# PECULIARITIES OF BURNING-THROUGH OF GRAIN AND CHANNEL TYPES OF POROUS FLAME-ARRESTERS

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Recently the base for optimization of flame-arrester parameters with the purpose of fireresistance improvement were empirical observations and theoretical ideas on burning-through process. It was assumed, in particular, that the cause of burning-through is heating-up of flamearresting element by the flame, stabilized on its surface [1]. As a result of heating-up the critical diameter of flame quenching decreases and flame propagates through the porous flame-arresting element. Progress in filtration gas combustion allowed us to correct understanding of the reasons for flame-arrester burning-through. Presently it is evident that the course of burning-through is flame propagation through the porous flame-arresting element in the low velocity regime (LVR) of filtration gas combustion (FGC) [2-4]. In the frame of this conception the lows of burning-through of filled flame-arresters were analyzed in [5] in 1-D approximation. As a result of this study two distinct stages of burning-through process were revealed: the stage of flame entering in porous element and the stage of flame propagation through it. This fact was justified also experimentally [5]. The full time flame-arrester fire-resistance is consists of entering time and propagation time correspondingly. It was shown (numerically and experimentally) that fire-resistance of grain filled flame-arresters is controlled by propagation time [5]. Therefore all, that decreases the velocity of flame propagation through a porous bed, results in fire-resistance improvement. This fact, in particular, explains linear dependence of fire-resistance of filled flame-arresters on its length [1].

Grail filled porous beds, used in adapter flame-arresters, doesn't allow to vary parameters of flame-arresting module in a wide range. So porosity can change from 0.4 to 0.5. Effective channel diameter can not be decreased strongly due to sharp increase in flow resistance. Thermal conductivity of porous bed is determined mainly by heat transfer between grains of the filling, therefore it depends weakly on filling material also. It restricts the possibility of improvement of adapter flame-arresters. Porous media of channel type, used in cassette flame-arresters, allow more possibilities for parameters variation. The object of the present paper is the analysis of lows of channel flame-arrester burning-through in order to reveal the ways of fire-resistance increasing of cassette flame-arresters.

## Results

The analysis of burning-through process was carried out on the base of FGC model [3]. Fig. 1 shows the model system. In a tube of radius  $R_w$  there is a porous module of length h. Combustible mixture flows in the tube at the left and it flows in the porous module. Combustion products flow out at the right. Gas mixture ignites in the empty part of the tube on the right of the porous module. The tube has thermal conductivity and heat capacity that is it takes part in heat transfer, modeling the case of flame-arrester. The system of equations, describing propagation of one-dimensional



Fig.1. Scheme of the model system.

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nonsteady-state combustion wave in chemically inert porous medium, consists of the equations of heat transfer in gas and porous medium, mass transfer of a deficit component of gas mixture, conservation of mass and gas law. The system was decided numerically. Detailed description of the system and solution procedure has been done in [5].

The program calculates instant temperature profiles of gas and porous medium and determines the flame front position. From these data the time of flame entering in porous module and time of propagation through it can be determined. Simulation was carried out for stoichiometric methaneair mixture. For gas mixture the following parameter values were given [5]. Specific heat capacity at pressure constant  $c_p=10^3$  J/(kg·K), thermal conductivity 0.1 W/(m·K), the temperature of adiabatic flame  $T_b=2320$  K. The rate of chemical reaction was given in the form of  $W = \eta k_0 \exp(-E/RT)$ , were  $\eta$  is relative concentration of the deficit component of gas mixture,  $k_0=1\cdot10^{11}$  s<sup>-1</sup>,  $E=2.26\cdot10^5$  J/mol, *R* is gas constant. Values of porous module parameters were varied. The case of flame-arrester was modeled as a part of steel tube of radius  $R_w=45$  mm and thickness 5 mm, that corresponds to the real flame-arrester OII-50. Heat loss from the unit of external flamearrester surface was given by the value  $\alpha_w=50$  W/(m<sup>2</sup>·K) [5].

Channel porous medium differs from a grain one mainly by the thermal conductivity values. In flame-arrester of filled type thermal conductivity of porous module is determined by heat transfer between grains of the filling and is  $1\div4$  W/(m·K). In flame-arresters of channel type thermal conductivity of porous module is determined by the thermal conductivity of module material and it can change in very wide range. Channel flame-arresting module can be done in the form of roll of laid together straight and corrugated metal tapes or in the form of monolithic perforated module. As a perforated module we mean monolithic cylinder with cylinder channels distributed uniformly on its cross section. Channel structure can be formed also by packing of tube section by cylinder rods. This variant however differs from perforated module only by the channel form and fixed value of porosity equaled about 0.1. Cassettes from metal foil have porosity equaled about 0.8÷0.95. Perforated module allows to vary the porosity in wide range from 0.8 to lower.

