Characterizing the Unconfined Ceiling Jet under Steady-State Conditions: A Reassessment

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ABSTRACT

Detailed velocity and temperature measurements using cross-correlation velocimetry were obtained for unconfined ceiling jets under ceiling transient and steady-state conditions. Small fires of 0.5 to 2.0 kW were produced with a premixed methane-air burner. These measurements represent one of the most detailed studies of unconfined ceiling jets to date and seem to be in general agreement with large-scale data. Empirical correlations for the steady-state ceiling jet temperature and velocity profiles are described herein. The correlations compare well with, and have improved, results from previous works. The maximum temperature may not be scaled as a function of fire-to-ceiling heights for large radial distances. Furthermore, the Gaussian and boundary layer thermal and momentum thicknesses of the ceiling jet are not equal, contrary to the assumptions made in other works.

Key words: ceiling jet, velocity, temperature, unconfined, detection

NOMENCLATURE

c_p	Heat capacity, (kJ/kg K)	Ri	Richardson No.($=[g\Delta\rho\ell/\rho\infty]^{1/2}/V$)
d	Thermocouple pair dist., (mm)	r	Radial axis, meas. from plume impingement pt, (m)
g	Gravitational accel., (m/s^2)	t	Time, (s)
H	Burner to ceiling dist., (m)	T	Temperature, (°C)
ℓ_V	Gaussian momentum thickness, (m)	$T\infty$	Ambient temperature, (°C)
ℓ_T	Gaussian thermal thickness, (m)	ΔT	$T-T\infty$
Pr_t	Turbulent Prandtl number	V	Ceiling jet vel., (m/s)
Q_*	Heat source strength, (kW)	z	Vertical dist. measured from the ceiling, (m)
Q^*	Non-dimensionalized convective heat release rate, (Eq. 2)		

Greek Symbols

δ_{Tmax} Distance from the ceiling to maximum temperature, (m)
δ_{Vmax} Distance from the ceiling to maximum velocity, (m)
λ_r Radiation fraction of heat released by fire
ρ Density, (kg/m^3)

INTRODUCTION

Characterizing the ceiling jet formed by a fire-induced buoyant plume is essential, since most fire detection and suppression devices are designed to operate within this jet. Although many investigators have studied the ceiling jet, detailed measurements of velocity and temperature, together, have not been obtained to date.

The velocity and temperature profiles and ceiling jet growth quantify the momentum and energy contents and their transport within the ceiling jet. Wall-jet studies of Glauert [1] and Poreh, et. al. [2] have established the ceiling jet to be a boundary-layer type flow. The key parameters which define the behavior of the ceiling jet as a function of position under steady-state conditions can be identified according to Fig. 1. The ceiling jet momentum and thermal boundary layer thicknesses are denoted as δ_{Vmax} and δ_{Tmax}, respectively. They identify a region of the jet where flow velocity and temperature vary from the wall no-slip conditions to maximum values V_{max} and ΔT_{max}. At distances beyond δ, the ceiling jet flow behaves like a free jet and its growth may be defined by thermal and momentum Gaussian thicknesses, ℓ_T and ℓ_V, respectively.

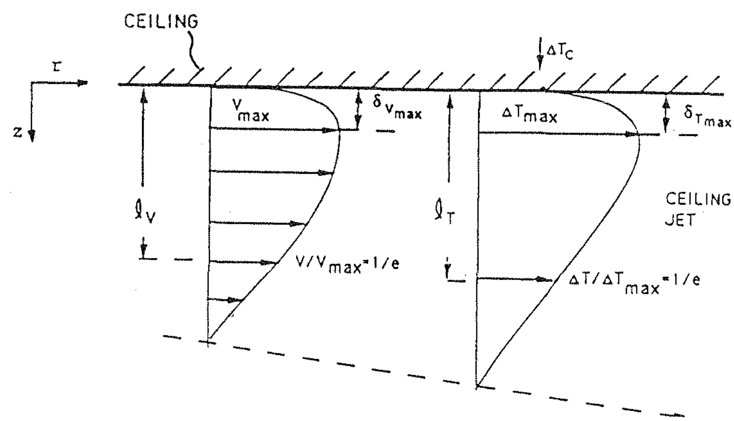

FIGURE 1 - Schematic of the ceiling jet and its characteristic parameters

The ceiling jet is characterized using detailed temperature and velocity measurements as a function of respective maximum values, vertical distance from the ceiling, z, and radial distance from the plume impingement point, r, (i.e. $\Delta T(r,z)$ and $V(r,z)$).

