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THE SIZE OF FLAMES FROM NATURAL FIRES

by

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SUMMARY

Uncontrolled fires produce flames where the initial momentum of the fuel is low compared with the momentum produced by buoyancy. The heights of such flames with wood as the fuel have been examined and are discussed in terms of both a dimensional analysis and the entrainment of air into the turbulent flame and are compared with other experiments on the flow of hot gases.

Some recent experiments on the effects of wind on such flames are also reported.

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Notation

A = area of vent

D = characteristic dimension, side of square, diameter, or width of infinite strip

F = shape function of $^{L}/D$ affecting velocity of rising gases

G = shape function of $^{L}/D$ affecting surface area of flame envelope

H = convective heat flux

L = flame length

Q = volumetric rate of flow

T = absolute temperature

U = wind speed

W = width of rectangular burning zone, width of window

X = modified dimensionless flame length

a = curtained area

c = specific heat

d = depth of curtain

f = a function of (general)

g = gravitational acceleration

h = height of building

l = length of rectangular burning zone

m = mass flow rate

n = shape factor

p = curtain perimeter

q = index

r = Yokoi's characteristic dimension, effective radius

s = distance along the trajectory

v = sideways velocity of entrainment

w = upward velocity on central vertical axis

x = horizontal length

z = height

μ	viscosity
ρ	density
θ	temperature rise
Θ	dimensionless temperature
Ω	dimensionless wind speed
R_e	Reynolds number

Suffices

1	fuel at burner
o	surrounding air
c	centre-line of plume or flame
t	flame tip - instantaneous
fl	flame zone
w	wood
$'$	per unit length of line or strip
$''$	per unit area

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INTRODUCTION

This paper discusses one of the features of natural fires that has been least studied, namely the length of the turbulent flames rising from the burning fuel.

Horizontal sources of fuel in still air are considered first, either circular or square or in the form of an infinite strip, each characterized by a single linear dimension D (diameter or width). The effects of wind are discussed later. The fuel is the gas or vapour generated by the heating of a solid or liquid. This heating is, of course, accomplished for large fires by the heat transfer from the flame zone itself. However, the solid or liquid fuel can be regarded as a burner of dimension D, and the mass rate of burning m treated as an independent variable.

The fuel burns in a flame zone to a height L producing a column of hot gases. At heights above the top of the flame this column may be considered as a thermal plume with constant convective heat flux. It is possible to correlate data on velocity and temperature in this plume for isothermal atmospheres by means of dimensionless variables deduced either from the appropriate differential equations or from elementary considerations of buoyancy and the conservation of convected heat. Because it will be shown that data on flames can be related approximately to data obtained in studies of non-reacting hot gases, reference will first be made to such dimensionless variables.

The temperature rise θ at a height z, in the centre of a plume of negligible initial momentum is determined by the convected heat flux H, the specific heat c, the density ρ the coefficient of expansion of the gas $(1/T_0)$ the linear size of the source D and the acceleration due to gravity g. Density is conventionally assumed constant in plumes and jets except where it affects local buoyancy. Considerations of the conservation of heat and the relation between momentum and buoyancy or, alternatively, a direct dimensional analysis of the above variables leads to the relationship for a plume

$$\textcircled{H} = \frac{\theta_c D^{5/3}}{(H^2 T_0 / \rho^2 c^2 g)^{\frac{1}{3}}} = f\left(\frac{z}{D}\right) \quad \dots\dots\dots\dots (1)$$

For a point source or for an extended source at values of z large compared with D this correlation must become independent of D and the well known result is obtained

$$f\left(\frac{z}{D}\right) \propto \left(\frac{D}{z}\right)^{5/3}$$

i.e.

$$\theta_c \propto H^{\frac{2}{3}}/z^{5/3} \quad \dots\dots\dots\dots (2)$$

For a line source, the correlation must similarly be independent of D except that H must only appear as the heat per unit length of the line source, i.e. in equation (1) H is replaced by $H'D$ and a function is found such that θ is independent of D. The well known result for the line source is then obtained

$$f\left(\frac{z}{D}\right) \propto \frac{D}{z}$$

i.e. $$\theta_c \propto H^{2/3}/z \qquad \text{.......... (3)}$$

Equation (1) is a general form for finite sources except that the unspecified function f depends on the shape of the source. Yokoi[1] has in fact presented correlations of this form for a variety of different shapes of source in horizontal and vertical planes. Lee and Emmons[2] have recently given a theoretical treatment of a strip source.

Where there are density differences between the two mixing fluids, the mixing, and consequently the expansion of the plume, can be related to the excess momentum[3][4]. However, in applying such arguments in detail to flames other difficulties arise. Tall flames will be much taller than the potential core, but smaller flames will not necessarily be so. Heat is generated in flames so that the conservation of sensible heat in the conventional treatments must be modified to allow for the progressive release of heat as a result of mixing with air. The application of theoretical analysis is also more difficult because the flame zone does not necessarily have the simple geometry associated with point or line sources. Arguments have previously been given[5][6] for assuming that for any one fuel the height of a turbulent diffusion flame is related to the volumetric flow rate of fuel Q_1 and the burner dimension D, as described by:

$$\frac{L}{D} = f\left(\frac{Q_1^{\,2}}{g\,D^5}\right) \qquad \text{.......... (4i)}$$

For an infinite strip source equation (4i) is used in the form:

$$\frac{L}{D} = f\left(\frac{Q_1'^{\,2}}{g\,D^3}\right) \qquad \text{.......... (4ii)}$$

or more generally:

$$\frac{L}{D} = \left(\frac{Q_1''^{\,2}}{g\,D}\right) \qquad \text{.......... (4iii)}$$

The variable quantities in these equations are similar to those in equation (1) if θ_c is regarded as constant at the flame tip or if equation (1) had been replaced by a similar equation involving concentration, and concentration were put as equal to a constant. The connection between the two equations is discussed below but a more direct derivation of equations (4) follows immediately which shows the physical basis more clearly. Some experimental results for the mean upward velocity of the gas in the flame zone are first discussed.

VELOCITY OF GASES IN THE FLAME ZONE

Rasbash et al[7] presented regression equations for the rate of increase of flame height during the course of the short pulsation of a flame. They found that the time of burning was a significant, though small, factor for petrol and kerosine but not for alcohol and benzole, despite the fact that the rate of burning varied with time most for benzole and alcohol and varied little for kerosine and petrol. However, plotting their original data averaged over all times of burning and introducing their values for the estimated flame temperature which varied between 921 and 1218°C for the four fuels, and assuming an ambient temperature of 15°C enables the upward velocity w_t to be plotted against $\sqrt{2g\ \theta_{f\ell}\ z_t/T_o}$ (Fig.1) which is the theoretical maximum velocity at a height z_t if the lateral transfer of momentum and friction are neglected. The straight line drawn in Fig.1 is:

$$w_t = 0.36\ (2g\ \theta_{f\ell}\ z_t/T_o)^{\frac{1}{2}} \qquad \text{.......... (5)}$$

Rasbash[8] recently presented his original data in the form

$$\rho_{f\ell}\ w^2 = 0.27\ Z\ (\rho_l - \rho_{f\ell})$$

which is virtually identical with equation (5).

The value z_t extended from about $^D/_2$ for alcohol to 5D for the other fuels. If the flame zone is treated as a region of uniform temperature which is constant for a given fuel and a large enough fire, the characteristic mean upward velocity for similarly shaped flames where the injection velocity w_1 is small compared with $\sqrt{gL}$ (where L is the mean flame height i.e. the mean of z_t) will, from dimensional arguments, be of the form $\sqrt{gL}$. For differently shaped flames the inclusion of a shape factor may be necessary and the mean velocity would then more generally be written as:

$$\bar{w} \propto \sqrt{gL}\ \ F(\tfrac{L}{D}) \qquad \text{.......... (6)}$$

where the bar denotes the mean value over the whole flame height.

The numerical value of $\sqrt{gL}$ for flames say 200 cm high is about 450 cm/s. The rate w_1, at which fuel gases leave a burning surface, for example a tank of fuel, is of the order of 1 cm/s which explains why the velocities are correlated with buoyancy and not with the rate of burning or burner size.

AIR ENTRAINMENT

Taylor[9] introduced the assumpton, later used by Morton Taylor and Turner[10] that if air enters a rising column by entrainment, the entrainment velocity v is proportional to the local rising velocity w_z. The total flow into the rising plume may be then represented by:

$$Q_o \propto \bar{V}\ G\ (\tfrac{L}{D})\ D^2 \qquad \text{.......... (7)}$$

where G represents a shape factor for the envelope of the flame zone. For the two dimensional flame from a strip source Q_o' is considered instead of Q_o. The flame area per unit length of strip would be represented by $G\ (\frac{L}{D})\ D$. From the above assumption regarding the proportionality between v and w_z, which is discussed in more detail below, and with the total quantity of air Q_o. proportional to the quantity of fuel Q_1 the following relation is obtained from equations (6) and (7)

$$Q_o \propto Q_1 \propto \sqrt{gL}\quad F(\tfrac{L}{D})\ G(\tfrac{L}{D})\ D^2 \qquad \text{.......... (8)}$$

from which equation (4) follows.

For turbulent flames in which the momentum of the injected fuel is significant compared with buoyancy, equation (6) must be generalized to

$$w_L \propto \sqrt{gL}\ f\!\left(\frac{L}{D},\ \frac{Q_1^{\,2}}{gD^5}\right) \qquad \text{.......... (9)}$$

where $\dfrac{Q_1^{\,2}}{gD^5}$ is the form of a Froude number expressing the ratio of the initial momentum to the buoyancy in terms of the characteristic dimension. Clearly this does not change the essential result of equation (4) except that it shows how Q_1 can have a double significance, one related to momentum the other to fuel and air quantity. A decrease in buoyancy relative to orifice momentum leads to a decrease in the velocity in the fuel stream and hence to a lower rate of entrainment and a larger flame. Thus $\frac{L}{D}$ is an increasing function of $\frac{Q_1^2}{gD^5}$ and $\frac{L}{D}$ should tend to an upper limit which has the value typical of a turbulent jet[11][12][13][14] where buoyancy is of minor importance and $\frac{L}{D}$ cannot depend on g.

In equation (7) G is proportional to $\frac{L}{D}$ for cylindrical flames and also for conical flames with the burner as the base and the flame top as the apex. It is proportioned to $(\frac{L}{D})^2$ for long conical flames with the flame zone expanding upwards.

Thus if

$$G(\frac{L}{D}) \propto (\frac{L}{D})^q \qquad \text{..........} (10)$$

the index q might be expected to increase from 1 to 2 with increasing $\frac{L}{D}$.

If $\bar{v}$ is taken as proportional to $L^{\frac{1}{2}}$ and F constant, equations (8) and (10). lead to

$$\frac{L}{D} \propto \left(\frac{Q_1^2}{gD^5}\right)^{\frac{1}{2q+1}} \qquad \text{..........} (11)$$

This equation shows that the $\frac{L}{D}$ versus $\frac{Q_1^2}{gD^5}$ relation on a log-log basis is convex upwards. The index of $\frac{Q_1^2}{gD^5}$ thus varies from $\frac{1}{3}$ to $\frac{1}{5}$ as $\frac{L}{D}$ increases, until at high values of $\frac{Q_1^2}{gD^5}$, when the effect of orifice momentum becomes significant, it tends to zero and $\frac{L}{D}$ becomes constant. q is 1 for strip sources when $\frac{L}{D} \gg 1$, and the index of $\frac{Q^2}{gD^3}$ is $\frac{1}{3}$. Thus neither for long flames from finite burners nor from infinite line burners does theory suggest that L depends on D.

