On Effect of Gravity Field and Pressure Differences on Heterogeneous Combustion in Porous Media

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1 Introduction

Combustion in porous media is quite common in nature. From the point of view of mechanics porous media include soil, peat, rock, debris of destroyed buildings and so on. Thus, the centers of combustion in porous media can arise, for example, during the explosions at atomic and industrial facilities, in underground explosions and fires in places of the extraction of natural resources. There are a lot of publications devoted to both solid porous media combustion and gas combustion in the filtration mode, among which we can note the following [1-7]. One application of the theory of filtration combustion is the study of spontaneous combustion of solid waste dumps (landfills). On researching such objects we deal with the heterogeneous combustion in porous media under free convection. When combustion of solid waste dumps is studied the gas dynamics in such objects isn't investigated in detail as a rule. In [8] the one-dimensional unsteady processes of heterogeneous combustion in porous object under free convection in the gravity field have been considered. Two regimes of combustion wave propagation have been revealed – wave movement up the object (cocurrent burning) and down the object (countercurrent burning) – which differ significantly from each other by the degree of burnout of solid combustible material, the temperature in the combustion zone and the speed of combustion wave propagation. This work is devoted to the numerical investigation of the effect of gravity field and pressure difference at the boundaries of the porous object on the appearance of stable heterogeneous combustion waves in object under free convection. To this end, the one-dimensional unsteady combustion regimes have been compared in the following porous objects: the vertical (in which there are effect of the gravity field and the pressure difference on object borders), horizontal (in which there aren't effect of the gravity field and the pressure difference on object borders), the object with gravity field and without the pressure difference on object borders, the object with the pressure difference on object borders and without gravity field.

2 Physical and mathematical models

Consider a homogeneous motionless porous object with a height H, which is bounded of impermeable non-heat-conducting side walls and opened on two opposite sides. The heat-evolutional process in solid phase results from the process of chemical reaction. The cold gas may flow into the open walls of the porous object; the gas may flow through porous medium and flow out. Suppose that a solid porous substance consist of combustible and inert components, and at the same time the solid combustible material transforms into a gas in the reaction with gaseous oxidizer, so we have the following expression:

$$\text{Solid Fuel} + (\mu)\text{Oxidizer} \rightarrow (1+\mu)\text{Gaseous Product} \tag{1}$$

where μ is the mass stoichiometric coefficient for oxidizer.

The model is based on the assumption of interacting interpenetrating continua [9] using the classical approaches of the theory of filtration combustion [1-3]. In the energy equation for the solid components not only heat generation is taken into account but also the thermal conductivity and the intensity of the interphase heat exchange which is assumed to be proportional to the difference of the phase temperatures at the considered point of the medium. In the energy equation for gas the thermal conductivity is not considered because of its smallness, and it is assumed that homogeneous reactions do not occur. To describe the dynamics of gas the conservation of momentum equation for porous media is used, which is more correct than the classical Darcy's equation. The solid phase is assumed to be fixed, so the equation of motion for it degenerates. In model the changes in volume and weight of the phases in their interaction are taken into account, the diffusion of the oxidizer as well as the validity of the perfect gas equation take place. Combustion processes are described by one-step chemical reaction of first order with respect to both arguments. As it is shown in [10] the allowance for the temperature dependence of gas viscosity in its motion through a porous heat-evolutional medium would change the solution both quantitatively and qualitatively, we will assume that the dynamical viscosity of gas is temperature dependent by Sutherland's formula. Thus the system of equations modeling the time-dependent gas flow in a porous object with zones of heterogeneous combustion is the following:

$$\begin{gathered}
(\rho_{cf} c_{cf} + \rho_{ci} c_{ci}) \frac{\partial T_c}{\partial t} = -\alpha (T_c - T_g) + Q \rho_{cf0} W + (1-a_g) \lambda_c \Delta T_c , \\
\rho_g c_{gp} \left(\frac{\partial T_g}{\partial t} + (\mathbf{v}_g \cdot \nabla) T_g \right) = \alpha (T_c - T_g), \\
\rho_g (1 + \chi (1-a_g)) \left(\frac{\partial \mathbf{v}_g}{\partial t} + (\mathbf{v}_g \cdot \nabla) \mathbf{v}_g \right) = -a_g \nabla p + \rho_g \mathbf{g} - a_g^2 \frac{\mu_1}{k_1} \mathbf{v}_g - \rho_{cf0} W \mathbf{v}_g , \\
\frac{\partial \rho_g}{\partial t} + \nabla \cdot (\rho_g \mathbf{v}_g) = \rho_{cf0} W , \qquad p = \rho_g R T_g / (a_g \cdot M), \\
\rho_g \left(\frac{\partial C}{\partial t} + (\mathbf{v}_g \cdot \nabla) C \right) = \nabla \cdot (\rho_g D_g \nabla C) - \mu \rho_{cf0} W - \rho_{cf0} W C , \\
D_g = D_{g0} (T_g / 273)^b , \qquad W = (1-\eta) C k \exp(-E/(R T_c)), \\
\frac{\partial \eta}{\partial t} = W , \qquad \rho_{cf} = (1-\eta) \rho_{cf0} , \qquad a_g = a_{g0} + a_{cf0} \eta , \qquad \mu_1 = c_{s1} \frac{T_g^{1.5}}{c_{s2} + T_g} .
\end{gathered} \tag{2}$$

where a is the volume concentration, b is the exponent in the expression for the diffusion coefficient, C is the mass concentration of oxidizer, c is the specific heat, c_{s1} and c_{s2} are the constants in Sutherland's formula, D_g is the diffusion coefficient of gas, E is the activation energy, $\boldsymbol{g}$ is the gravity acceleration, k is the pre-exponential factor in the expression for the rate of reaction, k_1 is the permeability coefficient, M is the molar mass of gas, p is the gas pressure, Q is the heat of reaction, R is the universal gas constant, t is the time, T is the temperature, $\mathbf{v}_g$ is the gas velocity, W is the rate of the chemical reaction, α is the constant determining the interphase heat transfer intensity, η is the degree of conversion of the combustible component of the solid medium, λ is the thermal conductivity, μ_1 is the dynamic viscosity of the gas, ρ is the effective density, χ is the coefficient, taking into account the inertial interaction of the phases in their relative motion [9]; subscripts: "0" denotes the initial moment, "*c*" denotes the condensed phase (solid medium), "*i*" denotes the inert component, "*f*" denotes the combustible component, "*g*" denotes the gas, "*p*" denotes values at constant pressure.

In this paper we investigate one-dimensional regimes of heterogeneous combustion in the following porous objects: the object with gravity field and without the pressure difference at the boundaries of the object, the object with the pressure difference at the object boundaries and without gravity field. It is assumed that pressure difference at the boundaries of the object is equal to the pressure difference at the boundaries of the vertical porous object, i.e. the natural pressure difference in the atmosphere at a height equal to the length of the porous object. Subsequently, these results are compared with the heterogeneous combustion in the vertical object (in which there are effect of the gravity field and the pressure difference on object borders) [8] and the horizontal object (in which there aren't effect of the gravity field and the pressure difference on object borders).

So we assume than at the inlet of the porous object (at the open boundary where gas flows into the porous object) gas pressure, gas temperature and mass concentration for the oxidizer are known. At the outlet (the open boundary where gas flows out the porous object) the pressure is known. The conditions of heat exchange at the inlet and outlet from the porous object and on the bounding impermeable walls are also known. A distinctive feature of the considered model is that the flow rate and gas velocity at the inlet to the porous object are unknown and have to be found from the solution of the problem. Thus the boundary conditions for (2) are as follows:

$$
\begin{gathered}
p\big|_{x\in G_1} = p_0 \text{ or } p_0(x), \quad \lambda\, \partial T_c/\partial n\big|_{x\in G_1} = \beta\big(T_{g0} - T_c\big|_{x\in G_1}\big), \\
T_g\big|_{x\in G_1} = T_{g0} \text{ and } C\big|_{x\in G_1} = C_0, \text{ if } \mathbf{v}_\mathrm{g}\big|_{x\in G_1}\cdot \mathbf{n}\big|_{x\in G_1} \le 0, \\
\partial T_g/\partial n\big|_{x\in G_1} = 0 \text{ and } \partial C/\partial n\big|_{x\in G_1} = 0, \text{ if } \mathbf{v}_\mathrm{g}\big|_{x\in G_1}\cdot \mathbf{n}\big|_{x\in G_1} > 0, \\
\partial T_c/\partial n\big|_{x\in G_2} = 0, \quad \partial T_g/\partial n\big|_{x\in G_2} = 0, \quad \mathbf{v}_\mathrm{g}\big|_{x\in G_2}\cdot \mathbf{n}\big|_{x\in G_2} = 0.
\end{gathered}
\tag{3}
$$

where G_1 is object boundary opened to the atmosphere, G_2 is impermeable boundary of object, $\boldsymbol{n}$ is outward vector directed normally to G_1 or to G_2, β is heat removal coefficient.

For the investigation of unsteady gas flow in a porous object with zones of heterogeneous combustion an original numerical method has been developed, which is based on a combination of explicit and implicit finite-difference schemes [8]. This method is the development of earlier proposed numerical algorithm for the computation of the gas flows through porous objects with heat sources when gas pressure at object boundaries is known [10-13]. The energy equations, momentum conservation equation and equation for oxidizer concentration are transformed into the explicit finite difference equations. The gas temperature, solid phase temperature, gas velocity and oxidizer concentration are determined from these equations. The continuity equation is transformed into the implicit finite difference equation. From this equation taking into account the perfect gas equation of state the gas pressure is determined using Thomas algorithm [14]. The effective gas density and the remaining unknown quantities are determined trivially from the perfect gas equation of state and other closure equations.

3 Numerical Results

Suppose that prior to the start time the gas flow in the object is absent and its temperature is equal to ambient temperature T_{g0}. At initial time in the place of ignition, which is located either on the object border or at its center, the temperature of the solid phase reaches a value T_{c0} equal to or exceeding the self-ignition temperature T_{kr}, and burning is started. We use the following parameter values:

$H = 10\,\mathrm{m}$, $\rho_{cf0} = 1.1\cdot 10^2\,\mathrm{kg/m^3}$, $\rho_{ci} = 6.6\cdot 10^2\,\mathrm{kg/m^3}$, $c_{cf} = 1.84\cdot 10^3\,\mathrm{J/(kg\,K)}$,

$c_{ci} = 1.84\cdot 10^3\,\mathrm{J/(kg\,K)}$, $\alpha = 10^3\,\mathrm{J/(m^3\,K\,s)}$, $c_{gp} = 10^3\,\mathrm{J/(kg\,K)}$, $\lambda_c = 1.2\,\mathrm{J/(m\,K\,s)}$,

$c_{s1} = 1.458\cdot 10^{-6}\,\mathrm{kg/(m\,s\,K^{1/2})}$, $c_{s2} = 110.4\,\mathrm{K}$, $k_1 = 10^{-8}\,\mathrm{m^2}$, $\beta = 10\,\mathrm{J/(m^2\,K\,s)}$, $\chi = 0.5$,

$g = 9.8\,\mathrm{m/s^2}$ or $0\,\mathrm{m/s^2}$, $R = 8.31441\,\mathrm{J/(mole\,K)}$, $M = 2.993\cdot 10^{-2}\,\mathrm{kg/mole}$, $Q = 8\cdot 10^6\,\mathrm{J/kg}$,

$k = 3.16\cdot 10^7\,\mathrm{1/s}$ [15], $E = 110\cdot 10^3\,\mathrm{J/mole}$ [15], $D_{g0} = 1.82\cdot 10^{-5}\,\mathrm{m^2/s}$, $b = 1.724$,

$\mu = 2.667$, $a_{g0} = 0.3$, $a_{cf0} = 0.1$, $T_{g0} = 300\,\mathrm{K}$, $C_0 = 0.23$, $p_0 = 10^5\,\mathrm{Pa}$.

