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FLAME-ARRESTING PERFORMANCE OF ROUND HOLES AND POROUS DISCS FOR BATTERY VENT PLUGS

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Summary

Flame-arresting vent plugs are being introduced on lead-acid batteries to prevent explosions following accidental ignition of vented charge gases. Increasingly, sintered material discs are incorporated in the plugs to act as a flame arrester. Here, the performance characteristics of these are related to that of discs with isolated holes. Tests on the latter confirm that material thermal conductivity and disc thickness to hole diameter ratio do not affect flame-arresting behaviour significantly. For a stoichiometric hydrogen/oxygen mixture of charge gases, the quenching diameter was found to be in the range 0.25—0.28 mm. The sintered material discs perform in a qualitatively similar way to discs with isolated round holes, though greater sample to sample variation has been observed, and the threshold velocity for flame stabilisation on the sintered disc is lower than for the equivalent isolated-hole disc.

Introduction

The potential explosion hazard associated with venting hydrogen and oxygen during the charging of a lead-acid battery has received relatively little attention until recent years. The principal concern is that near to the battery vents, the concentration of hydrogen mixing with air and oxygen is sufficiently high to be inflammable. Once initiated, a flame front can advance back through the vent plugs into the confined space within the battery case. In order to avoid this, manufacturers have developed flame-arresting vent plugs. This was done mainly by trial and error methods and without recourse to a fundamental analysis of the processes involved.

All flame-arresting plugs have a dual purpose which is usually reflected in the basic components. Firstly, in order to minimise the rate of electrolyte loss, the plugs contain elements which separate liquid droplets entrained by the charge gases. The performance of these elements will be the subject of a later publication. Secondly, the plug has elements specifically designed to arrest the flame front at the plug. Increasingly, sintered material discs are being used for this purpose.

The utility of sintered material discs as flame arresters is beyond question.

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There is little information available on which to base performance predictions, however, or to minimise manufacturing costs whilst ensuring satisfactory flame-arresting operation. The authors have addressed this problem by attempting to relate the performance of sintered material discs to that of discs with isolated round holes.

In the following sections, the results of a literature survey, Ref. [1], are discussed in the context of vent plugs. The principal parameters which influence flame-arresting performance are identified, and performance is related to the range of battery operating conditions which are of interest. The flame-arresting behaviour of discs with isolated round holes has been determined by experiment and is shown to be qualitatively similar to that of sintered material discs covering a range of mean pore size and porosity.

Further tests were conducted on isolated-hole discs to investigate the effect of material thermal conductivity, geometry, and hole diameter. In view of the similarity noted above, the results provide evidence that the thermal conductivity and, within limits, the thickness of the sintered material discs are not important.

The experimental results show that the quenching diameter for isolated holes is large compared to the mean pore size of sintered material discs in use. Consequently, variations in pore size about the mean in these discs are not a significant problem regarding flame-arresting performance.

Qualitative flame propagation/quenching characteristics

Figure 1 shows a cross-section through a current generation design for flame-arresting vent plugs. (The example shown is a Chloride Duovent Plug.) The charge gases flow into the plug through slots in the base. They then

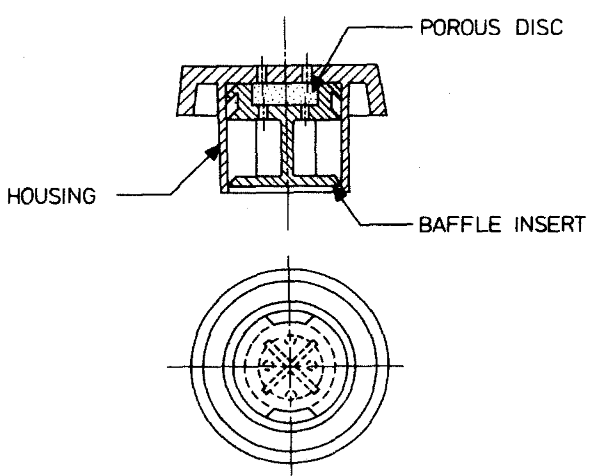

Fig. 1. Assembly of a typical vent plug.

circulate through the baffle arrangement, where a proportion of the entrained electrolyte is separated, before filtering through the sintered material disc. After passing through the disc the gases are vented through two 1.5 mm diameter holes in the cover above the disc.

