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ON THE SIZE AND ORIENTATION OF BUOYANT DIFFUSION FLAMES AND THE EFFECT OF WIND

by

P. H. Thomas, R. W. Pickard and H. G. H. Wraight.

Summary

The length of a flame and the height to which it rises above a long horizontal wood fire have been measured for a range of values of the burning rate per unit base area of burning zone, wind speed, and size of burning zone. It is shown that the results can be expressed in forms derived from dimensional analysis.

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1. Introduction

The work described in this paper forms part of a programme designed to study the rate of spread of fire in forestry materials. This type of fire generally advances on a wide front, the rate of spread being dependent on the extent of the heating of the unburnt fuel ahead of the burning zone. The thermal radiation from the flames may play an important part in this heating and this depends, amongst other factors, on the size and orientation of the flames. Further, an estimate of flame size enables the minimum requirements for the design of firebreaks to be made and is of general interest also.

The rate of development of a forest or heathland fire will depend on many factors such as the type and geometry of the fuel involved and its moisture content. A factor common to all fires which occur in the open, however, is that of wind. The winds which frequently occur in the U.K. will affect this type of fire since their speeds are generally of the same order as those due to the natural convection in fires. The velocity of the rising hot gas will be shown to be approximately $\sqrt{gL}$ where g is the acceleration due to gravity and L the flame height. For flames 3 ft high, this velocity is of order 10 ft/sec, the same order as commonly occurring in natural winds.

As a result of the installation of a large wind producing apparatus(1) at the Fire Research Station a study of the effect of wind on fires has been possible and this paper is concerned with the way in which wind will affect the size and orientation of flames as a first step in determining its effect on the rate of spread of fire.

2. Theory

The height of flames in still air from the windows of burning enclosures, from horizontal wooden cribs on a square base and from strips of fabric burning vertically have been studied previously(2). By the application of diffusion theory to buoyant flames it was shown that for one particular fuel a general relationship between the flame height L, volumetric flow rate of gaseous fuel Q_f, and a characteristic dimension of the fuel source D, could be derived.

A somewhat different argument to that previously presented can be employed to derive the general result below. For any diffusion flame of a given fuel/air system in still air we have,

$$\rho_f \quad Q_f = k\, Q_a \rho_a \qquad (1)$$

where Q_f is the volumetric rate of supply of fuel of density ρ_f (at temperature of fuel source)

Q_a is the volumetric rate of entrainment of air at density ρ_a into the flame zone

and k is a constant for any fuel

The surface over which air is entrained may be represented by $D^2 f(\frac{L}{D})$ where f is a shape factor for the flame zone and we therefore have

$$Q_a \propto \bar{V}_e D^2 f\,(\frac{L}{D}) \qquad (2i)$$

where $\bar{V}_e$ is the velocity of the inflowing air and the bar denotes a mean value

We next assume that the momentum per unit mass of the entrained inflow $\rho_a V_e^2$, is proportional(3) to the mean momentum per unit mass of rising gas $\rho_{fl}\bar{\omega}^2$ where ρ_{fl} is the density of the gases in the flame zone and ω is the velocity of rising gases

$$\text{i.e.}\quad \bar{V}_e \propto \bar{w}\sqrt{\rho_{fl}/\rho_a} \qquad (2ii)$$

For a turbulent fuel jet the flow pattern everywhere is determined by the conditions in the "burner or fire", where the velocity is proportional to Q_f/D^2. It follows that $\bar{w} \propto Q_f/D^2$ and from equations (1) and (2) with a given k, and a given ρ_{fl}/ρ_a and a given ρ_f/ρ_a that $f\ (\frac{L}{D})$ and hence $\frac{L}{D}$ is constant. This is the well known law for turbulent fuel jets(4).

In a flame of negligible initial momentum w is determined by buoyancy rather than by conditions at the "burner" and from dimensional arguments we assume that

$$\bar{w} \propto \sqrt{\frac{gL(\rho_a - \rho_{fl})}{\rho_{fl}}}\ F_1\,(\frac{L}{D}) \qquad (3)$$

F_1 is some function dependent on flame shape from which it follows that

$$\bar{V}_e \propto \sqrt{gL\,\frac{\Delta\rho}{\rho_a}}\ F_1\,(\frac{L}{D}) \qquad (3i)$$

where $\Delta\rho = \rho_a - \rho_{fl}$

We can replace $\Delta\rho/\rho_a$ by θ_{fl}/T_{fl} where T_{fl} is the absolute temperature and θ_{fl} the temperature rise in the flame zone above ambient. In particular we have

$$\bar{w} \propto \sqrt{\frac{gL\,\theta_{fl}}{T_o}}\;F\left(\frac{L}{D}\right) \qquad (3ii)$$

There are indeed some experimental data to support this equation. Rasbash et al[5] measured the rate of rise of the flame tip in still air during the ascent of the flame prior to the breaking away of the top of the flame. The flame tip rises gradually up to a point and then suddenly collapses before the cycle starts again. Photographic measurements of this rise were made for four different fuels - alcohol, kerosene, benzole and petrol. It was found that the velocity was a function of the instantaneous height and the time for which the fuel had been burning. In each case the data were analysed as linear regressions involving linear variation of velocity with height and time, the coefficients varying with the fuel.

The results are plotted for the mean time of burning in Fig.1. Because the maximum possible vertical velocity at a height z neglecting friction and the lateral transfer of momentum is

$$\sqrt{\frac{2g\,Z_t\,\theta_{fl}}{T_o}}$$

where T_o is taken as 290°K

and Z_t is the instantaneous height of the flame tip (L denoting the mean), this quantity has been used as a horizontal scale in Fig.1.

Measurements were made of the mean flame temperature and these varied from 921°C for benzole to 1214°C for alcohol.

The line drawn in Fig.1 follows

$$w_t = 0.38\sqrt{\frac{2g\,Z_t\,\theta_{fl}}{T_o}} \qquad (4)$$

For a nominal mean temperature rise of 1050°C

$$w_t = 1.0\sqrt{g\,Z_t} \qquad (4i)$$

Heselden[6] has measured the rate of rise of the tip of a town gas flame for a constant rate of burning and his results are also shown in Fig.1 and give coefficients about 10 per cent less than those in equations (4) and (4i).

Further experiments are to be made to investigate the general validity of equation (3i) but the above results are consistent with the special case of it at the flame tip.

Returning then to equations (1), (2) and (3) we have

$$Q_f \propto \sqrt{\frac{g\,L\,\Delta\rho}{\rho_a}}\;\frac{\rho_a}{\rho_f}\;F_1\left(\frac{L}{D}\right).D^2.f\left(\frac{L}{D}\right) \qquad (5i)$$

from which

$$\frac{L}{D} = F_2\left(\frac{Q_f^2\,\rho_f^2}{g\,D^5\,\rho_a\,\Delta\rho}\right) \qquad (5ii)$$

For flames from a given fuel system we assume that $\Delta\rho/\rho_a$ which for ideal gases depends only on the ambient temperature and the mean flame zone temperature is constant. It is anyway a much less powerful term than Q^2/D^5.

Therefore $$\frac{L}{D} = F_2\left(\frac{\rho_f^2\,Q_f^2}{\rho_a^2\,gD^5}\right) \qquad (6)$$

Generalizing equation (3ii) so that $\bar{w}$ and hence $\bar{V}_e$ depend on the ratio of velocity head at the burner to buoyancy head makes no difference to equation (6) except that ρ_f/ρ_a appears as a separate dimensionless group.

