

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

AND

FIRE OFFICES' COMMITTEE

JOINT FIRE RESEARCH ORGANIZATION

FIRE RESEARCH NOTE

NO. 559

**BUOYANT DIFFUSION FLAMES:
SOME MEASUREMENTS OF AIR ENTRAINMENT, HEAT TRANSFER AND
FLAME MERGING**

by

**P. H. THOMAS, R. BALDWIN and A. J. M. HESELDEN
FIRE RESEARCH STATION, BOREHAM WOOD, ENGLAND.**

This report has not been published and should be considered as confidential advance information. No reference should be made to it in any publication without the written consent of the Director of Fire Research.

June, 1964.

Fire Research Station.
Boreham Wood.
Herts.
(phone ELStree 1341)

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

BUOYANT DIFFUSION FLAMES:
SOME MEASUREMENTS OF AIR ENTRAINMENT, HEAT TRANSFER AND
FLAME MERGING

by

P. H. Thomas, R. Baldwin and A. J. M. Heselden
Fire Research Station, Boreham Wood, England

SUMMARY

Thistle-down has been used as a tracer to measure the flow of air towards ethyl alcohol and wood fires 91 cm in diameter and a smaller town gas fire. The total quantity of air below the mean flame height is approximately one order times the stoichiometric requirements, a substantial part of the air flowing upwards around the flame. The total flow also exceeds that estimated from entrainment theory and measurements of flame tip velocity. The mean concentration of oxygen on the flame axis and the heat transfer back towards the fuel surface have also been measured. The convection transfer at 1-2 cm above the fuel surface was found to be about $\frac{1}{5}$ of the total heat transfer at the centre increasing to about $\frac{1}{2}$ at the edge. The measured mean axial temperature rise at the mean flame height was about 300-350 degC for wood and alcohol and 500 degC for town gas. The average period of the eddies outside the flame and the corresponding length were about 0.7 sec and 15 cm respectively. No variation was found with height above the base.

Elementary considerations of entrainment and the motion of flames have been applied to the merging of the flames from two nearby rectilinear fuel beds and there is reasonable agreement between theory and experiment.

BUOYANT DIFFUSION FLAMES:
SOME MEASUREMENTS OF AIR ENTRAINMENT, HEAT TRANSFER AND
FLAME MERGING

by

P. H. Thomas, R. Baldwin and A. J. M. Heselden
Fire Research Station, Boreham Wood, England

Introduction

Flames in freely burning fires, whether in buildings or in the open, have generally a low initial momentum compared with that induced by their buoyancy. Following the work of Hawthorne, Weddel and Hottel⁽¹⁾ for high momentum flames the heights of buoyant flames have been correlated by Thomas et al⁽²⁾⁽³⁾ for a given fuel by equations of the form

$$\frac{L^*}{D} = f\left(\frac{m_F^2}{D^5}\right) \quad (1)$$

and Putnam and Speich⁽⁴⁾ showed that the correlation

$$L^* \propto m_F^{2/5}$$

held for long flames from small diameter burners ($\frac{L}{D} \sim 10-100$). It is not known how these correlations should be extrapolated to the low values of L/D typical of most mass fires, say, beyond the range of 50 m linear size. Theory suggests that Eq. (1) can be described by power laws but the index may be a weak function of the value of L/D . There is some likelihood that a simple power law extrapolation from laboratory experiments, in which there is a continuous flame envelope, overestimates the flame length of large fires where the flame envelope may cease to be continuous over the whole burning area.

Putnam and Speich⁽⁴⁾ and Thomas⁽⁵⁾ have attempted to interpret equations of the above kind quantitatively in terms of the rate of entrainment of air into the rising gases and Yokoi⁽⁶⁾ has treated flames as if they were plumes, obtaining the flame length from the point where the temperature fell to some given value.

The use by Thomas of the concept of entrainment was based on a simple extension of the result obtained from work on plumes⁽⁷⁾⁽⁸⁾⁽⁹⁾ such as has been made for flames with high initial momentum⁽¹⁰⁾. The entrainment constant expressed as a ratio of the sideways flow to the maximum upward velocity is 0.16 for a plume from a line source and where there are substantial density differences it was assumed that this was a ratio of momenta, so that the entrainment constant becomes $0.16 (\rho_F / \rho_A)^{1/2}$

The effective vertical velocity was taken as

$$w = 0.36 \left(\frac{2g\theta_{F,z}}{T_0} \right)^{1/2} \quad (2i)$$

so that the inflow velocity was

$$u = 0.16 \times 0.36 \left(\frac{2g\theta_{F,z}}{T_F} \right)^{1/2} \quad (2ii)$$

and the mean rate of mass flow per unit area into a flame of height L was

$$\begin{aligned} \dot{m}_A &= 0.16 \times 0.36 \times \frac{2}{3} \rho_A \left(\frac{2g\theta_R L}{T_R} \right)^{1/2} \\ &= 0.05 \rho_A \left(\frac{g\theta_R L}{T_R} \right)^{1/2} \end{aligned} \quad (2iii)$$

This equation was used to estimate the air flow into various flames including a flame from a square source under a canopy where each side was treated as one side of a strip source. Putnam has extended this approach to multiple fires⁽¹¹⁾.

Although the quantitative results appear to be reasonably satisfactory there have been few direct measurements of entrainment into flames and none for short turbulent flames. This paper describes experiments where the entrainment into the flames from ethyl alcohol (industrial methylated spirit), and wood (European Redwood (*Pinus sylvestris*)) fires 91 cm in diameter has been directly measured at various heights together with the oxygen concentration in the flames and the thermal feedback to the burning fuel. Some measurements have also been made for town gas burning from a 30 cm square burner. In a second part of the paper the simple concepts of entrainment and the deflection of flames have been applied to the merging of flames from nearby fires.

These measurements and their interpretation are acknowledged to be incomplete but in view of the current interest in the subject these data are presented at this preliminary stage of the study.

Apparatus and measurements

Both the alcohol and wood cribs were burnt in a circular vertical-sided steel tray, 91 cm in diameter surrounded by a circular asbestos wood board, 276 cm in diameter, covered with aluminium foil, in the plane of the top of the tray. For most of the fires, the tray was supported on a calibrated weighing apparatus incorporating a strain gauge; this necessitated a gap of about 1 cm between the tray and surrounding board. In a few of the alcohol fires the burning rate was measured by volume replacement. Most of the wood cribs were made from ten layers of 1.1 cm square section sticks spaced 4 cm apart, alternate layers being laid at right angles and nailed together. Measurements of thermal feedback have also been made for cribs of five layers of 2.5 cm sticks spaced 8 cm apart. The cribs were cut to fit closely within the tray, the top of the crib being about 1 cm below the top of the tray. About 300 ml of kerosine was applied to the lowest layer of sticks so that the whole of the crib could be ignited quickly by a gas poker. Measurements of air flow were made with the alcohol surface 11-14 cm, and heat transfer measurements with the surface 2.5-4 cm, below the tray edge. Oxygen concentrations have been measured for both depths.

Town gas was burnt by passing a measured flow through a horizontal burner 30 cm square formed from a square porous-refractory, surface-combustion heater. An asbestos wood board covered with aluminium foil extended 60 cm around the burner in the same plane.

The velocity of air flowing towards the flame was found by photographing the movement of illuminated thistle-down against a black background. The achene was removed from the pappus of the Creeping Thistle, *Cirsium arvense* (L.) Scop. and the pappus expanded in an oven at about 60°C. These particles were chosen because their low inertia and large surface area enabled them to follow low and varying air currents and they were large enough to show up well in photographs taken at some distance from the flame. They had a terminal velocity of 18 cm/sec, and their horizontal velocity would be effectively the mean horizontal air velocity within a few cms of their release point.

The camera was placed behind a rotating shutter which exposed and covered the lens for alternate periods of 0.11 sec and the film was exposed for about 2 sec just after releasing the thistle down about 1 m from the flame. The time to travel between two points of the image of the trace on the negative, and hence the velocity, were found from the number of interruptions in the trace.

Several particles were released simultaneously and each photograph usually exhibited several long regularly interrupted traces. Photographs were taken and particles released from different positions until a large number of traces covering the region near the flame was obtained. Readings were taken on both sides of the flame to eliminate as far as possible the effect of any systematic draught in the laboratory.

The mean flame height was obtained from other photographs taken at 5 sec intervals over the whole period of the experiments and the upward velocity of the tip of the visible flame was determined from a short cine record.

Gas was extracted from the wood and alcohol flame by a water-cooled probe and, after drying, its volumetric oxygen concentration was determined by means of a paramagnetic oxygen meter.

The temperature at points at 20 cm intervals on the flame axis near to the flame tip was measured by means of six thermocouples.

The downward convection and radiation heat transfer at the base of the alcohol and wood flames were measured with an instrument developed by the Joint Fire Research Organization⁽¹²⁾. The receiving surface was about 1-2 cm above the level of the liquid surface or in the plane of the top of the crib.

Burning rate

Air flow measurements with the alcohol flame were made after a steady burning rate had been attained. There was some variation between runs, the highest burning rate being 13 per cent greater than the lowest.

The rate of burning of the 1.1 cm wood cribs varied during each burn, rising to a maximum at about 3 min after ignition. The rate of burning of the 2.5 cm wood was sensibly constant between 3 and 8 min after ignition. The mean rates of burning, together with the flame heights and other quantities are given in Table 1.

The flame height of the wood cribs calculated from the measured mean burning rate and the relation given by Thomas et al.⁽²⁾⁽⁵⁾ for flames from square fuel beds, was about 60 per cent higher than that measured. In the present experiments the sides of the fuel beds were enclosed, while those from which the correlation was derived had open sides. This difference will be the subject of further study.

AIR FLOW INTO FLAMES

Analysis of data

The turbulent motion of the flame caused fluctuations in the motion of the inflowing air and to find the pattern of the mean air flow it was necessary to obtain as many values of the air velocity as possible over the region of interest. Because it was impracticable once the particles had been released to control the position of each measurement the data were grouped at a number of specified points. A vertical mesh of squares, of 15-cm side including the flame axis, was defined and a mean velocity found for each square from velocities obtained from those parts of the traces falling within the square. Over curved parts of the traces the length and inclination of the straight line joining the beginning and end of each trace within the square were measured. The velocity was then calculated from the known frequency of interruption over the measured length of trace. To investigate the variation of the mean inward velocity with position the mean value found by the system of grouping was taken as representing the mean value at the centre of the 15-cm square; to calculate the volume rate of air flowing into the flame this mean value was taken as the mean velocity over the whole square.

