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ON THE LENGTH OF FLAMES
UNDER CEILINGS

Research financed by the Swedish Fire Research Board (BRANDFORSK)

Lund, December 1990

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List of symbols

A_f	=	Fuel area
C_p	=	Specific heat
D	=	Burner size
g	=	Acceleration due to gravity
H	=	Height of room
H^*	=	H corrected to represent a virtual source
L	=	Vertical flame length
L_r	=	Horizontal flame length
m_f	=	Mass flow of combustion gases
Q	=	Energy release rate
t	=	Time
T	=	Temperature
T_o	=	Ambient temperature
ΔT	=	Temperature rise above ambient
ν	=	Kinematic viscosity

Summary

Two sets of experimental data on flame length under flat ceilings from a burner in a lower corner of a room have been correlated by conventional dimensionless variables.

The correlations are shown to have considerable similarity to those of temperature distributions under ceilings caused by a heat source below. Matching is effected by a choice of temperature rise of approximately 180°C .

1. Introduction

The lengths "L" of vertical buoyant diffusion flames are most simply correlated by formulae

$$L \sim Q^{2/5} \quad (1)$$

where Q is the heat release rate.

The only independent length in the physical system is "D" the burner orifice size and the approximation $D/L \rightarrow 0$ is implicit.

More generally

$$\frac{L}{D} = \text{Fnc} \left[\frac{Q}{\rho_A C_p T_o D^2 \sqrt{gD}}, \text{ ratios of fuel properties, } \rho_f/\rho_A \right] \quad (2)$$

where ρ is air density
 ρ_f is fuel density at source
 C_p is specific heat
 T_o is ambient temperature
 g is acceleration due to gravity

Whereas Q is conserved above the flame, m_f the mass of injected fuel is the relevant variable before combustion is completed. The Q form however permits closer analogies between flames and noncombusting plumes and draws attention to the early identification by Yokoi (1) of flame length with the distance to a particular isotherm in non-combusting systems and allows us to compare our correlation with those which might be derived from the work of Alpert (2) and Heskestad & Delichatsios (3). The use of " m_f " on the other hand draws attention to the dual role of mass flow " m_f " — the one as the source of thermal energy i.e. Q and the other as determining for a given D, the momentum of the source flow.

For a purely thermal system in a geometric system characterised by dimensions H, B, and C say, we can write, for a particular fuel.

$$\frac{L}{D} = \text{Fnc} \left[\frac{Q}{\rho_A C_p T_o D^2 \sqrt{gD}} \cdot \frac{D}{H} \cdot \frac{D}{B} \cdot \frac{D}{C} \text{ etc} \right] \quad (3)$$

2. Scaling for enclosed flows

For an enclosure with a window other dimensions are required. The height and width of the window, dimensions defining its position as well as the length, width and depth of the enclosure.

Consider a point source in an open corner H below a ceiling but without a floor.

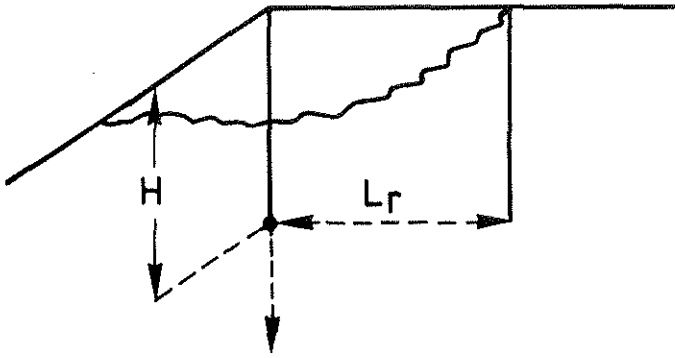


Fig 1.

Here H is the only dimension in the system and we should expect horizontal distances to a given isotherm in similar directions on different scales to be scaled as

$$\frac{L_r}{H} = \text{Fnc} \left[\frac{Q}{\rho_A C_p T_o H^2 \sqrt{gH}} \cdot \frac{\sqrt{gH} \cdot H}{\nu} \right] \quad (4)$$

The second term inside the brackets is a Reynolds number, the ratio of a characteristic turbulent eddy viscosity to the molecular kinematic viscosity ν . Such a variable necessarily must be considered because of the presence of bounding surfaces and the stratification occurring in horizontal flow which dissipates turbulence.

In so far as the assumption can be made that flame lengths scale like distances to isotherms, the above will be appropriate to flame lengths. It should be noted that Babrauskas (4) has recently developed a method of scaling flames under ceilings based on the assumption that flames in different geometric orientations entrain the same quantity of air i.e. their dilution is the same. This is essentially similar in concept to the original analogy between a flame length and distance to an isotherm which is a measure of the degree of dilution.

