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SOME TENTATIVE CALCULATIONS OF FLAME MERGING IN MASS FIRES

by

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SUMMARY

A simple model of flame merging in mass fires is examined for fuel beds placed in a regular array. The model leads to an estimate of the critical conditions at the onset of merging which is in agreement with the scanty data available.

The theory indicates that the critical conditions expressed in terms of the flame height, fuel bed separation and size, are independent of the number of fires except insofar as the number determines the flame height, and a simple means of visualizing the effect of increasing numbers is given.

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

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Introduction

Separate fuel beds placed sufficiently close together give flames which tend to merge together and behave as the flames of a single larger (or mass) fire. The critical condition at which the transition from multiple single fire to mass fire behaviour occurs may be defined as the point when the flames are so inclined that the flame tips just meet. An increase in the separation of the fuel beds would then cause the flames to move apart, whilst a decrease in the separation would increase the degree of flame merging until ultimately the flames would merge completely. For separations greater than the critical, the flames behave as separate fires (although their inclination and rate of burning are influenced by the other fires) and their aerodynamic properties may be calculated largely from single flame data. Once the flames begin to merge, however, single flame data is inappropriate, and the interaction between the fires is such that the entrainment of air to the inner flames is considerably restricted and flame height increased. When the flames are completely merged the flames once again behave as a (large) single fire and the increase in flame height may be calculated approximately from single flame data[2] as follows[1]:

$$L/_{L*} = N^{\frac{1}{3}}$$

where L = flame height of merged flames

L* = height of flames when the separation of the fuel beds is infinite, the burning rate being the same as at zero separation

N = number of fires.

The critical conditions for merging have been studied by Thomas & Baldwin[1] for simple configurations of two and four fires and have been discussed in terms of a theory in which the flames merge due to the interplay of two forces on the flame:

1) A pressure thrust induced by the restriction of the air to the inner surfaces of the neighbouring fires
2) A buoyancy force drawing the flame upwards.

Reasonable agreement was obtained between the results of experiments and theoretical prediction over a fairly wide range of configurations and scales although a highly simplified entrainment theory was employed. The present report extends these calculations and predicts the critical condition at which merging occurs in more complex situations.

The most general problem requiring solution is that of a random distribution of isolated fires, contained in a given area, for which the critical separation at which merging occurs or the degree of merging are to be calculated. However, the degree of merging also influences the rate of feedback of heat to the fuel bed and hence the rate of burning, which itself influences the flame height and hence the degree of merging. This problem is extremely complex and little is known of the feedback mechanisms involved, so in a first analysis an idealised model will be considered taking no account of variation of burning rate from bed to bed and in which the burning fuel beds will be supposed to form a regular circular or rectangular array. The problem solved is that of relating the flame height, fuel bed size and separation, and the number of fires at the onset of merging. The flame height is itself a measure of the rate of burning, and also governs the rate of entrainment of air.

Theory

Consider a regular square array of n^2 fires each with a square base of side D and separated by a channel of width S. To the degree of approximation required this could with small modification be regarded as a circular array. We will number the rings of fires, those on the perimeter being defined as ring 1, the next ring of fires ring 2 and so on. Let n_i be the number of fires along one side of the square in the i^{th} ring and u_i the velocity of the air flowing into the channel separating two fires on the i^{th} ring.

The fluid flow problem now posed is that of a number of finite sinks drawing air from the surroundings. The velocity of the air flowing around the fires may be solved as a problem in potential flow but in view of the limited accuracy required and the uncertainties in some of the quantities to be estimated, this degree of sophistication seems unjustified at this stage. Suppose as an approximation that the flow down each of the channels in the i^{th} ring is the same; this assumption is true for circular configuration but is only an approximation for rectangular arrays. The value of u_i may be evaluated by equating the total air requirements of the flames to the total air flowing down the channels between the fires.

Thus $\quad S\, u_i\, (n_i - 1) \;=\; (n_i^2 - n_i)\, D\bar{v}_e$

$$\therefore \qquad u_i = \frac{n_i\, D\bar{v}_e}{S}$$

where it has been assumed that each of the flames is entraining air at the same rate, $\bar{v}_e$, where $\bar{v}_e$ is a mean entrainment velocity. Hence no account is taken of the variation of flame height from ring to ring nor of the variation of burning rate.

