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SOME MODEL-SCALE EXPERIMENTS WITH MULTIPLE FIRES

by

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SUMMARY

The paper describes some experiments undertaken to test the feasibility of designing a small-scale model that may be used in the laboratory for the study of multiple fires. The results are discussed in terms of a geometric scaling law, relating the inflow velocities to the square root of the flame height, and compared with some observations on large scale fires conducted under the auspicies of Project Flambeau.

The behaviour of the array of fires was influenced by the separation between the fuel beds and the type of fuel. In some of the fires persistent fire whirls were observed.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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1. Introduction

This report describes a scale model for use in the study of multiple fires. The situation envisaged is that in which a large number of similar square-based fires are burning in a regular geometric pattern forming a square matrix. Large-scale experiments with such a configuration have been conducted elsewhere under the auspices of Project Flambeau, in which each individual fuel bed comprised 20 tons of assorted wildland fuel in a square pile approximately 50 ft square and 7 ft high and in the most recent fire, the largest of the series, the matrix contained 342 fires. These large experiments, covering 50 acres, are very costly and time consuming and there is clearly a great advantage in devising a small-scale model, incorporating the essence of the multiple fire, which can be studied under laboratory conditions. Comparisons with such a model would also assist in assessing the value of theoretically-derived scaling laws.

The present paper is concerned with some aspects of the aerodynamic behaviour of multiple fires in the absence of rotation and in particular with the scaling laws for such fires. The experiments described, which preceded the last 50-acre fire, were undertaken to test the feasibility of designing a model that could be used in the laboratory and partly to examine the validity of the scaling laws. This examination was rather restricted because of the limited instrumentation available, but comparison with Flambeau and with theoretical predictions enables some useful conclusions to be drawn.

2. Theory

In the absence of rotation and an ambient wind the only forces present are buoyancy, inertia and friction. Apart from the ground boundary layer there is no balance of forces to be conserved in scaling and hence the only independent dimensionless parameters are

$$S/D,\ L/L^*,\ L/D,\ N.$$

where L = mean flame height for the assembly

L^* = mean flame height for one of the unit fires burning by itself at the same rate, and hence measuring the burning rate

D = linear size of a unit fuel bed

S = separation between the fuel beds

and N = number of fuel beds.

For flames which are not merged $L/_{L^*} \simeq 1$, so that if N is held constant the only independent scaling parameters are $S/_D$ and $L/_D$. Thus for fires involving the same number and arrangement of unit fires a geometric scaling law is appropriate in which $S/_D$ and $L/_D$ are held constant.

A particular case of this scaling law has been derived by Baldwin[1] to show that the separation S_M at the onset of merging is independent of N and given by a relationship

$$\frac{S_M}{D} = f\frac{(L)}{(D)}$$

3. Experimental

Project Flambeau fires have been conducted with N ranging from 36 to 342, the remaining parameters having the following values:

L = 50 ft

D = 50 ft

S = 25 and 125 ft

The experimental fires so far conducted do not appear to exhibit any phenomena near the burning fuel that are not also present in smaller fires; there appears to have been little or no interaction between the atmosphere and the burning fuel, and where fire whirls have occurred they have been restricted to a very small area of the fire. Therefore for these fires, the geometric scaling law derived above would seem to be appropriate, and the values of the scaling parameters are

$$\frac{L}{D} = 1, \ \frac{S}{D} = 0.5 \text{ and } 2.5$$

The size of the laboratory made it necessary to restrict the size of D to about 1 ft even for small separations and thus the first task was to find a suitable 1 ft square fuel bed with flames about 1 ft high, so that $L/_D \simeq 1$. From a number of different fuel beds tested, three were selected the details of which are recorded in Table 1. Each of the quantities recorded is an average of five measurements, and the scatter is small. The fires burnt for about 10 min with the flame height shown, and the height then decreased until the flames were about 6 in high and there was no longer a single coherent flame. For this work, the period from ignition to the loss of coherence is defined as the duration of the fire.

The selected unit fires were then burnt in combination in the multiple fire configurations described above, in matrices of three different sizes, 6 x 6, 10 x 10 and 16 x 16 with spacing ratios $S/_D$ of $\frac{1}{4}$ or $\frac{1}{2}$. In some of the experiments the square unit fires were placed side by side with no spacing to form a large continuous fuel bed. Of these spacings that of $S/_D = \frac{1}{2}$ was chosen because it was the smallest Flambeau spacing, $S/_D = \frac{1}{4}$ because this was the theoretical prediction for the separation at the onset of merging, and $S/_D = 0$ in order to investigate the possibility of a different type of behaviour in large continuous fuel beds.

