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Influence of heat conductivity and pore size of porous materials on the efficiency of cylindrical radiative burners with filtrational gas combustion

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Abstract.   The problem of filtrational gas combustion wave stabilization in a porous cylindrical burner with different pore sizes and heat conductivities of porous carcass is numerically investigated. Simulation is carried out within the framework of the conventional one-dimensional diffusion-thermal model of filtrational gas combustion with allowance for radiative heat losses from the external surface of the burner. The data on influence of the carcass pore size and the thermal conductivity of porous material on the radiative efficiency is investigated.

1. Introduction

Development of thermal energy sources based on the gas combustion with controlled temperature and power characteristics is an actual problem in energy sector of economy. Combustion in porous media is one of the effective methods for burning gaseous fuels. Combustion here occurs inside the porous body. Heat from the combustion zone is transferred along the porous frame towards the gas flow and heats the mixture of initial reactants. In contrast to the open (unrestricted) flames, porous burners are characterized by the possibility of combustion of the lean mixtures, a broad range of adjusting, the higher specific capacities and low level of pollution. The porous body is heated by combustion products and emits the energy from the outer surface in IR range. Due to this effect, porous burners are used in devices of heating, drying, caking, and treatment substances [1–4]. The main characteristic of the radiating porous burner is the radiation efficiency η, which is defined as the ratio of the amount of radiated energy value to the total capacity of the burner. The radiative characteristics of porous burners are largely determined by the temperature of the outer surface of porous body which, in turn depends on the rate and kinetics of burning reactions, flame localization and the characteristics of the porous material. The cylindrical form of the burner allows uniform gas supplying and the flame stabilization inside the porous body. It allows effectively converting the energy of the fuel into the IR radiation [5]. The aim of this study is to determine the optimal porous body parameters which influence on the efficiency of the cylindrical burner. The study is focused on the average pore size and the thermal conductivity of the material of porous burner.

2. Governing equations. Boundary value problem statement

The porous burner is a hollow cylinder with an inner radius r_1 and an outer radius r_2. The space between r_1 and r_2 is filled by a porous medium. A premixed gas mixture is supplied into the interior of the cylinder.

Combustion occurs inside the porous body, and combustion products leave the cylindrical burner from its outer side.

Simulation is carried out within the framework of a two-temperature diffusive-thermal model [6], consisting of the thermal conductivity equations for the solid porous frame and the gas mixture, and diffusion equation for the deficient component of the gas mixture. The dimensionless equations of heat transfer over the gas and the solid and the equation for the fuel concentration have the form:

$$V_b(r)\frac{\partial G}{\partial r} + \frac{\partial G}{\partial t} = \frac{1}{r}\frac{\partial G}{\partial r} + \frac{\partial^2 G}{\partial r^2} + (1-\sigma_0)W(r,t) - \Omega_g(G-S),$$

$$\frac{\partial S}{\partial t} = k\left(\frac{1}{r}\frac{\partial S}{\partial r} + \frac{\partial^2 S}{\partial r^2}\right) + \Omega_s(G-S),$$

$$V_b(r)\frac{\partial C}{\partial r} + \frac{\partial C}{\partial t} = \frac{1}{Le}\left(\frac{1}{r}\frac{\partial C}{\partial r} + \frac{\partial^2 C}{\partial r^2}\right) + W(r,t),$$

$$W(r,t) = \frac{(1-\sigma_0)^2 N_a^2}{2Le}C\exp\left(N_a\left(1-\frac{1}{G}\right)\right), \quad d_s = \frac{(1-m)d_p}{m},$$

$$G = \frac{T_g}{T_b}, \quad S = \frac{T_s}{T_b}, \quad V_b(r) = \frac{r_1 V_0}{r U_b m}, \quad \sigma_0 = \frac{T_0}{T_b}, \quad k = \frac{\lambda_s c_{pg}\rho_g}{\lambda_g c_{ps}\rho_s}, \quad N_a = \frac{ER}{T_b},$$

$$Pe = \frac{\rho_g c_{pg} U_b d_p}{\lambda_g}, \quad \Omega_g = \frac{2Nu}{Pe^2}, \quad \Omega_s = \frac{d_p c_{pg}\rho_g \Omega_g}{d_s c_{ps}\rho_s}, \quad l_{th} = \frac{\lambda_g}{U_b \rho_g c_{pg}}.$$

