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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
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THE MOVEMENT OF BUOYANT FLUID AGAINST A STREAM AND THE VENTING OF UNDERGROUND FIRES

by

P. H. Thomas

Summary

The movement of smoke and hot gases in underground tunnel fires is discussed and some numerical data given for the backflow against the flow. The use of a forced ventilation installation to clear the smoke is considered and it is suggested that in general little is to be gained from it. The creation of a natural draught may be a more useful method of clearing heat and smoke.

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1. Introduction

If a fire occurs in a basement or an underground tunnel system, it is usually found that smoke and heat are even greater obstacles to the firemen fighting the fire than in the more common building fires. This report discusses certain factors involved in the movement of smoke and hot gases against a ventilation flow. Many of the points discussed would apply to the movement of a fluid of low density over one of greater density. Some preliminary experiments are described and a tentative quantitative interpretation is given.

2. Spread of hot gases

Consider a section of a tunnel in which there is a source of heat e.g. a fire, or a source of low density fluid, and in which the air flows along the tunnel - see Fig. 1.

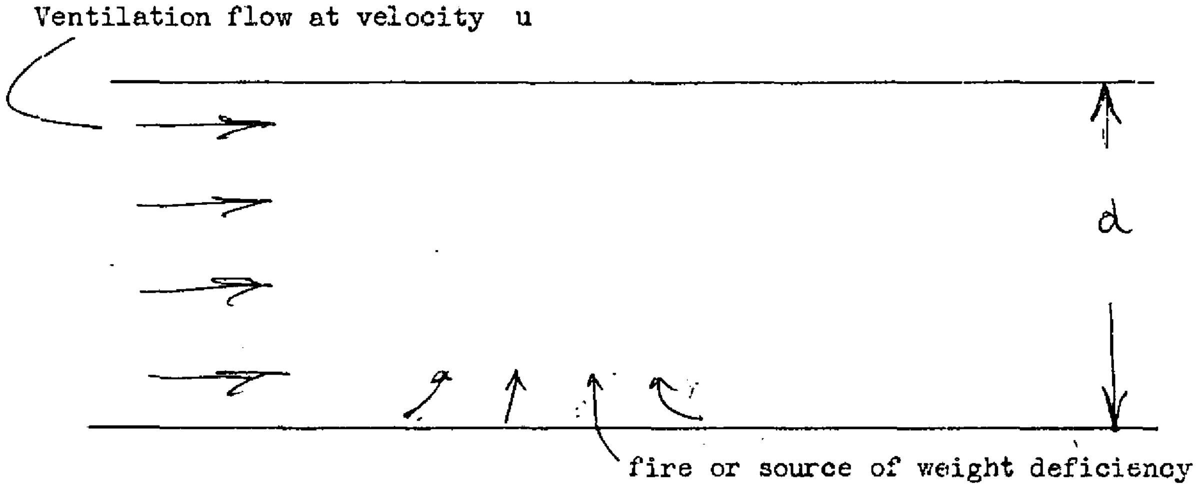

Fig. 1. Fire in a tunnel

The ventilation flow has a velocity u. We shall assume in what follows that fresh air is introduced into the working tunnels through grilles from a separate inlet duct. If the fans are operating reversed they extract air into the grilles and the tunnel becomes the inlet.

2.1. Spread of smoke and heat downstream

Products of combustion will be taken downstream. If the fans are operating normally the products of combustion will be diluted downstream by the influx of fresh, cold air through the inlet grilles downstream but, in practice, this dilution will rarely be sufficient to reduce the smoke concentration sufficiently to improve the visibility to any extent. The visibility is of course lower nearer the fire.

If the fans are reversed, combustion products downstream are taken into the grilles. The concentration of smoke particles is not reduced by dilution and the visibility will be largely constant at all points downstream. It is to be emphasised that however much contaminated air is extracted, the visibility tends to be constant because the concentration is approximately constant even if the total flow in the tunnel is reduced. The heat produced may be less than that for complete combustion but for simplicity it is assumed to equal it, an assumption which is justified for the level of accuracy adopted here. The heat produced may be expressed as:-

$$Q = \frac{CR}{60}$$

where R is the rate of burning - lb/min
Q is the heat produced - C.Th.U/sec*
and C is the calorific value in C.Th.U/lb

If all this heat is convected downstream the maximum temperature downstream θ, neglecting the effect of the inlet air downstream is given by equating Q to the heat content of the air and the material burnt.

$$\text{i.e. } (u \rho_0 A + \frac{R}{60}) c\theta = Q \qquad \text{...... (1)}$$

where u is the velocity of cold air upstream of the fire
ρ_0 is the density of the cold air
R is the rate of burning in lb/min
c is the specific heat of the products of combustion
A is the cross-sectional area of the tunnel of height "d".

