



Fire Research Note

No. 723

FIRE PROTECTION ASSOCIATION
68/584
3-A53
LIBRARY

17 OCT 1968

29 NOV 1968

THE MOVEMENT OF SMOKE IN HORIZONTAL PASSAGES AGAINST AN AIR FLOW

by

P. H. THOMAS

September 1968

FIRE RESEARCH STATION

THE MOVEMENT OF SMOKE IN HORIZONTAL PASSAGES AGAINST AN AIR FLOW

by

P. H. Thomas

SUMMARY

Experiments, mainly in a 90 cm x 90 cm wind tunnel, on the movement of hot gas and smoke, show that a certain minimum air velocity is necessary to prevent the smoke flowing back, upstream, in a passage.

These experiments confirm the theory that the critical air velocity to prevent such backflow in a horizontal duct increases as the cube root of the heat release rate.

If this heat release is expressed as the area of wood burning at $1/40$ in. per minute per unit width of duct, the critical velocity U_c is

$$U_c \approx 30 \sqrt[3]{W}$$

where U is in cm/s

and W is the area of wood per unit width in cm.

Key words: Smoke, movement, ducts, critical, air, flow.
Crown copyright

This report has not been published and should be considered as confidential advance information. No reference should be made to it in any publication without the written consent of the Director of Fire Research.

THE MOVEMENT OF SMOKE IN HORIZONTAL PASSAGES AGAINST AN AIR FLOW

by

P. H. Thomas

INTRODUCTION

If smoke and hot gases escape from a fire into a horizontal duct through which there is a bulk flow of air, the smoke and hot gases flow mainly downstream but some can flow upstream. This flow usually travels as a layer flowing above and against the main downwind stream and only disappears when the velocity of the air stream exceeds a certain critical value¹. This paper describes the experiments and the method of calculating the critical velocity.

THEORETICAL

Consider a duct in which there is a fire or into which hot gases enter at the point P, rise and flow downstream, mixed with cold air which flows in the passage (Fig. 1).

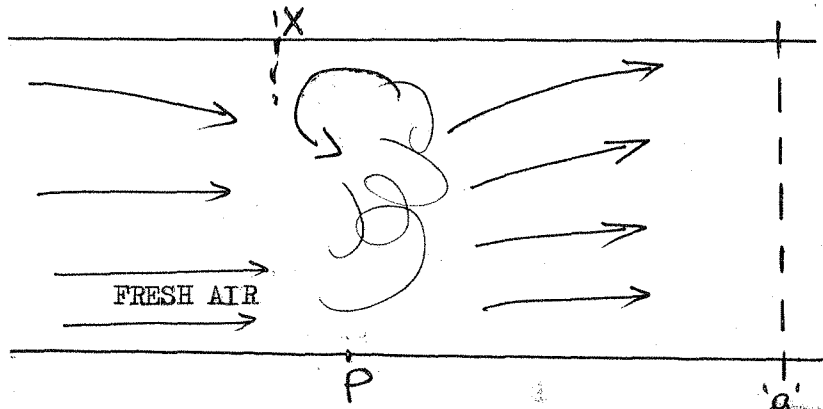


Fig. 1

Let A be the cross section of the passage

d its height

R the mass flow of hot gases

$\bar{\theta}$ the mean temperature rise downstream

ρ and c the density and specific heat of the downstream gases

U the upwind velocity of the air

T its absolute temperature

and g the acceleration due to gravity

... section at sufficiently far downstream for the temperature to be uniform across the section. The only forces in the fluid are buoyancy, the viscous and the Reynolds stresses due to turbulent mixing. If we neglect molecular diffusion and viscosity and, in the ideal case, heat loss and friction at the walls, the flow pattern can only be a function of the ratio of buoyancy and inertial forces - the latter being assumed proportional to $\rho_0 U^2$

i.e. the flow pattern depends on the ratio $\frac{g \bar{\theta} d}{T U^2}$

The critical condition of no back flow must correspond to a transition between one type and another type of flow pattern

i.e. $U_c^2 \propto \frac{g \bar{\theta} d}{T}$ (1)

where U_c denotes the critical value.

Since the buoyancy head is $\frac{\bar{\theta} d}{T}$ and the velocity head is U^2/g one might expect from a consideration of the equilibrium at X, between the stagnation pressure head and the buoyancy head that these will be of the same order of magnitude at the critical condition.

We consider only small values of $\bar{\theta}/T$ and $R/\rho_0 AU$

Then $Q = U \rho_0 A c \bar{\theta}$ (2)

and from equations (1) and (2) we have $U_c = k \left(\frac{g Q}{c T \rho_0} \right)^{\frac{1}{3}}$

where $Q' (= Q \frac{d}{A})$ is the heat release per unit width of passage.

