DETERMINISTIC PROPERTIES OF TURBULENT DIFFUSION FLAMES FROM LOW Q^* FIRES

Yuji Hasemi

Building Research Institute

Ministry of Construction

Tatehara 1, Tsukuba-City, Ibaraki-Pref.

Mitsuru Nishihata

Center for Fire Science and Technology

Science University of Tokyo

Yamazaki, Noda-City, Chiba-Pref.

(Received, December 20, 1987)

ABSTRACT

General geometry and height of diffusion flames and the height-dependence of centerline temperature above propane burners of relatively low heat release rate for the fuel size are described. The flame behavior is classified into 3 regimes according to the difference in the height-dependence of centerline temperature and in the general behavior of the flame. Flame height is represented as a function of $Q^* = Q/\rho_0 C_p T_{0g}^{1/2} D^{5/2}$. The criterion for the adequacy of the concept of "virtual source" for the prediction of centerline temperature from the point-source turbulent plume theory is discussed.

1. INTRODUCTION

Turbulent diffusion flames are generally a major element in the development of a fire. In the early stages of a building fire, flames have a role to preheat the surfaces of the whole enclosure by radiation and to drive hot gas to the ceiling layer. Also in urban or wildland fires, flame radiation and confluence of individual flames into a huge flame have a significance not only for the development of fire but also for the generation of difficulties of fire suppression.

Practical properties concerning these aspects of fire safety have been studied for various purposes (1-6). Dimensional analysis of the flame geometry has established the dependence of the ratio of flame height to fuel size on $Q/D^{5/2}$, and its significance has been often represented by a dimensionless heat release rate $Q^* = \rho_0 C_p T_{0g}^{1/2} D^{5/2}$ or some other parameter representing an essentially same implica-

Fig.1 Correlation between fuel size and Q^* for unconfined natural fires (data from various sources)

- gasoline
- heptane
- ◇ kerosene
- wood crib

tion (4–6,10); temperature, velocity and entrainment in the turbulent plume above a flame have been also found to be influenced by the flame geometry, and its significance in the application of point source theory, location of virtual source, has been correlated with Q^* or flame height (7–10). Figure 1 summarizes the correlation between fuel size and Q^* for typical natural fires in unconfined environment. While low Q^* fires may appear both in building fires and in mass fires (9–11), in most of the experiment heat release rate has been chosen to generate a flame height considerably greater than the characteristic fuel size, i.e. $Q^* \gg 0.1$. Sand-wick experiments by Wood et al (12) provide only available data to have a peep of the practical properties in the $Q^* < 0.1$ regime. The dimensional analysis expects a dependence of flame height only on the heat release rate per unit area, Q/D^2 , in the low Q^* regime (1). This relation is also derived from the dimensional relationship among L_f , x , and Q obtained from the heat balance of an axisymmetric turbulent flame (5),

$$Q \propto \sqrt{L_f} x^2 \quad (1)$$

Since the characteristic width of an extremely low Q^* flame is strongly restricted by the fuel size, $x \propto D$ is adequate for this regime. Substituting this into Equation (1), the proportionality of L_f to $(Q/D^2)^2$ is easily obtained. Also earlier experimental work seem to show this tendency (10,12); however there is still considerable discrepancy and scattering among the relevant experimental data. Also for the properties of the upper plume region, the concept of virtual source is expected to fail in the limit of low Q^* fires, since low Q^* fires must be essentially closer to a flat heat source with finite area than to a point source.

The difficulty in the experiments on low Q^* fires is essentially the necessity of relatively large fuel and therefore a huge experimental facility. Since Wood et al's data still seem to show some instability probably due to the use of

sand wicks, accumulation of experimental data on low Q^* fires using various fuels is important as a basis for predicting their practical properties.

The purpose of this paper is to report some characteristic behaviors of low Q^* fires obtained from experiments using a large porous refractory burner, which may allow a more controllable and stable combustion even in the low Q^* regime than any other conventional fuels do.

2. EXPERIMENTAL DESCRIPTION

The experiments were conducted primarily using a porous square burner of 1.0m with propane as the fuel, and supplementary experiments were made using 0.20m and 0.50m square burners to study some source-size dependence of the flame properties.

The burners were filled with ceramic beads of approximately 8mm diameter, and the height of their surfaces was approximately 0.5m above the floor of a laboratory, 27m by 20m in plan and 27m high without artificial floor surround at the level of the burner exits. Anticipating that burner exit velocity would become less uniform by reducing the fuel supply, plumbing inside the 1.0m burner was carefully made; the burner surface appeared to be covered with flames at every experiment reported in this paper.

