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Burning-through of Porous Flame Arresters with a Channel Flame-Arrester Element

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Numerical analysis of the burning-through of porous flame arresters was performed. It was shown that the burning-through time for porous flame-arrester elements of the channel type is determined by the time of flame entry into the porous element, and for granular-type elements, it is determined by the propagation time in the element. The fire resistance of a channel flame arrester increases with increasing thermal conductivity of the material of the porous flame-arrester element and its length and with decreasing effective size of the channels and porosity of the flame-arrester element. It is established that, by increasing the length of the porous element or by decreasing the channel diameter and porosity, it is possible to ensure that the flame that arises behind the flame arrester is stabilized on the exit surface of the flame-arrester element without penetrating into it.

Key words: combustion, porous medium, flame arrester.

INTRODUCTION

One of the major applications of the thermal theory of flame extinction [1, 2] is the design of industrial flame arresters. The working element of a flame arrester is a layer of a porous medium (of the granular, mesh, or channel type). The action of flame arresters is based on flame extinction in channels with an effective diameter smaller than the critical diameter due to heat losses from the combustion zone into the channel walls [3]. However, laboratory studies and extensive experience with use of flame arresters in the industry have shown that, for effective operation of a flame arrester, the above condition is necessary but not sufficient [4]. The most severe conditions from a viewpoint of flame localization are those under which stabilization of the combustion zone occurs on the surface of the flame-arrester element [5]. In this case, most of the flame arresters used in the industry localize combustion for a short time of 4–30 min, after which the flame penetrates into the volume to be protected. This phenomenon is often called the burning-through of a flame arrester [6].

Efforts of many researchers and designers are directed at overcoming this impediment since, under industrial conditions, the indicated time may be insufficient for preventing accidents. An analysis of the possible methods for increasing the fire resistance of flame arresters is given in [4]. They are divided into the following groups according to the operation principle.

1. Placement of devices above flame-arrester elements to increase the gas flow velocity from the porous element. This prevents flame stabilization and, hence, the burning-through of the flame arrester but considerably increases its hydraulic resistance.

2. Cessation of the supply of the explosive mixture to the flame arrester. It should be taken into account that the gas supply cannot be stopped instantaneously. Under industrial conditions, the delay can reach several minutes. In addition, this can lead to an accidental stop of the entire production process, and renewal of the gas flow can initiate repeated ignition.

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3. Alarm indicating the occurrence of a flame on the surface of the flame suppressing bed. In this case, concrete actions of the staff or the presence of automated systems are necessary.

4. Suppression of flame by extinguishing reagents. This method is effective but not always suitable.

The above methods are aimed at preventing long-term interaction of flame and flame-arrester elements. In essence, this is a combination of a porous flame-arrester element with elements that, in some cases, can be used independently to localize a propagating flame.

Another group of methods is designed to increase the duration of the protective action of flame-arrester elements. They include [4]:

1) partitioning of a porous element along the length into a number of elements with an air gap between them;

2) alternation of layers with high and low thermal conductivity in a flame-arrester element;

3) introduction of a heat transfer device into a flame-arrester element with a circulating coolant.

In the first two methods, it is assumed that the flame is retarded on the boundary of separate layers, which should lead to an increase in the fire-resistance time. However, tests of some designs of flame arresters with two- and three-layer flame-arrester elements have shown that the division of an element into separate sections increases the fire resistance only slightly and, in some cases, even decreases it [7]. This is due to the fact that the heat from the flame is perceived not by the entire flame-arrester element but only by its part [7]. This results in a rapid heating of the element and more rapid entry of the flame into the porous space. Flame-arrester elements made of aluminum melt in this case [7]. As a result, part of the channels are blocked, and the gas flows through the remaining channels at a higher velocity. This can lead to an increase in the fire resistance. Obviously, this method of increasing the fire resistance is unacceptable.

The introduction of a heat-transfer device into a flame-arrester element significantly increases the fire resistance [7]. In this case, however, the reliability of operation of the flame arrester depends on the uninterrupted circulation of the coolant.