Air velocities

Figure 1 shows the variation in the horizontal component of the air velocity with height at different distances from the axis of the flame, for each fuel, each plotted point being the arithmetic mean of three to sixteen readings. The smooth line is deduced by interpolation from data for other radial and axial positions. The velocities of the air entrained by the alcohol flames show greater scatter about the line than the velocities for the wood or town gas flames, at corresponding distances from the flame axis.

Volume flow of air

Figure 2 shows the variation with distance from the flame of the volume rate of flow through cylindrical surfaces of various heights surrounding and concentric with the flame. This variation has been assumed to be effectively linear; this appears to be valid near the base of the flame although at the tip the variation is almost certainly non-linear. The horizontal volumetric air flow is then constant until it decreases with the radius because of the upward air flow near the flame. However, since the errors are cumulative the results are not sensitive enough to enable the true variation to be found. It is clear from these results that for the larger fires there is a measurable upward air movement on a level with the top of the flame, even at the farthest points for which the measurements were obtained, so that it is not possible to determine the total air flow towards the fire over the whole height of the flame. The results give an underestimate.

The original calculation by Thomas assumed that the effective entrainment surface was pyramidal. However, for these experiments in which a considerable upward flow has been found, it would seem more realistic to compare measured and calculated flows through a cylindrical surface having the same radius as the fuel bed. Values of this flow were estimated from the measurements by extrapolating the data to this surface. The results are shown in Table 2, together with values calculated from Eq. 2(iii) for the same surface which are seen to be about two thirds of the estimates based on measured values. Figure 3 shows the variation of the ratio m_A/m_F with height for different fuels at a distance of 68 cm from the axis, a position for which data are available for each fuel. These curves were obtained from the data in Fig. 2 and were used to draw the lines shown in Fig. 1.

In calculating the m_A/m_F curves an average rate of burning was taken for each fuel. Since the variation in the rate of burning of wood was large, the m_A/m_F ratio for these fires was derived by an additional method, for comparison. The individual velocity readings obtained from the photographs were divided by the instantaneous value of the burning rate and the results grouped and averaged as in the first method. There was little difference between the m_A/m_F curves found by the two processes.

Figure 3 shows that the m_A/m_F curves for wood and alcohol at 68 cm from the flame axis are indistinguishable up to a height of about 70 cm, while the curve for town gas at 68 cm from the axis lies somewhat below them.

Oxygen concentration

The measured concentration of oxygen in the dried gas on the axis of the flame is shown in Fig. 4. An appreciable amount of oxygen is present quite low in the flames, suggesting either that the rate of chemical reaction is slow compared with the rate of mixing of fuel and air, or more probably that even low down in the flame air penetrates to the flame centre in some of the large turbulent fluctuations. The increasing concentration with height within the flame implies that pockets of air mixed with combustion products are present on the axis for relatively longer periods. It will be seen that oxygen penetrates more readily into the flame where the alcohol surface is higher, i.e. where the ullage is less.

Flame tip measurements

The flame tip is defined as the mean position of the fluctuating visible flame zone and its mean height is shown in Table 1, but there is some speculation as to its meaning in relation to other flame variables. It is sometimes defined as the point where sufficient air has been entrained for stoichiometric combustion. However, Table 1 and the m_A/m_F curves show that sufficient air is drawn towards the flame quite low down and it has been shown that oxygen is present near the fuel bed. Yokoi⁽⁶⁾ and Thomas⁽⁵⁾ have defined the flame tip by a certain rise in temperature, and by a simple heat balance this can be associated with an air to fuel ratio.

Thus if $m_T = m_A + m_F$

$$m_T \theta_T c_T = m_F H (1-R)$$

$$\text{Therefore } \theta_T = \frac{m_F H (1-R)}{m_T c_T} \quad (3)$$

The data of Rouse, Yih and Humphries⁽⁸⁾ show that the mean centre line temperature of plumes is given by

$$\theta_T = 1.67 \theta_C$$

and Thomas⁽⁵⁾ has used this in estimating the flame tip temperature assuming that at the top of the flame the horizontal temperature distribution is the same as for a plume. Table 3 shows the temperatures for the different fuels computed from Eq. (3) using the information in Table 1 and the values of m_A/m_F extrapolated to the tray edge assuming $R = \frac{1}{4}$.

Also included are a few previously unreported measurements together with a measurement by Yokoi⁽¹³⁾, and values calculated by Thomas⁽⁵⁾ and Putnam and Speich⁽⁴⁾.

The use of the pyramidal surface by Thomas led to a mean temperature rise of 510 degC at the tip of a flame from a wood fire. This is seen to exceed the values that have now been measured (300-360 degC). If a cylindrical surface is used in calculating the air flow from Eq. 2(iii) the ratio of the air flow to the measured fuel flow leads to a lower value of 290 degC, which is seen to be in good agreement with the measured data. As shown above, there is a difference between the two estimates for the total air flow through a cylindrical surface and this difference, perhaps fortuitously, corresponds to the difference between the burning rate calculated from the flame height and that measured.

Rasbash, Rogowski and Stark⁽¹⁴⁾ have measured the upward velocity of the flame tip during an oscillation for pool fires and Heselden⁽¹⁵⁾ for town gas fires; their results are consistent with the velocity being proportional to the square root of the height⁽⁵⁾. The upward tip velocity has been determined from a cine record of the 91 cm diameter alcohol fires and the results are shown in Fig. 5. These results have been analysed by grouping the data at 15-cm intervals, so that each plotted point is the mean of a number of readings. The velocity is proportional to the square root of height at the top of the flame zone but when the flame tip is near its lowest point the power of the height is greater.

The measured flame tip velocity w from the graph is given by:

$$w = 1.1 (gz)^{1/2}$$

The constant of proportionality 1.1 compares with that of 1.0 obtained from the results of Rasbash et al on which Eq. (2i) was based, and with the value of 0.95 obtained by Heselden. The mean upward velocity of the gases has not yet been determined although the mean inflow can be used to estimate it once a distribution has been assumed. However, it is expected that the time mean upward velocity of gases on the axis will be greater than the flame tip velocity near the base.

Distinction between rising column and flame zone

The flame shape and residence time of the alcohol flames are shown in Fig. 6, the residence time for a given height being the time during which the flame is continuous up to that height. It is clear that there is a marked difference between the mean position of the flame and the surface across which air flow has been measured. Before entering the flame and being destroyed, some of the thistledown particles were conveyed upwards so that all the air measured flowing towards the flame did not enter the flame zone. The allowance made for this in the heat balance was based on the assumption that the distributions of vertical velocity and temperature across the plume at the top of the flame were those eventually established in the plume higher up. Calculated temperatures were too low for wood and town gas and too high for alcohol which suggests that any systematic error in this assumption is masked by other effects.

Measurements were made in the thistledown experiments of the upward component of air velocity around the alcohol flames allowing for the free fall velocity of the thistledown particles; its increase with height at a distance of 76 cm from the flame axis is shown in Fig. 7.

Fluctuation

Some of the particles used as tracers followed a looped path and from these it was possible to measure some of the characteristics of the eddy movements they represented. The average length and period of the eddies, measured as the distance and time between consecutive peaks of the looped path was 14.7 cm and 0.66 sec respectively for the alcohol flames (average of 30 results) and 15.2 cm and 0.71 sec respectively for the wood flames (average of 20 results). These times and lengths did not vary with height in the fifty available measurements.

The period of oscillation of the alcohol flame tip, measured from the cine record was 0.6 sec, which corresponds to the period of the eddies.

HEAT TRANSFER MEASUREMENTS

The heat transfer measurements are given in Table 4. As would be expected both in the alcohol and in the wood flames the radiation fell towards the perimeter of the fire, the decrease being relatively larger in the wood flames probably because they were shorter and the configuration factor of the flame varied more. The radiation at the centre of the tray was some 30 per cent larger for the 1.1-cm wood fires than for the alcohol fires even though the wood flames were some 30 per cent shorter. At 19 cm from the centre of the tray the radiation for the 1.1-cm wood crib was only slightly lower than for the comparable alcohol fires. A higher radiation would be expected for wood fires because of their higher flame emissivity⁽¹⁵⁾.

The measured values of convection transfer in the alcohol flame were lowest at the tray centre, presumably because this was a relatively stagnant low-temperature region, while near the rim hot gases were flowing over the receiver and fuel surface. Because the receiver of the heat-flux meter was between 1 and 2 cm above the alcohol surface the measured convection values are likely to be higher than the actual transfer to the surface particularly towards the rim of the tray where the region of vapour above the liquid surface was thinner than at the centre. At the tray centre the measured

convection component was about $1/5$ of the radiation component, and 8 cm from the tray rim it was about $1/2$. This is in accordance with the view of Hottel(16), and Burgess et al(17)(18), that radiation transfer is the predominant mechanism controlling burning rate for large trays of liquid fuel. Although the radiative and convective components varied, their sum i.e. the total heat transfer was relatively constant over the whole of the surface of the fuel.

The convection transfer in the wood flames was of the same order as in the alcohol flames but it was generally highest at the crib centre. This difference in convection distribution between alcohol and wood cribs (if real and not due to an overestimate of the alcohol convection heat transfer) is presumably related to the different disposition of the fuel, which allows some air to fall into the crib.

A thermocouple on the same level as the heat flux meter and 11 cm from the tray centre recorded temperatures of $500-600^{\circ}\text{C}$ so that the measured convection transfer to the heat-flux meter receiver held at 90°C corresponded to a mean heat transfer coefficient at the tray centre of about $4-5 \times 10^{-4} \text{ cal cm}^{-2}\text{sec}^{-1} \text{ degC}^{-1}$. The corresponding value for the wood cribs was similar.

Although the data are insufficient to permit an accurate correlation to be made of the burning rate of wood and the total downward heat transfer a comparison of the results suggests that for comparable burning rates the heat transfer from the flame to the 1.1-cm wood crib was at least 50 per cent greater than that for the 2.5-cm wood crib which was equivalent to 200 cal/g. This difference implies that the burning rate of these cribs was not controlled entirely by heat received from the flame above the crib.

The heat transfer to the alcohol corresponded to a value of 360 cal/g for the heat required to evaporate alcohol which is higher than the calculated increase in enthalpy of ethyl alcohol between liquid at room temperature and vapour at the boiling point (about 250 cal/g). This may to some extent be due to an overestimate of the radiation transfer since the heat-flux meter receiver was 1-2 cm above the liquid surface and some radiation may be absorbed in the alcohol vapour just above the surface. The convection component mentioned earlier might also have been overestimated.