In automotive batteries, such plugs are expected to vent charge gases at rates corresponding to charge currents of up to 40 amps. For a fully charged battery, under steady state conditions, the combined flow rate of hydrogen and oxygen would be typically 120 cc/min per cell in stoichiometric proportions. During transient charging, the mixture can be non-stoichiometric.

The most common cause of ignition of the mixture above the vent plugs is likely to be loose contact sparking; experiments show [2] that this may dissipate about 0.5 J in 500 μsec. This is many orders of magnitude greater than the minimum ignition energy (about 0.02 mJ) for hydrogen in air or oxygen [3]. Once initiated, the flame front propagates back through the unburnt mixture by deflagration. The flame speed depends on mixture composition and pressure, but under typical operating conditions it is of the order of 1 to 5 m/s [3]. The flame speed also depends on whether the flow is laminar or turbulent, but elementary calculations show that the Reynolds number is well below the transition range, and hence the flow will normally be laminar.

With regard to flame arrester design, the main concern is that the flame front is extinguished and not just stabilised. The classic concept of a flame-quenching diameter, or distance, provides a useful approach to understanding at least part of the quenching mechanism in vent plugs. Apertures which have a diameter equal to the quenching diameter will stop flames moving at low velocities relative to the arrester. Flame fronts moving at higher velocities will transmit the explosion, because although the arrester will quench the flame, the hot combustion products following the flame front will penetrate the arrester apertures and ignite the unreacted mixture on the other side of the arrester. In practice, the apertures should have a diameter not larger than half of the appropriate quenching distance. Typical values for quenching distance are 0.25 mm for a stoichiometric H_2/O_2 mixture and 0.64 mm for a stoichiometric H_2/air mixture [3]. Appropriate data is scarce however, particularly with regard to the effect of material properties and gap to depth ratio.

The behaviour of the flame front in the region of an isolated vent hole depends on hole diameter and the discharge rate of the gases. Figure 2 presents a prediction based on data drawn from the literature [3 and 4], which identifies operating zones for a particular behaviour. The 'velocity gradient' parameter, g, has been used to determine the boundaries between flame flash back and stabilisation, and between flame blow-off and stabilisation. Values for g were obtained from [3] (suffixes b and f refer to blow-off and flash back boundary values, respectively). In Fig. 2, region A corresponds to conditions for which a flame front is extinguished and represents the region of safe plug operation. Region B conditions permit the stabilisation of the flame front on top of the vent hole. This is an unsafe operating condition which will lead to failure of the flame arrester through overheating. Region C conditions allow

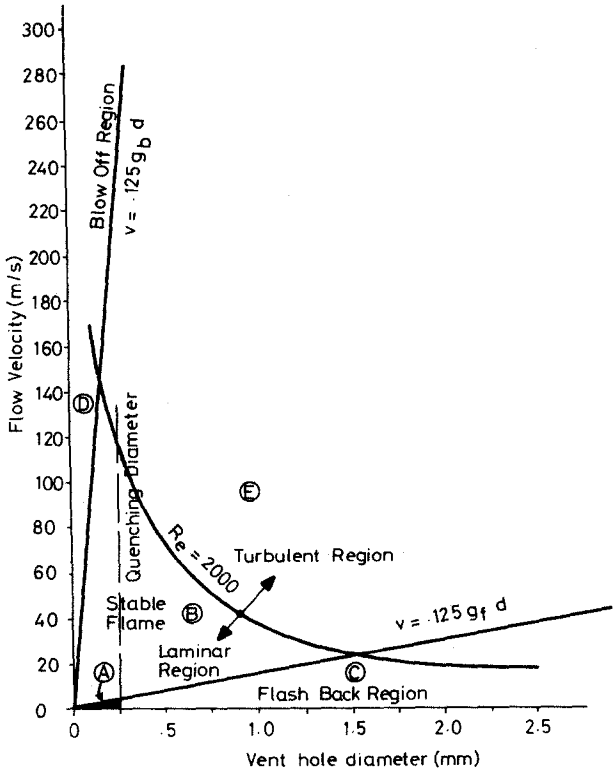

Fig. 2. Operation limits for vent plugs.

the flame front to propagate through the arrester and is obviously unsafe. Regions D and E (corresponding to conditions when the flame front is blown off and when the flame becomes turbulent, respectively) are outside of the range of conditions normally prevailing in vent plugs.