Only very limited instrumentation was attempted for these experiments, but one of their objects was to discover the possible modes of behaviour of multiple fires, and from this point of view the most important features could be recorded photographically. A small selection of the photographs is shown in Plate 1.

Air speeds at the edge of the fire were measured by means of four simple expendable vane anemometers described in the Appendix, placed at ground level 6 in outside the fire area, in line with the central channel of each side. The details of these measurements together with the other details of the experiments are recorded in Table 2. The duration of these fires is measured in the same way as for the unit fires, that is the period from ignition to loss of coherence when the flames were about 6 in high. This is a rather subjective measurement, but was observed by the same person throughout and is probably repeatable within about a minute.

Table 1

Characteristics of the individually burnt unit fires

Shape	Fuel	Amount	Duration	Flame height
Circular	Fibreglass soaked in kerosine, covered with a layer of asbestos paper.	500 ml of paraffin	17 min	15 in
Circular	A number of small wood blocks each 2 in x 1 in x 1 in, packed randomly into a containing collar or tray.	2 lb	14 min	14 in
Square		2 lb 10 oz	14 min	14 in

Table 2

Data from model-scale multiple fire experiments

Matrix size	Unit fuel bed	S/D	Duration min	Mean flame height in	Mean velocity ft/s
6 x 6	Circular kerosine wick	$\frac{1}{2}$	8	Up to 60	-
6 x 6	Circular wood	$\frac{1}{2}$	18	15	1.0
6 x 6	Circular wood	$\frac{1}{2}$	18	13	-
6 x 6	Circular wood	$\frac{1}{4}$	16	12	1.15
6 x 6	Square wood	$\frac{1}{4}$	16	8	0.9
6 x 6	Square wood	0	18	17	0.7
10 x 10	Square wood	$\frac{1}{4}$	18	11	0.9
10 x 10	Square wood	0	20	16	1.5
16 x 16	Square wood	$\frac{1}{4}$	13	18	-

4. Discussion

The fire behaviour was sensitive to both the type of fuel bed and to the separation between the individual fuel, but appeared to be relatively insensitive to the number of fires involved.

The most marked effect of the type of fuel on fire behaviour occurred with the kerosine-wick fire which burnt about twice as quickly as the corresponding isolated unit fires. The wood block fires tended to burn rather more slowly in combination than the corresponding unit fires, presumably because of oxygen starvation near the centre. This difference in behaviour is even more marked in the photographs (Plate 2): in the kerosine fire the flames were about 5 ft in height forming a merged body of flame, whereas the wood fires burned quietly with flames rather shorter than the isolated unit fire.

Since the heat output of the unit fires is very similar this difference in behaviour is due to the different responses of the two fuel beds to thermal feedback and to changes in oxygen concentration. The rate of emmission of volatiles in a wick fire is governed by the rate at which heat is received by the surface of the wick, which in multiple fires is increased by the proximity of other fires, whereas the rate of burning of piles of randomly packed wood blocks depends more on the heat and mass transfer and the chemical processes within the fuel bed itself and since these are shielded from external radiation, the wood fires are hardly sensitive to thermal feedback.

Persistent fire whirls occurred within the fire area with continuous fuel beds, sometimes as high as 6-8 ft and 1 ft in diameter, and their size appeared to increase with the size of the fuel bed. However, except for the 16 x 16 fire in which a few whirls occurred in the centre, the whirls in the fires with separated fuel beds occurred largely in the period when the fire had died down and were not usually in the centre. The whirls always rotated in the same direction and may presumably be attributed to a slight vorticity induced by the asymmetry of the air inlets of the laboratory: by opening a door to admit inflowing air in a direction opposed to the rotation of the vortex the fire whirls could be destroyed. One of the whirls is shown in Plate 3.

For the fires with separated fuel beds, theory[1] predicts the onset of merging when $S/_D = \frac{1}{4}$. This is consistent with observations in the experiments in that the fires were certainly not merged when $S/_D = \frac{1}{2}$, but in most cases were merged when $S/_D = \frac{1}{4}$. Thus if this is a true representation of large-scale multiple fires, the experiments show that the separation employed in Project Flambeau ($S/_D = \frac{1}{2}$) was too large to produce a merged fire. This result is consistent with the recent large-scale Flambeau experiment in which the merging was not sustained and where it did occur was only local and transient.