In addition, the fire resistance of a flame arrester depends on the type of porous flame-arrester element. According to [7], flame arresters are classified into the mesh, cassette, and packed-bed types. Mesh-type flame arresters consist of several layers of brass or steel wire meshes. Such flame arresters burn through very quickly and can be used only to prevent flashback. A cassette flame-arrester element is a roll of a flat metal strip and a corrugated metal strip placed together and coiled around a rod. Packed-bed flame arresters comprise beds of granulated or granular materials: gravel or spheres of metal, glass, cement, porcelain, etc. Cassette and packed-bed flame arresters have some fire resistance. As noted in [7], packed-bed flame arresters mostly have higher fire resistance than do cassette flame arresters. At the same time, the highest fire resistance was obtained for a flame arrester with an aluminum cassette [7].

Variation in the parameters of flame-arrester elements in experiments has shown that the fire resistance increases with decreasing effective diameter of the porous-element channel and with increasing length of the porous layer [7].

The basis for the optimization of the flame arrester performance for the purpose of increasing the fire resistance were empirical observations and theoretical concepts of the burning-through process. It has been assumed, in particular, that burning-through is caused by the heating of the flame-arrester element by the flame stabilized on its surface [7], resulting in a decrease in the critical extinction diameter and flashback in the porous bed. The development of knowledge about filtration gas combustion has provided a better understanding of the nature of the burning-through of flame arresters. It has become clear that burning-through is caused by flame propagation through the flame arrester element in the regime of low-velocity filtration gas combustion (FGC) [6, 8, 9]. This concept in a one-dimensional approximation has been used [10] to analyze the burning-through of packed-bed flame arresters. The major result of the analysis was the identification of two stages in the burning-through process: flame entry into the porous element and flame propagation in it, which has been proved by experimental observations [10]. Accordingly, the total fire-resistance time of a flame arrester is the sum of the times of these two stages. It has been shown (in calculations and experiments) [10] that, under the most severe conditions, the fire resistance of packed-bed flame arresters is determined by the propagation time. Therefore, everything that reduces the flame propagation velocity in the porous bed promotes an increase in the fire resistance of the flame arrester. This, in particular, explains the linear dependence of the fire resistance of packed-bed flame arresters on the bed length [7].

The granular porous beds used in packed-bed flame arresters do not allow wide variation in the parameters of the flame-arrester element. For example, the bed porosity varies from 0.4 to 0.5. The effective channel diameter cannot be significantly reduced because of a sharp growth in the hydraulic resistance. The thermal conductivity of a porous bed is determined mainly by heat transfer between the grains of the bed and, hence, also depends weakly on the bed material. This limits

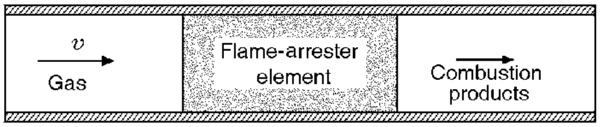

Fig. 1. Geometry of the model system.

the possibility of improving packed-bed flame arresters. The porous elements of the channel type used in cassette flame arresters offer greater opportunities for varying the parameters. The objective of the present paper is to analyze the burning-through of channel flame-arrester elements for the purpose of developing methods for increasing the fire resistance of cassette flame arresters.

RESULTS

The burning-through process was analyzed numerically using the filtration gas combustion model [8]. The geometry of the modeled system is presented in Fig. 1. A porous block of finite length h is housed in a tube of radius R_w. A combustible mixture flows from the left into the porous block, and the combustion products are discharged on the right side. The gas mixture is ignited at the tube section on the right of the porous block. The tube housing the porous block has heat capacity and thermal conductivity; i.e., it participates in heat transfer, modeling the flame arrester case. The system of equations describing the propagation of a one-dimensional unsteady combustion wave in a chemically inert porous medium consists of the equations of heat transfer in the gas and the solid phase, mass transfer of the deficient component of the gas mixture, mass conservation in the flow, and the gas equation of state. The system was solved numerically. A detailed description of the system of equations and the method used for their solution are given in [10].

