Flame Length and Width produced by Ejected Propane Gas Fuel from a Pipe

by

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ABSTRACT

Flame tip height, width, and height to base of a lifted flame were observed based on eye observation using a ejected fuel gas through a pipe. Fuel gas was supplied through regulators at the rate of 100l/min, 200l/min, and 400l/min which was ejected from a pipe of 1/8B, 1/4B, 3/8B, 1/2B, 3/4B, and 1B, respectively. Pipe heights from the top surface of a dummy bomb were set at 200mm, 700mm, and 1700mm, respectively in order to measure the effect of stand-off distance which reduced the feed back of radiative heat flux to the dummy bomb. Radiative heat flux were also measured at 0.1m, 0.27m, 0.71m, 1.1m, 1.27m, 1.71m, 1.9m, 2.9m from the pipe at the same horizontal level of the dummy bomb. Temperatures in the dummy bomb and on which surface, as well as in a flame along the flame axis (center line of the flame) were measured. Dimensionless flame height, Ha/D, and dimensionless flame width, W_f/D were correlated well by 1/3 power of dimensionless heat release rate, $Q^{*1/3}$. Radiative heat fluxes to the dummy bomb were also estimated using the view factor, and center-line temperature, assuming translucent and mufti- ring flame configuration piled up. Estimated radiative heat flux to the dummy bomb were compared with the measured ones and good conformation between them was obtained. This implies that the estimation method on radiative heat flux to the foot of the flame ejection pipe is useful to assess the radiative heat flux for fire safety design of propane gas bomb.

1. Introduction

Fuel gas is supplied through piping networks in urban area but its suburbs propane gas, as a fuel gas for house use, is supplied by transportable bombs of 20kg or 30kg weight. Periodic delivery of bombs, once or twice a month in an average, has been demanded to maintain stable fuel gas supply for houses. Delivery service of heavy bomb is hard business, and frequent delivery service causes latent traffic jam in poor road network of suburbs. In order to get the higher cost performance and lower consumption of labor in the bomb delivery service, in other words to get infrequent delivery service and lessen the numbers of bombs transported to houses, it is planned to set a big volume bomb of 1500kg in house yard (or in basement) and of which refuel will be made directly by connecting bomb with a LPG bulk loll track. However, the setting of a big bomb in house yard may have high potential of fire risk in case of a neighbor fire occurred. Fire in neighbor may give great radiative heating to the bomb and which may cause high pressure in bomb and ejection of jet flame. Pressure reduction is designed by the ejection of gas through a safety-pipe and bulb system so that ejected jet flame will be generated on/above the nozzle of pipe and which may feed extra radiative heating to the bomb. Before realization of the plan of setting a larger bomb to houses, it is demanded to assess how much radiative heat may be fed from the neighbor flame and from the ejected jet flame on/above the safety nozzle. In the first series of the experiment, the semi-full scale test had been carried out using a bomb and which was exposed to a neighbor model fires (wood crib fires). Temperatures of bomb surface and its atmosphere were measured and also function of a safety bulb for pressure reduction was verified [1]. In the second series of the test, basic information on flame figure of the jet flame which generates on a nozzle of a safety pipe (pressure reduction pipe) is required to establish one of the fire safety measures. Measurements and observations are planned on jet flame height, flame width, height to the base of lifted jet flame from a nozzle, and radiative heat flux to the dummy bomb which locates on the same horizontal level of the bomb.

In this paper, we deal with the results on the second series of the tests and will report on flame figure, height to the base of a lifted flame, and radiative heat flux from the jet flame to surface the dummy bomb. And we also propose a practical estimation method on radiation heat flux to a bomb at the foot of the pipe.

2. Experimental Procedure

2-1. Similarity on flame figure

As a first step, we planed to carry out the experiments avoiding the natural wind effects on flame figure. In order to make the experiments in the facility which has ceiling height of 12m, we have to consider the reduced flame height keeping the similarity on flame height as function of heat release rate. The relationship between dimensionless flame height and dimensionless heat release rate, Q^*, is well known for the wide range of Q^*. McCaffrey [2] presented this wide relation and for the range of $10^3<Q^*<10^5$ which will be expressed roughly by $H_f/D = 27.5 \cdot Q^{*0.232}$ based on his paper [2]. Dimensionless heat release rate estimated for the full size pipe connected to the full scale bomb is order of 6.6×10^4 assuming the stoichiometric chemical reaction and no blow-off of flame at the ejection velocity of about 280m/sec. This Q^* will give the flame tip height estimated is order of 20m using a 2B (52.9mmΦ) pipe. The flame height estimated is taller than the ceiling height of the facility, so that we have to reduced the flame height scale of 1/3~2/3 in the scale of Q^*.