Previous Studies of Unconfined Ceiling Jets

Alpert [3], Veldman, et. al. [4], You and Faeth [5] and Heskestad and Delichatsios [6] have produced correlations for the ceiling jet maximum velocity and temperature. Alpert assumed a Gaussian behavior for the velocity and temperature profiles and has developed an integral model for the boundary layer thickness. Beyler [7] has also compiled and compared a list of ceiling jet correlations. The comparisons demonstrate that the agreement between the empirical models presented is not always as good as desired and no correlations defining the velocity and temperature profiles exist. Furthermore, very limited ceiling jet velocity measurements have been obtained.

EXPERIMENT APPARATUS AND APPROACH

Cross-Correlation Velocimetry

Simultaneous measurements of temperature and velocity profiles of the ceiling jet required a technique which would provide multi-point velocity and temperature data without significantly disrupting the flow. Many such considerations led to the adoption of the Cross-Correlation Velocimetry (CCV).[8,9]

The cross-correlation of temperature-time records from a pair of thermocouples placed in the streamwise direction of the flow and separated by a distance, d, can be used to obtain the most probable mean velocity of the flow in the streamwise direction for flows with a preferred component such as is observed in the ceiling jet [9]. The fluid temperature can easily be measured using the temperature-time records directly. An extensive discussion of the fundamental principles of the CCV technique and its verification using the Laser Doppler Velocimetry calibration has been presented elsewhere [10,11].

Velocity and temperature probe The CCV probe consisted of 8 pairs of 25.4 μm, type E (chromel-constantan) thermocouples stretched between non-conductive thin support arms. The bead sizes for the thermocouples were approximately 76.2 μm with an estimated time constant of 0.05 seconds [10]. The thermocouple pairs were vertically positioned at: 1.19, 3.175, 6.35, 9.525, 12.7, 19.5, 25.4 and 50.8 millimeters measured from the top of the probe. The thermocouple beads were positioned at the mid-point between the holder arms, which were 11.5 cm apart.

Unconfined Ceiling and Burner Apparatus

A ceiling 2.13 m in diameter was constructed from 1.27 cm thick fiber-board material. The back face of the ceiling was insulated. The surface of the ceiling was painted and the emissivity was measured to be 0.9 [10].

A premixed methane-air burner with a 2.7 cm inside diameter was used. Small steady fires in the range of 0.5 to 2.0 kW were produced using this burner. This ensured a blue, short flame producing a nearly pure buoyant plume. The resulting gas exit velocity was between 0.27 to 1.08 m/s. The burner mouth was placed flush with an artificial floor whose distance to the ceiling could be altered in order to vary the floor to ceiling height.

PROCEDURE

Fire strengths of 0.75, 1.0 and 2.0 kW were used and measurements were made for two heights of 0.5 and 1.0 m at r/H locations of 0.26, 0.5, 0.75, 1.0, 1.5 and 2.0. Due to the limited number of thermocouple pairs and their distribution, each experiment was repeated 3 to 4 times. Each time, the probe was positioned at a different distance from the ceiling. This provided enough data to form complete velocity and temperature profiles. By default, this procedure also demonstrated the high degree of repeatability obtained.

STEADY STATE RESULTS AND DISCUSSION

Alpert [3] and Veldman, et. al. [4], among many other researchers, have used the following non-dimensionalized form for the ceiling jet velocity and temperature:

$$V^* = V/\ Q^{*1/3}\ (gH)^{1/2} = f(r/H) \quad \text{and} \tag{1}$$

$$\Delta T^* = \Delta T/\ Q^{*2/3} T_\infty = f(r/H) \tag{2}$$

where Q^* was later defined by Cooper [12] as: $Q^*=(1-\lambda_r)Q/\rho_\infty c_p T_\infty\ g^{1/2}H^{5/2}$ and λ_r is the fraction of heat lost due to radiation from the source. In this work, λ_r is thought to be negligible because flames from premixed combustion are small and blue. It is believed that the use of H as a length scale in equations 1 and 2 is only valid if $H \gg \ell$ (discussed later).

Ceiling Jet Maximum Velocity

The steady-state maximum velocity of both heights and all fire strengths collapsed onto a single curve using Eq. (1). A linear least square fit to the data yields the following empirical equation:

