AN EXPERIMENTAL STUDY ON THE EVAPORATION OF FREELY FALLING DROPLET UNDER HIGH TEMPERATURE AND HIGH PRESSURE GAS STREAM

Sung Sik Chung* and O. Kawaguchi**

(*Received June 18, 1990*)

An experimental apparatuses and measuring system have been made to obtain characteristics connected with evaporation, ignition delay, combustion of a freely falling liquid fuel droplet in high temperature and high pressure gas stream. In this study some systematic experiments were performed to test the utility of the system. The newly devised apparatus was ensured reliability and utility from the tentative experimental results.

Key Words: Droplet, Droplet Generator, Evaporation Rate Constant, Critical Evaporation Constant.

NOMENCLATURE

D,d	: Droplet diameter
dn	: Rudy orifice inner diameter
E	: Voltage
Keo	: Critical evaporation constant
keo_p	: Critical evaporation constant at constant temperature
keo_T	: Critical evaporation constant at constant pressure
Mf	: Evaporation rate under forced convection
Ms	: Evaporation rate in absence of convection
Nu	: Nusselt number
Pa	: Environment gas pressure
Re	: Reynold number
Sc	: Schmidt number
Ta,t	: Environment gas temperature, Time
tc	: Constant voltage period
tf	: Voltage-fall-down period
tr	: Voltage-rise-up period
Vd, Va	: Droplet velocity, Environment gas velocity
Z	: Distant of measuring section
σ	: Turbulence intensity

Superscript

$-$	: Mean

Subscript

0	: Initial
10	: Mean of ten droplets

1. INTRODUCTION

In the current stage spray combustion of liquid fuel is not sufficiently known yet while practical combustors widely utilize liquid fuel. It comes from the complexity of chemical and physical process of liquid spray combustion, which is an obstacle to improve and optimize combustion systems.

There exist two experimental approaches for analyzing spray evaporation and combustion. One of them is to observe and analyze the phenomena from the global view point and to treat the burning fuel spray in a mass. In another approach individual liquid droplets in the spray are followed on their process and fixed droplets or freely falling droplets are observed and analyzed. Each one has merits and demerits, but the selection must be done depending on whether one emphasizes easiness of measurements and analysis or better aproximation to the real combustion phenomena.

From this point of view, Kawaguchi et al.(1986) have measured characteristics of evaporation, ignition, and combustion of continuously falling free combustible fuel droplets in an electrically heated hot gas stream at atmospheric pressure. Similar studies have been performed by Felnandes Pello(1981), and C.K. Law(1984), but they introduced a fuel droplet array to a premixed flame and the post combustion zone where the temperature and gas composition could not be freely fixed, and consequently the influence of environment condition could not be sufficiently discussed. In the present work the environment condition can be controlled almost freely and its influence on the characteristics of liquid droplets can be examined through a wide range of conditions.

Combustible liquid droplets flowing in a hot gas stream are pursued using an optical and electrical technique and the size, as time process, are measured to obtain the data evaporation, ignition delay and combustion. The freely falling droplets are generated by a droplet generator using a piezoelectric transducer and the droplet size can be made to the same order as that of droplets in a fuel spray.

In this paper, after explaining to the utility of the experimental aparatus, the measurement techniques are presented with some examples of measured data.

2. EXPERIMENTAL APPARATUS

2.1 Specification

In the spray combustion each fuel droplet injected form a

*Departmet of Mechanical Engineering, Dong-A University, Pusan, 604-714, Korea
**Faculty of Science and Technology Keio University, Yokohama 223, Japan

fuel injector is exposed to an environment whose temperature and composition vary in wide ranges as the droplet flies to the downstream region. Accordingly, the experimental apparatus for obtaining the physical or chemical characteristics of fine droplets is necessary to realize a similar environment to the practical one.

