Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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Abstract. The filtration gas combustion in a porous tube with injection of a combustible mixture through the end surface of a porous cylindrical tube is theoretically studied. The simulation of the filtration gas combustion was carried out in the framework of the two-temperature thermal-diffusion model. Numerical modeling allowed to estimate the range of gas flow rates at which a stable combustion regime is observed, to find the temperature distribution in the gas and the porous body, and to evaluate the radiation fluxes inside the reactor.

1. Introduction

Development of thermal energy sources based on the gas combustion with controlled temperature and power characteristics is an actual problem in power engineering. 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. 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 [1, 4].

The theoretical research of the new type of a porous burner with axial gas flow is presented in the paper. The filtration combustion occurs in a porous tube with injection of a combustible mixture through the end surface. The samples under treatment can be placed inside a porous tube, the side surface of which is covered with quartz shells transparent for infrared radiation emitted by porous carcass. The outer surface of porous reactor is heat insulated. Radiation from the inner surface of the porous solid phase allows heating materials under treatment to high temperatures. This scheme of filtration gas combustion can be used to create chemical reactors for non-contact heating of various materials.

The aim of this study is to carry out the numerical modeling of filtrational combustion in a porous pipe: to find the temperature distribution in the gas and the porous body, the radiation fluxes inside the burner, to investigate the influence of heat loss and the geometric characteristics of the burner on the flame stabilization.

2. Governing equations. Boundary value problem statement

The porous burner is a pipe of length h 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. Fresh gas mixture is injected through the end surface. Combustion occurs inside the porous body and combustion products leave the cylindrical burner from its other end surface. Scheme of the burner is presented on the Fig. 1.

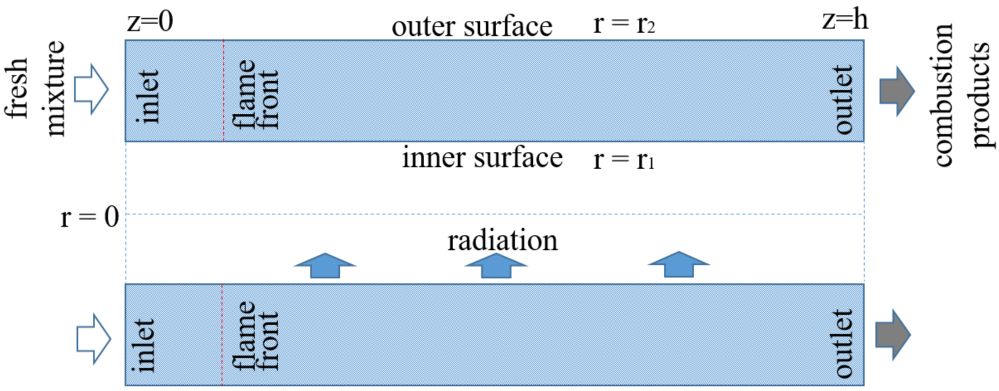

Figure 1. Scheme of the porous burner.

Simulation was conducted within the framework of a two-temperature diffusive-thermal model [2, 5, 6], consisting of the heat conduction equations for the gas and solid phases and diffusion equation for the deficient component of the mixture:

$$\begin{aligned}
\rho_g c_{pg}\left(\frac{\partial T_g}{\partial t}+u_z\frac{\partial T_g}{\partial z}\right) &= \lambda_g\left(\frac{1}{r}\frac{\partial T_g}{\partial r}+\frac{\partial^2 T_g}{\partial r^2}+\frac{\partial^2 T_g}{\partial z^2}\right)+Q\cdot W(Y,T_g)-\frac{2\alpha}{d_p}(T_g-T_s)\\
\rho_s c_{ps}\frac{\partial T_s}{\partial t} &= \lambda_s\left(\frac{1}{r}\frac{\partial T_s}{\partial r}+\frac{\partial^2 T_s}{\partial r^2}+\frac{\partial^2 T_s}{\partial z^2}\right)+\frac{2\alpha}{d_s}(T_g-T_s)\\
\frac{\partial Y}{\partial t}+u_z\frac{\partial Y}{\partial z} &= D_c\left(\frac{1}{r}\frac{\partial Y}{\partial r}+\frac{\partial^2 Y}{\partial r^2}+\frac{\partial^2 Y}{\partial z^2}\right)-W(Y,T_g)\\
W(Y,T_g)=A\cdot Y\exp\left(-\frac{N_a}{T_gR}\right); &\qquad \alpha=\frac{Nu}{d_p}; \qquad d_s=\frac{d_p(1-m)}{m}
\end{aligned} \tag{1}$$

Here T_g and T_s are temperatures of gas and porous media, Y - fuel mass fraction, d_p is the average pore size, d_s is the mean space between the pores, R is the universal gas constant. Other parameters of the equations (1) are presented in the Table 1.