DISCUSSION

It was not possible to estimate the total amount of air moving towards the upper part of the flame because measurements could not be made far enough away from the flame outside the region where there was some upward movement. Even so, the measured amount of air is considerably in excess of the stoichiometric requirements and a considerable part of it does not enter the flame zone but is dragged upwards outside the flame.

Calculations of the air flow into the flame zone itself, based on Eq. (2), and the approximation that the flame zone is a cylinder with a diameter equal to the burner, give air flows about $2/3$ of those measured.

Ricou and Spalding(19) have correlated $\left(\frac{m}{m_F}\right) F^{-1/2}$ with $\frac{z}{D} \left(\frac{\rho_A}{\rho_F}\right) F^{-1/2}$ where F is a Froude Number including an allowance for the initial momentum and the heat released in combustion but our data lie outside the range of values correlated by this method. They based their correlation for radially symmetrical plumes on the equation.

$$\frac{dm}{dz} = 0.282 (\rho_A M)^{1/2}$$

where M was taken as the local momentum at the height z . However, values of $\frac{dm}{dz}$ obtained from our data are much more constant with z than is $M^{1/2}$. A part at least of this difference probably arises because the above relation is inappropriate when mixing is not complete across a horizontal section as in the potential core of a jet. In the lower part of a flame

the vertical velocity is probably greater near the edge where reaction is occurring than in the centre, and mixing would be expected to be related to the properties of the flow near this edge rather than to those of the section as a whole.

This demonstrates one of the limitations to the concept of entrainment, i.e. if it is generally physically valid it must be related to readily identifiable and definable velocities and boundaries - a difficulty partly responsible for the difference between the air flow measured as moving towards the flame and that actually entering the flame zone.

A second limitation is inherent in the assumptions made in justifying the use of an entrainment constant. The only velocity to which the sideways velocity can be proportional is the local vertical velocity and not only may the constant of proportionality be dependent on the shape of the velocity distribution across the section but also on any other dimensionless parameter so that the ratio of pressure head gradient to velocity head gradient is also, in principle, a factor. Pressure gradients are conventionally neglected in plumes and jets and insofar as they affect entrainment will be neglected in the discussion of merging flames below, but it is known that the flow of air into a fire inside an enclosure with, say, one window is determined by the pressures induced by the "chimney effect" when the window is small. As the windows become larger this chimney effect becomes less and eventually the flow approximates to that in the open where the concept of entrainment would seem to be appropriate.

The use of an entrainment relation for flames where the boundary across which the entrainment is calculated is identified with the boundary of the visible flame is, at best, an approximation; and any theory for these flames must take this into account as well as providing a rational criterion for determining the height of the flame.

The main conclusion from this work so far is that the amount of air flowing towards the fire and the extent of the penetration of oxygen to the axis of the flame are more than previously estimated from theory based on analogy with plumes. The heat transfer for these experimental fires is mainly by radiation.

MERGING FLAMES

Whilst the properties of flames from one isolated fuel bed are still inadequately known it is desirable in many practical situations to have some knowledge of the behaviour of flames from a number of nearby fuel beds. Putnam and Speich⁽²⁰⁾ have measured the increase in flame length for various arrangements of different numbers of fires from effectively point sources, but there are very little data for fires with relatively short flames. The height of the flames from a single fuel bed has been related to the burning rate by equations of the form of Eq. (1). However, where there are two or more nearby flames, the flame height L will also be a function of S , where S is characteristic of the separation between the beds. Thus

$$\frac{L}{D} = f_1 \left(\frac{m_F^2}{D^5}, \frac{S}{D} \right) \quad (4i)$$

where f_1 is a function of the number of fuel beds and their orientation one to the other. Equations (1) and (4i) can be combined to give

$$\frac{L}{L^*} = f_2 \left(\frac{L^*}{D}, \frac{S}{D} \right) \quad (4ii)$$

The multiple fire problem is complex and, for a first analysis, a considerably simplified model is necessary. Here only two nearby fires burning at a constant rate are considered. Experiments have been conducted to measure the separation S of the two fuel beds and the flame heights when the flames have just merged and these measurements compared with a simplified theory. Because a theoretical model of multiple fires has to take into account the complexities of their arrangement and the interaction between them, the description of each single fire must be as simple as possible.

Equation (2) has previously been used to estimate the flow of air into the flame zone, but as yet no direct confirmation has been obtained of its accuracy. It gives about $\frac{2}{3}$ of the measured flow towards the fire for the experiments described above but some of this air does not enter the flame zone. Air cannot be said to flow upwards outside the flame on the inner sides of merging flames. In view of these and other uncertainties the air entering the flame is calculated by Eq. (2): this should be expected to give results of the right order.

Theory

A column of hot rising gases entrains air from its surroundings, so that when a flame is placed in the neighbourhood of another, the resulting restriction of the air flow causes a pressure drop in the space between the two. The flames are thus deflected from the vertical, the greatest deflection occurring where the pressure drop is greatest. Consider two rectangular horizontal fuel beds on a continuous horizontal surface, the long sides being parallel as shown in Fig. 8. Suppose the two flames, height L , are just merging. If the radius of curvature of each flame is large compared with its length we may take the axis of the flame as straight. Then the only forces acting on the flames, other than the viscous forces and the upward thrust from the burner, which are generally both negligible in actual fires, are the buoyancy B upwards, and a resultant pressure thrust P acting normal to the axis. Let each axis be inclined at angle ϕ to the vertical. Then resolving normal to the axis

$$B \sin \phi = P \quad (5)$$

The buoyancy force is due to the density differences between the flame and its surroundings and acts on a column of hot gases of width D , say. Consider an element of the plume of hot gases of volume δV in a plane perpendicular to the long side of the rectangle, height L , width D . Then

$$B = \int_{\delta V} \rho_r \frac{\theta}{T_0} g \, dV$$

If as a first approximation θ is assumed constant over the height of the flame, and over the width D

$$B \doteq \rho_r \frac{\theta}{T_0} g \, LDW \quad (6)$$

When the flames are touching, air flows down a channel whose cross section is approximately triangular and if u is the average velocity of the air flowing into the ends of the channel

$$\frac{SLu}{2} = W \int_0^L v \, dz \quad (7)$$

It will be assumed that entrainment is unaffected by the pressure drop on one side of the flame or by the leaning of the flames. This assumption is not expected to be true for all situations involving a group of fires, but is probably a reasonable first approximation in the situation under discussion.

From Bernoulli's equation and Eq. (2) the pressure drop, for small values of S/W is

$$p = \frac{1}{2} \rho_A u^2 = \frac{1}{2} \rho_A \left(\frac{4W}{3S} \right)^2 (0.16 \times 0.36)^2 2g \frac{\theta_{fl}}{T_{fl}} L \quad (8)$$

$$= (0.077)^2 \rho_A \frac{W^2}{S^2} \frac{\theta_{fl}}{T_{fl}} gL$$

The pressure thrust on each flame for small values of ϕ is then given by

$$P = (0.077)^2 \rho_A \frac{W^3}{S^2} \frac{\theta_{fl}}{T_{fl}} gL^2 \quad (9)$$

When the flame tips are touching

$$\sin \phi = \frac{S}{2L} \quad (10)$$

Substituting Eq. (6) (9) and (10) into (5) we obtain

$$\frac{W^2 L^2}{S^3 D} = \frac{\rho_{fl}}{\rho_A} \frac{T_{fl}}{T_A} \frac{1}{2} \left(\frac{1}{(0.077)^2} \right)$$

or, since $\frac{\rho_{fl}}{\rho_A} = \frac{T_A}{T_{fl}}$

$$\frac{L}{D} = 9 \left(\frac{S^3}{DW^2} \right)^{\frac{1}{2}} \quad (11)$$

Experimental

Burners 60 x 30 cm and 30 x 30 cm comprising surface-combustion radiant panels 30-cm square supplied with town gas were each arranged horizontally in pairs and the space between and surrounding the two burners was filled in to provide a continuous flat surface between them. The flame height and separation were varied and the condition when the flames just merged was determined. From these experiments $L/L^* \sim 6/5$ when the flames were just merging. These results are plotted in Fig. 8 together with the theoretical curve of Eq. (11). Also included is an observation from a large timber fire at Southall, Middlesex, in which flames from two stacks of timber, 150 ft x 40 ft, separated by a 20 ft gangway, merged at 50 ft. These flames were probably fully merged and therefore this result gives a lower limit for S : it demonstrates that the flame height predicted by theory is realistic. For this fire

$$W/D = 15/4; \quad L/D = 5/4; \quad S/D = 1/2$$

For long flames from small burners ($L/D \gg 1$) Eq. (4) would not be expected to include D i.e. L/L^* will be a function of L/S only, and Putnam and Speich have presented data for long flames in this way. The approximations made above in deriving Eq. (11) do not apply when S/D is large, but the effective

characteristic dimension for a long flame should be some fraction of L instead of D or W ; from Eq. (11) the condition of merging would then be

$$L/S = K$$

where K is a constant

Taking an effective mean diameter for the flame of order $L/20$ gives $K = 12$; for $L/10$, K is reduced to 9.

With nozzles 0.371 in. in diameter and comparatively long flames Putnam and Speich⁽²¹⁾ have measured the increase in height of the flames from two burners for two different separations, 2 in and 4 in; as the gas flow, and thus the single flame height was increased. The data were presented in a graph as L/L^* plotted against L^*/S ; taking L/L^* as 1.2 for the criterion of merging in the experiments by Putnam and Speich, L^*/S was found by interpolation to lie between 20 and 25. This is about twice the expected value of K but there is a factor of 30 between the values of L/D of the Joint Fire Research Organization and those of Putnam and Speich. Their data are shown in Fig. 8 with $S = 2$ in, $D = 0.371$ in and $129 < L/D < 161$. If the condition of merging for two long flames can be taken as a constant ratio of L/S the slope of the line shown in Fig. (8) must decrease as L/D increases and it is desirable to obtain data in the region $10 < L/D < 100$.

Discussion

Certain limitations must be imposed on the experimental results reported above.

1. Small flames tend to be non-turbulent particularly in the lower part of the flame so that theory over-estimates entrainment, and hence the pressure drop between the flames. Also the estimated pressure drop is too high when small flames from each burner become discontinuous.
2. The gas burners tend not to burn evenly over their entire area at very small gas flows so that the separation between the flames is then strictly larger than that measured between the burners.

The calculation gives reasonable estimates of the separation producing merging between two flames. Extrapolating the results obtained by Putnam and Speich to smaller values of L/D would considerably underestimate the separation producing merging when L/D is less than 10. This is because D , the linear dimension of the fuel bed, is an important factor influencing the merging when L/D is not large.

Attempts are being made to extend this approach to more complex situations.

