Effect of Fuel Properties on Spray Combustion

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The effects of fuel properties on the blow-off limit, the flame stability, the temperature distribution and emissions in a swirl type combustor were studied. The fuels used were gasoline, kerosene, and heavy oil. Gasoline and heavy oil were used as representing the most and the least volatile fuels, respectively. The momentum flux and the Sauter mean diameter of the issuing sprays of the three fuels were controlled to have the same value.

For all fuels used in this paper, the fuel flow rate of blow-off limit decreased with increasing swirl strength. Under weak swirl, the fuel volatility had a greater effect on the blow-off limit than under strong swirl where the recirculation zone had a greater effect on flame stability. Emissions of soot and NO_x had high values in the heavy oil flame and low values in kerosene flame. The exhaust soot emission increased by increasing the swirl strength of the flow for all three fuels.

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 fuels have been made.

Recently, the use of low quality fuels is widely spread to save the fuel costs in industrial furnaces. So fuel conversion from high to low quality fuels is a problem 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 fuels of – low or high quality – meeting the demands of fuel economy and air pollution control.

A recirculating flow is commonly used to increase flame stability and combustion intensity in all conventional combustion devices. Effects of this recirculating flow on flame stabilization of premixed gaseous flame have been studied by many researchers^{1)~4)}. Effects on spray flames, however, have been discussed only in a limited number of papers^{5)~10)}, because there is little information available about the aerodynamic interaction between fuel spray and swirling flow, especially in the recirculation zone.

To understand the effects of fuel properties on spray combustion, it is necessary to keep both the spray characteristics and combustion air flow characteristics constant. In these combustion systems, spray characteristics such as mean diameter and size distribution are different for each fuel-supplying system. Furthermore, the flow pattern

and mixing process of fuel and air are not the same^{11),12)}. In addition, there are many difficulties in comparing the spray combustion characteristics of different fuels that are used in different types of combustion equipment.

In this study, the effects of fuel properties on flame stability and temperature distribution in a small swirl type combustor have been studied. The fuel used were gasoline, kerosene, and heavy oil. Gasoline and heavy oil were used as representing the most volatile and the least volatile fuel, respectively. The momentum flux and the Sauter mean diameter of the issuing spray were controlled to have constant values for comparing the properties of the fuels studied.

Furthermore, the effects of fuel properties on flame length, distribution of oxygen, total hydrocarbon, nitrogen oxides, and soot have been studied in the same swirl type combustor by changing the swirl strength of the flow.

2. Experimental Apparatus

A flow diagram of fuel and combustion air system and the combustion equipment is shown in **Fig. 1**. Gasoline, kerosene, and heavy oil can be run in this system. Both gasoline and kerosene were directly supplied from the fuel tanks but heavy oil was preheated, because of its high viscosity. Thus, the entire line was heated with an electric heater to keep the temperature of the fuel at 363 K (90°C).

The swirl type combustor was used for the study because swirlers are very popular as a flame

Fig. 1 Fuel Lines and Combustion Equipment

Fig. 2 Swirl Type Combustor

stabilizer. Details of the combustor are shown in Fig. 2. It consists of a fuel atomizer ①, a swirler ②, a swirler cone ③, a combustor ④ and colling jacket ⑤. Five swirlers having the same blockage ratio but different vane angles were used. Swirl number S , an indicator of the swirl strength, was defined as proposed by J. M. Beer and N. A. Chigier¹³⁾. The swirl numbers referring to the five swirlers were 0, 0.23, 0.5, 0.87 and 1.5, respectively.

The fuels used are gasoline, kerosene, and heavy oil; and their physical properties are shown in Table 1. Since the flow pattern in the combustor is controlled by the momentum of combustion air and spray, all the sprays should be burned in the same momentum flux of the fuel spray for studying the effects of fuel properties. In this study, an air blast atomizer was used for this purpose. The injection thrust of the fuels was about one or two percent of the atomizing air of the air blast atomizer. Therefore, when the fuel flow rate changed without changing the atomizing air, the thrust of the spray could be assumed to be unchanged. The Sauter mean diameter D_s of the spray was calculated using the equation of S. Nukiyama and Y. Tanasawa¹⁴⁾. The orifice diameter of the air blast atomizer for the three fuels

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

Fig. 3 Calculated Sauter Mean Diameter

were calculated using the equation, together with the injection thrust. In this study, the thrust was kept at 0.427 N, and the Sauter mean diameter of the spray was controlled at 80 μm for a fuel flow rate of $M_f=2.0$ g/s. The outer diameter of the fuel nozzle is 1.12 mm, and the air orifices are 3.9 mm, 4.1 mm, and 5.6 mm for gasoline, kerosene, and heavy oil, respectively.

