# ENTRAINMENT OF LINE THERMAL PLUMES

Li-Ming Yuan
(State Key Laboratory of Fire Science, USTC, Hefei, Anhui 230026, P. R. China)

Geoff Cox
(Fire Research Station, Garston, Watford WD2 7JR, UK )

## ABSTRACT

The measurement of the centerline temperature rise and velocity above a line heat source was made. The entrainment of the line thermal plume was calculated based on the centerline data. The mass flux of the hot gas above the line fire was measured and compared with the calculation results. The comparison between the experimental results and literature values gives an appropriate equation to calculate the entrainment of the line thermal plume.

## 1. INTRODUCTION

The entrainment of thermal plumes from a circular or a square heat source have been investigated by many researchers[1,2]. Nowadays more interests are developing in the entrainment of the thermal plumes above a line heat source because of some practical applications in smoke control design in the building [3,4]. Some works have been carried out in the line thermal plumes. Rouse.H,Yih.C.S. and Humphreys [5] made an elementary analysis of the mean patterns of free convection from a line source. Velocity and temperature measurements were made in the thermal plume. Their velocity measurement was thought with a large uncertainty. Yokoi [6] made a more complicated and more precise analysis of the upward current from an infinite line heat source. He also measured temperature and velocity distribution over the line heat source with a very low heat release rate.. Lee and Emmons [7] investigated natural convection above a line fire. A similar theoretical analysis was also made and just temperature distribution over the line fire was measured. Thomas [3] derived an equation to calculate the entrainment of the line thermal plume from Lee and Emmons' analysis and experimental results. Zukoski [8] also did some works about the thermal line plume. In the environmental research area similar works were also done without fire. Kotsovinos et al [9] made an extensive study on plane buoyant jets and plumes. Recently Ramapr- ian and Chandrasehora [10] made a similar research. Hasemi et al [11] studied the fuel shape effect on the deterministic properties of turbulent fire plume. Flame height and maximum excess temperature in the thermal plume were measured over a line burner.

In this paper two different aspect ratio line burners were used to produced line heat sources. The centerline temperature and velocity above line fires was measured with the heat release rate ranging from 2kw-104kw. A simple model was developed to calculate the mass flux of the hot gas above the line fire based on experiment data and real mass flux of the hot gas were also measured in a similar way described in [2]. All experimental results in this paper can help to fully understand the behavior of the thermal line plumes and improve the smoke control design.

## 2. THEORETICAL CONSIDERATIONS

From Rouse et al's derivation [7], for a conventional thermal plume above a line heat source, the width of the plume b, the centerline velocity um and centerline temperature rise $\Delta$ Tm have the following relationships with the height z respectively:

$$b \propto z,\ \ u_m \propto z^0,\ \ \Delta T_m \propto z^{-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Assuming the uniform profiles for the temperature and velocity distribution, the mean motion is then governed by the following three conservation equations for continuity, momentum and buoyancy:

$$\frac{d(2blu)}{dz} = 2lu\alpha \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$$\frac{d(2blu^2)}{dz} = 2bgl(\rho_0 - \rho)/\rho_0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$$\frac{d[2blug(\rho_0 - \rho)/\rho_0]}{dz} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Here l is the length of the line burner, $\alpha$ is the entrainment of the line thermal plumes, $\rho$ is the density, $\rho_0$ is the constant ambient density and g is the acceleration due to gravity. The buoyancy equation can be related to the convective heat Q in the plume,

$$Q = 2blu\rho C_p(T - T_0) = 2bluC_p(\rho_0 - \rho)T_0$$

Here Cp is the specific heat at constant pressure and T0 is the ambient temperature. Equation (4) can be integrated to

$$2blug(\rho_0 - \rho)/\rho_0 = \text{constant} = gQ/\rho_0 C_p T_0 \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Combining equations (1),(2), (3) and (5) gives to

$$b \propto z\alpha$$

$$u \propto \left(\frac{gQ_l}{2\alpha\rho_0 C_p T_0}\right)^{1/3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

$$\frac{\Delta T}{T_0} \propto \left(\frac{Q_l}{2\alpha\sqrt{g}\rho_0 C_p T_0}\right)^{2/3} z^{-1}$$