It will usually be necessary to employ m_1 - which is measured directly by weighing instead of Q_1, and hence use will be made of the relations

$$\dot{m}_1'' D^2 \propto m_1 \propto \rho_1 Q_1$$

i.e.

$$\frac{Q_1^2}{gD^5} = \frac{m_1''^2}{\rho_1^2 gD}$$

EXPERIMENTAL

CRIBS ON SQUARE HORIZONTAL BASE

Cribs of wood (spruce) sticks arranged on a square horizontal base of side D have been burnt in the laboratory (Fig. 2). By varying the amount of wood and the design of the crib various mass rates of burning i.e. rates of weight loss m_1 could be obtained by direct weighing for a given value of D. The flame was photographed and the height measured from the base of the shallow crib. The burning rate reached a maximum value which remained steady for a period; this and the mean height of the continuous flame zone corresponding to it were recorded as m_1 and L respectively, the flame heights being averaged over a period considerably longer than the fraction of a second taken for a single fluctuation. In the period of steady burning it is mainly the volatiles from the wood that are involved. Apart from a small amount of carbonaceous residue burning at the crib edge little carbon burnt until the flames subsided and the gross rate of burning fell. The results are plotted in Fig.3 as $\frac{L}{D}$ in terms of $\frac{m''}{\rho_0\sqrt{gD}}$. The viscosity of the volatiles, μ, was assumed to be 10^{-4} c.g.s. units and the density taken as 1.3×10^{-3} gram/cc. This is the density of air but the density of the wood volatiles is not properly known and the value for air has been inserted solely to enable the order of magnitude of the dimensionless parameter to be seen. Apart from one result where it was 1,250, the Reynolds number R_e at the orifice $\left(\frac{m_1 Q_1}{\mu_1 D}\right)$ was over 2,000 in all experiments but in more than half it exceeded 10^4.

Gross[15], at the National Bureau of Standards, Washington, has burnt sticks of Douglas Fir of square section assembled in the form of cubical cribs. The Reynolds numbers based on 10^{-4} c.g.s. units for μ_1 fell in the range 13 to 6,400 so that some of the results clearly referred to laminar flames, but all the data where the flames were less than 2 feet (50 cm) high have been excluded and the rest are plotted in Fig.3. These results where the flame height was measured by eye follow the same trend as the others but are about 20 per cent higher. For these cubical cribs the crib height is also D, but a reduction of $\frac{L}{D}$ by 0.5 on the assumption that the effective source is at the mid height of the crib is not sufficient to explain the difference between the two sets of data. Some more recent comparisons suggest that this may be mainly a difference between visual and photographic measurement.

Use has also been made of some data given by Fons et al[16]. These refer to experiments on the spread of a burning zone along a crib of wood (white fir). Data obtained photographically from these experiments have been plotted using an equivalent square base defined by $D = (Wl)^{\frac{1}{2}}$, where W is the width of the crib and l the measured length of the flame zone in the direction of flame spread along the crib. The few results where the flame height was not greater than three times the larger of either W of l have been excluded because they cannot be regarded as approximately radially symmetical. The remainder are shown in Fig.3.

The best equation for the photographed flames is in terms of the measured quantities

$$\frac{L}{D} = 4.4 \left(\frac{m_w^{2} \times 10^6}{D^5}\right)^{0.30} \quad \text{c.g.s. units} \qquad \ldots\ldots\ldots\ldots (12i)$$

In accordance with the notion of using air density for the purpose of plotting results on a dimensionless scale this equation may be written as

$$\frac{L}{D} = 42 \left(\frac{m''}{\rho_0\sqrt{gD}}\right)^{0.61} \qquad \ldots\ldots\ldots\ldots (12ii)$$

Rasbash has recently evaluated the flame height of a fire in a whisky warehouse and estimated the rate of burning from the thermal conditions in the fire. The result is shown in Fig.4 where the data of Fig.3 are also shown. Blinov and Khudiakov's[17] data are shown in Fig.4 for tanks greater than 80 cm diameter but no attempt has been made to allow for the different character of these fuels.

There are in addition two "large-scale" wood fires reported in detail. These are the Camps Park fire, reported by Broido and McMasters[18] and the Trensacq test reported by Etienne[19] and Faure[20], (see Table 1). The results are plotted in Fig.4 and lie below the extrapolation of the laboratory data.

TABLE 1

Details of large test fires

Type of information	Details of fire	
Fire and reference for source of details	Camps Park fire[18]	Trensacq fire[20]
Ground area within fire boundary - D^2	$\dfrac{4 \text{ acres}}{162 \times 10^6 \text{ cm}^2}$	$\dfrac{803 \text{ acres}}{325 \times 10^8 \text{ cm}^2}$
D	12.7×10^3 cm	18×10^4 cm
Amount of fuel	"About half of 500 tons of assorted scrap timber" "About 2000 (U.S.) gallons of used crankcase oil" Oil assumed equal to 34 000 pounds timber Total: 594 000 pounds	"Small bushes and gorse" 1.7 kgm/m^2 i.e. 550×10^4 kgm
Arrangement of fuel	Stacks of timber in concentric squares (discontinuous)	Natural vegetation
Combustion time	After 20 min some of the piles had stopped flaming	"About 35 min
How rate of burning 'R' is evaluated here	Assumed that 2/3 of calorific value released in the time of 20 min	Assumed whole calorific value released in 35 min because Faure's own calculations were derived this way
Estimated rate of burning per unit area $m'' = R/D^2$	$\frac{2}{3} \times \frac{594 \times 10^3 \times 454}{162 \times 10^6 \times 20 \times 60} =$ 0.93×10^{-3} gram cm^{-2} s^{-1}	$\frac{1.7 \times 10^3 \times 10^{-4}}{35 \times 60}$ $= 0.81 \times 10^{-4}$ gram cm^{-2} s^{-1}
Observation relating to wind	Because flames were still bent towards centre 7 min after ignition the effect of the wind was disregarded	The smoke plume rose vertically so effect of wind on flames neglected
Flame height	50 feet (15.2 m) Only observation recorded. Account implies that there was a period when the flames from the individual stacks merged.	"10 - 12 m" Value taken as 11 m
$\frac{L}{D}$	0.12	0.0061

In the Camps Park fire the flames were reported as merged, for a short time, but because the fuel was in separated piles of timber the fire may not strictly be comparable with those in which fuel is spread over the whole "burner" area. The average rate of burning per unit area m_1'', was about 1 mgm cm^{-2} s^{-1} which is about an order less than the values for the laboratory data given in Fig.3. The fuel loading in Etienne's experiment was lower still giving a mean value of m_1'', of about 0.08 mgm cm^{-2} s^{-1}. Clearly rates of burning per unit area comparable with the laboratory fires might lead to flames several hundred feet high and under such conditions the properties of the atmosphere near the ground would presumably influence not only the plume of hot gases but the flame too.

For a very large fire area and rates of burning of the order found in a large fire, $\frac{L}{D}$ may be so small that turbulence might be expected to break up the flame envelope. Therefore a large fire could not be considered as having a continuous envelope bounded by the fire area, but would tend to become a collection of fires of probable varying area and number. The flame height would therefore tend to be intermediate between that appropriate to an isolated fire of smaller size and that obtained by extrapolating the laboratory data assuming no break up, i.e. assuming these fires are fully merged. This has the effect of reducing the value of L below that given by equation (12i) or (12ii). These results suggest that the index $\frac{1}{2q+1}$ in equation (11) increases above $\frac{1}{3}$ for small values of $\frac{L}{D}$. This may be due to the break-up of shallow flame envelopes: Fig.(4) shows how the position of the points would be affected by taking a smaller value of D. The suggestion given in a previous paper(6) as to how the index might increase above $\frac{1}{3}$ for small values of $\frac{L}{D}$ is to some extent unsound as it considers total flame envelope area not that projected vertically. But consideration might be given to the possibility of heavy cold air 'falling' into the flame zone from above in between areas of rising fuel and combustion products.

RELATED GAS EXPERIMENTS

Putman and Speich's data(21) for city gas, which appears to be similar to methane, follow the law appropriate to a point source (equations (10) and (11) with $q = 2$), and are represented by

$$\frac{L}{D} = 29 \left(\frac{Q_1^2}{g\, D^5} \right)^{1/5} \qquad \text{............ (13)}$$

in the range $100 < \frac{L}{D} < 200$

For the sake of presenting as much data on one graph as possible this correlation has been modified to make it comparable to the data for wood fires. This has been done on the assumption that the flame tip is defined approximately by a certain temperature rise and that in flames wholly controlled by buoyancy the only role of Q_1 or m_1 is to be a measure of the fuel supply. Hence for different fuels L has been assumed to be determined by the enthalpy supply and the modification based on the ratio of the calorific values of wood volatiles and city gas. Equation (13) may be written as

$$L = 140 \; m_1^{2/5} \qquad \text{............ (14)}$$

where 0.6×10^{-3} gram cm^{-3} was taken at the density of city gas.

Allowing for the difference in calorific values between wood and city gas the equation for wood volatiles would be

$$L = 90 \; m_w^{2/5} \qquad \text{............ (15)}$$

The lower calorific value of wood volatiles means that a higher volumetric flow (about three times) would be required to achieve the same flame length. But this higher flow and higher velocity could result in the initial momentum (increased about eight times) becoming significant so that equation (15) may well overestimate the flame length. With this reservation equation (14) is used in Fig.4 to show the extent of the range of interest and the limited parts of the range for which data are available. The data in Fig.4 covers an immense range of $\left(\frac{m^2}{\rho_o^2 g D^5}\right)$ and it is desirable to adopt different dimensionless variables. X is accordingly defined as:

$$X = \frac{L}{D}\left(\frac{\rho_o\sqrt{gD}}{m''}\right)^{\frac{2}{3}} \qquad \text{............. (16)}$$

Figure 5 shows the data of Figs.3 and 4 plotted as X, with ρ taken as ρ_o, against $\left(\frac{m''}{\rho_o\sqrt{gD}}\right)^{\frac{2}{3}}$ for wood and city gas, transformed as above to a wood basis.

FLAMES FROM CUBICAL ENCLOSURES AND WINDOWS

The second experimental arrangement for which data on flame lengths are available is shown in Fig.6. Varying amounts of wood (spruce) were burnt inside a cubical enclosure having one side completely open. The mean rate of burning in the period when the burning was approximately constant and the corresponding mean flame height were measured, the latter visually. Some unpublished data of Webster and Smith of the Joint Fire Research Organization are included in addition to data previously published[6]. The results which cover a range of $\frac{1}{2}$, 1 and 2-inch sticks in cribs of heights varying from 4 to 16 inches in 2 and 3 feet cubes are plotted in Fig.7. The Reynolds number $\left(\frac{m}{D\mu_1}\right)$ with μ equal to 10^{-4} c.g.s. units varied from 2 300 to 5 400. These results also lie on a line of similar form to that for the open fires given in Fig.3 but this correlation is relatively less well established in view of the small range of D.

As shown above flames from an infinite strip source should follow equation (11) with $q = 1$ and Q_1 replaced by $Q_1' D$ so that

$$L \propto Q_1'^{\frac{2}{3}} \qquad \text{............. (17)}$$

In the range of these experiments with cubical boxes the results do follow this law although departures from it might be expected when

(a) the flames are short in comparison with the size of the wood crib and the box and

(b) when the flame is very much longer than the width of the strip, in this case D, so that it is no longer two dimensional.