The volumetric flow rate of the atomizing air was kept constant for the three fuels. Therefore, the Sauter mean diameter of the spray was variable with the flow rate of each fuel. Figure 3 shows the effect of fuel flow rate on the Sauter mean diameter, which was calculated using the Nukiyama and Tanasawa equation. The calculated result showed that the Sauter mean diameter widely changed with flow rate, but it was nearly the same at the same flow rate for three fuels.

3. Combustion Characteristics

3.1 Velocity Distribution on the Combustor Center-line

Since the Sauter mean diameter and the thrust of sprays were constant, the flow rate and the

Fig. 4 The Velocity of the Atomizing Air Jet

atomizing air velocity were different for each fuel spray. Therefore before each combustion test, the effect of atomizing air velocity on the overall flow pattern in the combustion chamber had to be checked without combustion. Air velocity was measured by a hot-wire anemometer. **Figure 4** shows air velocities of atomizing air jets under the three fuel conditions, in which the air jet was issued in stationary ambient air. It is clear from these measurements that if the axial distance Z is greater than 50 mm, the air jets under these atomization conditions have almost the same velocity, as long as the thrust of the atomizing air jet is kept constant.

3.2 Effect of Fuel Volatility on the Blow-off Limit

The effects of fuel volatility on the blow-off limit at swirl strengths 0.0, 0.50, and 1.50 are shown in **Figs. 5, 6, and 7**, respectively. In the

absence of a swirl with increasing fuel volatility, the fuel flow rate of blow-off limit decreases. In other words, with increasing fuel volatility, the air flow rate of the blow-off limit increases, *i.e.*, the flame stability increases. Further, the difference in the Sauter mean diameters of these fuels is small as long 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. Also the difference in the blow-off limits of heavy oil and C heavy oil implies the effect of the difference in the Sauter mean diameters.

Fig. 6 The Effect of the Fuel Volatility on the Blow-off Limit at $S=0.5$

Fig. 5 The Effect of the Fuel Volatility on the Blow-off Limit at $S=0$

Fig. 7 The Effect of the Fuel Volatility on the Blow-off Limit at $S=1.5$

The blow-off limits for gasoline, kerosene, and heavy oil show small differences as shown in **Fig. 6**. But the blow-off limit for C heavy oil is different from that of the other three fuels. **Figure 7** shows the blow-off limits of the above four fuels at swirl strength 1.50. The fuel flow rate of the blow-off limit for kerosene is the smallest, and the flow rate of blow-off limit increases in order of heavy oil, gasoline, and C heavy oil. Summarizing these results, the effects of fuel volatility and the Sauter mean diameter of the spray on the blow-off limit appear clearly in weak swirls, and does not appear in strong swirls where the flame stabilizing effect of the combustor is improved.

The fuel flow rates of the blow-off limits for the three fuels and C heavy oil and swirls are compared with the flow rate of the blow-off limit for kerosene at $S=1.50$. **Figure 8** shows non-dimensional comparison at the air flow rate of 75 g/s. This flow rate of air is relatively high for the combustion chamber. When the swirl strength is small (for example $S=0.23$), the blow-off limit for gasoline is observed at a lower fuel flow rate

Fig. 8 The Comparison of Blow-off Ratio at $M_a=75$ g/s

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

3.3 Temperature Distribution and Flame Length

Temperature distributions in the combustor were measured to compare the combustion characteristics of gasoline, kerosene, and heavy oil flames at the same flow rate of fuel and combustion air. **Figure 9** shows the result for $S=0.0$, which is the condition where the combustion air flow is coaxial to the spray. Under this condition, the flame stability was not so good, because a reversed flow was not created by the swirler. The flow was so simple that it flowed uniformly to the exit of the combustor and mixed it with the spray. Thus, it was considered that this flow condition might reveal the net effect of fuel properties on spray combustion. **Figure 10** shows the axis temperature distribution of each fuel. It is clear that the temperature increases first in gasoline flame and then in kerosene and in the heavy oil flame in that order.