The program calculates temperature profiles of the gas and the porous medium and determines the position of the flame front at each time. From these data, it is possible to calculate the time of flame entry into the porous block and the time of propagation through it. The calculations were performed for a stoichiometric methane–air mixture. For the gas mixture, the following parameter values were adopted [10]: constant pressure specific heat capacity $c_p = 10^3$ J/(kg $\cdot$ K), thermal conductivity $\lambda = 0.1$ W/(m $\cdot$ K), and adiabatic flame temperature $T_b = 2320$ K. The chemical reaction rate was given by $W = \eta k_0 \exp(-E/RT)$, where η is the relative concentration of the deficient component of the gas mixture, $k_0 = 1 \cdot 10^{11}$ sec^{-1}, $E = 2.26 \cdot 10^5$ J/mole, and R is the gas constant. The values of the parameters of the porous medium were varied. The flame arrester case was modeled as a steel tube section of radius $R_w = 45$ mm and thickness 5 mm, which corresponds to a real OP-50 flame arrester. The heat loss per unit outer surface of the flame arrester was estimated as $\alpha_w = 50$ W/(m$^2 \cdot$ K) [10].

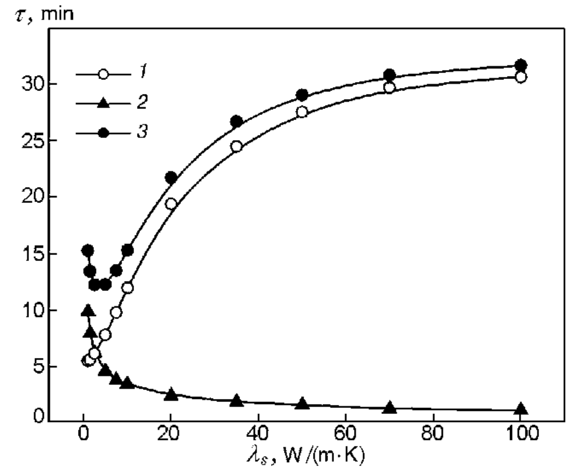

Fig. 2. Effect of the thermal conductivity of a porous block on the time of flame entry into the porous block (1), the propagation time in the block (2), and the total burning-through time (3).

Channel porous media differ from granular porous beds in thermodynamic parameters, mainly, in thermal conductivity. In granular-type flame arresters, the thermal conductivity of the porous bed is determined by heat transfer between the grains and is 1–4 W/(m $\cdot$ K). In flame arresters of the channel type, the thermal conductivity of the porous block is determined by the thermal conductivity of the porous material and can vary over very wide ranges. The flame-arrester element of a channel flame arrester can be made in the form of a roll of a flat foil strip and a corrugated foil strip placed together or in the form of a monolithic perforated block. Here by the perforated block is meant a monolithic cylinder with cylindrical channels of equal diameter distributed equally over the cross section. The channel structure can also be implemented by packing a tube section with straight cylindrical rods. This case, however, differs from the perforated block only in the channel shape and fixed porosity $\approx$0.1. For foil cassettes, the porosity is 0.8–0.95. Perforated blocks allow the porosity to be varied over wide ranges from 0.8 and below.