$$V^*_{max} = 0.0415\ (r/H)^{-2} + 0.427\ (r/H)^{-1} + 0.281 \tag{3}$$

As the initial momentum of the ceiling jet diminishes with increasing r/H, the maximum ceiling jet velocity asymptotically approaches zero. Figure 2 shows a comparison of V_{max} empirical equation with the results of other investigators. In this figure, the maximum velocity is normalized by $Q^{1/3}H^{-1/3}$ (adopted from Beyler [7]). There is a general agreement between the different correlations. Heskestad and Delichatsios [6] data are from large-scale experiments. Cooper's model [13] is based on less direct data and is developed from wall-jet theory of Poreh, et. al. [2] His model agrees well with Heskestad and Delichatsios at r/H>0.4, but overestimates authors' data by 30% to 50% at r/H < .7 and even more compared to Alpert's model. Since Heskestad and Delichatsios's equation is only valid for r/H>0.4, it is not certain if Cooper's model would have any agreement with their equation in that region. Figure 2 also shows that Cooper's model predicts an unreasonably high V_{max} at small r/H values (r/H<0.4) and probably is not accurate in that range. Alpert's data were obtained using a hot-wire probe while Heskestad's measurements were made employing a bi-directional probe. The empirical equation from this work seems to closely agree with that of Alpert and is in a general agreement with Heskestad and Delichatsios's correlation, both of which are for large-scale experiments. The velocity measurements by the authors are also much more detailed than those by other investigators.

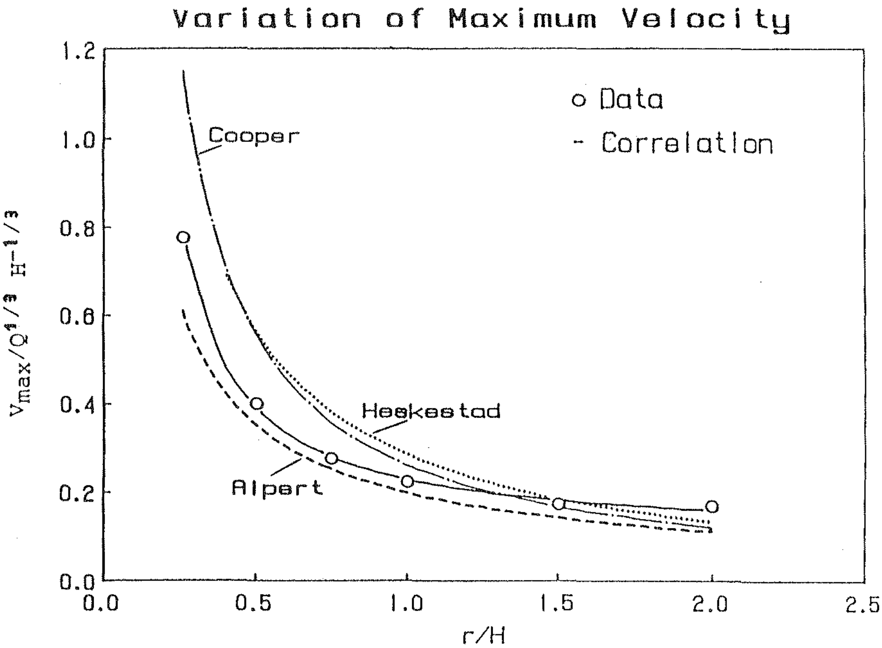

FIGURE 2 - Comparison of empirical equations of ceiling jet maximum velocity from Alpert[3], Cooper[13], and Heskestad & Delichatsios[6] with authors'.

Ceiling Jet Maximum Temperature

Plots of ΔT profiles at different times and r/H locations revealed that as r/H approaches 1.0, ΔT^* profiles do not correlate for the two heights. Comparison of the temperature profiles clearly showed that as the ceiling is heated, the normalized temperature profiles diverge for the H=1.0 m and 0.5 m cases at r/H>0.75 locations. Velocity profiles did not demonstrate this behavior, however, the scatter in velocity profiles increased substantially for r/H > 0.75.

The above discrepancies could be explained if a significant portion of the plume were not turbulent. However, if H=0.5 m was too small for a turbulent flow and the plume had a laminar length, which is not scaled, then the normalized ceiling jet temperatures for H = 0.5 m ought to have been higher due to reduced air entrainment and mixing. The results point to the opposite. Measurements of the thermal fluctuations both in the plume and ceiling jet also indicated turbulent plume behavior. In addition, the premixed flame provided short flame lengths (2 to 3 burner diameters long) leading to production of a purely buoyant plume only a few burner diameters downstream of the exit. These observations led to development of two separate empirical equations for H=1.0 m and 0.5 m cases shown in Fig. 3.

$$\Delta T^*_{max} = 0.166(r/H)^{-2} + 1.2(r/H)^{-1} + 2.0 \qquad 0.26 \leq r/H \leq 1.0,\ H=1.0\ m \qquad (4)$$

$$\Delta T^*_{max} = 0.082(r/H)^{-2} + 1.9(r/H)^{-1} + 0.966 \quad 0.26 \leq r/H \leq 2.0,\ H=0.5\ m \qquad (5)$$

It appears that the Richardson number, Ri, of the ceiling jet might be changing across the critical number of 1.0 at about r/H=0.75 [10]. Thus the dominance of buoyancy (Ri>1) at these large r/H values may be the cause of divergence in the ΔT_{max} curves.