The equation to the line in Fig.7 is

$$L = 400\, m_w^{\frac{2}{3}} \text{ c.g.s. units} \qquad \text{............. (18)}$$

for $1.5 < \frac{L}{D} < 4$

In an enclosure there is the added feature of entrainment in the horizontally moving stream under the 'roof', but this might be expected to be small because of the relative difficulty of exchanging cold gas with lighter hot gas flowing over it[22]. Equation (18) should be increasingly close the the equation for a horizontal strip source as the ratio $\frac{L}{D}$ increases.

Some experiments have been made by Thomas, Pickard and Wraight[23] for wood fires on effectively infinite strips of width D and the results are shown in Fig.7 together with equation (18). There is indeed a discrepancy for small values of $\frac{L}{D}$ but at higher values the two sets of data tend to a similar form. The discrepancy at small values of $\frac{L}{D}$ arises from the difference in geometry between the two situations. The slight discrepancy at large values of $\frac{L}{D}$ may well arise from the difference between visual and photographic assessments of L. It should be emphasized here that these results do not apply where there is a vertical 'wall' above the opening though such results would be expected to be correlated by a relation of the same form. A one-sided flame could be regarded as having the same height as a two-side flame burning twice the fuel (1). From this argument it would be expected from equation (18) that a one-sided flame would be $2^{\frac{2}{3}}$, i.e. 1.6 times taller than a two-sided flame for the same value of m_1.

COMPARISON WITH CALCULATIONS OF ENTRAINMENT

It has been shown that flame lengths can be correlated by equations deduced from simple flow theory. These theoretical equations do not give the numerical value of flame length but only the form of the variation with m_1 and scale. However, in the following sections the significance of the numerical results obtained experimentally will be discussed in the light of quantitative considerations of the entrainment of air with flames. These results will be compared with those from experiments on the flow of hot gases for which Yokoi[1] assumed the flame length to be the distance to the point where the rise in temperature 500 degC.

Entrainment into buoyant turbulent flames as opposed to plumes, where the density difference is small, has not so far been widely studied but it can be shown from the data of Rouse, Yih and Humphries[24] that the horizontal velocity of entrainment v, is 0.16 times the upward velocity w in the centre of the plume at the same level. A momentum jet of local density ρ_θ entrains surrounding fluid of density ρ_0 at a rate dependent on the excess momentum[3][4] and it can be shown that this implies that

$$v \propto \omega \sqrt{\rho_\theta / \rho_0} \qquad \text{............. (19)}$$

which will be here assumed to apply to flames. In a flame from an infinite strip source it is therefore assumed that

$$v \propto 0.16 \sqrt{\frac{\rho_{fl}}{\rho_0}}\ \omega \qquad \text{............. (20)}$$

and for a nominal temperature rise of 1000 degC and T_0 equal to 290°K this becomes

$$v = 0.075\ \omega$$

Because this discussion is only concerned with obtaining an approximate comparison it is assumed that equation (5) applies at all values of z less than z_t as well as at z_t itself and that it applies to line sources as well as radially symmetrical ones. Likewise equation (21) will be assumed to apply to radially symmetrical sources as well as to line sources. These approximations are sufficient for the immediate purpose of this paper; further experimental work in these fields is necessary before it is worthwile undertaking more detailed analysis.

The mean mass rate of air entrainment per unit area in the vertical plane of the flame envelope is, from equations (5) and (20)

$$m''_o = \tfrac{2}{3} \times 1.3 \times 10^{-3} \times 0.16 \times 0.36 \times \sqrt{gL}\,\sqrt{2\theta_{fe}/T_{fe}}$$

$$= 0.062 \times 10^{-3}\sqrt{gL}$$

Since m''_o is proportioned to $\sqrt{\theta_{fe}/T_{fe}}$ small variations in θ are not important.

The total mass rate of air entrainment per unit length of strip is

$$m'_o = 0.062 \times 10^{-3} \sqrt{gL} \times 2L \qquad \text{in c.g.s. units}$$

Eliminating L by means of equation (18) gives m'_o / m'_w as 31. If the nominal calorific value is taken as 2500 cal/gram (allowing for radiation loss) and the specific heat as 0.24 cal gram^{-1}°C^{-1}, the value of 31 gives an effective mean temperature rise of 320 degC.

If it is assumed that the temperature distribution across a horizontal plume through the mean flame tip is the same as for a plume from a thermal line source, the data of Rouse, Yih and Humphries can be employed to obtain the equivalent centre line temperature.

The effective mean temperature is given by $H'/m'c$ where m' is the integrated mean mass flux. From the equations for velocity and temperature given by Rouse, Yih and Humphries, the ratio of the maximum centre-line temperature to H/mc can be evaluated as 1.47, giving the flame tip temperature rise as 470 degC. This is of the same order but is less than the temperature at which a hot carbon particle is visible.

For a flame idealised in the form of a cone or a pyramid with the burner as a base the vertical projection of the flame envelope may be taken as $\pi DL/2$ for a circular base and 2DL for a square fire. The total rate of air entrainment for a square-based fire will therefore be expected to be about

$$m_o = 0.06 \times 10^{-3}\; 2DL\sqrt{gL} \qquad \text{in c.g.s. units.}$$

If instead of equation (12i) a line were drawn through the data of Fig.3 having a slope of $\frac{1}{3}$, a slight distortion is introduced but this makes the comparison between theory and experiment much easier. The best line of slope $\frac{1}{3}$ is

$$\frac{L}{D} = 420\left(\frac{m_w^2}{D^5}\right)^{\frac{1}{3}} \qquad \text{c.g.s. units} \qquad \ldots\ldots\ldots\ldots (21)$$

Eliminating L by means of equation (21) gives the ratio of air to fuel (m_o/m_w) as 33.

For a radially symmetrical source the factor 1.47 is replaced by 1.67 as a result of applying the appropriate plume equations and it may then be shown that the air/fuel ratio 33, corresponds to a flame tip temperature rise of 510 degC. In view of the assumptions and approximations made, these results can be regarded as satisfactory.

A PRACTICAL APPLICATION OF ENTRAINMENT CALCULATIONS TO FIRE PROTECTION WITHIN BUILDINGS

An interesting practical problem arises in the control of fire spread in a building without a complete fire division wall. Consider a fire extending over that area of the floor beneath a part of the ceiling bounded by vertical curtains extending down from the ceiling, as illustrated in Fig.8. Air enters the fire from four sides and hot gases are exhausted through a hole in the roof. It is assumed that the total inlet area is large enough in relation to the roof vent for the horizontal air flow to be given by equation (21). The value of the vent area A is sought for given values of building height h curtain depth d curtain perimeter p and curtained area a. For $\theta = 1000$ degC and $T_o = 290$ degK the application of equations (5) and (21) gives the total air flow, neglecting effects at the corners, as

$$m_o = 0.06 \times 10^{-3} \sqrt{g\,(h-d)}\; p\,(h-d)$$

The mass rate of fuel input is $m''_1 a$. With 0.6 as the discharge coefficient for the roof vent, the discharge due solely to the buoyancy of hot gases of depth d is calculated as

$$0.6\ \rho_{fl}\ A \sqrt{2g\ \theta_{fl}\ d/T_o}$$

Combining these quantities and inserting numerical values

$$1.9_4 \times 10^{-3}\, p\,(h-d)^{3/2} + m''a = 0.015\ A\sqrt{d} \qquad \text{..........}\ (22)$$

in c.g.s.units
which is the theoretical relationship between A and $h-d$ for no flames or hot gases to emerge under the curtain. Some experiments were made with $a = 61$ cm^2 $d = 30$ cm, $p = 244$ cm and $m''a = 6$ gram/s of town gas. The measured and calculated results given in Table 2 agree satisfactorily. The calculations are for no spill of hot gas while the observations refer to no visible flame.

TABLE 2

Heights of opening to prevent spillage of flame

Vent area A cm^2	Opening height (h-d)	
	Measured cm	Calculated cm
232	8	8.5
522	21	17
932	33	28

If this is the major part of the explanation for the slight difference, practical applications of this method will incorporate a safety factor.

Calculations for this kind of situation employing methods described by Fujita[25], Kawagoe[26] and Yokoi[27] lead to air flows approximately an order larger and consequently to much greater vents or deeper curtains than are in fact necessary. This discrepancy arises because the method used by the Japanese workers is applicable only to situations where there is a relatively slow movement of the hot gases within the enclosure. This allows the velocity head of the inlet and outlet flow to be calculated from pressure differences arising within the enclosure as in conventional "chimney theory". Such large pressure differences do not arise where there is a significant vertical acceleration.

COMPARISON WITH YOKOI'S DATA

Yokoi[1] has measured temperatures at various heights above alcohol fires of various sizes and has employed the dimensionless parameters H and z/r appearing in equation (1) except that to make presumably a first approximation for the secondary effects of density in the "hot" part of the plume he has used the local density ρ instead of ρ_o. For different rectangular shapes of burning tray with sides W and l he took an equivalent radius

$$r = (Wl/\pi)^{\frac{1}{2}}$$

instead of D

and a shape factor

$$n = W/l$$

The range of H^2/r^5 which arises in equation (1) was relatively small, about 2:1, and although no data on flame heights are reported, only about 25 per cent variation in L/r would be expected on the basis of equation (12). The dimensionless relation similar to equation (1) was used by Yokoi to obtain flame heights taking a temperature rise of 500 or 550 degC to define the limits of the radiating region which may for practical purposes be regarded as the visible flame tip. These results may now be compared with those described earlier in this paper, using the criterion of 500 degC which as seen from the above is close to the values calculated from the entrainment of the air into the flame.

Inserting the value Yokoi employs for c, the value of ρ at 500 degC, 2500 cal/gram for the net convective calorific value of wood, and inserting θ_c = 500 degC, his correlation which is the form of equation (1) can be redrawn as a relation between $\frac{z}{r}$ and m_W^2/r^5 and a direct comparison made with the correlations given in this paper. However, to retain his results in their original form the reverse procedure was adopted, namely, equation (12) has in effect been superimposed on Yokoi's results as shown in Fig.9. The discrepancy in trend between the two sets of data is a result of their different basis. However, the results agree in the region of z/r in the range 2 to 3 corresponding to the heights of the flames for Yokoi's experiments.

Yokoi gives data relating the temperature rise to S, the distance along the trajectory of hot gas emerging from windows, when there is no wall above them, a condition Yokoi refers to as "free space".

He also gives data relating S to the corresponding vertical height z which is always less than S

In comparing these data with corresponding data on flame height the following approximations and assumptions have been made:-

(1) $z \doteqdot S$

(2) In equation (18) m_w is the total rate of burning whilst in Yokoi's correlation H is the heat passing through the window. It has been assumed that the difference in origin is partially compensated for by using L from the base of the window in a manner analogous to S from the top of the window. The error entailed in this procedure tends to decrease at large values of $\frac{L}{D}$ and z/r.

(3) Flame height and temperature depend on m' and H' respectively not on m and H.

In the region of z/r and (H) where the results follow the expected relation for a line source, i.e. $(H) \cdot z/r$ is constant; it would be expected from this last assumption that $(H) n^{\frac{1}{3}} z/r$ is constant.

