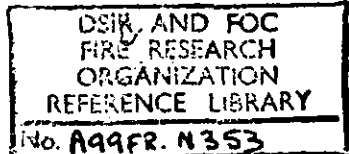


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THE FUNDAMENTAL STUDY OF FLAME ARRESTERS

2. (a) Wire gauze arresters in a short wide tube.
(b) The rise in temperature of gauzes when quenching a flame.

by

K. N. Palmer and P. S. Tonkin

SUMMARY

The performance of single layers of wire gauze as flame arresters for gas and vapour explosions in ducts has been studied using a straight vertical tube whose diameter was 14.9 cm. The fuels used were propane and ethylene and the flammable mixtures were ignited at the open lower end of the tube. Measurements were also made in two tubing systems of the temperatures attained by the gauze when arresting a flame.

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Fire Research Station,
Boreham Wood,
Herts.

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INTRODUCTION

In an earlier report⁽¹⁾ an account was given of experiments on the arresting by wire gauzes of flames propagating through a flammable gas mixture in a short-narrow vertical tube. It was shown that a given gauze assembly was able to arrest flames travelling at less than a certain critical velocity, faster flames passing through the arrester, and that with single layers of gauze the critical flame velocity was approximately inversely proportional to the width of the mesh of the gauze. Similar results were obtained with propane, ethylene, and town gas flames, and with brass, steel, and phosphor-bronze gauzes. In all experiments the gas was ignited at the open end of the tube. A simple theory based on the assumption that the quenching of the flame resulted from the abstraction of heat by the wire of the gauze was shown to be in broad agreement with the experimental results for propane flames. It followed from the theory that the relation between the critical flame velocity and the mesh width of the gauze should be independent of the diameter of the tube. Insufficient fundamental information relating the burning velocity to the heat loss from the flame was available to test the theory on the results for ethylene and town gas.

The present work was carried out to determine whether the relation between the critical flame velocity and the width of the mesh of the gauze was affected by a change in the diameter of the tube. The tube used was of more than double the diameter of that used previously. In addition measurement was made of the rise in temperature of gauze arresters when a flame impinged upon them; the flame being initiated at the open end of the tube.

EXPERIMENTAL

Materials and apparatus

A range of gauzes of various meshes was used as the arresters; some characteristics of the gauzes are listed in Table 1. In each case the value for the wire diameter and the mesh width (the width of a hole in the gauze) are the means of three determinations.

TABLE 1

Characteristics of the wire gauzes

Material of gauze	Nominal mesh	Nominal wire gauge S.W.G.	Mesh width cm	Wire diameter cm	Mass per cm ² of gauze g
Brass	6	20	0.329	0.0940	0.258
"	10	24	0.198	0.0559	0.161
"	18	28	0.106	0.0356	0.136
"	40	34	0.0404	0.0231	0.111
"	60	37	0.0248	0.0175	0.094
Phosphor-bronze	120	43	0.0125	0.0089	0.046
" "	200	46	0.0065	0.0061	0.040

The two fuels used in the preparation of the explosive gas mixtures were propane and ethylene. The propane was specified by the manufacturers as being at least 97 per cent pure; the ethylene was specified as being 98.2 per cent pure. With both fuels fast flames were obtained by enriching the fuel/air mixture with oxygen; the oxygen was of normal commercial purity.

The tube in which the explosions were produced was of perspex; the length of the tube was 165.7 cm, the internal diameter was 14.9 cm, and the wall thickness was 0.6 cm. The tube was cut into two sections, the shorter section being 58.5 cm in length, and the two sections were held vertically, with the larger one uppermost, so that they butted endwise on to each other; the arrester was sandwiched between the two sections. In all experiments the gas mixture was ignited at the open lower end of the tube, with the upper end closed. Measurements of flame velocities on the axis of the tube near the gauze were made using a rotating drum camera; a metal plate with a 0.3 cm wide vertical slot was placed centrally against the tube to restrict the field of vision of the camera. The speed of the drum of the camera was calibrated either by means of an argon lamp giving 50 flashes/sec or by a signal generator in conjunction with a cathode ray oscilloscope.