Here Q1 =Q/l. Now we can assume further:

$$b = C_l z,$$

$$u_m = C_u\left(\frac{gQ_l}{\rho_0 C_p T_0}\right)^{1/3},\ \ \frac{\Delta T_m}{T_0} = C_T\left(\frac{Q_l}{\rho_0 C_p T_0\sqrt{g}}\right)^{2/3} z^{-1} \ \ldots\ldots(7)$$

$$\frac{u}{u_m} = \exp(-y^2/b^2),\ \ \frac{\Delta T}{\Delta T_m} = \exp(-\beta^2 y^2/b^2)$$

Three conservation equations still hold with following forms:

$$\frac{d}{dz}\int_0^\infty 2ludy = 2l\alpha u_m \text{..........}(8)$$

$$\frac{d}{dz}\int_0^\infty 2lu^2dy = g\int_0^\infty 2ldy\Delta T / T_0 \text{..........}(9)$$

$$\frac{d}{dz}\int_0^\infty 2lugdy\Delta T / T_0 = 0 \text{..........}(10)$$

Equation 10 can be changed to:

$$\int_0^\infty 2lugdy\Delta T / T_0 = \text{constant} = Qg / (\rho_0 C_p T_0) \text{..........}(11)$$

Substituting equations (7) into equations(8),(9) and (11), yields

$$C_l = 2\alpha / \sqrt{\pi}$$
$$\sqrt{\beta}C_u^{\ 2} = \sqrt{2}C_T \text{..........}(12)$$
$$C_u C_T C_l = (1+\beta)^{1/2} / \sqrt{\pi}$$

In these three equations if Cu and CT are determined by experimental results,Cl , β and α can be calculated.
From above analysis, the mass flux of the thermal plume can be calculated :

$$m = \int_0^\infty 2lu\rho dy$$

If we still assume $\rho = \rho_0$,

$$m = \int_0^\infty 2lu\rho_0 dy = \sqrt{\pi}C_l C_u l(g\rho_0^{\ 2} / C_p T_0)^{1/3} Q_l^{\ 1/3} z$$
$$m / l = \sqrt{\pi}C_l C_u (g\rho_0^{\ 2} / C_p T_0)^{1/3} Q_l^{\ 1/3} z \text{..........}(13)$$

If the mass flux of the fuel is neglected the entrainment of the line thermal plumes will be equal to the mass flux of the hot gas.

## 3. EXPERIMENTAL DETAILS

The experiments were conducted using a 0.018 × 0.5m and a 0.05 × 0.5m line burners. These burners were constructed of porous refractory material. The fuel is natural gas (35kJ/l) and the rate was controlled through a flow meter. The heat release rate was calculated from flow rate and changed from approximately 2-110KW. The burner sat 0.71m above the floor and under a passive hood in a large laboratory. The instruments was located over the centerline of the burner using a plum bob. Thereafter, vertical and side to side movement of the instrument cluster was accomplished with a micrometer lathe-type movement device which held the pressure probe and thermocouples.

Temperature measurements were made using approximately 0.2mm diameter chromel-alumel thermocouples. The time constant of the temperature measurement is approximately 10 seconds. No corrections have been made for the radiation and conduction losses from the junction of each thermocouple. For 0.2mm chromol-alumel thermocouples with an emissivity of around 0.9, the error due to radiation loss will range from 2 to 20% over the temperature range 300-1000 ℃. To eliminate the influence of accidentally sway of the flame, temperature was monitored at each height not only just above the burner center but also at two different points 5 cm apart from the center in the direction of shorter side. The reported values of temperature are the average of the temperature at each height over more than 3 minutes during which the temperature above the burner center was higher than the other two.

Velocity was measured using bidrectional pressure probes which responds like a pito-tube static probe except the measuring area is quite large which spatially averages the signals in order to obtain the gross structure of the flame. The output of the microman-ometer was time-averaged over more than 3 minutes. The pressure signal is very sensitive to any disturbance caused by draught. A mesh screen was hung up from the hood bottom to the floor at one side parallel to the burner center(another side was a experiment rig). The disturbance couldn't be prevented completely. Some disturbance still could be found on the data record and data recorded during these disturbance was not used. The density was calculated by the temperature from the attached thermocou-ples on the probe according to ideal gas law. Each probe was calibrated in a standard wind tunnel before use. The calculated velocity was then inverted to real velocity acc-ording to calibration.

