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# STABILITY OF FILTRATION COMBUSTION IN A CYLINDRICAL RADIATION HEATER WITH A POROUS WORKING MEDIUM

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*Special features of the localization of a combustion front in a cylindrical radiation heater with a porous working medium, for which use was made of charges of aluminar, magnesite sand, and expanded clay aggregate with different grain sizes, are studied experimentally. A qualitative analysis of thermohydrodynamic instability of filtration combustion (FC) is made, based on which the existence of a critical radius of localization of the combustion front in the cylindrical burner is established. A qualitative agreement between analysis and experiment in filtration from the center to the periphery is shown.*

The processes of combustion of gaseous mixtures in porous media, or filtration combustion (FC), are actively studied at present in connection with the prospects for practical use, in particalar, for creating radiation heaters [1, 2].

Compared to traditional heaters, radiation heaters with a porous ceramic structure have a higher efficiency of conversion of the thermal combustion energy to radiation, i.e., a higher radiation efficiency. Furthermore, because of the decrease in the maximum temperature of the flame the content of $NO_x$ in combustion products of porous burners is much lower than that of traditional burners.

One possible configuration of these heaters is a cylindrical configuration with filtration of an energy-transfer agent from the center to the periphery [2]. This geometry ensures the compactness of the system and, what is the most important, automatic stabilization of the combustion surface in a skeleton due to the decrease in the filtration rate at a large radial distance. The issues of the localization of a wave and its stability become of paramount importance.

Currently available foamy and discrete ceramic structures permit manufacture of heaters that successfully withstand a rather long heating to high temperatures but their longevity is limited by the failure induced by heating-cooling cycles. The use of ceramic charges instead of continuous bodies enables us to circumvent these difficulties. Because of the randomness of the structure of porous materials and the complex character of heat and mass transfer it is difficult to rigorously model FC. For this reason, construction of qualitative physical models of FC is important as is an experimental investigation of this kind of systems.

The present work reports the experiments with a cylindrical radiation heater in which charges of ceramic materials are used as a porous body. The position of a combustion wave as a function of the flow rate of a fuel mixture (the filtration rate) and the form of the charge was determined. A qualitative analysis of thermohydrodynamic instability of FC is made, based on which the existence of a critical radius of localization of a combustion front in the cylindrical burner that corresponds to approximately 2/3 of the outside radius of the skeleton is shown. This result is checked experimentally.

**Qualitative Analysis of Thermohydrodynamic Instability of FC.** The stability of an FC front was investigated in [3-6], where the dynamics of small perturbations of the temperature and the position of the front

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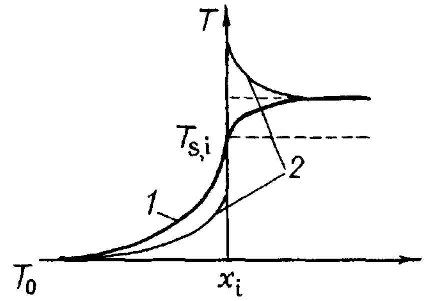


Fig. 1. Temperature profiles in a skeleton (1) and a gas (2).

was considered. In spite of the models that are quite appropriate in a number of cases, the results obtained do not provide information on the behavior of the system in a nonlinear stage of the development of a perturbation. Furthermore, they do not contain macroscopic parameters of the system, such as the geometry, the width of the heated zone, external heat losses, etc., which render them unsuitable for practical calculations and evaluations. Therefore a qualitative physical analysis of the system is gaining in importance.

Let us consider FC in the regime of low rates. We distract ourselves from the model of chemical heat release and evaluate the heat balance of the region of heating of a porous skeleton to the left of the axis $T$ in Fig. 1. With respect to this region of the skeleton the incoming gas flow takes in the heat (through convective heat transfer) with the average specific (referred to unit area of the front) intensity $\tilde{q}_u$, while the conductive flux delivers the heat from a high-temperature skeleton region with the average intensity $\tilde{q}_\lambda$. It is evident that the front is in the quiescent state when these fluxes are equal and moves cocurrently when $\tilde{q}_u > \tilde{q}_\lambda$ and countercurrently when $\tilde{q}_u < \tilde{q}_\lambda$. The evaluation of these fluxes within the framework of a one-temperature model with instantaneous reaction and within the framework of a simplied two-temperature model [7] yields:

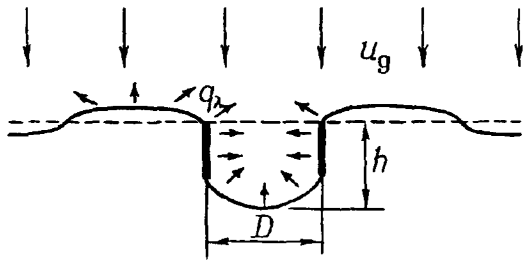
$$\tilde{q}_\lambda \cong (c\rho)_g u_g (1 - u)\, \Delta T_{s,i}\,, \quad \tilde{q}_u \cong (c\rho)_g u_g\, \Delta T_{s,i}$$

and consequently:

$$\tilde{q}_\lambda / \tilde{q}_u = 1 - u\,, \tag{1}$$

where $\Delta T_{s,i}$ is the skeleton temperature that corresponds to the ignition of the gas (see Fig. 1). The "tilde" sign denotes the value averaged over the cross section. The notation of the remaining quantities is given at the end of the work. Knowing $q_\lambda/q_u$ at each point of the cross section, we can model the evolution of the front and the perturbations; however, this modeling falls outside the scope of the qualitative analysis. Therefore we adopt the following method for studying the dynamics of perturbations. First, we will consider the perturbation of the front not locally (at each point) but as a geometric structure, a hole that has cross dimension $D$ and depth $h$ and is characterized by the average value of $Q_\lambda/Q_u$ ($Q_\lambda$ and $Q_u$ are the fluxes referred to the area of the perturbation cross section). Second, we consider that the temperature of the front does not vary with its deformations. Third, we will investigate not the absolute values of the heat fluxes $Q_u$ and $Q_\lambda$ but their increments (variations) induced by variation of the parameters of the front perturbation, which enables us to not pay attention to the absolute accuracy of formulas for the fluxes $Q_u$ and $Q_\lambda$ but to allow for the most important parametric dependences of the latter.

Perturbations of the scale of pore size are always present in the FC front and can be modeled by the superposition of sinusoidal or other deformations of the front (Fig. 2). The convective flux, more precisely, the inhomogeneity of the convective flux due to the inhomogeneity of the porous body and the gas-filtration field, is a disturbing factor for the front (from the viewpoint of an increase in its deformations). The conductive heat fluxes in the skeleton that tend to compensate for temperature nonuniformities in the system are a stabilizing factor. The perturbation cannot increase for a stationary homogeneous filtration field (by homogeneity of the convective flux we mean its correspondence to the initial unperturbed state of the front and the system as a whole rather than the



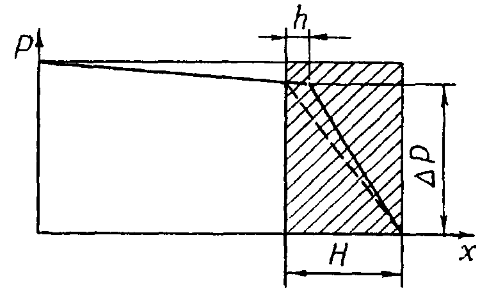




Fig. 2. Formation of a hole as a result of the development of a small perturbation.

Fig. 3. Pressure variation in filtration along the $x$ axis through low- and high-temperature (dashed) regions.

absolute constancy of the flux). These fluxes mutually affect each other and determine the evolution of the front and its perturbations.

We consider simple models of variation of the convective and conductive heat fluxes $q_u$ and $q_\lambda$ for the heating region of the combustion front. Let the filtration rate be prescribed by the local pressure gradients and the filtration coefficient according to the Darcy law

$$u_g = -k_f \operatorname{grad}(P), \tag{2}$$

where $k_f$ is the filtration coefficient; $P$ is the pressure.

Let us assume that the pressure in the system drops mainly in a high-temperature region of width $H$ without defining in detail the notion of "a high-temperature region." The beginning of the high-temperature zone coincides with the position of the combustion front, its length is associated with the heat losses into the ambient medium, the instant (if the process is transient), thermophysical properties of the porous body, and other parameters. The average unperturbed rate of filtration at the boundary of the hot zone is evaluated (see Fig. 3) as

$$u_{g0} = -k_f \operatorname{grad}(P) = -k_f \Delta P/H. \tag{3}$$

We consider a portion of the skeleton cross section covered by the hole (Fig. 2), and this portion will be assumed to be isolated (the stream tube). This assumption enables us to evaluate an increase in the filtration rate in this cross section due to the increase in the pressure gradient caused by the hole. We can proceed from the assumption of a constant pressure difference in the system and the high-temperature zone (which is implied in what follows) or from the assumption of a constant flow rate of the gas. In the first case, $u_g(h) = -k_f\Delta P/(H - h)$ or, in view of (3),