In the determinations of the temperatures attained by the gauzes a 40 S.W.G. chromel-alumel thermocouple was silver-soldered to the centre of the gauze arrester which was then supported in the tube as before; the output from the couple and a cold junction was fed into a d.c. pre-amplifier. The pre-amplifier was connected to a cathode-ray oscilloscope and the deflection of the oscilloscope beam recorded with a drum camera.

Procedure

The gauzes were cut to form circular discs whose diameter equalled that of the outside of the tube. After washing in carbon tetrachloride or boiling water the gauzes were dried and sandwiched horizontally between the ends of the two sections of tube. The system was made gas tight by binding the junction with transparent adhesive cellulose tape. The explosive gas mixture was metered through the tube, allowing about ten changes of gas in the tube, and the supply was then cut off. The lower end of the tube was then opened and the quiescent gas mixture in the tube ignited by a small gas flame applied to the open end of the tube; the movement of the flame near the gauze was recorded by the drum camera. The velocity of the flame was measured at a point about 1.5 cm from the gauze surface on the approach side, as described earlier⁽¹⁾. The flame velocity was calculated from measurements of the slope of the flame front on the photographic record and the speed of rotation of the camera drum.

In experiments on the temperature rise of gauzes the increase in temperature was calculated directly from the photographic record of the oscilloscope beam. Temperature records were usually only considered for flames that were quenched by the gauze since the thermocouple and the gauze were frequently damaged if the flame passed the gauze.

Results

The arresting of propane flames by single layers of gauze was investigated over a wide range of mesh sizes and the results are given in Fig. 1. Both the flame velocity and the mesh width are plotted on logarithmic axes and distinction is drawn as to whether or not the flame passed the gauze. As in the earlier report⁽¹⁾ no account was taken of variation in the composition of the explosive mixture; this will be considered in a later note.

The results of experiments under similar conditions with ethylene flames are given in Fig. 2; in many of the experiments with the 120- and 200-mesh gauzes the behaviour of the ethylene flames differed from that observed previously in experiments with the narrow vertical tube⁽¹⁾. In some cases, marked 'g' in Fig. 2, the flame was arrested by the gauze but was not quenched immediately and persisted underneath the gauze for several seconds; the gauze glowed dull red as a result and audible sound vibrations were emitted. In other instances, marked 'd' in Fig. 2, the flame was arrested by the gauze, but flickering continued underneath as before, and after a few seconds the gas above the gauze was ignited. As the flame was initially arrested by the gauze, the results marked 'g' or 'd' in Fig. 2 have been included amongst those for which the flame was quenched by the gauze in the usual manner. With propane flames in a few instances the flame continued to burn under the gauze before being quenched, even with a gauze as coarse as 40-mesh, but the flame never passed the gauze after being delayed. It was considered that the continued burning under the gauze might have resulted from compression of unburnt mixture in the upper section of the tube whilst the flame was propagating through the lower section, the excess pressure being slowly relieved through the gauze when the flame ceased to advance. In tests with a water manometer, however, no such pressure rise was detected. This point is discussed below.

The rise in temperature produced in a gauze arrester by a flame took place in two stages. The duration of the first stage (t_1 sec) was a fraction of a second and the rise in temperature (θ_1 °C) was moderate with fast flames and often undetectable with slow flames. An example is shown in Plate 1. The second stage usually occupied several seconds (t_2 sec) and the temperature rose slowly to a maximum value (θ_2 °C) which was frequently considerably greater than in the first stage. A record of this comparatively lengthy heating is shown in Plate 2; in this experiment the flame continued to burn under the gauze before extinguishing. The values of θ_1 for stoichiometric propane- or ethylene-air mixtures were too small for detection, even with 200-mesh gauze, i.e. $\theta_1 < 5^\circ\text{C}$, but values for some oxygen enriched propane flames are given in Fig. 3. Details of the second stage of the rise in temperature are given in Table 2 for several flammable mixtures and gauzes.

TABLE 2

Temperature rises of gauze arresters in a wide vertical tube (14.9 cm I.D.)

