SFPE Classic Paper Review: The Size of Flames from Natural Fires by Philip Thomas*

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LOOKING BACK OVER the prolific contribution that Philip Thomas has made to fire safety science, the paper in Combustion and Flame in 1961 [1] concerning flame length, which was preceded by the brief "letter to the editor" the previous year [2] must rank among his most influential. Using deceptively simple dimensional reasoning, these papers together with the *piece de resistance* presented in Cornell at the 1962 Combustion Symposium and published in its Proceedings the following year [3] laid the foundations for our current understanding of what length of flame we might expect from any given fire.

Thomas explained that rate of fuel flow has a duel significance in determining flame length. On the one hand, it controls the initial momentum of the fuel gases leaving the fuel bed and thereby the physical mixing of the ambient air into the flame and on the other, it controls the quantity of air required by the chemistry of the fuel's combustion.

He argued that flame height, L, in still air, should be related to the fuel flow rate and a characteristic dimension of the fuel bed by a relationship of the form,

$$\frac{L}{D} = f\left(\frac{V^2}{gD^5}\right)$$

*Published in the Proceedings of the Ninth Symposium (International) on Combustion, Academic Press, New York, 1963.

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where V is the volume flow rate of fuel (Thomas used Q at the time but this is now more widely used for heat release rate) and D is a linear horizontal dimension of the fuel bed, the diameter or side length of a square bed.

He further argued that the form of f could be determined from consideration of an "entraining" surface area of the flame and an averaged air entrainment velocity into that flame surface (for buoyancy dominated flame systems $\propto L^{1/2}$). If the surface could be considered to be axisymmetric, then

$$\frac{L}{D} \propto \left(\frac{V^2}{gD^5}\right)^{1/2n+1}$$

where $n=0$, for very short conical flames whose base is the fuel bed and apex the flame "tip", or $n=1$, for cylindrical flames and $n=2$, for truncated conical flames with the smaller diameter at the fuel bed, in the limit as though emanating from a point source. This led to the simple equations currently used by practising fire safety engineers to provide estimates of the hazards to be expected of fire before any enclosure influences the outcome. Of course, Thomas had much to say on the effects of the enclosure, as well as many other issues, but this is not the subject of this particular review.

The $n=2$ case, being independent of fuel bed dimension gives flame length being simply related to $V^{2/5}$, or in current usage $\dot{Q}^{2/5}$ where $\dot{Q}$ is the rate of heat release of the fire.

He was musing on Hottel's description of the large tank fire data of Blinov and Khudiakov referred to in Alpert's recent classic paper review [4]. He was concerned that the fuel momentum in these large tanks was much too low for the fuel to be considered as behaving as a jet. How is buoyancy influencing flame length? A hint was provided by another of Hottel's papers published in the Third Combustion Symposium and co-authored by Hawthorne and Weddell [5]. In that paper, which analyzed both cold and hot momentum-controlled gas jets, a "secondary" correction proportional to $V^{2/5}$ was introduced to account for the effects of buoyancy. In their work, buoyancy played only a minor role but, with natural fires, the relative contributions of buoyancy and momentum were reversed.

The arguments first proposed in the first two papers by Thomas and his co-workers were developed further for the 1962 Combustion Symposium [3]. The analysis was now extended to encompass flame lengths from two dimensional strip sources and from windows, the rates of air entrainment into fires and the effects of wind.

In the Ninth Combustion Symposium, Thomas reports comparisons of experimental determinations of flame length with theoretical formulations based upon the dimensional reasoning presented in his earlier "Letter". These are tested against flames above "axisymmetric" fires from wood cribs, against "strip" fires from a cubical enclosure with one side open and against "strip" fires in a cross wind generated by the large wind tunnel at the Fire Research Station (FRS). For each of these cases, the constant of proportionality and power law dependence of L/D on fuel mass burning rate are established.

The theoretical power law dependency of L/D on V^2/D^5, for axisymmetric buoyant fires, is shown to vary progressively from 1 to 1/3 through to 1/5 as flame shape varies with increasing L/D, or source Froude number (Q^* as we now tend to refer to it). At the time of publication, oxygen depletion calorimetry was not available and measurements involved the use of weight loss from the fuel.