Chigier(1973) and Kawaguchi(1982) have measured the structure of a spray flame stabilized with a recirculation zone and obtained the behaviors of fuel droplets. Their results showed that the gas temperature of droplet environment in the vicinity of fuel injector is about 1050K at most, and any droplets hardly exist in the hot and burning region in the spray flame, which disappear due to evaporation prior to combustion. Based on the experimental results, the highest temperature which needs to be fixed in the experiments is around 1050K.

Droplets immediately after being ejected from the fuel injector are surrounded by air. As the droplet flies to the downstream, the fuel vaporizes from the surface of each droplet to the environment where the partial pressure of fuel vapor increases as time passes. After the droplet ignited, it is surrounded by intermediated and final products of chemical reaction and thermally decomposed fuel. In the spray flame stabilized by a recirculation region ejected droplets penetrate into the hot combustion gas flowing upstream.

In this way, the environment of fuel droplets vary from air to combustion gas. This apparatus, therefore, was designed to control the compostion of the environment gas flowing in it to simulate a condition of spray combustion by mixing various pure gases.

2.2 Experimental Apparatus

Figure 1 shows the experimental apparatus prepared for this investigation. The main portion of the structure folded by a carbon steel tube is designed to endure a high pressure up to 1MPa. It consists of a heating section, a measuring section and a heat recovering section.

Gas supplied to the apparatus, from outside and fixed the composition and flow rate, is preheated at the heat exchanger before being sent to the heating section. The heating section is made of heat resisting cement having a gas passage inside. Supplied gas flowing in the passage of heating section is reheated to a desired temperature by electric heaters fixed in it. The heated gas flows into the measuring section after a velocity profile reformed through a smoothing passage. The flowing passage of the measuring section is made of ceramic parts having a circular cross section of 50mm in inner diameter and has an electric heater in the wall to prevent the gas stream from cooling down. Quartz glass plates of 10mm in width and 300mm in length are attached to the vertical openings of the passage and Pyrex glass plates of 35mm in width and 350mm in length are installed on the observing windows of the measuring section so as to measure the droplet profiles from the outside.

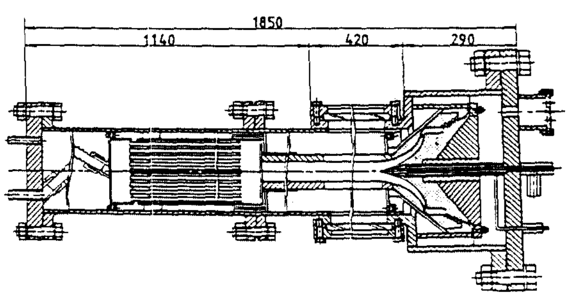


Fig. 1 Experimenttal apparatus

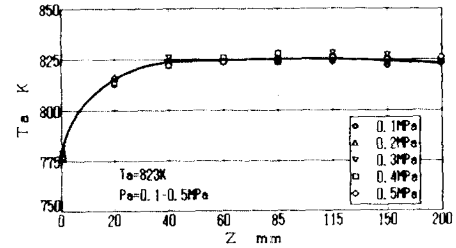
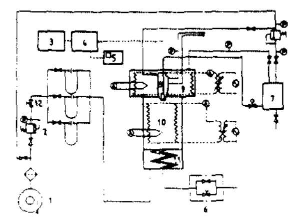


Fig. 2 Environment temperature distribution along the axis of the measuring section



1. Screw compressor
2. Pressure control valve
3. Amplifier
4. Trapezoid-pulse generator
5. Oscilloscope
6. Pressure control valve
7. Fuel tank
8. Cooling jacket
9. Heating section
10. Measuring section
11. Heat recovering section
12. Needle valve
13. O_2 bomb
14. N_2 bomb
15. CO_2 bomb

Fig. 3 Experimental system

An example of the temperature profiles along the central axis of the measuring passage is shown in Fig. 2, which are measured with a suction pyrometer installed by K type (CA) thermocouple. The uniformity of the temperature is almost satisfactory through the measuring passage, while there exists a temperature rising-up region near the central nose cone where the droplet generator surrounded by a water jacket is included inside.