Figure 2 shows calculated curves of the burning-through time of a flame arrester (τ) versus thermal conductivity of the porous block (λ_s). The porosity of the block is set equal to $m = 0.5$, the specific heat capacity $c_s = 400$ J/(kg · K), and the length of the porous block $h = 75$ mm. It is evident that the time of entry of the combustion wave into the porous block increases monotonically with increasing λ_s. This is clear because for the flame to propagate into the depth of the porous bed, it should heat its boundary layers. The higher the thermal conductivity of the block, the more rapidly the heat transferred to the porous medium from the flame spreads over the block thickness and more time is needed to heat the surface layers to the required temperature. The propagation time in the block, in contrast, decreases with increasing λ_s. This is due to the fact that the velocity of propagation of the FGC wave in the porous medium is directly related to the rate of heat transfer in the porous block. The latter is the higher, the higher the thermal conductivity of the porous medium. Due to the opposite trends in the variation of the entry time and propagation time with the thermal conductivity, total burning-through time is a nonmonotonic function with a minimum, which for a block of length 75 mm is reached at $\lambda_s \approx 4$ W/(m · K). In this case, for $\lambda_s < 3$ W/(m · K) the total burning-through time is determined mainly by the propagation time of the combustion wave in the porous block, and for larger values of λ_s, it is determined by the time of entry of the wave into the porous block. For granular porous media, $\lambda_s < 3$–4 W/(m · K) [11], and for channel porous media, $\lambda_s = 10$–100 W/(m · K). Taking this into account, one can state that the burning-through of granular flame-arrester elements is limited by the propagation stage, and for channel flame-arrester elements, it is limited by the entry stage. For example, it is evident from Fig. 2 that, for $\lambda_s = 70$ W/(m · K), the entry time is $\tau_{\rm ent} \approx 30$ min, and the propagation time is only $\tau_p \approx 1$ min. To the observer, this looks like as if the flame stands at the flame arrester exit for 30 min, gradually heating it, and then disappears behind the flame arrester and almost immediately appears ahead of it. This may have led to the well-known erroneous belief that burning-through is caused by flame flashback in the flame arrester preheated by the flame stabilized at its exit.

Thus, for flame arresters with channel porous beds, one should try to increase the time of flame entry into the porous bed since it determines the fire resistance. Figure 3 shows curves of the entry time versus gas velocity at the entrance into a porous element. The calculations were made for a perforated steel block of porosity $m = 0.5$, density $\rho_s = 8$ g/cm^3, heat capacity $c_s = 400$ J/(kg · K), and thermal conductivity $\lambda_s = 70$ W/(m · K); the block length is $h = 75$ mm. As in the case of granular porous beds, these dependences are U-shaped. For low and high flow velocities, the entry time becomes infinite, i.e., the flame is stabilized on the surface of the porous block, without entering it. The lowest fire resistance for all channel diameters is observed at a gas velocity $v = 22$ cm/sec. These conditions are the most stringent, and all further calculations were performed for this gas velocity. From Fig. 3, it follows that the smaller the channel diameter, the narrower the range of velocities at which burning-through is possible and the larger the entry time under the most stringent conditions. Therefore, to increase the fire resistance, it is necessary to use blocks with the minimum possible channel diameter. The minimum diameter is determined by a compromise between the desired time of fire resistance and the hydraulic resistance of the block.

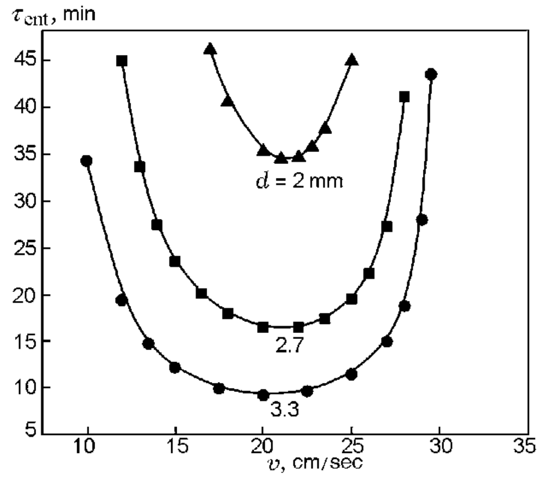

Fig. 3. Time of flame entry into a porous element versus gas velocity for various channel diameters [$h = 75$ mm and $\lambda_s = 70$ W/(m · K)].