When an additional variable U the wind speed is included equation (6) must be modified by including a further dimensionless parameter involving U. If one assumes that the flames are fully turbulent so that $\frac{L}{D}$ is independent of viscosity and hence of Reynolds number the appropriate parameter is the Froude number $\frac{U^2}{gD}$. The suggested general equation for a given fuel is thus

$$\frac{L}{D} = \phi\left(\frac{Q_f^2\,\rho_f^2}{gD^5\,\rho_a^2}\,,\;\frac{U^2}{gD}\right) \qquad (7)$$

where ϕ is an unspecified function. In an actual fire Q_f will depend on U but here they are regarded as independent variables.

The experiments to be described in this paper were designed to examine the validity of this form of grouping of the variables Q_f, U and D and to determine, within the limits of their experimental values, the form of the function ϕ. As far as possible the fuel was designed to represent the burning zone of a fire spreading on a wide front with the wind direction perpendicular to the greater dimension which we shall designate the width. With this type of source the characteristic dimension D is the length of the source (measured in the direction of the wind) which is small compared with its width W. Further, since it is to be expected that the flame length and orientation will be independent of the width we may consider only a square section of the fuel source of side D. If the volumetric fuel rate per unit area from this section is Q_f'' then Q_f is replaced by $Q_f'' D^2$ in equation (2). In practice a mass fuel rate is measured, i.e. $\rho_f Q_f$ where ρ_f is the fuel density at the temperature of its release from the solid fuel surface, i.e. the "burner". The mass rate of burning per unit base area m", is thus $\rho_f Q_f''$ and the form in which equation (7) is to be examined is

$$\frac{L}{D} = \phi_1 \left(\frac{m''^2}{g \rho_a^2 D} , \frac{U^2}{gD} \right) \qquad (8)$$

Although $\Delta\rho/\rho_a$ has been treated as constant, some thermal radiation measurements from flames subject to an imposed wind[7] have indicated that the flame temperature may be a function of U. If we assume, however, that $\Delta\rho/\rho_a$ is a function of U^2/gD only, for a given fuel we may still write :

$$\frac{L}{D} = \phi_2 \left(\frac{m''^2}{g \rho_a^2 D} , \frac{U^2}{gD} \right) \qquad (9i)$$

Small changes in θ_f may make an important difference to the radiation and hence to m". But that part of the fractional change in θ_{f1} which is not correlated with U^2/gD is unlikely to be large, and therefore has been assumed to have no great effect on the buoyancy.

A characteristic constant value of $\Delta\rho/\rho_a$ is implicit in equation (9i).

Another property of the flame which may be expected to depend on the same parameters as the flame length is the maximum height of flame H (Fig.4.). This is a useful property in estimating the extent of the heating of unburnt fuel ahead of the burning zone by the flames above the surface of the fuel. One expects a functional relation of the form

$$\frac{H}{D} = \psi_1 \left(\frac{m''^2}{g \rho_a^2 D} \right), \left(\frac{U^2}{gD} \right) \qquad (9ii)$$

If when D becomes small the value of m" remains small compared with $\rho\sqrt{gH}$ the orifice momentum will not have any effect in determining the flow pattern. Only under such circumstances will the significance of m" in equations (8) (9i) and (9ii) be one of fuel quantity not fuel momentum. It would then follow that when D/H becomes small H cannot depend on D which loses its significance except when combined with m" in the form m"D for a strip (line) source and $m''D^2$ for a square (point) source. Equation (9ii) degenerates for a line source of low momentum to

$$H = \frac{U^2}{g} \psi_2 \left(\frac{g\, m''D}{\rho_a U^3} \right) \qquad (10)$$

and similarly for L.

Such a simplification will not apply if $D \rightarrow 0$ while $m''D$ remains approximately constant since m'' must then increase and the initial momentum of the fuel would become important. On the other hand if $m''D$ does decrease the flow cannot remain turbulent. In principle, the simplification implicit in equation (10) will have only a limited range of usefulness.

Since only one fuel has been examined we shall not be able to explore the effect of ρ_f/ρ_a or θ_{fl} and for the purposes of this paper dimensionless variables are plotted in the graphs using the value for air of 0.080 lb/cub.ft.

3. Experimental

The fuel used in these experiments was designed to represent at any instant the burning zone of a fire spreading on a wide front. For this purpose wooden cribs constructed of White Pine in square section sticks were used (Plate 1). In order to vary the rate of burning of the cribs independently of their dimensions sticks of 1, ½ and ¼ in. section were used. All the cribs were 3 ft wide with their sides (parallel to the wind) protected by incombustible boards to increase their effective width, Fig.2.

The length of the crib D was varied between 6 in. and 2 ft. Those constructed of 1 in section timber were 4 in high with a ratio of spacing to stick size of 3 to 1. The same spacing to stick size ratio was used with the ½ in. section timber but the crib height was 6 in. Those constructed of ¼ in. section had a spacing to stick size ratio of 5 to 1 with a height of 6 in.

The moisture content of the timber was controlled as closely as possible by conditioning all the wood at a temperature of 65°F and a relative humidity of 65 per cent prior to burning. The moisture content was 12 ± 3 per cent of the dry weight. (Table 1).

This variation was subsequently found to have no effect compared to other sources of experimental variation.

Each crib was mounted on a balance in the working section of a large wind producing apparatus. The width of the crib was perpendicular to the direction of the wind. In the majority of the experiments - the later ones - the base on which the crib was mounted was extended on the lee side by an incombustible board, (Plate 1). This represented ground in front of a spreading fire which will, in practice, restrict the flow of air to the underside of the flame. The lee side of the crib was protected by wire-netting to prevent the loss of wood from the crib due to the wind.

Each type of crib was burnt in still air and in three wind speeds between about 5 and 15 ft/sec. The wind speed was adjusted to the required value as measured by a vane anemometer (Plate 1) and the crib then shielded. It was ignited by strips of fibre insulating board treated with a small quantity of kerosene and allowed to burn for $1\frac{1}{2}$ minutes, after which the shield was removed.

The loss in weight of the crib was recorded and the experiment photographed throughout at 5 second intervals by a time-lapse camera. The mass rate of burning was determined over the period for which this remained constant. The flame length L and deflection ϕ were measured from the photographs, (Plate 2) over the same period and a mean value of each determined. The flame length was defined as the length of the line joining the mean flame tip to the central axis in the upper surface of the crib in the direction of its width. The maximum height H of any part of the main body of flame above the top surface of the crib was also determined. The deflection was defined as the angle between the line defining the flame length and the vertical. The data obtained from these experiments are given in Table 1, each value of L and H being the mean of about 10 values obtained from photographs taken at the time when the flame length was around its maximum. The results for ϕ will be dealt with in a separate report.

The Reynold's number relevant to the wind is UD/ν where ν is the kinematic viscosity of air. This is tabulated in Table 1 with ν taken as 1.6×10^{-4} ft^2/s or 0.15 cm^2/s. The Reynold's number for the gases leaving the fuel bed is $m''D/\mu$ where μ is the viscosity of fuel vapour which is also tabulated in Table 1. μ was taken as 10^{-4} C.G.S. units as a typical value.