We assume the following values:-

u - 1 ft/sec (2 ft/sec is regarded as the highest speed for normal comfort conditions)
ρ - 0·08 lb/cu ft
c - 0·24 C.Th.U/lb/°C
C - 4000 C.Th.U/lb
A - 78 sq ft (d equal to 10 ft, which is probably typical of working tunnels)

we have

$$\theta = \frac{4000 R}{90 + 0{\cdot}24 R}$$

For R equal to 5 lb/min - approximately equivalent to 30 sq ft of wood burning on both sides - θ is about 220°C. In practice the contribution to the mass flow of the actual burning material can be neglected, since $0{\cdot}24 R \ll 90$.

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*1 Centigrade Thermal Unit (i.e. the pound calorie) is equal to 1·8 B.Th.U and 1 C.Th.U/lb equals 1 cal/gm.

2.2. Spread of smoke upstream

The differential pressure head due to the chimney effect within the tunnel is equal to $\frac{d.\theta}{T}$ where T is the absolute temperature of the hot gases; the velocity head of the inlet air is $\frac{u^2}{2g}$.

Only if $\frac{u^2}{2g}$ is comparable or greater than $\frac{d.\theta}{T}$ can the hot gases be expected not to flow upstream. What may happen is illustrated in Fig. 2.

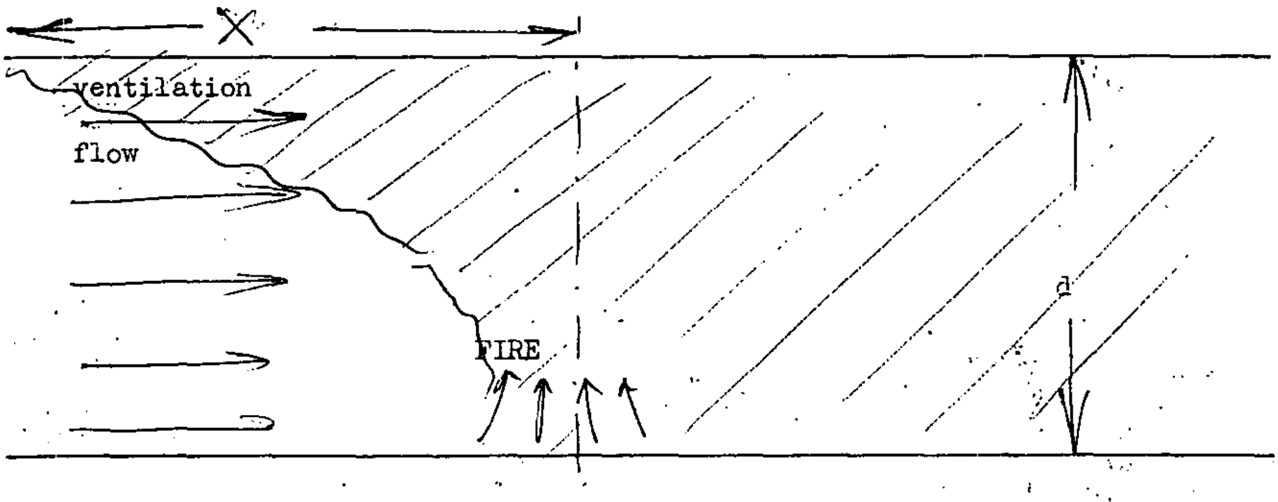

Fig. 2. Backflow of smoke

The problem arises of how far this backflow proceeds. We expect that if only inertia and buoyancy forces are relevant, i.e. the system is fully turbulent and the flow pattern is not significantly affected by boundary layers, the ratio X/d would be a function of the ratio of $\frac{u^2}{2g}$ to $\frac{d\theta}{T}$. This ratio, called the Froude number is

$$N_{Fr} = \frac{Tu^2}{2g.d.\theta} \qquad \ldots\ldots (2)$$

and

$$\frac{X}{d} = F(N_{Fr})$$

For θ equal to 220°C and with the above values for u and d we have N_{Fr} equal to 0·002 approximately. The inertia head of the ventilation stream is so much less than the buoyancy head that the hot gases will readily flow back upstream.

Equation 1 is approximately reducable to

$$Q = u.\rho.c.A \qquad \ldots\ldots (3)$$

so that the Froude number can be written as

$$N_{Fr} = \frac{T.\rho.c.u^3.A.}{2g.d.Q.} \qquad \ldots\ldots (4)$$

Some full-scale experiments have been made in mine roadways [1] and small-scale model experiments have also been performed (see Appendix). With various assumptions one can deduce a relationship (see Appendix)

$$\frac{X}{d} \doteqdot 0\cdot6 \left(\frac{1}{N} - 5\right) \quad (N > 1/5)$$

If u is 1 ft/s, R 5 lb/min, A 78 ft^2 and d 10 ft; X is very large, of order 100 diameters. The importance of u in determining X suggests that reversing the fans might even increase the total length of tunnel contaminated through the loss of efficiency on reversal.