We also suppose that exothermic reactions can occur at any temperature.

At first we consider the case when the ignition is on the bottom or on the left border of the object. In the porous object with gravity field and without the pressure difference at object boundaries the countercurrent combustion wave can appear. The wave moves up, burning solid combustible substance incompletely, than it is reflected from object boundary and moves down with reburning completely the remaining solid combustible substance. In the object with the pressure difference at object boundaries and without gravity field the cocurrent combustion wave can appear and move down, burning solid combustible substance completely. This fact is clearly demonstrated in Fig. 1, which shows the distribution of the solid medium temperature in the porous object at different times when the width of ignition zone L = 0.4 m and ignition temperature at the initial time T_{c0} = 750 K. In horizontal porous object (in which there aren't effect of the gravity field and the pressure difference on object borders) there is no long-lived combustion wave in this case. In vertical porous object (in which there are effect of the gravity field and the pressure difference on object borders) the cocurrent combustion wave can appear in this case but the velocity of combustion wave is much lower than in the case without gravity field. So the gravity field and the pressure difference at object boundaries lead to the opposite effects. In the real vertical porous object the pressure difference at object boundaries defeats the effect of gravity field, but the gravity force leads to reducing the velocity of combustion wave.

When the ignition zone is at the top or on the right border of the object we can see that in the porous object with gravity field and without the pressure difference at object boundaries the cocurrent combustion wave can occur, but in the porous object with the pressure difference at object boundaries and without gravity field the countercurrent combustion wave can occur, as in the case of a vertical porous object, but with a higher speed of spread (Fig. 2). When the ignition zone is in the central part of the object the countercurrent combustion wave can occur both in the porous object with gravity field and without the pressure difference at object boundaries, and in the object with the pressure difference at object boundaries and without gravity field (Fig. 3). It should be noted that countercurrent wave does not occur immediately, first cocurrent wave occur, which soon turns around and becomes a countercurrent wave. Pressure difference at object boundaries leads to the spread of the wave in the same direction as in the real vertical porous object. So we can again see that the gravity field and the pressure difference at object boundaries lead to the opposite effects; in the real vertical porous object the pressure difference at object boundaries defeats the effect of gravity field.