Another method for improving the characteristics of channel flame arresters is illustrated in Fig. 4, which shows the effect of the porous-block length on the entry and burning-through times. For the thermal conductivity $\lambda_s = 1$ W/(m · K) characteristic of granular flame arresters, the entry time is almost independent of the block length and is $\tau_{\rm ent} \approx 5$ min. The burning-through time τ_b increases linearly with increasing length of the porous layer. This dependence is obvious since, for a small entry time, the burning-through time is determined by the propagation time, and the latter is equal to h/u, where u is the steady-state propagation velocity of the FGC wave.

For $\lambda_s = 20$ W/(m · K), the main contribution to the burning-through time comes from the stage of entry into the porous block. The significant growth in $\tau_{\rm ent}$ with increasing block length up to $h = 11$ cm is due to that fact that the heat transferred to the porous element from the flame stabilized on its surface spreads

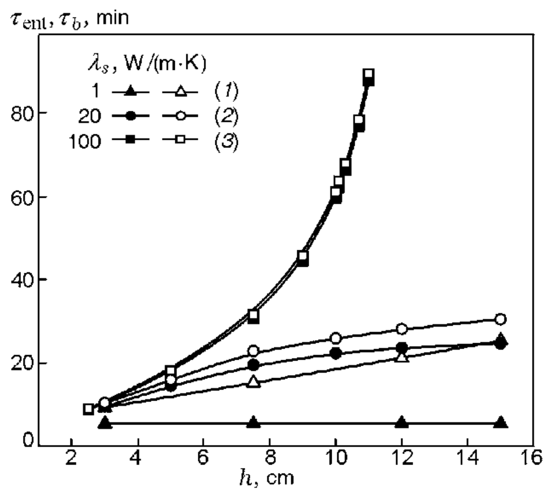

Fig. 4. Time of flame entry into a porous block (filled points) and the burning-through time of the flame arrester (open points) versus length of the porous block for various thermal conductivities.

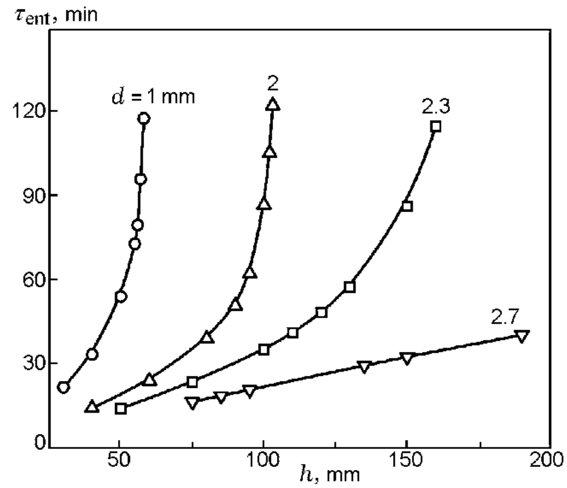

Fig. 5. Time of flame entry into a porous element versus element length for various channel diameters [$\lambda_s = 70$ W/(m·K) and $v = 22$ cm/sec].

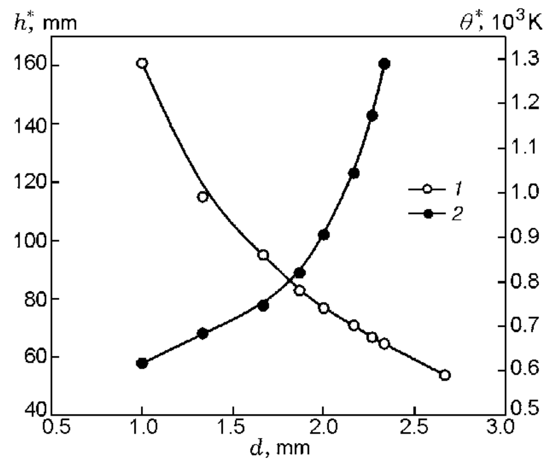

Fig. 6. Critical length (1) and maximum heating of a porous element (2) versus channel diameter [$\lambda_s =$ 70 W/(m·K) and $v = 22$ cm/sec].