5. Scaling of velocities

Table 2 gives details of the measurements of mean air speed at ground level 6 in outside the fire area in line with the central channel of each side. Within the limitation of the few results available there appears to be no systematic variation with the number of fires or their spacing, and for these fires we may take a representative value of 1 ft/s for the velocity at this point.

In the recent 18 x 19, $\frac{1}{2}$-spacing, Project Flambeau fire, Lommasson[2] measured an air inflow velocity of 4-7 ft/s at a point about 100 ft outside the fire area near one corner of the array. Heselden and Woolliscroft[3] also obtained some rough estimates of air speed within the fire zone by placing two types of indicator designed to blow over at 30 and 60 ft/s on the ground on the axes of symmetry of the array. Except in a region in which there was intense fire whirl activity it was observed that the 30-ft/s indicators were blown over, but the others not, indicating that each experienced a velocity of somewhere between 30 and 60 ft/s. It is likely that this was due to gusts rather than to the steady component of the wind, since this type of device is biassed towards indicating the maximum velocity rather than the mean.

For a previous Flambeau fire with 15 x 16 closely spaced piles, Nielsen[4] has given the velocities at a point midway between the centre and outside, at a height of 7 ft on the axis of symmetry of the array. The average velocity over the first $\frac{1}{2}$ hour of the fire was about 20 ft/s, but there was considerable scatter, with gusts up to 30 ft/s.

These measurements of air velocity in the different fires may be discussed in terms of scaling laws, as follows. At a point outside the fire area, at a sufficient distance for the flow to be reasonably uniform, the fire acts rather as a large finite sink, drawing in air towards itself. The flow is then determined by the total air entrainment of the fire, A, say, and the distance from the edge, together with the macroscopic length scale, that is the linear size of the whole fire, R, say.

A simple scaling law now follows if we assume that:

(i) the flames are not fully merged

(ii) the air requirement of the whole fire is the sum of the air requirements of the individual fires

(iii) all air flows horizontally from outside the fire area through the channels separating the fires.

(iv) the entrainment of air by the individual fires is unaffected by the presence of the other fires.

The entrainment theory of Thomas[6] then shows that:

$$A \propto LND\sqrt{gL}$$

where N is the number of fires.

Thus if v is the inflow velocity at distance r from the edge of the fire, a dimensional argument based on continuity of air flow shows that:

$$\frac{Rv}{ND\sqrt{gL}} = f\left(\frac{r}{R}\right)$$

and since

$$R \simeq \sqrt{N}\,(S + D)$$

Therefore

$$\frac{v}{\sqrt{gL}} = \frac{\sqrt{N}}{1 + S/D}\, f\left(\frac{r}{R}\right) \qquad (1)$$

Lommasson[5] assumes that a large fire behaves as a horizontal section of a straight-sided plume from an effective point source below so that the well known plume results can apply, i.e. inflow velocities are proportional to the upward axial velocity in the flame, and the inflow velocity at the edge of the fire is therefore proportional to $(Q/R)^{\frac{1}{3}}$ where Q is the total heat release rate of the fire. A similar argument to that above leads to:

$$\frac{v}{(Q/R)^{\frac{1}{3}}} = f\left(\frac{r}{R}\right) \qquad (2)$$

This can be shown to be approximately equivalent to equation (1) because Thomas[6] has shown that for single piles at least

$$\frac{L}{D} \propto \left(\frac{Qs}{D^{5/2}}\right)^{\frac{2}{5}}$$

where Qs is the heat release of a single pile. Equation (2) may now be rewritten to give:

$$\frac{v}{\sqrt{L}} = \left(\frac{\sqrt{N}}{1 + S/D}\right)^{\frac{1}{3}} f_2\left(\frac{r}{R}\right) \qquad (3)$$

Thus it appears that apart from a weak function of the number of fires and the ratio S/D, the scaling laws derived from two different sets of assumptions are equivalent and exactly so for similar geometries in which N and S/D are the same;

Then

$$v \propto \sqrt{L}$$

Clearly an examination of the limited data available can give no indication of the validity of either set of assumptions. The result that $v/\sqrt{L}$ is a function of the geometry is not based on arguments leading to a similarity of Froude Number. The v and $\sqrt{L}$ are here associated with velocities and quantities of air not with a balance of imposed vertical and buoyancy forces.