For the flame to be stable in the absence of a recirculation zone, the spray has to receive heat directly from the main reaction zone, and this heat must be adequate for heating-up, evaporating and igniting. Therefore, a high axial temperature gradient is necessary to sustain a stable flame. **Figure 11** shows the temperature gradient along the axis under the same conditions of **Fig. 10**. The temperature gradient along the flame axis is

Fig. 9 Temperature Distribution ($S=0.0, M_a=75$ g/s and $M_f=2.0$ g/s, Temp. in $^{\circ}\text{C}$)

Fig. 10 The Axial Temperature Distribution at $S=0.0$

Fig. 11 The Gradient of Axial Temperature at $S=0.0$

affected by many factors; for example, local heat release, flow direction, gas velocity, and heat flux due to convection and radiation. But it can be considered that the temperature gradient along the axis corresponds 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 spray are the same, the difference between the three temperature gradients is due to the difference in volatilities of the fuels. The axial temperature gradient of gasoline flame has two peaks. The first peak appears before the beginning of combustion and the second is in the mixing zone of the part of the spray and combustion air, *i.e.*, the main combustion zone. Due to convection and radiation, the axial temperature increases, and ignition occurs at the axial distance of 200–250 mm. Because of high volatility of gasoline, evaporation of gasoline occurred at a rapid rate, and the rate of mixing could not overtake the rate of evaporation. Accordingly, the burning rate was low, and the temperature increased once more in the main combustion zone. The axial temperature gradient distribution of kerosene flame is similar to that of gasoline flame, but the first peak shifted towards downstream. The axial temperature gradient of the heavy oil flame has only one peak in the mixing zone of spray and fresh air. This is due to the low evaporation rate of the heavy oil.

Figure 12 shows temperature distribution patterns, and **Fig. 13** shows axial temperature distributions for the swirl number $S=0.5$. It seems that the primary combustion zone, which is recognized as a high temperature zone, promotes a stable ignition and flame holding. This zone is located just inside the inlet combustion air flow and just outside the spray sheath. This primary combustion zone is maintained by the combustion of a mixture that consists of combustion air and

Fig. 12 Temperature Distribution ($S=0.5$, $M_a=75$ g/s and $M_f=2.0$ g/s, Temp. in $^{\circ}\text{C}$)

Fig. 13 The Axial Temperature Distribution at $S=0.5$

Fig. 14 The Gradient of Axial Temperature at $S=0.5$

fuel vapors and small drops which are carried by the reverse flow from the spray sheath. The primary combustion zone is controlled mainly by the reverse flow caused by swirling combustion air. 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 $S=0.5$ is high enough to evaporate and to ignite all fuel sprays. The axial temperature gradients of these flames are shown in Fig. 14. Since the flames under these conditions are mainly controlled by 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 gasoline flame is twice the height of the heavy oil flame.

Fig. 15 Flame Length

The effects of fuel properties and swirl strengths on flame lengths are shown in Fig. 15. Under nonswirling flow conditions, a stable flame could not be maintained at this flow rate. The flame length decreases with increasing swirl number. Comparing the fuels, the flame of gasoline combustion is the shortest, and the flame of the heavy oil combustion is the longest. The effects of fuel properties are not clear under high swirl conditions; because, under low swirl conditions, combustion characteristics are controlled by fuel properties, but under high swirl conditions, they are controlled by swirling flow conditions.

4. Distribution of Combustion Products and Others

Figures 16, 17, and 18 show the concentrations of oxygen, nitrogen oxides, total hydrocarbon, and soot, as well as the temperatures at various axial distances for the three kinds of fuels, respectively. The total hydrocarbon in the heavy oil flame could not be measured by using FID because of its high concentration under these conditions. Since the mixture flows uniformly to the exit of the combustor, the changes in the concentration along the combustor axis can be regarded as representing the time history of the flowing mixture. The results of gasoline flame are shown in Fig. 16. The oxygen concentration decreases at first in line with the increase in temperature in the downstream of the ignition point; and, thereafter, it shows a constant value of around 3%. The concentration of nitrogen oxides increases with a short delay in increase in temperature, and reaches a constant value at the combustor exit. The total hydrocarbon increases after the decrease in oxygen. Soot

