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ON THE RATE OF SPREAD OF FIRE IN CITIES AND FORESTS

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No satisfactory theory of fire spread in high winds has yet become established and comparisons between theory and laboratory or field data are only possible in broad terms, such is the variation of field data. In this note, a few such comparisons are made and discussed.

Some general results

A recent survey of U.S. forest and city conflagrations by Phung and Willoughby[1] has shown that the rate of spread 'R', though increasing with the wind speed V does not increase so rapidly that d^2R/du^2 is obviously positive. Indeed, a linear regression is a satisfactory correlation of the trend.

On the other hand, a mean curve for pre-war conflagrations in Japanese cities[2] shows a positive d^2R/dU^2 and was drawn close to

$$R \propto U^{1.5} \qquad \text{.........(1)}$$

but here too a linear regression might be all that is justified; the data are unevenly distributed over the range of wind speed and the curvature depends heavily on a few fast spreading fires. However, this collection of data excludes ignition by flying brands over long distances, so these very fast fires cannot so easily be regarded as belonging to a different class of fire.

This 1.5 power law is similar to that reported by Curry and Fons[3] and by Anderson and Rothermel[4] for the spread of fire over pine needles in a wind. They give power laws with indices in the range 1.5 to 1.7.

On the other hand, experiments by Thomas and Pickard[5] and by Byram, Clements, George and Elliot[6] with cribs of somewhat thicker fuel show a zero of negative d^2R/dU^2.

It is possible to interpret these crib experiments by regarding the spread as driven by a radiation flux through the fuel bed[7,8], the wind causing the fire front to deflect and to spread perpendicularly to this deflected front at a rate almost independent of wind speed, i.e.

$$R \rho_b \cos \phi = 5 \to 8 \text{ mg cm}^{-2} \text{s}^{-1} \quad \ldots\ldots\ldots (2)$$

where ϕ is the deflection from the vertical and ρ_b is the bulk density of the fuel bed. Byram et al report ϕ as the deflection of the flame. This is probably somewhat larger than the deflection of the fire front within the fuel bed itself.

The numerical value of the constant in equation (2) tends to increase with increasing fuel thickness. The relation between ϕ and U is discussed below but both the alternative forms make d^2R/dU^2 negative. The effect of the wind on burning rate per unit surface of wood and hence on the radiation intensity is small, for cribs of 1 cm thick wood but could well be significant for thinner fuels; this would raise R above that given by equation (2). Clearly at low wind speeds any power law is improper and equation (2) applies with ϕ equal to zero.

The data for fire spread over pine needles in still air agrees well enough at low moisture contents[4] with predictions from equation (2) and the equation is also satisfactory when applied to some data for full scale fires. The average fuel loading of pre-war Japanese houses, allowing for the fraction of land occupied, is about 3 g/cm^2 [9]. If their mean height is taken as 500 cm ρ_b is 6×10^{-3} g/cm^3, which gives R as 0.83 to 1.3 cm/s or 30 to 50 m/h and this is in good agreement with reported values[2] and so is the value estimated for a forest crown fire reported by Van Wagner[10]. Is it possible, however, to interpret the 1.5 power law, however crudely?

Some theoretical aspects of wind driven fires

Any heat balance of the fuel ahead of the fire front must allow for several heat transfer mechanisms. These derive from the fuel bed and the flame, radiation and convection, and, sometimes, flying brands, though these are not considered here.

Fuel thickness

Before considering a series of hypotheses as to which heat transfer mechanism controls the spread, we must distinguish between two extreme possibilities regarding fuel thickness. Firstly, each element of fuel can be thought of as thin enough to be heated uniformly. The heat transfer must then be proportional to the total mass of fuel burnt per unit area of ground. Secondly, only the outer surface of a thick fuel element needs to be heated. The depth of penetration by thermal conduction is of order $(kt)^{\frac{1}{2}}$ where k is the thermal diffusivity and t is the time which, here, can be represented by

$$t \propto S/R \qquad \text{..........(3)}$$

where S is an effective distance ahead of the fire front over which heat transfer takes place.