We can make a rough numerical check on the validity of equations (1), (2) and (3) from the measurements as follows:

For the present model experiments

$\frac{r}{R} = 1/40$ $\qquad$ $S/_D = 0.25$ $\qquad$ $N = 256$

$L = 1.5$ ft $\qquad$ $v = 1$ ft/s

and for the Flambeau fire

$L = 50$ ft $\qquad$ $S/_D = 0.5$ $\qquad$ $N = 342$

and thus equation (1) predicts that at $\frac{r}{R} = 1/40$ (or 35 - 40 ft from the edge of Flambeau fire) the mean velocity v is 5.4 ft/s. This is not directly comparable with Lommasson's measurements of 4 - 7 ft/s at $\frac{r}{R} = 1/14$ but as the function $f\left(\frac{r}{R}\right)$ is probably a fairly weak function for these values of $\frac{r}{R}$ (it certainly would be if the fire were actually behaving as a finite sink) the agreement is encouraging.

The rate of burning of the model-scale experiments was about 2.5 lb in 15 min (the exact amount is not important since the rate of burning is raised to the $\frac{1}{3}$ power). In the Flambeau experiments about half the fuel was burnt in $\frac{1}{2}$ hour. Equation (2) then predicts that $v = 4.5$ ft/s, which is in reasonable agreement with the Lommasson observation.

No measurements comparable with those of Nielsen or Heselden and Woolliscroft were made in the present model experiments, but if we employ the assumptions made about air flow in the first model discussed above, we may derive a theoretical expression for the velocity u in the channels separating the fires namely:

$$u \simeq K \frac{D}{S} \sqrt{\frac{N \theta_{fl} gL}{T_{fl}}} \qquad (4)$$

where N is the number of fires at equal or less distance from the fire centre and θ_{fl}, T_{fl} are the temperature rise and absolute temperature of the fire, taken to be about 1000°C. The constant K (= 0.054) is a feature of Thomas' entrainment theory[6] and has been evaluated by an analogy with thermal plumes rather than by direct measurements and its application in the present context must be viewed with some reservations. For Nielsen's measurements

$$\sqrt{N} \simeq 7, \; S/_{D} \simeq \tfrac{1}{2}, \quad L = 50 \text{ ft}$$

and then equation (4) predicts

$$u = 26.5 \text{ ft/s}$$

which is a little high but within the scatter of the data. A similar calculation for the data of Heselden and Woolliscroft leads to a maximum value of the velocity of $u \simeq 68$ ft/s which is once again a little high and by about the same fraction as for Nielsen's results. In view of the very crude approximation employed in deriving equation (4) the agreement is remarkably good.

6. Conclusions

1. The behaviour of an array of fires was sensitive to the separation between individual fuel beds. The large continuous fuel beds were especially sensitive to ambient vorticity; but the same behaviour was not exhibited by separated fires of comparable overall size.
2. The results of the experiments are consistent with calculations of the degree of flame merging in multiple fires, and suggest that the 25-ft spacing ($S/_{D} = \frac{1}{2}$) adopted in the Project Flambeau fires was too small to produce a merged fire.
3. In modelling real fire situations such as fires in cities care must be taken to reproduce the response of the individual fuel beds to thermal feedback.

4. Given the absence of significant rotation, the measurements of induced air velocity in the model fires and in Project Flambeau are consistent with a simple scaling law.

7. Acknowledgements

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8. References

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(4) NIELSEN, H. Analysis of experimental fire data. Proceedings of Mass Fire Research Symposium, Tripartite Co-operation Program, Panel N3. Defence Atomic Support Agency, Washington, October 1967.

(5) LOMMASSON, T. E. Preliminary investigation of firestorm start-criteria. Dikewood Corporation DC - TN - 1050 - 1, Alberquerque, Mexico, 1965.

(6) THOMAS, P. H. The size of flames from natural fires pp. 844-59. Ninth Symposium (International) on Combustion. U.S. Combustion Institute. New York, 1963, Academic Press.

APPENDIX

Air flow measurements

The air flow towards the fires was measured by means of simple vane anemometers in which the vanes consisted of a strip of one or two layers of aluminium foil, 10 cm x 1 cm x 0.002 cm thick, suspended from a nail in a vertical piece of wood. A quadrant of cardboard, marked in degrees, was also mounted on the upright to enable the deflection to be observed. A diagram is appended in Fig. 1.

Several complete anemometers were calibrated for different wind speeds of 1 - 10 ft/s in a small wind tunnel, and the results are shown in Fig. 2. It was found that, within the accuracy required, similar vanes gave the same deflection at a given wind speed, so that a single calibration could be employed for all vanes of the same thickness.