A fine fuel droplet array emitted from a droplet generator installed in the center of the heating section is dropping into the hot gas stream and is observed by an optical system from the outside through the glass windows. Individual droplets of the droplet array are photographed to measure the size afterwards using an optical system with a back light source synchronized with the droplet generating time interval. Time histories of reducing droplet size are utilized to estimate the evaporation or combustion coefficients.

Figure 3 displays the whole system for the experiments including the flow line to supply environment gas and the liquid fuel supplying line. Various pure gases can be supplied from pressurized containers after being measures the flow rates. The gas temperature in the measuring section is automatically controlled by adjusting the electric current of the heater based on the reading of the thermocouple.

2.3 Droplet Generator

There have been several different generating methods devised for the fundamental studies of the spray combustion. In the present work the method using a piezoelectric trans-

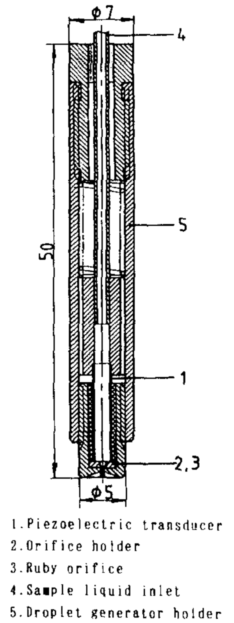


Fig. 4 Droplet generator

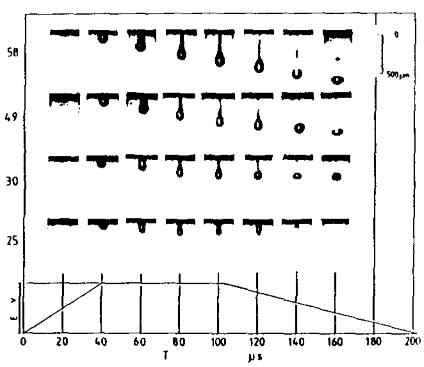


Fig. 5 Pictures of generating deoplets

ducer was chosen, because the generated droplet size is of the same order as those of a practical spray, and also the diameter and time interval of generation can be controlled in a wide range. The repeatability of the size and velocity is also excellent. The authors have improved the droplet generator developed by Honoki (1985) et al. to be suited to the present work.

Figure 4 shows a cross section of the droplet generator, The piezoelectric transducer made of nickel plated ceramics has dimensions of 1.1mm in inner diameter, 2mm in outer diameter and 12mm in length. At the tip of the generator, a ruby orifice of 100μm in hole diameter is mounted to a orifice holder. Liquid fuel is fully charged in the device without including any gas bubbles.

Intermittent trapezoidal electric signals force the piezoelectric transducer to contract to the radial direction intermittently so that the pressure waves arose push out the liquid to the outside through the orifice. Figure 5 shows some pictures of generating droplets taken by successive back lights. The way of droplet generation by the electric signal is classified into two categories, that is, plural droplets genera-