Yokoi's data for different values of n do in fact follow this law as is seen in Fig.10 and the equation is

$$n^{\frac{1}{3}} \cdot (H) \cdot z/r = 1.0$$

where he uses half the window height for ℓ

After substituting for n and r the expression becomes

$$z = 1.0 \left(\frac{\pi T_0}{\rho^2 c^2 g}\right)^{\frac{1}{3}} \frac{H'^{\frac{2}{3}}}{\theta_c}$$

With T_0 290°K, $c = 0.24$ cal gram^{-1} °C^{-1} $\theta_c = 500$ degC $\rho =$ 0.000456 gram/cc and an effective calorific value of 2,500 cal/gram

$$z = 160 \; m'^{\frac{2}{3}}$$

which may be compared with equation (18) which is also plotted in Fig.10 in the equivalent form

$$n^{\frac{1}{3}} \cdot (H) \cdot z/r = 2.5 \qquad \text{............ (23)}$$

For line sources on the ground Yokoi gives

$$n^{\frac{1}{3}} \; (H) \; z/r = 1.76 \qquad \text{............ (24)}$$

also shown in Fig.10.

The discrepancy between this latter set of temperature data and the flame length data is less. To get still better agreement a higher effective calorific value or a lower temperature criterion would have to be assumed. Some increase in the assumed calorific value is possible of course, but not nearly enough to account for the discrepancy. A much lower temperature would not seem reasonable either. The use of the normal ambient density for air (1.3×10^{-3} gram/cc) makes the discrepancies greater.

There is however no real reason why there should be any close agreement although correlations exhibiting the same trends would be expected between the variables z and (H). On the one hand there is a variation in a parameter through a region where conservation of heat obtains and on the other a variation determined by the limiting position of an extended region of heat generation. It will be shown in the next section that a similar comparison can be usefully made when there is the added influence of a wind.

EFFECT OF WIND ON FLAME LENGTH

Cribs of white-pine sticks have been burnt in a wind. The experimental arrangement is shown in Fig.11. In order to vary the rate of burning independently of the overall base dimensions of the cribs, sticks of square sections 1, $\frac{1}{2}$ and $\frac{1}{4}$ inches were used. The cribs were 3 feet wide with their sides parallel to the wind protected by non-combustible board. The length of the cribs in the direction of the wind was varied from 6 inches to 2 feet and the cribs were all less than 6 inches high. The moisture content of each crib was determined and in most of the experiments it was 11 per cent though in some it was as low as 9 or as high as 15 per cent. Each crib was mounted on non-combustible insulating board extending to the lee and the whole supported on a balance and loss of wood from the crib was prevented by surrounding the lee side with wire netting. The results of experiments in still air have been referred to previously.

The speed of the applied wind which was in the range 5 – 15 ft/s was adjusted first to the required value using a vane anemometer. The crib was shielded and lit using a small quantity of kerosine and the shield removed after $1\frac{1}{2}$ min. The loss in weight of the crib was recorded and time-lapse photographs taken at 5-second intervals. The mass rate of burning was determined during the period when it was effectively constant and the ten or so photographs taken during that time were used to obtain average values of the flame length L to the tip of the continuous flame (Fig.11).

Values of the inclination of the flame and the height above ground were also obtained but will be reported elsewhere. In some of the early experiments the extension of the base board was very short and the results were studied to see if there was any noticeable difference arising from this. None that was significant compared with the experimental variation was found and these results were pooled with the others.

The results were analysed statistically and the following equation obtained:

$$\frac{L}{D} = 68 \left(\frac{m''^2}{\rho_0^2 g D}\right)^{0.43} \left(\frac{U^2}{gD}\right)^{-0.11} \qquad \text{.......... (25)}$$

where for the sake of presenting the results in dimensionless variables the value of ρ for air ρ_0 was inserted. Had the cribs not been effectively infinite or had the Reynolds number been relevant there would have been a residual effect of D over and above that in the two variables $\frac{m''^2}{D}$ and $\frac{U^2}{D}$. There was in fact a slight one but it was not significant at the 5 per cent level. Its sign was positive, i.e. $\frac{L}{D}$ increased slightly with D and this probably corresponds to an effect of

Reynolds number not of crib width. The range of Reynolds number (UD/ν) was 10^4 to 2×10^5 and over this range flame length varied as

$$L \propto R_e^{\,0.08} \text{ for a given } \frac{m''^2}{D} \text{ and } \frac{U^2}{D} \qquad \ldots\ldots\ldots\ldots (26)$$

In some experiments the Reynolds number at the base of the flame was below 10^3 but there was no systematic effect on L and moreover this is not regarded as a major criterion, the more relevant Grashof number based on the height of the top of the flame was in the range 10^8 to 5×10^{10}. In view of the weakness, and lack of statistical significance of the effect it was disregarded.

The results are shown graphically in Fig.12 as $\frac{L}{D}\left(\frac{U^2}{gD}\right)^{0.11}$ plotted against $m''/\rho_0\sqrt{gD}$. The range of values of $\frac{U^2}{gD}$ was between 0.5 and 20. For comparison the data from Fig.7 are also shown with $\left(\frac{U^2}{gD}\right)^{0.11}$ nominally constant at 0.82.

The standard deviation of the individual results about the regression line of equation (25) corresponds to ± 16 per cent and the overall correlation coefficient was 0.985. No part of this variation could be ascribed to the variation in moisture content. Further controlled experiments are being made to explore this factor.

There are two points of interest in equation (25) and Fig.12. Firstly, the index 0.43 is somewhat larger than was found in any of the preceeding correlations but the graphical plot in Fig.12 shows that a power law is an approximation only and at large values of $\frac{L}{D}$ the index is lower and the results lie closer to those for strip sources and windows in still air where the index is $\frac{1}{3}$.

Secondly, the effect of wind speed on flame length is relatively small.

Over a range of 4.5 in $\frac{U}{gD}$, L varies by only 37 per cent. Other results show that the height which the flame reaches above the ground is affected much more.

The reduction in flame length with increasing wind speed is presumably a result of better mixing.

Equation (25) can be rearranged with no loss of accuracy as

$$L\left(\frac{g\rho_0^2}{m'^2}\right)^{\frac{1}{3}} = 68\left(\frac{U\rho_0^{1/3}}{(m'g)^{1/3}}\right)^{-0.21}\left(\frac{m''^2}{\rho_0^2 gD}\right)^{0.06}$$

where $m' = m''D$

It may be noted in passing that the variable containing L is related to χ as defined in equation (16).

To obtain the equation for a line source

$$L\left(\frac{g\rho_0^2}{m'^2}\right)^{1/3}\left(\frac{U\rho_0^{1/3}}{(m'g)^{1/3}}\right)^{0.21}$$

was plotted linearly against $\frac{D}{m''^2}$ and extrapolated to the zero value of $\frac{D}{m''^2}$

This gives a provisional equation for a line source as

$$L \left(\frac{g\rho_0^2}{m'^2}\right)^{\frac{1}{3}} = (55 \pm 5) \left(\frac{U\rho_0^{1/3}}{(m'g)^{1/3}}\right)^{-0.21} \qquad \ldots\ldots\ (27)$$

and this equation is shown in Fig.13.

The results for strip sources tend, at large values of $\frac{L}{D}$, to approach equation (18) (Figs.7 and 12) which corresponds to

$$L \left(\frac{g\rho_0^2}{m'^2}\right)^{\frac{1}{3}} = 47$$

This may be taken as a limiting value for zero wind speed and is shown as such in Fig.13.

In the same way as the data for flames in still air have been compared with Yokoi's temperature data, equation (27) can be compared with a dimensionless correlation obtained from Rankine's data[28]. This will be described in more detail[23] elsewhere, but a brief outline of the comparison follows. Rankine measured velocities and the temperature rise (always less than 30 degC) at various distances downwind and above ground from a line burner over a range of heat outputs from 3-35 cal cm^{-1} s^{-1} and wind speeds of 45-150 cm/s. Except near to the ground the temperature data would be expected on dimensional grounds to be correlated by

$$\Theta_x = \frac{\theta x}{(H'^2 T_0/\rho^2 c^2 g)^{1/3}} = f\left(\Omega, \frac{z}{x}\right) \qquad \ldots\ldots\ (28)$$

where $\Omega = \left(\frac{\rho c T_0}{H' g}\right)^{1/3} U$

and except near the ground where there is heat loss and the cool edges of the flow, correlation based on these variables is very good.

Rankine's own detailed heat balance suggests there is about a 5 per cent loss to the ground and this has been disregarded here, as have the small variations in density in calculating the dimensionless parameters. The maximum value of Θ_x occurred slightly above the ground (at z/x in the range 0.05 to 0.07). This maximum was evaluated for each of a range of values of Ω. The following values were then inserted into Θ_x and Ω, $T_0 = 290°K$,

$\theta = 500$ degC, $\quad c = 0.24 \quad \rho = \frac{290}{790}\rho_0, \quad H' = 2500\ m'_w$

and $x = L$, where 2500 cal/gram was again taken as the effective calorific value of wood allowing for radiation loss, etc., and the flame tip has been assumed to be defined by a temperature rise of 500 degC. The relation between the maximum Θ_x and Ω then appears as a relation between $L\,(g\rho_0^2/m'^2)^{\frac{1}{3}}$, and $U\rho_0^{1/3}/(m'g)^{\frac{1}{3}}$ which has been plotted in Fig.13. Yokoi's data for line sources in still air (equation (24)) have similarly been used to obtain a limiting value of zero wind speed.

Unlike the results for flames, the trend is for dimensionless temperature to increase with wind speed though there is some sign that this increase is lower at higher wind speeds, but since small variations in heat loss might produce sufficient changes in Θ to make a weak trend reverse its direction, it is not possible to attach too much significance to this feature of the comparison without further analysis. What is interesting and from a practical point of view, useful, is that the actual values deduced for the dimensional flame length are comparable with the ones measured in what is in fact a very different experiment.

DISCUSSION - CONCLUSIONS

It has proved possible to apply a highly simplified dimensionless analysis to relating flame length to rate of burning and scale. Limitations to the accuracy of these experiments are not of much consequence to the type of practical application envisaged but preclude a discussion of some of the detailed aspects of the behaviour and more experimental results are required, particularly for the effect of wind on flames to pursue some of the questions involved. Nevertheless, reasonable quantitative agreement has been achieved in relating the concepts of entrainment in plumes to the determination of flame size and the work has been in part related to similar work on the scaling of flow of hot gases.