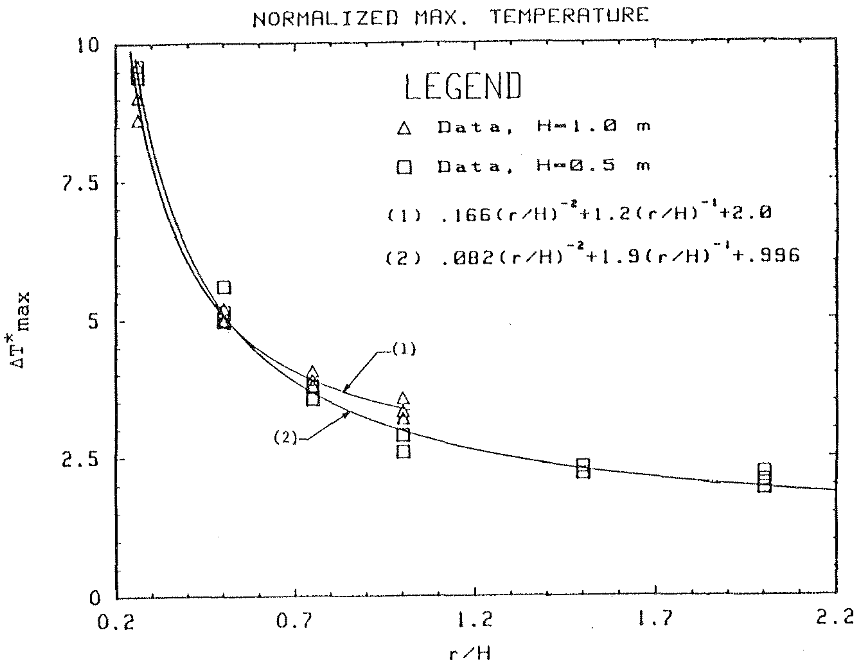

FIGURE 3 - Non-dimensionalized ceiling jet maximum temperature (1) H=1.0 m, (2) H=0.5 m

The ΔT^*_{max} empirical equation is compared to those obtained by other investigators and data of You & Faeth and Zukoski et. al., as reported by You & Faeth [5], in Fig. 4. Data of You and Faeth are from a very detailed study of a steady-state ceiling jet induced by a 0.25 kW fire. Zukoski et. al.'s data are from study of 1.17 kW and 1.53 kW fires. The general agreement between their data and Eq. (5) indicates that these small-scale experiments correlate quite well. Furthermore, You & Faeth concluded that Alpert's integral model generally underestimates the measured maximum temperature by 20%. Data from this work indicate a 30% to 18% ($0.26 \leq r/H \leq 2.0$) underestimation of the measured maximum temperature by Alpert's model. Cooper's model [12] seems to underestimate the maximum temperature even more, especially at r/H>0.75. Heskestad and Delichatsios [6] also show lower temperature in their large-scale experimental results. In the authors' view, the overriding factors in correlating results of ΔT_{max} are the actual value of the convective heat release rate used in each investigation, the distance from the virtual origin and differences between heat transfer characteristics in large and small-scale experiments. The convective heat release rate were determined quite accurately for the premixed flames used here. In addition, accurate determination of the location of maximum temperature requires very detailed measurements. While authors and You and Faeth obtained very detailed temperature measurements, data of Alpert & Ward and Heskestad & Delichatsios were not as detailed.