$$u_g(h) = u_{g0}(1 + h/(H - h)). \tag{4}$$

When the flow rate of the gas is constant the pressure difference will depend on deformations of the front and a variation in the rate in the perturbation cross section should be evaluated with allowance for the equality $u_{g0}S = u_g(h)S_1 + u_g(0)(S - S_1)$, where $S$ and $S_1$ are the areas of the total cross section of filtration and the perturbation cross section, respectively. It can be shown that in the regime of a constant flow rate, the filtration rate varies more slowly than (4) as the hole depth increases:

$$u_g(h) = u_{g0}\left(1 + \frac{(1 - S_1/S)\,h}{H - (1 - S_1/S)\,h}\right). \tag{5}$$

In the initial stage of the formation of a perturbation, Eqs. (4) and (5) are equivalent. In a later stage when $S_1 \sim S$, the differences of the regimes of a constant pressure and a constant flow rate can be significant.

As a consequence of the continuity of the flux the flow rate of the gas will also increase and in the immediate vicinity of the hole on the source side of the cold zone. The assumption of an isolated portion of the cross section covered with the hole leads to underestimation of estimates (4) and (5). Disregarding the pressure drop in the cold portion, conversely, leads to overestimation of this quantity. Within the framework of this model the convective and conductive fluxes will depend on the dimensions of the perturbation $h$ and $D$ and the width of the high-temperature region $H$. The best model of a shallow hole ($h < D$) is a spherical segment. The area of its surface and its average depth defined as the volume referred to the area of the base are expressed by the known formulas [8]. Considering the conductive flux as being proportional to the area of the hole surface and the convective flux as being related to its average depth, according to (4), we obtain:

$$Q_\lambda = \frac{\pi D^2}{4} \left(1 + 4 \left(\frac{h}{d}\right)^2\right) \tilde{q}_\lambda , \tag{6}$$

$$Q_u = \frac{\pi D^2}{4} \left(1 + \left(\frac{h}{2} + \frac{2}{3}\frac{h^3}{D^2}\right) \Big/ (H - h)\right) \tilde{q}_u . \tag{7}$$

A small perturbation can, apparently, increase if the increment in the convective flux caused by this perturbation exceeds the corresponding increase in the conductive flux, $\delta Q_u > \delta Q_\lambda$, or, according to (6) and (7):

$$\frac{4h}{D} \tilde{q}_\lambda < \frac{D}{2(H - h)} \tilde{q}_u + \frac{2}{3} \frac{h^2}{(H - h) D} \tilde{q}_u . \tag{8}$$

An elementary analysis of inequality (8) that is quadratic relative to $h$ shows that the perturbations $h \ll D$ and $h \ll H$, which are small in amplitude, always increase. Depending on discriminant (8) their increase can cease for a certain value or continue until the front is completely broken. For the second variant to be realized, it is necessary that discriminant (8) should have a negative value relative to $h$. The corresponding evaluation for $h \ll H$ yields:

$$\frac{D}{H - h} > 2\sqrt{3}\, \tilde{q}_\lambda / \tilde{q}_u . \tag{9}$$

We can easily make sure that the model of a cylindrical hole yields a similar condition for a perturbation increase

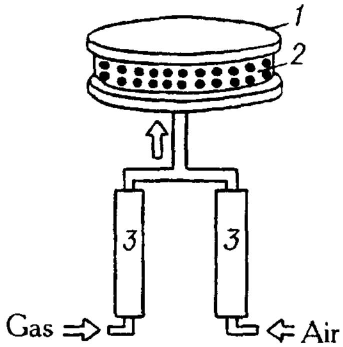
$$\frac{D}{H - h} > 4\tilde{q}_\lambda / \tilde{q}_u . \tag{10}$$

as the model of a spherical hole does.