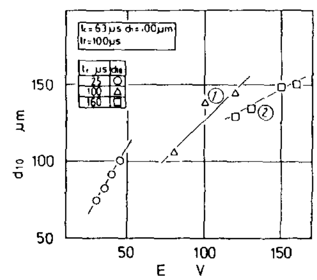


Fig. 6 Relations of impressed voltage and droplet diameter

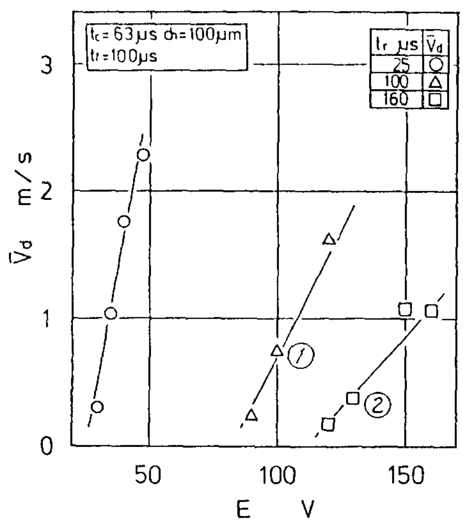


Fig. 7 Relations of impressed voltage and droplet velocity

tion and isolated droplet generation due to the time-to-voltage relation suplied to the piezoelectric transducer. It is possible to control the droplet diameter and velocity by adjusting the voltage-rise-up period, tr, constant voltage period, tc, voltage-fall-down period, tf, and the voltage value of the signal. Figures 6 and 7 show the diameter and velocity of initial droplet as functions of the impressed signal voltage, respectively.

3. EXPERIMENTAL METHOD

3.1 Environment Gas Condition

The environment gas condition is desired to be simplified as much as possible to analyze the data obtained afterwards. At the measuring section, the environment gas temperature is to be settled constant from the droplet appearing position to the disappearing position. The gas velocity is fixed to 1.5m/s so as to be almost equal to the initial droplet velocity so that the relative velocity is small enough to neglect its influence on the evaporation and combustion rate. Droplets generated from the generator are so fine and steady that, the effect of the relative velocity on the physical process may be very small.

In a case of higher pressure than atmospheric pressure, the gas velocity can be controlled by adjusting the inlet pressure control valve, needle flow valve and outlet needle valve. The gas pressure is fixed in the range of 0.1 to 0.5MPa and the gas temperature in the range of 623 to 1023K.

3.2 Diameter and Velocity Measurement

Droplets are to be measured accurately in their diameter and velocity along the flying route in order to estimate the evaporation and combustion rate constant. A specially devised optical and electrical system schematically shown in Fig. 8 is used to measure the diameter and velocity of droplet flying in the measuring section.

Two electrically controlled flash units are prepared and the optical axes agree with each other by means of a half mirror. Cyclic trapezoid electric signals from an oscillator make the piezoelectric transducer of droplet generator contract and generate a fine droplet array, and the signals also operate two flashing light units successively after a certain time delay from individual droplet generating singals set by individually connected time retarders. Since the flash signals and droplet signals are synchronized, the flying droplets are observed from the observing window just like two standing droplets and double-exposed on a 35mm still film with a telephoto lens. The exposed 35mm film is magnified on a screen and the droplet velocity can be estimated from the spacing of double-exposed droplet images and the flashing time interval. The droplet diameter, of course, can be measured from the image but when double-exposed images are not clear, films exposed by single flashes are analyzed to measure the diameter.

When using a pure material as the liquid fuel, the droplet is, first of all, heated up in the hot environment and then the droplet diameter increases a little due to swelling. After the surface reaches the temperature close to the boiling point, the steady evaporation starts and the diameter decreases. It is well-known that, in a steady state, the squared droplet diameter decreases linearly with the time elapsed. In the present work, the expected relation has been also verified as shown in Fig. 9. The liquid fuel used is iso-octane and the environment is air of 623K in temperature and 0.2MPa in pressure. The droplet velocity is also indicated in the figure.