The power law determined from a correlation of measured flame height for Thomas's "axisymmetric" experimental data using wood cribs is 0.61. This covered a range of Q^* from about 0.5 to 5. His data together with those of Gross [6] and Fons [7] were plotted together to support the proposal (Figure 1).

The paper also includes an analysis of air entrainment into a large fire truncated by a ceiling or a smoke layer. This relationship between mass of air entrained and entrainment height is now widely used – or misused in Thomas's view – by many in the fire engineering community particularly in Europe for the design of smoke control systems. The relationship between

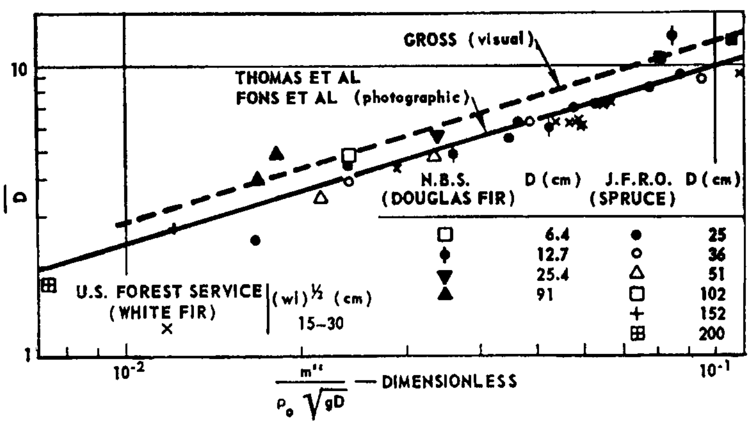

Figure 1. *Correlation of flame height data (m″ is the mass loss rate per unit area of fuel, ρ_0 is the ambient air density – Figure 3 of Reference [3]).*

mass ,$\dot{m}$, of air entrained by a fire of fuel bed perimeter P at a particular height z, now commonly written as;

$$\dot{m} = 0.19Pz^{3/2}$$

can only be valid for the region up to the flame tip but not beyond where it is often used and Thomas has had to write many letters to various editors explaining the physical basis of this relationship.

To derive it, Thomas assumed that the mass entrainment into the flame could be calculated by assuming that the perimeter of the large fire could be taken to be a "curved" line source entraining air only into its outer surface. The rate of entrainment into this surface then being deduced from the measurements of air entrainment made by Rouse et al. [8] but modified to account for the large density difference between flame and ambient. Thomas was here using the then recent results of Ricou and Spalding [9] which had demonstrated that this rate was dependent on excess momentum.

For local axial gas velocity in the fire, Thomas argued that this must be related to $\sqrt{gz}$ and used the measurements of Rasbash et al. [10] to provide the constant of proportionality. With research conducted since, a lower entrainment coefficient would probably be used and a higher proportionality constant in the velocity expression but the function form remains the same for entrainment *below the flame tip*.

This work formed the core of the practical guidance on the role of roof venting to alleviate conditions in buildings in the event of fire [11,12]. Further work on the direct measurement of air entrainment and on the merger of proximate flames was published in the next Combustion Symposium [13].

The fire Research Station was a different place to what it is now, as I write. Scholarly enquiry was much more in demand and this paper is just one of the many in that tradition that can be found in, for example, the collection of selected papers of Phil Thomas published on his formal retirement from FRS in 1986 [14]. A short list of the Fire Research Notes published by Thomas between 1961 and 1964 on this topic is provided at the end of this article after the primary references. Interested readers may also wish to consult Read [15] who provides a glimpse into the history of the FRS.

Thomas has, of course, far from retired from contributing to our understanding of fire as those who read the fire literature will know.

Designing for fire safety is not like designing for a marginally more efficient power station or prime mover where high precision is vital. Getting the physics and chemistry right is more important than seeking a third significant figure. He still is very keen on formulating problems (including solution by CFD) for dimensional analysis and correlation and for showing up limitations in the scope of experiments.

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Phil Thomas joined the UK Civil Service at the Fire Research Station from Cambridge in 1951. He spent a sabbatical year at the Building Research Institute of Japan in 1966 which established a lifelong friendship with the late Kunio Kawagoe. Among his many positions, he Chaired the international standards committee ISO TC92 from 1976 to 1995 and was Co-ordinator of the fire commission of CIB, W14 over roughly the same period. He was also first Chairman of the International Association for Fire Safety Science from 1985 to 1991.