3. <u>The effect of the low density of hot gases on the extract capacity of the grilles</u>

Any gases entering a grille near a fire will be heated and of lower density than normal. The effect of this is to reduce the capacity of the grilles in terms of mass flow. The effect of this is to accentuate any tendency for the contamination to spread.

4. <u>Effect of draught in upshafts</u>

In normal running the pressure developed by the fans overcomes the friction loss which occurs mainly in the ducts and grilles. If an upshaft fills with hot gases, a draught is created of, "h" equal to $H\theta/T$ where H is the height of the shaft and θ is the mean temperature difference between two shafts (T is the absolute temperature in the upshaft). If H is 100 ft the maximum value of "h" is $1\frac{1}{2}$ in. of water.

This chimney effect of the hot gases cannot be utilised in conjunction with the forced ventilation - whether the fans are or are not reversed - because the friction loss in the small ventilation ducts controls the flow and the value of "h" is unlikely to be significant compared with the head developed by the fan, which is probably of order 1 - 5 in. water. One way, however, of utilising this chimney effect to advantage is to have free ventilation system down one main shaft and up another so that the flow is confined to the working tunnels, and although the available head is reduced the resistance of the path may be decreased by a much bigger factor.

<u>Discussion and conclusions</u>

For fires in tunnels of order 10 ft diameter and ventilation flows of about 1 ft/sec it would seem impractical to attempt to clear smoke and heat by the forced ventilation from the flames. The chimney effect may well be a more suitable source of pressure difference if this can be made to operate across a tunnel of wide section and low resistance, not including any small ventilation ducts in the flow path. The possibility of using this method effectively depends, however, on a number of factors which are not discussed here, for example, the position of the fire in relation to the vertical shafts, the dimensions of the shafts and working tunnels.

APPENDIX

Correlation of experimental data on backflow

We have

$$N_{Fr} = \frac{T.\rho.c.u^3.A}{2g.d.Q}$$

and the penetration upstream expressed in a dimensionless form is assumed to be a function of this i.e.

$$\frac{X}{d} = F(N_{Fr})$$

This neglects the influence of viscous forces and therefore of the Reynolds number.

If it is assumed that the resistance to backflow is turbulent friction along the boundary between hot and cold streams the friction resistance per unit width of tunnel is of order ρXu^2. The buoyancy force over the tunnel section is of order $\frac{\rho g\theta}{T}$ per unit width of the tunnel.

These forces are equal so that

$$\rho Xu^2 \doteq \frac{\rho g\theta d^2}{T}$$

$$\text{i.e.} \quad \frac{X}{d} \doteq \frac{1}{N}$$

We have some results of small-scale experiments and one large-scale experiment, which we consider first. A fire was made in an 8 ft diameter roadway at the Safety in Mines Research Establishment by suspending strips of rubber 5 ft long x 4 in. wide on both sides of the roadway for a distance of 5 ft. The rubber is assumed to burn at the same rate as cellulose when hanging vertically and burning freely, i.e. at 0·08 gm/cm/sec (2) but to produce heat in proportion to its greater calorific value. The rate of production of heat is then calculated as 400 C.Th.U./s.

The tunnel had a 1/30 gradient in the direction of ventilation, and the measured backflow is a conservative estimate for a level tunnel, so that the point marked (A) in Fig. 3 obtained from this experiment probably underestimates the effect of heat on backflow.

Some small-scale experiments were made at Joint Fire Research Organization in a 13 in. square tunnel by J. H. McGuire and Miss Cheshire. The penetration upstream of the heated gases was measured and the results of these and the Safety in Mines Research Establishment experiment are shown in Table 1 and Fig. 3. The tunnel was not long enough to study greater backflows than 4 ft 6 in.

The equation of the straight line in Fig. 3 is

$$\frac{x}{d} = 0{\cdot}6\left(\frac{1}{N_{Fr}} - 5\right) \quad \left(\frac{1}{N_{Fr}} > 5\right)$$

which for large values of the backflow is of similar form to the expected relation. In the absence of other data this equation is regarded as a first approximation.

References

(1) Eisner, H. S. and Smith, P. B. Convection effects from underground fires; the banking of smoke against the ventilation. Safety in Mines Research Establishment, Ministry of Fuel and Power, Research Report No. 96.