Fuel bed heating

If the main source of heating for the unburnt fuel is the radiation transmitted through the fuel bed, S is the "mean free path" for that radiation, and for randomly arranged fuel elements

$$S = 4\rho_s/\rho_b\,\sigma \qquad \text{..........(4)}$$

where ρ_s is the density of the solid fuel

and $$\rho_b = w/h \qquad \text{..........(5)}$$

where w is the mass of fuel per unit area of ground

h is the height of the fuel bed

and σ is the specific surface of the solid fuel.

The following equation has been given[11] for the deflection of bent over flames

$$\cos \phi = 0.7 \left\{ \frac{(g R w / \rho_0)^{1/3}}{U} \right\}^{1/2} \qquad \text{..........(6)}$$

where g is the acceleration due to gravity

and ρ_0 the density of air, was used to obtain a convenient dimensionless wind speed. Physically, a thermally based dimensionless wind speed is preferable but here only proportionalities will be discussed so the distinction is irrelevant.

A heat balance perpendicular to the deflected fire front moving at constant speed may be written as

$$i_1 = R \rho_b \cos \phi . H \qquad \text{..........(7)}$$

where H is the enthalpy rise from ambient to ignition for unit mass of fuel and i_1 is the heat flux, which for the radiation from the burning one in the fuel bed is independent of ϕ

For thin fuel, we therefore have from equations (6) and (7)

$$R \propto U^{3/7}$$

$$\text{i.e. } R \propto U^{0.43} \qquad \text{..........(8)}$$

For thick fuel the heat balance becomes

$$i_1 \doteq R \rho_b (kt)^{1/2} \cos \phi \qquad \text{..........(9)}$$

so that from equations (4), (5), (6) and (9)

$$R \propto U^{0.75} \qquad \text{..........(10)}$$

Note that $R\rho_b$ is proportional to $\sigma^{-0.75}$ and so increases as the fuel thickness increases, as stated above.

Flame radiation

If flame radiation is the main mechanism of heating, the heat balance may be written as

$$F(\phi)\, L\, i_2 = R\omega H \quad \text{for thin fuels} \qquad \text{..........(11)}$$

and

$$= R\omega H\, \sigma (kt)^{1/2} \quad \text{for thick fuels} \qquad \text{..........(12)}$$

where L is the flame length

i_2 is the flame radiation intensity, assumed constant

F is a radiation exchange factor which lies between $\frac{1}{2}$ and 1 for a wide flame.

Because the vertical flame height controls the heat transfer ahead of the flame, we can put F equal to $\frac{1}{2}$ for a vertical radiator and, so long as the major part of the heating occurs while the fuel element is ahead of and not under the flame,

$$t \propto \frac{L \cos\phi}{R} \qquad \text{..........(13)}$$

The flame length L is given by[11]

$$L \propto (R\omega)^{2/3} \qquad \text{..........(14)}$$

so from equations (11) and (14) we have

R independent of U for thin fuels ....(15)

and from equations (6), (12), (13) and (14)

$R \propto U$ for thick fuels. ....(16)

If the major part of the heating is assumed to occur while the fuel element is beneath the deflector flame we should put $t \propto L/R$ and $F = 1$ and then R is independent of U for thin and thick fuels.

Convection

A possible form for convection heating may be derived if the flow of gases is considered as due to a boundary layer originating at the fire front. (Such an approximation would fail if the burning zone were long compared with the flame length, if for no other reason). Assuming flame gas temperatures are not strongly dependent on L, U R etc. one can then write the heat balance as

$$q' \propto h \propto (LU)^{0.8} \qquad \ldots\ldots\ldots\ldots(17)$$

where h is the heat transfer coefficient

and where, for thin fuel

$$q' = RwH \qquad \ldots\ldots\ldots\ldots(18)$$

For thick fuel

$$q' = RHw\sigma(kt)^{1/2} \qquad \ldots\ldots\ldots\ldots(19)$$

and

$$t = L/R \qquad \ldots\ldots\ldots\ldots(20)$$

From equations (14), (17) and (18)

$$R \propto U^{12/7} \text{ i.e. } R \propto U^{1.7} \text{ for thin fuel}$$

and from equations (14), (17), (19) and (20)

$$R \propto U^{8/3} \text{ i.e. } R \propto U^{2.7} \text{ for thick fuel}$$

Discussion

The above results are collected in Table (1)