by conduction over the thickness of the porous layer. The larger h, the higher the total heat capacity of the block, the slower its heating, and the later the block surface reaches the temperature at which the FGC wave is formed. Starting from $h = 10$ cm, the entry time ceases to change with increasing h. This implies that at the moment the combustion wave enters the porous block, the heat spread does not reach the opposite boundary of the porous block. The FGC wave that forms does not feel this boundary and behaves as if it enters a semibounded block. Thus, the initial rapid increase in the burning-through time with increasing h is due to an increase in the entry time, and the further slow increase at $h > 10$ cm is related to the increased propagation time.

For $\lambda_s = 100$ W/(m·K), the burning-through time almost coincides with the entry time and increases rapidly with increasing h. For $h > 12$ cm, the flame does not enter the porous block. Instead of this, a steady-state temperature profile is formed in the porous block, i.e., such a flame arrester does not burn through. The reason for the occurrence of the critical block length h^* above which the flame does not enter the porous block is likely an increase in the total heat loss from the block due to an increase in its length. As a result, a dynamic balance is established between the heat input and heat loss, leading to a steady-state temperature profile in the block. Indeed, calculations show that, if the external heat loss is eliminated, curve 3 is transformed to a curve of the form 2.

Figure 5 shows curves of the time of flame entry into a porous block versus block length for various channel diameters for $\lambda_s = 70$ W/(m·K) and $m = 0.5$. It is evident that, for channel diameters smaller than the critical value for flame flashback, there is a certain length of the porous block h^* for which the flame will never enter the porous block. The smaller the channel diameter, the smaller length of the flame-arrester element is required to prevent burning-through of the flame arrester.

Curve 1 in Fig. 6 shows the dependence of h^* on the channel diameter. The calculations were made for a perforated steel block of porosity $m = 0.5$, density $\rho_s = 8$ g/cm^3, heat capacity $c_s = 400$ J/(kg·K), and thermal conductivity $\lambda_s = 70$ W/(m·K). For $h > h^*$, a steady-state temperature profile is established in the

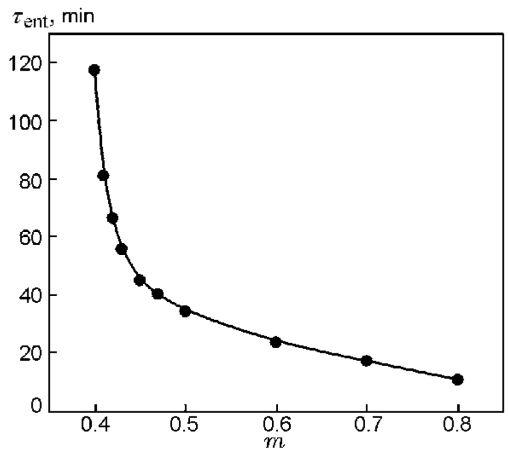

Fig. 7. Entry time versus porosity [λ_s = 70 W/(m · K) and v = 22 cm/sec].

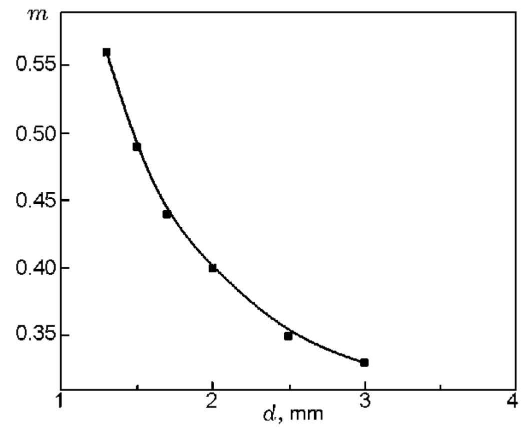

Fig. 8. Relationship between the channel diameter and porosity that prevents burning-through of a porous block 75 mm long.

porous element which has a maximum on the surface on which the flame is stabilized. Curve 2 in Fig. 6 relates each value of h^* to the maximum temperature in the porous block. It is evident that the smaller the channel diameter, the smaller the block length required to prevent burning-through of the flame arrester, but the higher the maximum heating of the porous block at the establishment of a steady-state temperature profile.