TABLE 1

Experimental Data

Stick size	Length of crib D (ft)	Wind speed U (ft/sec)	Rate of burning per unit base area m" (lb/ft²/sec) x 10^3	Flame length L (ft)	Height of flame H above crib (ft)	Moisture content (per cent of dry weight)	Reynolds Number UD/ν_{air}	Reynolds Number $m''D/\mu_{fuel}$
1 in x 1 in	1.0	15.0	6.7	1.1	0.55*	12	93800	1000
	1.0	6.5	6.5	1.3	0.58	12	40600	970
	1.0	10.3	7.1	1.2	0.54	12	64400	1060
	1.5	5.7	4.1	1.6	0.79	11	53400	920
	1.5	9.8	4.2	1.4	0.50	11	91800	940
	1.5	17.7	4.9	1.1	0.35*	11	166000	1100
	2.0	5.7	6.4	2.9	1.85	12	71200	1910
	2.0	12.3	7.2	2.8	1.03	12	154000	2150
	2.0	15.4	7.5	2.6	0.82	12	193000	2240
	0.42	5.3	5.4	1.0	0.34	11	13900	340
	0.42	8.2	6.7	0.8	0.22*	11	21500	420
	0.42	13.1	7.2	0.7	0.12	11	34400	450
	1.5	5.2	6.1	2.1	0.98	11	48700	1370
	1.5	10.3	6.5	2.1	0.71	11	96500	1460
	1.5	14.7	6.2	2.0	0.66	11	13800	1390
½ in x ½ in	1.0	9.1	20.7	4.8	2.05	12	56900	3090
	1.0	15.0	25.9	6.7	1.88	12	93800	3870
	1.0	6.2	21.9	4.2	1.87	12	38700	3270
	0.5	18.4	34.0	4.0	0.94	14	57500	2540
	0.5	12.1	30.0	4.2	1.39	14	37800	2240
	0.5	6.9	23.3	3.1	1.36	14	21600	1740
	1.5	6.3	13.9	5.3	3.00	15	59000	3110
	1.5	10.0	15.3	5.3	2.07	15	93700	3420
	1.5	13.7	20.5	5.9	1.63	15	128000	4590
	2.0	5.5	15.0	5.2	3.44	16	68800	4480
	2.0	11.2	17.2	6.0	2.18	16	140000	5130
	2.0	12.5	16.5	6.2	2.20	16	156000	4920
¼ in x ¼ in	1.0	10.5	28.3	5.1	1.88	14	65600	4220
	1.0	16.5	36.3	6.5	2.14	14	103000	5420
	1.0	4.8	22.0	4.6	2.95	14	30000	3290
	0.5	7.0	45.2	4.9	1.90	14	21900	3370
	0.5	11.7	49.7	5.2	1.97	14	36600	3710
	0.5	15.5	55.3	5.1	1.74	14	48400	4130
1 in x 1 in	1.0	Still Air	5.2	1.7	-	12	-	780
	1.5		4.9	1.8	-	11	-	1100
	2.0		6.1	3.3	-	12	-	1820
	0.42		4.6	1.3	-	11	-	290
	1.5		5.3	2.4	-	11	-	1190
½ in x ½ in	1.0		17.8	5.1	-	9	-	2660
	0.5		20.5	3.4	-	14	-	1530
	1.5		16.4	5.8	-	15	-	3670
	2.0		14.1	7.4	-	16	-	4210
¼ in x ¼ in	1.0		20.0	5.2	-	14	-	2990

*see page 11.

4. Analysis of results

(a) Flame length L – effect of wind.

Since theory has suggested that $\frac{L}{D}$ is a function of m", U and D the flame length data was first analysed assuming a relation of the form

$$\frac{L}{D} \propto m''^{\alpha} \; U^{\beta} \; D^{\gamma} \tag{11}$$

A power law was chosen in the first place since the flame length data for still air[2] had been successfully correlated in this way. The regression analysis gave

$$\frac{L}{D} \propto m''^{0.90} \; U^{-0.16} \; D^{-0.25} \tag{12}$$

All three indices proved to be significant at higher than the 2 per cent level of significance. Had the cribs not been wide enough to be regarded as infinite one might expect the dimensionless ratio $^{D}/_{W}$, where W is the width, to be a factor affecting L or H. Since W was constant this would lead to L being dependent on D other than in the form of $m''^2/g\rho^2 D$ and U^2/gD. It was therefore necessary to determine whether in fact equation (12) was consistent with a grouping of the terms in the form m''^2/D and U^2/D, i.e. to show that $\alpha/2 + \beta/2 + \gamma$ was not significantly different from zero.

Equation (11) can be rearranged to give

$$\frac{L}{D} \propto \left(\frac{m''^2}{D}\right)^{\alpha/2} \left(\frac{U^2}{D}\right)^{\beta/2} D^{\left(\gamma + \frac{\alpha+\beta}{2}\right)}$$

The value of $\gamma + \frac{\alpha + \beta}{2}$ obtained from equation (12) is 0.12. This small positive value was found to differ significantly from zero only between the 5 and 10 per cent levels and in view of the higher levels of significance found for the indices in equation (12) $\alpha/2 + \beta/2 + \gamma$ was taken as effectively zero.

Had the ration $^{D}/_{W}$ any effect on the correlation we would have expected a negative index because decreasing W at a constant value of D would allow relatively more entrainment of air around the sides of the flame, thus shortening it, i.e. L should decrease as W decreases and $^{D}/_{W}$ increases. It would appear justifiable, therefore, on the two grounds of significance level and the sign of $\gamma + \frac{\alpha + \beta}{2}$ to regard the experimental source of fuel as effectively infinite.

The dependence of $\frac{L}{D}$ on a variable other than $m''^2/\rho_a^2 D$ and U^2/gD could be attributable to an effect of the Reynolds number for the air flow. Equation (12) can be rearranged to show

$$\frac{L}{D} \propto (Re)^{0.08}$$

for given values of m''^2/D and U^2/D.

The index of 0.08 is not significant but its sign is positive and this is the sign expected for the effect of Reynolds number. If the eddy diffusivity is written as

$$\epsilon = D_m + aUD$$

where Dm is the molecular diffusivity

u is a velocity

and a is a constant, though it may depend on the ratio $\frac{L}{D}$ it follows that

$$\epsilon/Du = \left(a + \frac{b}{Re}\right)$$

where b is a constant depending only on the physical properties of the gases.

This ratio ϵ/Du decreases as Re increases. Thus, relative to the above formula where ϵ is assumed proportional to Du, the flame length increases as ϵ decreases with increasing Re. However the effect is not significant at the 5 per cent level, and because the value of UD/ν was greater than 10^4 (see Table 1) for all the results it has been neglected. The data were subsequently analysed in the form

$$\frac{L}{D} \propto \left(\frac{m''^2}{D}\right)^M \left(\frac{U^2}{D}\right)^N \qquad (13i)$$

This gave a regression equation

$$\frac{L}{D} = 70 \left(\frac{m''^2}{g\,\rho_a^2 D}\right)^{0.43} \left(\frac{U^2}{gD}\right)^{-0.11} \qquad (13ii)$$

ρ_a was taken as 80×10^{-3} lb/ft^3

By forming the dimensionless group $\frac{L}{D}\left(\frac{U^2}{gD}\right)^{0.11}$ the data are shown graphically in Fig.3 where $\frac{L}{D}\left(\frac{U^2}{gD}\right)^{0.11}$ has been plotted against $\frac{m''}{\rho\sqrt{gD}}$ on logarithmic scales.

(b) Flame length L - still air.

Since the data from the still air experiments could not be included in the above analysis, these were analysed separately. By assuming a relation of the form $\frac{L}{D} \left(\frac{m''^2}{D}\right)^{\beta}$ the following regression equation was obtained for the still air data.

$$\frac{L}{D} = 72 \left(\frac{m''^2}{g \rho_a^2 D}\right)^{0.41} \qquad (14)$$

The data are also shown in Fig.3 where $\frac{L}{D}$ is plotted against $\frac{m''}{\rho_a \sqrt{gD}}$ on logarithmic scales. The confidence limits on the regression coefficients in these equations appear in Table 2. As is discussed below it is possible to plot the results of still air experiments if a value of 0.82 is taken for $\left(\frac{U^2}{gD}\right)^{0.11}$.

(c) Height reached by flame H.