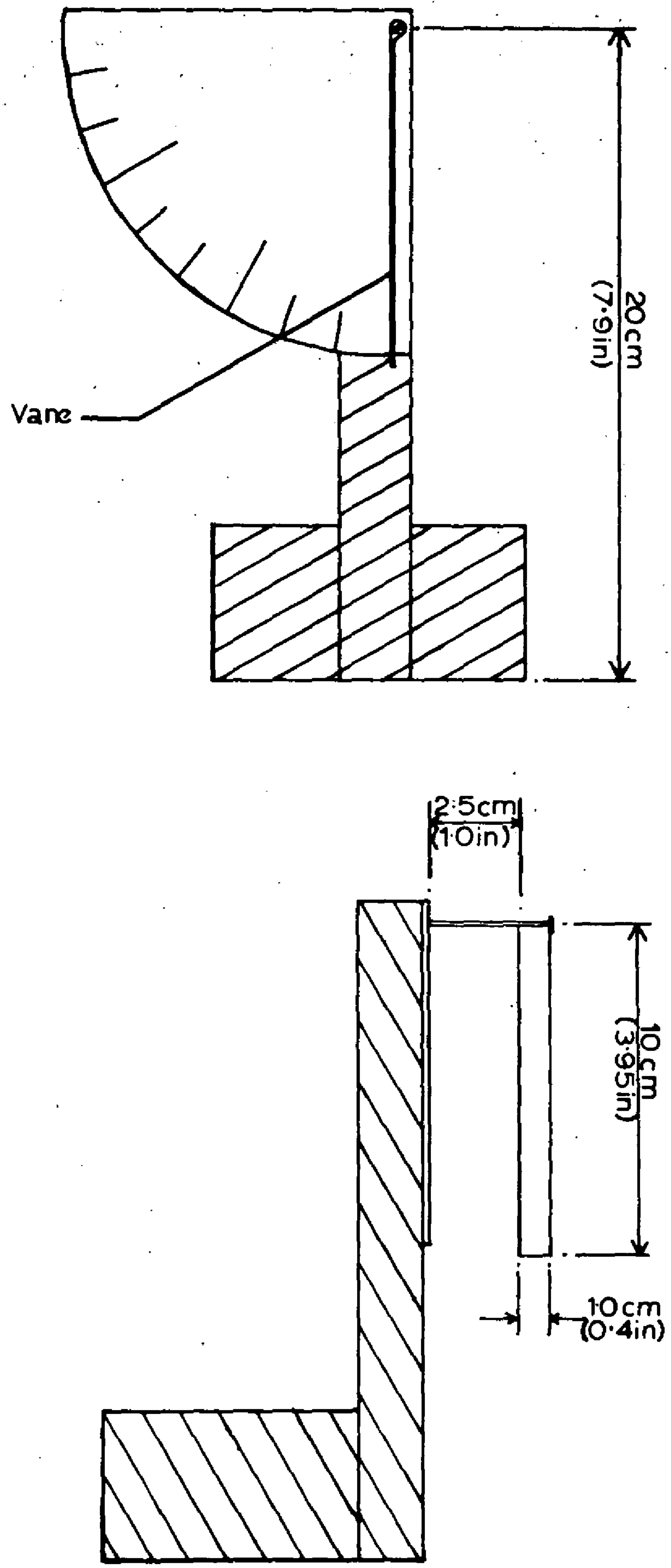
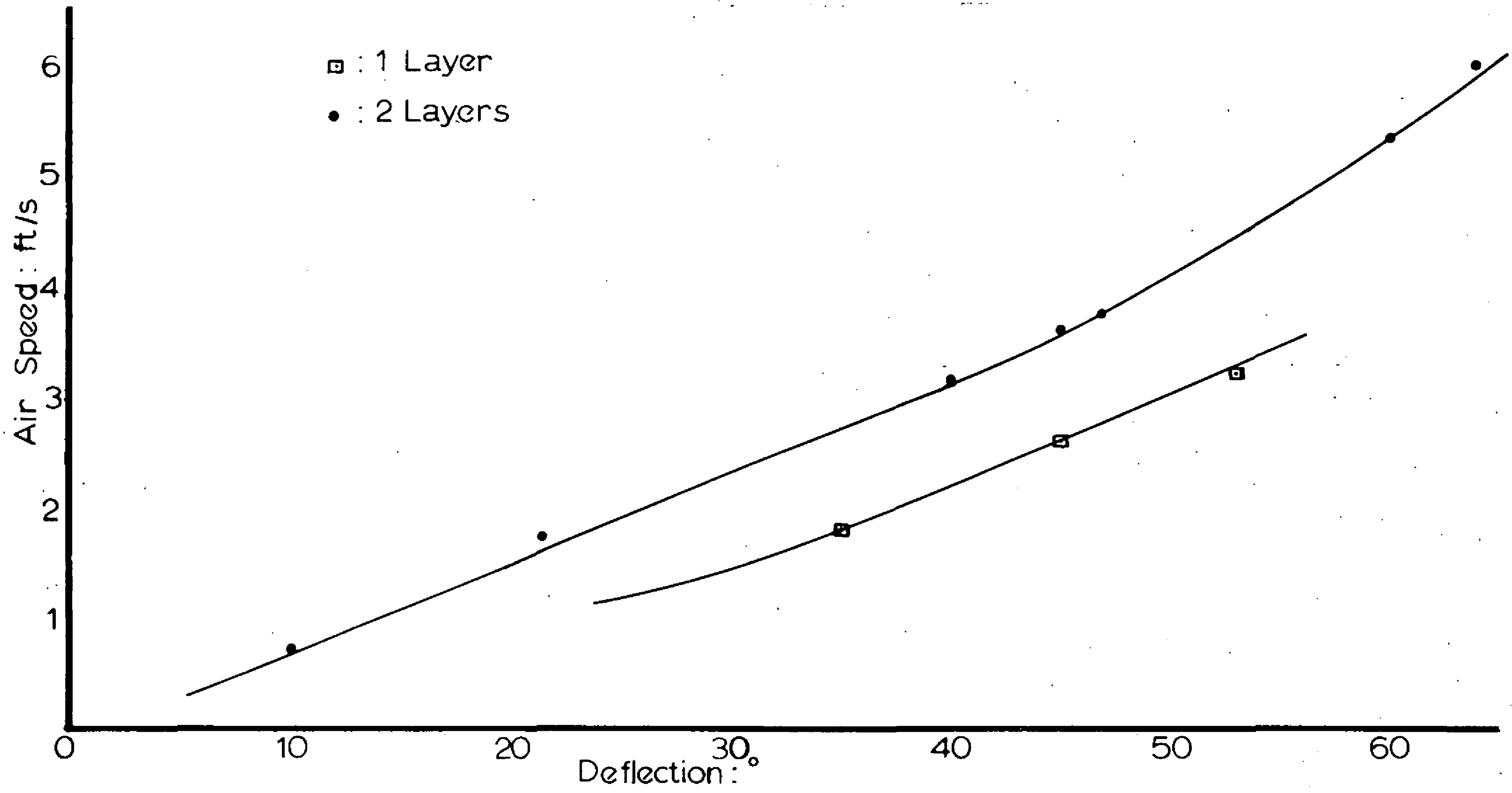