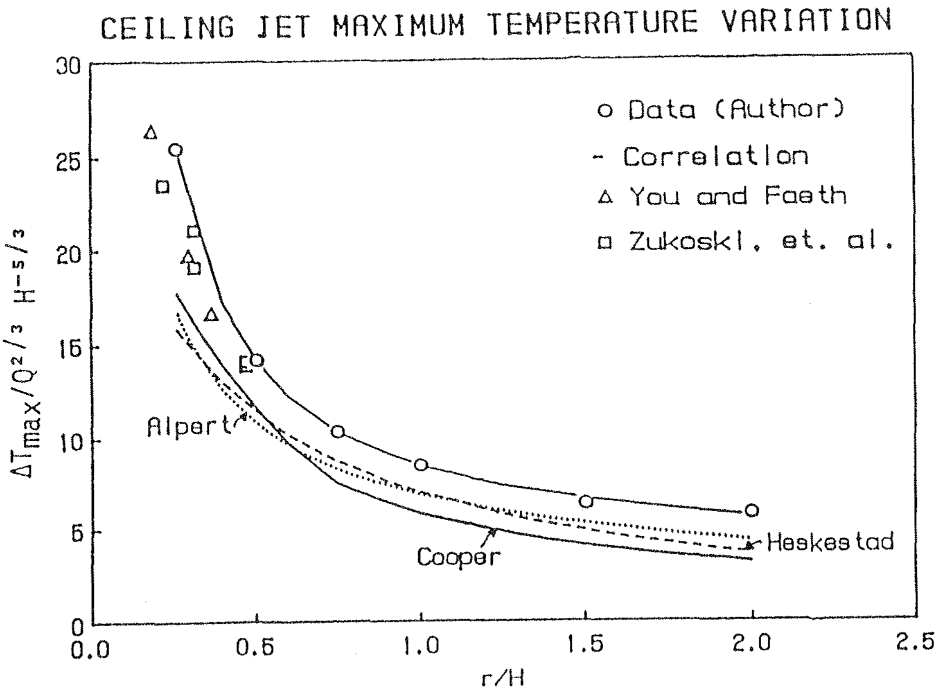

FIGURE 4 - Comparison of empirical equation of authors (Eq. 4), Alpert & Ward[14], Cooper[12], Heskestad and Delichatsios[6]. Data of You & Faeth, H=0.695 m, Q=0.25 kW, Zukoski (H=0.813 m, Q=1.17, 1.53 kW) from [5].

Ceiling Jet Velocity and Temperature Profiles

The velocity profiles did not correlate very well for r/H>0.75 locations. Plots of the normalized velocity profiles (V/V_{max} vs. z/ℓ_v, after Alpert [3]) showed that the data near the ceiling collapsed reasonably well whereas away from the ceiling there was considerable scatter. Some of the scatter is due to combining data sets from multiple runs and difficulties in velocity measurements near the lower edge ($z>\ell_v$) of the ceiling jet. The Richardson number effect may also be playing a significant role in increasing the scatter. To test this hypothesis, the velocity data for r/H>0.75 were eliminated and the remaining data were plotted in Fig. 5. The scatter reduced considerably and the normalized velocity data for $0.26\leq r/H\leq 0.75$ are correlated well by:

$$V/V_{max} = 1.59\ (z/\ell_v)^{0.14} \exp[-1.517(z/\ell_v)] \qquad 0.26\leq r/H\leq 0.75 \qquad (6)$$

where V_{max} and ℓ_v are defined by empirical equations which appear later. Equation (6) had a variance of 0.101. It has been determined that the ceiling jet velocity is not affected by the ceiling heating [10], therefore, Eqns. 3 and 6 may be valid for ceiling transient conditions.

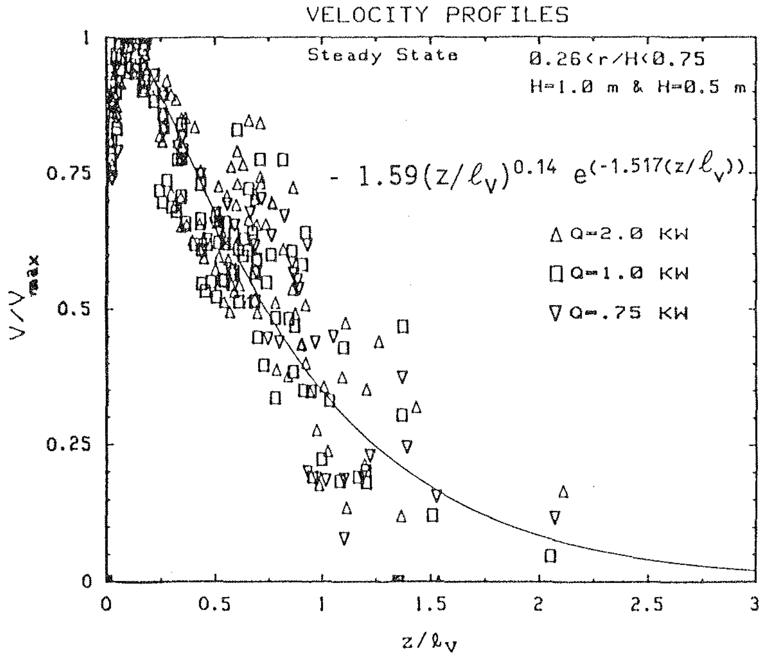

FIGURE 5 - Steady-state normalized velocity profiles

The temperature data was normalized with respect to ΔT_{max} and ℓ_T for each individual experiment. A plot of all the normalized temperature profiles is presented in Fig. 6. This plot consists of over 600 data points from 27 different temperature profiles. A single linear least square fit to the data of Fig. 6 is shown below:

$$\Delta T/\Delta T_{max}=4.24(z/\ell_T + 0.094)^{0.755} \exp[-2.57(z/\ell_T)] \qquad 0.26\leq r/H\leq 2.0 \qquad (7)$$

Equation 7 is only restricted by high H or Q until it can be compared with detailed large-scale temperature profiles.