Gas mixture, by volume	Flame velocity cm/sec	Nominal mesh of gauze	θ °C	t_2 sec
Propane 4% Air 96% (stoichiometric)	85	40	71	7.0
	123		58	7.3
	96	200	48	8.2
Propane 1 part Oxygen 5 " Nitrogen 14.1 "	171	40	87	7.3
	203	200	62	6.9
Propane 1 part Oxygen 5 " Nitrogen 9.5 "	384	200	390	8.1
	510		380	9.4
	960		380	7.7
Propane 1 part Oxygen 5 " Nitrogen 7.6 "	895	200	380	7.4
	1640		380	8.1
Ethylene 1 part Oxygen 3 " Nitrogen 7.6 "	570	200	195	5.7
	580		330	8.3
	610		215	7.6
Ethylene 1 part Oxygen 3 " Nitrogen 5.6 "	645	200	280	2.9
	1440		350	3.5

In order to determine whether stoichiometric propane-air flames could give appreciable values of θ_1 some experiments were carried out with the gauze arresters mounted in a horizontal perspex tube, of 6.4 cm internal diameter, with a run-up of 313 cm between the igniting source and the gauze. Owing to the long run-up the flame velocities were considerably greater than with the same flammable mixture in the vertical tube. Further details of the horizontal tube will be given in a later report. The values obtained for θ_1 are included in Fig. 3 and for θ_2 in Table 3. As the flames were vibratory near the gauze the temperature rise θ_1 often developed stepwise, the value at the topmost step being taken for θ_1 . The minimum value of θ_1 detectable in these experiments was 2°C

TABLE 3

Temperature rises of gauze arresters in a horizontal tube (6.4 cm I.D.)

Gas mixture, by volume	Flame velocity cm/sec	Nominal mesh of gauze	θ_2 °C	t_2 sec
Propane 4% Air 96% (stoichiometric)	870	200	15	1.2
	1170		30	0.8
	1410		56	3.2
	1420		21	2.5
	1420		29	0.8
	1460		15	1.9
	1500		65	1.5
	1630		103	3.0
	1680		153	1.4
	1710		24	1.1
	2030		43	1.3

DISCUSSION

The arresting of flames by the gauzes

The results for propane and ethylene flames given in Fig. 1 and 2 show that the flames tended to pass through the gauzes at lower velocities than in the previous experiments with the narrow tube⁽¹⁾. The scatter of the present results was greater than that obtained previously and no clearly defined line could be drawn such that flames with velocities below the line were quenched, and flames with velocities above the line passed the arrester. However the velocities of propagation at which the flames became able to pass the gauzes were of the same order as in the earlier tests. The reasons for the greater scatter in the present experiments are not clear, but the method of measurement of the flame velocities may be one factor. These velocities were measured near the axis of the tube, but in some instances the flames were not symmetrical so that when vibrations developed the fastest part of the flame front was considerably off centre. From the photographic record obtained it would then appear that the flame passed the gauze whilst travelling at a lower velocity than was actually the case. The effect would be more marked in the wide tube than in the narrow tube used previously⁽¹⁾. The results obtained for propane flames in the wide tube fell about the theoretical line (Fig. 1) which was derived in the earlier report⁽¹⁾ by assuming the quenching of the flame was due to cooling by the gauze with no assistance from the walls of the tube. A similar line could not be drawn for ethylene flames since, as described earlier, insufficient basic information is available.

Rise in temperature of gauze arresters

The first stage of the rise in temperature (θ_1) developing in a gauze when a flame impinged upon it took place rapidly (Plate 1) and was probably the direct result of the flame front coming into contact with the gauze. The second stage was considerably slower, and usually involved higher temperatures (θ_2) and could have been the result of the abstraction of heat by the gauze from the products of combustion behind the flame front and, in some cases, assisted by the prolonged burning of flames under the gauze. This prolonged burning is discussed separately, below.

The results in Fig. 3 indicate that the temperature rise in the first stage (θ_1) was dependent upon the flame velocity, and although the results were scattered an approximate line for 4 per cent propane-air flames can be drawn on the graph. From the slope of this line a value can be derived for the thickness of a flame moving with the standard burning velocity, which is

the linear velocity of propagation of a plane flame front normal to itself into an unburnt gas mixture. It has been shown⁽¹⁾ that for a 4 per cent propane-air flame to be quenched whilst travelling at the standard burning velocity a quantity of heat = $2.468 \times 10^{-2} x_s$ cal must be removed from each cm^2 of flame; where x_s is the thickness of the flame.