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

$$\begin{aligned}
r=r_1: \quad -\lambda_s\frac{\partial T_s}{\partial r} &= \sigma_{sb}(T_s^4-T_{ref}^4), \quad \frac{\partial T_g}{\partial r}=0, \quad \frac{\partial Y}{\partial r}=0;\\
r=r_2: \quad \frac{\partial T_s}{\partial r} &= 0, \quad \frac{\partial T_g}{\partial r}=0, \quad \frac{\partial Y}{\partial r}=0;\\
z=0: \quad \frac{\partial T_s}{\partial r} &= 0, \quad T=T_0, \quad Y=T_0;\\
z=h: \quad \frac{\partial T_s}{\partial r} &= 0, \quad \frac{\partial T_g}{\partial r}=0, \quad \frac{\partial Y}{\partial r}=0.
\end{aligned} \tag{2}$$

Here σ_{sb} is the Stefan-Boltzmann constant, T_{ref} - internal temperature, which sets the level of radiation heat flux. Value of T_{ref} varies to determine the effect of heat losses on the temperature distribution in the porous media. We assume that the flow velocity field is uniform and it has axial direction:

$$u_z=const, \quad u_r=0 \tag{3}$$

3. Results

Calculations of the system (1) – (2) were carried out for the material constants presented on the Table 1:

Table 1. Simulation parameters

Symbol	Quantity	Value
h	length of the pipe (m)	0.16
r_2	outer radius of the pipe (m)	0.06
T_0	ambient temperature (K)	300
D_c	diffusivity (m^2/s)	$3.5 \cdot 10^{-5}$
Nu	Nusselt number	4
E_a	activation energy (J)	$125 \cdot 10^3$
m	carcass porosity	0.5
ρ_s	carcass density (kg/m^3)	2650
ρ_g,	mixture density (kg/m^3)	1.2
λ_s	carcass thermal conductivity (W/(K m))	20
λ_g	mixture thermal conductivity (W/(K m))	0.052
c_{pg}	mixture heat capacity J/(kg K)	1200
c_{ps}	carcass heat capacity (J/(kg K))	700
d_p	the average pore size (m)	0.001
Q	heat release (J/kg)	$35 \cdot 10^6$
A	pre-exponent (1/s)	10^9
Y_0	inlet fuel mass fraction	0.048

Simulation was performed by means of the finite element method. The result of the calculations is a sequence of stationary solutions of the system (1). At the first stage the problem under adiabatic conditions was solved. Due to the absence of heat loss on the inner surface, the formulation of the problem is equivalent to the one-dimensional case in which all solutions depend on z coordinate. These solutions were used as the initial conditions for two-dimensional formulation of the problem taking into account radiation on the inner surface. Solutions allowed to obtain the flow rate range at which stationary combustion mode occurs. It was shown that values of velocities have the range $1.2 < u_z < 2.8\ m/s$. The upper speed limit decreases to the value $u_z = 2.4\ m/s$ under maximum radiation flux on the inner surface ($T_{ref} = T_0$). Value $u_z = 2.4\ m/s$ was used as optimal flow velocity for further calculations.

Fig. 2 demonstrates stationary temperature distribution for gas and solid phases under condition $T_{ref} = T_0$. It was shown, that combustion occurs under super-adiabatic temperature. Maximum level of T_g corresponds to a flame front location. Calculations were carried out for the set of values $T_{ref} = 300, 600, 900, 1200, 1500, 1990\ K$. Simulation demonstrates that the flame front location weakly depends on different levels of T_{ref}. Maximum heat flux density on the inner surface takes place at $T_{ref} = 300\ K$. Temperature distribution on the inner surface for different values of inner radius r_1 is shown on the Fig. 3.