Table 1

Fuel	Radiation		Convection
	Fuel bed	Flame	
Thin	$U^{0.43}$ (U)	U^{0}(constant) (U^{0})	$U^{1.7}$
Thick	$U^{0.75}$ $(U^{1.33})$	$U^{0} \rightarrow U^{1.0}$ $(U^{1.5})$	$U^{2.7}$

Hamada[12] gives a form for the deflection which is physically more realistic than equation (14) when the burning zone is long compared with the flame length. This is

$$\cot \phi \propto gD/U^2 \qquad \text{..........(21)}$$

D is the length of the base of the flame which, here, may be taken as

$$D = R t_B \qquad \text{..........(22)}$$

where t_B is the duration of flaming for a fuel element. This time varies with the wind speed but Anderson and Rothermel[13] give some values for pine needles which show that the variation may be small for their experiments.

If the variation of t_B is neglected and we put

$$\cos \phi \approx \cot \phi$$

when ϕ approaches $\pi/2$, the results are altered to those shown in brackets in Table (1).

Another equation based on a slightly different definition of flame height, given by Thomas[11], is

$$L \cos \phi . U \propto R W \qquad \text{..........(23)}$$

This gives powers of U which are within the ranges shown in Table (1) for radiation control, and in particular it gives a 1.5 law for flame control and thick fuel - the same as Hamada's equation does.

It is thus apparent that the index of U may increase from some value less than unity to a value greater than unity as the fuel becomes thicker and as the main source of the heat transfer changes from the fuel bed to the flame and as the importance of convection increases.

The apparent similarity between the data for pine needles and Japanese cities may well be fortuitous. It is not unreasonable to regard fires in pine needles as convection controlled fires in thin fuel and fires in cities as radiation controlled thick fuel fires.

It is, however, difficult to reach any definite conclusion for any particular type of fire. Considerable help in this task could be derived from data on the dependence of 'R' on 'w'.

Equations (6), (14), (21) and (23) are probably the least accurate of all those quoted; indeed equations (6) and (23) are strictly contradictory. Nevertheless the tendencies shown in Table (1) are likely to be real enough. It is clear that to identify the physical laws from field data alone requires data over a large range of several of the variable factors, not just the wind speed.

References

1. PHUNG, P. V. and WILLOUGHBY, A. B. Prediction Models for Fire Spread following Nuclear Attacks. United Research Services Report URS 641-6 (1965).
2. "The Rate of Fire Spread". Research Committee of Tokyo Fire Brigade Report No. 1. (1942).
3. CURRY, J. R. and FONS, W. L. J.Agric. Res. (1938), 57, 4, 239.
4. ANDERSON, H. E. and ROTHERMEL, R. C. 10th International Symposium on Combustion, Cambridge, England. (1964) Academic Press, New York. (see also the discussion by Thomas).

5. THOMAS, P. H. and PICKARD, R. W. Report on Forest Research. (1961) p. 105. H.M.S.O. London.

6. BYRAM, G. M., CLEMENTS, H. B., ELLIOT, E. R. and GEORGE, P. M. "An Experimental Study of Model Fires" Technical Report No. 3. (1964). U.S. Forest Service. Southeastern Forest Experiment Station, Macon, Georgia.

7. THOMAS, P. H., SIMMS, D. L. and WRAIGHT, H. G. H. "Fire Spread in Wooden Cribs". Department of Scientific and Industrial Research and Fire Offices' Committee Joint Fire Research Organization. Fire Research Note No. 537/1964.

8. THOMAS, P. H. ibid Part 3. Fire Research Note 600/1965.

9. KAWAGOE, K. Building Research Institute, Tokyo. Private communication.

10. VAN WAGNER. History of a small crown fire. Forest Research Branch. Contribution No. 554. Forestry Chronicle June 1964. Vol. 40. No. 2.

11. THOMAS, P. H. 9th International Symposium on Combustion, Cornel Univ. (1963) Academic Press. New York.

12. HAMADA, M. Bull. Fire Prev. Soc. Japan. (1952), 1, (2), 41.

13. ANDERSON, H. E. and ROTHERMEL, R. C. Fire Spread Characteristics Determined in the Laboratory. Feb. 1965. Northern Forest Fire Laboratory. Intermountain Forest and Range Experiment Station, U.S. Forest Service, Missoula, Montana.