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THE MERGING OF FLAMES FROM SEPARATE FUEL BEDS

by

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SUMMARY

The flames from nearby fuel beds tend to merge, causing an increase in flame height and radiation. The critical conditions of merging are deduced by elementary considerations of entrainment and the motion of flames for two different configurations, 1) Two rectangular fuel beds. 2) Four square fuel beds. There is reasonable agreement between the theory, experiments using 1 ft town gas burners, related experiments with small nozzles, and a full-scale fire.

Nomenclature

B	Buoyancy force
c	Constant
D	Linear dimension of fuel bed. Shorter side of rectangle.
F	Thrust of gases leaving burner.
g	Acceleration due to gravity.
K	Constant = 0.16 x 0.36
L	Flame height
L^*	Flame height of an isolated flame.
$\dot{m}''$	Mass burning rate per unit area.
p	Pressure difference
P	Pressure thrust
S	Separation between fuel beds
T	Absolute temperature
u	Velocity of gases entering channel between two flames
v_e	Entrainment velocity
w	Velocity of flame gases at the burner
W	Length of long side of a rectangular fuel bed
z	Height above fuel bed
θ	Temperature rise
ρ	Density
Σ	Dimensionless seperation
ϕ	Inclination to the vertical

Subscripts

o	Surrounding air
1	Fuel
fl	Flame
E	Entrance to channel between two flames.

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Introduction

This report discusses the condition under which flames from separated fuel beds merge together and behave like the flames of a single fire. Merging of the flames without an increase in height would reduce the total flame surface area of each flame, thus restricting the entrainment of air. To entrain sufficient air for complete combustion, therefore, the flames must extend to a greater height. The resulting increase in radiation may increase the heat transfer back to the fuel, extending the flame height still further and increasing the rate of spread of the ground fire. The situations investigated here, in which flames from two or four separate fuel beds burning at a constant rate just merge, are simple examples of the more general problem of many separate fuel beds, which will be studied in further experiments.

For single fires the flame height is related only to the dimensions of the fuel bed and the burning rate of the fuel. Thus the height of flames from square and approximately radially symmetric fuel beds have been related[1] by

$$\frac{L^*}{D} = f\left(\frac{m''}{\rho\sqrt{gD}}\right) \tag{1}$$

where L^* = flame height of isolated fire

D = linear dimension of fuel bed

m'' = mass burning rate per unit area

ρ = density of air taken as constant

g = acceleration due to gravity

However, where two or more separate fuel beds are burning, the flame height L will also be a function of S, where S is characteristic of the separation between the beds, so that

$$\frac{L}{D} = f_1\left(\frac{S}{D}, \frac{m''}{\rho\sqrt{gD}}\right)$$

where f_1 is a function depending on the shape of the fuel beds and will differ for different orientations of one bed to another. We can replace the term containing the burning rate by means of equation (1) and obtain

$$\frac{L}{L^*} = f_2\left(\frac{S}{D}\ ,\ \frac{L^*}{D}\right) \tag{2}$$

When the fires are a long way apart so that the flames are behaving like those from individual fires $\frac{L}{L^*} = 1$. When $S = o$, the flames merge completely and behave like the flames of a single fire. The flame height L in both cases can be estimated from (1). For example the height of the flames from a burner of side D is given by

$$\frac{L^*}{D} = A\left(\frac{\overset{\prime\prime}{m}}{\rho\sqrt{gD}}\right)^{\alpha}$$

where A and α are constants. The area occupied by n burners of side D placed together to form a single burner is nD^2 so that the linear dimensions of this burner will be approximately $n^{\frac{1}{2}}D$. Thus the flame height L_n is given by

$$\frac{L_n}{n^{\frac{1}{2}}D} = A\left(\frac{\overset{\prime\prime}{m}}{\rho\sqrt{gD}}\quad {}^{1}/_{n^{\frac{1}{4}}}\right)^{\alpha}$$

or

$$\frac{L_n}{L^*} = n^{\frac{1}{2}-\frac{\alpha}{4}}$$

and since it has been shown[1] that $\alpha \simeq \frac{2}{3}$, it follows that

$$\frac{L_n}{L^*} \simeq n^{\frac{1}{3}}$$

For intermediate values of $\frac{S}{D}$ the flames lean towards each other (Plate 1) and attain a height between L^* and L_n. When the flame tips touch the flames are just merged and the separation and flame height at this point are defined as the critical separation s^1 and critical flame height L^1 respectively. Clearly the flames will no longer merge if $s > s^1$, or $L < L^1$.