The mass flux above the flame was measured in an apparatus similar to that described in [2]. The experimental set-up was shown in figure 1. The hood with the dimensions of 1.0m × 0.6m × 0.6m was made of fireboard and the duct with a diameter of 0.4m was made of steel. The bidirectional probe was used to measure the velocity distribution over the duct cross-section. Because of short distance (0.6m) above the hood, the velocity distribution isn't homogeneous. A typical velocity distribution was shown in Fig.2. It can be found an approximate axiysimmetry holds well. The mass flux was calculated by integrating over the section. It was estimated that this method could cause the maximum error within 15%. Because of limited dimension of the hood, the interface layer between the cool room air and the hotter hood gas was kept as close to the bottom of the hood as possible by changing the height of the burner which was fixed on a jack according to different heat release rate. The location of the interface layer was determin- ed from the temperature distribution measured with the vertical arrays of thermocouples which span the interface. The 0.2mm thermocouples was used at intervals of 0.04m for the distance near the bottom and 0.1m for the other distance. A typical temperature profile is shown in Fig.3. In the regions both above and below the interface the gas temperature is nearly constant. In the interface layer there exist a large temperature gradients and fluctuations. Typical interface thickness were 10-20cm. The interface height was defined as the height at which the temperature is nearest to 0.5(Tu +Tl )+Tl , where Tu is the upper layer temperature and Tl is the room temperature.