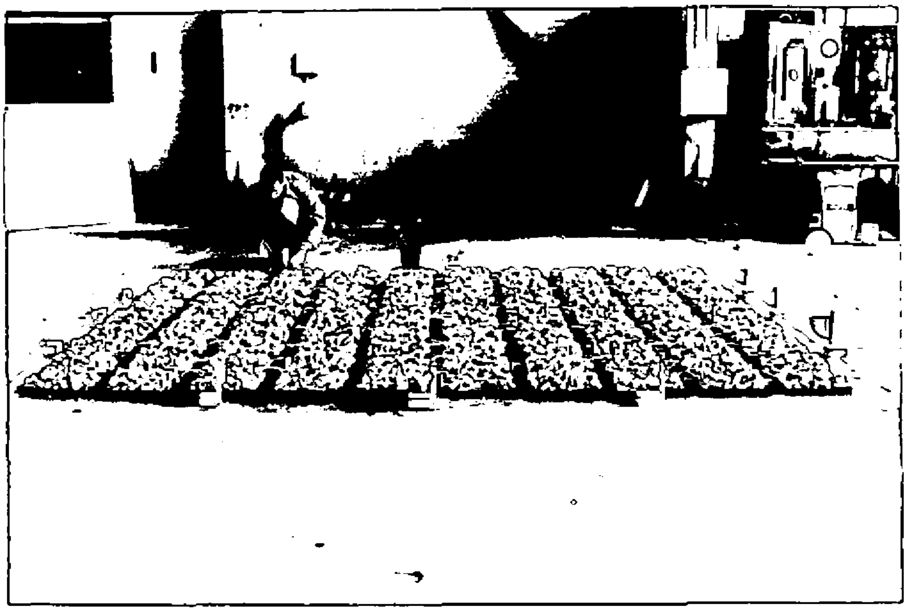