(1)

Here $r = r/l_{th}$ is the dimensionless spatial coordinate measured in the units of the thermal thickness l_{th}, $t = (tU_b)/l_{th}$ is the dimensionless time, where U_b is the adiabatic speed of a planar laminar flame. The concentration of the deficient species of the mixture C is measured in the units of mass fraction of the fuel in the fresh mixture. The temperatures of the porous carcass S and the gas G are measured in the units of the adiabatic burning temperature T_b; $\sigma_0 = T0/Tb$ is the dimensionless initial temperature of the gas. $V_b(r)$ is the dimensionless velocity of the mixture that describes the change in the gas velocity in the cylindrical burner and the velocity dependency on radius is followed from the mass conservation equation in the approximation of a constant density of the gas. d_p is the average pore size, d_s is the mean space between the pores, R is the universal gas constant. Other constants of the system (1) are presented in the table 1.

The set of governing equations (1) is coupled with the following boundary conditions :

$$r = r_1 : \qquad G = \sigma_0, \quad S = \sigma_0, \quad C = 1;$$

$$r = r_2 : \qquad \frac{\partial G}{\partial r} = 0, \quad -\frac{\lambda_s}{l_{th}}\frac{\partial S}{\partial r} = \sigma_{sb}\mu T_b^3(S^4 - \sigma_0^4), \quad \frac{\partial C}{\partial r} = 0;$$

(2)

where μ is the carcass emissivity, σ_{sb} is the Stefan-Boltzmann constant. Radiative efficiency of the porous burner η is defined as ratio of radiative flux from outer burner surface to the flux of chemical energy incoming to burner with combustible gas mixture:

$$\eta = \frac{\mu\sigma_{sb}r_2 T_b^4(S(r_2)^4 - \sigma_0^4)}{\rho_g c_{pg} r_1 V_0(T_b - T_0)}.$$

(3)

3. Results
Calculations of the system (1)–(2) were carried out for the material constants presented on the table 1:

The simulations are conducted with use of Flex PDE program. The numerical solutions of (1)–(2) equations were conducted by two stages. At the first stage, the initial distributions of temperatures and

Table 1. Material constants.

| Symbol	Quantity	Value
r_1, l_{th}	inner radius of the burner	200
r_2, l_{th}	outer radius of the burner	600
T_0, K	ambient temperature	300
T_b, K	adiabatic burning temperature	1500
Le	Lewis number	0.9
Nu	Nusselt number	4
U_b, m/s	adiabaticspeedofaplanarlaminarflame	0.1
E, J	activation energy	120000
m	carcass porosity	0.7
μ	carcass emissivity	0.6
ρ_s, kg/m^3	carcass density	2650
ρ_g, kg/m^3	mixture density	1.2
λ_g, W/(K m)	mixture thermal conductivity	0.052
c_{pg}, J/(kg K)	mixture heat capacity	1100
c_{ps}, J/(kg K)	carcass heat capacity	900
d_p, mm	the average pore size	4

concentration are set by using adaptive grid with 100 knots as follow:

$$S = G = \begin{cases} \sigma_0, & r_1 \leq r < (r_1 + r_2)/2 \\ 1, & (r_1 + r_2)/2 \leq r < r_2 \end{cases} \quad ; \quad C = \begin{cases} 1, & r_1 \leq r < (r_1 + r_2)/2 \\ 0, & (r_1 + r_2)/2 \leq r < r_2 \end{cases} \tag{4}$$

At the next stage, the obtained solutions are used as initial conditions for simulations with grid having 800 knots. The accuracy of simulations is controlled by comparison of flame front positions r_f, obtained by simulations conducted with different nets. The difference in the flame positions r_f was less than 0.5%, when the number of knots was varied from 800 to 3200.