2-2. Piping and Experimental system

Figure 1 shows the outline of the piping and layout of the experimental system. Reservoir gas (LPG) bombs were set outside of the facility and fuel gas was let into the system through pressure reducers and valve system controlling the supply rate of 100l/min, 200l/min, and 400l/min. The final flow rate of the piping system was monitored by a mass flow meter every 10seconds. Nozzle height were adjusted at 200mm, 700mm, and 1700mm high from the grand level. The top surface of the dummy bomb located about 145mm high from grand level.

Fuel gas supply rates, bore size with mmΦ, nozzle height and dimensionless heat release rate designed are shown in Table 1.

2-3. Measurements and Observations

Temperatures in the ejected flame were measured along the center line by K-type thermo-couples at 1m, 2m, 3m, 4m, 5m, 6m, and 7m from ground level. Temperatures were also measured at the surface and in the dummy bomb, with monitoring the inner pressure of the dummy bomb.

Radiation heat flux meters were set at 0.1m, 0.27m, 0.71m, 1.1m, 1.27m, 1.71m, 1.9m, and 2.9m apart from the pipe at the same level of the top surface of the dummy bomb.

Tow sets of video system, which records 30 images in every second, were used for recording the flame images from North and East direction. Prior to the flame generation above the nozzle, standard points in 3D-space were recorded as 2D-image on the video recording system and these points were used on the estimation of height, width of the flame, and height to the base of the lifted flame.

Table 1 Experimental Conditions

Experiment Number	Fuel Flow Rate (l/min)	Bore Size (mm)	Nozzle Height (mm)	Q* (-)
1	100	1/8B, 6.5mm	700	2.27×10^{3}
2	200 →180→160	1/8B, 6.5mm	700	3.64×10^{3}
3	100	3/8B, 12.7mm	700	4.26×10^{2}
4	200	3/8B, 12.7mm	700	8.53×10^{2}
5	300	3/8B, 12.7mm	700	1.28×10^{3}
6	400	3/8B, 12.7mm	700	1.71×10^{3}
7	100	1B, 27.6mm	700	6.12×10^{1}
8	200	1B, 27.6mm	700	1.22×10^{2}
9	400	1B, 27.6mm	700	2.45×10^{2}
10	400	1/4B, 9.2mm	200	3.82×10^{3}
11	200	1/4B, 9.2mm	200	1.91×10^{3}
12	100	1/4B, 9.2mm	200	9.54×10^{2}
13	400	3/8B, 12.7mm	200	1.71×10^{3}
14	200	3/8B, 12.7mm	200	8.53×10^{2}
15	100	1/2B, 16.1mm	200	2.36×10^{2}
16	200	1/2B, 16.1mm	200	4.71×10^{2}
17	400	1/2B, 16.1mm	200	9.42×10^{2}
18	400	1B, 27.6mm	200	2.45×10^{2}
19	400	3/4B, 21.6mm	200	4.52×10^{2}
20	200	3/4B, 21.6mm	200	2.26×10^{2}
21	100	1/8B, 6.5mm	1700	2.27×10^{3}
22	400	1/4B, 9.2mm	1700	3.82×10^{3}
23	200	1/4B, 9.2mm	1700	1.91×10^{3}
24	100	1/4B, 9.2mm	1700	9.54×10^{2}
25	400	3/8B, 12.7mm	1700	1.71×10^{3}
26	200	3/8B, 12.7mm	1700	8.53×10^{2}
27	400	1/2B, 16.1mm	1700	9.42×10^{2}
28	200	1/2B, 16.1mm	1700	4.71×10^{2}
29	400	3/4B, 21.6mm	1700	4.52×10^{2}
30	200	3/4B, 21.6mm	1700	2.26×10^{2}
31	400	1B, 27.6mm	1700	2.45×10^{2}

* In the test #2, gas supply rate was changed 200l/min to 160l/min with the changing rate of 20l/min to observe the blow-off of the flame.