Ceiling Jet Boundary Layer Characteristic Thicknesses, δ_{Vmax} and δ_{Tmax} The ceiling jet growth and thickness is characterized by the two parameters δ and ℓ as defined in Fig. 1. Alpert [3] developed an integral model for the ceiling jet where δ_{Vmax} was shown to be a function of r alone when Q is on the order of tens of kilowatts. He also assumed that the momentum length scales and thermal length scales to be the same; i.e. $\delta_{Vmax}=\delta_{Tmax}$ and $\ell_V=\ell_T$. The dependency of δ on r alone was confirmed by plots of δ_{Vmax} and δ_{Tmax} vs. r and the empirical equations constructed, Eqns. (8,9).

$$\delta_{Vmax} = 0.0187(r)^{0.668} \qquad 0.26\leq r/H\leq 2.0 \qquad (8)$$

$$\delta_{Tmax} = 0.0152\ (r)^{1.35} \qquad 0.26\leq r/H\leq 2.0 \qquad (9)$$

It should be noted that equations 8 and 9 can be simply normalized by H so that they can be used for floor-to-ceiling heights other than those used in this study.

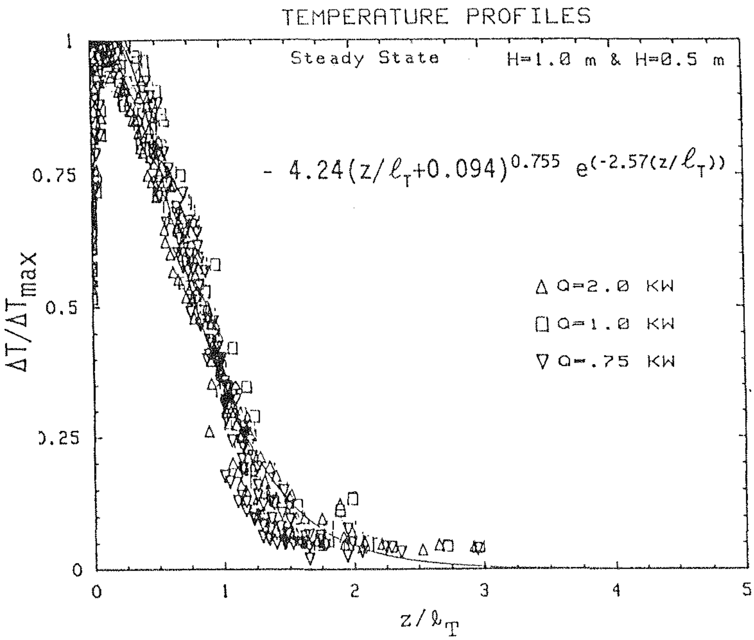

FIGURE 6 - Empirical fit to steady-state normalized temperature profiles

Although the uncertainty in locating the position of maximum velocity increases beyond r/H>1.0 due to the fixed vertical spacing of the thermocouples, this correlation seems to be quite accurate since it is based on a much larger data set and a more accurate measurement technique. Equation (9) predicts that the momentum boundary layer is retarded and approaches an asymptotic value, as would be expected. The least square fit of Eq. (10), however, suffers due to increased uncertainty in locating δ_{Tmax} for r/H>1.5. Hence, the relation for δ_{Tmax} does not approach an asymptotic value. Therefore, its use in its normalized form should be limited to $r/H \leq 2.0$.

The boundary layer region of the ceiling jet is driven by the initial momentum of the plume. In this region, the flow velocity and temperature are forced to zero and ceiling temperature, respectively, from the centerline plume velocity temperature. The outer region of the ceiling jet does not go through the same drastic transformation. Therefore, δ does not have an analogous parameter in the plume whereas ℓ is similar in definition for both the ceiling jet and the plume.

A comparison between the empirical Eq. (8), Alpert's formula developed for large and small-scale fires, and Cooper's equation [13]; $\delta_{Vmax}/H = 0.023\ (r/H)^{0.9}$ is shown in Fig. 7. Cooper's model shows that δ_{Vmax} increases indefinitely with r/H. Alpert's formula indicates the same behavior. Physically, it is expected to assume that the ceiling layer growth would be retarded as the initial momentum of the jet diminishes due to viscous losses and as buoyancy of the ceiling jet becomes dominant (Ri>1). This effect, however, is observed on the overall characteristic thickness, ℓ, more than it is on δ. The comparison in Fig. 7, also demonstrates that Eq. (9) agrees well with the large-scale correlation of Alpert.