Fig. 16 Distribution of Combustion Products and Others in Gasoline Combustion ($S=0.0$)

Fig. 19 Distribution of Oxygen Concentration

Fig. 17 Distribution of Combustion Products and Others in Kerosene Combustion ($S=0.0$)

Fig. 20 Distribution of Total Hydrocarbons

Fig. 18 Distribution of Combustion Products and Others in Heavy Oil Combustion ($S=0.0$)

Fig. 21 Distribution of Nitrogen Oxides

concentration reaches the maximum value in the zone where the concentration of total hydrocarbon decreases, and then the soot concentration decreases near the combustor exit. In both kerosene and heavy oil combustions, the concentrations of products along the axis change in the same way as

in gasoline combustion, but all distribution curves shift towards the downstream.

The effects of fuel properties on O_2 , THC, NO_x and soot concentrations are shown in **Figs.** from 19 to 22. The oxygen concentration changes in the same way for both gasoline and kerosene combustions. But the decrease in the oxygen concentration for the heavy oil combustion is less than that

Fig. 22 Distribution of Soots

for the other two fuels. Therefore, the heavy oil combustion is probably controlled by some other factors than those that control the oxygen concentration. The total hydrocarbon changes as shown in Fig. 20. In this figure, there is only a small difference between the combustion of gasoline and that of kerosene; but, in the heavy oil combustion, the concentration of THC is extremely high. The nitrogen oxides concentration is the lowest in kerosene combustion and the highest in the heavy oil combustion. In the case of the heavy oil combustion, the maximum concentration of nitrogen oxides appears at the farthest position in these cases. Kerosene combustion shows the lowest soot concentration.

5. Exhaust Emission Concentrations

For industrial utilization, combustion under swirling flow conditions is more important than combustion under nonswirling conditions. Thus exhaust emissions under swirling flow conditions will be studied in the same way as will the complicated distribution in the combustor. Using the experimental apparatus shown in Fig. 1, average exhaust emissions could not be analyzed by direct measurements of the exhaust emissions because they were diluted by secondary flow of air. Therefore, the experimental apparatus was modified by connecting to it an exhaust duct of 1,250 mm to prevent the dilution effect of the secondary flow. Furthermore, to homogenize the radial distribution of exhaust emissions, mixer plates were set in the exhaust duct. The modified apparatus is shown in Fig. 23.

Figures 24, 25, and 26 show the effects of swirl strengths on exhaust emissions under such conditions as $M_a=75$ g/s and $M_f=2.0$ g/s, however, when $S=0$, the flame could not be stabilized. Figure 22 shows the effect of swirl strength on total hydrocarbon emission. It decreases with

Fig. 23 Experimental Apparatus for the Study of Exhaust Emissions

Fig. 24 Effect of Swirl on Total Hydrocarbon Emission

Fig. 25 Effect of Swirl on Nitrogen Oxides Emission

Fig. 26 Effect of Swirl on Soot Emission

increasing swirl strength because such combustion is improved by swirl. In both gasoline and kerosene combustions, the nitrogen oxides emission has almost the same value. It is not affected by swirl strength as shown in Fig. 25. In the heavy oil combustion, the nitrogen oxides show a high value under low swirl strength, because the spray drops seem to burn as an enveloped flame, and a high temperature zone was locally produced by the enveloped flames. In the heavy oil combustion under high swirl strength, the nitrogen oxides also show a value which is higher than that of the two fuels. This is due to the nitrogen compounds found in the heavy oil fuel.

The exhaust soot emission increases by increasing the swirl strength as shown in Fig. 26. It is considered that with an increase in the swirl strength, the soot emission increases by the reaction process of changing the hydrocarbons to soot, or by the quenching process of soot combustion caused by high turbulent swirling flow¹⁵⁾. In gasoline combustion, the soot emission is higher than that in kerosene combustion. As mentioned before, the results have shown that the rate of vaporization of gasoline spray is faster than the rate of mixing.

6. Conclusions

The following results were obtained from gasoline, kerosene, and heavy oil combustions in a swirl type combustor.