The pressure drop across a flame in the i^{th} ring is given by considering the flow down channels in neighbouring rings. From Bernoulli's Theorem:

$$p_i - p_{i+1} = \tfrac{1}{2}\rho_A\,(u_i^2 - u_{i+1}^2)$$

$$= \rho_A\,(n_i - 1)\;{\frac{D\bar{v}_e}{S}}^{2}$$

since for square arrays

$$n_{i+1} = n_i - 2$$

The pressure thrust on the flame, P_i, is given by

$$P_i = A\,(p_i - p_{i+1})$$

$$= 2\,(n_i - 1)\rho_A\;{\frac{D\bar{v}_e}{S}}^{2}\;A$$

where A is the projected area of the flame in a vertical plane in which the pressure thrust acts.

The pressure thrust is balanced by a buoyancy force B on the flame, acting upwards,

$$B = \rho_{fl}\, V\, \frac{g\,\theta_{fl}}{T_A}$$

where V is the flame volume, and ρ_{fl}, θ_{fl} are the density and temperature rise of the hot flame gases, assumed to be constant throughout the flame volume.

Let ϕ_i be the inclination to the vertical of flames in the i^{th} ring.
Then $\tan \phi_i = P_i/B$

$$= 2\,(n_i - 1)\,\rho_A/\rho_{fl} \quad D/S^2 \quad \frac{\bar{v}_e^{\,2}\,T_A}{g\,\theta_{fl}}$$

taking $V/_A = D$

We have now established the inclination of the flames in terms of the pressure thrust and buoyancy force acting and it remains to evaluate the geometric conditions relating the inclination to flame height and separation when the flame tips are just touching. The critical condition for merging of two consecutive rings i and $i + 1$ is

$$S/L_i = \tan \phi_i - \tan \phi_{i+1}$$

where L_i is the mean flame height of flames in the i^{th} ring.

Substituting for $\tan \phi_i$ and $\tan \phi_{i+1}$, and remembering that $n_i - n_{i+1} = 2$, the critical condition becomes

$$\frac{S^3}{L_i D} = 4\,\frac{\rho_A\,T_A}{\rho_{fl}\,\theta_{fl}}\;\frac{\bar{v}_e^{\,2}}{g}$$

This condition may only be evaluated by estimating the value of $\bar{v}_e$. For flames burning in isolation the simplified entrainment theory of Thomas[2] gives

$$\bar{v}_e^{\,2} = K^2\;\frac{g\,\theta_{fl}}{T_{fl}}\;L$$

where $K = 0.054$ and L is the mean flame height.
We now assume that entrainment is unaffected by the flames leaning or by the pressure drop across the flame. This assumption has also been employed by Thomas and Baldwin[1] for simpler configurations than in the present report. We will re-define L as a mean flame height for fires in all rings.

The critical condition then becomes

$$\frac{S^3}{L L_i\, D} = 4\,K^2 = \text{constant}$$

Thus the flames will merge first at the ring of fires with the maximum flame height, which is the height of the flames when considered as a large single fire. Taking L as a measure of the flame height then gives the critical condition of merging.

$$\frac{S^3}{L^2 D} = 4 \ K^2 = \text{constant} \qquad (1)$$

Discussion and conclusions

The critical condition of equation (1) expresses the relative values of the separation, flame height and fuel bed size at the onset of merging. It is independent of the number of fires except insofar as this factor determines the flame height and it is thus the critical condition for any number of fires in an ordered array. If there is little variation of L_i with i, then equation (1) is the critical condition for each of the rings of fires and hence the onset of merging occurs simultaneously for all the rings. This may be visualised by the following representation. Suppose that each fuel bed is represented by a point separated from its neighbours by a distance S, and that the flames in the i^{th} ring are represented by a line inclined at an angle ϕ_i to the vertical. Then at the onset of merging the lines representing the flames will all meet at a point at height L, independent of the number of fires. Any increase in the number of fires by addition of further rings of fires on the perimeter burning at the same rate will only have the effect that the lines representing the additional fires will pass through the original point of merging. This argument also applies before the onset of merging when the limiting conditions on the application of the theory are more likely to apply: the lines representing the fires when produced all meet at a point.

There are little experimental data on flame merging, and for this reason the calculations presented above may only be regarded as tentative at this stage. Table 1 summarises such data as are available and compares them with critical values of S/D calculated from Equation (1). These data are now described in more detail:

(a) The critical condition of Equation (1) is that found previously by Thomas and Baldwin[1] for four fires in a square array, and is in reasonable agreement with experimental results obtained using 1 ft square town gas burners. A similar calculation procedure gave reasonable agreement between theory and experiment for two rectangular burners over a wide range of shapes and scales. The degree of approximation in these cases is somewhat less, however, since the flow through the channels is determined by symmetry.