The constant "k" is expected to be of order unity but will vary with the position and size of fire in the passage. To derive it requires a detailed argument of the flow dynamics as for example described by Bakke and Leach² who discussed the related problem of the flow of methane layers in mine roadways.

We have from the above

$$\frac{\bar{\theta}}{T} = \frac{Q}{U \rho_0 A c T} \approx \frac{U^2}{g d k^3}$$

and for $U \sim 100 \text{ cm/s}$

$$k \sim 1$$

$$d > 200 \text{ cm}$$

$$g = 981 \text{ cm/s}^2$$

We have $\frac{\bar{\theta}}{T} < 0.1$

If we have $\frac{\bar{\theta}}{T} \ll 1$

$$\text{then } \frac{R}{\rho_0 AU} = \frac{Q}{C \rho_0 AU} = \left(\frac{c T_0}{C} \right) \cdot \frac{\bar{\theta}}{T_0}$$

where C = the calorific value of the fuel which is of order 4000 cal/gm

$$\text{and } \frac{R}{\rho_0 AU} \sim 10^{-3} \sim 10^{-2}$$

so that in most practical conditions the approximations are satisfied.

EXPERIMENTAL RESULTS

Experiments were made in a wind tunnel 90 cm square. All but two of the data in the main series of experiments were obtained by burning methyl alcohol in 1, 2 or 3 narrow troughs (1 cm wide) across the floor of the tunnel 150 cm from the entrance to the wind tunnel. The other experiments were made with an electric heater, the wires being kept at a low temperature to minimize radiation loss as opposed to convective loss. Thermocouples could be moved into various positions upwind and downwind of the burner.

The alcohol fires did not burn at a uniform rate although for each fire there was a middle period when burning was steady as judged by a thermocouple reading. The rate of heat output at any time was estimated by

$$Q = \frac{y \cdot C \cdot m}{\int y dt}$$

where y was the deflection of the temperature recorder, C is the calorific value of methyl alcohol taken as 5,365 cal/g and m the mass of alcohol burnt. The integral was taken over the whole burning period of the fire.

This method is based on the linearity of the recorder with temperature and the approximation that the spatial pattern of the temperature distribution is constant throughout the burning. Errors in Q' are not of great importance since the critical velocity depends in theory only on $(Q')^{1/3}$.

An experiment consisted of burning the alcohol and releasing a small puff of ammonium chloride smoke in the upper part of the mouth of the wind tunnel. Smoke was observed to move back or not during the burning. In most runs the decision was simple. In the few where there was some doubt, either because the backing was momentary only or because the backing, if it occurred, was only a short distance - 150 cm between the burner and the opening of the tunnel - the result was omitted, and decisive observations at a lower and higher wind speed recorded.

In all cases the maximum steady value of Q was used. The velocities of the inflow were obtained from a commercial hot wire recording anemometer. It was not always easy to record a steady velocity especially at low velocity $< \frac{1}{2}$ m/s. The velocities present before burning sometimes changed during the burning and mean velocities during the period of steady burning were taken. These are unlikely to be more than $\pm 20\%$ in error. For the higher velocities $> \frac{1}{2}$ m/s the variation was much less.

A few experiments at low heat outputs were made with an electric heater from an A.C. supply and the heat output taken from the recording voltmeter and ammeter. Results obtained with a 33 cm wide tunnel by Thomas, McGuire and Cheshire¹ also using an electric heater, and a wattmeter, are included.

The results are shown in Fig. 2. In addition an observation derived from a large scale fire test in a disused railway tunnel³ is shown. Here the main purpose of the experiment was concerned with other aspects of the fire and the observation that there was "very slight but negligible smoke backing" was almost incidental. The heat output was estimated from the upwind temperature profile and anemometer records of the wind blowing through the tunnel.

DISCUSSION

The experimental method was relatively crude but the short term investigation appears to confirm the dependance of U on $Q^{\frac{1}{3}}$ and the accuracy of the correlation is more than sufficient for practical purposes.

It is seen that the full scale tunnel result, which from the description of the smoke backing was somewhere near the critical condition, is consistent with the laboratory data and with a value of k about unity. This may well be peculiar to fires on the floor of passages and ducts. When hot smoke enters a passage at high level the downwind mixing may be less and k may be different. Bakke and Leach's experiments were for such a "top injection" and they deduced a value of k of about 2.5 by extrapolating data for inclined ducts. There are some difficulties in this extrapolation so it is not quite clear how the difference in the k 's arises, but the form of the relationship between U and $(\frac{Q'}{\rho_0 c T})^{\frac{1}{3}}$ is the same and until future work is done the value of k must not be applied without caution to geometries differing from the experimental one.