ACKNOWLEDGMENT

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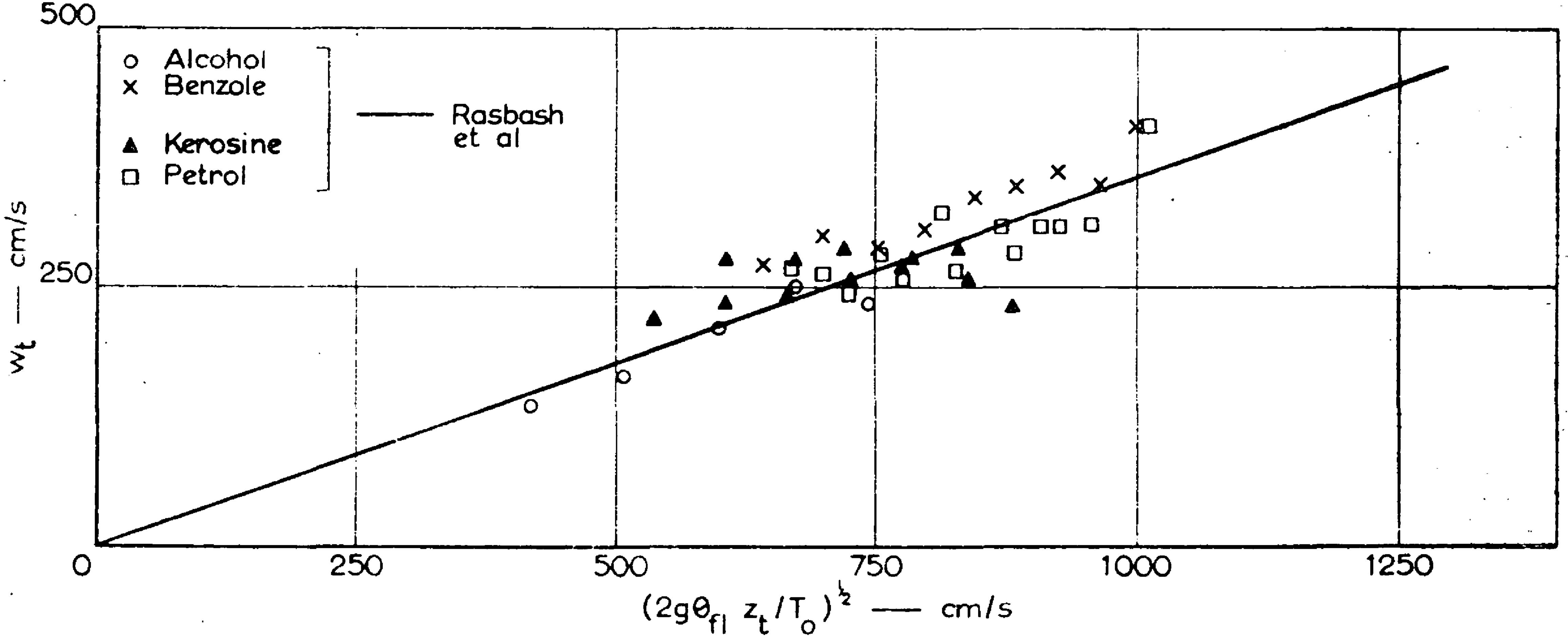

FIG. 1. UPWARD VELOCITY OF FLAME TIP

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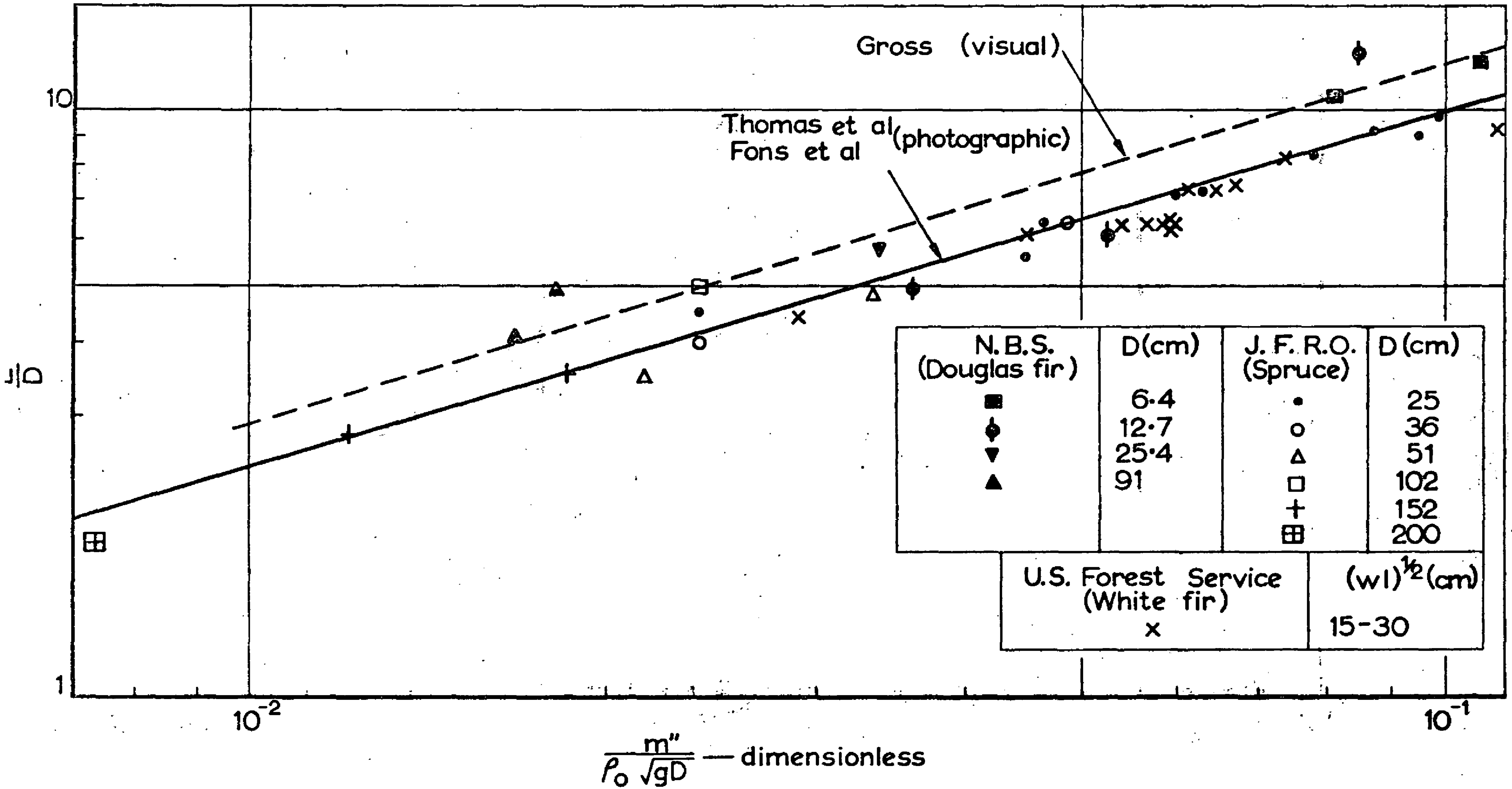


FIG. 3. CORRELATION OF FLAME HEIGHT DATA
Still air – approximately radially symmetrical

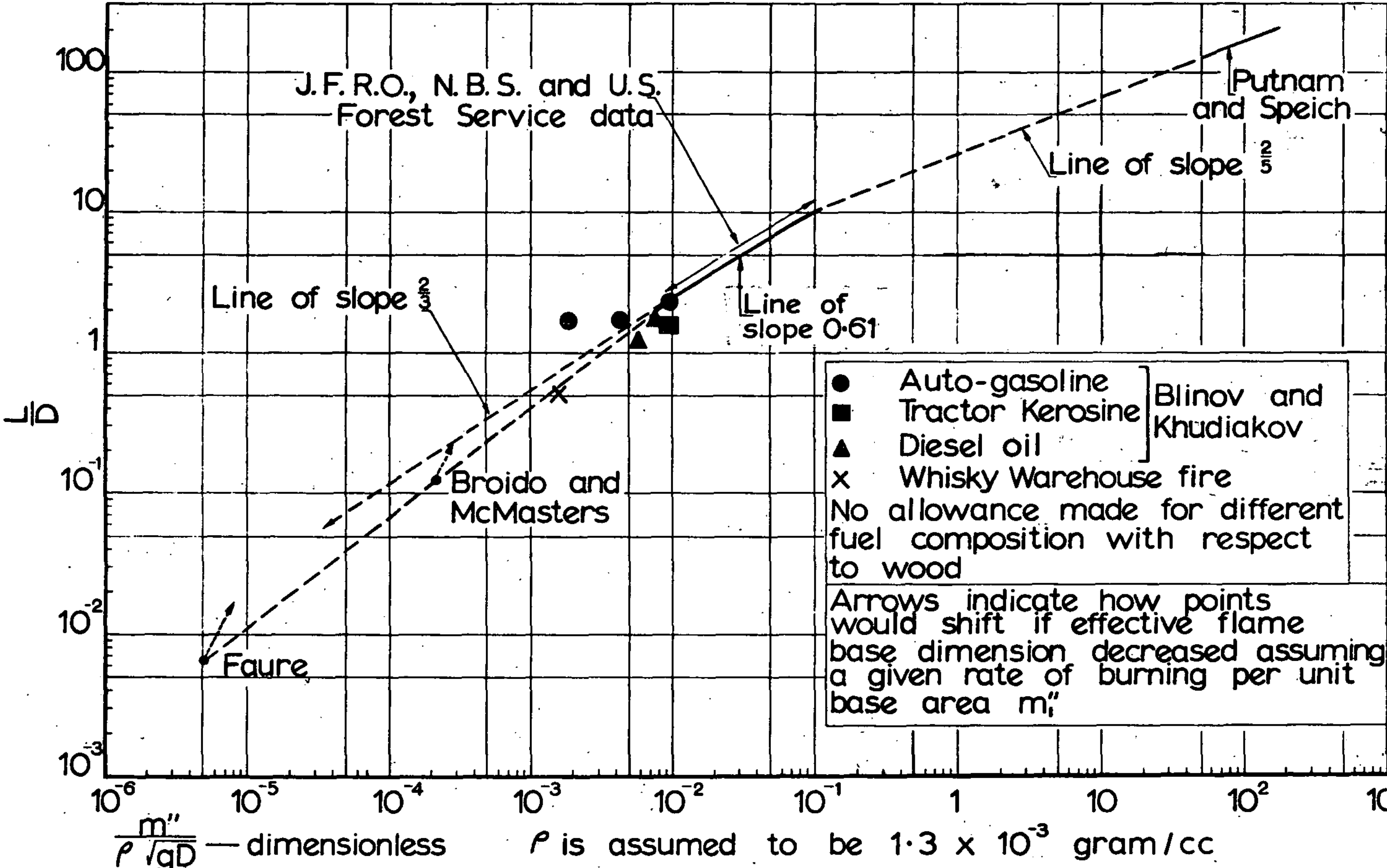
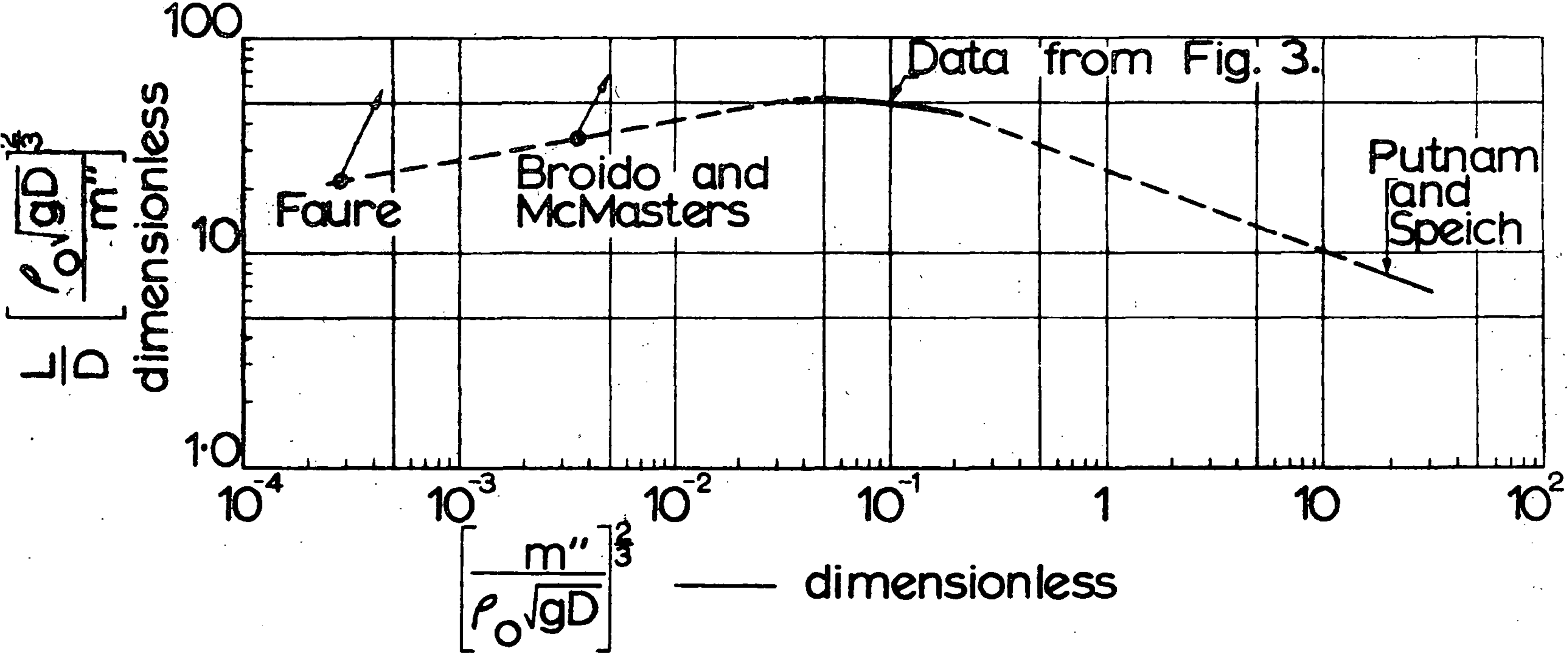