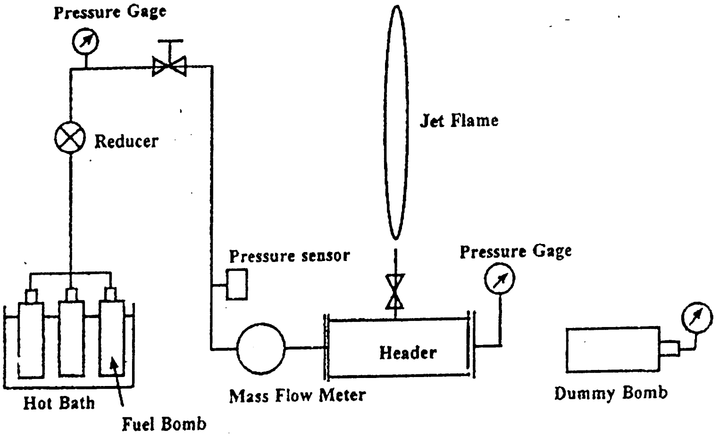


Figure 1 Outline of the experimental sets. Fuel gas bombs are set outside of the facility. Temperatures along a jet flame and on the surface of the dummy bomb were measured by sheathed K-type thermocouples. Radiation meters were set on the same level of the dummy bomb.

3. Results and Discussion

3-1. Flame Height and Width

Flame tip heights, Ha, were estimated from 90 successive images (for 3 sec on video system) and are shown representatively in Figure 2 by a rigid line. In this case about 600kW (400l/min) fire from 1/4B pipe was given to the system, and the averaged flame tip height estimated was 3.04m with its maximum and minimum heights of 3.43m and 2.75m, respectively. The difference between highest and lowest flame tip height was about 0.6m and of which standard deviation was about 10% of the full flame length. The intermittent flame length from Q* of $10^3 \sim 10^4$ fire observed showed about 20% of each full flame length and this percentage is smaller than that from diffusion pool fires with Q* of $10^0 \sim 10^2$. The flame widths, W_f, were estimated from the same images for 3seconds and are superimposed representatively in Figure 2 by a broken line. Standard deviation for W_f is about 20% and the fluctuation in both height and width of the flame is almost coincided with each other as shown in Figure 2.

Average flame tip height, Ha, was normalized by bore size, D, and are obtained in the form of dimensionless flame height of Ha/D. Figure 3 shows the logarithmic plots of dimensionless flame tip height, Ha/D, as a function of dimensionless heat release rate, Q*. The figure indicates the relation of $Ha/D = 25 \cdot Q^{*1/3}$ for higher flame height, $Ha/D = 20 \cdot Q^{*1/3}$ for lower flame height, and $Ha/D = 22 \cdot Q^{*1/3}$ for average jet flame height. Where dimensionless heat release rate was defined as $Q^* = \dot{Q}/\rho C p \Delta T \sqrt{gD}\, D^2$ after Zukoski[4]. The relation shown in Figure 3 indicates that Ha/D increase with 1/3 power of Q* and is expressed by for the range of $Q^*=10^2$ to 5×10^3 based on the tests. The number of power for the relation is greater than that of McCaffrey [2].

Widths of the flame, W_f, were also estimated and averaged based on 90 images and which was normalized by D giving the dimensionless form of W_f/D. Figure 4 shows the relation of dimensionless flame width and dimensionless heat release rate Q* in logarithmic scale. This figure shows W_f/D increased with the increase of 1/3 power of Q* and is expressed by $W_f/D = 4.9Q^{*1/3}$. Figures 3 and 4 indicate that the characteristic flame length, both height and width, grows with increase of 1/3 power of dimensionless heat release rate $Q^{*1/3}$.