Observations were made on the geometry of visible flames (general shape and height) and centerline temperature.

Visible flame was observed by eyes and monitored by a video camera during each experiment. Since the general shape of flame was found to change dramatically by the operation of fuel supply rate during a preparatory test using the 1.0m burner, the shape of flame was carefully observed. Data of the height of flame tips were obtained from observation of the videotape; the reported values of flame height are the average of the data observed for more than 3 minutes at the intervals of 1 s.

Temperature measurements were made using 0.2mm diameter chromel-alumel ther-

thermocouples. The time constant of the temperature measurement system is approximately 10 s. No corrections have been for the radiation and conduction losses from the junction of each thermocouple. For the elimination of the influence of accidental sway of the flame, temperature was monitored at each height not only just above the center of each burner but also at 4 different points 5cm apart from the center. The reported values of temperature are average of the centerline temperatures at the intervals of 10 s over 3 minutes during which the centerline temperature was higher than those at any other points.

3. RESULTS

3.1 Flame Geometry

The general shape of flame in the very low Q^* regime was apparently quite different from that in the regimes studied previously (mostly $Q^* > 0.1$). For $Q < 43\text{kw}$ ($Q^* < 0.039$) of the 1.0m burner, fire was broken into flamelets of approximately same height distributed over the burner surface. At $Q = 43\text{kw}$ ($Q^* = 0.039$), flamelets along the burner sides start to join together to build a "filmy" flame, and at approximately $Q = 130\text{kw}$ ($Q^* = 0.111$), small flametips start to appear above the filmy flame. Figure 2 shows

Fig.2 Three characteristic shapes of turbulent diffusion flame

Fig.3 Heat release rate vs. characteristic fuel size at the transition of the flame shape

a brief sketch of the characteristic flame shapes for these 3 regimes. The filmy flame in the region II looked like a combusting boundary layer above a horizontal flat plate under forced convection. Similar transition of the flame shape was also seen for the 0.50m burner, while the transition from flamelets to a filmy flame was somewhat ambiguous at the 0.20m burner. Figure 3 summarizes the Q - D relationships at these transitions; it is noteworthy that the critical heat release rate for the transition from a filmy fire to the appearance of flametips is almost proportional to the square of the characteristic fuel size, and practically represented as

$$(Q/D^2)_{\text{crit}} = 140 \text{ (kW/m}^2\text{)} \quad (2)$$

The slope representing the transition from individual flamelets to a filmy flame seems to be somewhat less steeper than this critical condition while the slope itself is not yet clear.

Fig.4 Normalized flame height vs. Q^*

The characters depict the regimes in Fig.2

Results of the flame height measurements are summarized in Figure 4 and compared with results from earlier works. While the flame height data for $L_f/D < 0.5$ or $Q^* < 0.1$ are generally scattered, it is evident at each experiment that the slope tends to become sharper in the low L_f/D regime. For $Q < 43 \text{ kW}$ of the 1.0m burner and for $Q < 23 \text{ kW}$ of the 0.50m burner, the expression, $L_f/D \propto Q^{*2}$ or $L_f \propto (Q/D^2)^2$, may be adequate, while, L_f/D seems to be proportional to $Q^{*2/3}$ for $Q \geq 130 \text{ kW}$ of the 1.0m burner and for $Q \geq 35 \text{ kW}$ of the 0.50m burner. The slope for the

(●◆■: regime I, △▽: regime II, ○: regime III).

region between these two characteristic regimes is somewhat less steeper than for the both regimes. This weak dependence of flame height on Q in the very low Q^* regime is one significant result which has not been reported in relevant reports (10,12). Interestingly, these divisions of the regimes correspond to the division for general flame shape in Figure 3.

3.2 Centerline Temperature

Fig.5 Centerline excess temperature vs. normalized height (1.0m burner)

The characters depict the regimes in Figure 2

(□: regime I, △▽: regime II, ○: regime III).