Now consider a finite source of size D . We shall not distinguish circular from square sources. In general we need to introduce the ratio D/H but it is commonplace in discussing plumes to exploit their boundary layer properties and introduce an addition to H to represent a virtual source. For vertical plumes in free space Taylor (5) estimated this addition to be $1.5\sqrt{A_f}$ where A_f was the source area. Because, in a corner the burner is $1/4$ of the apparent equivalent (see Fig.2) the correction is $3D$. Babrauskas uses $2.9 D$. Heskestad (6) has developed corrections which are dependant on $Q^{2/5}$ to allow for the generation of heat in a flame over a spatial region (and perhaps a momentum effect at the source). Here we follow Taylor and Babrauskas and incorporate the burner size into H and replace H in equation (4) by

$$H^* = H + 3D. \quad (5)$$

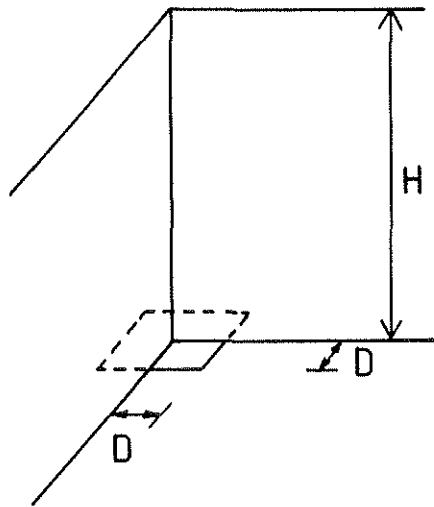


Figure 2

If there is a floor then its distance below the ceiling H_f is also relevant to the flow and H_f/H^* is an additional independent variable.

3. Swedish experiments

A form of the above arguments has been exploited by Babrauskas to calculate flame length data obtained by You and Faeth (7). The agreement is satisfactory. No allowance was made for surface friction and Babrauskas observes that agreement between calculation and experiment is better for larger fires, an observation consistent with there being some effect of friction. However the general agreement found by Babrauskas suggests the effect for the data concerned is secondary.

Hence we propose a scaling law

$$\frac{L_r}{H^*} = \text{Fnc} \left[\frac{Q}{\rho_A C_p T_o H^{*2} \sqrt{g H^*}} \right] \quad (6)$$

as a first approximation.

Andersson and Giacomelli (8) have performed experiments in an 0.8 m high enclosure 1.2 m long x 0.8 m wide with a 0.07 m square burner on the floor and half way up a corner. The values of H^* are 1.01 m and 0.61 m respectively.

Their data are shown in Fig. 3 and to a first approximation

$$L_r \sim Q$$

There is some suggestion of a small discontinuity between 15 KW and 25 KW but the above direct proportionality appears a reasonable summary of their data. Experimentally the ratios of the slopes is 2.05, and based on

$$\frac{L_r}{H^*} \sim \frac{Q}{H^{*5/2}}$$

it should be $\left[\frac{101}{61} \right]^{3/2}$ i.e. 2.13

On the basis of only two flow conditions the about 10% difference is possibly fortuitous. There is however no justification for refining the scaling law without

further data.

Using the scaling law proposed in equation (6) and plotting L_r/H^* versus Q^* gives results shown in Fig. 4. In the figure SW stands for Swedish data (data from Andersson and Giacomelli). Here

$$Q^* = \frac{Q}{\rho_a c_p T_o H^{*2} \sqrt{gH^*}}$$

The best linear fit to the data is

$$\frac{L_r}{H^*} = -0.078 + 24.26 Q^* \quad (7)$$

with a coefficient of determination $r^2 = 0.99$. The constant -0.078 indicates that $L_r = 0$ when Q^* is less than 0.0032. For the experiments mentioned above (where $H^* = 0.73 + 3 D$ and $D = 0.07$) the horizontal flame length under the ceiling is zero if Q is less than 3.2 kW.

4. Experimental data from Gross

Gross (9) measured luminous flame extensions in the corner — wall — ceiling configuration. Combining his data and the Swedish data referred to above and plotting L_r/H^* versus Q^* gives results shown in Fig. 5. Physically we cannot expect positive — or even a zero — L_r when Q^* is zero. The "best" statistical line gives a non-significant positive intercept and the straight line drawn through the data in Fig (5) is

$$\frac{L_r}{H^*} = -0.15 + 25 Q^* \quad (8)$$

However some curvature is apparent at low Q^* as well as a possible discontinuity at about $Q^* \sim 0.07$.