Now, as a flame travelling with the standard burning velocity is flat, it follows that the quantity of heat to be absorbed by unit area of gauze is $2.468 \times 10^{-2} x_s$ cal.

From Fig. 3, the temperature rise caused in a 200-mesh gauze by a flame travelling at the standard burning velocity (41 cm/sec) is 0.275°C.

$$\begin{aligned} \text{Now the thermal capacity of unit area of gauze (Table 1)} &= 0.04 \times 0.088 \\ &= 3.52 \times 10^{-3} \text{g} \end{aligned}$$

$$\text{Therefore } x_s = \frac{3.52 \times 10^{-3} \times 0.275}{2.468 \times 10^{-2}} = 0.039 \text{ cm.}$$

Although this value may be in considerable error (Fig. 3) it is still likely to be considerably less than the value 0.2 cm used previously⁽¹⁾ which was known to be uncertain and very probably an overestimation. It is also of the same order as the value of 0.02 cm given by Gaydon and Wolfhard⁽²⁾ for the thickness of the luminous reaction zone of a stoichiometric butane-air flame.

Sustained burning under the gauze

Both propane and ethylene flames gave instances of the flame being stopped by the gauze, but not quenched immediately, and in consequence the gauze was heated up (Fig 2 and Table 2). In some cases with ethylene as fuel the flame subsequently passed the gauze (Fig. 2). As in most cases with propane and ethylene a stoichiometric fuel-air-oxygen mixture was used, the products of combustion could not form a flammable mixture, and thus the flame stabilized under the gauze must have been supplied with fuel and oxygen from above the gauze. Two possible methods of supply are:

- (i) bulk flow of gas through the gauze,
- (ii) diffusion of gas through the gauze.

They will be considered in turn.

(i) Bulk flow of gas through the gauze

The flame is presumed to be maintained by a flow of gas driven through the gauze by an excess pressure above it. It is assumed that the minimum rate of flow for a stable flat flame is the burning velocity at the flammability limit, i.e., about 4 cm/sec⁽³⁾, so that if the gas velocity is less than this value the flame extinguishes.

Now the relation between the pressure drop across a gauze and the gas flow through it is given, for a small pressure drop by⁽⁴⁾:

$$\Psi = \frac{\Delta P g d f^2}{4 \rho U x^2 (1 - f)} \dots\dots\dots (i)$$

- where d = wire diameter
- f = volumetric porosity
- g = acceleration due to gravity
- ΔP = pressure drop across gauze
- U = gas velocity
- x = thickness of gauze
- ρ = gas density
- Ψ = resistance factor, dependent on Reynolds number Re.

Considering a 200-mesh gauze, and assuming the gas to be air, $f = 0.6$

$$\text{So } Re = \frac{4 \times 1.293 \times 10^{-3} \times 1.068 \times 10^{-3}}{1.83 \times 10^{-4} \times 0.6} \text{ using the hydraulic mean}$$

diameter of the wire (1.068×10^{-3} cm) as the characteristic dimension⁽⁴⁾ i.e. $\Psi = 108$. Also for a single layer of gauze $x = 2d$ approx.

$$\begin{aligned} \text{Thus } \Delta P &= \frac{108 \times 4 \times 1.293 \times 10^{-3} \times 4^2 \times 2 \times 0.4}{981 \times 0.6^2} \text{ cm w.g. from eq.(i).} \\ &= 2.02 \times 10^{-2} \text{ cm w.g.} \end{aligned}$$

A pressure of this magnitude would not have been detectable in the experiment with the water manometer; it could arise either from compression of unburnt mixture in the upper section of the tube whilst the flame was propagating through the lower section or from expansion of the gas in the upper section of the tube after heating of the gauze.