Notation

B	Buoyancy force
c	Mean specific heat of combustion products, taken as $0.26 \text{ cal g}^{-1}\text{degC}^{-1}$
D	Dimension characteristic of burning zone e.g. tray diameter
F	Froude number used by Ricou and Spalding ⁽¹⁹⁾
f, f_1, f_2	Unspecified functions
g	Acceleration due to gravity
h	Height from rim of tray and baseboard (cm)
H	Net calorific value of volatile fuel (cal/g)
L	Flame height (cm)
K	Constant
M	Momentum flux
m	Mass rate of flow (g/sec)
P	Force on flame due to pressure difference
p	Pressure difference
R	Fraction of heat generated by combustion lost by radiation from flame
S	Separation between fuel beds (cm)
T	Absolute temperature ($^{\circ}\text{K}$)
u	Mean velocity of air entering channel between two flames (cm/sec)
V	Volumetric flow at ambient temperature and pressure (l/sec)
\bar{u}	Mean entrainment velocity (cm/sec)
W	Length of long side of fuel bed (cm)
w	Mean upward tip velocity (cm/sec)
z	Height (cm)
θ	Temperature rise (degC)
ρ	Density (g/cm^3)
ϕ	Inclination to vertical

Subscripts

A	Air
C	Central vertical axis of flame
F	Fuel
fl	Flame
O	Ambient
T	Flame tip (mean across plume)

Superscripts

"	Per unit area
*	Flame from an isolated fuel bed

Acknowledgments

The work described in this paper forms part of the programme of the Joint Fire Research Organization of the Department of Scientific and Industrial Research and Fire Offices' Committee; the paper is published by permission of the Director of Fire Research.

The authors wish to thank Mr. G. H. Wraight for assisting with the experiments and Mr. E. Jackson for his photographic services.

References

1. HAWTHORNE, W. R., WEDDEL, D. S., and HOTTEL, H. C. Third Symposium (International) on Combustion, p.282, Williams and Wilkins, Baltimore, 1949.
2. THOMAS, P. H., WEBSTER, C. T., and RAFTERY, M. M. Combustion and Flame 5, 359, (1961).
3. THOMAS, P. H. Combustion and Flame 4, 381, (1961)
4. PUTNAM, A. A. and SPEICH, C. F. A model study of the interacting effects of mass fires. Battelle Memorial Institute Research Report. Columbus, Ohio, November 9th, 1961.
5. THOMAS, P. H. Ninth Symposium (International) on Combustion, p.844 Academic Press, New York, 1963.
6. YOKOI, S. Japanese Ministry of Construction. Building Research Report 34, (1960).
7. TAYLOR, G. I. U.S. Atomic Energy Commission MDDC-919 LADC-276 (1945).
8. ROUSE, H., YIH, C. S. and HUMPHREYS, H. W. Tellus, 4, 201, (1952).
9. MORTON, B. L., TAYLOR, G. I. and TURNER, J. S. Proc. Roy. Soc. A., 234, 1, (1956).
10. THRING, M. W. and NEWBY, M. P. Fourth Symposium (International) on Combustion, p.789, Williams and Wilkins, Baltimore 1953.
11. PUTNAM, A. A. Combustion and Flame, 7, 305, (1963).
12. HESELDEN, A. J. M. Joint Fire Research Organization Fire Research Note. (To be issued).
13. YOKOI, S. Japanese Ministry of Construction. Building Research Institute Occasional Report No. 12, 1963.
14. RASBASH, D. J., ROGOWSKI, Z. W. and STARK, G. W. V. Fuel, 35, (1956).
15. HESELDEN, A. J. M. Unpublished Data.
16. HOTTEL, H. C. Fire Research Abstracts Revs. 1, 41, (1958).
17. BURGESS, D. S., STRASSER, A. and GRUMER, J. Fire Research Abstracts Revs. 3, 177, (1961).
18. BURGESS, D. and GRUMER, J. Comments on "The burning rate of liquid fuels from open trays by natural convection" by D. B. Spalding Fire Research Abstracts Revs. 4, 236, (1962).
19. RICOU, F. P. and SPALDING, D. B. J. Fluid Mech., 11 (Part 1) 21, (1961).
20. PUTNAM, A. A. and SPEICH, C. F. Ninth Symposium (International) on Combustion p. 867, Academic Press New York, 1963.
21. PUTNAM, A. A. and SPEICH, C. F. A model study of the interacting effects of mass fires. Battelle Memorial Institute Summary Report No. 2. March 27th, 1963.

Table 1
Data for flames and fuel

	Fuel				
	Alcohol		Wood		Town gas
	Surface 11-14 cm below tray edge (Air flow measurements)	Surface 2 5-4 cm below tray edge (Heat transfer measurements)	1.1 cm stick thickness	2.5 cm stick thickness	
Shape of flame base	Circular	Circular	Circular	Circular	Square
Base dimension (cm)	91 (Diam.)	91 (Diam.)	91 (Diam.)	91 (Diam.)	30 (Side)
Mean burning rate (g/sec)	19	17	15	12	9
Mean burning rate (mm/min)	2.2	2.0	-	-	-
<u>Mean burning rate</u>					
Tray area (mg cm ⁻² sec ⁻¹)	2.9	2.6	2.3	1.8	10
Mean flame height (cm)	150	170	105	90	190
Net calorific value (cal/g)	6,400		2,500 to 3,500 (Volatiles only)		6,700
Stoichiometric air/fuel ratio (mass units)	9.1		4.0 to 4.5		8.4

Table 2
Volume flow of air

	Measured flow (V ₁) l/sec	Calculated flow l/sec		$\frac{V_3}{V_1}$
		Conical entrainment surface (V ₂)	Cylindrical entrainment surface (V ₃)	
Alcohol	1210	395	790	0.65
Wood	750	230	460	0.62
Town gas	520	185	370	0.72

Table 3
Flame tip temperature

Fuel	Source	m_A/m_F (extrapolated to tray edge radius)	Mean temperature rise across plume at flame tip (calculated) deg C	Axial flame tip temp- erature rise (calculated) deg C	Axial flame tip temp- erature rise (measured) deg C
Alcohol	JFRO (a)	75	245	410	320
Wood	JFRO (a)	60	120-165	200-280	320-360
	JFRO (b)	-	-	-	300
	Yokoi (c)	-	-	-	300
	Thomas (5)	-	-	510	-
Town gas (high proportion of coal gas)	JFRO (a)	~ 70	~ 275	~ 460	500
City gas (high proportion of methane)	Putnam and Speich (4)	-	-	340	-

(a) Present experiments.

(b) Previously unreported experiments with 30-cm square wood cribs.

(c) Experiments with 20-cm square wood cribs by Yokoi (13).

Table 4

Heat transfer measurements

Fuel	Distance of heat-flux meter receiver from tray centre cm	Burning rate for whole fuel surface g/sec	Mean flame height cm	Mean downward heat transfer* cal cm ⁻² sec ⁻¹			Number of Readings
				Radiation	Convection	Total	
Alcohol	0	17	170	0.79	0.16	0.95	7
	19	17	170	0.82	0.22	1.04	4
	38	17	170	0.57	0.29	0.86	5
Wood crib 1.1-cm stick thickness	0	17	120	1.09	0.24	1.33	1
		11	110	1.03	0.12	1.15	1
	19	15	95	0.68	0.06	0.74	1
		14	110	0.79	0.15	0.94	1
		10	110	0.65	0.13	0.78	1
Wood crib 2.5-cm stick thickness	0	7	70	0.24	0.07	0.31	1
		12	90	0.52	0.18	0.70	4
		12	90	0.37	0.11	0.48	8
2.5-cm stick thickness	38	12	90	0.15	0.13	0.28	4

*The standard deviation of one reading was about 0.1 cal cm⁻²sec⁻¹ for radiation heat transfer and about 0.05 cal cm⁻²sec⁻¹ for convection transfer.

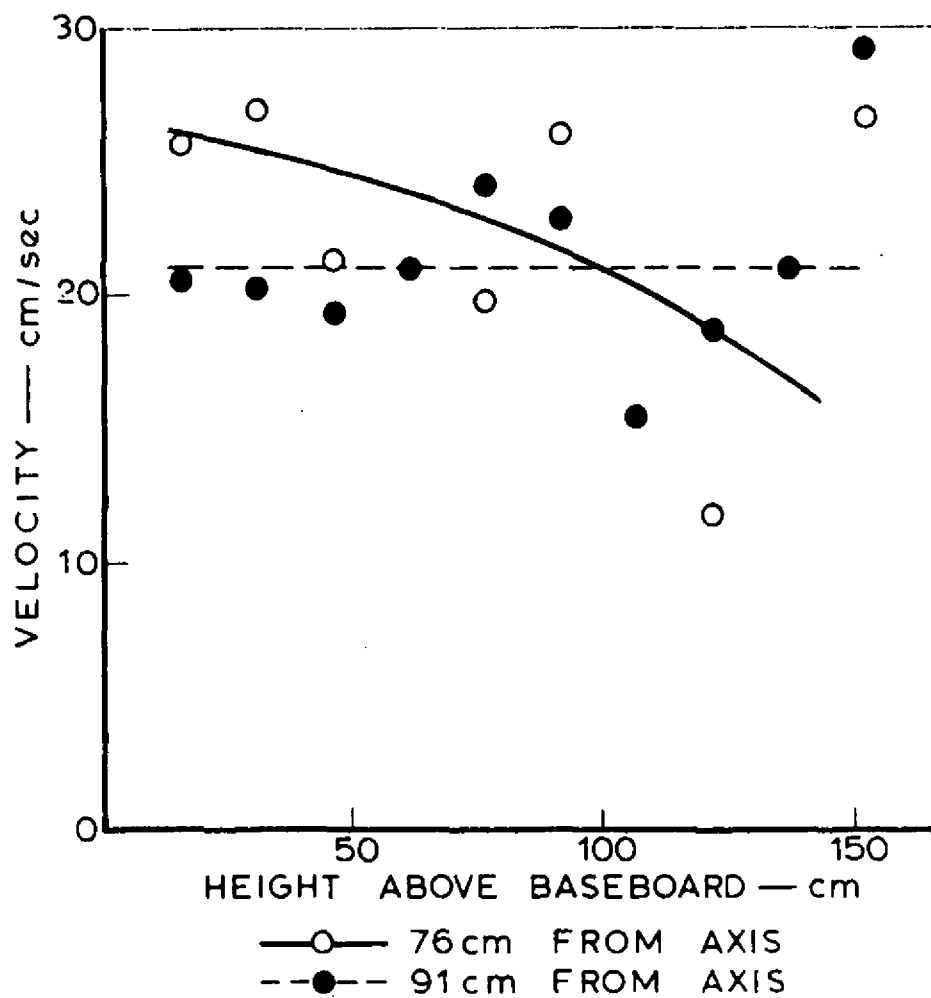


FIG. 1a. ALCOHOL FLAME — HORIZONTAL COMPONENT OF VELOCITY (Points are averages of 3-16 values at one radial distance, lines are interpolated from other radial distances and heights)