- (1) The fundamental combustion characteristics of spray flame are controlled by swirl strength. Flames of the three fuels above and heavy C fuel used have similar combustion characteristics as long as their swirl strengths are the same. The flow rate of the blow-off limit of all fuels decreases with increasing swirl strength.
- (2) With a weak swirl, the fuel volatility has a

predominant effect on the blow-off limit; but with a strong swirl, the fuel volatility has only a slight effect on the blow-off limit. Further, at high swirl strengths, the blow-off limit of gasoline flame is observed at a higher fuel flow rate than that of kerosene or of the heavy oil.

- (3) In the absence of a swirl, two peaks of axial temperature gradient appear in gasoline and kerosene flames, but only one peak appears in the heavy oil flame. The position of the first peak shifts towards upstream as fuel volatility increases.
- (4) In the presence of a strong swirl ($S=0.5$), only one peak of axial temperature gradient appears at the same position for each fuel. A fuel of higher volatility has a higher peak of axial temperature gradient.

- (5) Gasoline flame shows a higher soot concentration than does kerosene flame. But a concentration of nitrogen oxides of both flames are almost the same. However, the heavy oil flame shows almost twice that shown by the other two flames.
- (6) In the heavy oil combustion, the value of nitrogen oxides takes a higher value under low swirl conditions than under high swirl conditions.
- (7) Soot emission is lowest in kerosene combustion and highest in the heavy oil combustion, and it increases with increasing swirl strength.

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要 旨

噴霧燃焼の燃焼特性におよぼす燃料性状の影響

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液体燃料を微粒化し噴霧燃焼させる燃焼方式は工業的に広く使用されている。そこで本研究では、ガソリン、灯油、重油を揮発性の高、中、低程度の燃料として取り上げ、それらを平均粒径と噴霧推力の等しい噴霧として燃焼装置に供給し、燃焼特性、吹き消え限界、温度分布などに及ぼす燃料性状とスワール数の影響について調べた。さらに、火炎長さ、 O_2 、 NO_x 、THC、すすの各濃度に及ぼす燃料性状とスワールの影響を調べた。

使用燃料はガソリン、灯油、C 重油を用い、燃料噴射弁には気流噴射弁を使用した。微粒化用空気オリフィスを交換することにより、噴霧の平均粒径を燃料が異なっても同じ値になるよう調整した。また噴霧の推力も同一になるようにして実験を行った。燃焼装置はスワラにより火炎の安定をはかり、5 種類のスワール数のスワラを用意した。

燃料の違いによる吹き消え限界の変化は、Fig. 6 に示すようにガソリン、灯油、重油、C 重油と燃料の揮発性の順に燃料流量の少ない方から並ぶ。スワールが大きくなると吹き消え限界は燃料性状ではあまり大差がなく、噴霧の平均粒径の異なる C 重油のみが異なった吹き消え限界を示す。すなわちスワール数の小さい場合、いいかえれば燃焼筒内の保炎効果が弱い場合には燃料の揮発性や平均粒径による吹き消え限界の差が著し

く現れ、スワール数が大きく保炎効果も良好な場合にあまり顕著に現れない。

中心軸上の温度の変化を調べると、Fig. 11 に示すようにガソリンの場合は噴射弁近くから温度の上昇が開始されるが、その温度の立ち上がりは緩慢である。灯油の場合は軸距離 250 mm 付近で急激な温度の立ち上がりが見られる。重油の場合は灯油よりもさらに下流で温度の立ち上がりがある。火炎長さはスワール数が大きくなるにつれて短くなる。そして、スワール数にかかわらず、ガソリンの場合に火炎長さは一番短く、灯油、重油の順に長くなる。その差はスワール数が小さい場合に顕著に現れることがわかった。

3 種類の燃料についてスワールのない流れの場合、ある場合の燃焼筒中心軸上の酸素、窒素酸化物、未燃炭化水素、すすの各濃度分布を調べた。窒素酸化物濃度はガソリンの場合に灯油よりもいくぶん高い値を示す。また燃焼筒出口において重油は他の燃料の場合の約 2 倍の値を示す。すす濃度の変化は、灯油、ガソリン、重油の順に出口方向に移動している。

未燃炭化水素の排出濃度はスワール数の増加とともに減少していくが、すすについてはスワール数の増加とともに増加する傾向を示すことなどがわかった。

Keywords

Spray combustion, Burner, Fuel property, Emission, Nitric oxide, Flame stability