(ii) Diffusion of gas through the gauze

The rate of diffusion of propane required for the maintenance of a flame under the gauze arrester may be estimated by taking the lower flammability limit for propane-air mixtures as 2.4 per cent⁽⁵⁾; and then if the burning velocity at the lower limit is 4 cm/sec the required rate of supply of propane per sq. cm. of gauze is assumed to be at least $4 \times 0.024 = 0.096 \text{ cm}^3/\text{sec}$.

Now if the gas above the gauze is stationary the volume (V) of propane diffusing to the flame in time t is given for a low concentration of propane by⁽⁶⁾:

$$V = \frac{2c\sqrt{Dt}}{\pi} \quad \text{where } c = \text{initial concentration of propane} \\ D = \text{diffusivity,}$$

neglecting the resistance to diffusion of the wire gauze. For the mixture:

propane = 1 part by volume, oxygen = 5 parts, nitrogen = 9.5 parts,

$c = \frac{1}{15.5}$. Also D for propane = $0.106 \text{ cm}^2/\text{sec}$ ⁽⁷⁾; and so the volume of propane diffusing to the flame during the first 1 sec. is given by

$$V = \frac{2}{15.5} \frac{\sqrt{0.106}}{\pi} = 2.37 \times 10^{-2} \text{ cm}^3.$$

In fact, however, after the flame had become stabilized for a short time the gauze heated up and convection currents were set up above the gauze. When a steady state has been attained the system consists essentially of a horizontal hot plane surface above which gas is in motion due to natural convection of heat; the concentration of propane at the surface is zero and the concentration in the bulk of the gas is small. An estimate of the mass flow of propane to the surface was obtained from a mass transfer equation analogous to the equation for the natural convection of heat⁽⁸⁾. The estimated flow of propane to the surface, under equilibrium conditions, was of a similar magnitude to the diffusion flow during the first sec. from a stationary gas; both quantities were less than the estimated requirement ($0.096 \text{ cm}^3/\text{sec}$) by a factor of about 4. However the diffusivity D is sensitive to temperature⁽⁶⁾ ($D \propto T^{1.6} = 2.0$) so that at a gauze temperature of 300°C the value of D might be increased sufficiently for the required supply of propane to be produced.

No account so far has been taken of the resistance to diffusion of the gauze; this would cause the propane concentration above the gauze to be greater than zero. Since the concentrations are small, Fick's law applies

across the gauze and application of this law indicates that the resistance to diffusion of the gauze is small compared with that of the mechanisms considered above.

To sum up, it appears that the supply of fuel and oxygen to a flame stabilized under a gauze arrester could easily have been due to bulk movement of gases through the gauze resulting from heating of the gauze, and that an alternative mechanism, involving diffusion, might be possible particularly with the fine gauzes which attained high temperatures. In either event the effect appears to result from the structure of the gauze: its low thermal capacity and its thinness.

CONCLUSIONS

1. Both propane and ethylene flames tended to pass through the gauzes at lower velocities than in previous experiments with a narrower tube. The results were, however, less consistent than in the previous experiments, and some discussion of possible reasons for this is given. There is a need for further experiments on tubes of greater diameter than those used hitherto.
2. Sometimes the gauze stopped the flame, but did not quench it immediately, and the flame continued to burn under the gauze and heated it to redness. Some theoretical discussion of this is given.
3. The rise in temperature of a gauze arresting a flame occurred in two stages. In the first stage, which was rapid, the rise was small and from it a value of the thickness of the flame front was obtained. Although this value may be in error because of the scatter of the results it was still considerably less than the value assumed previously. The second stage of the rise in temperature of the gauze was slower and high temperatures sometimes developed.

ACKNOWLEDGMENT

Miss J. S. Hall assisted in the experimental work.