A preliminary analysis of the results showed that the quantity $HU/m''D$ was approximately constant to within a factor of 2 over all the results and since this ratio represents a nominal air/fuel ratio, i.e. the quantity of air moving into the layer above the surface of the burning fuel divided by the quantity of fuel burnt, the statistical analysis was undertaken with this ratio as the dependant variable.

In this preliminary analysis no difference was found between the value of this ratio for the early results without the extended baseboard and those with it. Also the values of $HU/m''D$ were more constant over the whole range of experiments than were the values of $\frac{(H + C)U}{m''D}$ where c is the height of the crib and H + c the height of flame from the base of the crib.

Accordingly a regression analysis similar to that for $\frac{L}{D}$ was undertaken on $HU/m''D$ excluding the results marked * in Table 1. This gave the relation

$$\frac{HU}{m''D} \propto m''^{-0.007} \; U^{0.339} \; D^{-0.052} \qquad (15)$$

the indices on m" & D not being significant. The value of $\frac{\alpha+\beta}{2} + \gamma$, where α, β and γ refer to the indices on m", U and D respectively, had a value for Student's 't' of only 1.6 and equation (15), like equation (12) for $\frac{L}{D}$ was therefore consistent with the independent variables being m''^2/D and U^2/D.

In a double regression analysis with m''^2/D and U^2/D as independent variables one obtains

$$\frac{\rho_a HU}{m''D} \propto \left(\frac{m''^2}{D}\right)^{-0.020} \left(\frac{U^2}{gD}\right)^{0.153} \qquad (16i)$$

but the index on m''^2/D was not significant. The best single regression in terms of U^2/gD gave

$$\frac{\rho_a HU}{m''D} = 56 \left(\frac{U^2}{gD}\right)^{0.13} \qquad (16ii)$$

All the results are shown in Fig.4 though as mentioned above points marked * were excluded from the analysis. One of these three results is significantly below equation (16ii) though the others are consistent with it. The left-hand side of equation (16ii) is a measure of a nominal air/fuel ratio; the confidence limits for the indices in equation (15) and (16ii) appear in Table 2. Since the point referred to above and two others, with a value of U^2/gD greater than 10, lie below the relation given by equation (16ii) it would be unwise to extrapolate the relation to higher wind speeds.

Flames from Line Sources

By a line source we mean a source where D does not appear amongst the factors influencing flame length except in so far as it occurs as $m''D$ the total fuel supply per unit length of line. Strictly this is only valid for a buoyant line source, for the reasons given earlier in connection with the use of equation (10).

Equation (13ii) is readily rearranged to give

$$\left(\frac{U \rho_a^{1/3}}{g^{1/3} m'^{1/3}}\right)^{0.212} \frac{L g^{1/3} \rho_a^{2/3}}{m'^{2/3}} = 70 \left(\frac{\rho_a^{2/3} g^{1/3} D}{m'^{2/3}}\right)^{-0.19} \qquad (17)$$

where $m' = m''D$.

Fig.5 shows the left-hand side plotted against $D^3/10^4 m'^2$. Given that a finite limit exists when $D \rightarrow 0$ virtually no extrapolation is necessary to obtain the limiting value of the left-hand side for a 'line' source ($D/m'^{2/3} \rightarrow 0$). This corresponds approximately to

$$\frac{L \rho_a^{2/3} g^{1/3}}{m'^{2/3}} = 55 \left(\frac{U \rho_a^{1/3}}{g^{1/3} m'^{1/3}}\right)^{-0.212} \qquad (18)$$

TABLE 2

95 Per cent Confidence Limits on Regression Coefficients

Regression equation	95 per cent confidence limits			
	Indices			Constant
$\frac{L}{D} \propto m''^{0.90}\ U^{-0.16}\ D^{-0.25}$	0.90 ± 0.08	-0.16 ± 0.13	-0.25 ± 0.05	-
$\frac{L}{D} = 70 \left(\frac{m''^2}{g \rho_a^2 D}\right)^{0.43} \left(\frac{U^2}{gD}\right)^{-0.11}$	0.43 ± 0.04	-0.11 ± 0.06	-	61 - 80
$\frac{L}{D} = 72 \left(\frac{m''^2}{g \rho_a^2 D}\right)^{0.41}$	0.41 ± 0.08	-	-	59 - 88
$\frac{HU}{m''D} \propto m''^{-0.007*}\ U^{0.339}\ D^{-0.052*}$	-0.007 ± 0.091*	0.339 ± 0.157	-0.052 ± 0.123*	-
$\frac{\rho_a HU}{m''D} = 56 \left(\frac{U^2}{gD}\right)^{0.130}$	0.13 ± 0.061	-	-	48 - 65

*Not significant

Equation (16i) may be rearranged without loss of accuracy as

$$\frac{H\rho_a^{2/3}g^{1/3}}{m'^{2/3}} \propto \left(\frac{m'^{1/3}g^{1/3}}{\rho_a^{1/3}U}\right)^{0.69}\left(\frac{m'^{2}}{\rho_a^{2}gD^{3}}\right)^{0.031} \qquad (19)$$

but the index on the term containing D other than in m' is not significant and the best single regression of the form suggested by equation (19) is

$$\frac{H\rho_a^{2/3}g^{1/3}}{m'^{2/3}} = 38\left(\frac{m'^{1/3}g^{1/3}}{\rho_a^{1/3}U}\right)^{0.70} \qquad (20)$$

The 95 per cent confidence limits on the coefficient 38 are 34 - 43 and on the index $\pm$ 0.165.

Equations (18) and (20) are in fact versions of equation (10). The correlation produced by equation (20) is slightly less than that produced by equation (16i) but the difference between them is not significant and the greater usefulness of an expression with a term in m' and no term in D is obvious. Equation (18) is an approximation for flame length provided $D/m'^{2/3}$ is small enough.

It will be convenient below to refer to the dimensionless terms on the left-hand sides of equations (18) and (20) as L^* and H^* respectively and the dimensionless term containing U as U^*.

5. Discussion

It should be noted that equations (13) and (16) show that for a given set of conditions both the flame length and the height of the flame above the surface of the crib are reduced when the wind speed is increased. This is consistent with the increase in wind speeds leading to better mixing of the fuel and air, thus permitting the fuel to be burnt in a shorter length.

The absence of a dimensionless parameter involving the ratio of crib length to width in the correlations for flame length and height of flame tip suggests that the 3 ft wide cribs with their sides protected can be considered as being effectively of infinite width since one would not expect flame length and height to depend on the width of the crib, if this is very large compared with its length.

The analysis of the data has shown that both the flame length and the height of the flame above the surface of the fire may be satisfactorily correlated in terms of the dimensionless parameters $m''^2/g\rho^2 D$ and U^2/gD in the form of a power law relation. However, extrapolation might be uncertain outside the range of the dimensionless variables owing to the assumptions made in the theory and to justify it would require data from fires with values of the dimensionless parameters lying outside those obtained in these experiments. The range covered by these experiments was approximately $0.7 < \frac{L}{D} < 10$, $0.1 < \frac{H}{D} < 3.5$, $0.5 < \frac{U^2}{gD} < 20$, $10^{-4} < m''^2/g\rho_a^2 D < 4 \times 10^{-2}$ and $2 < U(\rho_a/m'g)^{\frac{1}{3}} < 12$.