Fig. 2 shows calculated dependences of burning-through time on porous module thermal conductivity  $\lambda_s$ . Porosity of the module is equal to 0.5, specific heat capacity is 400 J/(kg·K), length of porous module *h*=75 mm. It is seen that the time of flame entering in porous module increases monotonically with  $\lambda_s$  increasing. This behavior is evident as for flame entering into porous bed one needs to heat up its surface layers. The more thermal conductivity of porous bed the faster heat,



Fig. 2. Influence of thermal conductivity of porous module on time of flame entering in porous module (1), propagation time through it (2) and total burning-through time (3).

which porous bed gets from flame, diffuses through the module thickness and the more time is needed for heating of surface layers of the module up to required temperature. The time of flame propagation through the module decreases on the contrary with  $\lambda_s$  increasing. This behavior is due to the velocity of FGC wave propagation through a porous bed is determined by the rate of heat transfer through it, which is proportional to thermal conductivity of porous bed. As the result of contrary tendencies of changing of entering time and propagation time with thermal conductivity the full burning-through time is nonmonotonic function with minimum. For module of 75 mm length minimum is achieved at  $\lambda_s \approx 4$  W/(m·K). At that at  $\lambda_s < 3$  W/(m·K) the full burning-through time is determined mainly by the time of propagation of combustion wave through the porous module, but at the more  $\lambda_s$  values – by the time of flame entering in porous module.  $\lambda_s$  values less than 3÷4 W/(m·K) are characteristic for filling porous media [6], and  $\lambda_s = 10 \div 100$  W/(m·K) – for channel type of porous media. Taking this into account one can consider that burning-through of filling flame-arresting modules is limited by the stage of FGC wave propagation through module and of channel one – by the stage of flame entering in the module. For example it is seen from fig. 2, that at  $\lambda_s = 70$  W/(m·K), the entering time  $\tau_{inp}$  is about 30 minutes and propagation time  $\tau_p$  is only 1 minute. For observer it seems as flame is situated at flame-arrester exit about 30 minutes, heating up it gradually, then it disappears and almost right away it appears in front of flame-arrester. Perhaps such behavior results in well known error that the reason of flame-arrester burning-through is flash back through the flame-arrester, heated up previously by the flame stabilized at its exit.

Thus in flame-arresters with channel porous media it is necessary to trend to increase of time of flame entering in porous module, as it determines its fire-resistance. Fig. 3 shows dependence of entering time on gas velocity at the porous module input. Calculations were carried out for perforated steel module with porosity m=0.5, density  $\rho_s=8$  g/cm<sup>3</sup>, heat capacity  $c_s=400$  J/(kg·K) and thermal conductivity  $\lambda_s=70$  W/(m·K), module length h=75 mm, channel diameter  $d=1\div3$  mm. So as for filling porous media, these dependencies have U-form. At low and high flow rates the entering time tends to infinity, that is, the flame, stabilized at porous module surface, doesn't not enter in it. The least fire-resistance for all channel diameters appears at gas velocity v=22 cm/s. This regime is



Fig. 3. Dependencies of time of flame entering in porous module on gas velocity. h=75 mm,  $\lambda_s=70 \text{ W/(m·K)}$ , *d*, mm: 3.3 (1), 2.7 (2), 2 (3).

Fig 4. Dependencies of entering time (dark symbols) and propagation time (light symbols) on porous module length.  $\lambda_s$ , W/(m·K): 1 (1), 20 (2), 100 (3).

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most rigorous. Therefore all following calculations were carried out for this gas velocity. Fig. 3 shows that the less channel diameter the more narrow the range of gas velocities, at which burning-through is possible, and the more entering time in the most rigorous regime. Therefore for fire-resistance increasing it is rationally to use porous modules with minimally possible channel diameter. The minimal diameter is determined by compromise between desired fire-resistance time and flow resistance of porous module.

One more way of improvement of channel flame-arrester characteristics follows from Fig. 4, demonstrated an influence of porous module length on entering time and burning-through time. At  $\lambda_s=1$  W/(m·K), characteristic for filling flame-arresters, entering time doesn't depend almost on module length and equals about 5 minutes. Entering time ( $\tau_b$ ) increases arcwise with the increase of porous module length. This dependence is evident as at low entering time the burning-through time is determined by propagation time and equals h/u, where u is steady-state velocity of FGC wave propagation.