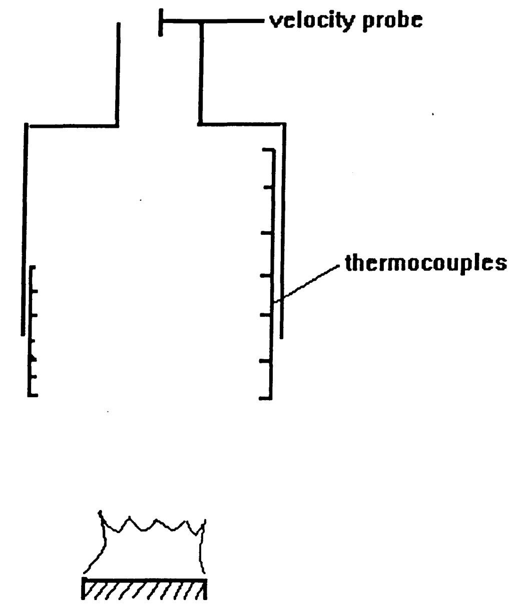


Figure 1 The experimental set-up

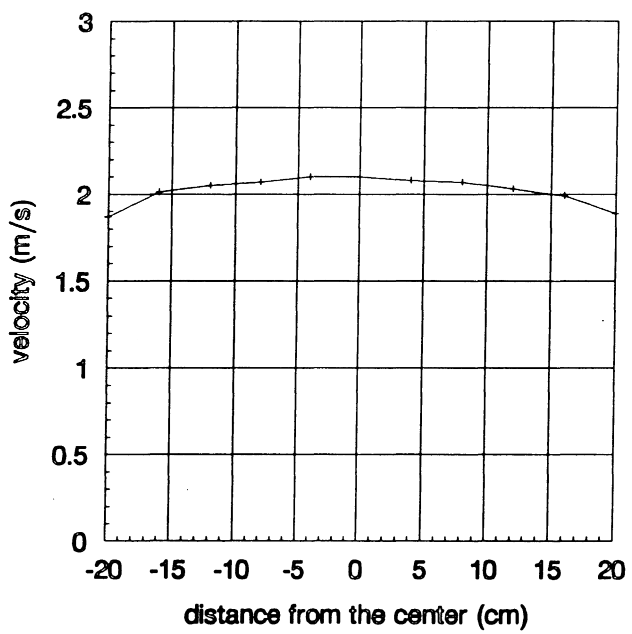


Figure 2 The typical velocity distribution in the duct

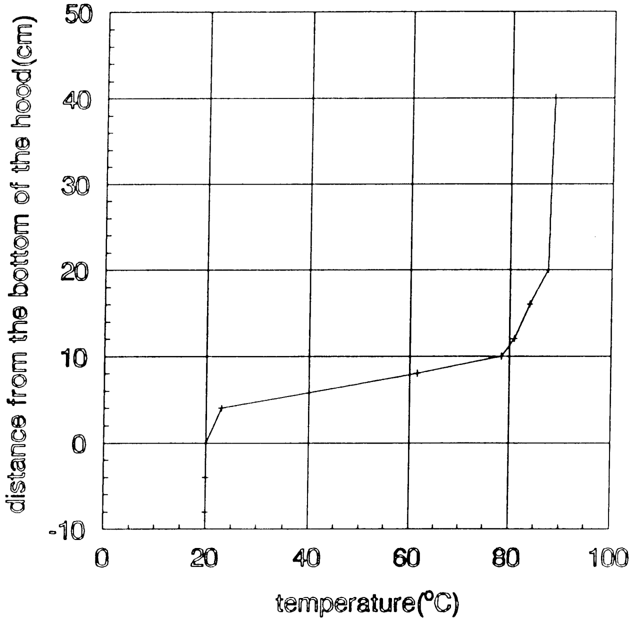


Figure 3 The typical temperature profile in the hood

## 4. RESULTS AND DISCUSSIONS

### 4.1 centerline temperature rise and velocity

Figures 4 and 5 presented the time-averaged centerline temperature rise and velocity against height z above the burner for heat release rate ranging from 2.21-66.9KW with two different aspect ratio line burners. The scaling factors $Q_l^{1/3}$ and $Q_l^{2/3}$ for u and z are from McCaffrey [13] with special consideration of line burner. It can be found that in the conventional plume region, the data exhibit the characteristic $z^{-1}$ and $z^0$ variation for $\Delta$Tm and um dependence. These are consistent with theoretical analysis [5,6,7]. The solid lines on figures 3 and 4 were taken from the weighed average values of the coefficients of the various expressions [14]. In details the centerline temperature rise and velocity in the thermal plume from a line burner can be expressed as follows:

$$u_m / Q_l^{2/3} = C_1(z / Q_l^{2/3}), \quad \Delta T_m = C_2(z / Q_l^{2/3})^{-1}$$

In this experiment $C_1$ =0.62, $C_2$ =7.20. Hasemi [11] got a very good result of ceterline temperature rise for thermal plume from a line burner (0.1x1.0m). The correlation line for thermal plume in Fig.3 is consistent with Hasemi's result. It can be found that center- line temperature rise in thermal plume in this experiment is not very good. Just above the flame tip most data are above the correlation line and far away the flame tip most data are under the correlation line. This is very difficult to give a satisfactory explanation except to suspect some interaction with environmental conditions of the laboratory. Considerable care was taken to collect data only when the flame appear undisturbed by laboratory air movements but above the flame tip any disturbances wouldn't be visible.

