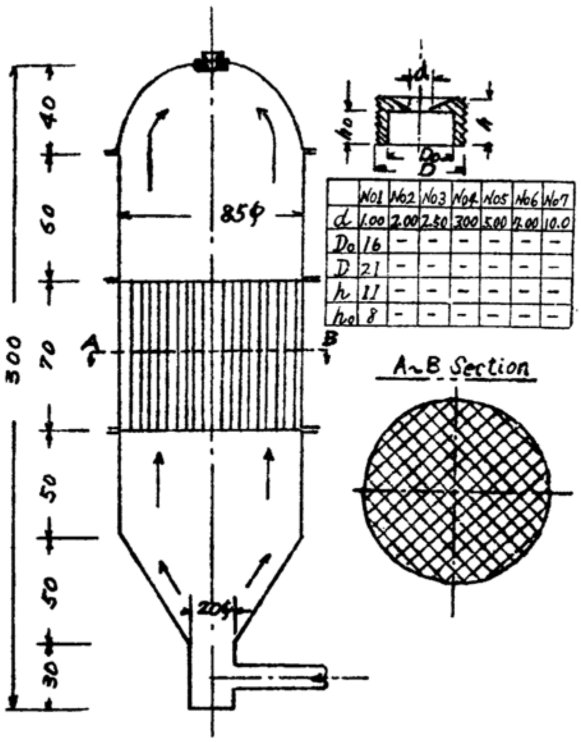
Flame Length and its Heat Radiation.

By Sakae YAGI.

(Recived November 16, 1948.)

This contribution involves our studies on flames during these ten years: Studies on Luminous Flames[1], Studies on Turbulent Diffusion (Flame Length)[2], and Studies on Flame Radiation[3]. In spite of wide application of flames for heating both in industrial and scientific purposes, few studies had been published particularly for design use.

The burner used in our measurement of flame length and radiation is shown in Fig. 1. Fuel gas compressed in a tank is flowed through a stream straighner and lighted at a burner nozzle, whose opening or diameter can be changed from 1 mm. to 10 mm.



	No1	No2	No3	No4	No5	No6	No7
d	1.00	2.00	2.50	3.00	5.00	7.00	10.0
D_0	16	-	-	-	-	-	-
D	21	-	-	-	-	-	-
h	11	-	-	-	-	-	-
h_0	8	-	-	-	-	-	-

Fig. 1. Burner for measurement.

Measurement of Flame. Length of flame is measured by the picture taken in front of a bright scale background as shown in Fig. 2. Relationship between (flame length L cm.)/(nozzle diameter d cm.) and (Fuel gas velocity at nozzle opening u cm./sec.) × (d cm.) is summarized as Fig. 3 with several sizes of nozzle diameter. At the lower value of ud, L/d increases almost proportionally to ud and at the higher ud, L/d is almost independent of ud, tending to $L/d = 50-70$.

(1) J. Soc. Chem. Ind., Japan, **1937**, 90, 93, 263.
(2) J. S. C, I. J., **1943**, 608, 821, 837.
(3) J. Chem. Soc. Japan, Ind. Ed., **52** (1949), 167.