We consider a cylindrical radiation heater with combustion filtration from the center to the periphery. We denote the radius of localization of the front as $r_1$ and the outer radius of the burner as $r_2$. The problem of thermohydrodynamic instability can be considered similarly to the case of a plane wave with the difference that a pressure distribution in filtration from the center is a nonlinear function with a downward convexity. However, in the approximation of $h \ll H$ the conditions of the development of perturbations will be similar to (9) or (10). For spherical and short (the height is smaller than the diameter) cylindrical burners, $D = 2r_1$ and $H \simeq r_2 - r_1$, and on simple rearrangements from (10) we will arrive at the condition of instability of the front

$$r_1 / r_{cr} = \frac{2}{2 + \tilde{q}_u / \tilde{q}_\lambda} r_2 . \tag{11}$$

Since for a stationary unperturbed front $\tilde{q}_u / \tilde{q}_\lambda \simeq 1$ we can infer that, for a radius of localization larger than $2/3 r_2$, the front becomes subjected to instabilities. It should be noted that in the presence of substantial lateral heat losses (a flat cylindrical layer) they are involved in the heat balance of the heating region of the front, as a



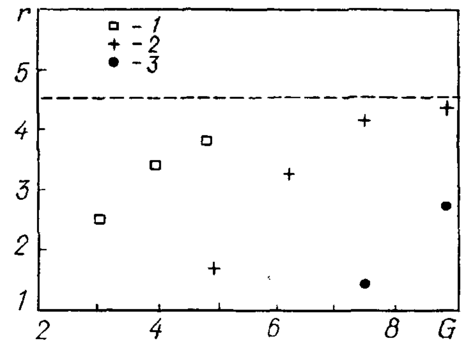




Fig. 4. Scheme of a cylindrical filtration burner: 1) cover, 2) perforated lateral wall, 3) rotameters.

Fig. 5. Radius of localization of a combustion wave vs. the flow rate of a gaseous mixture $G$, $m^3/h$: 1) expanded clay aggregate, 2) pellets of $Al_2O_3$, 3) magnesite sand; the dashed line is the stability limit $r_{cr} = 0.7r_2$.

result of which the stationary front is characterized by the relation $\tilde{q}_\lambda/\tilde{q}_u > 1$ and, according to (11), the limiting radius of stabilization will be somewhat larger.

The obtained instability conditions (9)-(11) do not contain in explicit form the characteristics of the combustion kinetics, the external heat losses of the front, thermophysical properties of the medium, etc. All the local characteristics of an FC process are contained in a unique simple parameter $\tilde{q}_\lambda/\tilde{q}_u$ (or parameters associated with it according to (1)), while global characteristics of the system are involved in the model in terms of the characteristic cross dimensions of the system and the perturbation $D_0$ and $D$ and the width of the heated zone (a gas-dynamic "plug") $H$.

**Experiment.** The basic experiments were carried out on a demountable heater of a cylindrical configuration with a height of the test portion of 25 mm and a diameter of 130 mm (Fig. 4). The ends were covered with metal covers, and a perforated lateral wall was manufactured from 3 mm-thick stainless steel. The diameter of the holes was 3.5 mm. The position of the combustion wave was determined visually (a luminous zone could be seen on the cover surface). The temperature of the combustion zone was measured by a platinum-rhodium thermocouple. An air-propane-butane mixture with a fuel–air ratio F/A = 1/30 was supplied from below to the center of the burner. The composition and the flow rate of the mixture were controlled by rotameters. The error of determining the flow rates is estimated at 15–20% and of determining the position of the front – at 5–10%.

Figure 5 presents the stationary position of the combustion wave as a function of the flow rate of the blown fuel mixture for different kinds of charges. For the latter, use was made of alumina pellets with an average diameter of 5 mm, magnesite sand with a characteristic grain dimension of 1.5–2.5 mm, and expanded clay aggregate in 6–10 mm grains. For charges with different characteristic grain dimensions when the flow rates of the gaseous mixture are the same, the combustion wave becomes steady-state closer to the center of the burner, the smaller the grain dimension. The combustion front formed a regular ring equidistant from the center, which indicated the absence of cavities and inhomogeneities in the charge. For different flow rates of the fuel, a stationary radius of localization of the front was visually recorded as the stabilization time passed. In the majority of measurements, it took 30 min for the position of the front to become stabilized. The points in Fig. 5 correspond to the radius of stationary combustion recorded in the experiment. In attempting to increase the radius further by increasing the flow rate of the mixture (for a charge of $Al_2O_3$ pellets and expanded clay aggregate) after a time of about a few minutes the combustion front in a narrow sector (about 30 angular degrees) shifted to the outer edge and broke; the unburned mixture burned down outside the burner. Then one or two more regions of break were formed, as a rule, while the part of the front that remained inside cooled down gradually. For the case of a charge of magnesite sand, we were unable to attain flow rates that ensure a rather large radius of localization of the front.