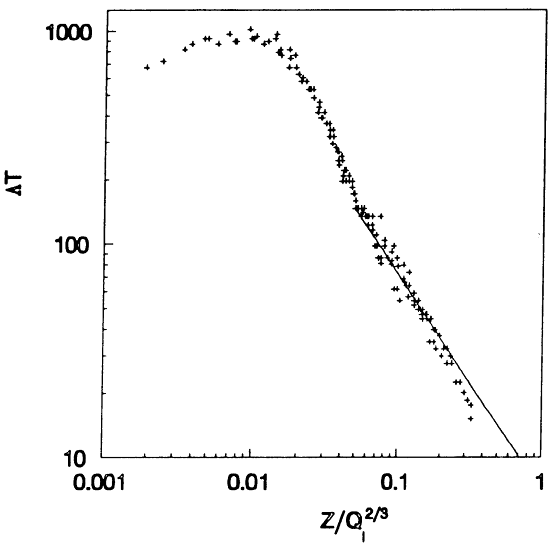


Figure 4 centerline temperature rise versus height

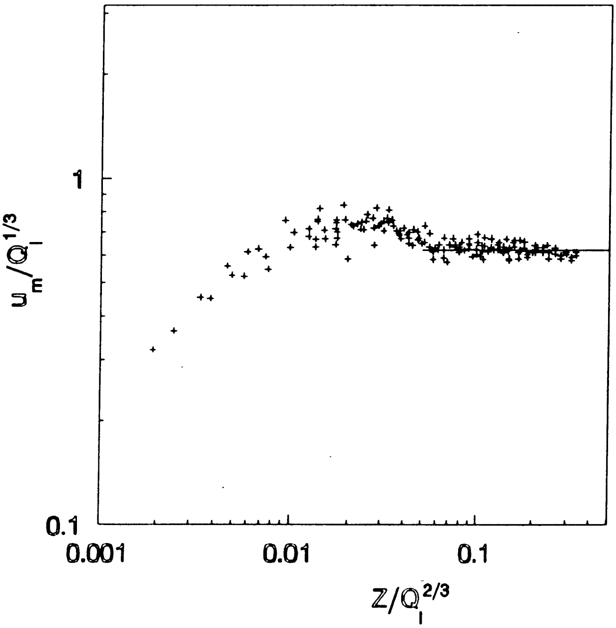


Figure 5 centerline velocity versus height

The result of centerline temperature rise and velocity was compared with other's results [5-12] as follows:

$$u_m = C_u[gQ_l/(\rho_0 C_p T_0)]^{1/3}, \quad \Delta T_m = C_T[Q_l/(\rho_0 C_p T_0 g)]^{2/3} z^{-1},$$

| Author | Cu | CT |
|---|---|---|
| This work | 2.04 | 2.6 |
| Rouse et al [5] | 1.8 | 2.6 |
| Yokoi [6] | 2.05 | 2.5 |
| Lee and Emmons [7] | -- | 2.6 |
| Hasemi [11] | -- | 2.6 |
| Zukoski [8] | 2.0 | 2.6 |
| Kotsovinos [9] | 1.66 | 2.38 |
| Ramaprian et al [10] | 2.13 | 2.56 |
| Chen and Rodi [12] | 1.7 | 2.5 |

The data of Lee and Emmons was indirectly derived from the value of α =0.16 and λ =0.9 based on theoretical consideration in section 2.

It can be found that for the centerline temperature rise, most of the experimental results agree well with Cu =2.6. The low value of Kotsovinos may contribute to thermistors they used to measure the temperature. As to the centerline velocity there is some extent of disagreement. Yokoi, Zukoski and this work agree well. Rouse et al. result may have big uncertainty. The big difference is between Kotsovinos and Ramaprian. The interest- ing thing is that they both used laser-Doppler Anemometer to measure the velocity. Probably different instruments is the main reason of disagreement.

### 4.2 Entrainment coefficient

The entrainment coefficient can be calculated based on the centerline temperature rise and velocity data and use the model described in section 2:

$$\alpha = (2C_T^{\,2} + C_u^{\,4})^{1/2} / (2C_u^{\,3} C_T)$$

The calculation results of entrainment coefficient from different researchers were showed as follows:

| Author | α |
|---|---|
| This work | 0.125 |
| Rouse et al [5] | 0.156 |
| Lee and Emmons [7] | 0.16 |
| Kotsovinos [9] | 0.199 |
| Ramparian [10] | 0.117 |

### 4.3 Mass flux of thermal plume

Values of plume mass flux have been obtained without the fan and the hot gas rise up by natural buoyance. Fig.6 presented the per unit length mass flux versus $z(Q_l^{2/3})$. This equation can be written as:

$$m / l = C_m (g\rho_0^2 / C_p T_0)^{1/3} Q_l^{2/3} z \quad (14)$$

Here Cm = $\pi^{1/2}$ClCu , The value of Cm from different investigators was showed as follows:

| Author | Cm |
|---|---|
| This work | 0.51 |
| Rouse et al [5] | 0.57 |
| Thomas [3] | 0.58 |
| Zukoski [8] | 0.51 |
| Kotsovinos [9] | 0.66 |
| Ramparian [10] | 0.50 |

It was found that big difference still exists in Kotsovinos's result because of his low value for Cu. Four different theoretical equations with Cm = 0.51 and 0.48 were compared with experiment result on figure 6 using normal ambient conditions: To =20C, $\rho_0$ =1.195Kg/$m^3$ , Cp =1.005KJ/Kg.K and $[g\rho_0 / (C_p T_0)]^{1/3}$=0.3622. Only Ramparian measured the mass flux for a plane plume and got a Cm =0.48 by the least square fit. It can be found from figure 6 that most of the data gather between the two lines with Cm =0.51 and 0.48.