FIG. 4. FLAME HEIGHT CORRELATION



Arrows show effect of reducing D for a given m″

FIG. 5. FLAME HEIGHT CORRELATION (MODIFIED SCALES)

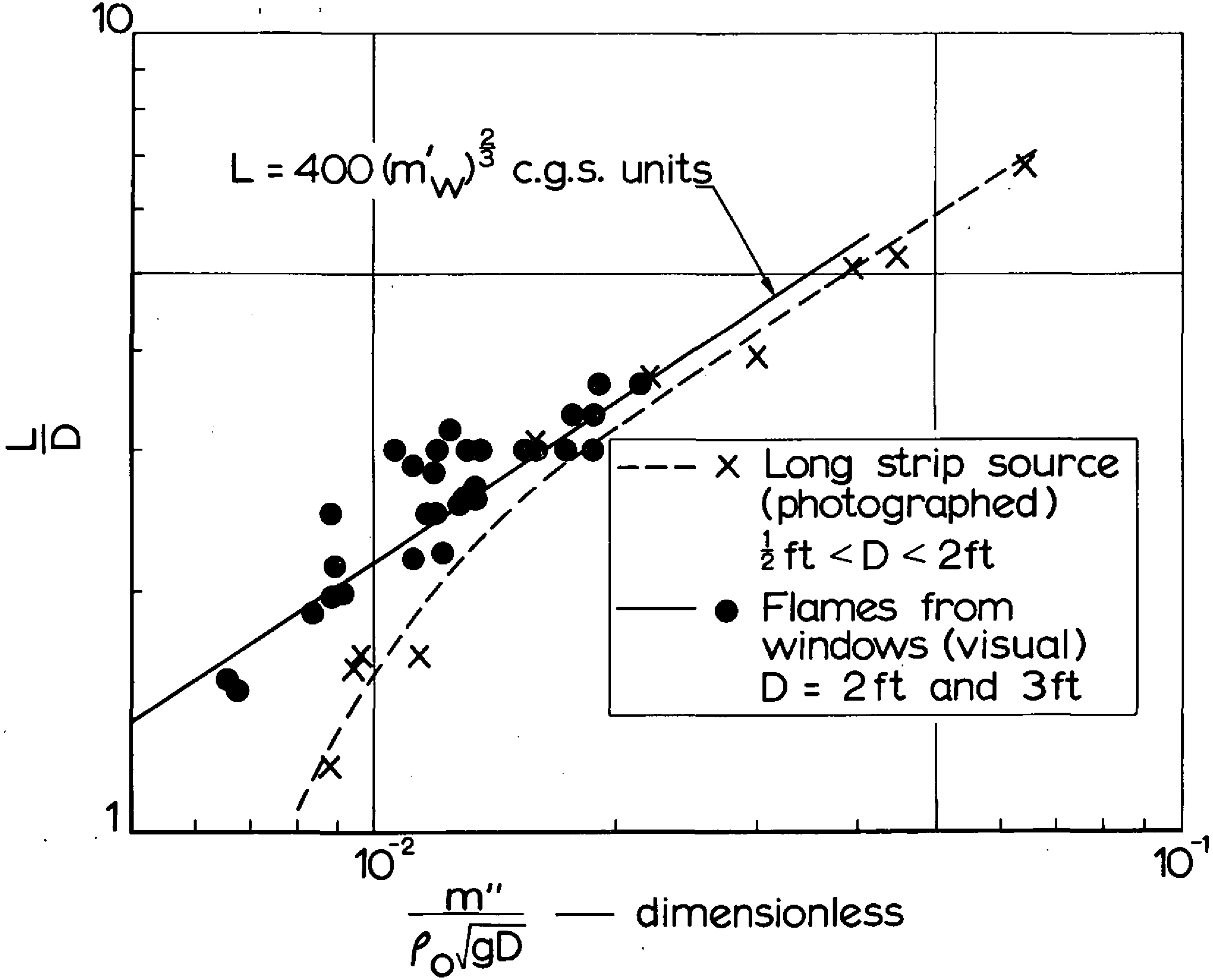


FIG. 7. FLAMES FROM LONG STRIPS AND WINDOWS

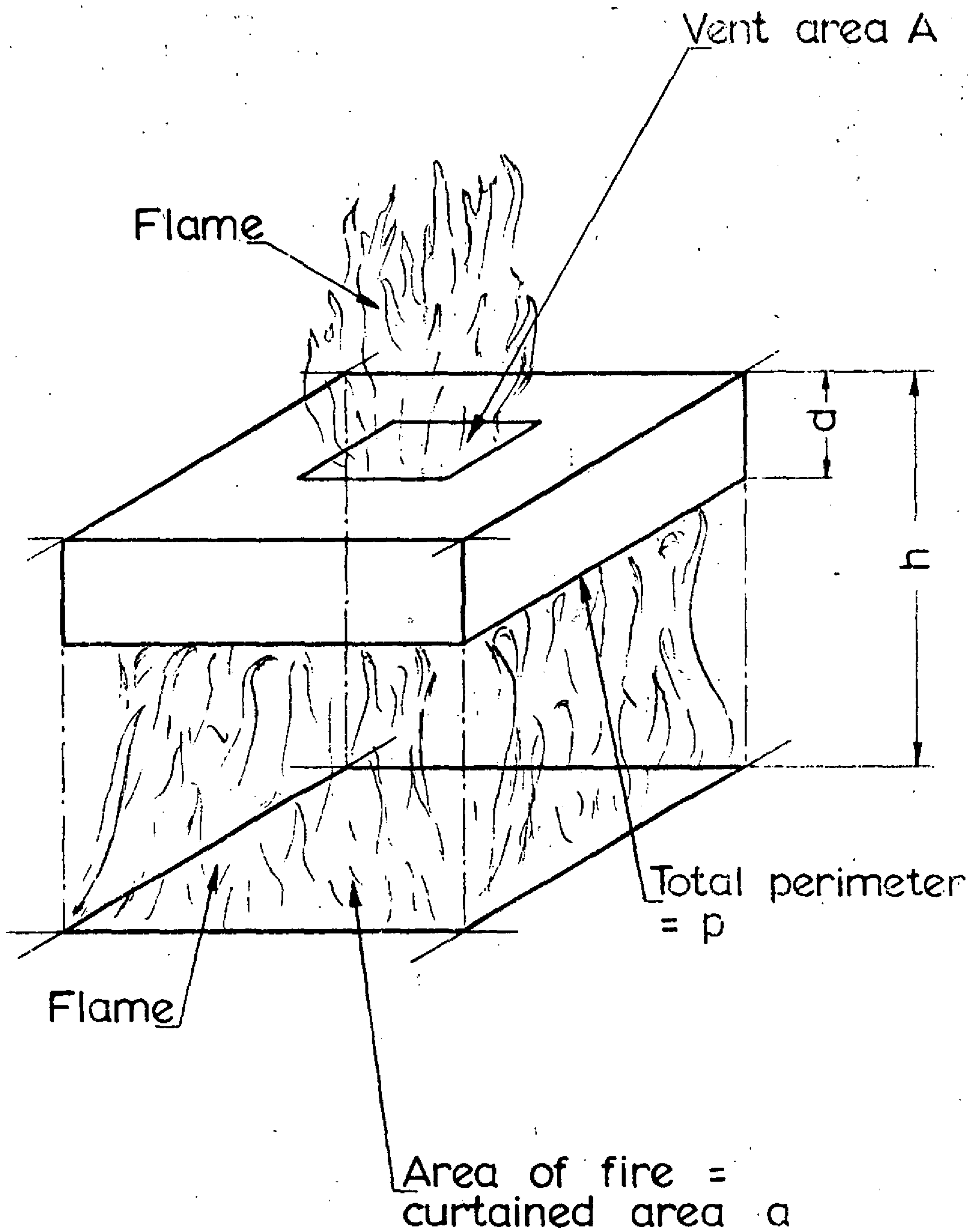
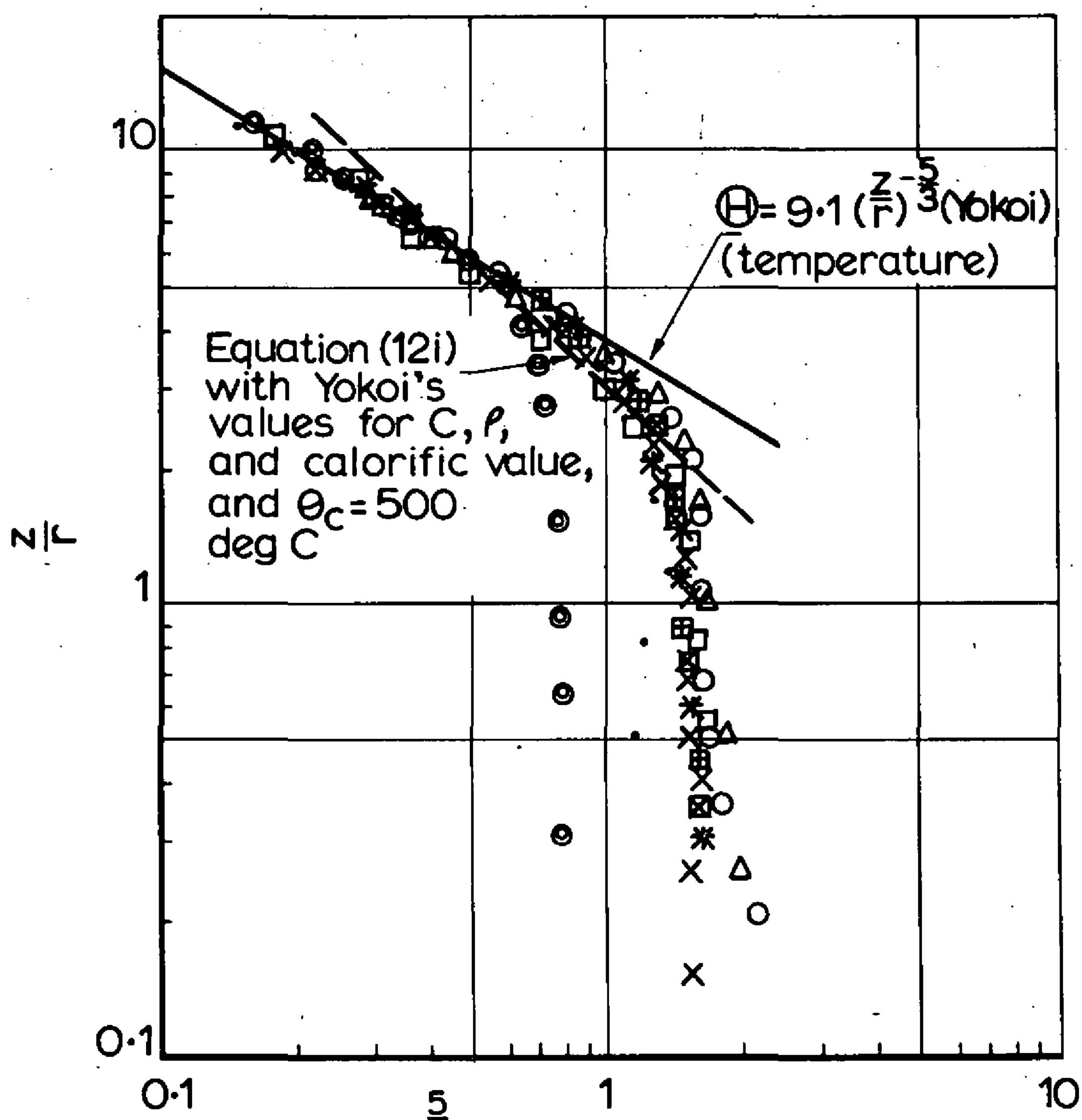