At  $\lambda_s=20$  W/(m·K) the main contribution in burning-through time is the time of flame entering in porous module. Essential growth of  $\tau_{inp}$  with *h* increase up to *h*=11 cm is due to conductive smearing through the porous module length of the heat, received by porous module from flame, stabilized at its surface. The more *h*, the more the total heat capacity of the module, the slower it heats up and the later the temperature of module surface achieves the value, corresponding to flame entering in porous medium. Beginning from *h*=10 cm, entering time stops to change with *h* growth. It means that at the moment of flame entering in porous medium the heat smearing doesn't achieve opposite end of porous module. Forming FGC wave doesn't feel this end and behaves as at the entering in semirestricted module. Thus initial fast growth of burning-through time with *h* increase is due to entering time increasing and the following slow growth at *h*>10 cm is due to increase of propagation time.

At  $\lambda_s = 100 \text{ W/(m·K)}$  burning-through time coincides almost with entering time and grows quickly with *h* growth. At *h*>12 cm the flame does not enter in porous module. Instead steady state temperature profile forms in porous medium, that is such flame-arrester does not burn through. The reason for appearance of critical module length *h*\*, beyond which the flame does not enter in porous module, is perhaps an increase of total heat losses from module under its length increase. As a result



Fig. 5. Dependence of time of entering in porous module on its length at values of channel diameter d, mm: 1 (1), 2 (2), 2.3 (3), 2.7 (4).  $\lambda_s$ =70 W/(m·K),  $\nu$ =22 cm/s.

dynamic equilibrium is set in between heat supply and heat sink. It results in steady-state temperature profile in porous module. Really, calculations show that elimination of heat losses results in transformation of curve (3) to curve of form (2).

Fig 5 shows dependencies of time of flame entering in porous module on its length and channel diameter at  $\lambda_s=70$  W/(m·K) and m=0.5. It is seen that for channel diameters less than critical one for flashback there is certain porous module length  $h^*$ , at which flame does not enter in porous module never. At that the less channel diameter the less porous module length required in order to flame-arrester doesn't burn through.

Curve (1) in fig. 6 shows dependence of  $h^*$  on channel diameter. Calculations were carried out for perforated steel module with porosity m=0.5, density  $\rho_s=8$  g/cm<sup>3</sup>, heat capacity  $c_s=400$  J/(kg·K) and thermal conductivity  $\lambda_s=70$  W/(m·K). At  $h>h^*$  a steady-state temperature profile forms in porous module with maximum temperature at the surface, at which flame is stabilized. Curve 2 in fig. 6 correlates  $h^*$  values with values of maximum temperature in porous module. It is seen, that the less channel diameter the less porous module length, required for flame-arrester does not burns through, the higher maximum heating-up of porous module when steady-state temperature profile in porous module is set in.

Quenching ability of flame-arrester can be changed also, changing module porosity m. In the case of perforated module m is changed easy by changing of compactness of channel positions. At a fixed channel diameter and porous module length time of flame entering in the module increases with porosity decrease (fig. 7). At reaching of certain value  $m=m^*$  flame stops to enter in porous module, that is flame-arrester with such module does not burn through. At given porous module length the flame stabilization on the right end of porous module can be achieved by decreasing of either channel diameter or porosity. Fig. 8 shows interrelation between critical values of porosity and channel diameter in steel module of 75 mm length, at which flame stops to enter in porous module. It is seen that the more channel diameter the less values of porosity are required for ensuring of nonburning-through of porous module.



Fig. 6. Dependencies of critical length (1) and maximum heating up of porous module (2) on channel diameter.  $\lambda_s=70 \text{ W/(m-K)}, \nu=22 \text{ cm/s}.$ 

### Discussion

Modeling carried out in the present paper and in [5], gives a base for porous flame-arresters optimization. Flame-arrester must comply with a set of requirements. It must defend against flashback, ensure high fire-resistance and have low flow resistance. Among of optimization means there are selection of porous medium type (grain, channel), porous module characteristics (thermal conductivity, heat capacity), effective channel diameter, porosity, length of porous module. The first requirement applies strong restriction on effective channel diameter. It must be less than the critical quenching diameter. From this point of view monolithic perforated module is the most appropriate variant of flame-arresting module. Exact channel calibration allows us to amount the reserve on channel diameter to nothing more than 5-10% of critical one. In the case of filling porous media sizes of individual channels depend among other on the filling quality that requires the more reserve coefficient. Channel porous media, done from laid together straight and corrugated metal tapes, require also essential reserve on channel diameter. It is due to lack of hardness in such porous medium. In the case of its heating up by flame, stabilized at its surface, individual foil layers can diverge, forming channels with more diameter.

Requirements of high fire-resistance and low flow resistance must be considered in complex, as often that increases fire-resistance, increases also flow resistance. In practice flame-arresters are divided in classes dependent on the time of fire-resistance [7]. As a rule one needs fire resistance more than 30 minutes. Ideal flame-arrester is flame-arrester, in which flame, stabilized on its surface, does not enter during any arbitrary large time.