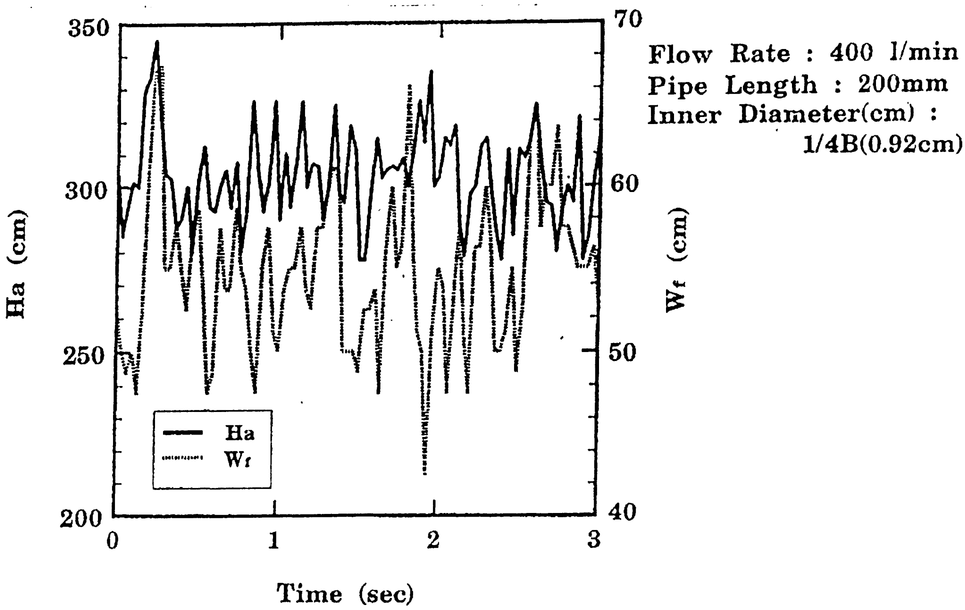


Figure 2 Typical time histories of flame tip height and its width. In this case, propane gas as a fuel gas was supplied at the rate of 400l/min from a 1/4B (0.92cmΦ) pipe of which length was 200mm from the grand level.

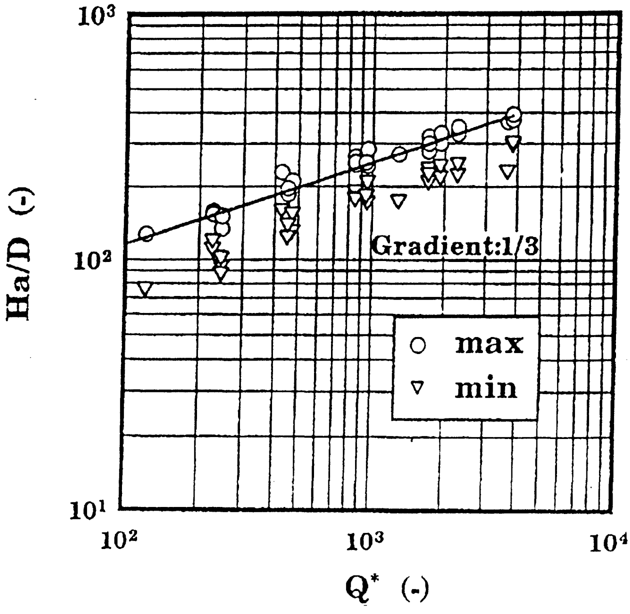


Figure 3 Logarithmic plots of dimensionless flame height, Ha/D, as a function of dimensionless heat release rate Q* with gradient of 1/3.

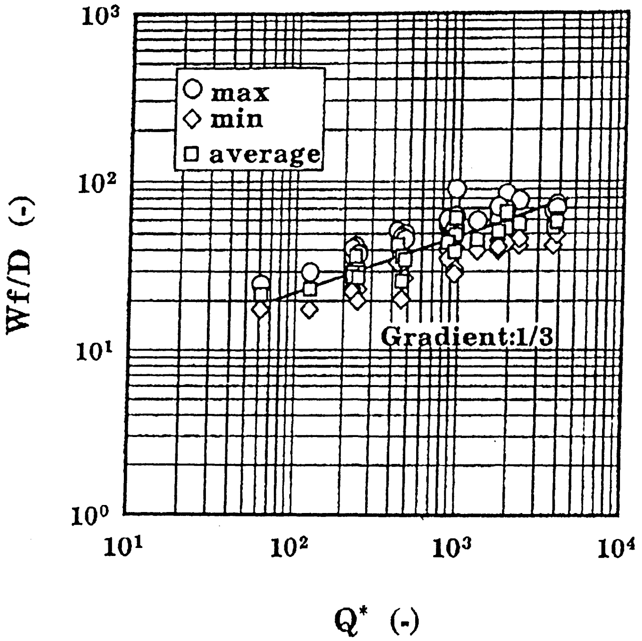


Figure 4 Dimensionless flame width, W_f/D, as a function of dimensionless heat release rate Q^*. W_f/D increase with 1/3 power of Q^*.

