The Effect of Fuel Volatility on Spray Flame Stabilization*

by

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The effects of fuel volatility on the blow-off limit and the flame stability in spray combustion were discussed. The fuels used were gasoline, kerosene, heavy oil and C heavy oil. Every spray from an air blast atomizer used in this experiment had the same initial thrust and also had the same mean droplet diameter. The axial temperature distributions on the flame center line at the condition with and without swirl were measured.

For all fuels used in this report, the fuel flow rate of blow-off limit decreased with an increasing swirl strength. At weak swirl, the fuel volatility had higher effect on the blow-off limit than at strong swirl where the recirculation zone had a higher effect on flame stability, the maximum temperature gradient decreased and the peak temperature position shifted downstream.

Combustion, Thermal Engineering Equipment, Furnace, Fuel, Volatility, Swirl, Blow-Off

1. Introduction

Spray combustion is widely used in all kinds of liquid fuel combustion systems. Many efforts to develop a high efficiency and low emission combustion system of liquid fuel had been made and lean combustion systems of high quality fuels have been used for this purpose. Recently the shortage of the fossil fuel has pushed its price up. Conversion from high to low quality fuel is a task that faces furnaces of all kinds. A multi-fuel furnace will in the near future be one of the most profitable furnaces which can burn many kinds of fuel, low or high quality, meeting demands of fuel economy and air pollution control.

A recirculating flow is commonly used to increase flame stability and combustion intensity in every conventional combustion device. Effects of this recirculating flow on flame stabilization of premixed gaseous flame were studied by many

workers^{1)~4)}. The effects on spray flames, however, have been discussed by a

few workers⁵⁾, because there is little information about the aerodynamic interaction between the fuel spray and the swirling flow, especially in the recircu-

lation zone. Chigier et al.⁶⁾⁷⁾ measured flight angles, velocities and diameters of burning droplets within a hollow-cone pressure jet flame stabilized by a disc. They showed that small droplets and vaporized fuel in a recirculation zone made a primary reaction zone on the zero velocity boundary of the reverse flow zone and the core of the spray was ignited by this reaction zone. In the previous works, the liquid fuel was usually kerosene or jet fuel. So the effect of fuel volatility on the flame stabilization mechanism has to be studied to permit the profitable conversion from high to low quality fuel. Further combustion characteristics of many kinds of fuels have to be compared in the same furnace and under the same flow condition, but there are few studies considering these conditions. In this study, the lean blow-off limit, the combustion characteristics and the temperature distribution were measured for five values of swirl strength of the flow, and for four types of fuel qualities in which gasoline and C heavy oil were the most and the least volatile fuels, respectively. Since all the fuel sprays issuing from the air blast atomizer had the same injection thrust and were burned in the same combustion device, the effect of fuel volatility could be studied.

2. Experimental Apparatus

A schematic diagram of the combustion apparatus is shown in Fig. 1. This apparatus could burn gasoline, kerosene and two kinds of heavy oils in the same condition. The service lines of heavy oil, kerosene and gasoline are 9~17, 18~24 and 25~31. The fuel is quickly exchanged by the valves 32, 33 and 34.

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Fig.1 Schematic diagram of the apparatus.

Fig.3 Swirler

Fig.2 Main parts of combustion device.

Table 1 Physical properties of fuels.

	Density ρ Kg/m ³	Surface Tension σ N/m	Viscosity μ Pa.s	Kinematic Viscosity ν m ² /s
Gasoline at 20°C	695	21.5×10^{-3}	0.56×10^{-3}	0.806×10^{-6}
Kerosene at 20°C	800	25.4×10^{-3}	1.25×10^{-3}	1.563×10^{-6}
Heavy Oil at 90 °C	856	29.5×10^{-3}	3.77×10^{-3}	4.404×10^{-6}
C Heavy Oil at 90 °C	896	31.4×10^{-3}	48.48×10^{-3}	54.107×10^{-6}