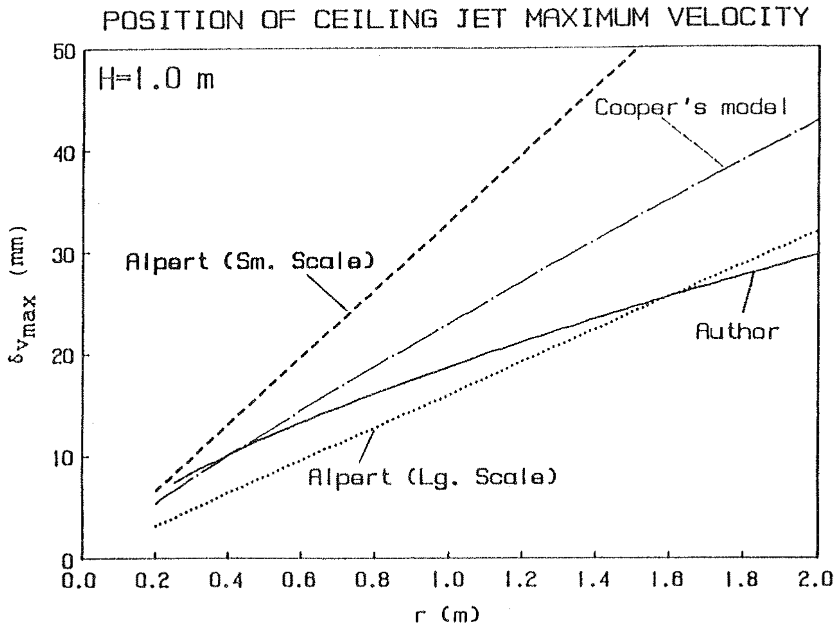

FIGURE 7 - Comparison of empirical equation of authors (Eq. 8), Alpert[3] and model of Cooper[13].

__Ceiling-jet Gaussian momentum and thermal thicknesses__, ℓ_V, ℓ_T A mathematical approximation of the form $Ax^b e^{-cx}$ was fitted to every steady-state velocity and temperature profile (a total of 30 profiles) and the respective values of ℓ_V and ℓ_T were obtained from these fits. Plot of ℓ_V/H vs. r/H correlated quite well for r/H≤0.75 whereas the correlation suffered significantly beyond this r/H value. The growth of ℓ_V and ℓ_T are retarded as r/H increases and they approach a constant thickness. The asymptotic behavior of ℓ_V and ℓ_T is thought to be due to the effect of Ri > 1. The free jet flow, and thus ℓ_T and ℓ_V, are effected much more by the buoyancy than the near ceiling flow region. It can also be stated that ℓ is scaled by H since it characterizes the free jet portion of the ceiling jet and it is analogous to the Gaussian thickness of the plume as long as ℓ<<H. This explains why ℓ_V data has more scatter beyond r/H=0.75 where ℓ_V is about 15% of H. The empirical relations defining ℓ_V and ℓ_T are shown below:

$$\ell_V/H = 0.205\ (1-\exp[-1.75(r/H)]) \qquad 0.26 \le r/H \le 1.5 \qquad (10)$$

$$\ell_T/H = 0.112\ (1-\exp[-2.24(r/H)]) \qquad 0.26 \le r/H \le 2.0 \qquad (11)$$

The data of ℓ_T correlated well for both heights; all fire strengths and at all r/H locations. Aside from a more accurate determination of ℓ_T (due to less scatter in the temperature data), ℓ_T<<H holds for this entire range explaining the superior correlation of the temperature profiles compared to that of the velocity.

The empirical equations for ℓ_V and ℓ_T are compared to those obtained by other investigators in Fig. 8. Note that Alpert and many other investigators have always assumed $\ell_V = \ell_T$, as well as $\delta_{Vmax}=\delta_{Tmax}$, which stems from considering the turbulent Prandtl number, Pr_t, to be 1.0. The equation of You and Faeth [5] in figure 8 is based on Alpert's integral model but for a friction factor of 0.3. Cooper's [13] model is again based on the wall-jet theory and data of Alpert. These models indicate a linear growth of ℓ. Retardation in the growth of the ceiling jet seems to be more reasonable. A significant conclusion from comparison of ℓ_V and ℓ_T is that $\ell_V > \ell_T$. Based on the data presented here, the ratio of ℓ_V/ℓ_T varies between 1.6 to 1.9.