3-2. Height to the base of lifted flame

In the tests, jet flames with high Reynolds number were made so that some of which showed the lifted flames. We also observed and estimated the height to the base of the lifted flame. When we give 200l/min and 180l/min to the 1/8B pipe (6.5×10^{-3}m), the lifted flame was observed once on the bore but it extinguished soon showing the lifting flame from the pipe. Ejection velocity, based on bulk mass flow rate, was over 250m/sec at the bore for these cases and which is over the sonic velocity for LPG so that blow off was occurred. After we observed these blow off flames, 160l/min gas supply rate was given to the system. In this case, semi-stable flame with lifted height was observed for about 4 min, then it also showed blow-off. Except this test #2, we could observe the stable flame and some of them showed the lifted flames. When lifted flame was observed, the height from the nozzle to the base of lifted flame, h, were estimated and averaged based on the 90 frames of successive images on the video system. Averaged one was normalized by bore size, D, giving the dimensionless lifted height, h/D. Figure 5 shows the dimensionless lifted height of the flame as a function of dimensionless heat release rate Q^* in log-log scale. The figure implies that dimensionless lifted height, h/D, increased with 3/5 power to Q^* in the region of $10^3 \sim 10^4$ and is expressed empiricaly by $h/D = 3.34\times10^{-2}\cdot Q^{*3/5}$.

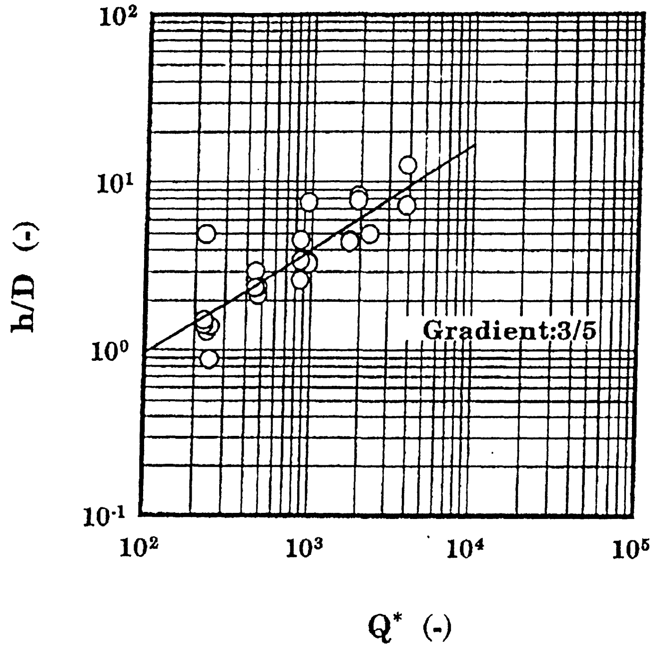


Figure 5 Dimensionless height to the base of lifted flame, h/D, are plotted against dimensionless Q* in log-log scale showing the power correlation of h/D increase with $Q^{*3/5}$.