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Propane: Oxygen: Nitrogen:: 1: 5: 9.5 by volume

Flame velocity: 384 cm/s

Tube diameter: 14.9 cm

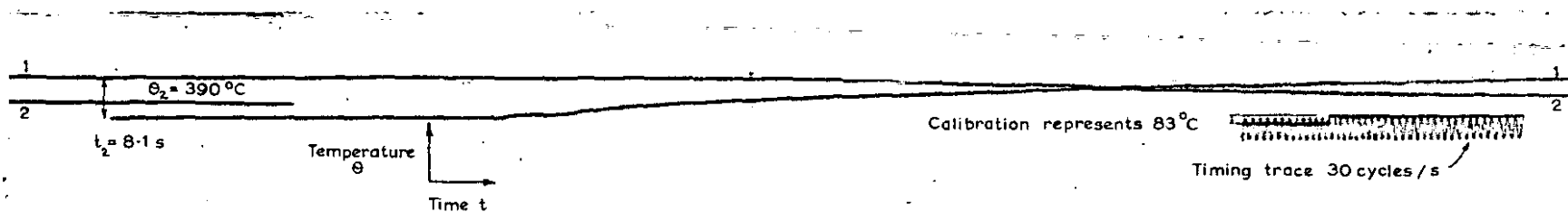


PLATE.2. THE SLOW SECOND STAGE OF THE RISE IN TEMPERATURE OF A 200-MESH GAUZE ARRESTER, CAUSED BY A PROPANE FLAME