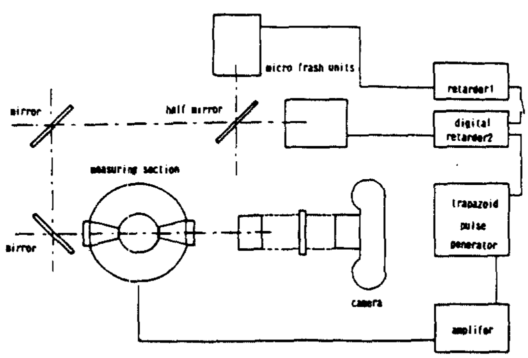


Fig. 8 Optical system for measurements of droplet diameter and velocity

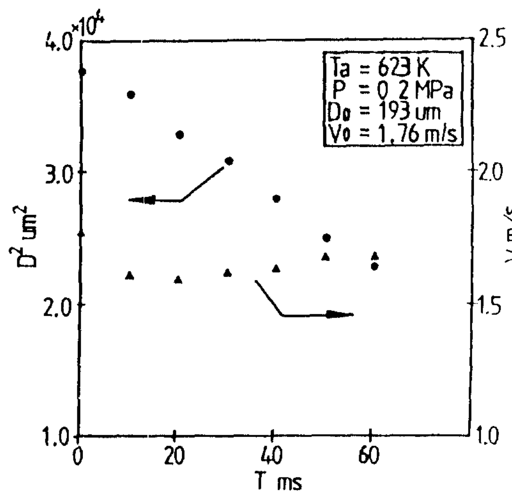


Fig. 9 Change of squared droplet diameter and velocity with time

4. EVAPORATION RATE CONSTANT

The evaporation rate constant Ke is defined as follows ;

$$dD^2/dt = -Ke \quad (1)$$

or

$$D_0^2 - D^2 = Ke \times t \quad (2)$$

The combusting rate constant Kb is also defined in the same way. Kb or Ke can be estimated by the squared droplet diameter with the lapse of time. The data range to be adopted is the linear part of the D^2-t curve excluding the unsteady period. Data scatters in the D^2-t curve are inevitable and caused by various primary factors, for example, droplet size measuring error, initial droplet size variation, environment condition setting error and so on. All the error factors can be reduced with sufficient caution at the experiment.

The authors have tentatively performed the systematic experiments of flying droplets of n-heptane, iso-octane and so on in high temperature and high pressure conditions and estimated the evaporation rate constant. Some examples of evaporation rate constant of n-heptane estimated from the D^2-t curve are indicated in Fig. 10 and Fig. 11. The relation of evaporation rate constant Ke with environment temperature is shown at a constant pressure in Fig. 10. With temperature increasing, Ke increases almost linearly and a liquid droplet evaporates more actively as expected. Figure 11 shows the relation between Ke and pressure at a constant temperature. With pressure increasing, Ke increases but the gradient becomes smaller.

It was found in this experiment that the evaporation rate constant of free falling droplet is similer to the tendency to the suspended droplet but there is a large difference on the value ; it was found out that the value of the suspended droplet had been reported to be twice or more than the obtained results of measuring the evaporation constant rate

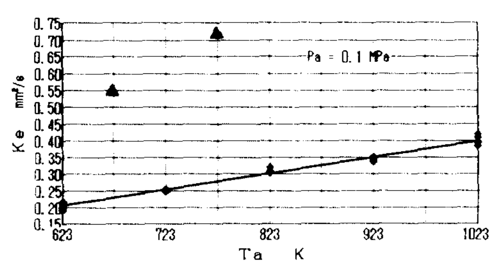


Fig. 10 Environment temperature effect on n-heptane evaporation rate constant

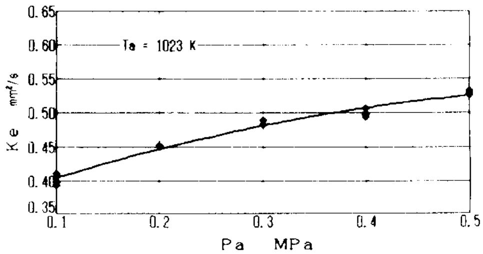


Fig. 11 Environment perssure effect on n-heptane evaporation rate constant

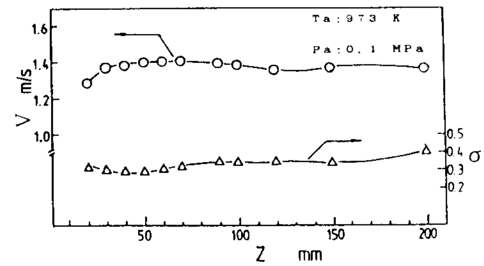


Fig. 12 Velocity and turbulence intencity distribution along the axis of the measuring section