Comparing equations (13ii) and (14) shows that the index on $m''^2/g\rho_a^2 D$ is nearly the same for the wind and still air experiments. The indices were not found in fact to be significantly different and assuming the index in equation (14) to be 0.43 the regression equation is modified to

$$\frac{L}{D} = 85 \left(\frac{m''^2}{g\rho_a^2 D}\right)^{0.43} \qquad (21)$$

Thus equation (13ii) can be considered as a correlating equation for the still air results if an equivalent constant value of $\left(\frac{U^2}{gD}\right)$ which makes equations (13ii) and (21) identical is inserted. The appropriate value of $\left(\frac{U^2}{gD}\right)^{-0.11}$ is 1.22 which corresponds to a wind speed of the order 2-3 ft/sec. It is thus possible to display both the still air and the wind data in the same manner. This is what has been done on Fig.3 where the values of $\frac{L}{D}$ for still air experiments have been divided by 1.22. As pointed out previously[2] the Reynolds number $m''D/\mu$ may have little relevance to determining the character of the flame because the gases on being heated are accelerated by buoyancy and the applied wind, and the type of flow is determined by these more than by the initial condition at the surface of the fuel bed. The four results with $m''D/\mu$ below 500 - a very low value - are on both sides of the line in Fig.3. There is then no apparent effect of a low initial Reynolds number of the fuel leaving the crib.

For flames emerging from windows[2], we have

$$L = 400\,(m''D)^{\frac{2}{3}} \text{ in c.g.s units} \qquad (22)$$

and this is plotted in Fig.3. for the range of $\frac{L}{D}$ for which the results were obtained where it is seen that the still air results of the present paper approach this line. Provisionally, therefore, equation (22) at large values of

$\frac{L}{D}$ is accepted as asymptotic to the results of the present paper.

Equations (18) and (20) are good approximations for wide fire fronts with a thin burning zone and for practical purposes have the considerable benefit of giving flame length and flame height in terms of wind speed and rate of burning per unit length of fire front without any information being required for the width of the burning zone. The left-hand side of both equations should lead to the same value in still air since H and L are then the same quantity.

Figure 6 shows the experimental results and equations (18) and (19) plotted with the values at low wind speeds sketched in so that both lines approach the value for still air given by equation (22), which as seen from Figs.3 and 6 may overestimate the actual flame length, as does equation (18) for values of D too large for the line source approximation to be valid.

To a first approximation H/L is the cosine of the deflection angle from the vertical. Figure 6 shows how this deflection increases with U^*, and although a more detailed discussion of deflection will appear in a later report the results in Fig.6 suggest that the difference between H^* and L^* and hence the deflection becomes significant only when U^* exceeds some value which is of order 0.5 for a line source.

The effect of wind on the flame length is not very large and variations of the experimental arrangement, such as an extension of the incombustible sides to prevent air entering from the sides are unlikely to have much effect. However, such an extension may have relatively more effect on the value of H. $\rho_a HU/m'$ is an effective air/fuel ratio and this increases slightly with U^2/gD. Preventing air entering around the sides would be expected to reduce the value of H, but it is not expected in such circumstances that $\rho_a HU/m'$ would decrease with increasing wind speed.

These questions will be studied in further experiments.

6. Conclusions.

The effect of wind on the length and orientation of flames from burning wooden cribs has been examined. It has been shown that the flame length data may be satisfactorily correlated, over a wide range, in terms of two dimensionless parameters formed from the rate of burning per unit base area, the wind speed and a characteristic dimension of the crib.

By a small modification to the flame length data it has been possible to include still air data in the correlation found to fit the data obtained from the experiments involving wind. Elementary quantitative relations between the still air and the wind data are satisfactory.

The use of the two parameters wind speed and the rate of burning per unit length of fire front, without specifying the thickness of the burning zone is sufficient to predict the height reached by the flame over a wide range of conditions. This procedure provides also a good approximation, albeit a slight overestimate, for flame length.

7. References.

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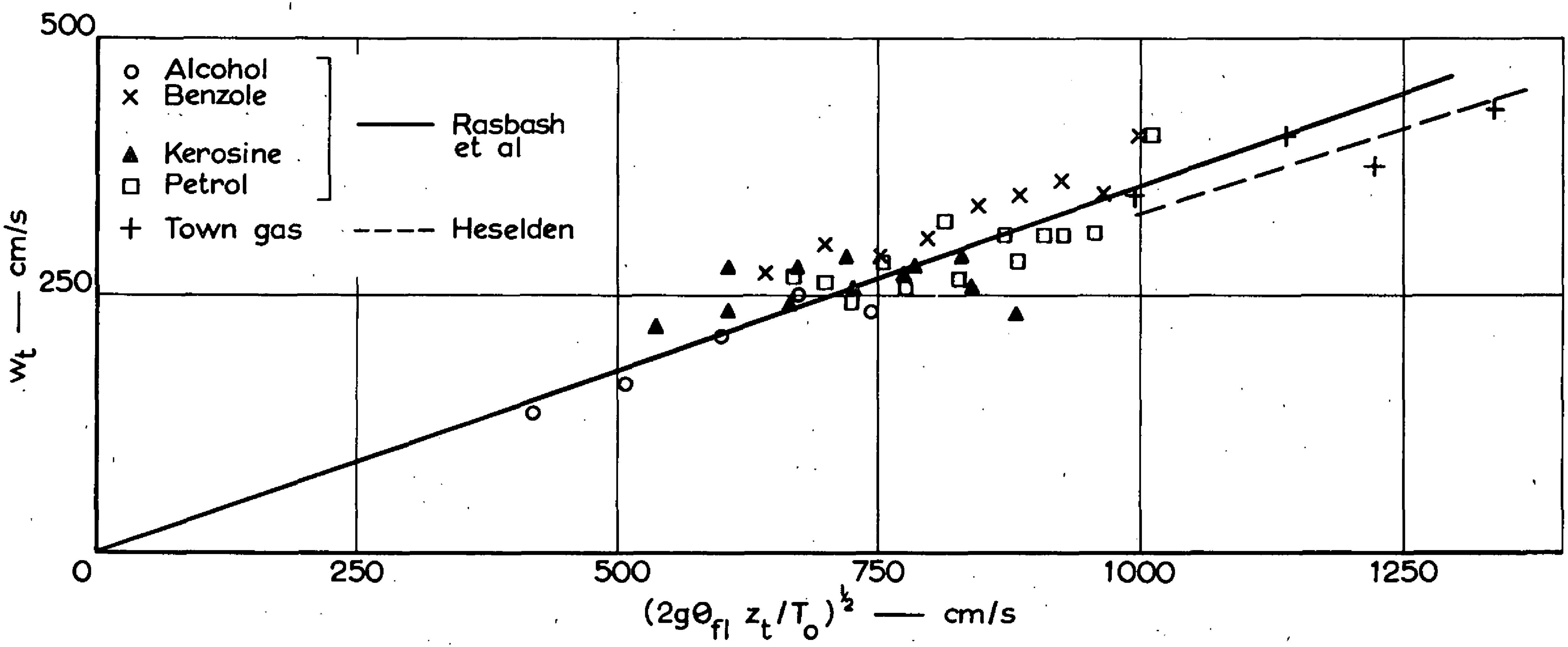