Propane: Oxygen: Nitrogen:: 1: 5: 9.5 by volume

Flame velocity: 810 cm/s

Tube diameter: 14.9 cm

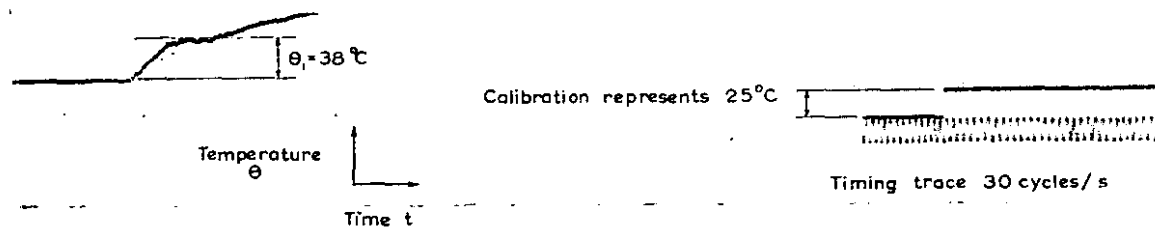


PLATE.1. THE RAPID FIRST STAGE OF THE RISE IN TEMPERATURE OF A 200 MESH-GAUZE ARRESTER, CAUSED BY A PROPANE FLAME

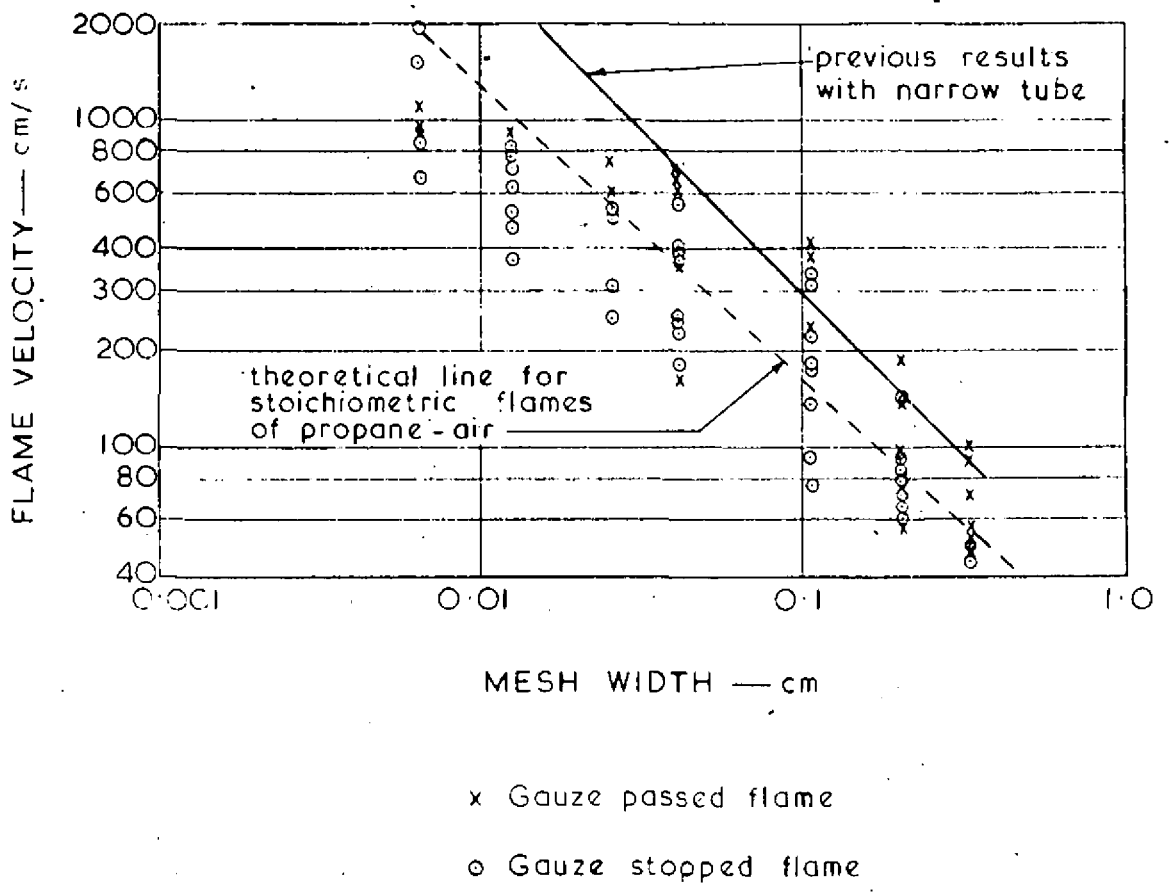