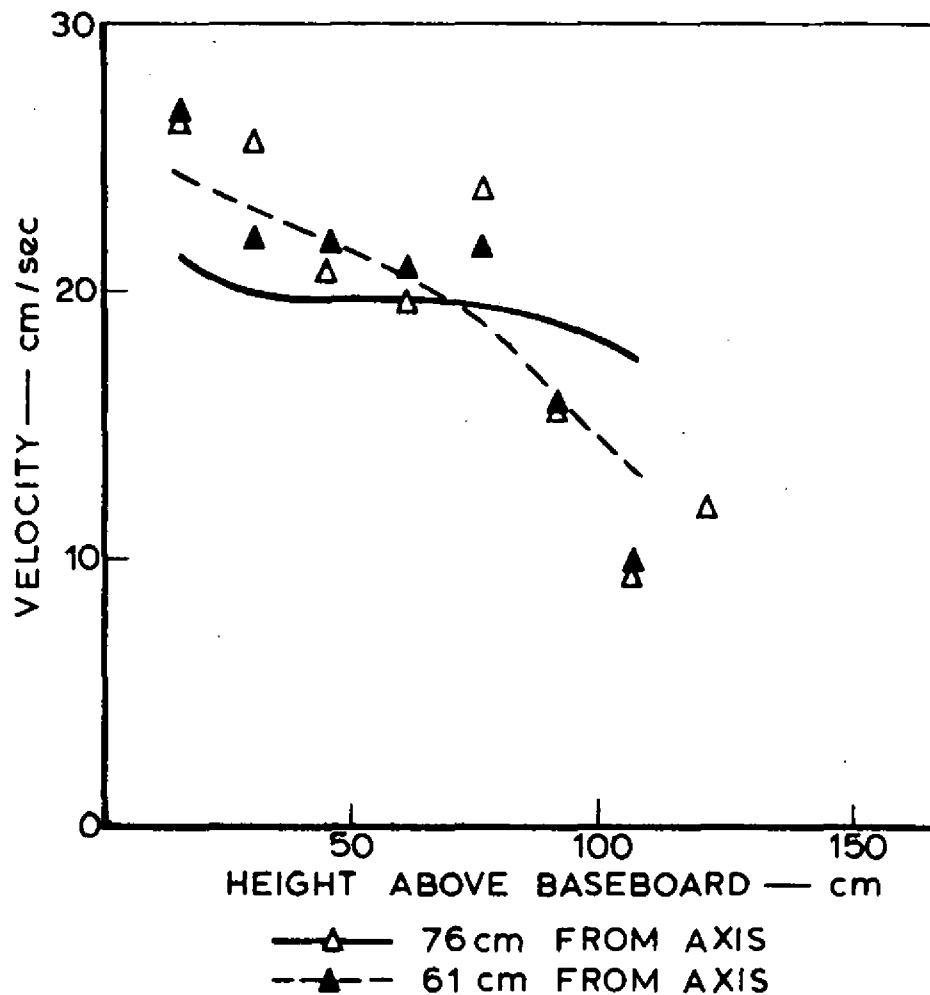


FIG. 1b. WOOD FLAME — HORIZONTAL COMPONENT OF VELOCITY
(Points are averages of 3-16 values at one radial distance, lines are interpolated from other radial distances and heights)

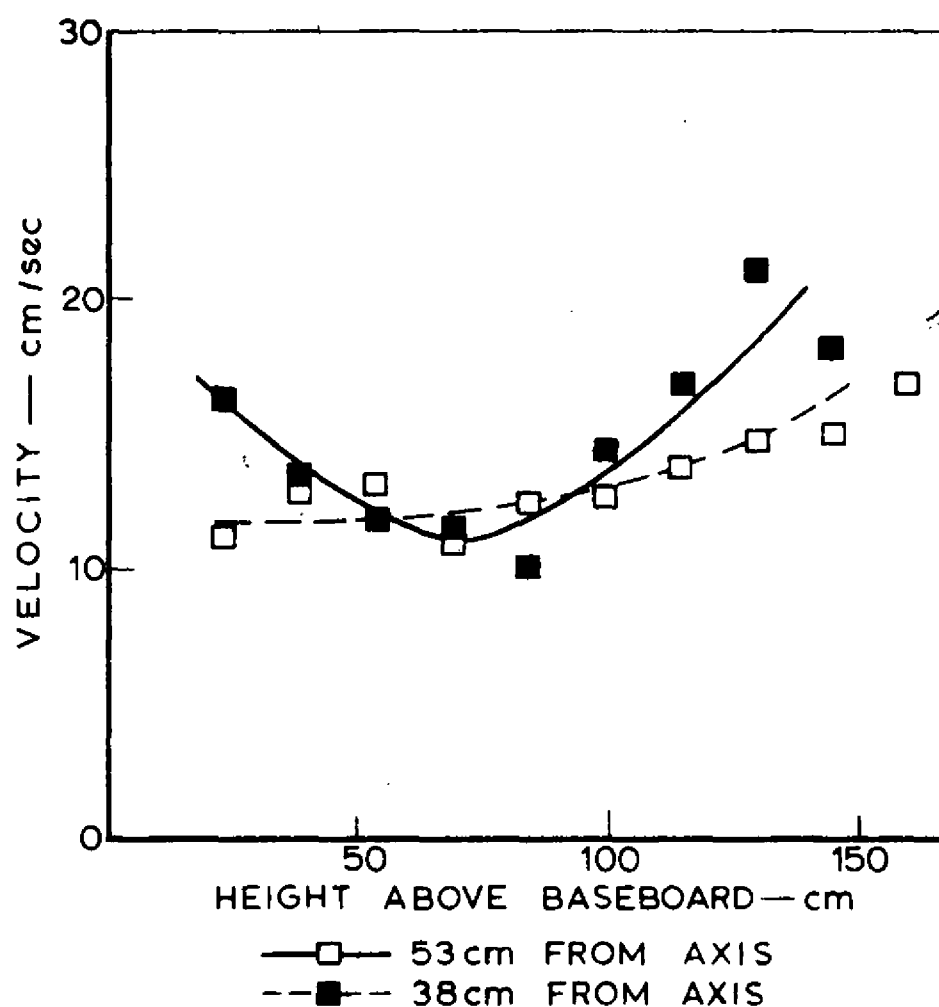


FIG. 1c. TOWN GAS FLAME — HORIZONTAL COMPONENT OF VELOCITY

(Points are averages of 3-16 values at one radial distance, lines are interpolated from other radial distances and heights)

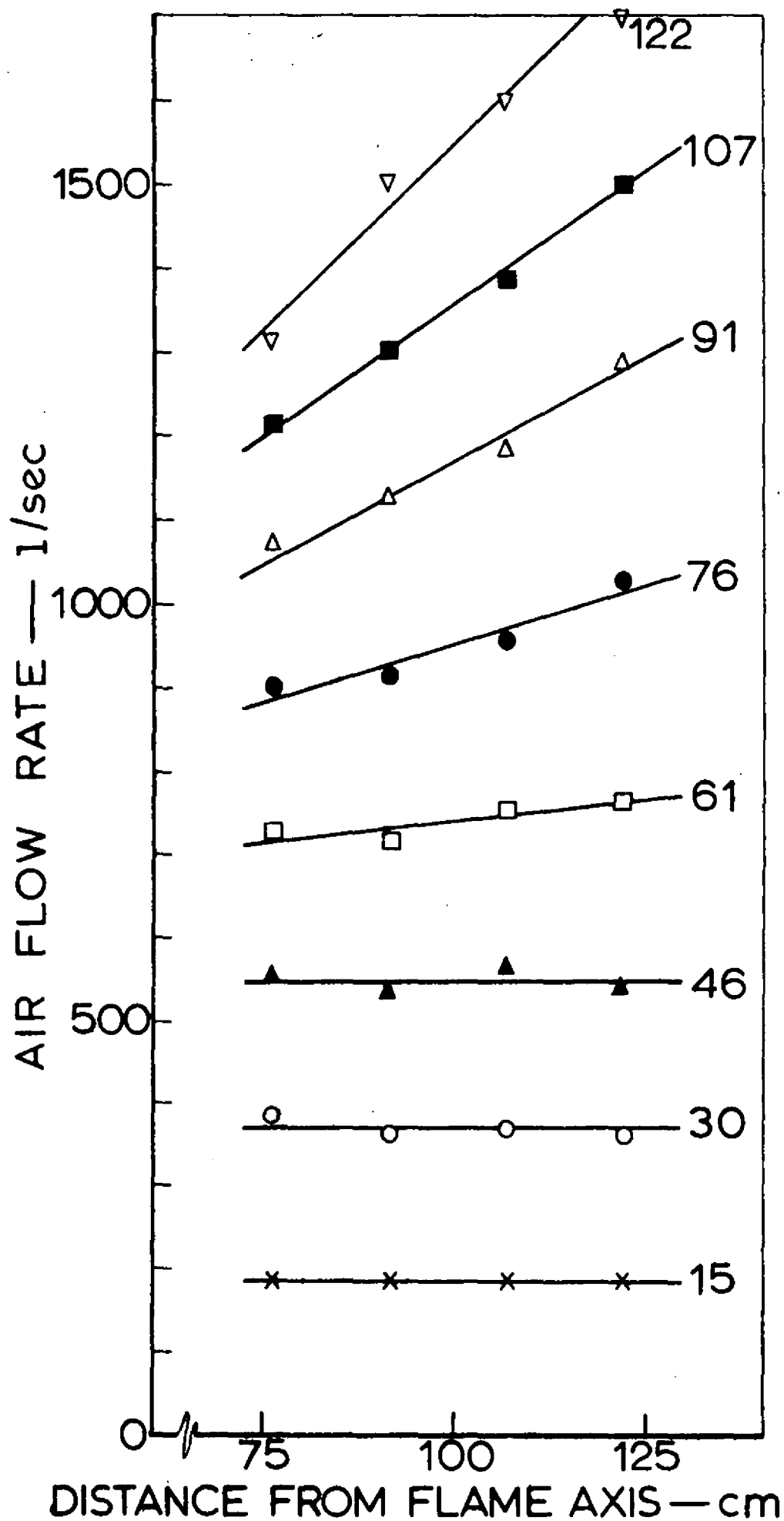


FIG. 2a. ALCOHOL FLAME — VOLUMETRIC AIR FLOW (AMBIENT TEMPERATURE AND PRESSURE) THROUGH CYLINDRICAL SURFACES OF HEIGHT (h) CONCENTRIC WITH THE FLAME. (The numbers against each line are the values of (h) in cm)