3-3. Excess Temperatures along the center line of a flame

For the region of ca. $0.07<Ha/Q^{2/5}<$ca. 0.3 excess temperature, ΔT, showed almost constant of 700 - 900°C for the vertical direction and then ΔT along the center axis of the flame decreased with Ha^n with $n = -3/2 \sim -5/3$. Where Ha was obtained as the height from the bore. This gradient is quite similar to the one obtained in the plume region of a diffusion flame. McCaffrey reported [3] that excess temperature along the flame axis of a diffusion flame showed the decreasing mode of $(Z/Q^{2/5})^{-1}$ for intermittent flame region which corresponded $0.08 < Z/Q^{2/5} < 0.2$. However, no such clear decreasing mode was not observed in our tests as shown in Figure 6-1. Maximum and minimum of each flame tip heights are also plotted in Figure 6-1, and which appeared between ca. $0.4 < Ha/Q^{2/5} <$ ca. 1.4 without showing clear decreasing mode of $(Ha/Q^{2/5})^{-1}$. Decreasing mode showed the gradient of $-3/2 \sim -5/3$ for wide regions of intermittent and plume given by ejected flame (or jet flame) in our tests. If we show the temperature distribution by an empirical equation for vertical direction along the center line of a jet flame,

$\Delta T = \alpha \cdot \{(Ha/D)/Q^{*2/5}\}^{-3/2}$, α=10250 °C for Ha > 0.86m and

ΔT = 850 ~ 950°C for lower flame region of "the base of flame" ≤ Ha ≤ 0.86m.

It is demanded to make a practical estimation method of the flame temperature as a function of height for a full scale flame from a full scale gas bomb. Normalized height, $Ha/Q^{2/5}$ used in Figure 6-1, has two dimensional terms of meter and $kW^{2/5}$ so that it is inconvenient to estimate the excess flame temperature for arbitrary pipe size at arbitrary heat release rate designed. Thus, height normalized by heat release rate, $Ha/Q^{2/5}$, was modified into dimensionless normalized height in the form of (Ha/D)/Q$^{*2/5}$ and is shown in Figure 6-2.

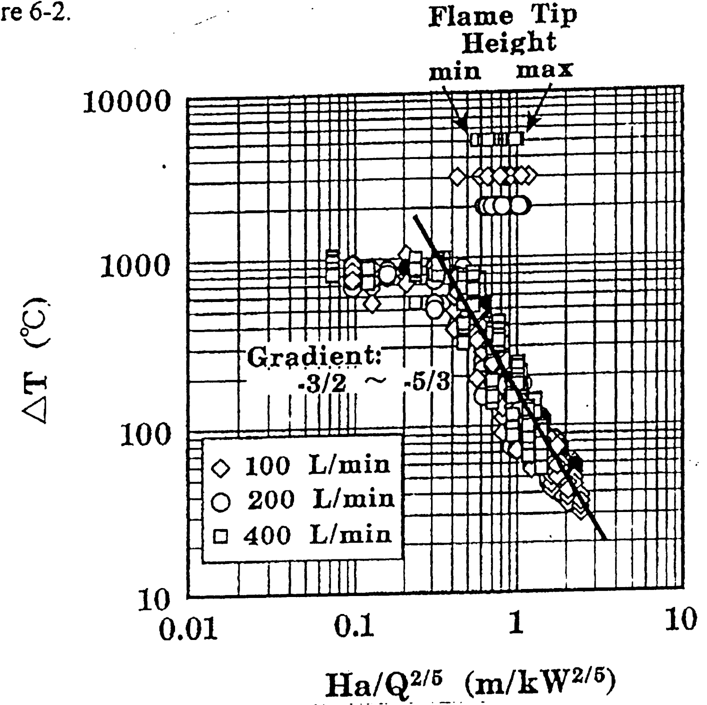


Figure 6-1 Excess temperatures along the center line of jet flame are plotted against normalized height by Q$^{*2/5}$. Highest and lowest jet flame tip height are also superimposed. Vertical distribution of excess temperatures decreased with Ha/Q$^{*2/5}$ for its upper part including intermittent flame region.