FIG. 1. UPWARD VELOCITY OF FLAME TIP

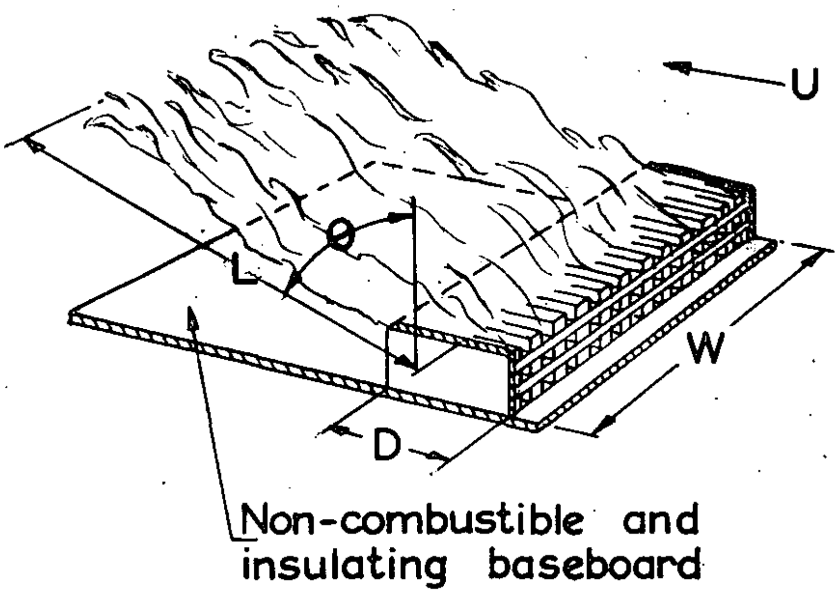


FIG. 2. CRIBS BURNING IN A WIND
(DIAGRAMMATIC SKETCH OF
EXPERIMENTAL ARRANGEMENT)