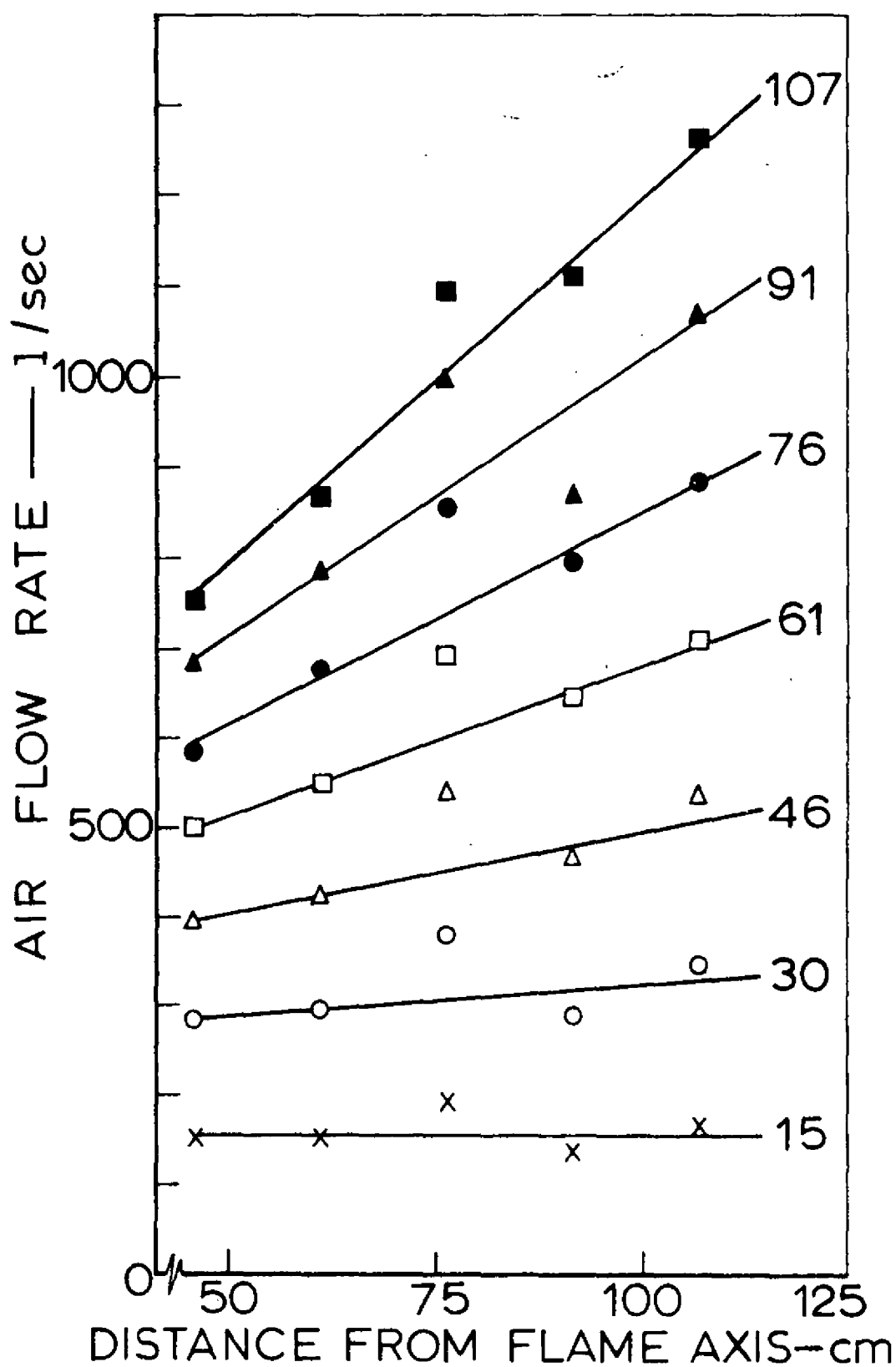


FIG. 2b. WOOD FLAME — VOLUMETRIC AIR FLOW (AMBIENT TEMPERATURE AND PRESSURE) THROUGH CYLINDRICAL SURFACES OF HEIGHT (h) CONCENTRIC WITH THE FLAME. (The numbers against each line are the values of (h) in cm)

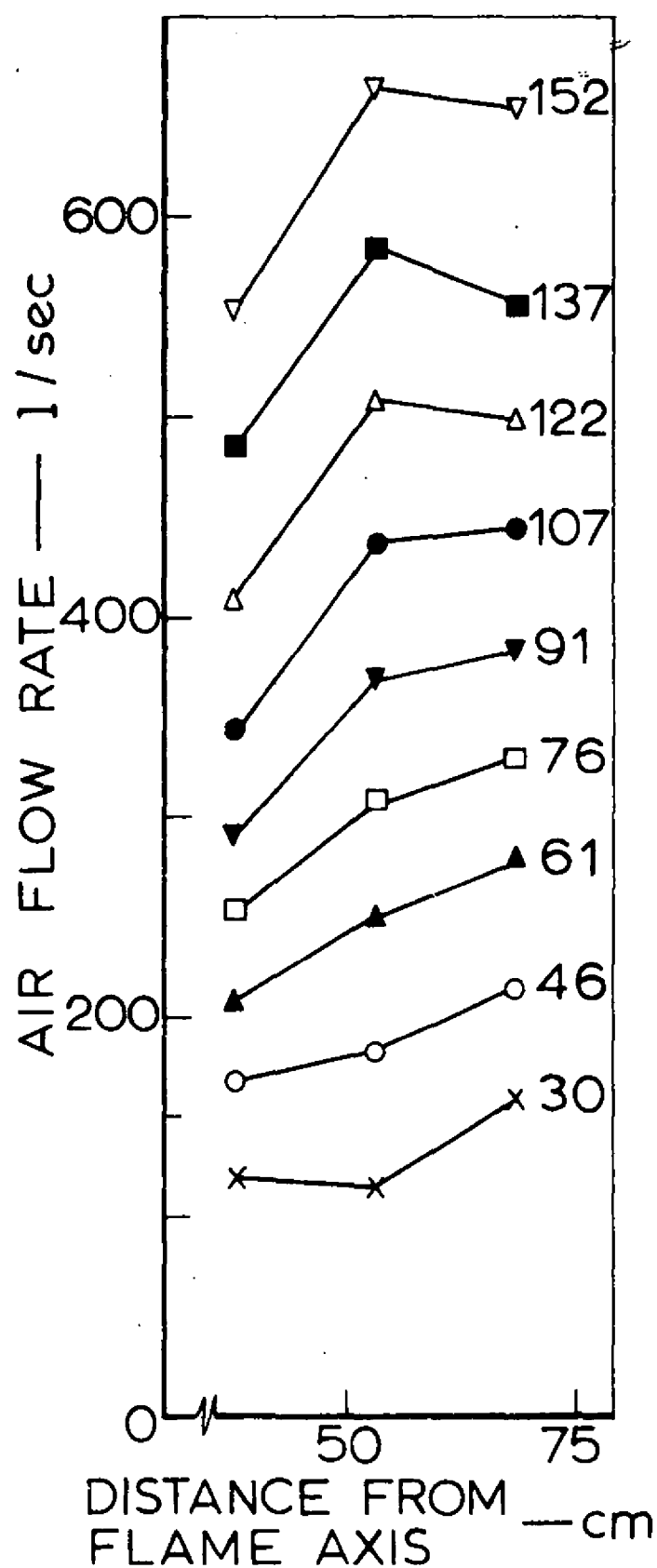


FIG. 2c. TOWN GAS FLAME — VOLUMETRIC AIR FLOW (AMBIENT TEMPERATURE AND PRESSURE) THROUGH CYLINDRICAL SURFACES OF HEIGHT (h) CONCENTRIC WITH THE FLAME. (The numbers against each line are the values of (h) in cm)