5. Comparison with plume and ceiling jet correlations

Alpert (2) gives the temperature rise at a radial distance "r" from the centre of a plume deflected by a flat ceiling as

$$\Delta T = \frac{5 \cdot 38}{H} (Q/r)^{2/3} \quad \left(\frac{r}{H} > 0.18\right) \quad (9)$$

Heskestad and Delichatsios (3) later, on the basis of additional experiments, gave

$$\Delta T = \frac{T_o \left[\frac{Q}{\rho c T_o H^2 \sqrt{gH}} \right]^{2/3}}{(0.188 + 0.313 r/H)^{4/3}} \quad (10)$$

Following Yokoi's identification of flame length as the distance to an isotherm (or degree of dilution) we replace H by H^* , r by L_r and Q in the above correlation by 4 Q where henceforth Q is heat released in one quadrant. We obtain from equation (9) with $\rho = 1.3 \text{ kg/m}^3$, $C = 1 \text{ KJ/kg}$, $T_o = 300 \text{ K}$ and $g = 9.81 \text{ m/s}^2$

$$\frac{L_r}{H^*} = 4 \frac{(5 \cdot 38)^{3/2}}{(\Delta T)^{3/2}} Q^* (\rho c T_o \sqrt{g}) = \left[\frac{250}{\Delta T} \right]^{3/2} 15 \cdot 6 Q^* \quad (11)$$

and from equation (10)

$$\frac{L_r}{H^*} = \frac{2 \sqrt{Q^*}}{0.313 (\Delta T / T_o)^{3/4}} - 0.60 = 6.39 \sqrt{Q^*} \left[\frac{250}{\Delta T} \right]^{3/4} - 0.60 \quad (12)$$

These are shown in Fig 5.

A good fit is obtained for $Q^* < 0.06$ i.e. $L_r/H^* < 1.2$ with $\Delta T = 180$ in Heskestad & Delichatsios's correlation. It exhibits the curvature referred to above.

Alpert's correlation appears to be closer to the general linear trend with $\Delta T = 180^\circ\text{C}$. It must be noted however that there are two data points responsible for the difference and for both L_r/H^* is 2 or more. This means that L_r is comparable with the length of the experimental facility (1.2 m) and the concept illus—

trated in Fig. 1 is distorted.

These temperatures must be seen as time space averages and accordingly lower than might be expected as representing the end of a stable continuous flame zone. Also correlations for radial flow under a flat ceiling will necessarily be distorted by the translation to flow in a quadrant. Flames tend to be extended near the corner of the wall and ceiling and so, one might expect, a lower temperature to effect matching. Nevertheless the analysis of flames as plumes appears to be extendable to flames under a ceiling.

It is important in discussing correlations using dimensionless variables to test the formulation representing the data.

We have therefore correlated

$$0.6 H^* + L \propto Q_o^m H^{*n}$$

finding

$$m = 0.473$$

$$\text{and } n = -0.158$$

$$\text{i.e. } n - 1 + 5m/2 = -0.063$$

$$\text{viz. } L/H^* + 0.6 \propto Q^{*0.473} H^{*-0.063}$$

The index -0.063 is not significant and the 0.473 is not significantly different from 0.5 so the flame data match the plume data correlation of equation (12).

6. Conclusions

Data for ceiling heights varying from 0.4 to 2.3 m with flames reaching horizontally up to 3 times this distance have been correlated by simple Froude scaling which incorporates a conventional burner size correction and which has a close similarity to established ceiling plume correlations.