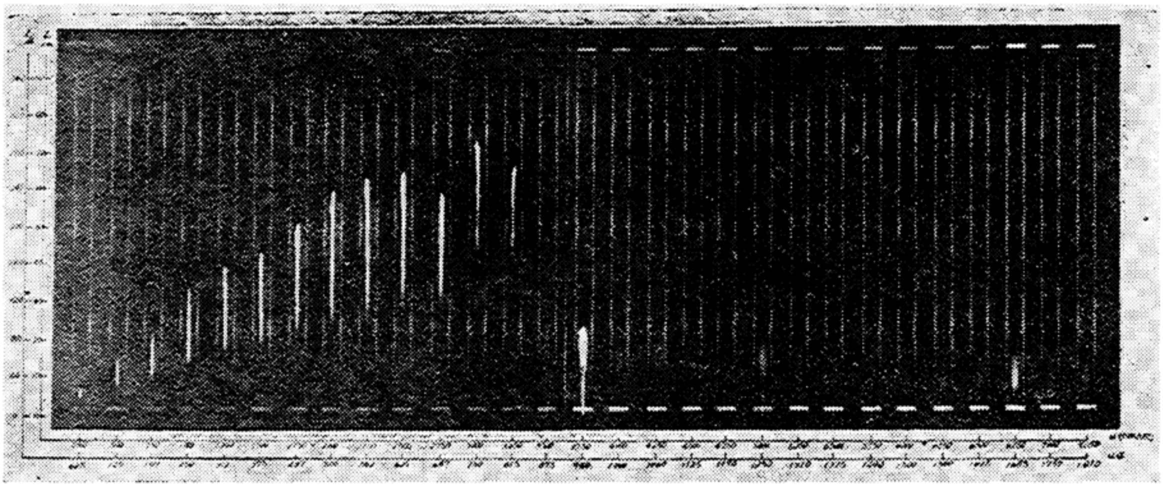


Fig. 2. Flame length of 4 mm. nozzle.

The two states of flame above mentioned are also observed by the photographic observation of flame (Fig. 2): one is a diffusional flame or laminar flow flame and the other a turbulent flame, and there can be seen some transitional region between the two states(4).

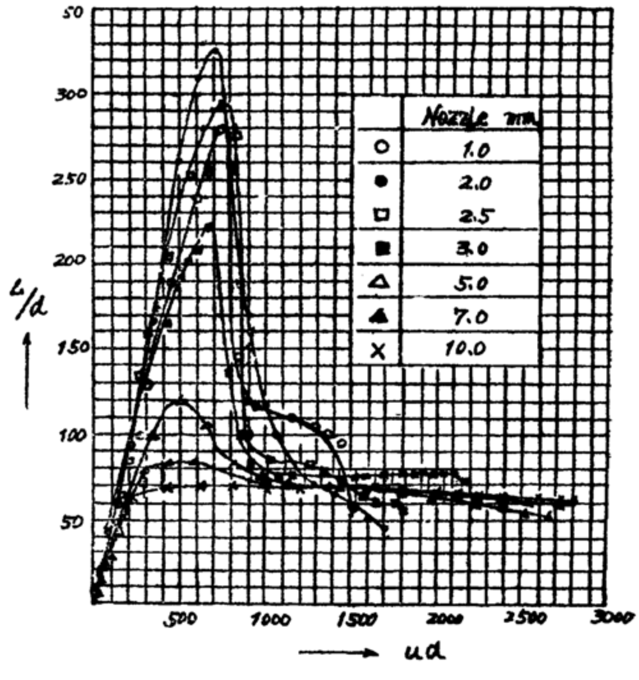


Fig. 3. Flame length.

Theoretical Consideration of Burning Rate. We can establish the following equation of material balance, if a flame in cylindrical form is assumed to be mixing status of air to fuel gas by means of molecular or turbulent diffusion, which means that the chemical reaction rate of combustion is assumed to be very large compared with the mixing rate,

$$\frac{\pi d^2}{4}\frac{dc}{dx}u = \pi d\frac{D+\varepsilon}{\delta}\Delta c \qquad (1)$$

(4) S. Yagi, J. S. C. I, J., **1943**, 873.

wherein d is diameter of flame, c: concentration of fuel in flame, D, ε: molecular and turbulent diffusion constant cm².⁄sec. of air into flame through a layer length δ cm., u: velocity of flame gas cm./sec., x: length from burner nozzle. The above equation can be integrated by using average value of u, D, ϵ at the boundary condition of ordinary atmospheric combustion: $\Delta C = C$, $C = Ci$ at $x = 0$

$$\frac{C}{Ci} = e^{-\frac{4(\bar{D}+\bar{\varepsilon})}{\bar{u}d\delta}x} = e^{-Kx} \qquad (2)$$

$$K = 4(\bar{D}+\bar{\varepsilon})/\bar{u}d\delta \qquad (3)$$

As the fuel concentration at the top of the flame measured was analysed as some figure like $0.1Ci$, the flame length L can be calculated by putting $C/Ci = 0.1$ and $x = L$ in equation 2.

