Experimental Study on Luminous Flame

By

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In the experimental furnace of comparatively large scale, the radiant heat transfer from the flame and the soot formation in the flames of the liquid fuel and gaseous fuel are studied. In the luminous flame of the liquid fuel, the soot concentrations and the size distributions of soot particles differ considerably by the burning methods, and particles larger than 10 μ are often found. Even in the luminous flame of the gaseous fuel, the large particles are also found and the size distributions are different from the previously accepted knowledge obtained in very small gas flames. The chemical compositions of soot particles of each flame also vary at the various positions. The radiation from the cloud of soot particles is affected remarkably by the size distribution of the soot particles and a little by the chemical composition. The relation by which the emissivity of the luminous flame can be estimated is obtained.

1. Introduction

The emissivities of luminous flames are generally higher than those of non-luminous flames, because of the soot particles contained which are believed to emit continuous infrared spectra. So luminous flames are used extensively in many industries.

Some experiments on luminous flame have been carried out at the National Flame Reseach Foundation at Ijmuiden[1] or at Sheffield[2]. Their data on the flame emissivities scatter considerably and, especially on the absorption coefficients of the soot particle layers, some have the values even more than twice of others. Furthermore, even in the case of the same furnace, the absorption coefficients take different values according to combustion means[3], but the cause of such scattering of the data has not been made clear.

The purpose of our study is to make clear the cause of the scattering among the data on the radiant heat transfer from the luminous flame, and the effect of the soot character on it. Moreover the mechanism of the soot formation is investigated,

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since some character of soot is considered to be remarkably influenced by the condition of the soot formation. The relation between the emissivities or the absorption coefficients of soot particle layers and the properties of soot is made clear.

2. Experimental arrangement and procedure

2.1. Furnace and equipment

Two horizontal furnaces are used. The one for liquid fuel has 2.7 m length and has the square section of 0.5 m side length. The horizontal walls are protected by fire-bricks and the vertical walls are water-cooled. The one side of the vertical walls has 42 observation windows in order to measure the conditions of flames at various positions. In the other side of the vertical walls, there are low temperature blackbody cavities for the precise measurement of the flame radiation. The other furnace for city gas has 2.2 m length and has a circular section of 0.4 m diameter. The inner wall is protected by fire brick except the observation windows and low temperature blackbody cavities. The number of observation windows is less than that in the former. The schematic diagram of the experimental equipment is shown in Fig. 1(a).

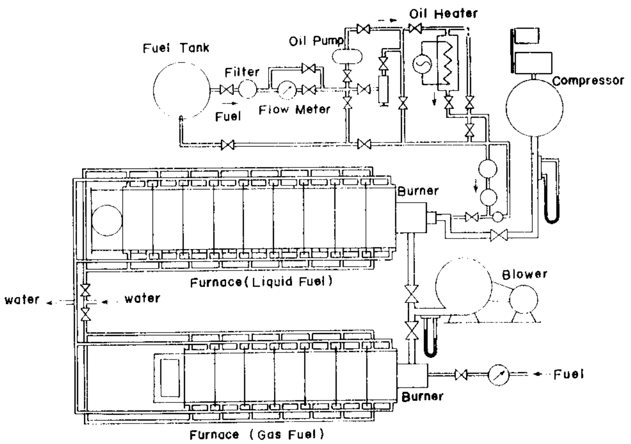


Fig. 1(a). Experimental equipment.

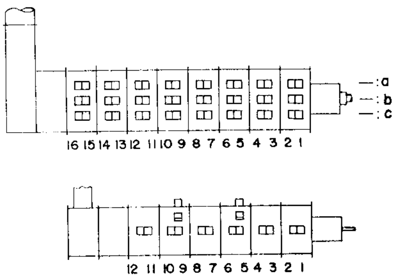


Fig. 1(b). Position of observation window.

Many types of burners for liquid fuel are utilized for industrial use, namely, the high pressure jet oil burner, the high pressure air atomizing burner, the high pressure steam atomizing burner, the low pressure air atomizing burner, the rotary cup atomizing burner etc. In this study the high pressure air atomizing burner and the low pressure air atomizing burner are chosen. Fig. 2(a) and (b) show the burners of these two types. For the combustion of the city gas, the gas burner

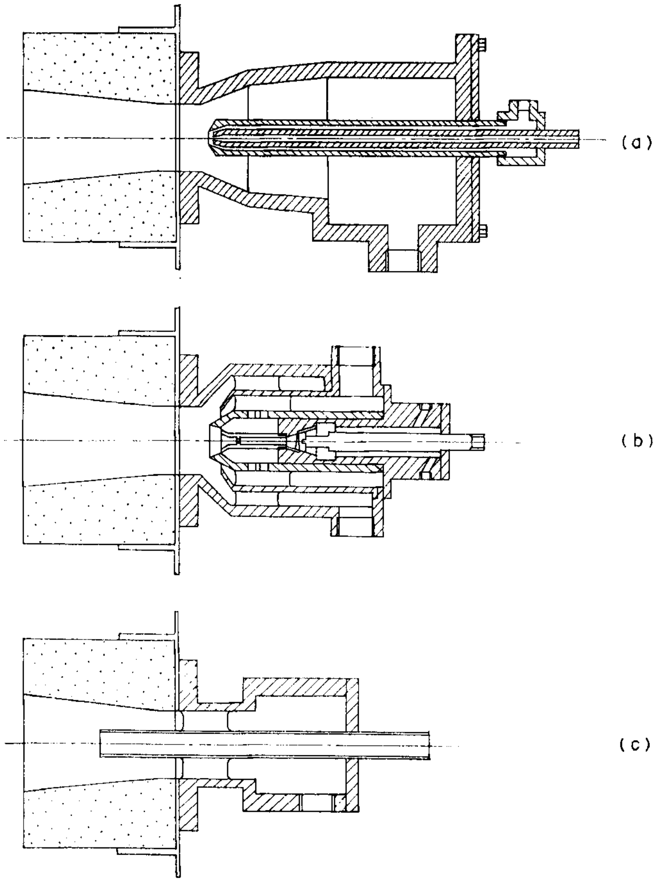


Fig. 2(a). High pressure air atomizing burner.
Fig. 2(b). Low pressure air atomizing burner.
Fig. 2(c). Gas burner.

Table 1. Nature of fuel

city gas

component	CO	H_2	CH_4	O_2	N_2	CO_2	high hydrocarbon
volumetric concentration %	8	46	16	3	12	9	6

liquid fuel

fuel		Diesel light oil	heavy oil A	heavy oil B
mass concentration %	C	85.75	86.74	86.00
	H	13.67	13.12	11.77
specific gravity gr/cc		0.805	0.85	0.92

shown in Fig. 2(c) is used. Air for combustion is supplied by the blower in the case of the low pressure burner and the gas burner. In the case of the high pressure burner, the primary air is supplied by the compressor and the secondary air by the blower.

2.2 Fuel

The fuels used are Diesel light oil, heavy oil A, heavy oil B and city gas. The chemical compositions and their other properties are shown in Table 1 and Fig. 3. Heavy oil A and heavy oil B are preheated in experiments.

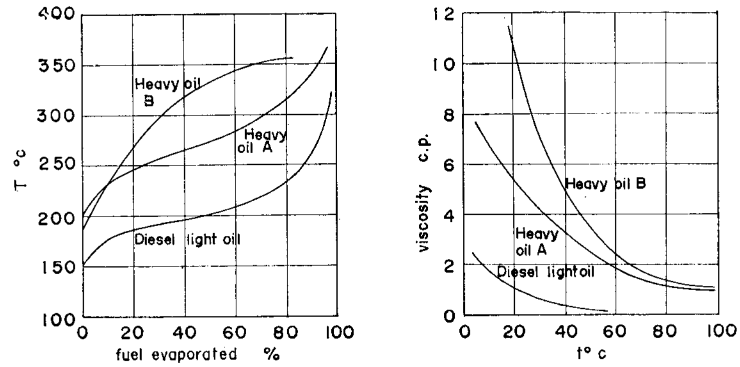


Fig. 3. Nature of fuel.