FIG. 1. THE ARRESTING OF PROPANE FLAMES BY SINGLE LAYERS OF WIRE GAUZE

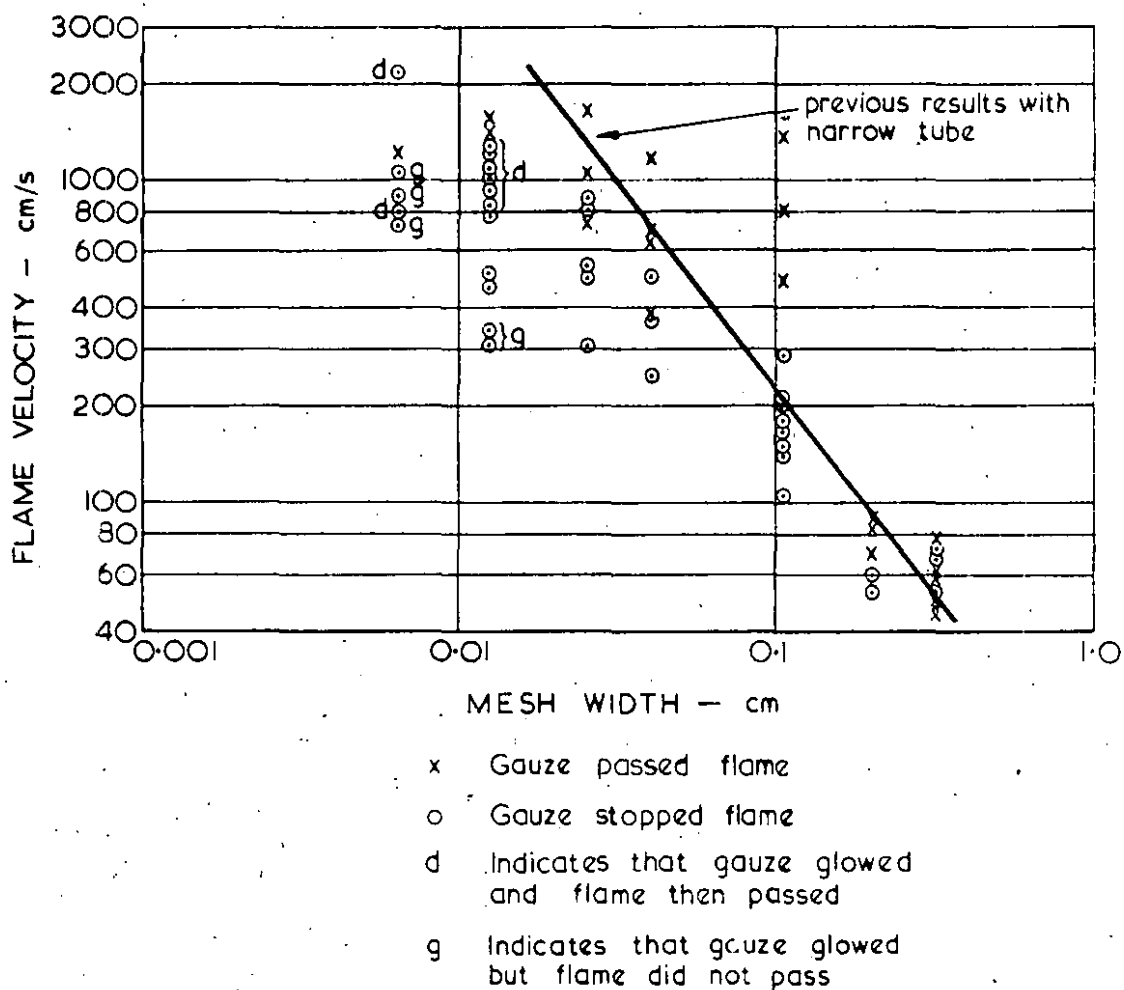


FIG. 2 THE ARRESTING OF ETHYLENE FLAMES BY SINGLE LAYERS OF WIRE GAUZE

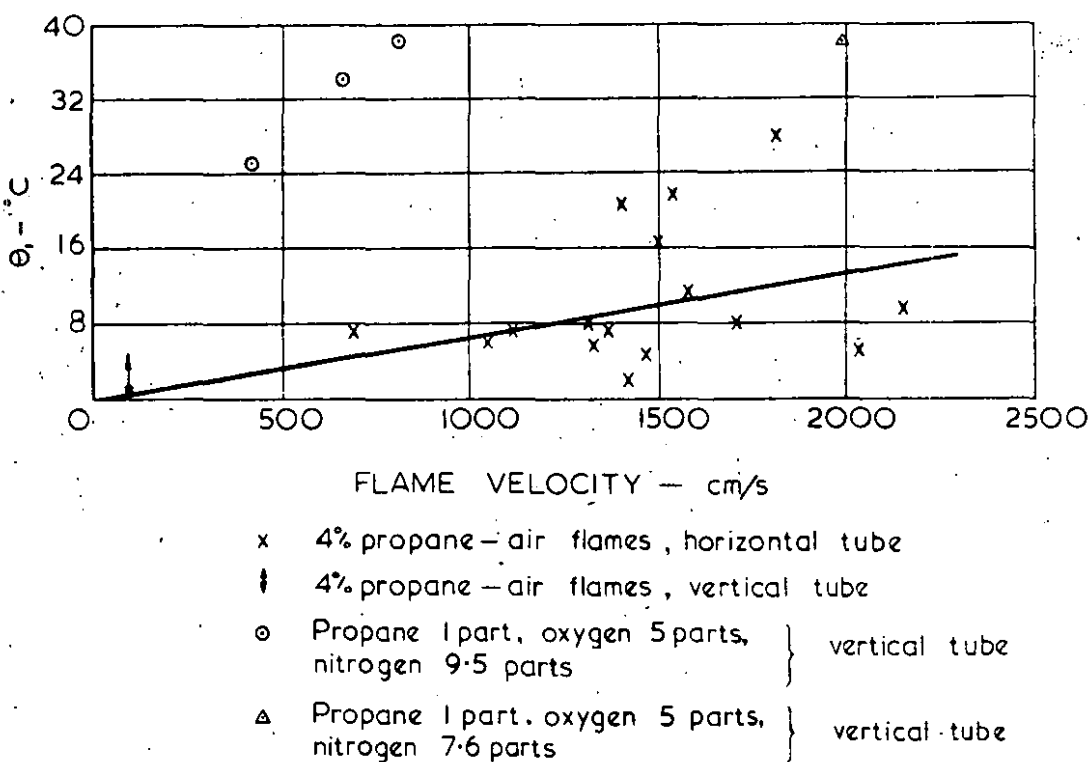


FIG. 3 RISE IN TEMPERATURE OF 200-MESH GAUZE CAUSED BY PROPANE FLAMES