Flame-arresters with filling porous media are most easy for manufacturing. The evident their shortcoming is that at the same effective channel diameter and porosity they have essentially larger flow resistance than channel flame-arresters. The structure of filling porous media does not allow to vary their parameters in a wide range. Their porosity varies in the range  $0.4\div0.5$ , thermal conductivity is  $1\div4$  W/(m·K). Calculations show that with such parameters and reasonable values of channel diameter at the most dangerous value of gas velocity 20 cm/s a flame enter in porous module always. Therefore nonburning-through flame-arrester can not be created on the filling base. There can be only optimized its fire-resistance. Characteristic entering time for filling porous modules is  $1\div10$  minutes. Fire resistance of filling flame-arresting modules is determined by the time of flame propagation through the porous module, that can be tens minutes and in some cases



Fig. 7. Dependence of entering time on porosity.  $\lambda_s$ =70 W/(m·K), v=22 cm/s, d=2 mm.

Fig. 8. Correlation between channel diameter and porosity, ensuring nonburning-through of porous module of length 75 mm.

can achieve one hour. Possibilities of influence on propagation time are limited very. Propagation time is proportional to the length of porous module. Therefore one can reach for some increasing of fire-resistance, increasing the length. However flow resistance increases at that proportional to the length also. Decreasing of effective channel diameter can result in essential increasing of propagation time. But at that flow resistance increases still stronger – inversely to diameter squired.

Channel porous media have thermal conductivity  $10 \div 100 \text{ W/(m·K)}$ . In according to fig. 2 their fire-resistance is determined be the time of flame entering in porous module. This circumstance transfer the problem of channel flame-arrester optimization in any plane: one needs to trend to deterioration of entering conditions in order to improve fire-resistance. In particular, the possibility appears to create nonburning-through flame-arrester, when the flame does not enter in flame-arrester at all.

Fig. 2 shows that it is appropriate to use high thermal conductivity materials, such as metals, in channel flame-arrester in order to improve their fire-resistance. This conclusion is confirmed marginally by the fact that in practice the best fire resistance was achieved for cassettes from aluminum foil [1]. I the same experiments shortcoming of such flame-arrester was revealed: they are melted. Calculation results allow us to analyze the reasons of this disadvantage. Foil cassettes have high porosity about  $0.8\div0.95$ . Fig. 8 shows that at high porosity good fire-resistance can be reached due to channel diameter decreasing. In particular, named flame-arrester [1] had channel diameter  $1\div1.25$  mm. From fig. 6 one can see, that at flame stabilization at porous module surface this surface is heated up stronger, when channel diameter is less. In particular, temperature 1100 K is reached for channel diameter 1.2 mm at module length more than 65 mm, that much more than melting point for aluminum [8].

Steel has rather less thermal conductivity, than aluminum, but essentially better heat resistance, that does it more appropriate material for flame-arresting module. Cassetes from steel foil don't allow to vary the porosity essentially. Flame-arresting module in the form of perforated monolithic module is more appropriate. This variant does not find wide application for practice of flame-arresters manufacturing. The reason for this is, perhaps, bad processibility, as it is hardly to do a set of orifices of 1-2.5 mm diameter through the all length of module, which can achieve 60÷200 mm. Such module, however, can be collect of individual sections of length 10÷20 mm. The only requirement is matching of orifices in individual sections so that continuous channels are formed through the all length of flame-arresting modules. At that special measures are not required for good thermal contact between individual sections. Calculations show, that even if air gaps of 1 mm are between sections, burning through time for such flame-arrester differs little from burning-through time of continuous module of the same length.

Selection of channel diameter and porosity of module must be carried out with accounting its flow resistance. Flow resistance of perforated module (determined as pressure drop in it) can be considered as proportional to its length and inverse to its porosity and channel diameter squired. Using data from fig. 8, which correlates porosity and channel diameter values, ensuring of nonburning-through of module of 75 mm length, it is easy to evaluate, that at a constant length the flow resistance increases with channel diameter decreasing. Therefore it is desirable to select maximum possible channel diameter in order to decrease flow resistance. Taking a good reserve for critical diameter, which for stoichiometric methane-air mixture is about 3 mm, one can select the value d=2mm and corresponding to it porosity 0.4 (fig. 8). At module length 75 mm such module must not burn through accordingly to calculations. At that maximum temperature of its surface at flame stabilization will no more than 750 K (fig. 6).

## Conclusions

1. Numerical analysis of burning-through process of porous flame-arresters shows that fireresistance for channel flame-arresting modules is determined by the stage of flame entering in porous module and for filling one by the stage of FGC wave propagation through the porous module.

- 2. For the purpose of improving of fire-resistance it is appropriate to do flame-arresting module of high thermal conductivity materials.
- 3. Flame-arresting module in the form of monolithic perforated module allows the utmost to optimize safety properties of flame-arrester.

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