2.3. Procedure and equipment for measurement

2.3.1. Gas temperature

A suction pyrometer is generally admitted to be the most accurate equipment for the temperature measurement of burning gas. But the suction pyrometer which is sufficiently small and simple for handling in the present middle scale exerimental furnace can not be made. So the naked PtRh(20–5) thermocouple of 100 μ in diameter is used for all experiments. As it is generally admitted that Pt shows the catalytic action in combustion gas, the naked thermocouple is compared with the suction pyrometer shown in Fig. 4, in furnace, before all experiments.

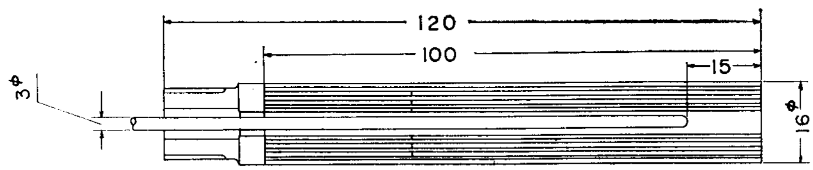


Fig. 4. Suction pyrometer.

2.3.2. Gas composition in flame

The gaschromatograph is used to measure the partial pressures of various comshown bustion gases. The carrier gas is Helium and the fillers are activated charcoal, molecular sieve and polyethylene glycol. Gases analyzed are O_2, H_2, N_2, CO, CO_2, H_2O, CH_4, C_2H_4 and C_2H_6.

2.3.3. Soot concentration

The soot concentration is measured by using the soot collector. The details of the soot collector have been shown in the previous paper[5].

2.3.4. Radiation from flame

The radiation pyrometer is used to measure the total radiation which is emitted perpendicularly to the observation window from the luminous flame. From the indication of the radiation pyrometer, the blackbody temperature of the flame can be easily calculated. Then the provisional flame emissivity ε_t' is defined from the blackbody temperature T_b and the mean flame temperature T_m as $\varepsilon_t'=(T_b/T_m)^4$. Considering the reflection at the opposite wall, the true flame emissivity ε_t can be obtained by $\varepsilon_t=\varepsilon_t'(1-r)/(1-r\varepsilon_t')$. The reflectivity r is considered as about 0.1, because the wall is covered with the thin soot layer.

From the partial pressures of CO_2, H_2O and CO, the flame breadth and the mean temperature at the observed section, ε_{CO_2}, ε_{H_2O} and ε_{CO} can be calculated by using the chart of Hottel and Ullich[6]. ε_{CH_4}, $\varepsilon_{C_2H_2}$, ε_{SO_2} and etc. are not taken into consideration because of their negligibly small values. The gas emissivity ε_g can be given by

$$\varepsilon_g=1-(1-\varepsilon_{CO_2})(1-\varepsilon_{H_2O})(1-\varepsilon_{CO}),$$

assuming that each gas behaves as graybody. Furthermore, by assuming that both gas and soot particles emit as graybody, the emissivity of the soot particle cloud can be expressed by $\varepsilon_s=1-(1-\varepsilon_t)/(1-\varepsilon_g)$. The effect of the temperature distribution upon ε_s is removed by the result of the previous study[7].

3. Experimental results

On the soot formation in the flame and the radiant heat transfer from the flame, many factors have an influence. For example they are the kinds of burner, the fuel kinds, the air excess ratio, the heat release quantity, the primary air quantity, the spray diameter, the flow velocity, the furnace scale and so on. It is usually not so easy to separate the effect of only one factor, because some change of one factor usually causes changes of other factors. Yet if the changes of other factors are regarded as small when one factor is changed in a wide range, the results obtained may be considered to be caused by the effect of that factor. By combination of many factors above mentioned, aflout 60 kinds of luminous flames are examined.

Series of experiments are expressed as follows. The first capital letters show the kind of burner.

H: the high pressure air atomizing burner
L: the low pressure air atomizing burner
G: the gas burner

The second capital letters show the fuel kinds.

L: Diesel light oil
A: heavy oil A
B: heavy oil B
C: city gas

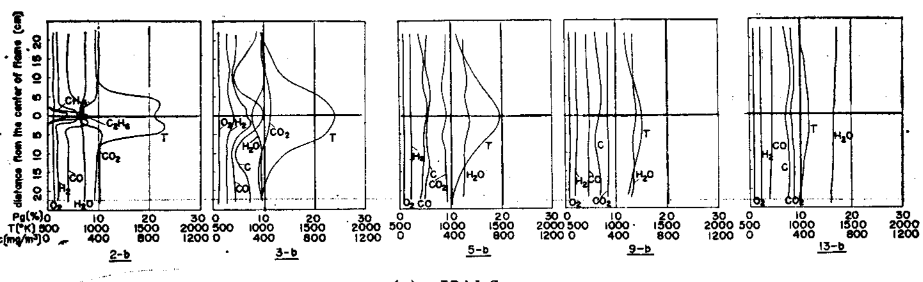
Next numbers show the experimental numbers in each series. The positions of the observation windows are shown in Fig. 1(b). Measurements are carried out only on the horizontal plane containing the flame axis. As the purpose of the present study is mainly to examine the relation between the soot formation and the radiation, the air excess ratio is very low and complete combustion is not attained often.

Table 2. Condition of Combustion

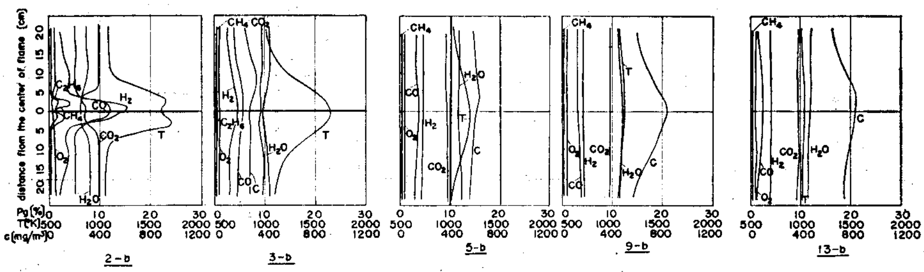
Experiment	Fuel flow rate	Air escess ratio
HL1	9.6 kg/h	0.84
HA1	10.1 kg/h	0.89
HB1	10.3 kg/h	0.87
HB2	7.8 kg/h	1.14
HB3	6.1 kg/h	1.46
HB4	4.5 kg/h	1.42
HB5	7.8 kg/h	1.11
LL1	6.94 kg/h	0.90
LA1	7.86 kg/h	0.85
LB1	7.6 kg/h	1.00
GC1	3.76 l/s	1.23
GC3	4.27 l/s	1.09

3.1. Variations in flame states

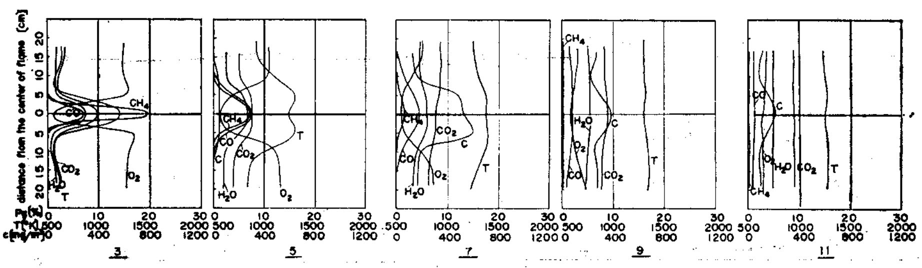
Twelve flames whose burning conditions are shown in Table 2 are chosen in order to examine the effects of several factors upon the flame radiation and the soot formation. Some examples of the sectional distributions of the measured values at each observation window are shown in Fig. 5(a), (b) and (c) and the variations of the mean values of the above sectional distributions are plotted in Fig. 6 according to the distance from the burner exit.