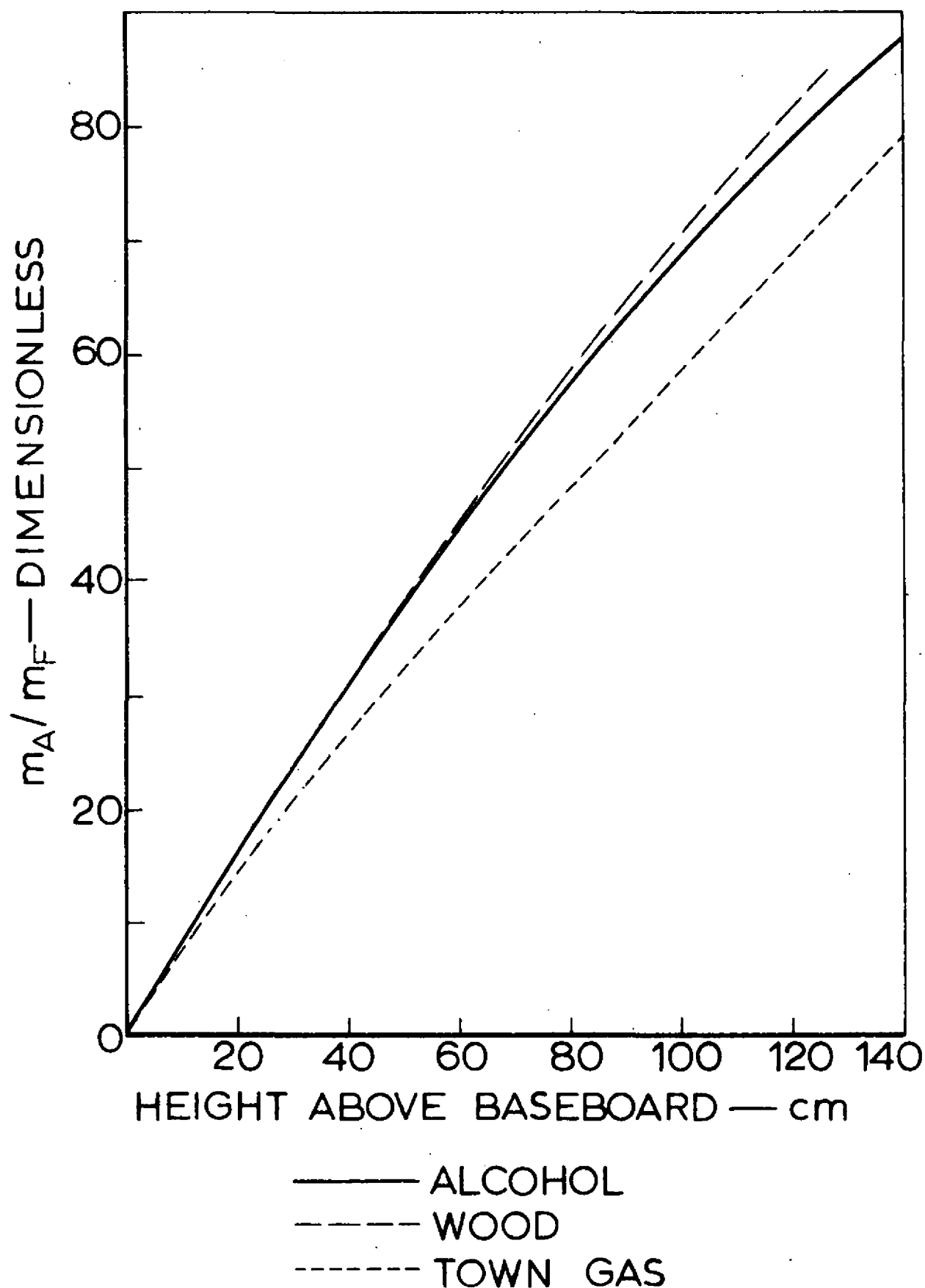
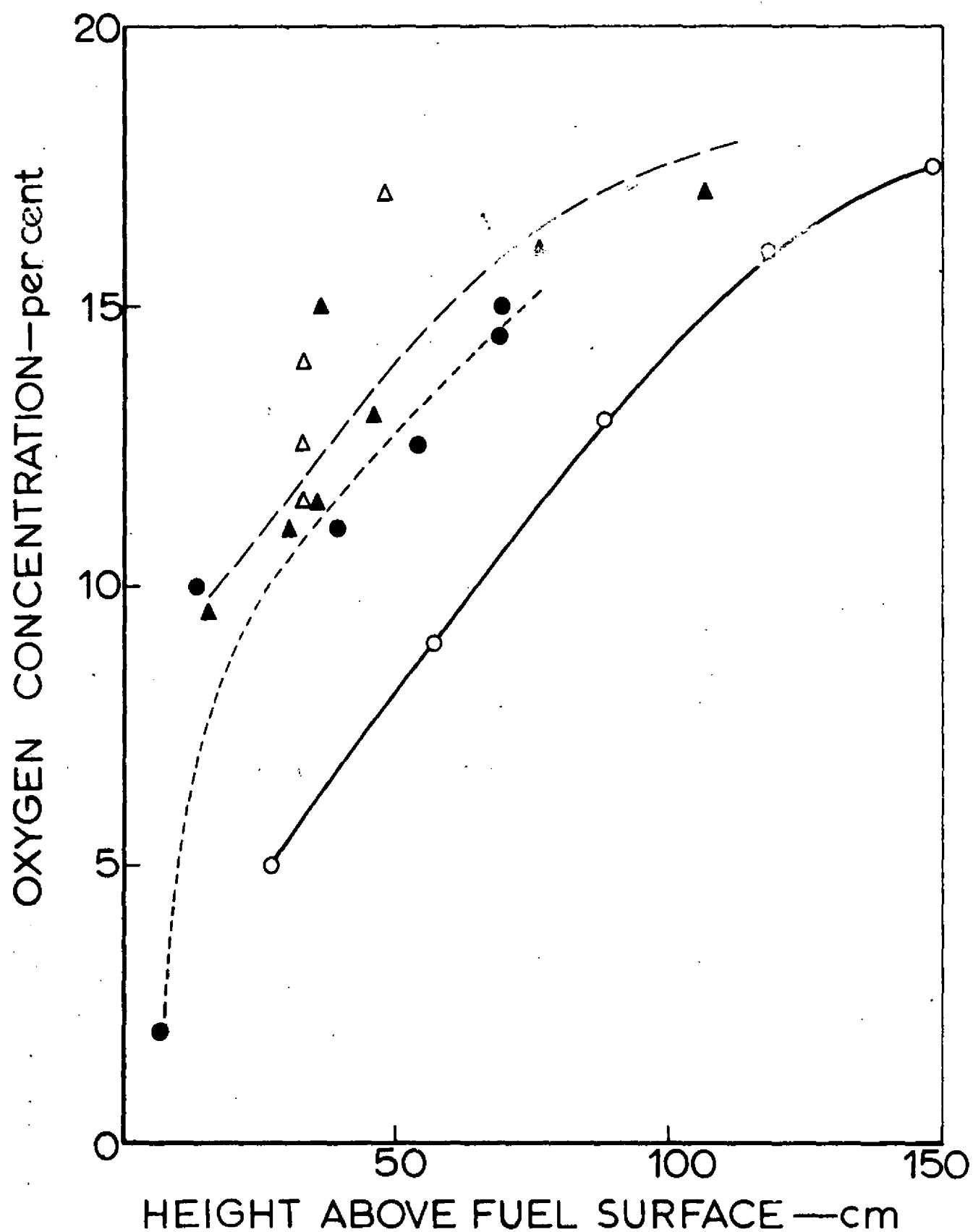


FIG. 3. MASS AIR FLOW PER UNIT BURNING RATE (m_a/m_f) THROUGH A CYLINDRICAL SURFACE (RADIUS 68cm) CONCENTRIC WITH THE FLAME. (The values of air flow are interpolated from Fig. 2.)



- ——— ALCOHOL 11cm BELOW BASEBOARD
- - - - - ALCOHOL 2.5cm BELOW BASEBOARD
- ▲ - - - - WOOD CRIBS 1.1cm STICK THICKNESS
- △ - - - - WOOD CRIBS 2.5cm STICK THICKNESS