(b) Waterman et al[3] burned 3 ft square wood cribs arranged in square arrays. It was observed that the onset of coalescence corresponded with a dramatic peak in the rate of burning of the cribs. However, many of the conclusions were based on rather scanty data and only two of the configurations investigated have been employed here.

(c) Broido and McMasters[4] report a large scale experimental fire at Camps Park, in which 250 tons of assorted scrap lumber was distributed in 70 piles each measuring 20 x 15 ft, 7 ft high and spaced 12 ft apart along three concentric rectangles. The report implies that the flames, which were 50 ft high, were merged at least part of the time, and that conditions were near to the critical conditions for merging, since after 10 minutes the merging flames had separated into a group of individually burning fires. For this fire $L = 50$ ft and we take $D = \sqrt{(15 \times 20)} = 17.5$ ft, and $S = 12$ ft.

A further point of interest that arises from the Camps Fire data is that the flame height may be predicted from the single fire data of Thomas[2], who has correlated L/D in terms of a Froude number depending on the rate of burning and the linear dimensions D of the fuel bed. The mean rate of burning of each individual pile can be evaluated, assuming that 2/3 of the fuel had been burned after 20 minutes, when some of the piles had stopped flaming, giving a value for the Froude number for each individual pile of 8×10^{-3}. The data of Thomas then predicts a value $L/D \simeq 2\frac{1}{4}$, so that $L \simeq 40$ ft, which compares with the observed 50 ft, probably the maximum attained during the fire. This calculation tends to support the view that conditions were near to the critical, since the flame height was not substantially increased by flame merging.

(d) Evans and Tracy[5] report a large scale experimental fire in which the flames did not merge. This does not represent a true comparison with the theory developed above for the critical conditions of merging, and this fire is only included because it does give some indication as to whether the predicted value is reasonable. In this fire 324 stacks of timber each 50 ft square were arranged in a square array of side 1300 ft with 25 ft spacing between stacks. The maximum flame height observed was 30 ft, and it was reported that the flames burned individually.

The observation that the flames did not merge at the measured value $S/D = 0.6$ is in agreement with theory, which predicts that for the measured value $L/D = 0.6$, the flames should merge when $S/D \simeq 0.2$.

The above data are summarised in Table 1 and compared with the calculated critical values of S/D for the measured value of L/D. These data are insufficient to verify the validity of the theory presented above, but they do indicate a reasonable degree of agreement over a wide range of scales and configurations.

More experimental data on different scales and over a wide range of separations and numbers of fires are necessary before the validity of the theory can be established.

Source	Flame State	Number of fires	D ft	Measured L/D	Measured S/D	Theoretical Critical value of S/D.	Comment
Thomas and Baldwin	Merged	4 (& 2)	1	Range of values $1 < L/D < 4$		Reasonable agreement	Experiments with town gas to measure critical values of separation.
Waterman et al	Merged	4 16	3 3	3.4 3	0.3 0.4	0.5 0.5	Experiments with wood cribs. Critical separation deducted from variation of burning rate with separation of fuel beds.
Broido & McMasters (Camps Park Fire)	Merged	70	17.5	2.9	0.7	0.5	Large scale fire. Conditions probably near critical.
Evans & Tracy	Not merged	324	50	0.6	0.5	0.2	Flames not merged.

Table 1. Summary of data on flame coalescence in model and large scale fires.

References

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4. BROIDO, A., and MCMASTERS, A. W. Effects of fires on personnel in Shelters. Pacific Southwest Forest and Range Experimental Station. Technical Paper 50. Berkeley, California, 1960.

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Symbols

A	projected area of flame in a vertical plane
B	buoyancy force acting on flame
D	length of square base of fire
g	gravitational acceleration
K	constant = 0.054
L	flame height
N	total number of fires
n	$\sqrt{N}$
P	pressure thrust on flame
p	pressure on one side of a flame
S	width of channel between flames
T	absolute temperature
u	velocity of air flowing into channel between flames
V	volume of flame
$\bar{v}_e$	mean entrainment velocity
ρ	density
θ	temperature rise
ϕ	inclination of flames to vertical

Suffices

A	value for air
fl	values for flame
i	measured for a flame in the i^{th} ring of fires