by making droplet forming spray in the practical combustion device the same order of droplets drop freely through pressurized hot gas stream. The triangular mark, in Fig. 10, showed evaporation rate constant of suspended droplet by Kadota (1976). As in Fig. 10, each of the data display approximately twice the difference and is caused by experimental approach. Therefore, in the study of evaporation, ignition and combustion by using droplet to obtain the fundamental data to clarify spray evaporation and combustion from this real point of view, it is understood that experimental approach to more exact degree should be considered to be the practical phenomena.

The whole systematic experiments conducted as Figs. 10, 11 indicate the reliability of the experimental apparatus and measuring technique for obtaining evaporation rate constant of fine free droplet of various liquid in the environment condition range of 0.1~0.5MPa in pressure and 623 to 1023K in temperature.

5. CRITICAL EVAPORATION CONSTANT

In the present work, the droplet inevitably has a relative velocity with the environment gas flow along the whole flying route. Forced convection can affect the evaporation of droplets, mainly because the local heat transfer and evaporation rates vary over the droplet surface. Several empirical and semi-empirical correlations of the evaporation rate have been obtained as the function of Re and Sc. Ranz and Marshall proposed the next correlation for the droplet evaporation rate under forced convection.

$$Mf = Ms(1 + 0.276 \times Re^{1/2} \times Sc^{1/3}) \tag{3}$$

where Mf ; evaporation rate under forced convection, Ms ; evaporation rate in absence of convection.

From the Eq. (3) the evaporation rate constant should be also converted into the value excluding the effect of convection by using the next relation.

$$Keo = Ke/(1 + 0.276 \times Re^{1/2} \times Sc^{1/3}) \tag{4}$$

where Keo is called the critical evaporation constant.

Since the evaporation rate in absence of convection is to be obtained as the fundamental physical data, the initial droplet velocity was fixed at the same value as the reference gas velocity so as to reduce the effect of the forced convection on the evaporation rate. The effect of relative velocity, however, exists more or less and can not be neglected for the free-falling droplet in a flowing gas. The quantitative estimate of

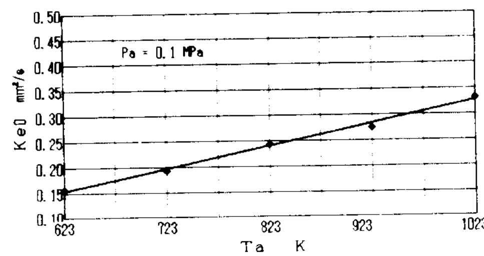


Fig. 13 Environment temperature effect on n-heptane critical evaporation constant

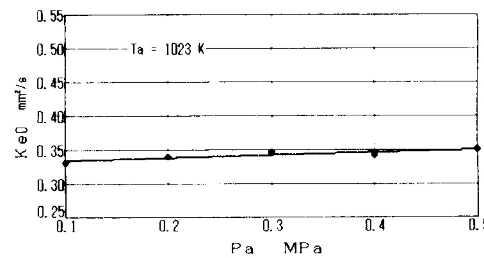


Fig. 14 Environment pressure effect on n-heptane critical evaporation constant

the effect of the forced convection on the evaporation rate constant of droplet was made by the Eq. (4) using the Ke, relative velocity obtained from experimental results and property values of matter concerning to the effect.

Figure 12 shows an example of flow velocity and turbulence intensity measured by a laser doppler velocitymeter along the axis of the measuring section. Figure 12 indicates the uniformity of the low velocity and the low-level of the turbulence intensity along the axis. The relative velocity is estimated from Fig. 9 and Fig. 12. Figure 13 and Fig. 14 show conversion of the mean value of Fig. 10 and Fig. 11 into Keo by Eq. (4). With temperature in Fig. 13 increasing, Keo actively increases almost linearly, but with pressure in Fig. 14 increasing, Keo increases more or less.