Figure 5 shows the centerline excess temperatures for the 1.0m burner as a function of the height from the burner surface normalized by $Q^{*2/5}D$; the centerline excess temperatures are somewhat scattered, while they tend to cluster around one curve obtained in previous experiments for around unity of Q^* (2,3). Since the slopes of most of the data for locations above the visible flame in the figure are evidently less steeper than $5/3$, the concept of virtual source was applied to adjust the slope to $5/3$ as shown in Figure 6. The adjusted data are divided into two groups; one includes only the data from $Q^* > 0.039$, namely the regimes II and III, and

Fig.6 Centerline excess temperature vs. normalized height from virtual source (1.0m burner)
The characters depict the regimes in Fig.2
(□: regime I, △▽: regime II, ○: regime III).

the other comes from those on $Q^* < 0.039$ fires. The data on the regimes II and III are scattering around the line obtained in the previous paper(9), whereas the other data are considerably lower than the previous results; this

Fig.7 Centerline excess temperature vs. normalized height (0.50m burner)
The characters depict the regimes in Fig.2
(□: regime I, △▽: regime II, ○: regime III).

suggests that concept of virtual source would fail in the regime I. The centerline excess temperatures for the 0.50m burner are also shown as a function of both $z/Q^{*2/5}$, and $(z+\Delta z)/Q^{*2/5}D$ in Figures 7 and 8. The difference of the regime I and the other in Figure 8 is less significant than in Figure 6. However, the centerline temperature in the regime I is still lower than those in the other regimes.

Fig.8 Centerline excess temperature vs. normalized height from virtual source (0.50m burner)
The characters depict the regimes in Fig.2
(□: regime I, △▽: regime II, ○: regime III).

The location of the virtual source thus obtained is summarized in Figure 9 along with the data from previous experiments(7,9). The depth of virtual source tends to become lower with decrease of Q^* for $Q^* > 0.039$, and apparently it turns to rise in the regime I. The virtual source locations for $Q^* \geq 0.1$ seems consistent with previous experimental works(7-9); however, for the regime II, the location is considerably lower than the expected value from the previous experiments, and in the regime I, the location is scattered around 0.

Fig.9 Location of virtual source vs. Q^*

4. DISCUSSIONS

The present experiments seem to show that the $L_f \propto (Q/D_2)^2$ relationship holds for very low Q^* fires, in the regime I of Figure 2 or 3, as anticipated from previous dimensional studies (1,5,10,11). However, there is still considerable discrepancy in the flame height among the 1.0m and 0.50m burners and previous experiments. This discrepancy is believed to be partly due to the difference in the definition of the flame height among the authors, or to the difficulties in the measurement of low Q^* fires. However, the discrepancy seems to be still significant in the extremely low Q^* regime than in the large Q^* regime which has been studied actively by many researchers. One possible cause for this significant discrepancy is the effect of the fuel density, or more essentially, the fuel stoichiometry. Although the dimensional analysis on the flame geometry is originally based on the comparison of the buoyancy and the inertial force of the fuel gas at the fuel surface (1) and there must be influence of the fuel density on flame properties, an analysis based on Q^* will not represent this effect. This effect is expected to become dominant in the low Q^* regime, where L_f is strongly sensitive to the change of the momentum of fuel gas.

Also the transition from the regime I to II does not seem to be governed by Q^* . While the flame condition around this transition is apparently laminar, similar transition from individual flames to a gigantic concentrated flame has been often reported at turbulent city fires. There must be a common mechanism leading to this transition both in a laboratory and in an actual fire.

The following is an exploratory discussion to seek a responsible mechanism for these criticalities based on the dimensional relationships obtained in the present experiments, while it should be noted in advance that different mechanisms may induce the identical dimensional relationship and there is still some possibilities of other mechanisms leading to the criticalities.

One possible cause for these transitions is the criticality of oxygen supply by entrainment. At the upper bound of the regime II for the 1.0m burner, the filmy flame appeared to cover the whole surface of the burner, and therefore the appearance of flametips is attributed to the lack of oxygen supplied onto the burner surface. Actually the heat release rate at this criticality is proportional to the burner surface area, D^2 , as seen in Figure 3, and it is expected that there is a critical available oxygen or fresh air rate per unit fuel surface area. Using the general value of reaction heat per unit mass of air for usual natural fuels (2700kJ/kg, see Ref.13), the critical available entrained air, M , per unit area based on the above hypothesis is estimated as

$$(M/D^2)_{\text{crit}} = 0.052 \text{ (kg/m}^2\text{)} \quad (3)$$

The transition from individual flamelets to a filmy fire must be related more to the entrainment through the circumference of the fuel surface, since the nature of this criticality is somewhat "local" in the sense that a filmy flame starts to develop along the margin of a fuel and gradually takes the place of flamelets in the central part of the fuel by the increase of Q . If this

criticality depends on the heat release rate per entrainment through the circumference, Q/D may be a primary parameter characterizing this criticality; this mechanism is worth studying since the power of D representing Q at this criticality in Figure 3 is close to 1.