Difference between maximum values of T_s reaches about 5 percents. It means that using of small domain with high temperature of porous media is more efficiently for thin pipe. Ideal thermal insulation of outer surface provides high temperature distribution for thin-walled pipe with maximum radiation heat flux on the inner surface. The heat flux distribution is presented on the Fig. 4. Energy flux on the inner

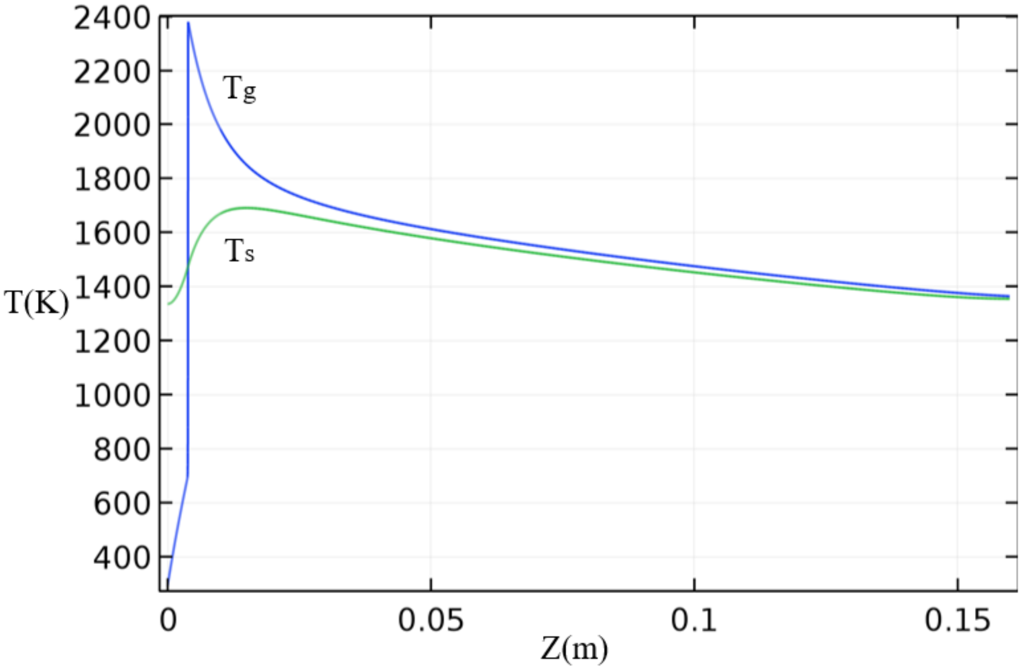

Figure 2. Temperature distribution of gas and solid body on the inner surface, $r_1 = 0.04\ m$, $T_{ref} = 300\ K$, $u_z = 2.4\ m/s$.