Experimental results

In order to quantify the information presented in Fig. 2, and to investigate the effects of material properties and hole geometry, experiments have been performed using the test rig shown schematically in Fig. 1 of Ref. [5]*.

Controlled flow rates of hydrogen and oxygen were vented through test specimens mounted on a test box and ignited by a spark above the specimen. The H_2/O_2 discharge was maintained in nominally stoichiometric proportions. The passage of the flame front through the specimen was detected by an audible explosion within the test box. Flames stabilised on the specimen were detected by a thermocouple mounted above the specimen. The rig and test procedure are described in greater detail in Ref. [6].

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*See p. 313 of this issue.

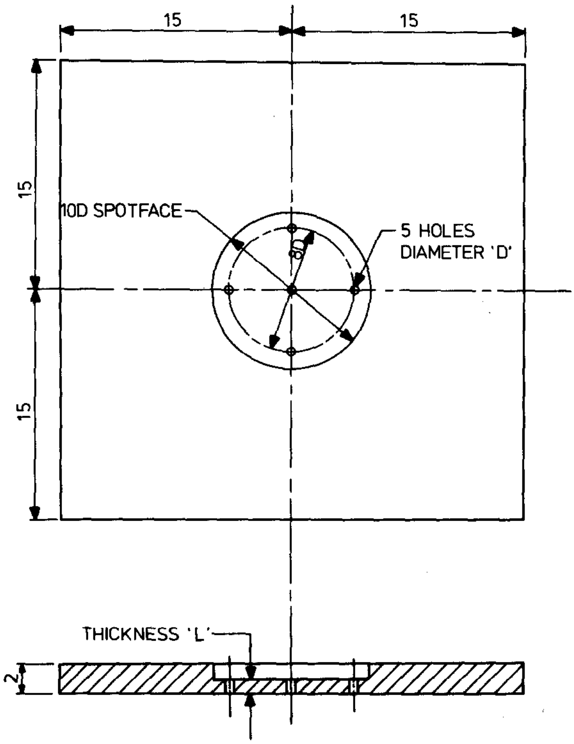

Fig. 3. The test specimen, dimensions are in millimetres (See Table 1 for D and L).

Isolated-hole discs

A typical test specimen is shown in Fig. 3. At the lowest hole size considered, five holes were drilled rather than one in order to obtain a total flow rate which could be measured accurately. The holes were spaced apart sufficiently to neglect interference. Specimens were machined from brass and perspex, which have thermal conductivities of 106 W/m K and 0.17—0.25 W/m K respectively. Table 1 gives details of the specimens and shows the range of L/D ratio which was covered (nominally 2.5 to 7).

The test results are summarised in Fig. 4, with the anticipated stable/unstable flame boundary and the quenching diameter reproduced from Fig. 2. The experimental results are in reasonable agreement with prediction. The lack of a marked difference between results for brass and perspex, or a dependence on disc thickness will be discussed later.

The range of hole diameters examined, between 0.15 mm and 0.42 mm, extended above and below the anticipated quenching diameter. No test gave rise to internal explosions for specimens with holes of 0.25 mm or less, indicating the quenching diameter is in the range 0.25 to 0.28 mm for stoichiometric mixtures. Since other mixture proportions correspond to larger quenching diameters [3], the value of 0.25 mm can be used safely in design calculations.