The extinguishing ability of the flame arrester can also be changed by varying the porosity of the block m. In the case of a perforated block, this is easy to do by changing the spacing between the channels. For a fixed channel diameter and block length, the time of flame entry into a porous block increases with decreasing porosity (Fig. 7). Upon reaching a certain value $m = m^*$, the flame ceases to enter the porous block, i.e., the flame arrester with this block does not burn through. For the specified block length, flame stabilization on the right boundary of the block can be achieved by decreasing the channel diameter or porosity. Figure 8 shows the relationship between the critical values of the porosity and channel diameter in a porous steel block 75 mm long for which the flame ceases to enter the porous block. It is evident that the greater the channel diameter, the smaller values of the porosity are required to prevent burning-through of the porous block.

DISCUSSION

The modeling performed in the present work and in [10] gives a basis for optimization of porous flame arresters. A flame arrester should meet a number of requirements: it should reliably prevent flame flashback and have high fire resistance and low hydraulic resistance. Among the optimization means are the choice of the type of porous bed (granular or channel) and characteristics of the porous block, such as the material (thermal conductivity and heat capacity), effective channel diameter, porosity, and thickness of the porous block.

The first requirement imposes a stringent upper-bound limit on the effective channel diameter. It should be smaller than the critical extinction diameter. From this point of view, the most profitable type of porous medium is a monolithic perforated block. In this case, strict calibration of the channels allows the minimum margin for the channel diameter to be reduced to 5–10% of the critical value. In the case of granular porous beds, the sizes of separate channels depend, in particular, on the quality of the porous medium, which requires a larger margin coefficient. The channel porous media made of adjacent flat and corrugated metal foil strips also require a significant margin for the channel diameter. This is due to the absence of rigidity in these porous media. When it is heated by the flame stabilized on the porous bed surface, the foil layers can separate from each other to form channels of greater diameter.

The requirements of high fire resistance and low hydraulic resistance should be considered simultaneously since, often, the factors increasing fire resistance also increase hydrodynamic resistance. In practice, flame arresters are divided into classes according to the fire resistance time [12]. As a rule, the required fire resistance time should be more than 30 min. In an ideal flame arrester, the flame stabilized on its surface should not enter it for an arbitrarily large time.

Flame arresters with granular porous beds are the easiest to produce. Their obvious disadvantage is that, for the same effective channel diameter and porosity, they have much higher hydraulic resistance than do channel flame arresters. The structure of granular porous beds does not allow wide variation of their parameters: the porosity varies in the range of 0.4–0.5, and the thermal conductivity in the range of 1–4 W/(m · K). Calculations have shown that, for such parameters and reasonable values of the channel diameter for the most dangerous gas velocity of ≈20 cm/sec, flame always enters the porous bed. Therefore, using granular beds, it is impossible to design a flame arrester that would not burn through. It is only possible to optimize its fire resistance. The characteristic times of entry into a granular porous bed are insignificant (1–10 min). The fire resistance of granular flame-arrester elements is determined by the time of flame propagation in the porous block, which can be several tens minutes and, in some cases, reach an hour. There are very limited possibilities of influencing the propagation time. The propagation time is proportional to the porous-block length. Therefore, by increasing the length, it is possible to reach a certain increase in the fire resistance. However, the hydraulic resistance in this case also increases in proportion to the length. A significant increase in the propagation time can be achieved by reducing the effective channel diameter. In this case, however, the resistance increases even more rapidly — in inverse proportion to the squared diameter.

The thermal conductivity of channel porous media is 10–100 W/(m · K). According to Fig. 2, their fire resistance is determined by the time of flame entry into the porous block. This leads to another aspect of the problem of optimizing channel flame arresters: to improve the fire resistance, one should deteriorate the entry conditions. In particular, it becomes possible to design flame arresters which do not burning-through and in which the flame does not enter the flame-arrester element.