A tentative theory is presented below whose object is to calculate the functional relationship of equation (2) at the onset of merging for two different configurations.

1) Two rectangular fuel beds

2) Four square fuel beds.

The results of laboratory experiments and of one large scale fire are discussed in terms of the dimensionless groups deduced and compared with predicted values.

Theory

A column of hot rising gases draws in, or entrain 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 and the flames are deflected from the vertical. When the flame tips are touching, the flames 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 an angle ϕ to the vertical as shown in Fig.1. Then resolving along the normal to the axis

$$B\sin\phi = P \tag{3}$$

We now estimate the values of B, P and ϕ for two different configurations:

1) Two rectangular burners.

Consider two rectangular fuel beds placed side by side on a continuous surface, the long sides being parallel as shown in Fig.(1a). If, as a first approximation, the temperature rise of the flame θ_{fl} is assumed constant over the height L and width D of the flame, the buoyancy force on each flame is

$$B = \rho_{fl}\frac{\theta_{fl}}{T_o} g \; LDW \tag{4}$$

where ρ_{fl} = density of hot flame gases
T_o = absolute temperature of the surroundings.

To find the pressure thrust on each flame we estimate the velocity of the air flowing along the channel between the flames and hence the pressure drop from Bernoulli's equation. 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, then

$$\frac{SL}{2}u = W\int_0^L v_e\,dz \qquad (5)$$

It will be assumed that entrainment is unaffected by the pressure drop on one side of the flames or by the leaning of the flames. This assumption is not expected to be true for all situations involving a group of fires, but it is probably a reasonable first approximation in the situation under discussion. The entrainment velocity has been estimated elsewhere[1] as

$$v_e = K\left(2g\,\frac{\theta_{fl}}{T_{fl}}\,z\right)^{\frac{1}{2}} \qquad (6)$$

where $K = 0.16 \times 0.36$

z = height above the fuel bed

T_{fl} = absolute temperature of the flame gases

From Bernoulli's equation and equations (5) and (6) the pressure drop p_E at the entrance of the channel between the flames is

$$p_E = \tfrac{1}{2}\rho_o\left(u^2 - v_e^2\right)$$

$$= \tfrac{1}{2}\rho_o\left(\tfrac{2}{3}\right)^2 K^2\ 2g\,\frac{\theta_{fl}}{T_{fl}}\,L\left(\frac{4W^2}{S^2} - 1\right) \qquad (7)$$

where ρ_o = density of surrounding air.

p_E is the maximum pressure drop along the channel, and thus it probably overestimates the mean pressure drop between the flames. The least pressure drop p_o is at the central point of the channel, where $p_o = o$ and thus a reasonable estimate of the pressure drop is $\frac{1}{2}p_E$

Write $$p = \frac{p_E}{c} \qquad (8)$$

where c is constant. Clearly $c \geqslant 1$, and from above a reasonable value is $c = 2$. The pressure thrust on each flame is then

$$P = \frac{WLp}{\cos\phi} \qquad (9)$$

When the flame tips are touching

$$\tan\phi = \frac{S}{2L} \qquad (10)$$

Substituting for B, P and o in equation (3) we obtain

$$\left(\frac{4L^2 + S^2}{SD}\right)\left(\frac{4W^2}{S^2} - 1\right) = \left(\frac{3}{2}\right)^2 \frac{2c}{K^2} \tag{11}$$

since $\dfrac{\rho_{fl}}{\rho_o} = \dfrac{T_o}{T_{fl}}$

In the situations considered here $\frac{4L^2}{s^2} \gg 1$ and equation (11) may be written

$$\frac{L}{D} = \frac{3}{2\sqrt{2}} \frac{c^{\frac{1}{2}}}{K} \Sigma \tag{12}$$

where $\left(\Sigma\right)^2 = \dfrac{S}{D}\left(\dfrac{4W^2}{S^2} - 1\right)^{-1}$

When $\frac{4W^2}{S^2}$ is large, i.e. $S \ll 2W$

$$\left(\Sigma\right)^2 = \frac{S^3}{4\,DW^2}$$

2) Four separate square burners.