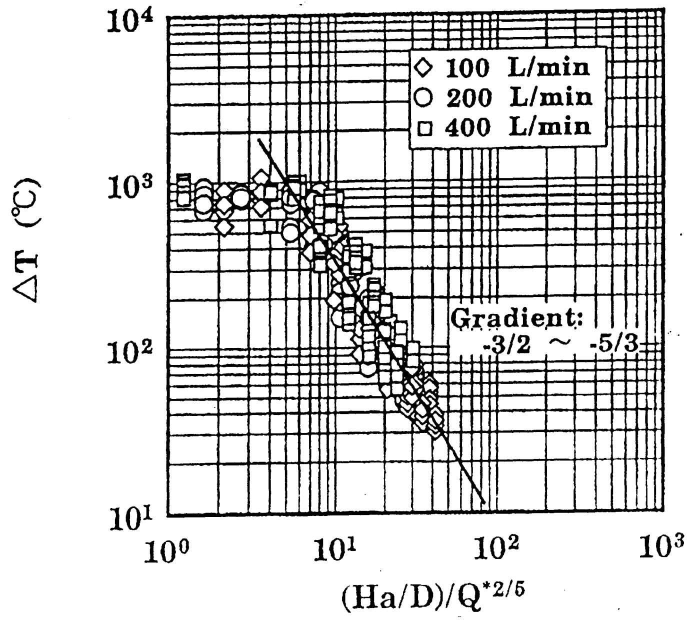
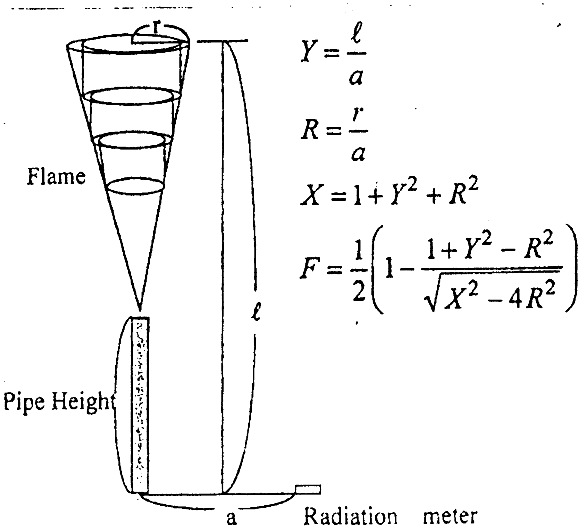


Figure 6-2 The same plots to Figure 6-1 but normalized height is rewritten into the dimensionless form of (Ha/D)/Q$^{*2/5}$.

3-4. Radiation Heat Flux

Figure 7 shows the typical radiation heat flux distribution profiles for horizontal direction at the same level of the dummy bomb with pipe heights of 200mm, 700mm, and 1700mm. It is clearly observed that distribution of radiation heat flux showed flat in the near region from the pipe and then decayed in far region. In order to estimate the radiation heat flux to the dummy bomb, we adopted following assumptions and a model of view factor on a disk to a target [5].

- Flame figure could be expressed by conical shape with average flame height, Ha, and width, W_f, and which were estimated as a function of Q* with a pipe bore size D based on Figures 3 and 4.
- Flame is translucent and its representative temperature at arbitrary heights can be estimated by the empirical equation described the above section.
- Two flame disks at the same height, as shown in Figure 7, are estimated as radiators to the target (in this case radiation meter was adopted). Firstly radiation from a full disk (outer ring in Figure 7) was estimated using representative flame temperature described above. Then radiation from smaller disk (inner disk) was subtracted from it so that the radiative heat flux from the ring figured flame to a target was estimated. View factor was estimated twice considering two thin flame disks at arbitrary height which radiate to arbitrary target located on the surface level. The same estimation method on radiation was accepted and repeated to the base of the flame.
- Standard deviation of the tip flame height was about 10% of the average flame length so that flame length was adopted as 90% of averaged flame length for the estimation on radiative heat flux to a target.
- Representative flame width, W_f, was appeared at the height of 90% of the average flame height, 0.9·Ha.



$$Y = \frac{\ell}{a}$$

$$R = \frac{r}{a}$$

$$X = 1 + Y^2 + R^2$$

$$F = \frac{1}{2}\left(1 - \frac{1 + Y^2 - R^2}{\sqrt{X^2 - 4R^2}}\right)$$

Figure 7 Model of ring flame to estimate the view factor.

Estimation of radiation heat fluxes to a target started at the height of 0.9Ha and then the same estimation method were carried out every reduction height of 0.01m to the base of jet a flame. Figure 8 shows the representative calculated radiative heat flux (test #19) to the surface of the dummy bomb using flame temperatures of 850 °C and 950 °C for its lower region and also shows the plots of measured ones against distance from a pipe. The figure shows that the estimation method on radiation from a jet flame is quite successfuly correlated with data. The comparison of the measured data with the calculated ones shows that the estimation method can be applicable to the prediction of the radiation flux to the dummy bomb with assumptions described in the previous section. The figure demonstrates also that the estimation method is useful to evaluate the radiation heat flux to the surface of the full scale bomb which is planned to set houses.