$$\frac{L}{d} = \left(\frac{2.3}{4}\right)\frac{\bar{u}d\delta/d}{(\bar{D}+\bar{\varepsilon})} \qquad (4)$$

$\bar{\varepsilon}$ was calculated at the jet nozzle by solving the Tollmien equation[5] as $2\times10^{-3}\ u_0d_0$, where u_0 and d_0 are jet velocity and diameter[6]. Comparing the result of flame length measurement (Fig. 3) with equation 4, we get the following conclusions:

1. For diffusional flame:

Theoretical calculation under condition that $\bar{\varepsilon} = 0$

$$\frac{L}{d} = \left(\frac{2.3}{4}\right)\left(\frac{\delta/d}{\bar{D}}\right)\bar{u}d \qquad (5)$$

Measured result according to nozzle diameter

$$L/d = (0.3\sim0.5)ud$$

Probable values of unknown figures

$$\delta/d = 2.0\sim1.2 \text{ changing at various } d$$

if $D = 2.4$ cm².⁄sec. at air diffusing through city gas at 1200°K

2. For turbulent flame at above 500 cm².⁄sec. of ud

Theoretical calculation under condition that $\bar{\varepsilon} = 2\times10^{-3}u_0d_0$ and $\bar{D} = 0$

$$L/d = (290)\ (\delta/d)\ u_0d_0/\bar{u}d$$

Measured average result of larger diameters

(5) Z. f. angew. Math. u. Mech., **1926**, 468.

(6) S. Yagi, J. S. C. I. J., **1943**, 609.

$$L/d = 60 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Probable values of unknown figures

$$(\delta/d)(u_0 d_0/\bar{u}d) = 0.2$$

at extreme turbulency.

3. For transitional flame:
Unable to be established definitely.

Effect of Primary Air. Although primary air in the burner frequently causes increase of combustion rate, it is not always that flame length decreases by addition of primary air as shown in Fig. 4.

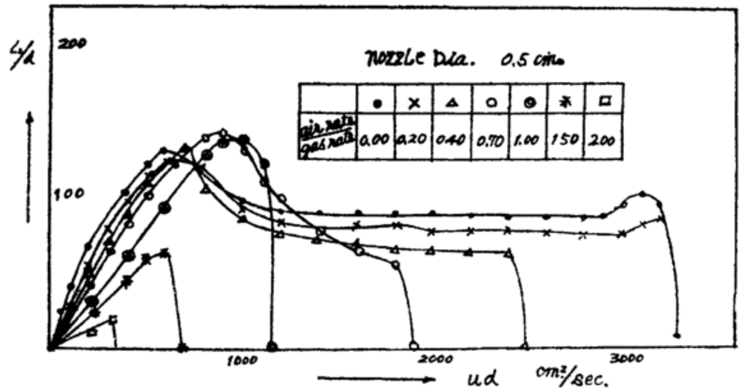


Fig. 4. Flame length adding primary air.

An important influence of adding primary air is that high primary air makes the blow limit of the gas burner have a smaller amount of ud, that means decrease in the capacity of the burner.

Further description and discussions will be available in "Flame Length III"(7).

Radiant Heat from Flame. The radiation from the flame of the above mentioned burner was measured along the length of the flame by a sensitive thermopile and galvanometer, which was calibrated with a standard black body furnace. The results measured are shown in Fig. 5, where Q_f is flame radiation integrated along the whole length of the flame, V_t is gas volume nl/h. The experiment was conducted with various openings of the burner nozzle, i.e. 1, 2, 5, 7, 10, mm. and various kinds of fuel gas, i.e.

I: City gas only of 3000 Kcal./nm.^{3},

II: City gas added with C_2H_2 6 vol. %,

(7) S. Yagi and T. Kimura, J. Chem. Soc. Japan, Ind. Ed., **1949**, in printing.