1 N/m = 0.102 kgf/m

1 Pa.s = 0.102 kgf.s/m²

The service line of heavy oil has a gear pump 9, a temperature controller 13 and an oval flow meter 15 and is heated up by electric cord heaters to keep the temperature of heavy oil at 363K(90°C). An air blast atomizer 47 is used and the Sauter mean diameter of a fuel spray is controlled by changing an air orifice of the atomizer. Atomizing air is supplied from an air compressor 35. Air for combustion and cooling air for combustor 49 are supplied from the air blower 1 and flow rates of them are measured by the orifice flow meters 3 and 6. Fuel spray is ignited by the pilot flame of propane gas which is fed from a cylinder 41 and is ignited by an igniter 51. The combustion device shown in Fig. 2 consists of a fuel nozzle 1, a swirler 2, a swirler cone 3, a combustor 4 and a cooling duct 5 for the combustor.

The construction of the swirlers is shown in Fig. 3. The vane angles of the swirler are $0, \pi/12, \pi/6, \pi/4$ and $\pi/3$ rad. and the swirl strengths S of these swirlers are 0, 0.23, 0.50, 0.87 and 1.5 respectively, according to the equation

proposed by N.A. Chigier et al.⁸⁾

The fuels used are gasoline, kerosene and two kinds of heavy oils with low and high viscosity. The heavy oil of high viscosity is called C heavy oil in this study because it corresponds nearly to the C heavy oil NO.3 of the Japanese Industrial Standard. Table 1 shows the physical properties of these fuels.

Since the flow pattern in a combustion chamber is controlled by the momenta of combustion air and spray, all

the sprays should be burned in the same momentum flux of fuel and atomizing air, in other words, in the same thrust of spray, to compare the effect of fuel volatility. In this study, an air blast atomizer is used for this purpose. The injection thrust of liquid fuel is usually about one or two percent of the atomizing air of the air blast atomizer. Therefore, when the fuel flow rate changes, but the atomizing air does not change during the experiment, the thrust of the spray can be

considered not to change.⁹⁾

The initial Sauter mean diameter D_s was calculated using the experimental equation of an air blast atomizer obtained

by Nukiyama and Tanasawa¹⁰⁾. Using that equation together with the injection thrust of the spray which is constant, air orifice diameters D_a of atomizers and the flow rate of atomizing air Q_a for the four types of fuels can be calculated. In this study, the thrust of injected spray was kept constant at 0.427N. At the fuel flow rate $M_f=2.0$ g/s, the initial Sauter mean diameter was equal to 80 μ m for gasoline, kerosene and heavy oil, but was equal to 210 μ m for C heavy oil. Table 2 shows the specifications of the atomizer and Fig. 4 shows the shape of the air orifice. The whole construction of the fuel nozzle is shown in Fig. 5. This nozzle consists of the air blast atomizer mentioned above and an annular slit for propane fuel that is used for a pilot flame.

Table 2 Atomizing condition of the four fuels.

	$\frac{Q_{a,a}}{Q_l}$	$Q_{a,a}$ l/s	$V_{a,a}$ m/s	D_a mm
Gasoline	617	1.78	220.7	3.9
Kerosene	761	1.90	206.1	4.1
Heavy Oil	1120	2.62	144.9	5.6
C Heavy Oil	1075	2.40	163.3	5.1

Thrust = 0.427 N (0.0435 kgf)

Fig.4 Air orifice of the air blast atomizer.

Fig.5 Fuel nozzle.

The volumetric flow rate of the atomizing air was kept constant for every fuel as shown in Table 2. Therefore the Sauter mean diameter of the spray was variable with the flow rate of every fuel. Figure 6 shows the effect of fuel flow rate on the Sauter mean diameter which was calculated by the Nukiyama and Tanasawa equation. The calculated result shows that the Sauter mean diameter widely changes with the flow rate, but it is nearly the same at the same flow rate of every fuel.