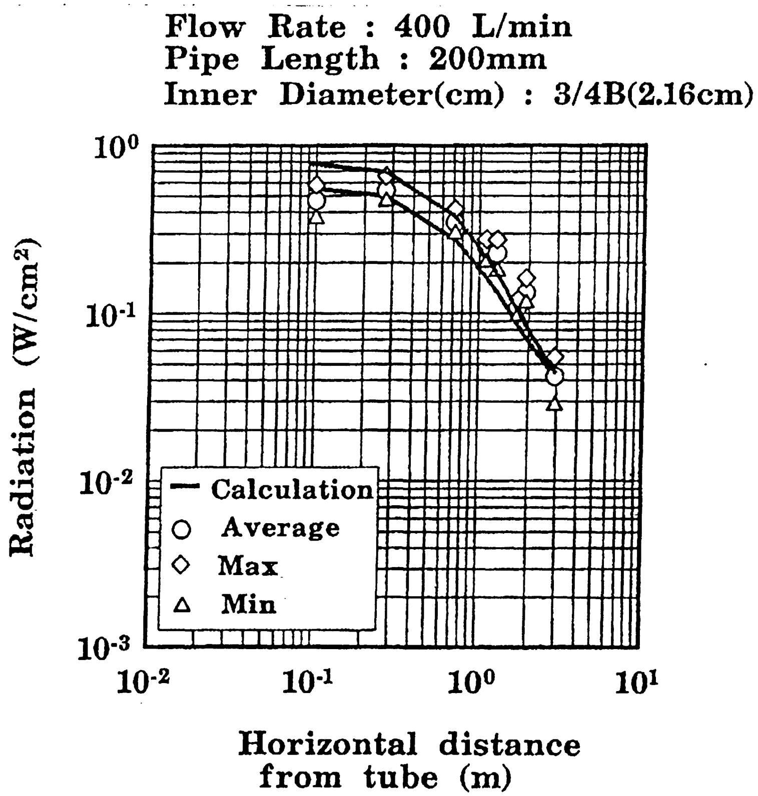


Figure 8 Radiation heat flux measured to the targets with calculated ones are illustratcd in log-log scale. Radiation meters were located on the same level of the dummy bomb. Horizontal distribution of the radiation flux to the surface of the dummy bomb were estimated using 750°C and 850°C for the lower part of the jet flame with representative temperatures for higher region of the jet flame, which were estimated by the model shown in Figure 6-2.

4. Conclusions

This work showed that the jet flame figures of height and width, and height to the base of lifted flame can be predicted as a function of power dimensionless heat release rate.

Excess temperature along the center line of the jet flame can be divided into two regions. Lower flame region, excess temperature showed almost constant of 750 ~ 950°C as is well known for diffusion flame from a pool fire. Both intermittent and plume regions, excess temperature decreased with -3/2 ~ -5/3 power to the height. This decreasing mode is similar to the diffusion flame from a pool fire except the decreasing mode of -1 power to height for intermittent region.

It is important to note that the ring flame figure model, as shown in Figure 7, indicates that the jet flame is translucent, while the representative flame temperature are well approximated by the center line temperature. And the ring flame figure model was applicable to estimate the view factor and successfully simulated the radiation heat flux to the bomb from a jet flame.

5. Acknowledgment

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6. Reference

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Nomenclature

a: distance from pipe to radiation meter as a target (m) in Figure 7
D: bore size (m)
Ha: flame height from nozzle along the center line of a jet flame (m)
h: height to the base of lifted flame from bore (m)
ΔT: excess temperature from room temperature (°C or K)
W_f: width of jet flame (m)
ℓ: height of flame disk from the radiation meter (m) in Figure 7
r: radius of flame disk at arbitrary height in Figure 7
X: $1+Y^2+R^2$ (-) in Figure 7
Y: ℓ/a (-) in Figure 7
R: r/a (-) in Figure 7
F: view factor (-) in Figure 7