TABLE 1

Data for specimens 1 to 12

No.	Material	Average diameter, D (mm)	Thickness, L (mm)	L/D
1	Brass	0.25	0.83	3.32
2	Brass	0.152	0.73	4.80
3	Brass	0.298	1.68	5.63
4	Brass	0.168	1.12	6.66
5	Perspex	0.196	1.25	6.38
6	Perspex	0.29	1.50	5.17
7	Perspex	0.333	0.81	2.44
8	Perspex	0.16	0.74	4.63
9	Brass	0.39	1.62	4.154
10	Brass	0.34	0.94	2.765
11	Perspex	0.42	0.95	2.26
12	Perspex	0.34	0.659	1.97

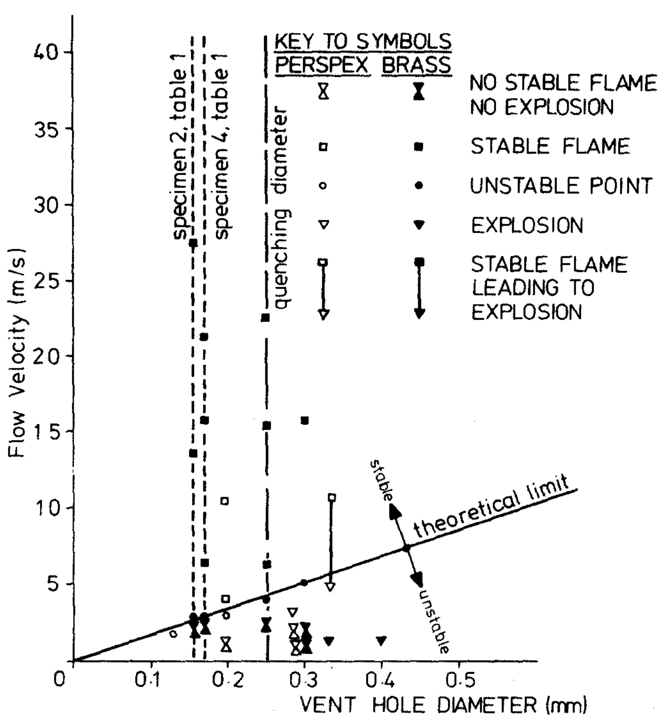

Fig. 4. Experimental assessment of the flame quenching criteria.

Sintered material discs

To facilitate comparisons between isolated-hole and sintered material discs, performance tests have been conducted on samples of sintered material covering a range of porosity and mean pore size. Details of the specimens are given in Table 2. The test procedure was the same, performance characteristics being determined by noting whether the spark-initiated flame front stabilised, was extinguished, or was blown off. None of the samples failed to arrest the flame, so the fourth possibility, that of the flame propagating through the disc, was not observed.

The experimental results are plotted in Fig. 5. The indicated flow velocity, V, is representative of the gas velocity through the pores of the disc surface, and is defined by

$$V = Q/AE$$

Here Q is the charge gas flow rate, A is the cross-sectional area of the disc, and E is the disc porosity.

Within the range of conditions considered, each type of sample behaved in a similar way. At low flow rates, flame fronts were arrested and quenched, whereas at high flow rates they stabilised on the disc surface. For a range of flow rates between the extremes, both flame stabilisation and flame quenching have been observed and this can be attributed to sample-to-sample variation. The effect of increasing the mean pore size is to increase the threshold flow velocity marking a change in disc performance.

Also shown in Fig. 5 is the variation in threshold velocity for a change from flame-extinguished to flame-stabilised behaviour for isolated round holes. Clearly the threshold velocity for sintered materials is much smaller than that for the single round hole of the same diameter as the nominal pore size. This can be attributed to the difference in mixing conditions above the surface. For the porous disc, the gases discharge through a number of pores across the surface, increasing the mixing with surrounding air. The increased dilution will reduce the threshold velocity from the maximum which corresponds to stoichiometric gas proportions [7].