(a) HAl flame



(b) LAl flame

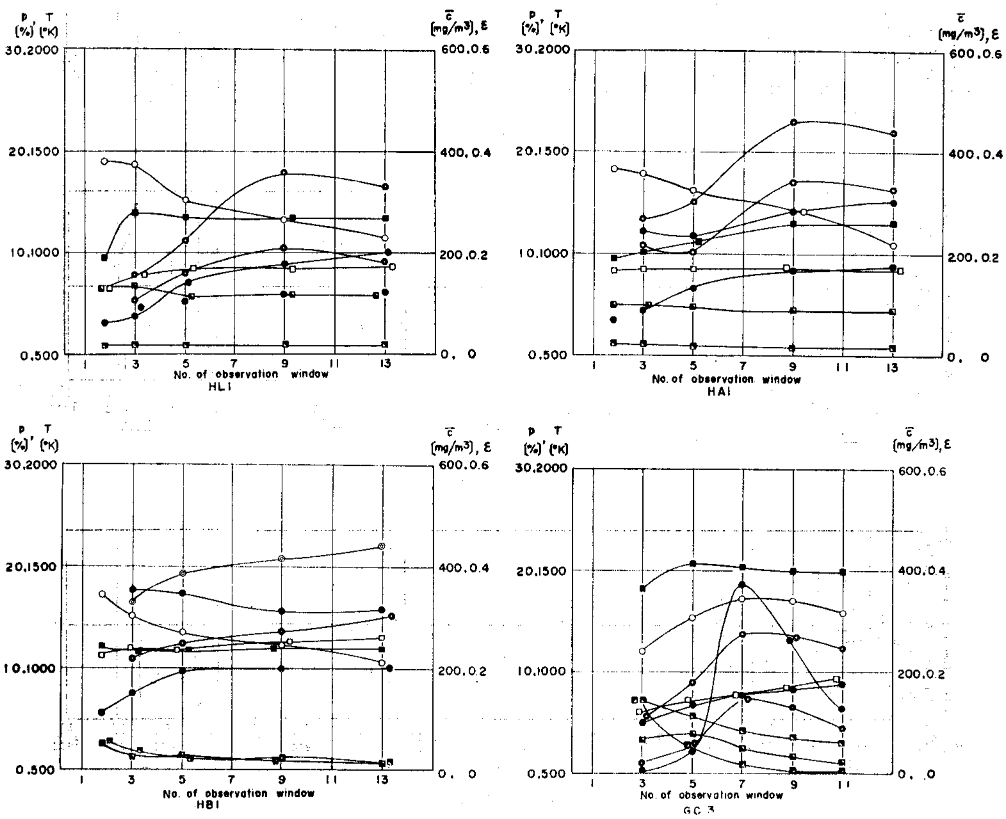


(c) GC3 flame

Fig. 5. Sectional distributions of measured values.

3.1.1. The effect of the fuel kinds

If the flames of HLl, HAl and HBl (Fig. 6(a)) are compared in order to examine the effects of the fuel kinds for liquid fuels, the remarkable variations in the soot concentrations and the partial pressures of CO_2 and CO are recognized. The soot concentrations increase in the order of HLl, HAl and HBl. The partial pressures of CO decrease in the same order. As the quantity of the primary air is 7~12% of the stoichiometric air quantity, these flames can be considered as the diffusion flames. If the evaporation rate of the fuel droplet is very small, the fuel can perform the complete combustion easily because at the point of the combustion the quantity of O_2 diffused is large enough. If the evaporation rate is high enough, the imcomplete combustion produces CO because of the small quantity of O_2 supplied by the diffusion compared with the amount of the evaporated fuel. So CO increases. CO once produced changes hardly into CO_2 because of the low concentration of O_2 and the small reaction rate at the flame temperature.



○Tm ◎ε_t ⊙ε_g ○ε_s ●C
□P_{CO_2} ■P_{H_2O} ◩P_{CO} ◩P_{O_2} ◩P_{O_2} ◩P_{CH_4}

Fig. 6(a). Effect of fuel kinds.

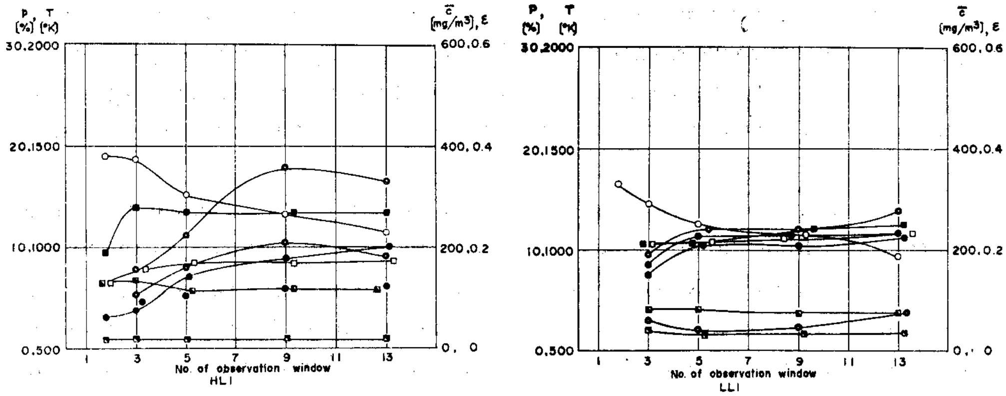
In the flame of the liquid fuel, two different processes of the soot formation can be considered. The one process is the condensation-polymerization of the gaseous hydrocarbon evaporated from the fuel droplets. The other process is the carbonization by the thermal cracking in the fuel droplet proceeding parallelly with the evaporation in the high temperature atmosphere. Considering the fact that the soot concentration increases in the order of HLl, HAl and HBl and the evaporation rate decreases in the same order, the main portion of the soot formed is considered to be caused by the thermal cracking and the carbonization of the fuel droplets themselves, which will be discussed again in the following section.

In these experiments, owing to the low oxygen concentration and the low temperature, the soot particles once educed do not burn easily and the soot particle concentrations scarcely change in the second half of the flame. If the oxygen concentration and the temerature are high enough, these soot particles may burn smoothly.