FIG. 8. DIAGRAMMATIC SKETCH OF EXPERIMENT SIMULATING ROOF VENTING OF A LARGE FIRE



$$\Theta = \frac{\theta_c r^{\frac{5}{3}}}{\left[\frac{H^2 T_0}{C^2 \rho^2 g}\right]^{\frac{1}{3}}}$$ ——— dimensionless

Continuous heat sources

Symbol	r cm
⊚	3·3
•	6
×	9·9
⊠	14·3
□	18·75
⊞	23·8
✱	37·5

Discontinuous heat sources

Symbol	r cm
△	16
○	20

FIG. 9. CORRELATION FOR HORIZONTAL CIRCULAR AND SQUARE HEAT SOURCES

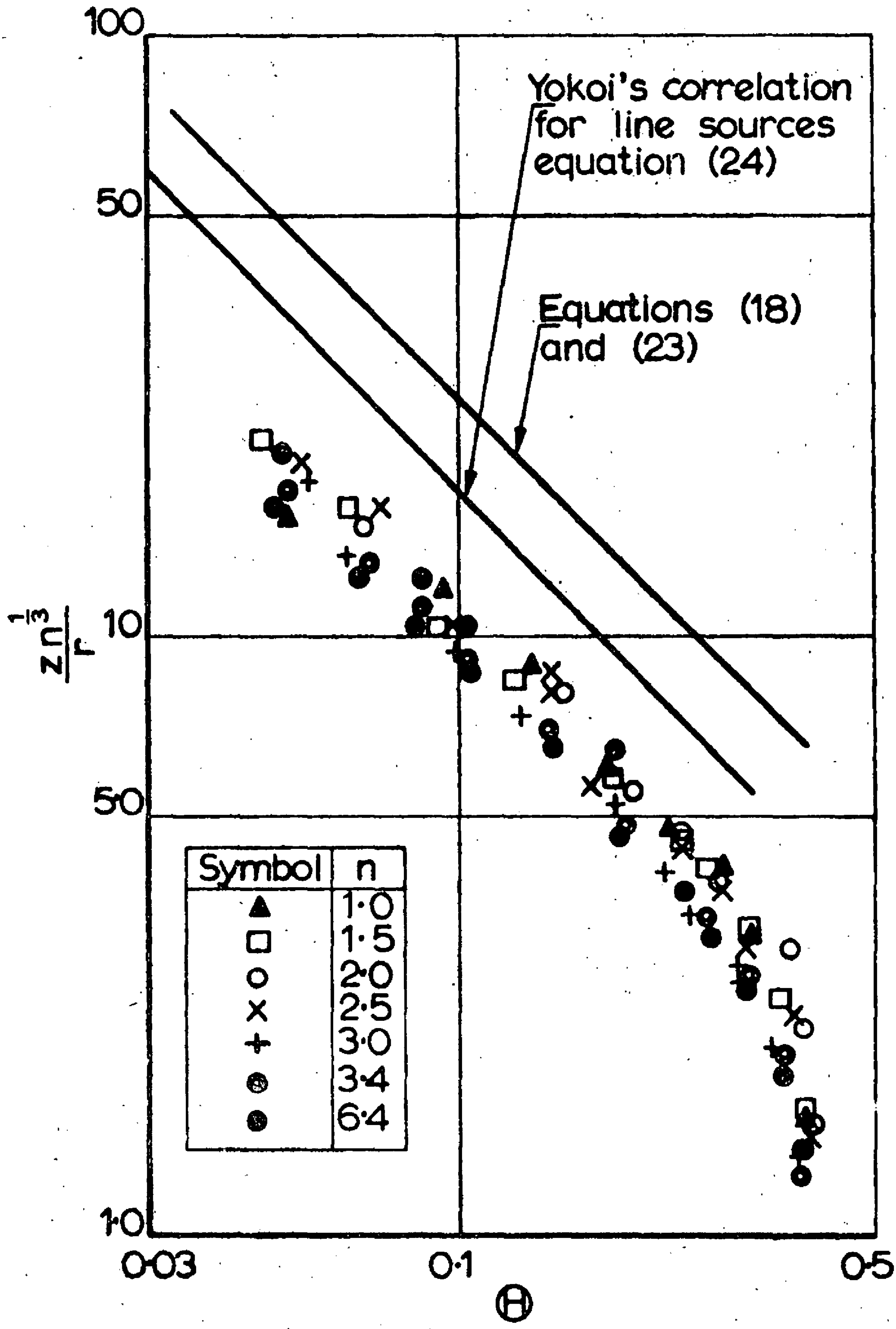


FIG. 10. YOKOI'S DATA REPLOTTED AS $\frac{zn^{\frac{1}{3}}}{r}$ (HOT GASES FROM WINDOWS)

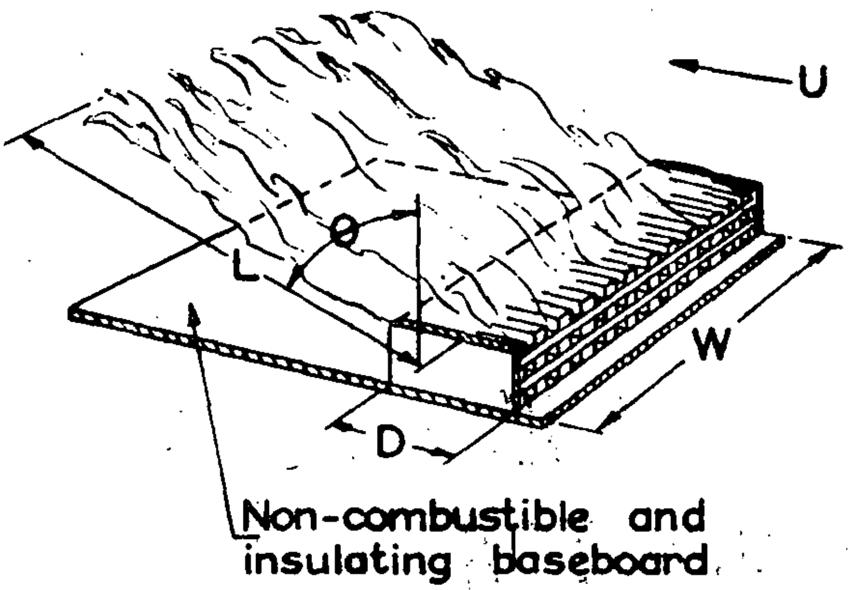


FIG. 11. CRIBS BURNING IN A WIND (DIAGRAMMATIC SKETCH OF EXPERIMENTAL ARRANGEMENT)