If the heat source is distributed or heat leaks into a passage from some other space, one cannot expect the correlation to apply in the same way. Consider Fig. 2.

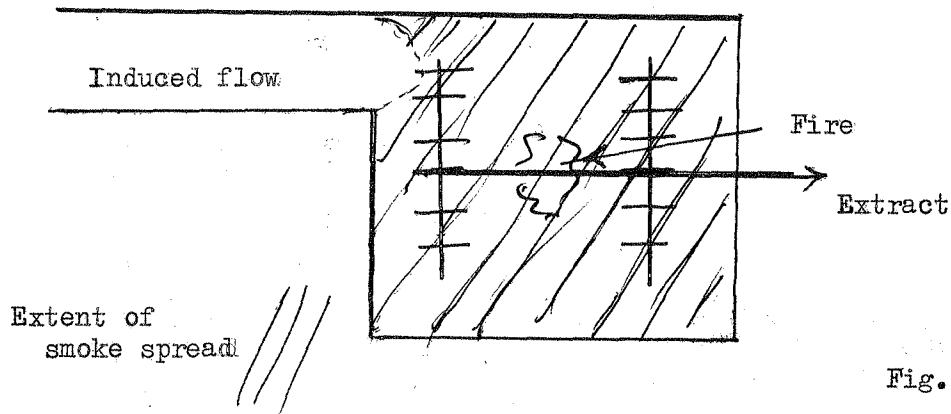


Fig. 3.

If gases are being extracted from a large area into which air is induced along the entry passage, there will be substantial heat loss into the roof, and the temperature distributions near the join of the passage to the large compartment will not correspond to the mean value of $\frac{Q}{U_p A_c}$

One would then over-estimate the tendency of the smoke to back up the passage. If there are deep beams or screens extending down from the ceiling as in Fig. 4

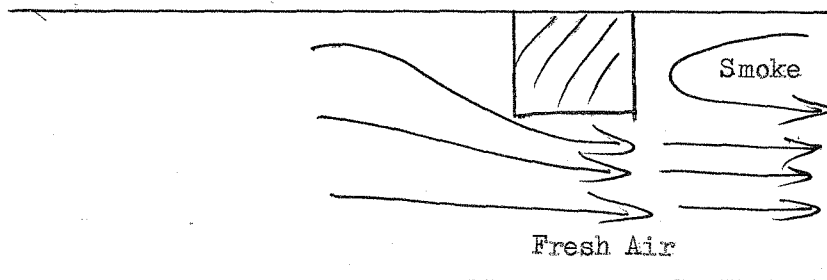


Fig. 4.

the higher velocity immediately under the beam will reduce the tendency for smoke backing.

For such situations we can take

$$U_c \ll \left(\frac{g Q'}{\rho_0 c T} \right)^{\frac{1}{2}}$$

or putting $g = 981 \text{ cm/s}^2$, $\rho_0 = 1.3 \times 10^{-3} \text{ g/cm}^3$, $c = 0.24 \text{ cal gm}^{-1} \text{ } ^\circ\text{C}^{-1}$ and $T_0 = 300^\circ\text{K}$.

$$U_c \ll 22(Q')^{\frac{1}{2}}$$

where U_c is in cm/s, and Q' is in $\text{cal cm}^{-1} \text{ s}^{-1}$

If we take wood of density 30 lb/cub ft as burning at $1/40$ in. per min with a calorific value of 4000 gal/gm we have

$$\dot{Q} = W \times \frac{1}{40} \times \frac{2.54}{60} \times \frac{30}{62.5} \times 4000$$

$$\dot{Q} = 2W$$

where W in cm is the area of wood surface per unit width of passage and hence

$$U_c \ll 30 W^{1/3}$$

We have arrived at the point where, if we know the leakage into the passage, we can decide whether smoke travels upstream or not, though we have no quantitative guide as to how much flows upstream, except it will be greater the smaller U/U_0 is compared with unity.

If the passage is "pressurized" there may be no leakage. Indeed, the mechanism of pressurization is to create high velocities in the small gaps around the door and so prevent "backflow" through them. However, any leakage that does take place - due to any drop in pressure consequent on opening doors in the passage - will behave in the passage in a way which is independent of the pressurization.

A room of area 4 m x 4 m may, with combustible furniture and a carpet in it, contain of order 30 sq m of burnable surface - so that if the door is fully open the value of U_c in a passage 2 m wide will be of order 3-4 m/s. Such an estimate is rather rough and ready but it is indicative of the kind of velocities required to prevent backflow from a fully developed fire. If the velocity is 1 m/s, backflow will commence when the fire is about $\frac{3}{4}$ sq m.