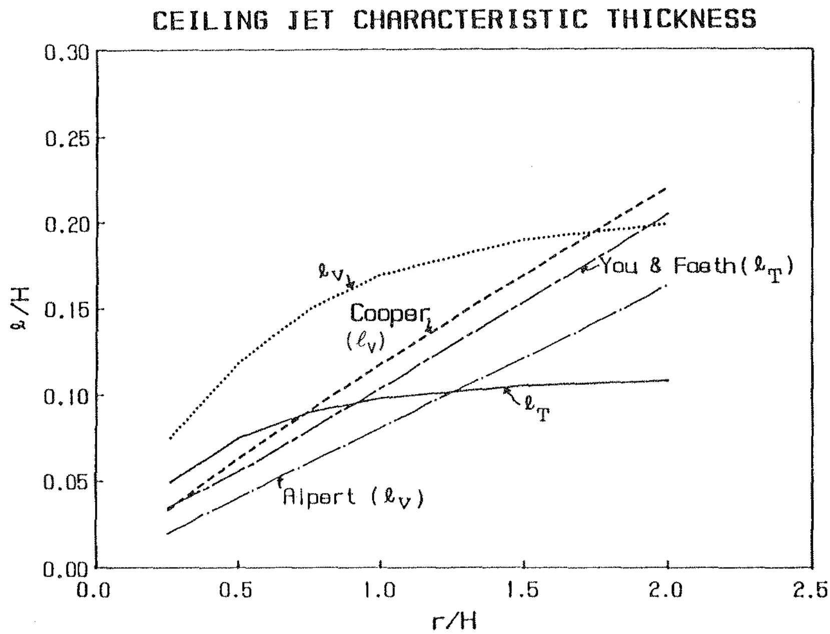

FIGURE 8 - Comparison of models for ceiling jet Gaussian characteristic thickness. Cooper[13], You & Faeth[5] and Alpert[3].

CONCLUSIONS

It was concluded that the wall-jet theory for cold flows is inadequate for the prediction of the ceiling jet velocity specially for the $0.2 \leq r/H \leq 0.5$ region, and it overestimates the maximum velocity and ceiling jet momentum thickness.

The measurements showed that the Gaussian thermal and momentum characteristic thicknesses of the ceiling jet are not equal and are a function of r/H. The boundary layer thicknesses, however, are a function of r alone for Q in the order of tens of kilowatts. The two regimes in the ceiling jet, i.e. near the wall and the free jet portion behave differently where the free jet flow is not strongly effected by the ceiling heating. Differences between the small-scale maximum jet temperature and large-scale data may be due to differences in the heat transfer characteristics and accuracy in determination of the convective heat release rates.

The effect of buoyancy at $r/H \geq 0.75$ becomes very significant and interferes with scaling of the ceiling jet parameters solely based on the fire heat release rate and H.

REFERENCES

1. Glauert, M.B., J. of Fluid Mechanics, 1, pp. 625-643, 1956.
2. Poreh, M., Tsuei, Y.G. and Cermak, J.E., J. of Applied Mechanics, pp. 457-463, 1967.
3. Alpert, R.L., "Fire Induced Turbulent Ceiling Jet", Technical Report, Factory Mutual Research Corp., FMRC Serial No. 19722-2, 1971.
4. Veldman, C.C., Kubota, T. and Zukoski, E.E., Nat'l Bureau of Stds., NBS-GCR-77-97, 1975.
5. You, H.Z. and Faeth, G.M, Nat'l Bureau of Stads., Rpt. No., NBS-GCR-79-188, 1978.
6. Heskestad, G. and Delichatsios, M.A., Proc. of 17th Int'l Symp. on Comb., pp. 1113, The Combustion Inst., 1978.
7. Beyler, C.L., "Fire Plumes and Ceiling Jets", Fire Safety J., 11, pp. 53-75, 1986.
8. Motevalli, V., Marks, C.H. and McCaffrey, B.J., ASME Winter Annual Meeting, 87-WA-HT-16, 1987.
9. Cox, G., "Gas Velocity Measurements in Fires by the Cross-Correlation of Random Thermal Fluctuations - A Comparison with Conventional Techniques", Comb. and Flames, Vol. 28, pp. 155-163, 1977.
10. Motevalli, V., Ph.D. Dissertation, University of Maryland, College Park, MD, 1989.
11. Motevalli, V., Marks, C.H. and McCaffrey, B.J., "Cross-Correlation Velocimetry for Multi-point Velocity and Temperature Measurements in Low-speed, Turbulent, Non-Isothermal Flows", submitted to the J. of Heat Transfer, 1990.
12. Cooper, L.Y., J. Heat Transfer, 104, pp. 446, 1982.
13. Cooper, L.Y., "Ceiling Jet-Driven Wall Flows in Compartment Fires", NBSIR 87-3535, 1987.
14. Alpert, R.L. and Ward, E.J., FMRC J.I. No. 01836.20, Factory Mutual Research Corp., 1982.