Because of a rather large width of the burner and a high thermal conductivity of the end covers the geometry of the front could deviate from cylindrical. To decrease these errors, we manufactured a narrower cylindrical burner of a thickness of 14 mm, whose lower flange was isolated by 1 mm-thick asbestos board, while the upper flange

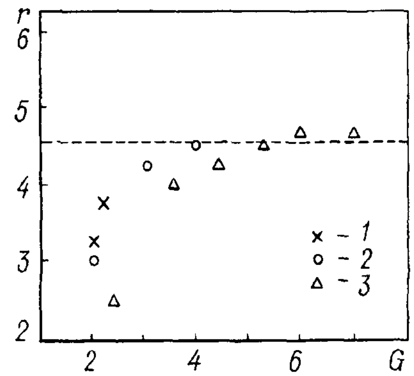



Fig. 6. Radius of localization of combustion vs. flow rate: 1) F/A = 1/35, 2) 1/33, 3) 1/30; the dashed line is the stability limit $r_{cr} = 0.7r_2$.

was manufactured of a 1 cm-thick ceramic plate. For better observation of the position of the front, transparent quartz beads were mounted into the upper flange. Pellets of $Al_2O_3$ 5 mm in diameter were used as the charge. The radius of the stationary localization of the combustion wave was measured for different stoichiometric relations of the mixture F/A and flow rates. Under our conditions, for leaner mixtures with F/A ~ 1/40, the combustion front did not become stabilized inside the burner because of the heat losses. For the mixture with F/A = 1/35, the limiting radius of the stationary localization was $0.6r_2$; for F/A = 1/33 and 1/30, it was $0.7r_2$. With increasing heat content of the mixture and significant filtration rates $u_0 \sim 5$ m/sec the combustion front ceased to shift as the flow rate increased (in the range of flow rates presented in Fig. 6), which could be due to the special features of the transient regime of FC. It follows from the figure that the limiting radii of localization obtained in the experiment do not exceed $0.7r_2$. The relative intensity of the lateral heat losses increases with energy release, which leads to an increase in the limiting radius of localization of the front.

**Conclusion.** The issue of the localization of a wave in a cylindrical radiation heater was investigated in [2], where the limiting radius of localization of the stationary front determined by the heat balance and the kinetics of combustion is found to be $\sim 0.85r_2$ for the system considered in our case. The results of the present work show that, actually, the stability of the stationary front is lost for a smaller radius of $\sim 0.7r_2$.

In the experiments carried out on the first burner, we failed to obtain a stationary position of the combustion front at a radial distance that exceeds $0.6r_2$ for $Al_2O_3$ pellets and $0.67r_2$ for a charge of expanded clay aggregate, respectively. The difference in the limiting radii can be attributable to relatively large radiant heat losses of the heating zone of expanded clay aggregate that are due to the increased pore size and the mean free path of a quantum and, accordingly, to the smaller effective width of the hot zone $H$. The experiments carried out on the second burner also indicate the existence of a limiting radius substantially smaller than $r_2$. Thus, by and large the results of the qualitative model are confirmed by experiment.

Specific properties of the problem considered (the stability limit of the wave was determined in the immediate vicinity of the external boundary of the burner) predetermined the possibility of obtaining simple formulas for variations of the fluxes and the stability criterion without accurate determination of $H$. We note that the hydrodynamic plug $H$ can easily be found experimentally or be calculated [9]. The absence in condition (11) of such parameters as the combustion temperature, the skeleton porosity, etc., is a consequence of model simplifications adopted in obtaining (6) and (7). If we complicate the model of filtration, for example, allowing for a pressure drop in the cold region of the skeleton, the maximum temperature of the skeleton will appear explicitly in the condition of stability of the front; however, we think that similar corrections are of a lower order of significance.

## NOTATION

$T_{s,i}$, skeleton temperature that corresponds to the ignition of gas; $\Delta T$, increment in the temperature relative to the ambient temperature $T_0$; $u$, dimensionless velocity of the FC front; $u_g$, average gas-filtration rate; $u_{g0}$, average unperturbed rate of filtration; $H$, width of a high-temperature zone or the zone of increased hydrodynamic resistance; $h$, average depth of the hole of perturbation; $D$, cross dimension of the perturbation region; $c$, specific heat at constant pressure; $\rho$, bulk density; $r$, radial coordinate; $r_{cr}$, limiting radius of stability of the front (11); F/A, volumetric fuel/air ratio. Subscripts: g, gaseous phase; s, solid phase; i, ignition; $u$, is due to gas motion; $\lambda$ is due to heat conduction.

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