (Experiment I, kerosene)

	1	2	1'	2'
d	5.0		2.1	
U	1.22	2.27	0.76	2.36
p_a	Atmospheric pressure		Atmospheric pressure	
t_a	300		460	437
Re_a	127	234	22	70

Fig. 7 Flame photographs (Experiment II, *n*-butanol)

3. Results of experiments

3.1 Observations on the flame

Typical flame photographs are shown in Figs. 3~9. From these photographs and direct observations, the following facts were found.

	1	2	1'	2'
d	5.1		2.2	
U	0.72	1.67	0.38	1.49
p_a	16.3	16.5	15.9	15.0
t_a	585		488	373
R_{ea}	633	1490	170	820

Fig. 8 Flame photographs (Experiment III, methanol)

	1	2	1'	2'
d	5.2		2.2	
U	0.52	1.79	0.40	1.26
p_a	6.5	5.9	16.6	15.8
t_a	339	313	327	278
R_{ea}	320	1080	376	875

Fig. 9 Flame photographs (Experiment III, *n*-butanol)

(1) When the air velocity was increased under a constant pressure, the upper part of flame became longer and the lower part of it approached the drop surface. At the transition velocity, the envelope flame changed suddenly into a wake flame and the flame height was reduced to $1/3 \sim 1/4$ of the former. At the air stream velocity of a few times the transition velocity, the flame was blown off. Ratio of the blow-off velocity to the transition

Fig. 10 Burning rate (Experiment I, methanol)

Fig. 11 Burning rate (Experiment I, *n*-butanol)

Fig. 12 Burning rate (Experiment I, kerosene)

velocity was increased with pressure and drop diameter. When a drop having a diameter of 2.5 mm was placed in a low pressure stream of 0.5 ata, the flame transition and blow-off were observed at the same time. Under all circumstances, the tail of flame became turbulent violently at a certain air velocity. This critical velocity was higher or lower than the transition velocity, depending on the circumstances i.e. whether the temperature and

pressure of air stream were low or high.

(2) The lower the pressure and temperature, and the smaller the drop diameter, the flame shape came the closer to the spherical one. Methanol flame of 2.5 mm ϕ drop was observed nearly as a sphere, when the pressure, temperature and air velocity were kept at 0.35 ata, the room temperature and 0.75 m/sec, respectively.

(3) Regarding the brightness of flame, the following facts were observed. When methanol was burned in air stream under the room temperature and vacuum pressure, a very faint blue flame was observed.

Fig. 13 Burning rate (Experiment II, methanol)

(a) $p_a = 6 \text{ ata}$

(b) $p_a = 16 \text{ ata}$

Fig. 14 Burning rate (Experiment III, methanol)

Fig. 15

(a) $p_a = 6 \text{ ata}$

(b) $p_a = 16 \text{ ata}$

	t_a °C		t_a °C
○	150~200	△	350~450
×	300~350	□	500~600

Fig. 16 (Experiment III, methanol)

When the pressure was raised, it became yellow, and glittered at 16 ata. With the air temperature raised, this tendency was promoted. In the case of *n*-butanol being burned at an atmospheric pressure, the flame tail glittered brightly and the neighborhood of drop surface was colored in faint blue. The bright region was enlarged with pressure. At 16 ata, the whole flame bright and the soot was formed. The soot formation was intensified with air temperature. In the case of kerosene, the flame glittered brightly and soot was formed even in the

atmospheric condition.

Generally, the color of flame changes from faint blue to bright yellow accompanied with soot, according to the increase of pressure, temperature, drop diameter and carbon contents of fuel.

3.2 Burning rate, $\dot{m}$ mg/sec

Some experimental results of $\dot{m}$ are shown in Figs. 10~14. The data measured under atmospheric pressure agree well with those obtained by Agoston et al.⁽¹⁾ The air velocity U , corresponding to the dotted line, is the transition velocity. From these figures, the following facts are known.

(1) $\dot{m}$ increases with air velocity, pressure and drop diameter. When one of these three factors is varied, the larger the values of the remaining two factors, the larger the varying rate of $\dot{m}$. Though the effect of air temperature is slight, $\dot{m}$ increases a little with it.

(2) $\dot{m}$ is not so much affected by the kind of fuels used, if air velocity, pressure and drop diameter are each kept the same.

(3) $\dot{m}$ decreases abruptly when air velocity exceeds the transition velocity. With further increase in the air velocity, $\dot{m}$ increases slightly again.

3.3 Flame shape

In the present study, the flame shape was defined by the dimensions shown in Fig. 15. Out of the

Fig. 17 (Experiment III, methanol)

Fig. 18 Relation between flame transition air velocity U_c and $p_a d$ (Experiment I)

Fig. 19 Flame transition air velocity (Experiment II)

results measured on them, only l_1 and l_2 of the methanol flame in Experiment III are shown in Figs. 16 and 17. The rest will be shown in summarized form in the 2nd Report. From these results, the following facts are known.