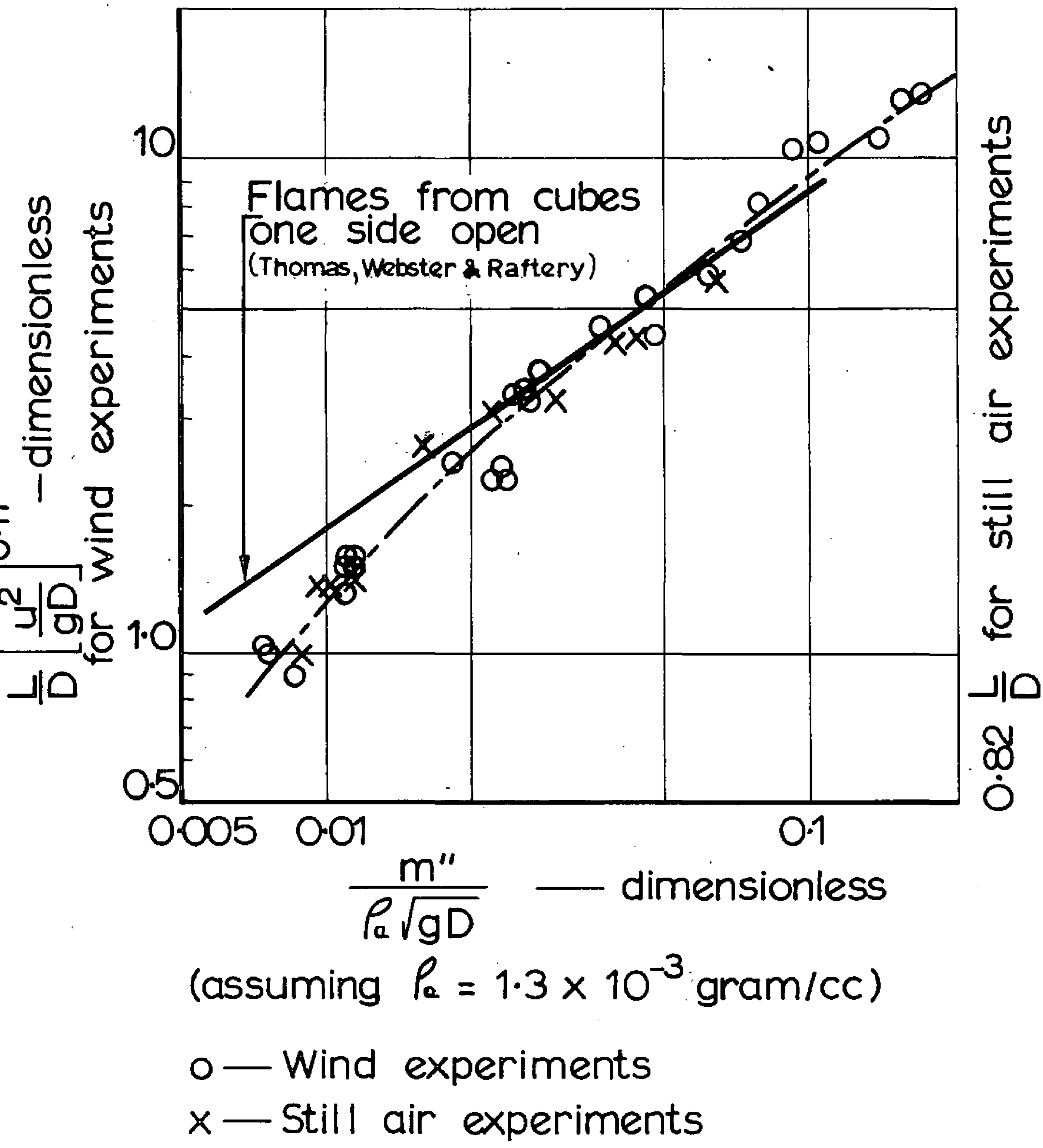


FIG. 3. EFFECT OF WIND SPEED AND BURNING RATE ON FLAME LENGTH

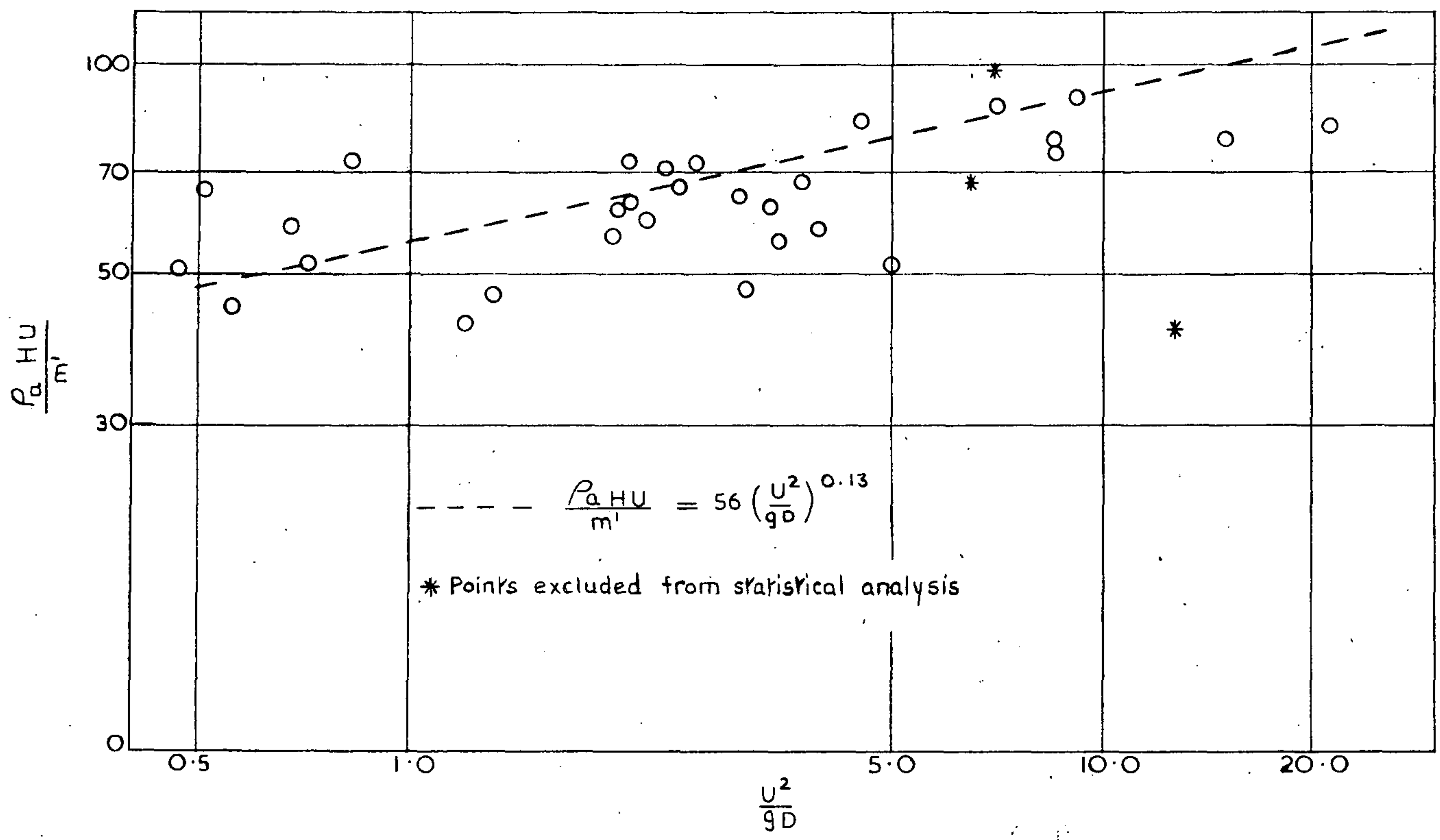
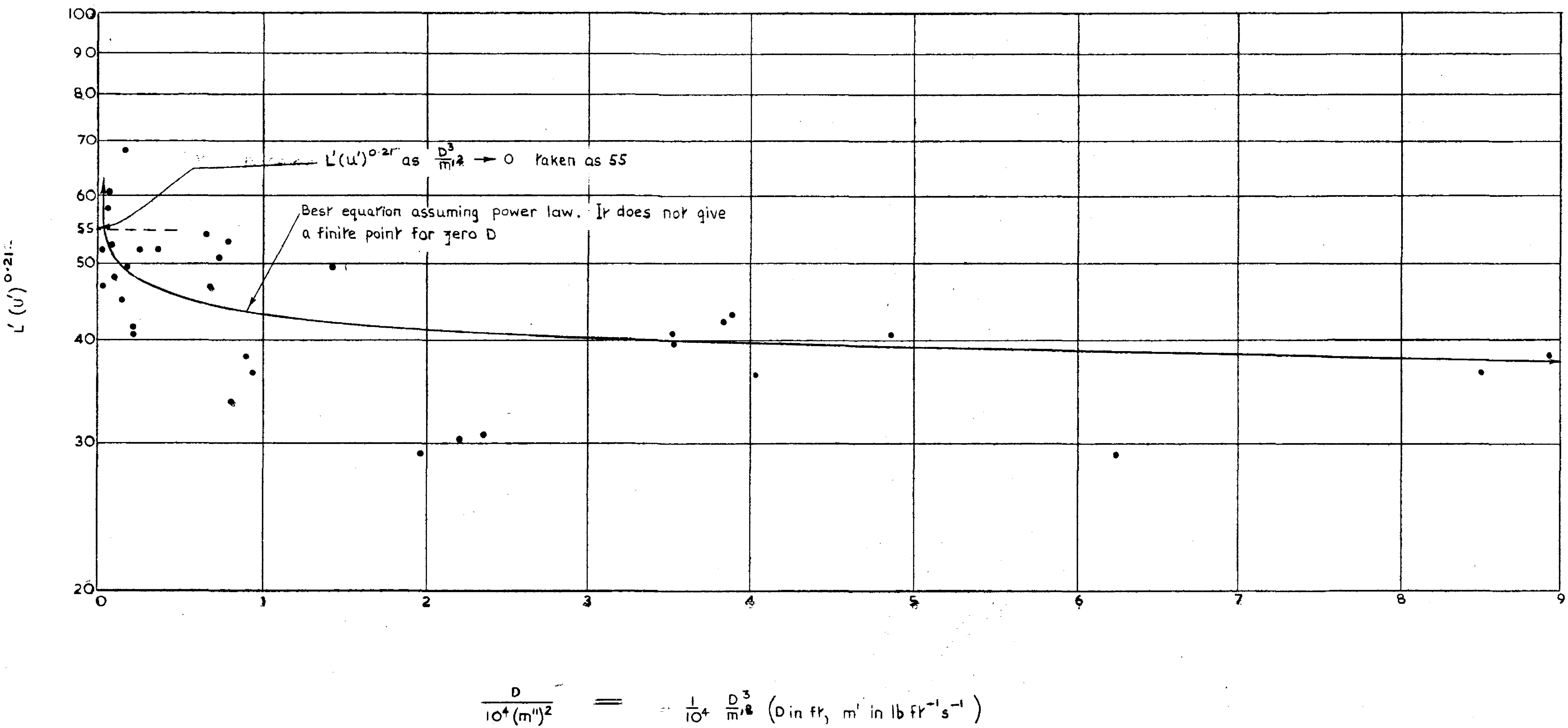


FIG. 4. THE HEIGHT REACHED BY FLAME IN A WIND



$L'(u')^{0.21}$ as $\frac{D^3}{m'^{4}} \to 0$ taken as 55
Best equation assuming power law. It does not give a finite point for zero D
$L'(u')^{0.21}$
$\frac{D}{10^4 (m'')^2} = \frac{1}{10^4} \frac{D^3}{m'^{8}}$ (D in ft, m' in lb ft^{-1}s^{-1})

FIG. 5.