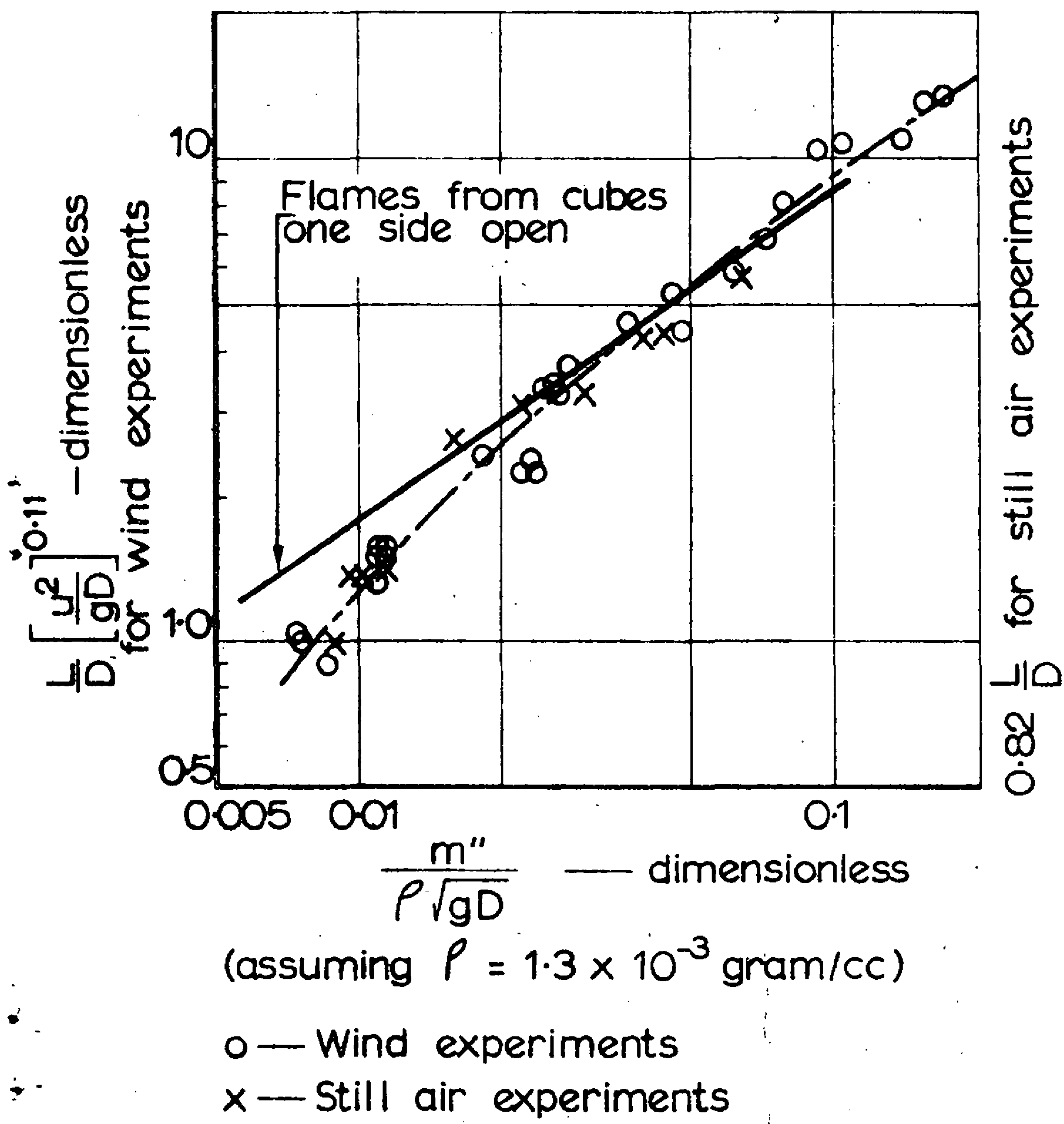


FIG. 12. EFFECT OF WIND SPEED AND BURNING RATE ON FLAME LENGTH

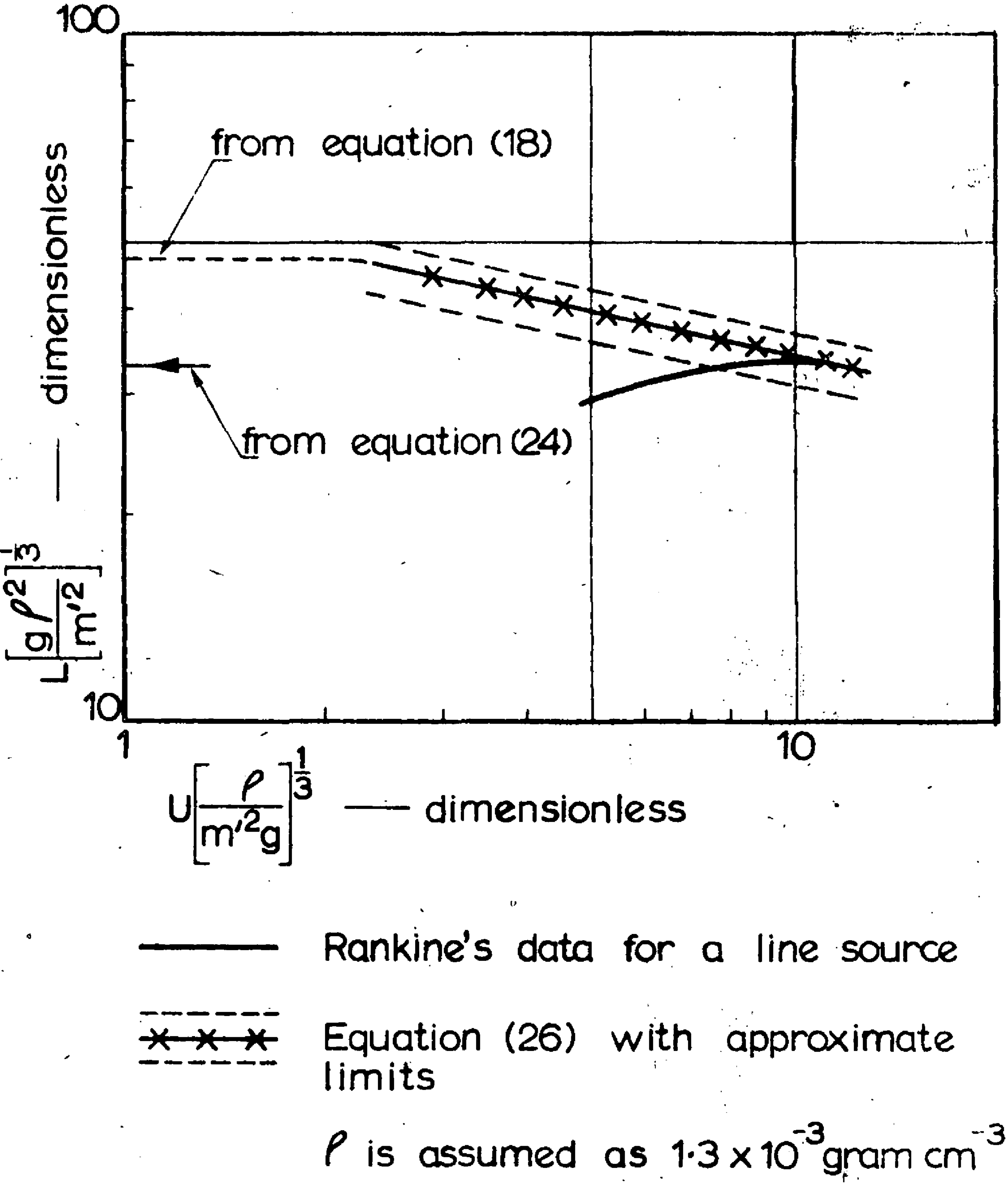
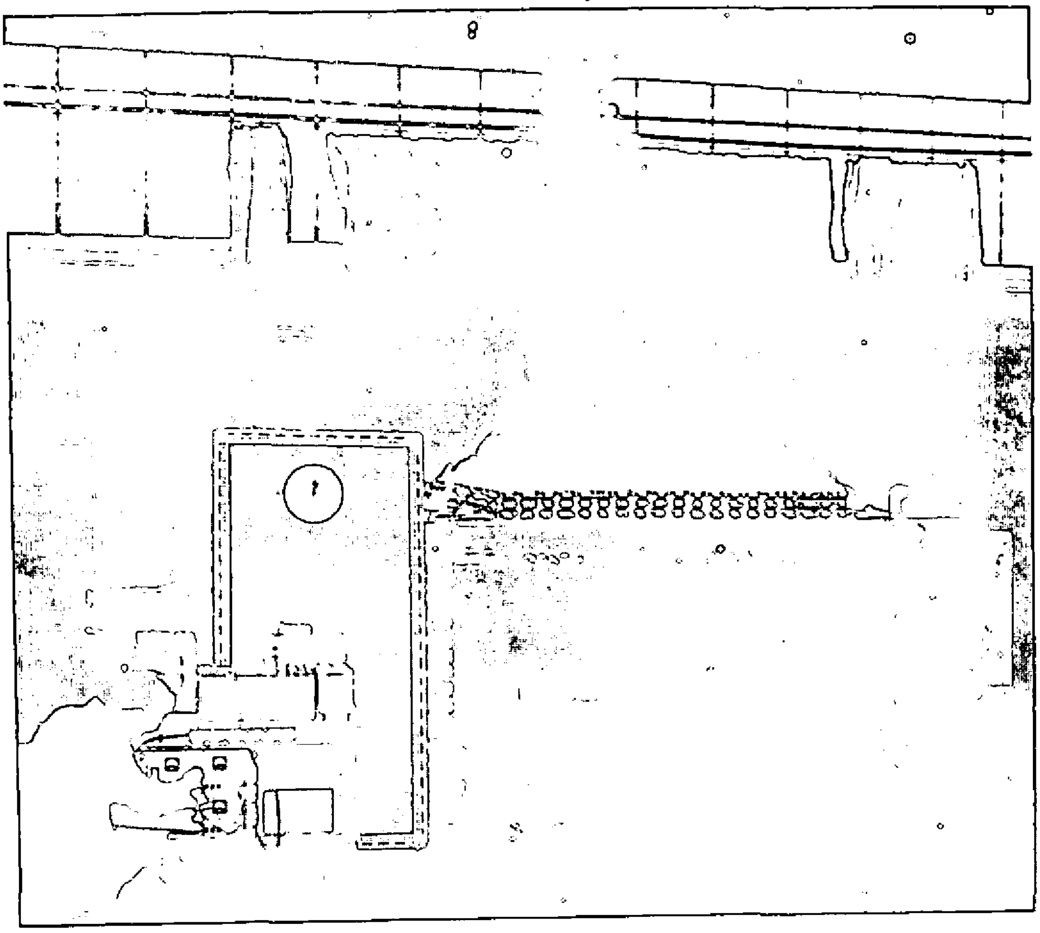
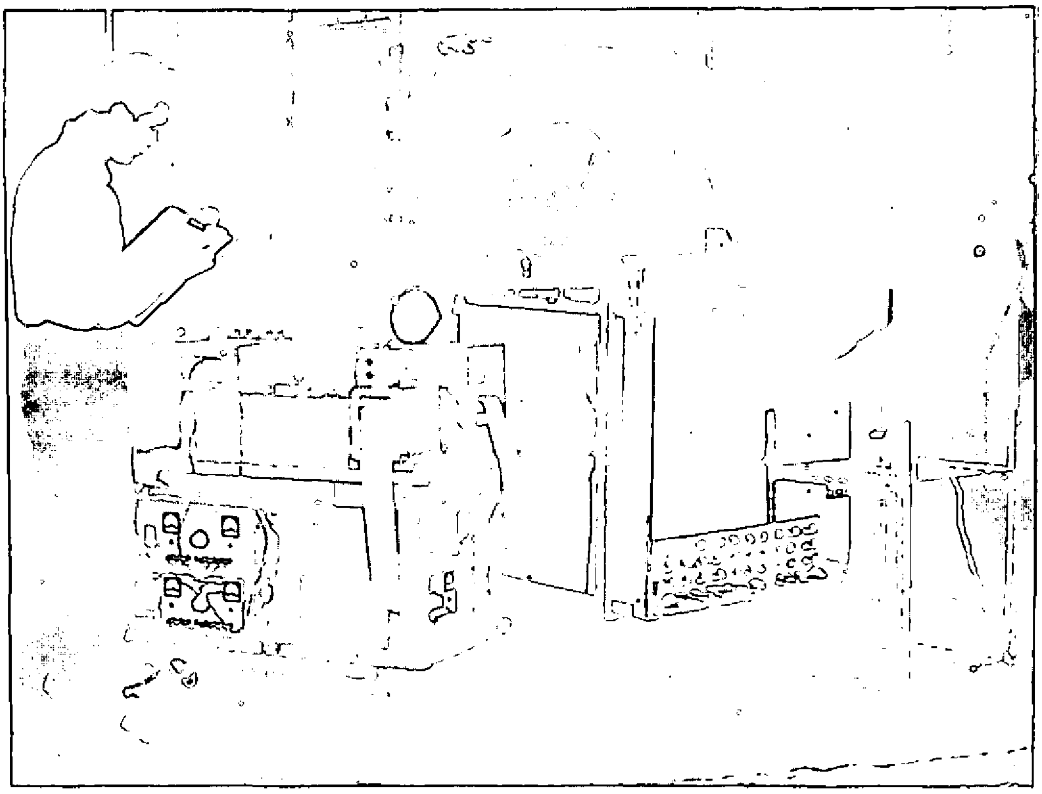


FIG. 13. ESTIMATED CORRELATION FOR A LINE SOURCE



FLAMES FROM CRIB ON SQUARE BASE OF 101 CM
(EXPOSURE TIME 1/10 SEC.)

FIG. 2



GENERAL VIEW OF EXPERIMENTAL ARRANGEMENT
FOR STUDYING FIRES FROM CRIBS BURNING IN
CUBICAL ENCLOSURES (MEASURED SCALE NOT SHOWN)
(EXPOSURE TIME 1/10 SEC.)

FIG. 6