TABLE 2

Details of sintered material disc specimens tested

Sample	Mean pore size (μm)	Porosity (%)
A	72	30.3
B	37	39.5
C	75	37
D	44	34

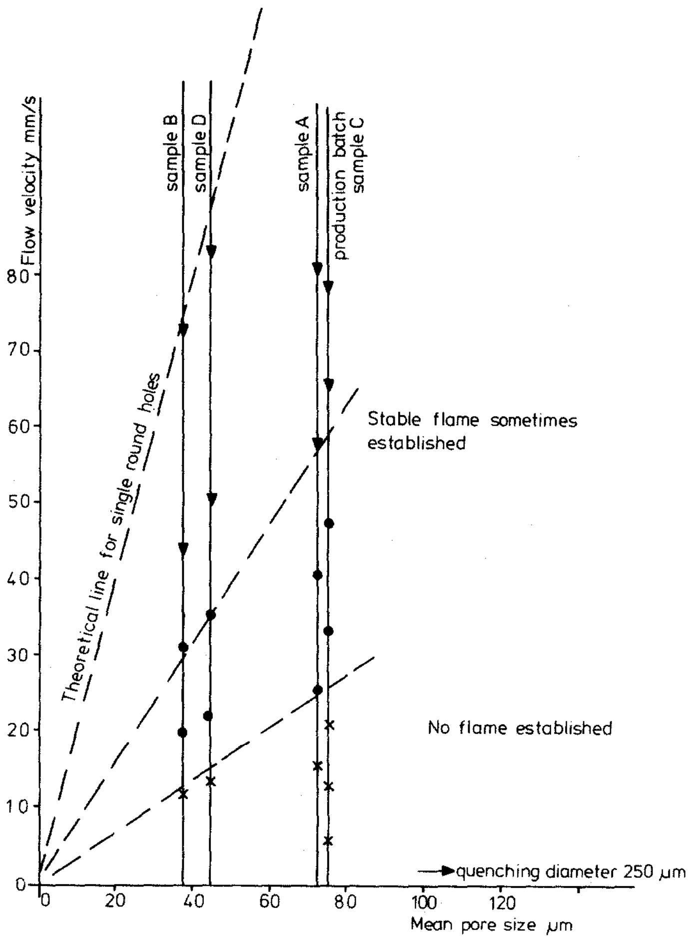

Fig. 5. Stable and quenched flame zones for sintered discs.

Discussion

Despite quantitative differences, the sintered material and isolated-hole discs performed in a similar way as indicated by comparing Figs. 4 and 5. The results confirm that the thermal conductivity of the sintered material will have little effect on performance since, for isolated-hole discs, brass and perspex specimens showed no marked difference.

Similarly, the disc thickness is not important to flame-quenching performance. For isolated holes, the thickness to hole diameter ratio was varied between about 2.5 and 7 without any apparent effect. As an example, compare specimens 2 and 4, identified in Fig. 4 which differed in L/D ratio by 38%; the performance is practically identical. The fact that performance is not dependent on L/D indicates that the sintered material discs in current use embody a substantial safety factor regarding disc thickness. This may be necessary to cover any statistical dispersion in equivalent passage diameter. The ratio of thickness to mean pore size is typically greater than 10.

All the sintered material samples prevented the passage of the flame front through the disc, and this is consistent with the mean pore size being small compared to the quenching diameter for round holes (less than 40%). The difference in flame stabilisation/quenching characteristics for nominally identical samples is due to the inherent variation in pore size in a given sample.

Finally, the evidence suggests that disc design can be based on manufacturing and pore-size quality control constraints. Material thermal conductivity is unimportant and, for the samples tested, the mean pore size is small compared to the quenching diameter. The ratio of disc thickness to mean pore size can be reduced below current values without impeding the flame-extinguishing mechanism. This ratio must be sufficiently large, however, to prevent a flame path through the disc, due to the connection of anomalously large pores.

Conclusion

The results of tests on isolated holes in discs confirm that material thermal conductivity has no effect, and disc thickness to hole diameter ratio does not significantly affect, flame-arresting behaviour. The results indicate, in line with results in the literature, that the quenching diameter for a stoichiometric hydrogen and oxygen mixture is between 0.25 and 0.28 mm.

Tests on sintered material discs show these perform in a qualitatively similar way to discs with isolated holes, but quantitative differences are apparent. Sample to sample variations give rise to significant variations in performance. The threshold velocity for flame stabilisation on the sintered discs is lower than for the equivalent isolated-hole discs.

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