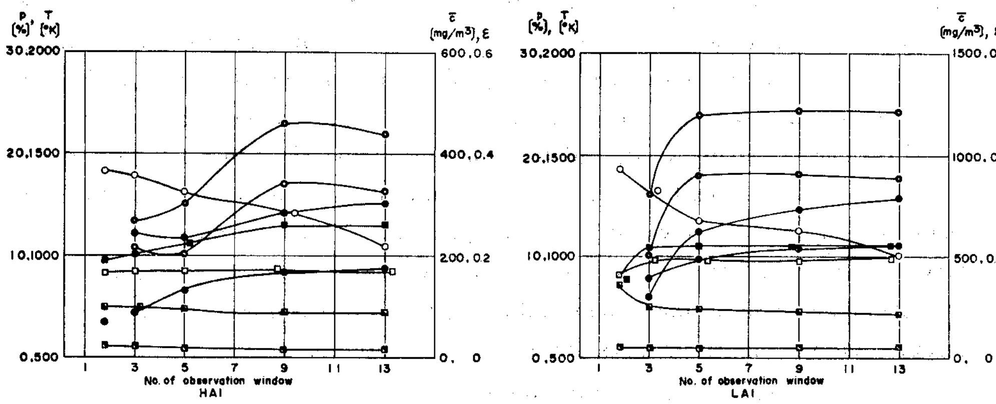
An example of the city gas flame is GC3(Fig. 6(c)-2). The gas fuel flame differs much from the liquid fuel flame upon the soot formation. In the former flame, the combustion is delayed and the soot formation curve has a sharp rise at the distance far from the burner exit, because the gas fuel jet has the larger diameter and the higher exit speed and moreover the primary air is not supplied. This result agrees with the fact that the soot formation from hydrocarbon gases in the thermal decomposition chamber increases rapidly with the temperature[8] and there is the dark space or the time interval before the soot formation in the small flame of the gaseous fuel[9]. On the other hand, in the case of the liquid fuel, the soot particles are formed mainly by the thermal cracking of the fuel dorplets and partially formed from the evaporated fuel. However, the amount of the evaporated fuel from the liquid droplet is usually small and the quantity of the air diffused for the combustion of the volatilized fuel is large enough, and it burns easily, therefore the soot quantity formed from the volatilized fuel is generally small. So the soot formation curve in the liquid fuel flame has not such a sharp rise. The soot concentration of GC3 flame decreases in the second half of the flame. It is due to the higher temperature and the higher air excess ratio compared with the other flames.

3.1.2. The effect of the burner kinds

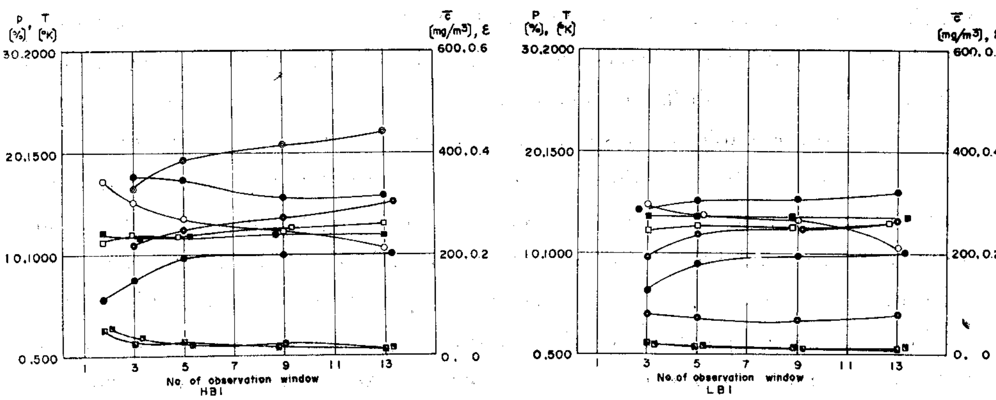
Next, the influence of the burner kinds can be examined for example by comparing the flames of HL1 and LL1 (Fig. 6(b)-1). The obvious difference between the flames of HL1 and LL1 is that the soot formation in LL1 is much stronger than that in HL1, though the air excess ratio is only slightly smaller in HL1 than in LL1. The air flow rate in both flames is kept at nearly same value and so the whole flow condition and the whole combustion condition do not differ from each other. The only different point between these flames is the means of the fuel atomizing of the burner. In the case of the high pressure air atomizing burner, the speed of the atomizing air is much higher and so the mean diameter of the fuel droplets is smaller. Accordingly if it is accepted that the larger fuel particle shows a marked tendency to change into soot by thermal cracking and carbonization before evaporation from the liquid droplet is completed, the results obtained above may be considered to be reasonable. Another point which may be noticed is that LL1 flame shows very low emissivity compared with HL1 flame in spite of its large quantity of soot. The con-



1. Diesel light oil



2. Heavy oil A



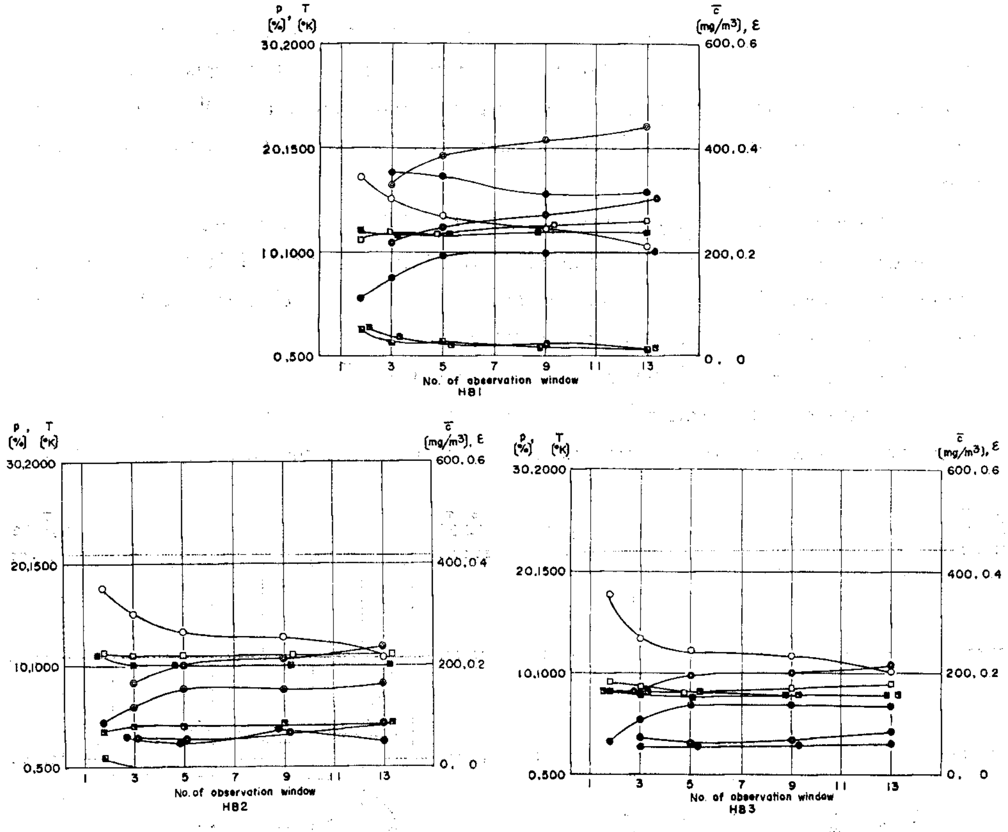
3. Heavy oil B

Fig. 6(b). Effect of burner kinds.

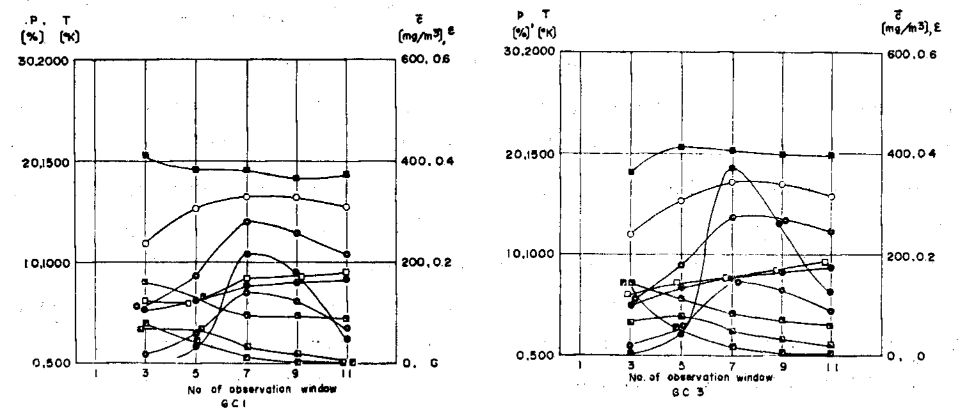
sideration of this point will be discussed in section 3.4.1. By comparing the flames of HA1 and LA1 (Fig. 6(b)–2) or the flames of HB1 and LB1 (Fig. 6(b)–3), the same phenomena are observed too.