The dependencies of radiative efficiency and the temperature of the burner outer surface on the gas flow velocity are shown in figure 1 and figure 2. The calculated dependency in figure 1 shows existence of maximal efficiency attained at an optimal gas flow velocity. The existence of optimal gas velocity corresponding maximal efficiency is general tendency which is not influenced by changing of the mixture content, heat conductivity of porous matrix and other parameters so that it is important feature of cylindrical porous burners with filtrational gas combustion. The conclusion is in quite in line with previous experimental and theoretical results obtained in papers [5, 6]. The dependency of the external temperature of the burner on the gas velocity is shown in figure 2. Although the increase of gas velocity leads to the increase of the temperature and correspondingly increase the total radiative flux, the efficiency of the burner is attained at the moderate gas flow velocities because efficiency is inversely proportional to the gas velocity (see expression (3)). Figure 3 shows the temperature distributions of the gas and the solid calculated for the (A), (B) and (C) points shown in figure 1 and figure 2, correspondingly. The case (B) corresponds to the maximal efficiency, when the optimal balance between radiative heat flux and the flux of chemical energy into burner is reached.

Simulations reveal other parameters which allow further increasing of the burner efficiency. In
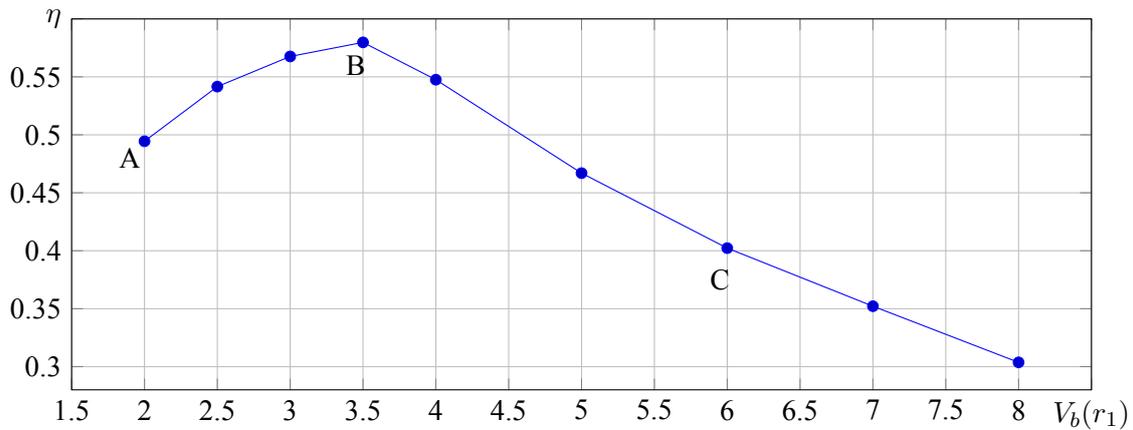
Figure 1. Dependence of the radiative efficiency on a porous burner on the gas flow velocity, $\lambda_s = 4$ W/(K m).
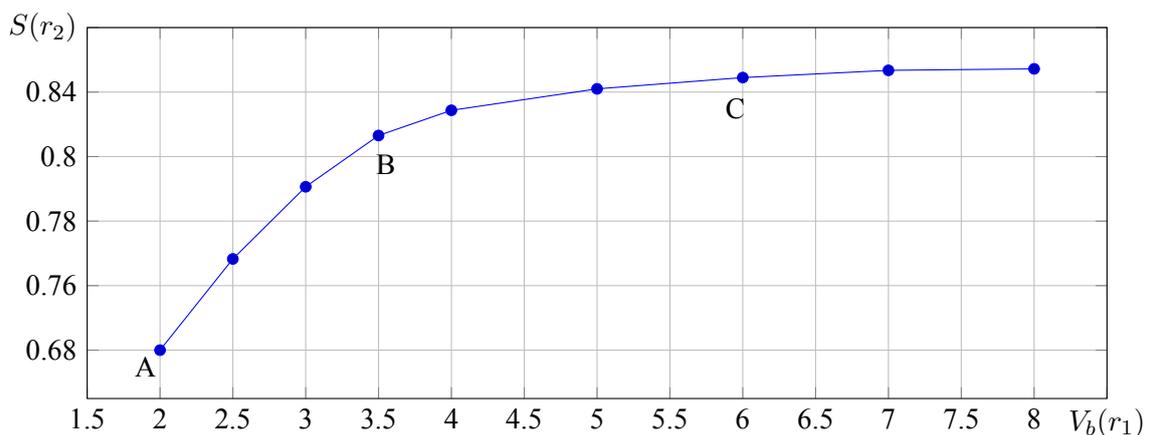