Consider four square fuel beds placed symmetrical on a continuous horizontal surface, the outer edges lying on the sides of a square, as shown in Fig.(1b). We make the same assumptions as in 1) regarding entrainment and temperature rise θ_{fl}. The buoyancy force on each flame is then

$$B = \rho_{fl}\ g\ \frac{\theta_{fl}}{T_o}\ LD^2$$

As before let u be the velocity of the air entering the channel between two flames and p_E the pressure drop at this point.

Then $SLu = 4D \int_o^L v_e \, dz$

and $p_E = \frac{1}{2}\rho_o \left(u^2 - {v_e}^2\right)$

$$= \frac{1}{2}\rho_o \left(\frac{2}{3}\right)^2 K^2\ 2\ g\ \frac{\theta_{fl}}{T_{fl}} L \left(4^2 \frac{D^2}{s^2} - 1\right)$$

Write $p = p_{\frac{E}{e}}$

Then the resultant pressure thrust on each flame is

$$P = \sqrt{2} \frac{pDL}{\cos \phi}$$

At merging the flames touch at the central point and thus ϕ is given by

$$\tan \phi = \frac{S}{\sqrt{2} L}$$

Substituting for B, P and ϕ in (3) we obtain

$$\left(\frac{2L^2 + S^2}{SD} \right) \left(4^2 \frac{D^2}{S^2} - 1 \right) = \frac{c}{K^2} \left(\frac{3}{2} \right)^2$$

or for large $\frac{2L^2}{S^2}$

$$\frac{L}{D} = \frac{3}{2\sqrt{2}} \frac{c^{\frac{1}{2}}}{K} \Sigma \qquad (13)$$

where $$(\Sigma)^2 = S/D \left(\frac{4^2 D^2}{S^2} - 1 \right)^{-1}$$

$$= \frac{S^3}{4^2 D^3} \quad \text{for} \quad S^2 << 4^2 D^2$$

This equation is identical to equation (12) with $W = 2D$, for the same values of c.

Experimental

1. Burners 2 ft x 1 ft and 1 ft x 1 ft were each arranged horizontally in pairs as shown in Plate 1 with varying separations and flame heights to find the critical conditions of merging. Each fuel bed was made up of 1 foot square town gas burners and the space between and surrounding the two fuel beds was filled in to provide a continuous flat surface in their plane. The flame height L could be varied by varying the gas flow, independently of the heat transfer back to the fuel, which may itself depend on the degree of merging. The critical flame height at a given separation was determined from a series of photographs for the 2 ft x 1 ft fires, and visually for the 1 ft x 1 ft fires although it is not easy

to determine the critical flame height at a given separation. $\frac{L}{\bar{L}^*}$ was found to be approximately $6/5$.

2. Four 1 ft square burners were arranged symmetrically as shown in Fig.(1b) and the critical conditions of merging found as above. As the dimensionless groups deduced from the theory for this arrangement are identical to those for the arrangement above, the two sets of data are shown on the same graph, in Fig.2. For four burners $W = 2D$.

3. One large fire in a timber yard has been reported[2] in which flames from two separate piles of timber were merged. The two stacks of timber were each 150 ft x 40 ft, and separated by a 20 ft gangway. The flames from the two stacks merged at 50 ft; this therefore gives a lower bound for S.

For this fire, $\frac{W}{D} = \frac{15}{4}$, $\frac{L}{D} = \frac{5}{4}$ and $\frac{S}{D} = \frac{1}{2}$.