(2) Lawson, D. I., Webster, C. T. and Gregsten, M. J. The flammability of films. J. Text. Inst 1955. 46 (7) T.453.

Table 1

Data for flow against ventilation

Tunnel		Ventilation. U. ft/sec	Rate of heat release Q. C.Th.U/sec	Backflow (ft)	$\frac{2g\ Qd}{c.T.Au^3}$	$\frac{x}{d}$
d - Height (ft)	A - Area (ft^2)					
8	56	2·83	400 approx.	>114	28	14·3
1·08	1·16	1·5	1·06	None	3·2	-
1·08	1·16	1·0	1·06	4·1	10·8	3·9
1·08	1·16	1·5	1·59	None	4·8	-
1·08	1·16	1·2	1·59	1·4	9·4	1·3

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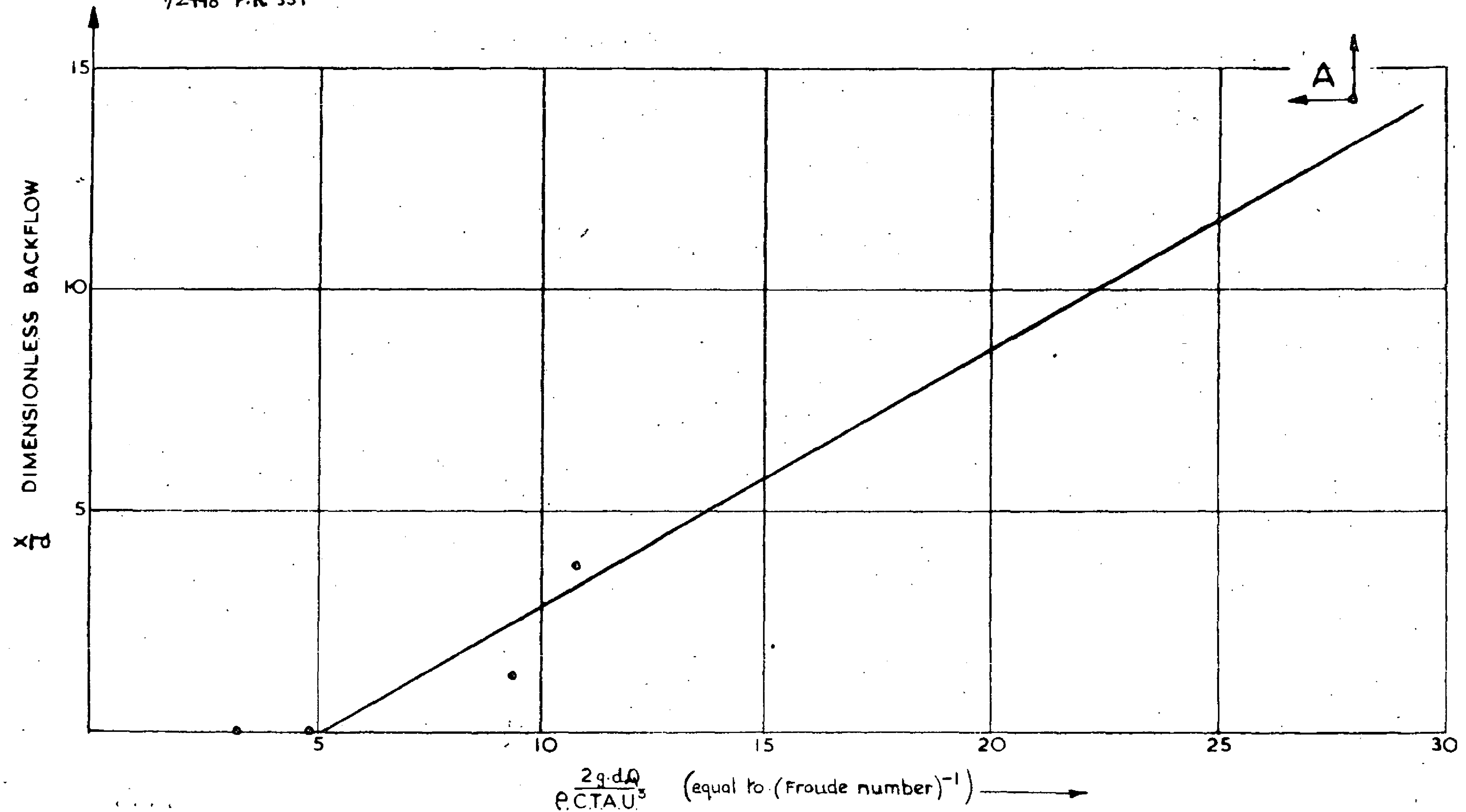

FIG. 3. CORRELATION OF DATA ON FLOW AGAINST VENTILATION CURRENT