From Fig. 2, it follows that to increase the fire resistance in channel flame arresters, it is reasonable to use high heat conducting materials, for example, metals. This conclusion is indirectly supported by the fact that, in practice, the best fire resistance was achieved by using cassettes made of aluminum foil [7]. The same experiments revealed a drawback of such flame arresters: they melt. The causes of melting can be analyzed on the basis of calculation results. Foil cassettes have high porosity $m = 0.8$–0.95. From Fig. 8, it follows that, in the case of high porosity, good fire resistance can be achieved by reducing the channel diameter. For example, in the above-mentioned flame arrester [7], the channel diameter was 1–1.25 mm. From Fig. 6, it is evident that, during flame stabilization on the porous block surface, the latter is heated more strongly the smaller the channel diameter. In particular, for a channel diameter of 1.2 mm and a block length of more than 65 mm, the temperature is 1100 K, which far exceeds the melting point of aluminum [13].

Steel has lower thermal conductivity than aluminum but better thermal stability, which makes it a more suitable material for flame-arrester elements. Cassettes made of steel foil do not allow the porosity to be changed significantly. The design of flame-arrester elements in the form of a perforated monolithic block is more appropriate. This variant has not found wide use in designing flame arresters. The reason for this is likely its low manufacturability because it is difficult to provide a number of small-diameter holes (1–2.5 mm) along the entire block length, which can reach 60–200 mm. Such a block, however, can be assembled from separate sections 10–20 mm high. The single requirement is to align the holes in individual sections so that continuous channels are formed along the entire length of the flame-arrester element were formed. In this case, special measures to provide thermal contact between the sections are not required. Calculations have shown that even if the sections are separated by air gaps of size about 1 mm, the burning-through time of such a sectioned block will differ only slightly from the burning-through time of a continuous block of the same thickness.

The channel diameter and block porosity should be chosen with the hydraulic resistance of the block taken into account. The resistance of a perforated block (determined as the pressure drop across it) can be assumed to be proportional to the block length and inversely proportional to its porosity and the square of the channel diameter. Using the data of Fig. 8, which shows the correlation between the channel diameter and the porosity that provides the absence of burning-through for a block 75 mm long, it is easy to estimate that, for a constant length, the resistance of the block which does not burn through increases monotonically with decreasing diameter of the channels. Therefore, to reduce the hydraulic resistance, it is desirable to choose the maximum possible diameter of the channels. Providing a good margin for the critical diameter, which for a stoichiometric methane–air mixture is 3 mm, it is possible to choose the value $d = 2$ mm and its corresponding porosity of 0.4 (see Fig. 8). According to calculations, a block 75 mm long should not burn through. During flame stabilization on its surface, the maximum temperature of the block, according to Fig. 6, should not exceed 750 K.

We note that, although the parameters used in the calculations were chosen so as to obtain results close to experimental values, the calculations performed here are largely illustrative because of the uncertainty of some physical and chemical parameters of the process. Nevertheless, the obtained qualitative trends should remain valid with variation in the system parameters such as chemical reaction rate, dimensions and thermodynamic parameters of the flame arrester case, external heat loss, etc. In addition, designing flame-arrester elements in the form of a perforated steel block makes it possible to vary the block parameters over wide ranges, allowing, if necessary, optimization of the burning-through process in an experimental way by using the principles described in the present paper.

CONCLUSIONS

• The numerical analysis of the burning-through of porous flame arresters shows that the fire resistance of the channel flame-arrester elements is determined by the stage of flame entry into the porous bed, and that of granular flame-arrester elements by the stage of flame propagation in the porous element.

• To increase the fire resistance, it is reasonable to make channel flame-arrester elements of high heat conducting materials.

• The flame-arrester element in the form of a monolithic perforated block offers better opportunities for optimizing the protective properties of flame arresters.

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