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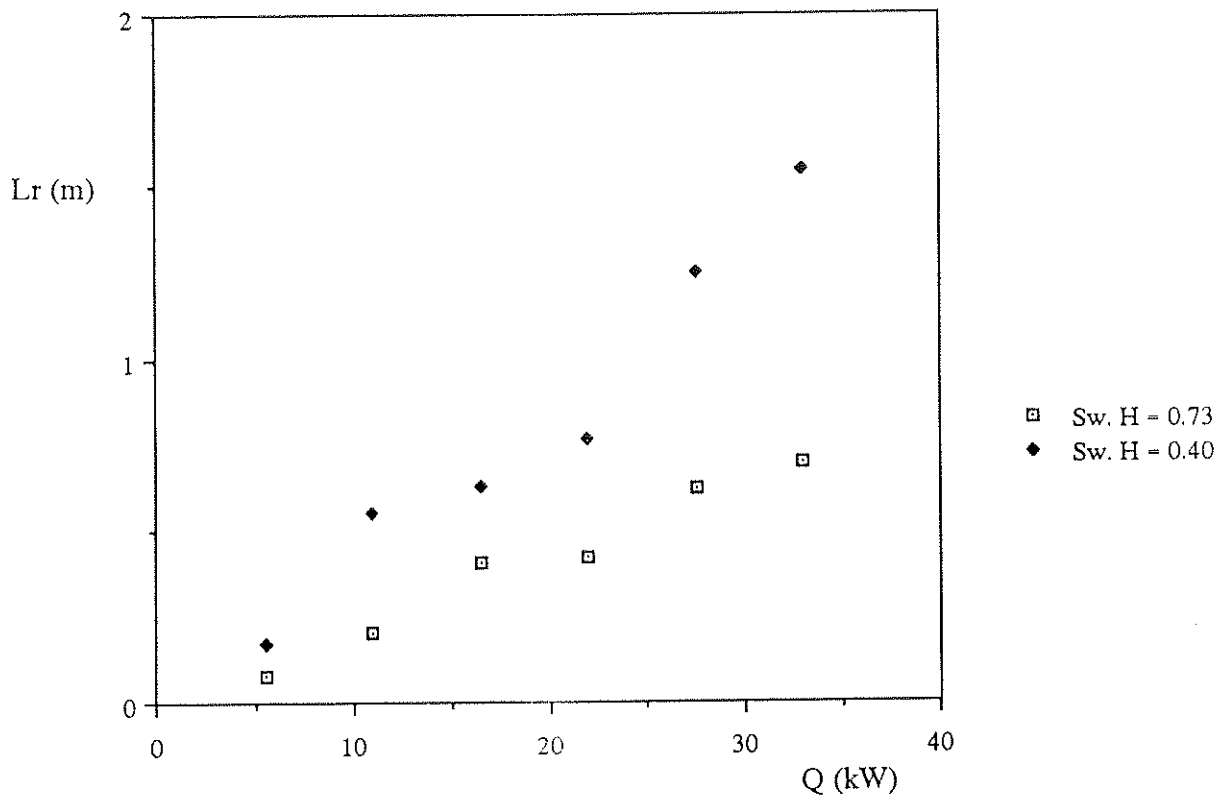