(1) According as the air velocity, pressure and drop diameter increase, the flame becomes slender. According as they decrease, the flame approaches spherical shape, as mentioned in 3.1. The whole size of flame is nearly proportional to the drop diameter, but l_1 is rather smaller than l_2 . The effect of surrounding air temperature upon the flame size is negligible.

(2) When the temperature and pressure are low and the drop diameter is small, h increases with air velocity. But, when these values are increased, h attains a maximum at a certain air velocity, and then decreases slightly. If the test conditions are the same, h increases stepwise in the order of methanol, *n*-butanol and kerosene, that is, according as the carbon content increases.

3.4 Flame transition air velocity, U_c m/sec

Experimental results of U_c are shown in Figs.

18~21. In Fig. 18, U_c obtained from Experiment I is plotted as a function of $p_a d$, in which p_a means the surrounding air pressure. Among these data, results obtained under the atmospheric pressure are in good agreement with those obtained by Agoston et al.⁽¹⁾ From these figures, the following facts are known.

(1) Generally, U_c increases with drop diameter. According as the pressure rises, U_c increases to a maximum, and then decreases. With a rising temperature, U_c steps up in the order of kerosene, *n*-butanol and methanol. That is, an envelope flame of the fuel having high carbon content shifts easily to a wake flame. (3) Spalding⁽²⁾⁽³⁾ measured U_c for relatively large spheres of 7~25 mm in diameter under the atmospheric pressure, and summarized the results into a simple relation that U_c/d is constant. But this relation does not agree well with our results shown in Fig. 18. This problem will be treated in the 3rd Report.

Fig. 20 Flame transition air velocity (Experiment III, methanol)

4. Examination on the method of experiment

4.1 Effect of the kernel on the burning rate

Though a porous sphere was used as the kernel in this experiment, it is needless to say that the object of this study is the burning of a fuel drop itself. Since the kernel was used for the purpose to increase the accuracy of measurement by making the flame stationary, this method becomes meaningless if the burning is affected by it. So the following examinations were performed, though this method has been often used.

(1) In the first place, the magnitude of error which may be caused by the sphere kernel by absorbing the radiant heat from the surrounding flame was examined. For this purpose, the burning constants measured by the sphere kernel method and by the drop suspension method were compared. The burning constant k_b is defined as

$$k_b = (4/\pi\gamma_l)(\dot{m}/d)$$

where γ_l is the specific weight of fuel. The compared result is shown in Fig. 22. From this figure, it may be found that the sphere kernel method has nearly the same reliability as the drop suspension

method.

(2) Secondly, the effect of the kernel material was examined. For this purpose, the results of experiments which were conducted with the alundum sphere in one case and the hollow copper sphere with many fine holes in the other case were compared. Both results are shown in Fig. 23. In this figure, there is no significant difference between them.

4.2 Effect of the natural convection

As will be mentioned in the 2nd Report, the effect of natural convection can be estimated by a factor $g^* = gd/U^2$, where g is the gravity constant, and the effect decreases with g^* . In Fig. 23, the results of two experiments conducted with upward and downward air streams are shown together. In this figure, it is difficult to distinguish them. According to Agoston et al., when U exceeds 0.2 m/sec for a drop of $d=0.01$ m, the effect of natural convection on the burning rate becomes negligibly small. Putting these values into g^* , it may be concluded

Fig. 21 Flame transition air velocity (Experiment III, *n*-butanol)

Fig. 22 Experimental results concerning burning constant versus droplet diameter

that, for U m/sec exceeding $2\sqrt{d}$ (denote d in m), the effect of natural convection is negligible. The present experiments were conducted under such conditions.

5. Conclusion

In order to get the fundamental knowledge on the burning characteristics of a single droplet in a spray injected into the combustion chamber of diesel engine, the burning rate, the flame shape and the flame transition air velocity of a fuel drop burning steadily in the air stream were measured by means of the sphere kernel method. The experiments were conducted on three kinds of fuel (methanol, *n*-butanol and kerosene) under various conditions of air stream. The pressure was varied from 0.4 to 16 ata, the temperature, from the room temperature to 600°C, and the velocity, up to the flame transition air velocity. The experimental results were plotted on the figures. They will be further discussed in the following reports.

	Kernel	Direction of air stream	Drop diameter mm	
●	Copper sphere	Upward	10.0	Authors
⊙	Alundum sphere	Upward	10.0	
▽	Alundum sphere	Downward	9.52	Agoston et al. ⁽¹⁾

In atmospheric condition

Fig. 23 Comparison of burning rates when alundum sphere and copper sphere were used as the kernel

References

- (1) G. A. Agoston et al.: *6th Symp. on Combustion*, (1955), p. 708.
- (2) D. B. Spalding: *4th Symp. on Combustion*, (1953), p. 847.
- (3) D. B. Spalding: *Fuel*, Vol. 32 (1953), p. 169.
- (4) G. A. E. Godsava: *4th Symp. on Combustion*, (1953), p. 818.
- (5) M. Goldsmith: *Jet Propulsion*, (1956-3), p. 172.
- (6) H. Isoda and S. Kumagai: *7th Symp. on Combustion*, (1958), p. 523.