3. Experimental Results

3.1. Velocity distribution on the combustor centerline

Since the Sauter mean diameter and the thrust of sprays are constant, the flow rate and the atomizing air velocity are different for every fuel spray. Therefore before the combustion test, the effect of atomizing air velocity on the overall flow pattern in the combustion chamber has to be checked without combustion. Air velocity was measured by a

Fig.6 Calculated Sauter mean diameter.

Fig.7 The velocity of the atomizing air jet.

Hot-wire anemometer. Figure 7 shows the air velocities of every atomizing air jet for every fuel condition, in which the air jet is issued in stationary ambient air. It is clear from this measurement that if the axial distance Z is far from 50mm, the air jets of these atomization conditions have almost the same velocity, as long as the thrust of the atomizing air jet is kept constant.

The atomizing air jet was affected greatly by the combustion air with swirl. Figures 8 and 9 show the effect on the axial velocity of the jet and its turbulent intensity, respectively. Since the recirculating motion of the combustion air increases with the swirl strength, the axial velocity of the jet decreases rapidly with an increasing swirl strength. The turbulent intensity of the jet is increased greatly in the condition of $S=0.50$, which is usually considered the critical swirl strength that can make a

recirculation zone of steady state⁵⁾⁸⁾. The overall flow pattern in the combustion chamber was similar to the flow pattern that was mentioned in the author's previous report⁹⁾.

Fig. 8 the axial velocity on the axis of the combustion chamber.

Fig. 9 the turbulent intensity on the axis of the combustion chamber.

3.2. Combustion characteristics

The combustion characteristics and lean blow-off limit in a given condition were measured by gradually and smoothly decreasing the fuel flow rate only. Figure 10 shows the combustion characteristics of a kerosene flame with no swirl, $S=0$. In this condition the flame was unstable everywhere. The flame was elongated on the center line of the combustion chamber as shown by the sketch in the figure. A blue flame was observed near the atomizer, but the main part of the flame was a yellow wrinkled flame which was usually observed as an open

flame of kerosene¹¹⁾.

When the swirl strength of the flow increases, the stability of a flame is increased and the fuel flow rate at the blow-off point shifts to the lean fuel side. The combustion characteristics of a kerosene flame at $S=0.50$ are shown in Fig. 11. In this condition, the flame was kept stable at a high flow rate of combustion air where the flame was blown-off in the condition of no swirl. At a low flow rate of combustion air, the spray flame was expanded to the combustor wall. When the swirl strength was higher than $S=0.50$, the stability of the flame was further improved and the stable flame zone was widened. For example, Fig. 12 shows the combustion characteristics with $S=1.50$.

Fig. 10 The combustion characteristics of the kerosene spray at $S=0$.

Fig. 11 The combustion characteristics of the kerosene spray at $S=0.50$.

Fig. 12 The combustion characteristics of the kerosene spray at $S=1.50$.

With regard to the visual observation of the flames, if the burning conditions of all the fuels were same, the flames of gasoline, heavy oil and C heavy oil were almost the same as the kerosene flame. But the fuel flow rates of the stable flame limit and of the blow-off limit are different from that of the kerosene flame.

3.3 Effect of swirl on the blow-off limit

The effects of swirl strength on the blow-off limit for every fuel of gasoline, kerosene, heavy oil and C heavy oil were studied. Figure 13 shows the blow-off limit of gasoline. When the combustion air has no swirl, the blow-off limit is nearly on the line that indicates an air fuel ratio of 25. With an increasing swirl strength, the stable flame zone is expanded to a high flow rate of the air. When the swirl strength is higher than 0.50, the blow-off limit is determined independently of the air flow rate, by the conditions of swirl strength and fuel flow rate. Further the blow-off limits with the swirl strengths of 0.83 and 1.50 are almost the same.

