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THE SPEED OF PROPAGATION OF FLAME ON FABRICS

by

P. H. Thomas and D. I. Lawson

Summary

The speed of vertical propagation of flame on fabrics is discussed in terms of heat transfer. It is shown that conduction along the fabric can be neglected and that a simple heat balance equation can be derived. From this it follows that the speed is inversely proportional to mass per unit area, which agrees with experiment. The quantitative agreement between theory and experiment is satisfactory.

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Fire Research Station,
Boreham Wood,
Herts.

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1. Introduction

During the course of experimental work on the propagation of flame on fabrics it was found that for a range of cellulosic materials (e.g. wood, paper and various textiles) the speed of propagation of flame was inversely proportional to the mass per unit area of the fabric (1). This work was performed with the material burning vertically but other results (2) (3) show that a similar relation exists for the speed of propagation on an ascending 45° slope, the rate of spread being approximately one-tenth of that in the vertical, and no doubt a similar relation exists for the rate of flame spread at other angles.

This paper discusses the interpretation of these data in terms of the heat balance within the burning materials.

2. Theoretical analysis

Heat is transferred from the flames to the nearby fabric surface by radiation and convection. The heat transferred in this way from the flames raises the temperature of the unburnt material at the edge of the burning zone until sufficient combustible vapours are produced to allow the burning zone to advance. The assumptions made in the following analysis are that:-

(1) the behaviour is controlled by the thermal parameters of the system;

(2) the speed of propagation of flame is constant;

(3) the fabric is thin enough for temperature gradients across it to be neglected;

(4) the heat flux to the fabric from the flame, the hot gases and the chemical reaction, can be represented by a simple function of the distance 'z' from a point on the fabric moving at constant speed;

The origin of the co-ordinate along the fabric is defined as the position at which the temperature is the "ignition temperature" of the fabric in question, θ_o. The heat flux is assumed to be given by $Q\phi(\alpha Z)$, $Z > 0$ where Q is the maximum heat flux and ϕ decreases as Z increases.

The qualitative aspects of the following theoretical discussion would not be affected by the form of ϕ provided that:-

(a) only one independent parameter such as $\frac{1}{\alpha}$ of dimension of length is involved;

(b) the heat flux tended to zero at large values of x.

If H is the cooling coefficient then with respect to a stationary co-ordinate x

$$K\Delta \frac{\partial^2\theta}{\partial x^2} = \rho c \Delta \frac{\partial\theta}{\partial t} - 2Q\,\phi(\alpha z) + 2H\theta \qquad \ldots\ldots (1)$$

Where $$z = x - vt. \qquad \ldots\ldots (2)$$

where Δ is the thickness of the fabric,
ρ is the density,
c is the specific heat,
K is the thermal conductivity,
t is the time,

and v is the velocity

At $x = 0$, $t = 0$ and $\theta = \theta_0$

From equation 2, the equation for steady burning is

$$\frac{d^2\theta}{dz^2} = -\frac{v}{k}\frac{d\theta}{dz} - \frac{2Q}{K\Delta}\phi(\alpha z) + \frac{2h\theta}{\Delta} \quad \ldots (3)$$

where $k = K/\rho c$ and $h = H/K$

The following dimensionless variables are introduced:-

$$A = \frac{2h}{\Delta\alpha^2} = \frac{\text{Surface loss of heat}}{\text{conduction in direction of flame propagation}}$$

$$B = \frac{v\rho c\,\Delta\alpha}{2H} \qquad \frac{\text{Heat given to material}}{\text{surface loss of heat}}$$

$$R = \frac{Q}{H\theta_0} \qquad \frac{\text{Maximum heat flux to surface}}{\text{maximum heat loss}}$$

$$u = \alpha z$$

$$\lambda = \theta/\theta_0$$

Equation 4 can then be written:-

$$\frac{1}{A}\frac{d^2\lambda}{du^2} = -B\frac{d\lambda}{du} - R\phi(u) + \lambda \quad \ldots (4)$$

The boundary conditions are:-

$$\lambda = 1 \;, \quad u = 0$$
$$\lambda \to 0 \;, \quad u \to \infty$$

The solution leads to relations between the "constants" A, B and R. The equation will be discussed in more detail elsewhere in connexion with the thermal limitations on flame propagation. Here, only the limiting form of the solution is discussed. B can be shown to tend to a maximum as A tends to infinity, that is, as the conduction term becomes less important in the heat transfer.

The value of h is near unity for fabrics, that is, H and K are of the same order so that for flames of length 10 cm and fabrics of thickness 0·1 cm or less, A is of order 10^3, R and B are of the same order and much less than this. The approximation of neglecting the conduction term is thus valid for normal propagation of flames.

In the limit where A becomes infinite equation 4 may be rewritten, after introducing the integrating factor $e^{-u/B}$ as,

$$\frac{d}{du}\left(\lambda e^{-u/B}\right) = -\frac{R}{B}\phi(u)\, e^{-u/B} \qquad \ldots\ldots (5)$$

Integrating equation 6 over the range $0 < u < \infty$

$$\frac{R}{B}\int_0^\infty \phi(u)\, e^{-u/B}\, du = 1 \qquad \ldots\ldots (6)$$

For a given value of R, it follows that B is a constant. If it is assumed that

$$\phi(u) = e^{-u} \quad (u > 0)$$

then $$B = R - 1 \qquad \ldots\ldots (7)$$

$$\therefore \quad \rho \Delta V = \frac{2(Q - H\theta_0)}{\theta_0 \, K C} \qquad \ldots\ldots (8)$$

an equation which can be derived directly from a simple heat balance.

θ_0 and C are basic properties of the fabric, Q is a property of the flame and is approximately constant and α is, presumably mainly a function of the rate of heat production which is itself proportional to $\rho\Delta V$. It follows that for any given type of material the product of the mass per unit area and the velocity is a constant

i.e. $\rho \Delta V$ = constant.

In addition to the effect of the variation in "Q", "C" and "θ_o" from one material to another, account would have to be taken of the dependence of flame length on calorific value. As long as the variation in these properties between two given materials is not large it might be expected that they have values of $\rho \Delta V$ of the same order.

Application of theory

Vertical flame speed

The heat transfer from flames is dependent on a number of properties which are not accurately known.

There does not appear to be any data available for convection to thin strips. One approximation involves an approximation to a non-circular pipe for which the diameter is twice the thickness This would give a result at least three times that calculated for a wide plate. The estimates based on a natural convection formula for vertical convective transfer to a plate or a cylinder gives a value of 0·2 to 0·6 cal cm^{-2} sec^{-1}.

The radiation transfer from the flames depends on their emissivity and though this is not known accurately for the thin flames considered here it is unlikely to exceed 0·1. The value of Q is thus of the order 0·5 cal cm^{-2} sec^{-1}. The total heat loss for a black body at the "ignition temperature" for cellulose, taken as 250°C is approximately 0·15 cal cm^{-2} sec^{-1}

$$\text{i.e. } R \doteqdot 3{\cdot}3$$

For cellulosic materials a mean value for C is 0·35 cal gm^{-1} $°C^{-1}$. The value found experimentally [1] for $\rho \Delta V$ was 8×10^{-2} gm cm^{-1} sec^{-1} so that from equation 8, the equivalent flame length

$$\frac{1}{\alpha} \doteqdot 10 \text{ cm}$$

This is not unreasonable in view of the assumptions made.

References

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