FIG. 4. AXIAL OXYGEN
CONCENTRATION ABOVE
FUEL SURFACE

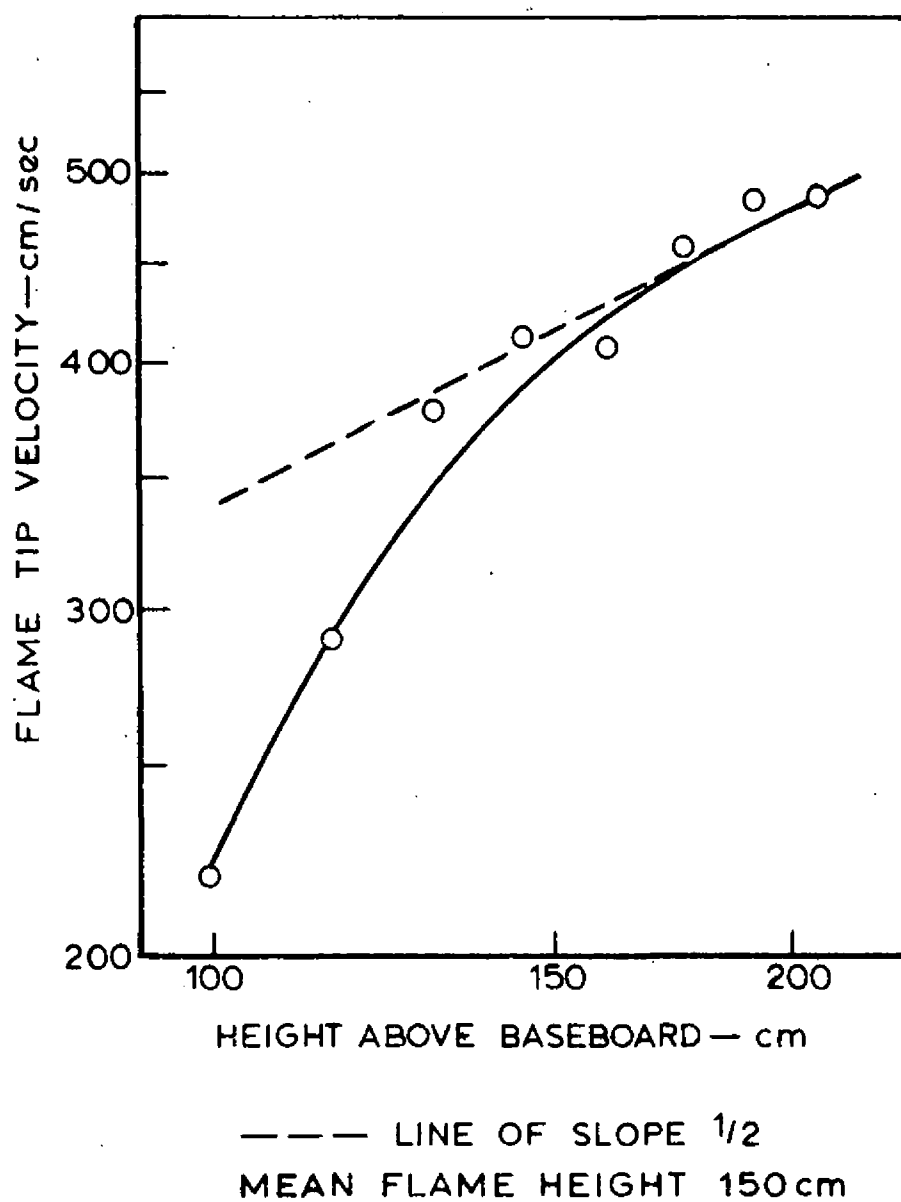


FIG. 5. UPWARD VELOCITY OF VISIBLE FLAME TIP — ALCOHOL FUEL

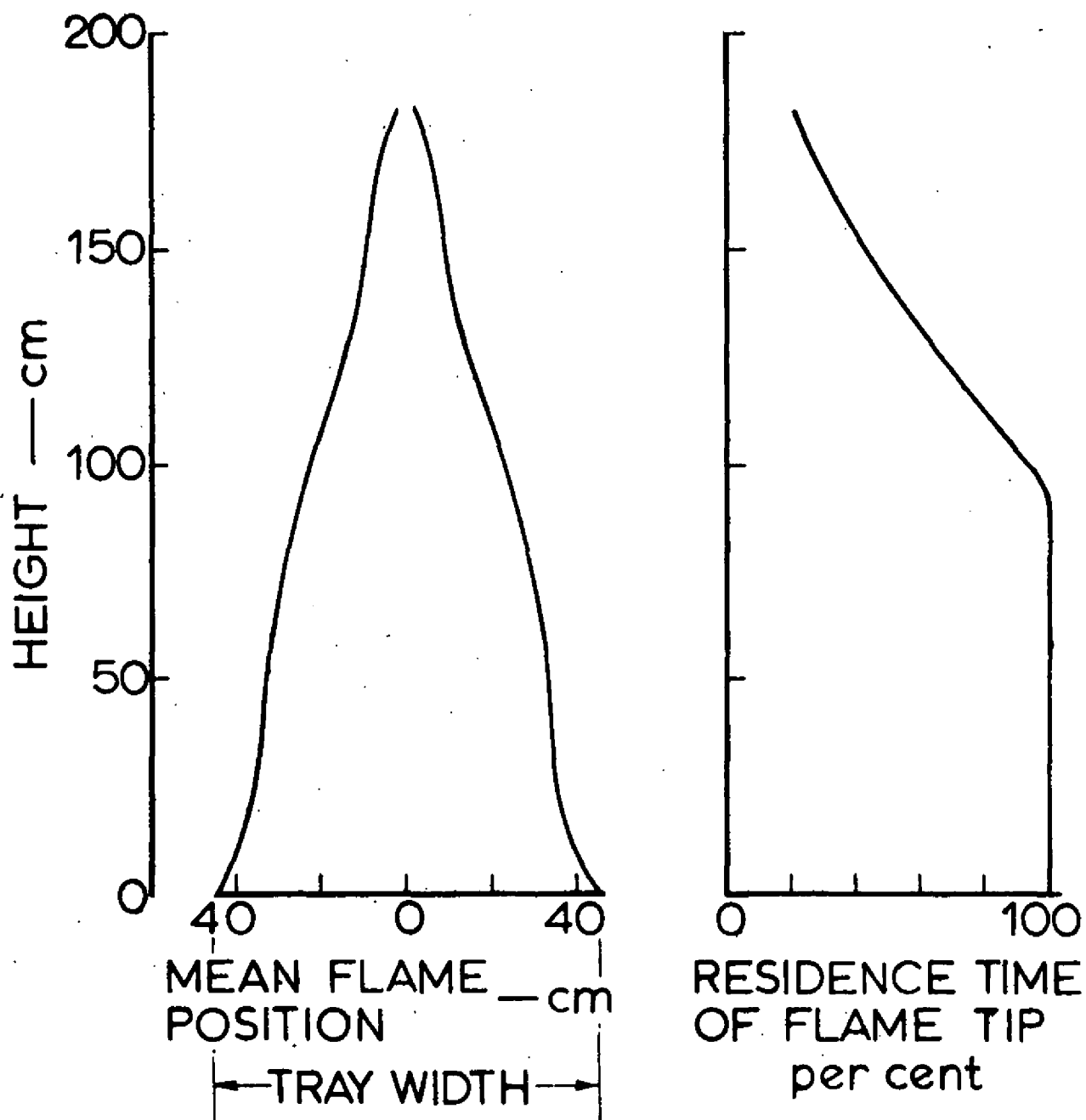


FIG.6. PROFILE AND RESIDENCE TIME OF ALCOHOL FLAME

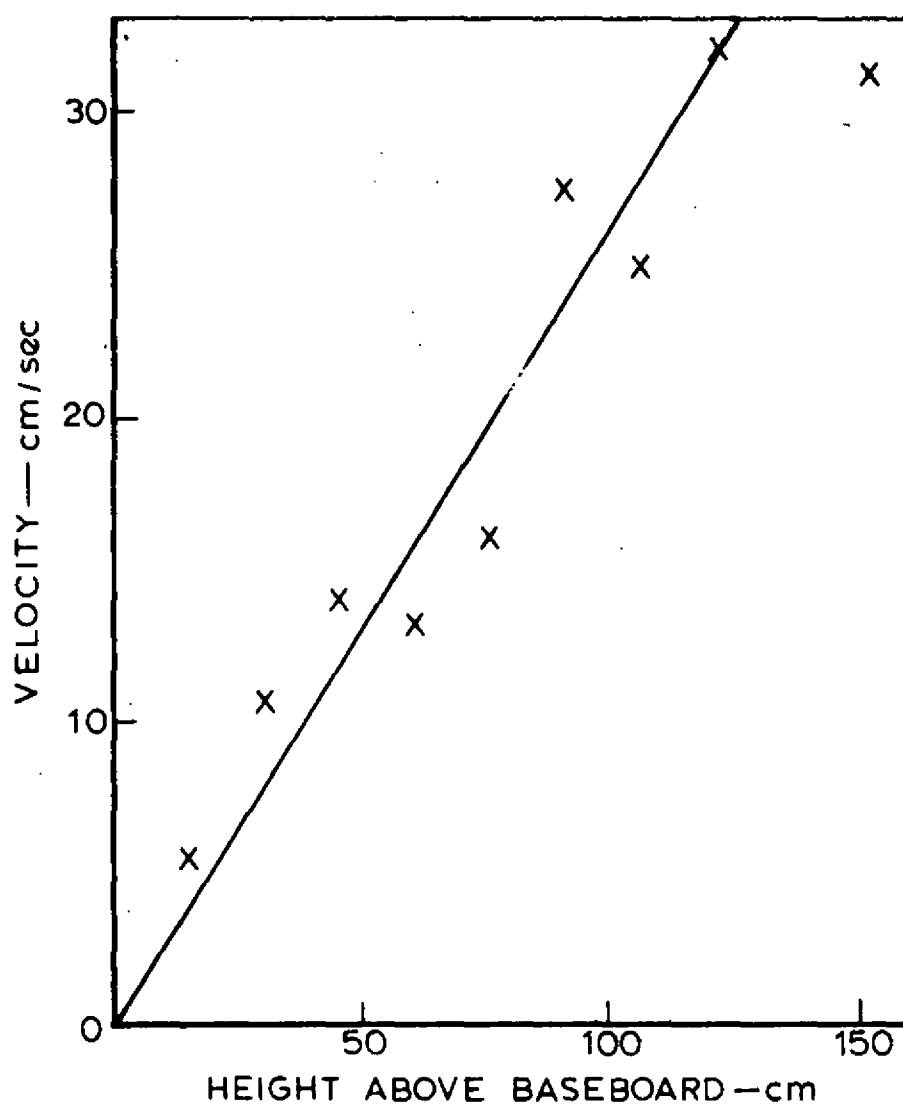
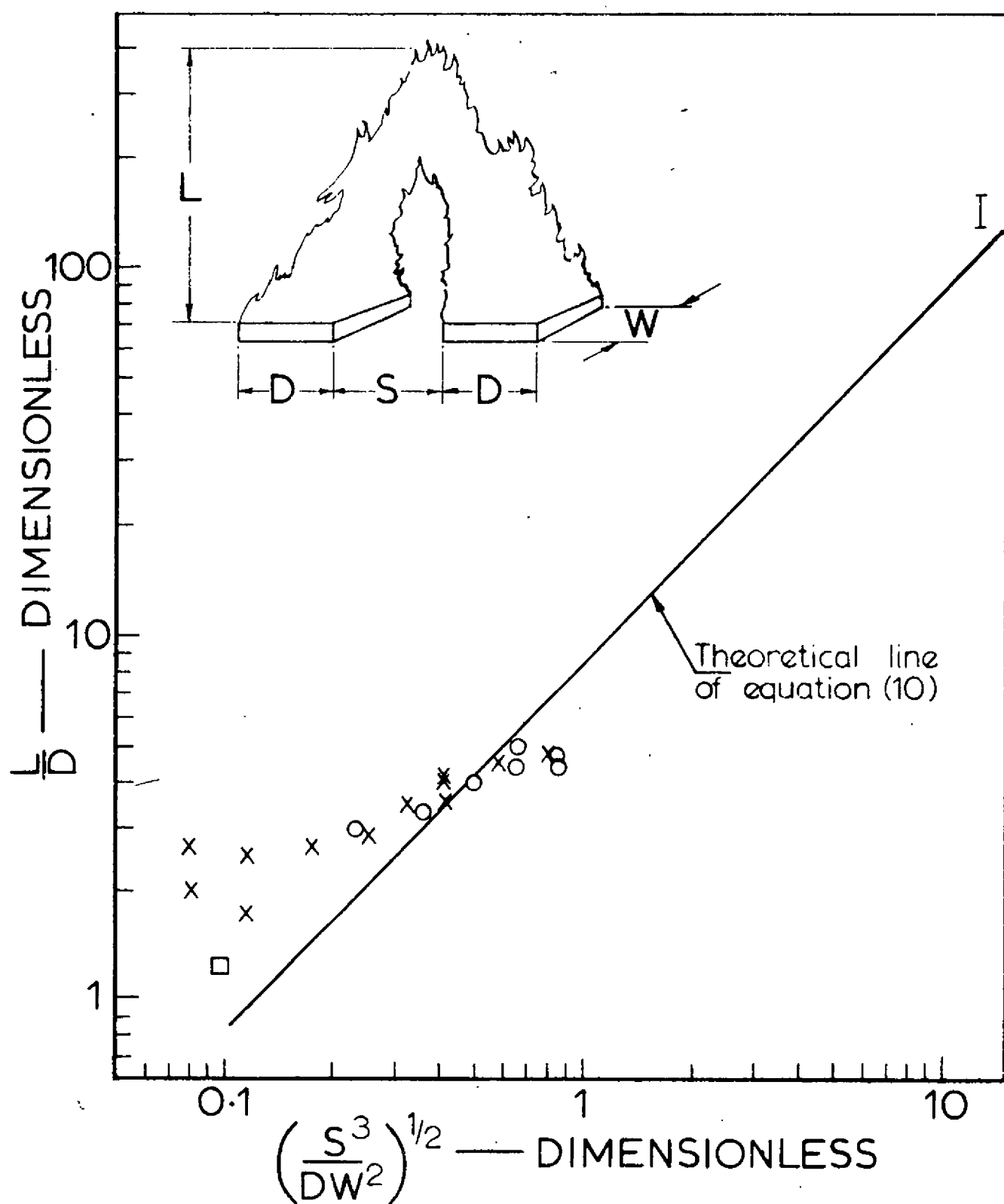


FIG. 7. UPWARD VELOCITY OF AIR OUTSIDE ALCOHOL FLAME (76cm FROM AXIS)



Source	Symbol	Dimension of fuel bed (W x D)	$\frac{W}{D}$
J. F. R. O. (Town gas)	o	30 x 30 cm	1
	x	60 x 30 cm	2
Putnam and Speich	I	0.371 in dia.	1
Southall timber fire	□	150 x 40 ft	3.75

FIG. 8. DIMENSIONLESS FLAME HEIGHT (L/D) AND SPACING FACTOR $\left(\frac{S^3}{DW^2}\right)^{1/2}$ AT MERGING