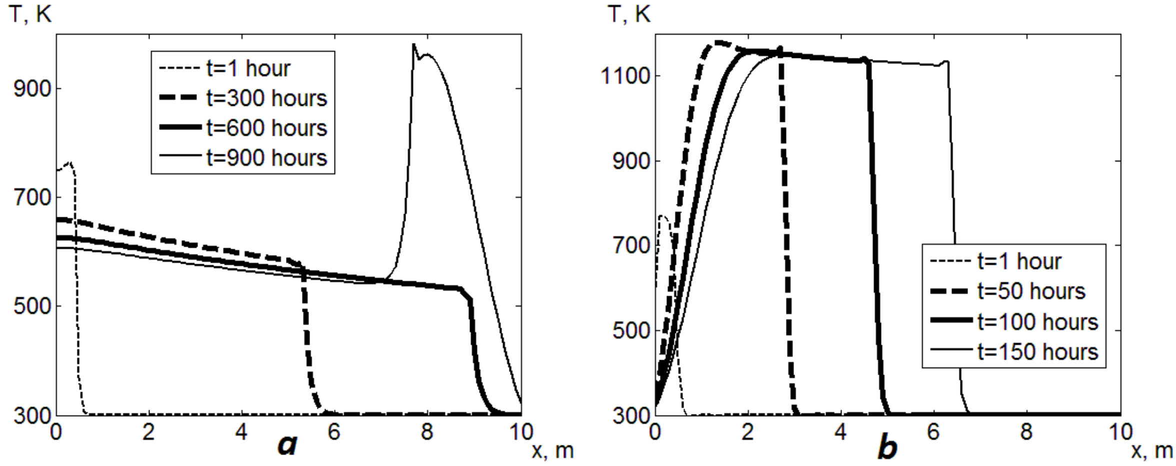

Figure 1. Distribution of the solid medium temperature in the porous object with gravity field and without the pressure difference at object boundaries (a), in the object with the pressure difference at object boundaries and without gravity field (b)

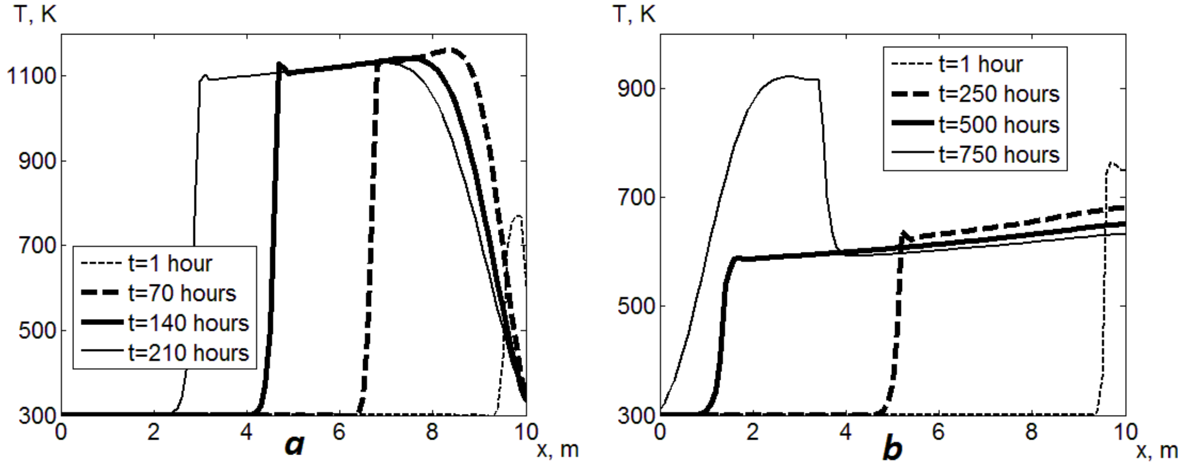

Figure 2. Distribution of the solid medium temperature in the porous object with gravity field and without the pressure difference at object boundaries (a), in the object with the pressure difference at object boundaries and without gravity field (b)