Fig.1 Aluminium Foil Vane Anemometers

Fig 2 Calibration of Aluminium Foil Vane Anemometers

Foil vanes: 10cm x 10cm
Thickness : 2 x 10^{-3} cm

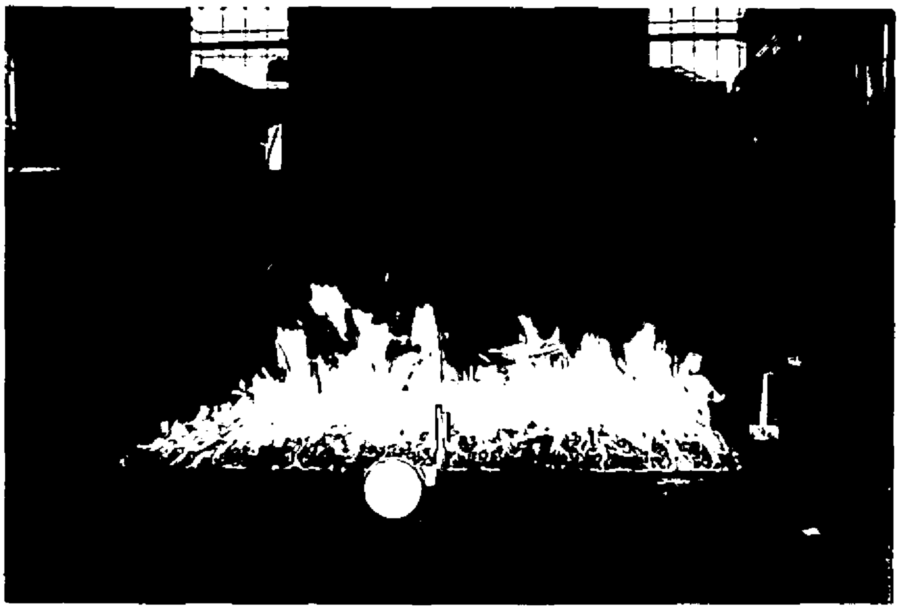




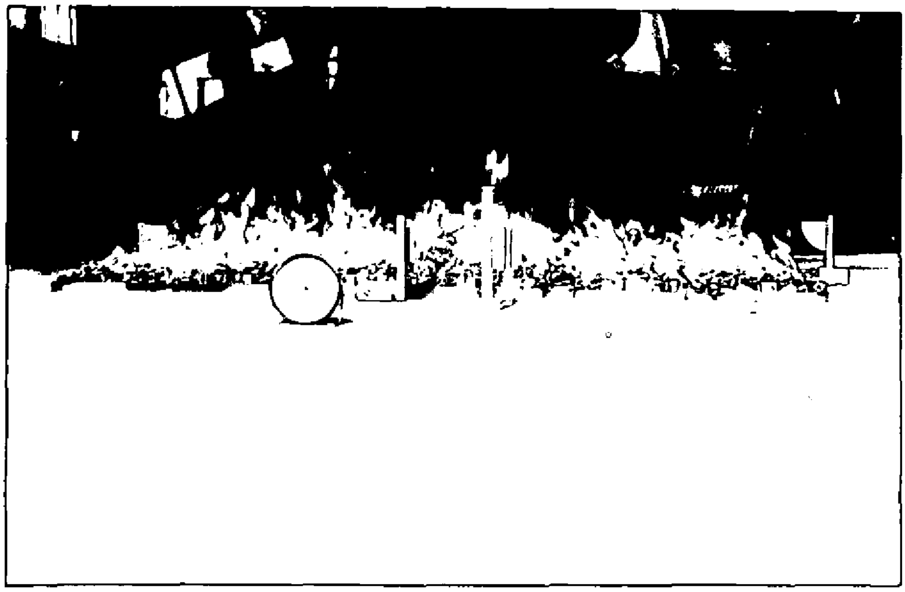
a) Multiple fire experiment before ignition
(10 x 10, $\frac{1}{4}$ spacing)

b) 6 x 6 fire with $\frac{1}{4}$ spacing. Circular unit fire
MULTIPLE FIRE EXPERIMENTS.

PLATE 1



c) 6 x 6 continuous fuel bed (zero spacing)
Square unit fires.