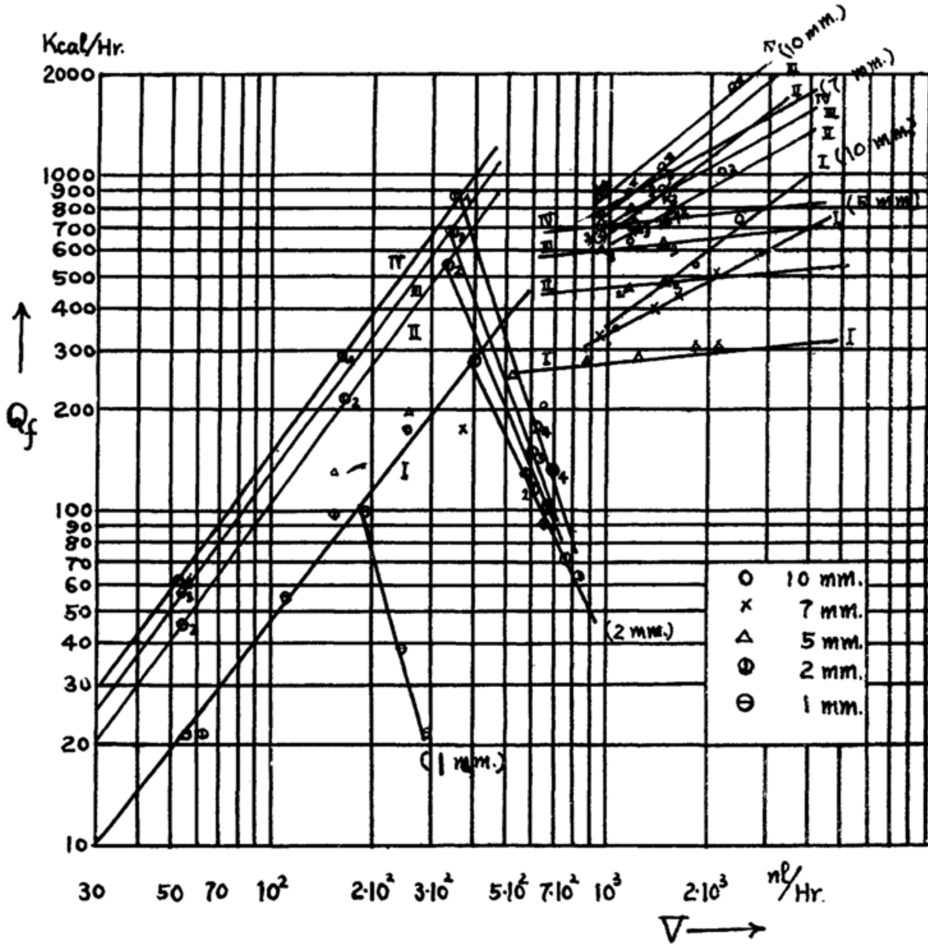


Fig. 5. Radiation from flame.

Curve I: Town Gas only.
Curve II: Town Gas plus 6 % C_2H_2.
Curve III: Town Gas plus 8 % C_2H_2.
Curve IV: Town Gas plus 10 % C_2H_2.

III: City gas added with C_2H_2 8 vol. %,
IV: City gas added with C_2H_2 10 vol. %,

In the laminar flow flame, the radiant heat Q_f is independent of burner opening, which is expressed as

$$Q_f = K(1+\alpha w)V^{1.35} \quad \ldots\ldots\ldots\ldots (7)$$

where K and α are constants, and w is the fraction of acetylene volume. In the turbulent flame Q_f decreases rapidly for smaller d and, in so far as the larger burner is concerned, Q_f is approaching the line of $Q_f = K'(1+\alpha' w)V$, which means that the industrial large burner gives such an amount of radiant heat as

$$Q_f = K'(1+\alpha'w)V \quad \text{.......................(8)}$$

The percentage of the amount of heat emitted per total heat content of fuel used, η, varies with ud and d as shown in Fig. 6. By means of data on the 10 mm. burner, it will be supposed that the larger burner for industrial use will give some definite value of η, as 10 % in the 10 mm. burner. Detailed data will be shown in "Radiant Heat from Flame"[(8)].