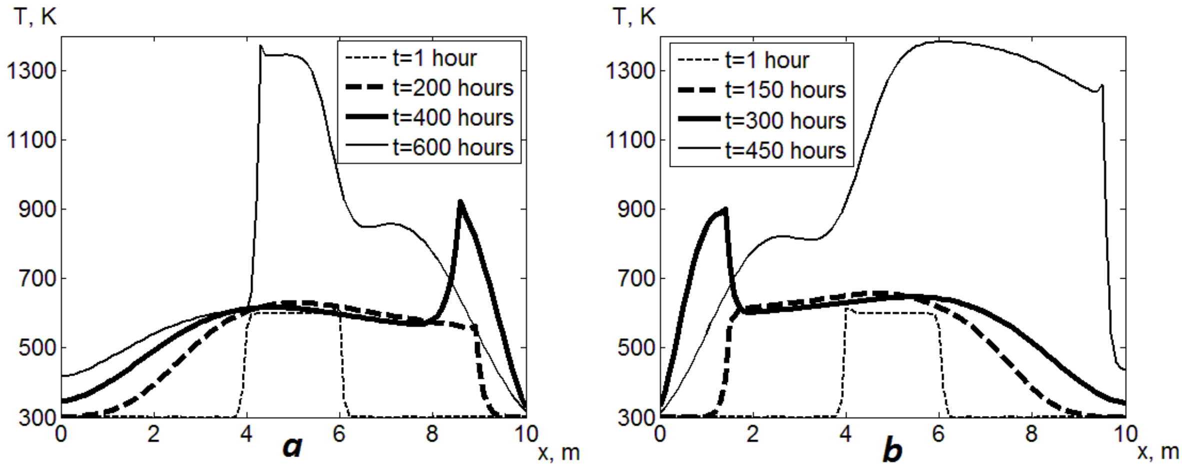

Figure 3. Distribution of the solid medium temperature in the porous object with gravity field and without the pressure difference at object boundaries (a), in the object with the pressure difference at object boundaries and without gravity field (b)

4 Conclusions

The effect of gravity field and pressure difference at the boundaries of the porous object on the appearance of stable heterogeneous combustion waves in object under free convection has been investigated. It is revealed that the gravity field and the pressure difference at object boundaries lead to the opposite effects. In the real vertical porous object the pressure difference at object boundaries defeats the effect of gravity, but the gravity force leads to reducing the velocity of combustion wave.

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References

[1] Aldushin AP, Merzhanov AG in: Matros YS (Ed.) (1988) Heat Wave Propagation in Heterogeneous Media, Nauka Publishers: 9 (ISBN 5-02-028726-1) (in Russian).

[2] Aldushin AP, Matkowsky BJ, Schult DA. (1997). Upward buoyant filtration combustion. J. Eng. Math. 31: 205.

[3] Aldushin AP, Rumanov IE, Matkowsky BJ. (1999). Maximal Energy Accumulation in a Superadiabatic Filtration Combustion Wave. Combust. Flame. 118: 76.

[4] Babkin VS, Korzhavin AA, Bunev VA. (1991). Propagation of premixed gaseous explosion flames in porous media. Combust. Flame. 87: 182.

[5] Dobrego KV, Zhdanok SA. (2002). Physics of Filtration Gas Combustion. Lykov Institute of Heat and Mass Transfer (ISBN 985-6456-29-0) (in Russian).

[6] Minaev SS, Potytnyakov SI, Babkin VS. (1994). Combustion wave instability in the filtration combustion of gases. Combust. Expl. Shock Waves. 30: 306.

[7] Salgansky EA, Kislov VM, Glazov SV, Zholudev AF, Manelis GB. (2008). Filtration combustion of a carbon-inert material system in the regime with superadiabatic heating. Combust. Expl. Shock Waves. 44: 273.

[8] Lutsenko NA. (2013). Modeling of heterogeneous combustion in porous media under free convection. Proc. Combust. Inst. 34: 2289.

[9] Nigmatulin RI. (1978). Principles of the mechanics of heterogeneous media. Nauka Publishers (in Russian).

[10] Levin VA, Lutsenko NA. (2006). Gas flow through a porous heat-releasing medium with allowance for the temperature dependence of gas viscosity. J. Eng. Phys. Thermophys. 79: 33.

[11] Levin VA, Lutsenko NA. (2008). Gas motion through porous objects with nonuniform local distribution of heat-release sources. Thermophys. Aeromech. 15: 381.

[12] Levin VA, Lutsenko NA. (2010). Time-dependent gas flows through axisymmetrical porous heat-evolutional bodies. Math. Models Comput. Simul. 2: 635.

[13] Levin VA, Lutsenko NA. (2011). Modeling unsteady two-dimensional gas flows in self-heating solid waste dumps. Fluid Dyn. 46: 826.

[14] Tannehill JC, Anderson DA, Pletcher RH. (1997). Computational fluid mechanics and heat transfer, 2hd ed. Taylor&Francis (ISBN 1-56032-046-X)

[15] Sørum L, Grønli MG, Hustad JE. (2001). Pyrolysis characteristics and kinetics of municipal solid wastes. Fuel. 80: 1217.