Figure 14 shows the experimental results for kerosene. The blow-off limit changes with swirl strength in almost the same manner as the previous mentioned results for gasoline. But when the air flow rate is lower than 40g/s, the blow-off limit changes in a very complicated way. One of the reasons for this result is that the effect of the swirl motion of the flow does not clearly appear, because the average velocity in the combustor is under 1m/s, and this velocity is not fitting to the spray combustion in this combustor.

The blow-off limit for heavy oil is shown in Fig. 15. Blow-off limit at swirl strength of 0.23 appears on the line of air-fuel ratio 25 and is different from the results of gasoline and kerosene fuel. The blow-off limit for C heavy oil is also shown in Fig. 16. The blow-off limit for C heavy oil is shifted to the fuel rich side unlike the results for heavy oil.

Fig.13 The blow-off limit of the gasoline spray.

This is because of the Sauter mean diameter of the spray of C heavy oil being larger than that of heavy oil as mentioned before.

Fig.14 The blow-off limit of the kerosene spray.

Fig.15 The blow-off limit of the heavy oil spray.

Fig.16 The blow-off limit of the C heavy oil spray.

Fig. 17 The effect of the fuel volatility on the blow-off limit at $S=0$.

Fig. 18 The effect of the fuel volatility on the blow-off limit at $S=0.50$.

Fig. 19 The effect of fuel volatility on the blow-off limit at $S=1.50$.

3.4. Effect of fuel volatility on the blow-off limit

The effects of the fuel volatility on the blow-off limit at swirl strengths 0, 0.50 and 1.50 are shown in Figs. 17, 18 and 19, respectively. In the absence of a swirl, with an increasing fuel volatility, the fuel flow rate of blow-off limit decreases. In other words, with an increasing fuel volatility, the air flow rate of the blow-off limit increases, i.e. the flame stability increases. This appears to be the fundamental combustion characteristics of every fuel, because the spray flames in this flow condition are similar to the open flame as mentioned in Fig. 10. Further the difference in the Sauter mean diameters of these fuels is small as far as the fuel flow rate being the same and the thrust of the spray being kept constant. It is considered that the effect of fuel volatility appears on the blow-off limit. And also the difference of the blow-off limit between heavy oil and C heavy oil implies the effect of the difference in the Sauter mean diameter.

The blow-off limits for gasoline, kerosene and heavy oil shows a small difference from each other as shown in Fig. 18. But the blow-off limit for C heavy oil shows a different manner from those of the previous three fuels. Figure 19 shows the blow-off limits at swirl strength 1.50. The fuel flow rate of the blow-off limit for kerosene is the smallest, and in order of heavy oil, gasoline and C heavy oil, the flow rate of blow-off limit increases. Summarizing these results, the effect of fuel volatility and the Sauter mean diameter of the spray on the blow-off limit appears clearly in the weak swirl condition, and does not appear in strong swirl condition where the flame stabilizing effect of the combustor is improved.

The fuel flow rates of the blow-off limits for four fuels and swirls are compared with the flow rate of the blow-off limit for kerosene at $S=1.50$. Figure 20 shows non-dimensional comparison at the air flow rate of 75g/s. This flow rate of the air is a relatively high velocity condition for the combustion chamber. When the swirl strength is small

Fig. 20 The comparison of blow-off ratio at $Ma=75g/s$.

(for example $S=0.23$), the blow-off for gasoline is observed at a lower fuel flow rate than with other fuels. But at a high swirl strength, the blow-off for gasoline is observed at the higher fuel flow rate of all the others. This is because in the case of the heavy oil flame, the combustion is heterogeneous due to the low evaporation rate, but the gasoline flame is homogeneous due to the high evaporation rate. So, the lean blow-off limit of the gasoline flame is more similar to a premixed gaseous flame than that of the kerosene or the heavy oil flame, and moreover, the combustion range of a premixed flame is narrower than that of a diffusion flame.