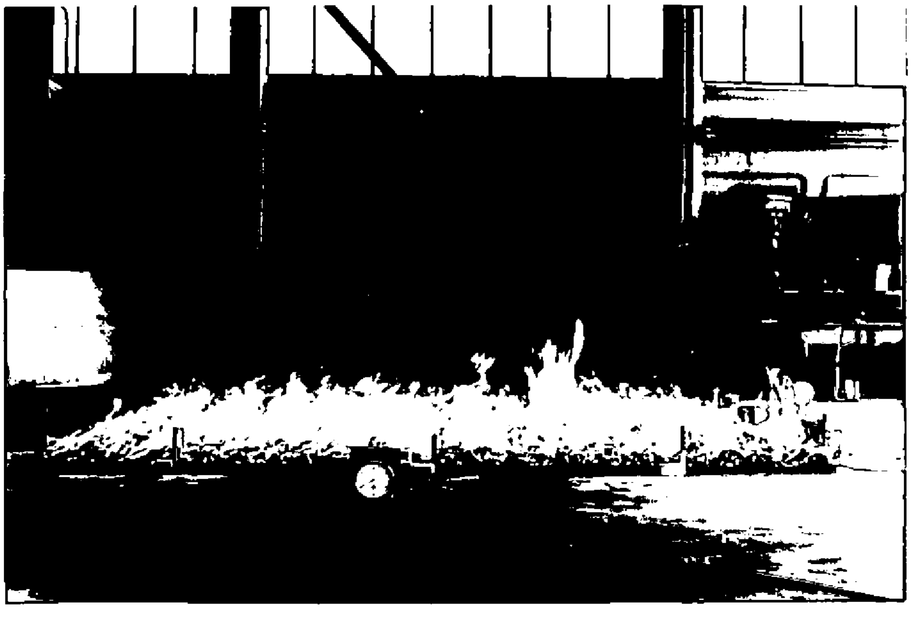


d) 6 x 6 fire with $\frac{1}{4}$ spacing. Square unit fires.

MULTIPLE FIRE EXPERIMENTS

PLATE 1

e) 10 x 10 continuous fuel bed (zero spacing)
Square unit fires.



f) 10 x 10 fire with $\frac{1}{4}$ spacing. Square unit fires

MULTIPLE FIRE EXPERIMENTS

PLATE 1

g) 16 x 16 fire with $\frac{1}{4}$ spacing. Square unit fires

MULTIPLE FIRE EXPERIMENTS

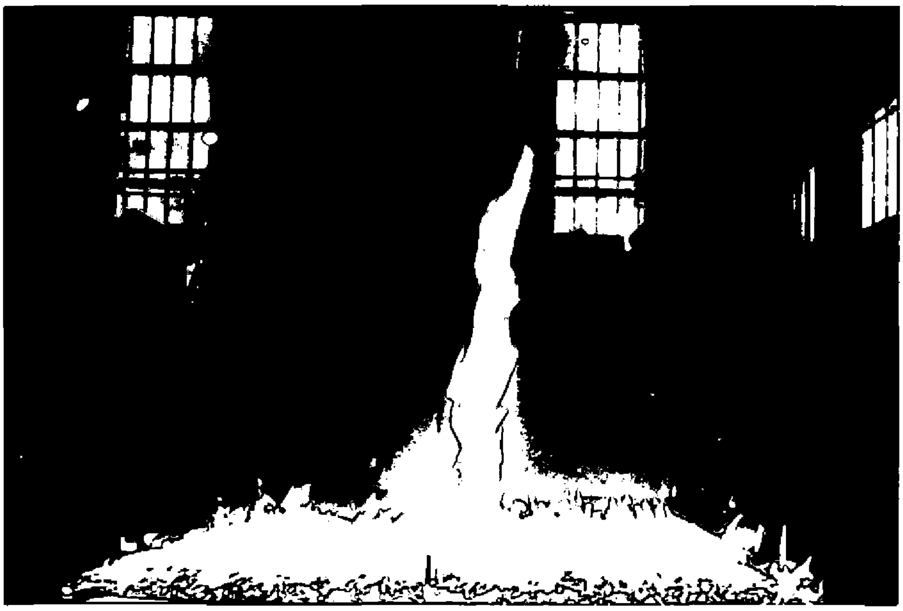
PLATE 1

a) Unit fuel bed : pile of small wooden blocks

b) Unit fuel bed : paraffin soaked wick

THE EFFECTS OF THERMAL FEED BACK. TWO EXPERIMENTS WITH 6 x 6 FIRES, $\frac{1}{2}$ SPACINGS AND DIFFERENT TYPES OF FUEL

PLATE 2



A PERSISTANT FIRE WHIRL OBSERVED
IN AN EXPERIMENT WITH A 10 ft SQUARE
CONTINUOUS FUEL BED

PLATE 3