3.1.3. The effect of the air excess ratio

If the flames of HB1, HB2 and HB3 are compared (Fig. 6(c)–1), the influence



1. Liquid fuel



2. Gas fuel

Fig. 6(c). Effect of air excess ratio.

of the air excess ratio can be examined. In these three flames of HB series, the flow rates of the primary air and the secondary air are kept constant and only the fuel flow rates are changed. The fuel flow rates and the mean diameter of the fuel sprays are decreased in the order of HB1, HB2 and HB3. The quantity of soot particles in HB2 flame is a quarter of those in HB1 flame. However, the HB3 flame does not show a marked change from the HB2 flame and contains the almost same quantity of the soot particles as the HB2 flame. The temperature and the gas partial pressures slightly decrease. As the quantity of the soot particles is not influenced by the air excess ratio in both flames, those soot particles are considered to be formed by the thermal cracking too.

In the case of the city gas flame, GC1 and GC3 are compared (Fig. 6(c)-2). As the air excess ratio of the GC3 flame is lower than that of the GC1 flame, the soot formation of the GC3 flame is of course stronger than in the GC1 flame, although the distribution tendencies of all factors resemble each other.

3.1.4. The effect of the quantity of the atomizing air

The flames of HB2 and HB5 are compared in order to examine the effect of the quantity of the atomizing or primary air (Fig.6(d)). In these flames, the fuel flow

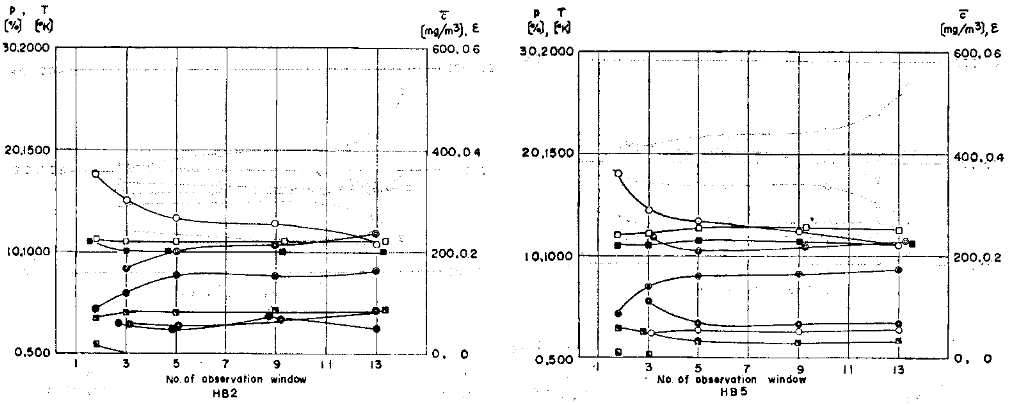


Fig. 6(d). Effect of quantity of atomizing air.

and the secondary air flow are kept nearly constant. The atomizing air is 12 % of the stoichiometric air in the HB2 flame and 9 % in the HB5 flame. The whole radiant character and the soot formation of the two flames are similar and the effect of atomizing air quantity is small. The only one different point is the higher emissivity of the HB5 flame than the HB2 flame at the observation window 3b. It is considered to be caused by the high absorption coefficient of the soot particles owing to the high hydrogen concentration in the soot because of wrong mixing and the delay of the carbonization as it will be discussed after in the section 3.4.2..

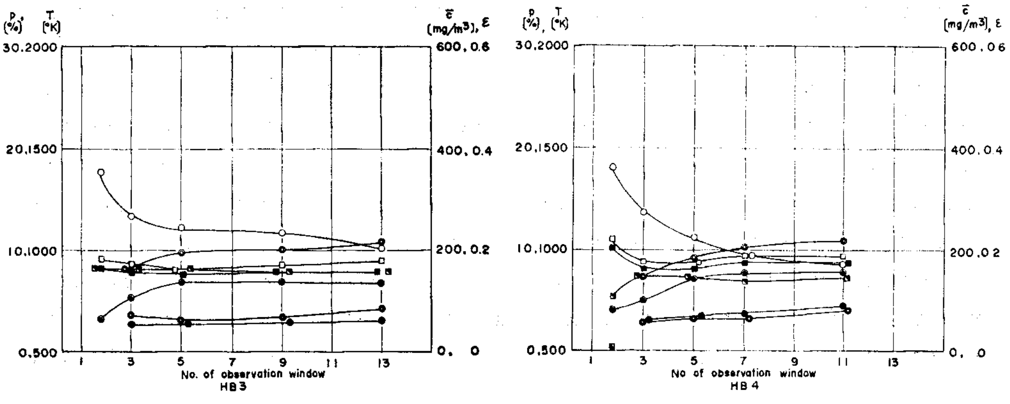


Fig. 6(e). Effect of heat release rate.

3.1.5 The effect of the heat release rate

In order to examine the effect of the heat release quantity, the flames of HB3 and HB4 are compared. The fuel flow rate, the primary air quantity and the total air quantity of the latter flame are about 3/4 those of the former. The emissivities, soot formations and the other values, except the temperature, resemble each other. The temperature of the latter flame is lower than that of the former because of the same emissivity and the lower heat release. The larger heat release may be considered to contract with the strong soot formation but it also corresponds to better mixlng, then the soot formation is considered to be equalized by the two contrary effects. Finally the change of the heat release rate does not remarkably affect the emissivity and the soot formation, but of course affects the radiation itself.

From the above rough examination of the effects of several factors upon the flame emissivity and the soot formation, the influences of the fuel kinds, the burner kinds and the air excess ratio are found to be very strong and the other factors do not show remarkable effects. In the following, the important matters which must be considered in connection with the flame radiation and the soot formation are rearranged and examined in detail from all experimental flames.

3.2 The relation between the soot formation and the air excess ratio

The soot formation in flames is especially important from the viewpoint of the flame radiation and air pollution. The most important factor that is considered to control the soot formation is the air excess ratio. In the case of the liquie fuel, the other factors such as the droplet diameter, the primary air quantity, the flame temperature and the heat release quantity have influence upon the soot formation too. However, the primary air quantity can not change easily because of the blow off or the wrong atomization, and the flame temperature does not change widely in many kinds of flames. Consequently the effects of these two factors are not so important. Further, the above trials upon the effects of the primary air quantity and the heat release quantity show only small influences. So if the data of the soot formation is related with the local or the initial air excess ratio, the simple relation may be expected according to the fuel kinds and the burner kinds though it may be very rough. The relation between the soot concentration and the air excess ratio averaged in the soot containing region of the flame is shown in Fig. 7. In the figure, the mean values of the soot concentration obtained at certain air excess ratio from many flames of the various burning conditions are plotted. The fuel kinds and the burner kinds influence the soot concentration greatly. Especially in the case of the heavy oil, even