4. Putman and Speich's data.

Putman and Speich[3] have measured the height of flames from burners comprising various arrangements of 0.371 in diameter nozzles as the rate of fuel supply was varied. The fuel used was city gas, which is similar to methane. Some of these data may be compared with the experiments reported above, as follows:

a) Two hexagonal burners. Each burner comprised seven of the nozzles, one placed at the centre of the hexagon and one at each of the diagonal points. The flames from each burner simulate approximately the flames from a continuous burner of the same area as the hexagon with the same total rate of fuel supply. For the purposes of comparison with other experiments each hexagonal burner will be taken as equivalent to a square burner whose size, D, is chosen so that $D^2 = A$, where A is the area of the hexagon. In this case, the separation of the nozzles was 4 in so that $D = 6.6$ in.

The data were presented in a table as follows:

$L/\bar{L}^*$	$\bar{L}^*/\bar{S}$
1.00	0
1.06	3.84
1.13	5.12
1.13	5.80
1.30	10.2
1.41	

where $\bar{L}^* = 61.4$ in is the height of the flames from each hexagonal array and $\bar{S}$ is the distance between the centres of the arrays. Now $\bar{S} = S + D'$ where D' is the diameter of the array, and when the flames are fully merged, $S = o$, so that $\bar{S} = D'$ ∴ By interpolation into the table, when $S = o$, $\bar{L}^*/\bar{S} \simeq 7.5$, $\frac{L}{L} \simeq 1.2$.

It is necessary to define a rational basis upon which to estimate the values of S when the flames are just merged. There can be no increase of flame height without some degree of flame merging or of air restriction on one side of the flame and it is reasonable to suppose that the flames are just merging when there is a measurable increase of flame height, say 10% increase. This is also $\frac{1}{2}$ the maximum increase of flame height.

Thus $\frac{L}{L^*} = 1.1$, so that by interpolation $\frac{\bar{L}^*}{S} \simeq 5$.

$$\therefore \; S = \frac{\bar{L}^*}{S} - D$$

$$= 5.7 \text{ in}$$

and $\frac{S}{D} = 0.865$, $\frac{L}{D} = 10.2$

b) Two nozzles, 0.371 in diameter, separation 2 in and 4 in and $\frac{L}{D} >> 1$. In this case, the thrust from the burner is no longer negligible and equation (3) should be modified so that

$$\left(B + F \right) \sin \phi = P$$

where F is the thrust of the burner

and $F = \frac{1}{2} \rho_1 \; w^2 D^2$

where w is the initial velocity of the gases and ρ_1 is the density of the fuel.

$$\therefore \; \frac{L}{D} = \frac{3}{2} \frac{c^{\frac{1}{2}}}{K} \sum \left(1 + \frac{w^2}{2gL} \frac{D}{W} \frac{\rho_1}{\rho_o} \frac{T_{f1}}{\theta_{f1}} \right)^{\frac{1}{2}} \qquad (14)$$

Putman and Speich have presented their data with $\frac{L}{L^*}$ plotted against L^*/S. Taking $\frac{L}{L^*} = 1.2$ as the criterion of merging, as found in the town gas experiments, L^*/S is found by interpolation to lie between 20 and 25. When $s = 2$ in, $D = 0.371$ in this gives $129 < L/D < 161$. This value may be modified to allow for the thrust of the burner, using equation (14), by dividing L/D by $\left(1 + \frac{w^2}{2gL} \frac{D}{W} \frac{T_o}{\theta_{f1}}\right)^{\frac{1}{2}}$ where $W = D$, $w \simeq 70$ f.p.s, $L \simeq 5$ ft and $\frac{T_o}{\theta_{f1}} \simeq \frac{3}{10}$ then $39 < L/D < 45$.

These data together with the Southall Timber fire and the town gas experiments are plotted in Fig.2.

<u>Discussion</u>

The theoretical conditions of Equation (12) and (13) for merging of flames from two burners and from four burners is drawn in Fig.(2) with $c = 1$ and $c = 2$. The true value of c can only be calculated when the velocity of the air at all points of the region between the flames is known. There appears to be some systematic difference between theory and experiment in that theory tends to underestimate the critical flame height at small separations of the gas burners and overestimate it at higher separations. However, the following reservations regarding the experimental observations should be noted.