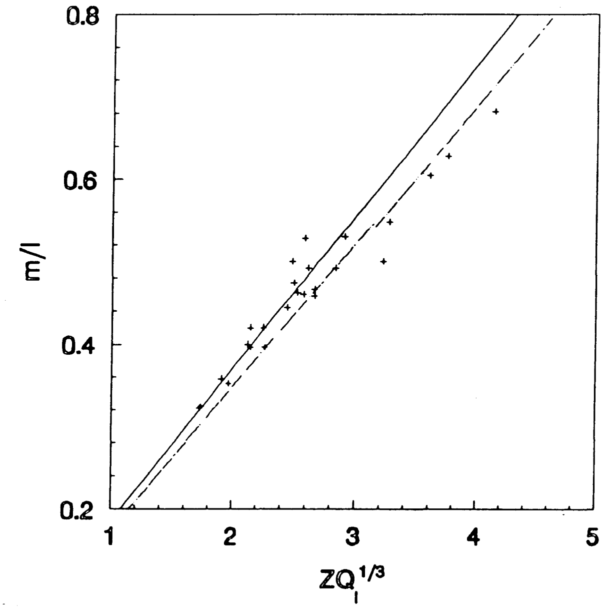


Figure 6 The mass flux versus height ( — Cm =0.51, ---Cm =0.48 )

## 5 CONCLUSIONS

The centerline temperature and velocity of line thermal plumes were measured. The centerline temperature is proportional to the $z^{-1/3}$ and the centerline velocity is a constant. This is constant with the theoretical analysis.

Based on the centerline data a simple model was developed to give an equation to calculate the entrainment of the line thermal plume (Eq.(14)). Thorough using a hood apparatus the mass flux of the hot gas above line fires was measured. The experimental results showed that the appropriate value for Cm in Eq. (14) is 0.48-0.51.

More works are needed to investigated the entrainment in the line fire regions.

## ACKNOWLEDGMENTS

One of the authors, L. M. Yuan wishes to thank Dr. D. Smith for her assistance in experiments.

## REFERENCES

[1].Cox, G. and Chitty R., A Study of the Deterministic Properties of Unbounded Fire Plumes, Combustion and Flame 39:191-209(1980)

[2].Zukoski E. E., Kubota T. and Cetegon B., Entrainment in Fire Plumes, Fire Safety Journal, 3(1980/1981) 107-121

[3].Thomas, P. H., On the Upward Movement of Smoke and Related Shopping Mall Problems, Fire Safety Journal, 12(1987)191-203

[4].Hansell G.O and Morgan, H.P, Design approaches for Smoke control in atrium buildings, BRE Report K23,Uk 1994

[5].Rouse,H., Yih,C. S. and Humphreys.H.W., Gravitational Convection from a Buoyancy Source, Tellus, 4 201(1952)

[6].Yokoi sizuo, Study on the Prevention of Fire-Spread Caused by Hot Upward Current, Report of the Building Institute of Japan, No.34, 1960

[7].Lee, S.L. and Emmons, H.W., A Study of natural convection above a line fire, Journal of Fluid Mechanics, 11, 353-368(1961)

[8].Zukoski. E.E. and Kubota. T., Two-layer Modelling of Smoke Movement in Building Fires, Fire and Materials, Vol 4 No.1 1980

[9].Kotsovinos, N.E., A Study of the Entrainment and Turbulence in a Plane Buoyant Jet, W.M.Keck Laboratory of Hydraulics and Water Resources Report No.KH-R-32, California Institute of Technology,Pasadena, 1975

[10].Ramaprian.B.R and Chandrasekra.M.S, Measurements in Vertical Plane Turbulent Plumes, Journal of Fluids Engineering, March 1989,Vol,111/69

[11].Hasemi. Y and Nishihata, M., Fuel Shape Effect on the Deterministic Properties of Turbulent Diffusion Flames, Fire Safety Science-Proceedings of the Second International Symposium, pp.275-284,1988

[12].Chen.C.J. and Rodi, A review of experimental data of vertical turbulent buoyant jets, SFB 80/7/69, December,1975

[13].McCaffrey J.B., Purely Buoyant Diffusion Flames: Some Experimental Results, NBSIR 79-1910

[14].Yuan L.M. and Cox,G.,An Experimental Study of Line Fires, (submitted to Combustion and Flame, 1995)