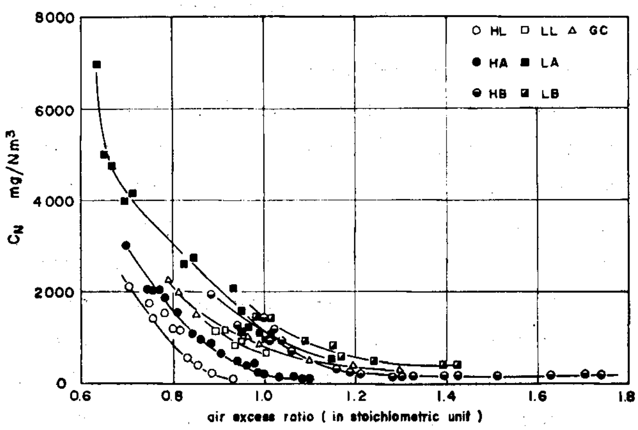


Fig. 7. Relation between soot concentration and air excess ratio.

at the air excess ratio greater than 1.0, the soot formation is very strong and does not approach to zero even at the higher air excess ratio because of the thermal cracking of the liquid droplet. On the contrary, in the city gas flame, the soot concentration becomes zero at the air excess ratio greater than 1.5. However, the soot formation is as strong as that in the liquid fuel flame at the air excess ratio smaller than 1.0. But such a result was obtained by using the special gas burner which is considered to be easy to use for the observation of the soot formation, and so by the usual burner, the soot concentration will be supposed to be smaller than this result. The scattering of the data may depend upon the other factors, but their effects are considered to be small as shown in the figure.

3.3. A few characters of the soot particles

The electron microscopic study of the soot is carried out to know if the diameter and the configuration of the soot differ from each other according to the burner types and the fuel kinds. Furthermore the chemical analysis of soot is carried out to assure the view that the soot is not pure carbon and contains considerable hydrogen and to know how much hydrogen the soot particle contains.

3.3.1. The electron microscopic observation on the soot

The photographs of the soot obtained by the electron microscope are shown in Fig.8. Being different from the previous knowledge that the soot particles in the flame have diameters smaller than 0.05 μ,[4] all flames contain soot particles whose diameter ranges are very wide such as $0.02\mu \sim 10\mu$. If the weight or volumetric distributions are considered, the large particles play important roles. Another remarkable fact is that the bee-hive like and the hollow particles can be found often especially in the large diameter range in the case of the liquid fuel. As to the formation of these particles, it is considered that the fuel droplets themselves or the splashes from the fuel droplets crack thermally or carbonized and that, in detail, as the droplet surface is first exposed to the high temperature, a carbonized spherical shell appears and then the inner liquid fuel blows out distroying the shell or making the small holes on the shell. On the other hand, the small soot particles also have the possibility to be formed by the process other than the condensation-polymerization from the gaseous hydrocarbon. That is, after the considerably large soot particles are formed from the liquid droplets, small and many graphite-like crystals develop in it and the occurence of the stress and strain leads large particles to collapse into small particles. Or the liquid fuel which jets out through the spherical shell carbonizes into the small soot.

Among the soot particles in the city gas flames there are no bee-hive like or hollow particles, of course. But, different from the previous experiments in the small gaseous flames which did not contain the large soot particles and in which the distribution range of the particle diameter was very narrow[4], the distribution range is very wide and the flame contains also the large particles as in the liquid fuel flame. In the gaseous diffusion flame of the large scale, the occuring positions of the soot exist in the very wide range of the distance from the burner exit. So the small soot particles formed in the early stage grow to large particles in the following stage while new small particles are formed there. From the above fact, it is obvious that the results in the very small scale flame can not be carelessly applied to the large scale flame.

As the observed number of particles is not enough to obtain the detail diameter distribution, the rough representation of the particle diameter in each flame series is expressed in Fig. 9. In the case of the liquid fuel flame, the diameter distributions in the flame series of the high pressure air atomizing burner considerably differ from

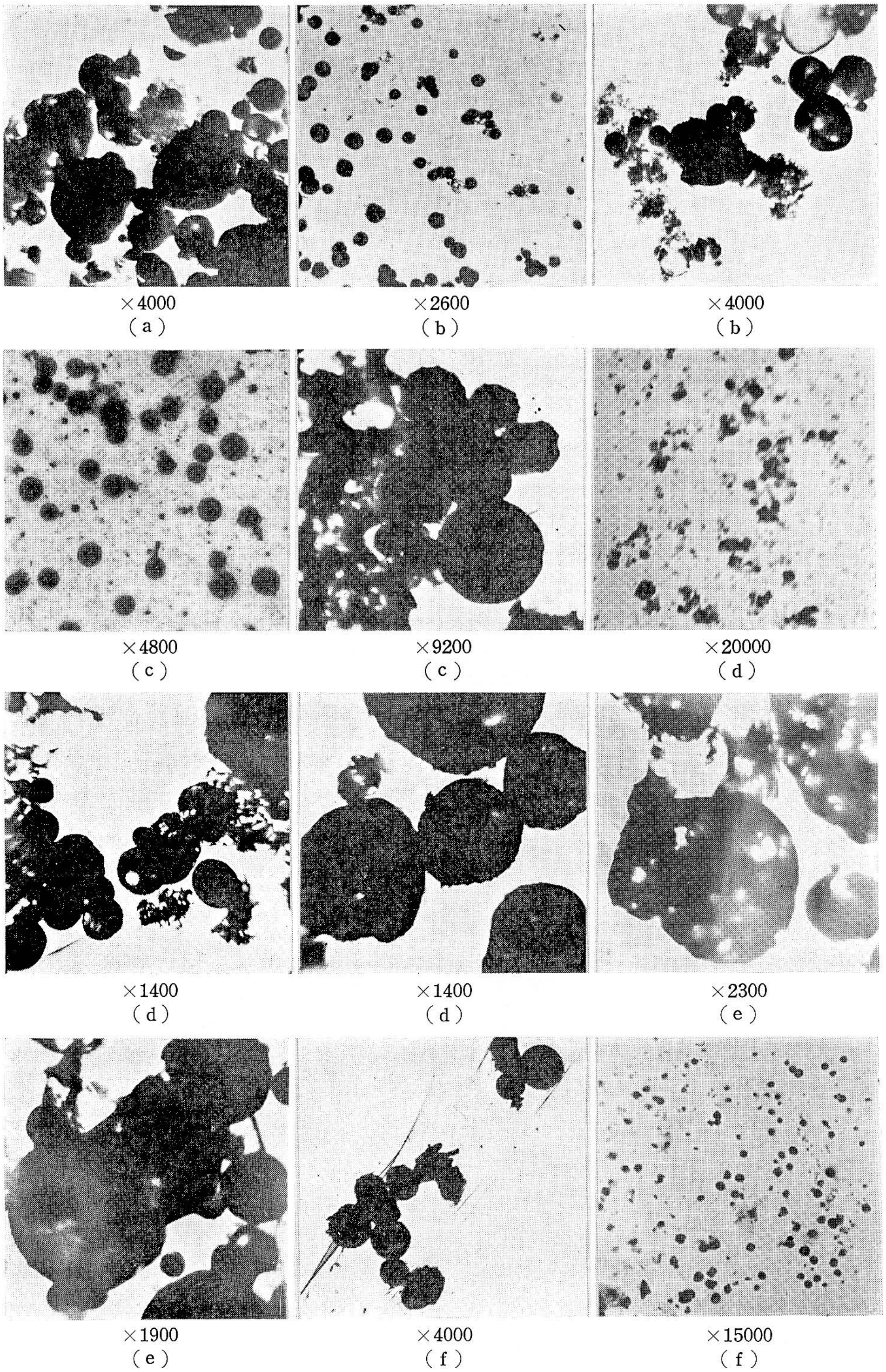


Fig. 8. Electron microscope photograph of soot particle.
(a) HL (b) HA (c) HB (d) LA (e) LB (f) GÇ

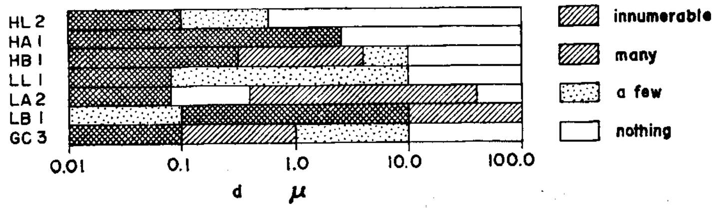


Fig. 9. Distribution of soot particle diameter.

those in the flame series of the low pressure air atomizing burner. The former contains many soot particles whose diameter range is 0.3~1.0 μ and the latter contains many particles larger than 1.0 μ. In the case of the same burner, the differences according to the fuel kinds are not remarkable. In the case of the city gas flame, not only small particles but also large particles are found as mentioned above. The distribution patterns are similar as those in the liquid fuel flame of the high pressure air atomizing burner.