1) For small flames from gas burners the critical flame height measured is greater than that predicted. These flames tend to become non-turbulent so that equation (6) overestimates their air requirement and hence the pressure drop between the flames. A further reduction in the estimated pressure drop is caused by the flames from each rectangular burner breaking up into two or more separate flames.

2) The gas burners tend not to burn over their entire area at small gas flows so the separation between the flames is greater than the separation between the fuel burners. Thus for given flame height the critical separation measured is rather smaller than one would expect.

Since no quantitative estimate is available yet for the effect of the above factors, no correction has been made for them.

Little comment is needed on the timber fire reported: the flame height is an estimate by an observer, and the flames were probably fully merged, so the flame height is greater than the critical flame height. However, it demonstrates that the critical flame height predicted by theory is realistic.

There is reasonable agreement between theory and practice and the extent of the agreement shows that useful conclusions may be drawn from the theory. In particular, the dimensionless groups deduced indicate that D and W, the linear dimensions of the fuel beds are important factors in determining the condition for flame merging. However, further experiments are necessary to verify the effect of scale.

The power relationship between the dimensionless groups is determined largely by the assumed form of the relationship between entrainment velocity and height, whilst numerical values depend on the averaging process used in determining the pressure drop and thrusts. Reliable measurements of these quantities have yet to be made.

Conclusions

Experiments investigating the critical condition for merging of flames from two separate rectangular fuel beds of different configurations and scales have been correlated using dimensionless groups deduced from a theory based on simplified equation of motion. The difference between theory and experiment appears to be systematic but this is attributed as much to limitations in experimental design as to theory. The extent of the agreement demonstrates at least the order at magnitude of the quantities involved and enables the important factors to be specified, namely, flame height, separation and the linear dimensions of each fuel bed.

References

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(3) PUTMAN, A.A. and SPEICH, C. F. A model study of the interacting effects of mass fires. Batelle Memorial Institute. Research Report. Columbus, Ohio, November, 9th 1961.