Figure 2. Dependence of the external temperature of the porous burner on the gas flow velocity, $\lambda_s = 4$ W/(Km).

particular, it was found that there is an optimal pore size at which the greatest value of η is reached. In the range of 1 mm<d_p<8 mm , the optimal size is d_p=4 mm, at which efficiency is increased by 10-15% compared to the values calculated for other pore sizes.

In addition, the influence of the thermal conductivity of the porous carcass on the value of the maximum radiation efficiency was investigated. Figure 4 shows dependencies of efficiency η on the gas velocity evaluated for different values of solid matrix thermal conductivity. As it follows from the graph, the maximum radiation efficiency is achieved when choosing a material with a lower thermal conductivity. With decreasing the heat conductivity the point of maximal efficiency shifts to the lower gas velocity values. The point of flame stabilization in this case is approached to the inlet of the burner.

At the same time, the experimental data indicate that the flame front due to the porous structure of the carcass surface should stabilize at some distance from the burner inlet. Therefore, the possibility of obtaining maximum efficiency is limited by the minimum value of the mixture velocity, below which the flame can not be stabilized near the inner surface of the burner.
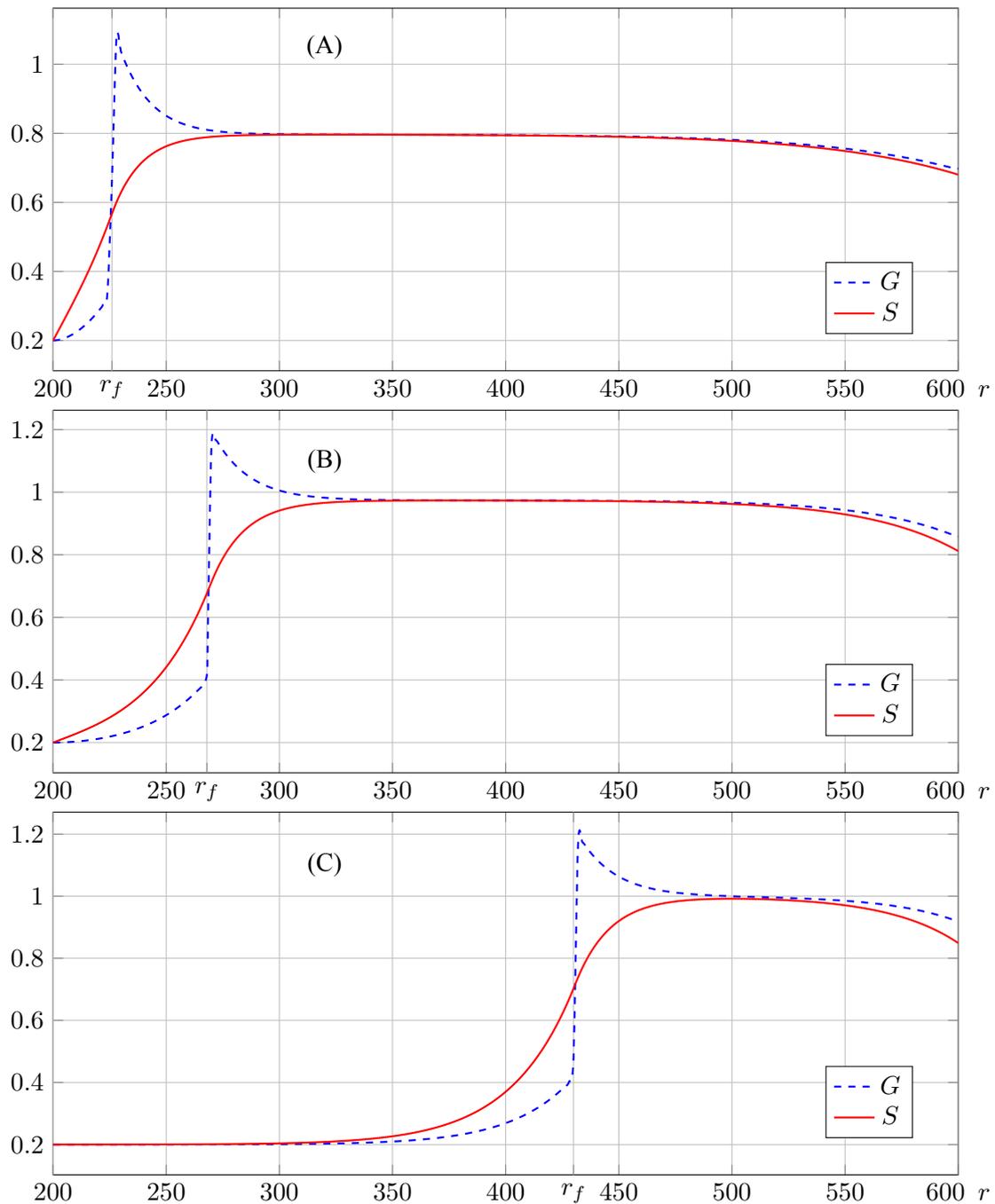
Figure 3. Temperature at the different gas flow velocity.