To investigate the dependence of the diameter distribution upon the distance from the burner exit in the liquid fuel flame, the detailed examination is carried out

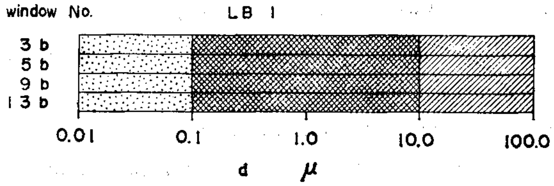


Fig. 10. Distribution of soot particle dismeter in each position of LBl flame.

as shown in Fig. 10, but no significant dependence is found. It is supposed that the soot once formed survives in the following section and is scarcely consumed in the present experiments.

3.3.2. The mass ratio of hydrogen and carbon in the soot particle

It is also important to know the chemical composition of the soot as it may affect the radiative characteristics. Though it is generally supposed that the mass ratio of hydrogen and carbon, H/C, of the soot in the flame is about 0.92, the ratio has not been examined exactly especially in the liquid fuel flame. Several examples measured in the present study are shown in Fig. 11. In the liquid fuel flame, the ratio H/C is large at the short distance from the burner exit and the longer the distance from the burner exit, the smaller the ratio H/C, approaching the constant value of 0.01~0.03. A strange result is that the ratio H/C rises slightly in the end part of the

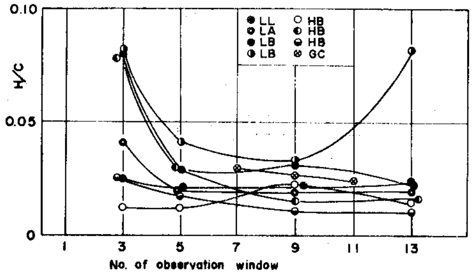


Fig. 11. Mass ratio of hydrogen and carbon in soot particle.

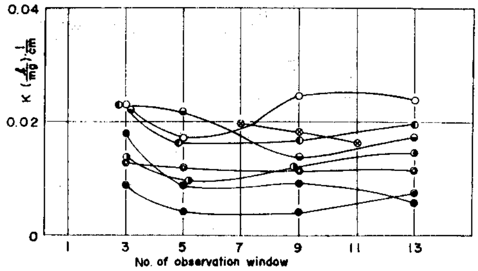


Fig. 13. Absorption coefficient of soot particle cloud.

flame in a few examples. the cause being as follows. In the end part, the temperature decreases to 1100°K sometimes. At these temeratures, the reactions which produce hydrogen such as

$$CO+H_2O=CO_2+H_2,$$
$$C+H_2O=CO+H_2 \quad \text{and}$$
$$C+2H_2O=CO_2+2H_2$$

have equilibrium constants near 1.0, so H_2 occurs at the soot surface and combines with carbon in the soot. Then the ratio H/C may increase. The large difference at the first part of the flames is considered to be caused by the difference of the rates of the combustion and the carbonization in each flame. The large value corresponds to the delayed combustion and carbonization, and the small value corresponds to the fast combustion and carbonization. In the city gas flame, the variation of the ratio H/C in the soot shows the same tendency as in the liquid fuel flame.

3.4. The relation between the emissivity of the soot particle cloud and its effective thickness

The relationship between the emissivity of the soot particle cloud and its effective emission thickness in all series is shown in Fig. 12. The relations differ remarkably according to the burner kinds. The data of the high pressure burner series and the city gas series are higher than those of the low pressure burner series. In the liquid fuel flame, the fuel kinds do not affect the relations. In the city gas flame, the relations are similar to those of the high pressure burner series of the liquid fuel. The relationship obtained previously in Ijmuiden furnace and Sheffield furnace is also shown for comparison. The scattering of the data of the present study and that of the other studies are nearly equal. Though the cause of the scattering has not been made clear in other studies, it can be explained as follows for our study.

As the chemical compositions of the soot particles do not show different ten-

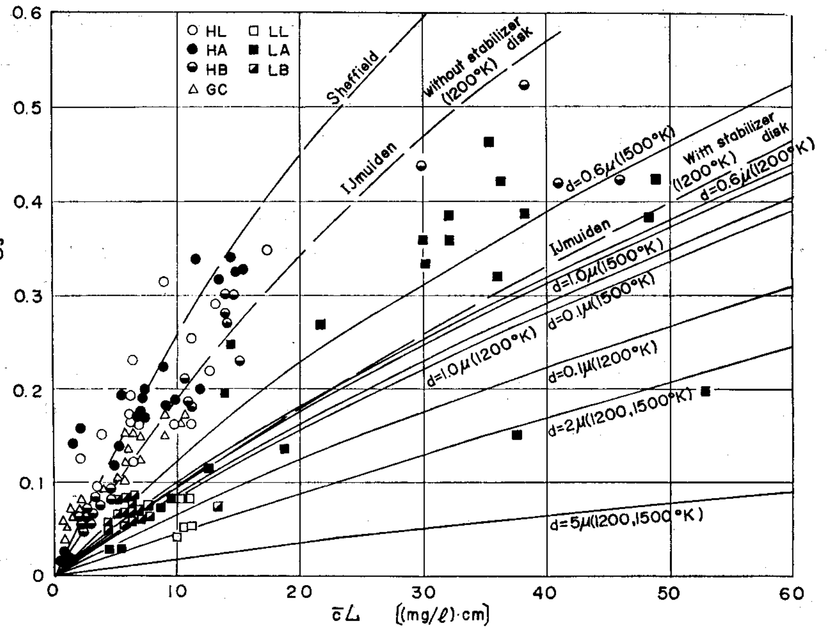


Fig. 12. Relation between emissivity of soot particle cloud and effective emission thickness.

dencies among all the series in the present study, the differences of the chemical compositions do not account for such large disparities, granting that they affect the radiation character. So these disparities must depend mainly upon the differences of the size distributions of the soot particles. In the following, the inquiry on these effects is discussed.

3.4.1. The effect of the particle diameter

On the effect of the particle diameter upon the absorption coefficient of the infrared radiation, A. G. Blokh reported the results calculated by the theories of Mie and Stull & Plass. The relation between the emissivity and the particle diameter obtained by using his result is that the emissivity shows a constant value in the diameter range smaller than 0.2 μ, shows the peak value in the range between 0.2~1.0 μ and then decreases suddenly in the range larger than 1.0 μ[5]. In Fig. 8, it is found that the soot particles of the high pressure air atomizing burner series and of the city gas series contain many particles that show the low emissivity. So it can be concluded that the large scattering on emissivities is caused mainly by the differences of the soot particle diameter in the flame. The theoretical values are shown in Fig. 12 too. However, the differences of the absolute values between the present results and the theoretical results are not so small, the reason being not explainable.