Fig. 3 Flame length under ceiling vs. energy release rate, Swedish data

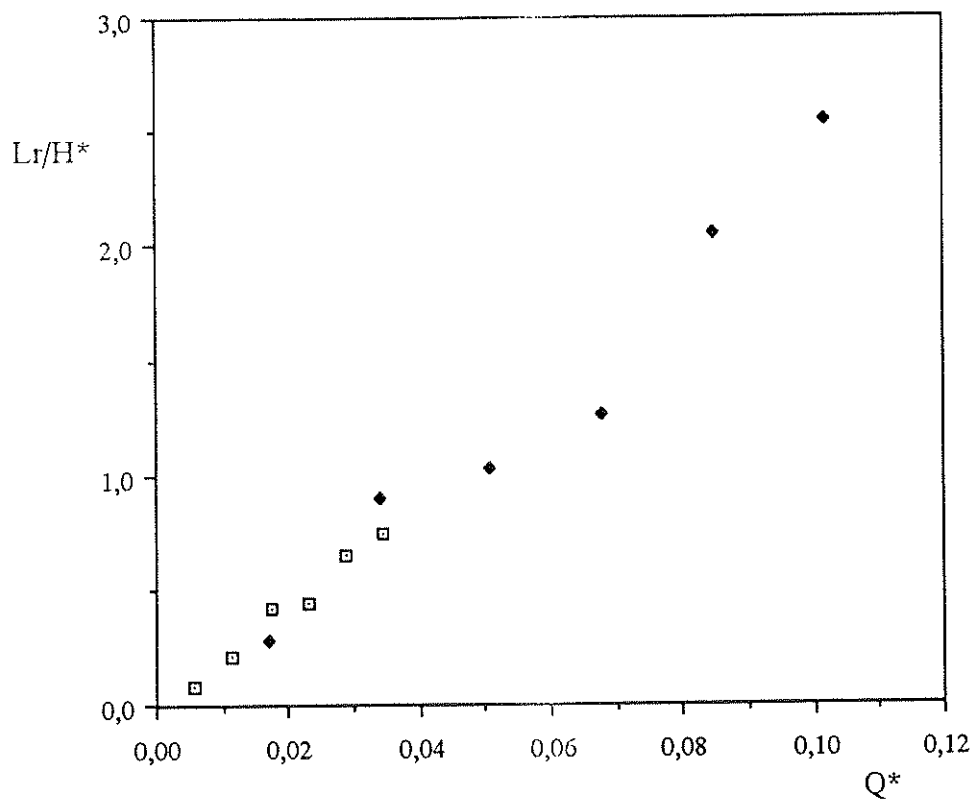


Fig. 4 Correlation of flame lengths under ceiling, Swedish data

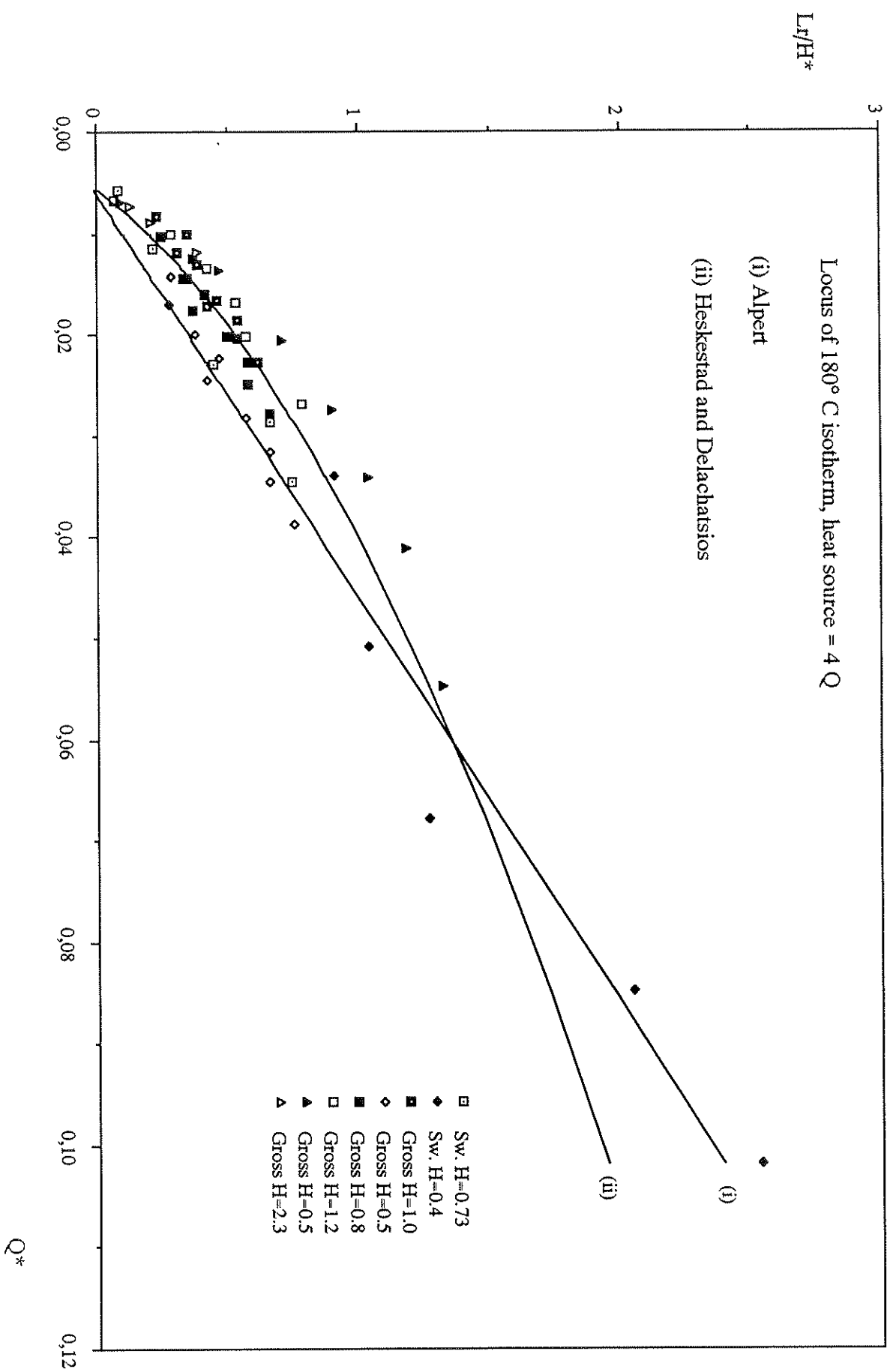


Fig. 5 Correlation of flame lengths under ceilings in a corner configuration