Critical evaporation constant, Keo, is effected by environmental temperature and pressure, thermal conductivity and diffusion coefficient of mixed gas formatting around droplet, and latent heat and density of droplet etc. It is understood that the results are shown as in Fig. 13, which show that with the environment temperature increased, there is much dependence on it, but on the other hand, at the constant pressure, the inverse proportion factor to Keo, latent heat and density, is fixed almost. At the constant pressure, saturation temperature of droplet is increased with environment pressure increased, so temperature gradient between environment and droplet is decreased more and more. Within the pressure limit in this study, Fig. 14 has a tendency to increase more or less and is shown to be the value of difference between increasing parameter and decreasing parameter to affect $Ke0$ in each pressure. Keo with environmental temperature and pressure, as in Fig. 13 and 14, can be shown in the next correlation.

$$Keo_T = 0.000433\,Ta + 0.001415 \tag{5}$$
$$Keo_P = 0.040443\,Pa + 0.33 \tag{6}$$

where Keo_T ; critical evaporation constant at constant pressure, Keo_P ; critical evaporation constant at constant temperature.

6. SUMMARY AND CONCLUSIONS

An experimental apparatus and a measuring system have been made to obtain characteristics of a freely falling liquid fuel droplet in a flowing hot and pressurized environment. Some systematic experiments were performed to ensure the reliability and utility of the system. The size of successively generated uniform droplets flying in the flow was measured by pursuing the droplet from time to time with a optical and electrical measuring system. Following conclusions have been obtained after the tentative experiments ;

(1) The newly devised apparatus has a fairly good performance to form an uniform pressurized flowing environment of a high temperature in the measuring section.

(2) The droplet generator working with a piezoelectric transducer works well and generates uniform fine liquid droplets successively in a high temperature and a high pressure condition.

(3) The droplet flying in the measuring section can be correctly pursued through the observing window by and electrically controlled optical system and the photographed image on 35mm still films can be analyzed to get the evaporation rate constant and velocity.

(4) The value of evaporation rate constant by suspended droplet had been reported to be twice or more in comparison with the obtained results by droplet used in this study.

(5) With environmental temperature increasing, at the constant pressure, critical evaporation constant, Keo_T, increases actively and almost linearly, but with pressure increasing, at the constant temperature, Keo_P, increases more or less.

When setting the environment to suitable conditions, the droplet is ignited and the apparatus can be also used to measure the ignition delay or combustion rate constant without any other problems.

REFERENCES

Honoki, H., Yagi, M., Tokuoka, N. and Sato, G.T, 1985, JSME, Vol. 51, No. 471, pp. 3615～3622.

Kadota, T., 1976, Ph. D. thesi, Hirosima Uni., Japan.

Kwaguchi, O., Kikuchi, K., Kanno, Y., 1985, "Ignition and Combustion of Free Liquid Fuel Droplet in an Hot Gas Stream," Proceedings of International Symposium On Refined Flow Modeling and Turbulence Measurements," Vol 1, No. C～22, pp. 1～9.

Kwaguchi, O., Sato, G. T., JSME, Vol. 48, No. 428, pp. 792～801.

Lasheras, J. C., Fernandez-Pello, A. C. and Dryer, F. L., 1981, "Onthe Disruptive Burning of Feee Droplets of Alcohol/n-Paraffin Solutions and Emulsions,"18th Symp.(International) on Combustion, pp. 293～305.

McCreath, C. G. and Chigier, N. A., 1973, "Liquid-Spray Burning in the Wake of a Stabilizer Disc," 14th Symp.(International) on Combustion, pp. 1355～1363.

Wang, C. H., Liu, X. Q. and Law, C. K., 1984, "Combustion and Microexplosion of Freely Falling Multycomponent Droplets," Combustion and Flame 56, pp. 175～197.