As the detailed data were shown in the case of the Ijmuiden furnace[3], the cause of the differences of the emissivities or the absorption coefficients of the soot particle clouds can also be explainable similarly for the results obtained in the Ijmuiden furance. Namely, in the case of the flame with the stabilizer disk, the flame front it extremely near to the burner exit. As fuel sprays fly immediately into the high temperature flame zone before enough evaporation, the carbonization from fuel droplets predominates. So large particles are formed in a large amount and the flame shows low absorption coefficient like the present flame series of the low pressure air atomizing burner. On the contrary, in the case of the flame without the stabilizer disk, the flame front exists somewhat far from the burner exit. The evaporation goes on considerably so the large soot particles are not formed in a large amount. Then the flame shows the high absorption coefficient like the present flame series of the high pressure air atomizing burner.

3.4.2. The effect of the chemical composition

Though the influence of the chemical composition is considered small, the effect may be examined if the relations between the absorption coefficients and the ratio H/C are compared locationally in one flame, because the diameter distribution in each flame does not change from the beginning to the end part, namely the effect of the diameter being removed. As the emissivities of the soot particle clouds and their effective emission thicknesses are known in each flame, the absortion coefficients are calculated by

$$k=-\frac{1}{\bar{C}L}\ln(1-\varepsilon_s).$$

The results for the flames shown in Fig. 11 are given in Fig. 13. The comparison between Fig. 11 and Fig. 13 shows the correspondence of the absorption coefficients and the ratio H/C. In each flame, the value of the absorption coefficient is small at the position showing the small H/C ratio and the large absorption coefficient corresponds to the large H/C ratio. This result is equivalent to the fact that the large H/C corresponds to the large disorder of the crystal structure and to the large electric resistance or to the high absorption of the electromagnetic energy, so corresponds to the high emissivity of the material surface. Finally, it is made clear that, upon the radiation from the soot particle cloud, the particle diameter distribution affects greatly and the chemical composition also a little.

4. The estimation of the flame emissivity

In the previous chapter, many factors that have the influences upon the flame radiation, such as the soot concentration, the soot particle diameter, the chemical composition and so on are examined. However, for practical use to calculate the radiative heat transfer from the luminous flame, the above results are not so convenient, because the soot concentration, the soot particle diameter and so on are not so easily assumed in the practical flame. Therefore it is very useful to give the criterion to obtain the soot particle cloud emissivity according to the combination of the burner kind, the fuel and the air excess ratio. On this problem it may be allowed to dispute only the main part or the middle part of the flame. In the main part of the flame, the gas emissivity may be easily calculated irrespective of the combustion means if the air excess ratio is given. So it is very convenient if the soot particle cloud emissivity is rearranged on the basis of the gas emissivity as to the air excess ratio. Mean values of the ratios of the emissivity of the soot particle cloud and the gas emissivity, $\varepsilon_s/\varepsilon_g$, obtained from the present experiments are given in relation to the air excess ratio in Fig. 14. In this figure, the ratios depend mainly upon the fuel kinds and the air excess ratio. The effect of the burner kinds almost disappears. Furthermore other burning conditions are considered to affect the relation scarcely. The reason using the effect of the burner kinds disappears is considered as follows. The flame using the low pressure air atomizing burner contain the soot particles of high concentration, while the flame using the high pressure air atomizing burner contain the soot particles of low concentration. But the soot particles themselves in the former flames show the weak emission and the soot particles in the latter flames show the strong emission. These two effects almost cancel out each other and so the effect of the burner kinds dissapears.

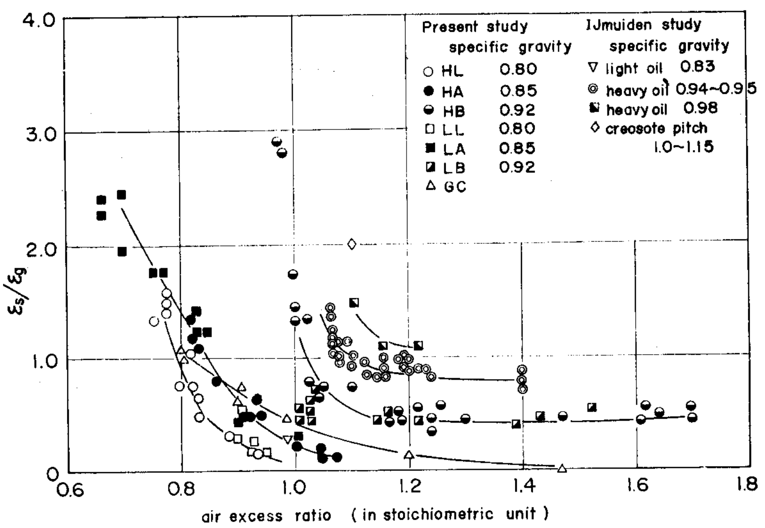


Fig. 14. Relation between the ratio $\varepsilon_s/\varepsilon_g$ and air excess ratio.

For the actual utilization, it must be made sure if the results obtained are general. The Ijmuiden furnaces have scales of about five or six times of the present study furnace. In those experiments, the fuels whose natures are different from those of the present study were used. The detailed experiments the same as the present study, containing many trials of the burner, the fuel, the heat release, the atomizing air or steam quantity and so on, were carried out there. The comparison between the present study and the Ijmuiden study may show the effect of the furnace or flame scale and that of the fuel kinds. Though most Ijmuiden reports state only the total emissivity, the non-luminous gas emissivity can be supposed from the diagrams given there. Then the mean values of the emissivities of the soot particle clouds in the main part of each flame can be calculated. Using these values, the relations between $\varepsilon_s/\varepsilon_g$ and the air excess ratio can be obtained too and they are also shown in Fig. 14. The specific gravities of the fuels used are shown too for comparison. The effects of the fuel natures upon the relation in both studies show the definite trend and coincide with each other very well. Also in Ijmuiden furnace, the effects of many other factors except the fuel nature and the air excess ratio can be considered small as in the present study. From the above results, the effect of the furnace scale can be neglected if such means of calculation are adopted. If the fuel and the air excess ratio are decided, the gas emissivity ε_g and the ratio $\varepsilon_s/\varepsilon_g$ may be obtained and then the flame emissivity ε_t can be calculated easily. Using this value, the flame state may be estimated and the radiative heat transfer from the flame to the surrounding surface in the furnace can be calculated by the various proposed means.

5. Conclusion

The results of the present study may be summarized as follows;

In the luminous flame of the liquid fuel, the soot concentration differs considerably according to the fuel kinds and the burner kinds, and the size distributions of the soot particles vary too. The distributed range of the diameter is very wide and the large particles are often found. Further there are many bee-hive like and hollow particles and these are considered to be formed by the thermal cracking and the carbonization of fuel droplets themselves or splashes from them.

In the lumious flame of the city gas, the size distributions of the soot particles do not differ from those in the liquid fuel flame and the large particles are found too. This result is different from the previously accepted opinion obtained from the small flame experiments which asserted the very small diameter. The bee-hive like and hollow particles are not found and this shows the soot formation process being different from that in the liquid fuel flame.

The chemical compositions expressed by the ratio H/C of the soot particle in each flame vary by the observed positions. The ratio decreases according to the distance from the burner exit and approaches to the constant value of $0.01 \sim 0.03$ at the end of the flame.

Upon the radiation from the luminous flame or from the particle cloud, the above mentioned size distributions of the soot particles have a great influence and the scattering of the emissivities can be explained mainly by the differences of the size distributions. The chemical compositions of the soot particles also influence a little.

Finally the recommending relation for the practical use by which the estimation of the emissivity of the luminous flame can be made when the fuel kind and the air excess ratio are decided, is obtained.

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