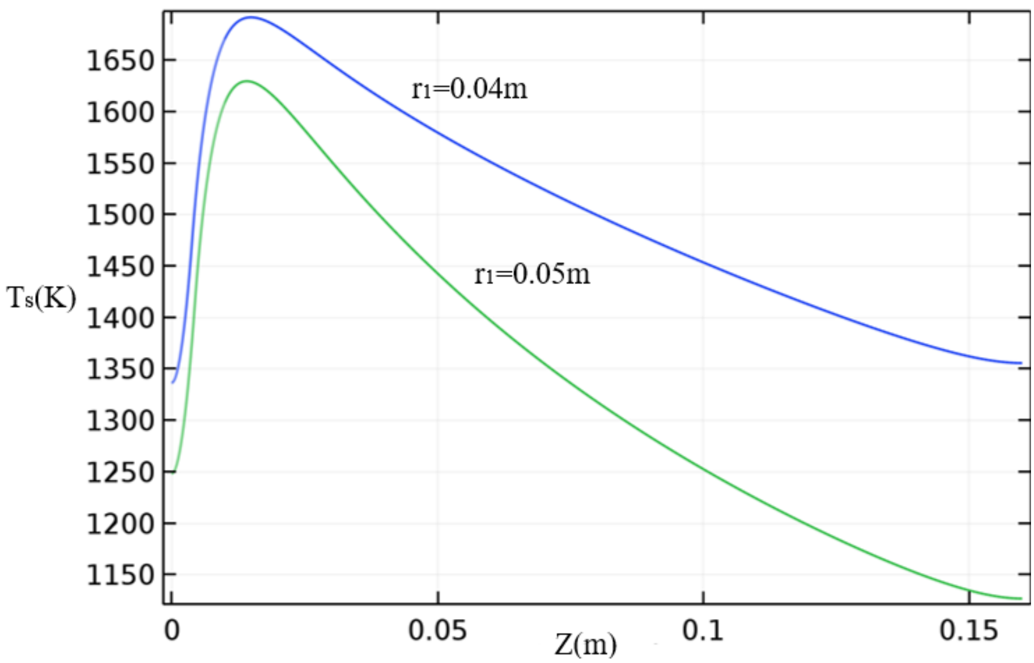

Figure 3. Temperature distribution on the inner surface for different radius r_1, $T_{ref} = 300\ K$, $u_z = 2.4\ m/s$.

surface was calculated. It was found that the energy flux for $r = 0.04$ is more than for $r = 0.05$ in the area $0 < z < h$. But we obtained the higher energy flux for a thin-walled pipe on the area $0 < z < 0.3h$.

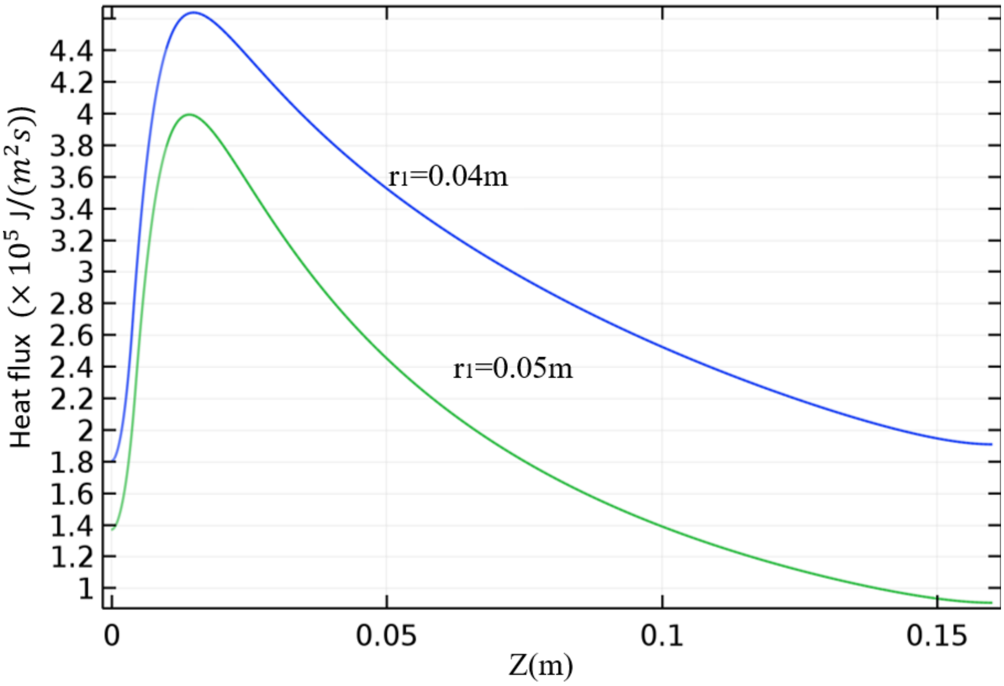

Figure 4. Axial temperature distribution of solid body on the inner surface for different radius r_1, $T_{ref} = 300\,K$, $u_z = 2.4\,m/s$.

4. Conclusion

The filtration gas combustion in a porous tube with injection of a combustible mixture through the end surface of a porous cylindrical tube is theoretically studied. The simulation of the filtration gas combustion was carried out in the framework of the two-temperature thermal-diffusion model. The influence of gas glow, heat loss, and the geometric characteristics of the reactor on the flame stabilization were studied. It was shown, that steady combustion can take place with maximum radiation loss in the inner surface. High levels of temperature distribution allow us to conclude that a burner of this type is a reactor of high efficiency. Further research is related to studying the effect of external heat losses on the temperature and heat flux formation.

Acknowledgments

The work was supported by the Russian Foundation for Basic Research (project No. №18-48-700037 r_a).

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