4. Conclusion

The influence of the pore size and thermal conductivity on the radiation efficiency of the porous burner has been studied within the framework of the diffusion-thermal model. It is found that the maximum efficiency of the burner is achieved at some optimum pore size. It is also concluded that the burner with lower thermal conductivity has a higher efficiency. At low thermal conductivity of the porous matrix the flame front is located near the inlet of the burner. This effect can impose limitation on the minimal value
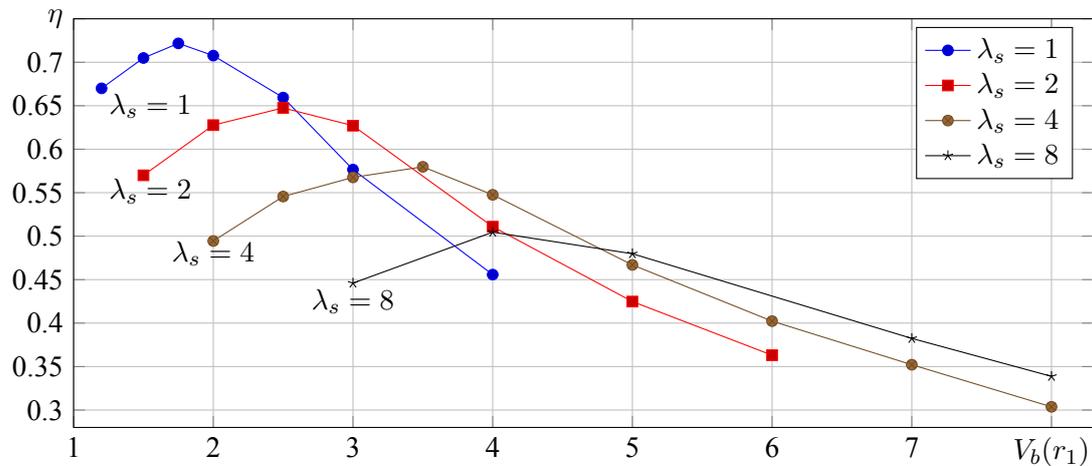
Figure 4. Radiative efficiency at the different values of thermal conductivity λ_s, W/(K m).

of heat conductivity because of flame quenching caused by discrete structure of porous matrix. This is open problem that have to be considered in future research. In the manufacture of burners from materials with low thermal conductivity, it is necessary to take into account the limitations on the possibility of establishing a flame front on the inner surface due to the porous structure of the framework.

Acknowledgments

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