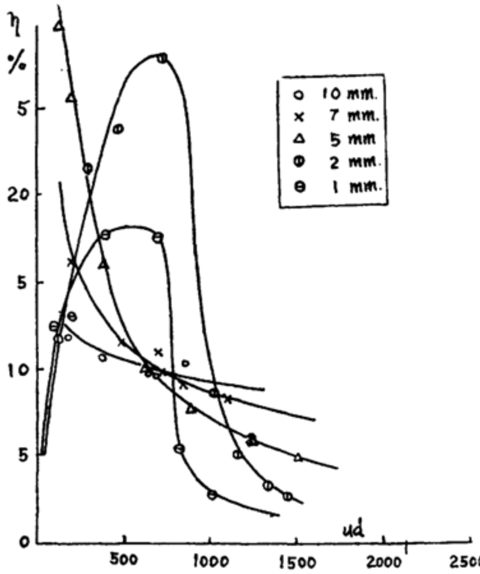


Fig. 6. Percentage of radiation.

Spectral Radiation of Luminous Flames. The author studied the absorption spectra of soot and luminous flames[(9)]. The burner was made for the convenience of measuring emission and absorption spectra. Absorption spectra of soot plate and luminous burning soot are expressed as

$$kl = 39.5\, \nu Nl\, (1-15[\rho\nu]^2) \quad \text{.....................(9)}$$

where k is the absorption coefficient of soot cm.$^{-1}$, l the thickness of flame, ρ radius of a soot particle in μ, N number of particles in cm.^{3}, ν the wave number of spectra cm.$^{-1}\times 10^4$. The above formula was derived from the theoretical standpoint of colloidal soot particle.

The results of the experiment are shown in Fig. 7a, Fig. 7b and Fig. 8. On adding benzene vapor to city gas, spectral radiation increases as shown in Fig. 7a as I, II, III and N in equation 9 increases proportionally as shown as equations in Fig. 7b. Fig. 8 denotes flame radiation and soot radiation (thick line) and the equivalent black body radiation (thin line), of which the soot radiation was calculated from soot equations in Fig. 7b, referring to the transparent region of gas absorption, and the black body emission was calculated by dividing the emission energy with absorption data. The thin broken line shows the ideal black body emission. The differences between full and broken lines in both

(8) S. Yagi, S. Yoshida and M. Yorizane, J. Chem. Soc. Japan, Ind. Ed., 52 (1949), 167.

(9) S. Yagi, J. S. C. I. J., **1937**, 90, 93, 267.

flame and black body emissions show the emission and absorption of CO_2 and H_2O in flame and surrounding atmosphere, whose temperatures are not the same as soot temperature. Therefore the two smooth curves are thought to have meaning of theoretical standard. Similar results were obtained, as described in the original contributions, in flames with added acetylene and primary air.

The effective temperatures concerning heat radiation were calculated from the distribution of of black body emission as shown in the following table compared with data measured by ordinary optical pyrometer and figures corrected from absorption 650 mμ in parenthesis below.