3.5. Effect of fuel volatility on the temperature distribution

The temperature distribution was measured to study the effect of fuel volatility using a Pt-PtRh 13% bare thermocouple. The temperature of the flame had some disturbances in itself. So, the time average of the temperature at every 5mm along the flame axis was measured ten times. Figure 21 shows the temperature distributions of gasoline, kerosene and heavy oil. The flow rate of fuel was 2.6g/s. The Sauter mean diameters of these three fuel sprays were nearly 110 and the difference of between them was very small. It is clear that the temperature increases first in the gasoline flame and those of kerosene and heavy oil follow.

For the flame to be stable in the absence of the recirculation zone, the spray has to receive heat directly from the main reaction zone, and this heat must be enough for heating-up, evaporation and ignition. Therefore, a high axial temperature gradient is necessary to sustain a stable flame. Figure 22 shows the temperature gradient along the axis at the same condition of Fig. 21. The temperature gradient along the flame axis is affected by many factors, for example: the local heat release, the flow direction, the gas velocity and heat flux due to convection and radiation. But, it can be considered that the temperature gradient along the axis corresponded mainly to the local heat release as long as the flow direction is forward. In this figure, because the burning conditions of the flow and the sprays are the same respectively, the difference between the three temperature gradients is due to the difference in volatility of fuels. The axial temperature gradient of the gasoline flame has two peaks. The first peak appears before the beginning of combustion and the second is in the mixing zone of the main part of the spray and the combustion air, i.e. the main combustion zone. Due to conduction and radiation, the axial temperature increases and the ignition occurs at the axial distance of 200~250mm. Because of the high volatility of gasoline, the evaporation of gasoline occurred quickly, but mixing could not overtake the evaporation. Accordingly, the burning rate was slow. Then the temperature increased once

Fig.21 The axial temperature distribution at $S=0$.

Fig.22 The gradient of the axial temperature at $S=0$.

more in the main combustion zone. The axial temperature gradient distribution of the kerosene flame is similar to that of the gasoline flame. But, the first peak shifted downstream. The axial temperature gradient of the heavy oil flame has only one peak in the mixing zone of the spray and the fresh air. This is due to the low evaporation rate of heavy oil.

Figure 23 shows the temperature distributions at $S=0.50$. In this case the difference between the three fuels does not clearly appear in the temperature distribution, because the mixing rate in the recirculating flow of $S=0.50$ is high enough to evaporate and to ignite every fuel spray. The axial temperature gradients of these flames are shown in Fig.24. Since the flames in this condition are mainly controlled by the swirling flow, the locations of the peaks of these axial temperature gradients come at the same axial position. The effect of fuel volatility on the axial temperature gradient is related to the height of the peak. The height of the peak of the gasoline flame is twice the height of the heavy oil flame.

Fig. 23 The axial temperature distribution at $S=0.50$.

Fig. 24 The gradient of the axial temperature at $S=0.50$.

4. Conclusions

The effect of fuel volatility on the spray flame were studied by controlling the swirl strength of the air, the thrust and the Sauter mean diameter of the spray. From the results, the following conclusions have been reached.

- (1) The fundamental combustion characteristics of the spray flame are controlled by the swirl strength. The flames of the four fuels used have similar combustion characteristics as long as the swirl strength is the same. The flow rate of the blow-off limit of all fuels decreases with an increase in the swirl.
- (2) With a weak swirl, the fuel volatility has a predominant effect on the blow-off limit. But with strong swirl the fuel volatility has a slight effect on the blow-off limit. Further at a high swirl strength, the blow-off of the gasoline flame is observed at a higher fuel flow rate than that observed in the kerosene or the heavy oil flame.

(3) In the absence of swirl, two peaks of the axial temperature gradient appear in the gasoline and the kerosene flames, but only one peak appears in the heavy oil flame. The position of the first peak shifts upstream with an increasing fuel volatility.

(4) In the presence of a strong swirl ($S=0.50$), only one peak of axial temperature gradient appears at the same position for every fuel. The fuel of higher volatility has a higher peak of axial temperature gradient.

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