REFERENCES

- (1) THOMAS, P. H. "The movement of buoyant fluid against a stream and the venting of underground fires". F.R. Note 351/1958.
- (2) BAKKE, P. and LEACH, S. J. App. Sci. Res. A(1965) 15, 97.
- (3) HINKLEY, P. L. Unpublished data.

ACKNOWLEDGMENTS

The experimental work in the wind tunnel was carried out by the author in Tokyo, while at the Building Research Institute of the Ministry of Construction and I should like to thank, in particular, Dr. Kawagoe, Dr. Wakamatsu, Mr. Onoma and Miss Kubayashi for their assistance.

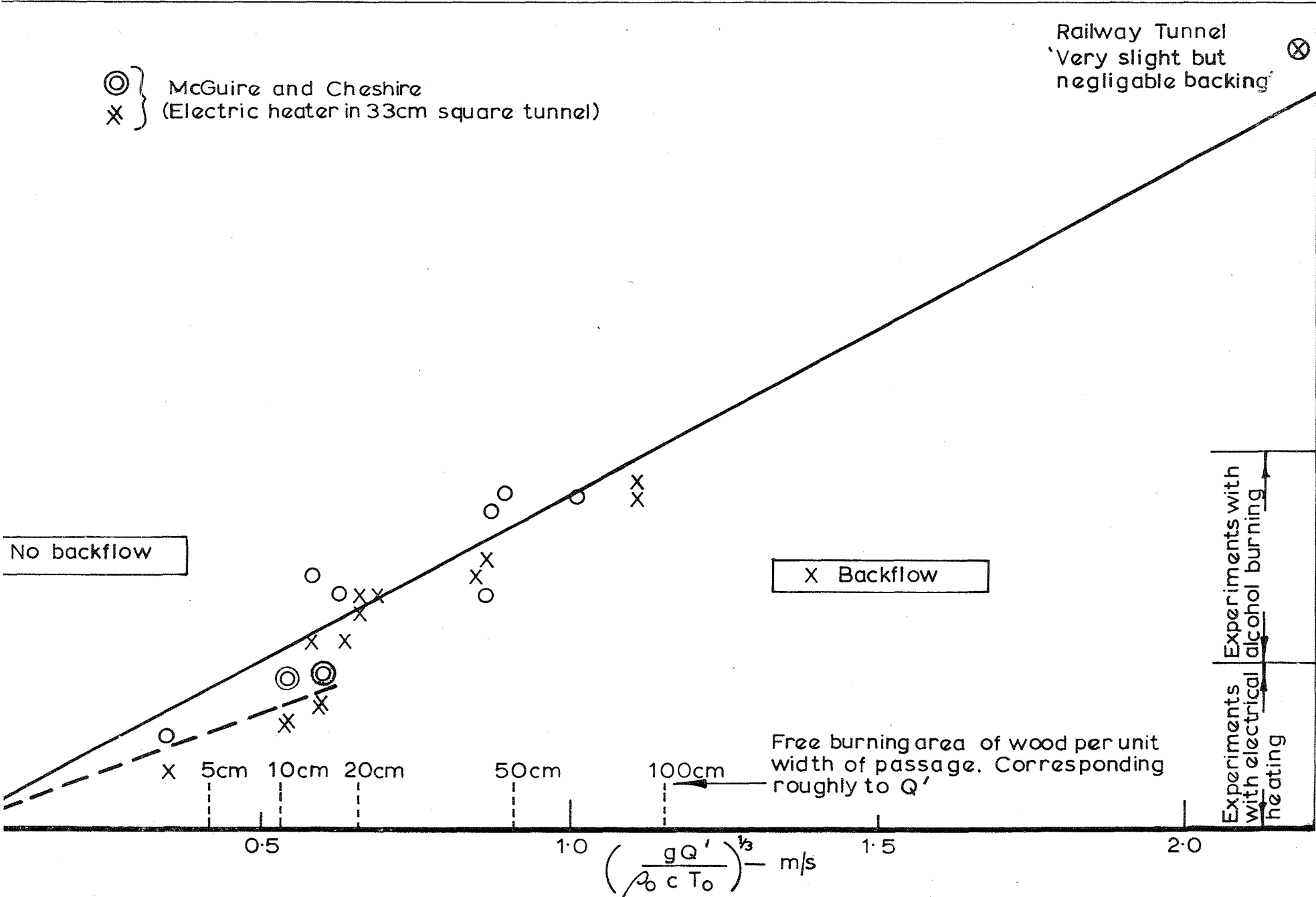


FIG.2. CONDITIONS FOR PREVENTING BACKFLOW