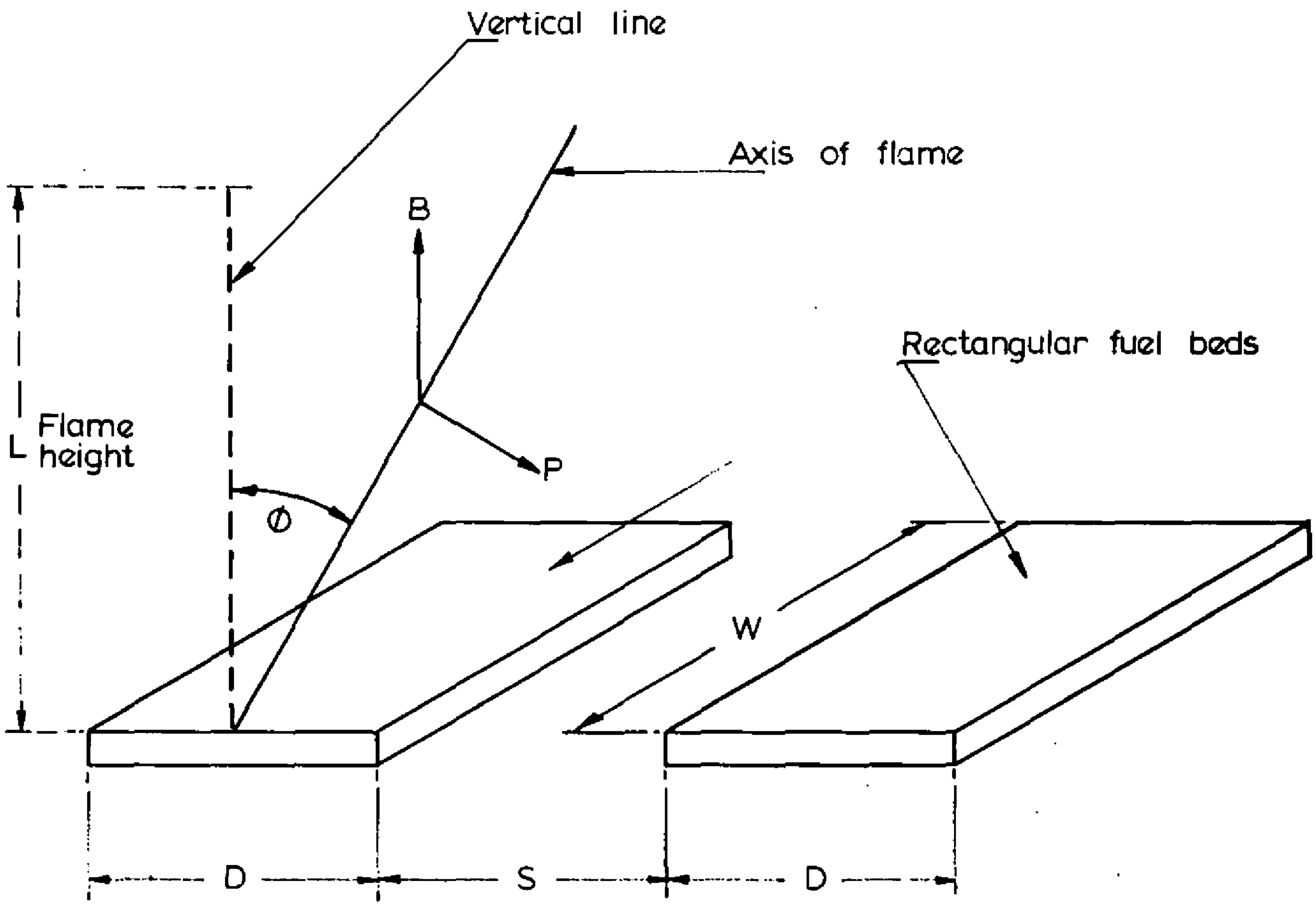


FIG. 1a. ARRANGEMENT OF THE TWO RECTANGULAR FUEL BEDS SHOWING THE FORCES ACTING ON AN INCLINED FLAME

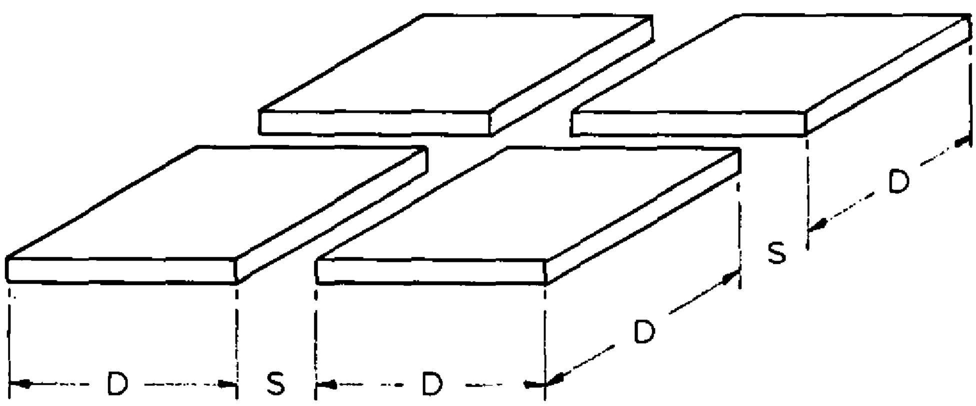
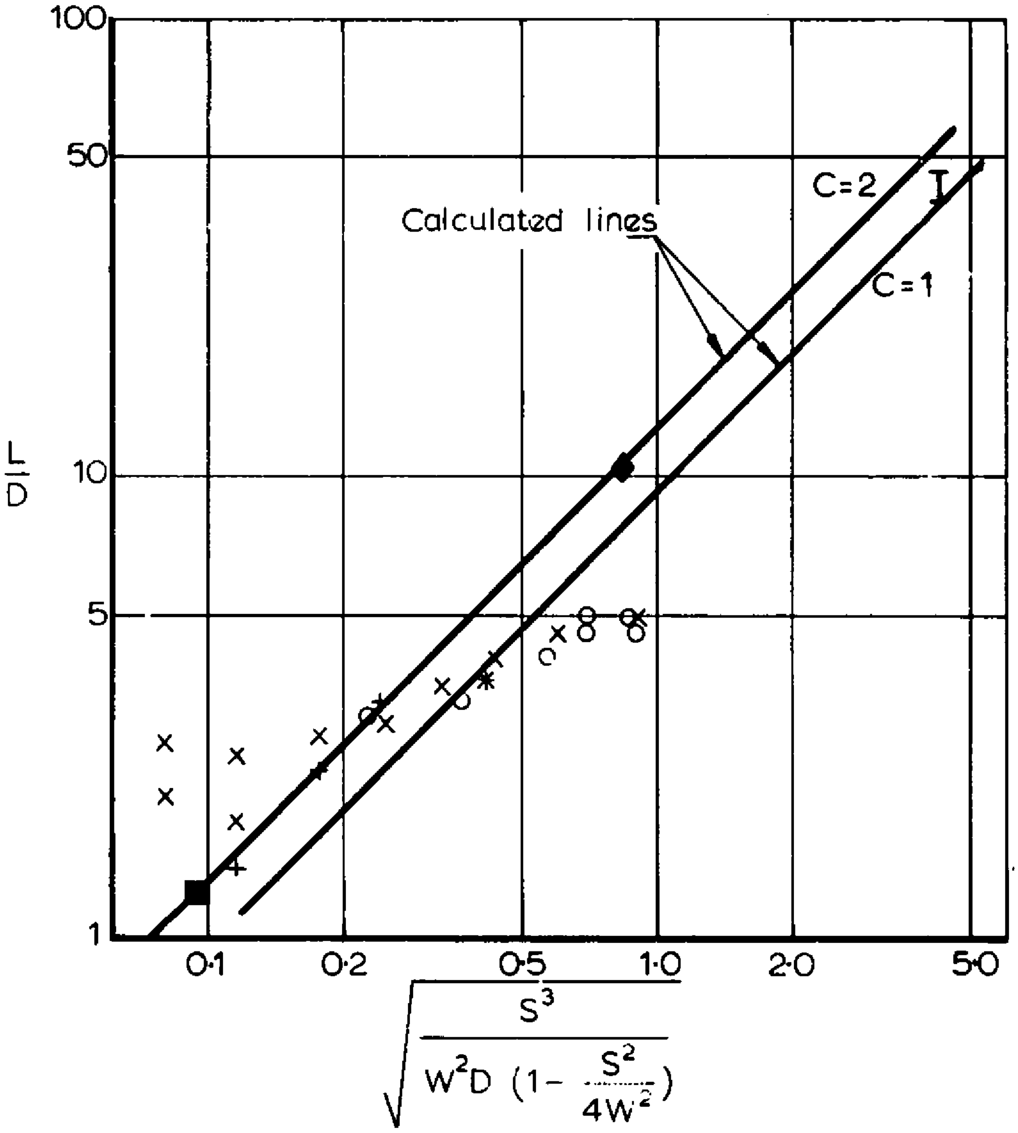


FIG. 1b. ARRANGEMENT OF THE FOUR SQUARE FUEL BEDS



Data source	Symbol	Fuel bed	W/D
JFRO (Town gas)	o	1′ x 1′ (2 burners)	1
	x	1′ x 2′ (2 burners)	2
	+	1′ x 1′ (4 burners)	equivalent to 2
Putman and Speich	I	2 burners 0·371″ dia	1
	◆	2 sets of 7 burners each 0·371″ dia	1
Southall timber yard	■	2 timber stacks each 150′ x 40′	3·75

FIG. 2. MERGING OF FLAMES FROM SEPARATED FIRES. DIMENSIONLESS FLAME HEIGHTS AND SEPARATIONS AT MERGING

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Merging flames

Leaning flames

EXPERIMENTAL APPARATUS

PLATE 1