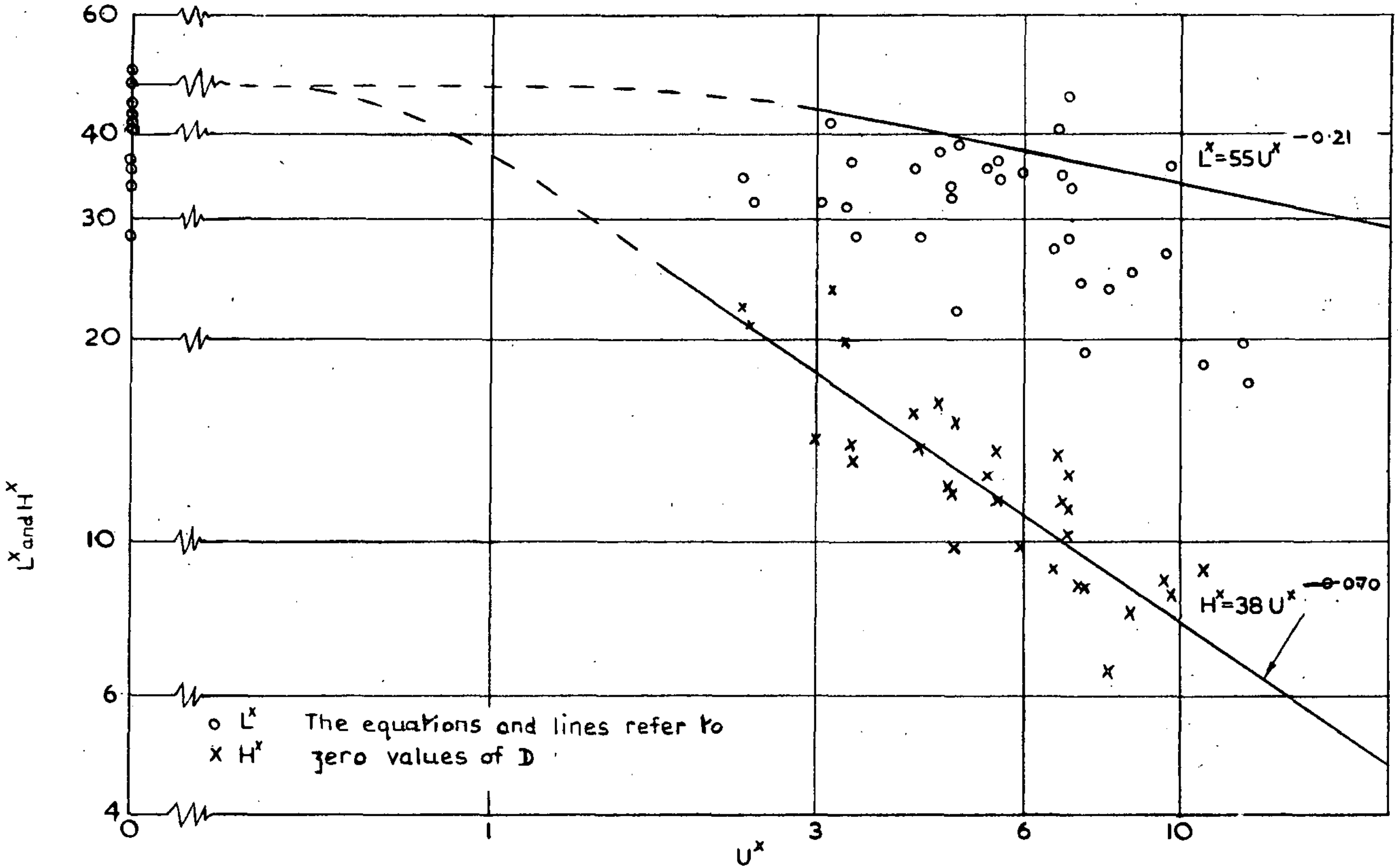
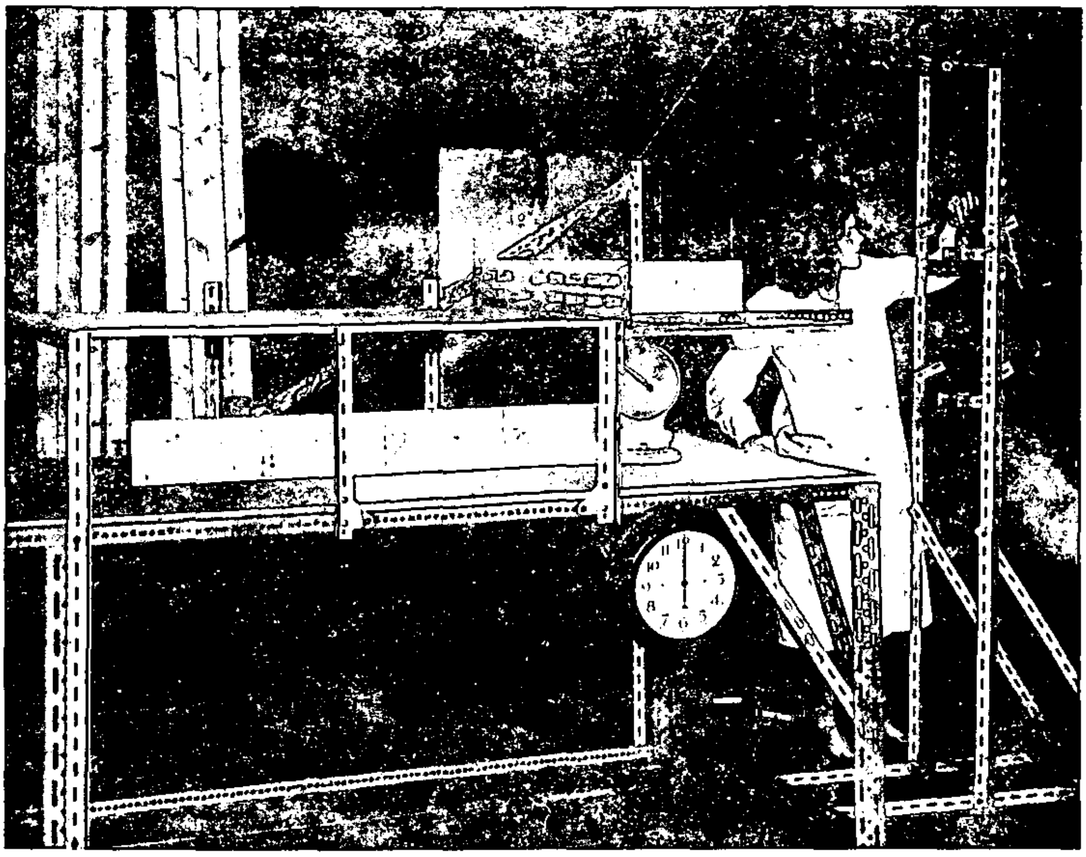
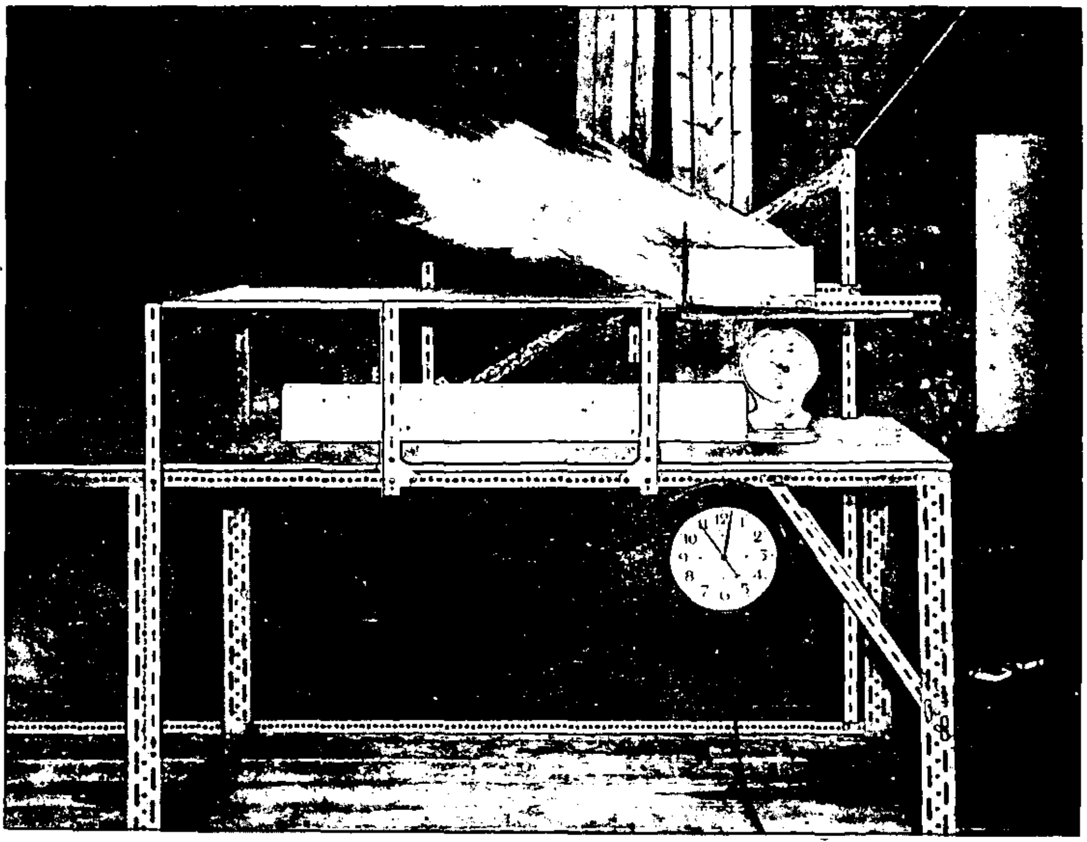


FIG. 6. FLAME LENGTH AND HEIGHT IN A WIND



Measurement of wind speed before a test

PLATE 1



Test in progress

PLATE II