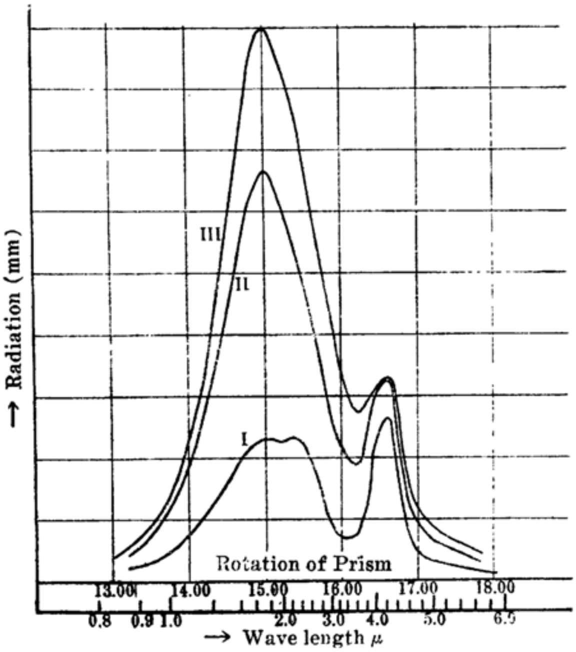


Fig. 7a. Radiation spectra of luminous adding benzene vapor

	I	II	III
		C_6H_6	
Hydrocarbon %	0	1.95	3.46
Town gas cc./mm.	144	106	100

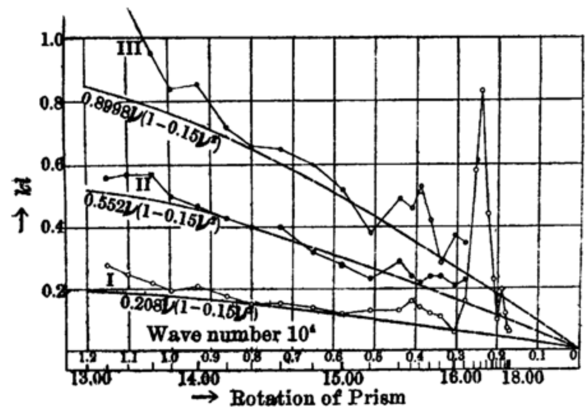
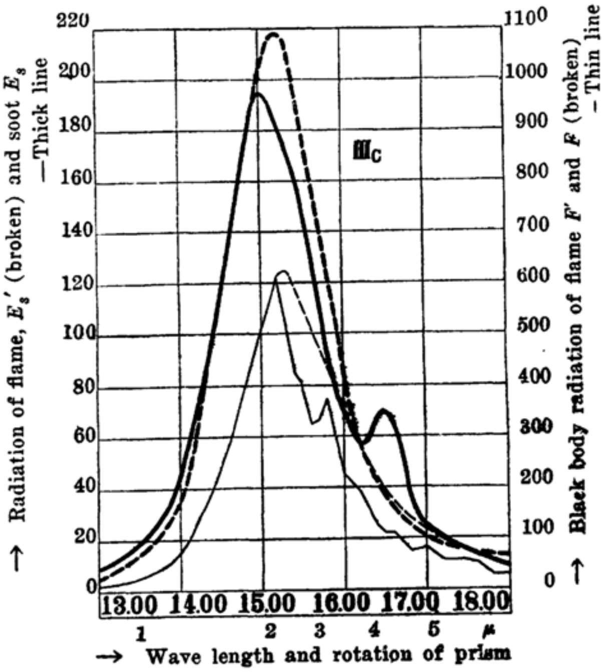


Fig. 7b. Absorption spectra of luminous flame adding benzene vapor.

Table 2. Temperatures of Several Luminous Flames.

Adding Primary Air (%)	Temp. (°C) from F′	Temp. (°C) Opt. Pyro.	Adding C_2H_2 (%)	Temp. (°C) from F′	Temp. (°C) Opt. Pyro.	Adding C_6H_6 (%)	Temp. (°C) from F′	Temp. (°C) Opt. Pyro.
0.0	1280	1370 (1450)	0.0	1360	1260 (1420)	0.0	1360	1260 (1420)
13.6	1330	1440 (1630)	3.76	1400	1400 (1515)	1.95	1260	1390 (1480)
20.8	1470	1250 (1480)	8.06	1330	1380 (1460)	3.46	1220	1320 (1440)

The temperature increases by addition of primary air and decreases by addition of hydrocarbon. The data measured by optical pyrometer even after the correction can not show the effective temperature of radiation, but seems to show some temperature of soot particles suspending in the zone of some high temperature but of relatively thin layer.



C_6H_3 3.46 %

Fig. 8.

The major part of this series of work was conducted in the Tokyo Institute of Technology with collaborators and some in the Massachusetts Institute of Technology under Prof. H. C. Hottel, to whom the author wishes to express his indebtedness.

Chemical Engineering Laboratories,
Tokyo University and Tokyo
Institute of Technology.