5. CONCLUSIONS

some experimental observations on low Q^* fires are reported. The following conclusions can be drawn.

1. Flame behavior can be classified into 3 regimes according to the shape of the flame.
2. For $Q/D^2 > 140 \text{ kW/m}^2$, flametips are observed above a continuous flame, and flame height is proportional to $2/3$ power of heat release rate.
3. For extremely low Q^* , a fire is broken into individual flamelets, and flame height is apparently proportional to $(Q/D^2)^{1/2}$. In this regime, the concept of virtual source for the prediction of plume properties fails evidently.
4. There is a transition regime between the above two regimes. In this regime, a fire looks like a combusting boundary layer under forced convection. The dependence of flame height on heat input is less significant than in either of the two regimes. While the concept of virtual source seems to hold still in this region, its location is deeper than estimation from previous work.
5. In the low Q^* regime, dependence of flame geometry on the fuel composition seems to be significant.
6. Experiments using larger fuels and different fuels are encouraged to develop a model to predict the practical properties of low Q^* fires.

ACKNOWLEDGEMENTS

The authors are indebted to Mr. Jun'ichi Izumi, research associate of BRI from Mitsui Homes, Co., for the assistance in the experiments. The authors are also grateful to

Mr. Hideo Matsumoto of BRI is fabricated the major apparatus for the experiments. His effort to build a large uniform burner is gratefully acknowledged.

This study was presented at the Ninth UJNR Panel Meeting on Fire Research and Safety held in 1987 at Boston. The authors wish to acknowledge the fruitful discussions at this conference.

TERMINOLOGY

C_p	specific heat air
D	characteristic fuel size
L_f	flame height
M	entrained air
Q	heat release rate
Q^*	dimensionless heat release rate defined as $Q/\rho_o T_o g^{1/2} D^{5/2}$
T	absolute temperature
g	gravitational acceleration
x	characteristic flame width
ρ	density
suffix	
o	ambient air
crit	criticality

REFERENCES

1. Thomas, P.H., Webster, C.T., and Raftery, M.M., "Some Experiments on Buoyant Diffusion Flames," *Combustion and Flame*, Vol.5, 1961, pp.359-367.
2. McCaffery, B.J., "Purely Buoyant Diffusion Flames: Some Experimental Results," NBSIR-79-1910, 1979.
3. Cox, G., and Chitty, R., "A Study of the Deterministic Properties of Unbounded Fire Plumes," *Combustion and Flame*, Vol.39, 1980, pp.191-209.
4. Zukoski, E.E., Kubota, T., and Getegen, B., "Entrainment in Fire Plumes," *Fire Safety Journal*, Vol.3, 1980/81, pp.107-121.
5. Hasemi, Y., and Tokunaga, T., "Deterministic Modeling of Unconfined Turbulent Diffusion Flames," *Transactions of ASME, Journal of*

- Heat transfer, Vol.108, 1986, pp.882-888.
6. Heskestad, G., "Luminous Heights of Turbulent Diffusion Flames," *Fire Safety Journal*, Vol.5, 1983, pp.103-108.
  7. Cetegen, B.M., Zukoski, E.E., and Kubota, T., "Entrainment and Flame Geometry of Fire Plumes," NBS-GCR-82 402, 1982.
  8. Heskestad, G., "Virtual Origins of Fire Plumes," *Fire Safety Journal*, Vol.5, 1983, pp.109-114.
  9. Hasemi, Y., and Tokunaga, T., "Flame Geometry Effects on the Buoyant Plumes from Turbulent Diffusion Flames," *Fire Science and Technology*, Vol.4, 1984, pp.15-26.
  10. Cox, G., and Chitty, R., "Some Source-dependent Effects of Unbounded Fires," *Combustion and Flame*, Vol.60, 1985, pp.219-232.
  11. Zukoski, E.E., "Fluid Dynamic Aspects of Room Fires," *Proc. First International Symposium on Fire Safety Science*, 1985, pp.1-30.
  12. Wood, B.D., Blackshear, P.H., and Eckert, E.R.G., "Mass Fire Model: An Experimental Study of the Heat Transfer to Liquid Fuel Burning from a Sand-filled Pan Burner," *Combustion Science and Technology*, Vol.4, 1971, pp.113-129.
  13. Huggett, C., "Estimation of Heat release by Means of Oxygen Consumption Measurements," *Fire and Materials*, Vol.4, No.2, 1980, pp.61-65.