Modeling and Investigation of the Effect of Mass Transfer in Capillary-porous Bodies

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Abstract
A set of issues related to the occurrence of physical processes in the formation of the necessary technological parameters for the passage of physico-chemical processes is considered. The effect of anomalous diffusion is shown. A mathematical model, methodology and the result of a numerical study of the heat and humidity and air state of a capillary-porous body are also presented.

Using the example of building microclimate systems, the ways of the most complete realization of the technical and economic advantages of materials are shown. Using the example of burner devices, the ways of accounting and using them for the most efficient economic modes of operation are shown.

Keywords: Modeling, Energy System, Heat and Mass Transfer

1. Introduction
The development of the economy of any country depends to a great extent on the availability of energy. Excess energy provides industrial growth, and with increased production and higher living standards, energy consumption increases.

Renewable energy resources are insufficient to cover the rapidly growing needs of mankind, as they are characterized by extremely low intensity of incoming energy and are currently economically unprofitable in most areas of the Earth. Therefore, efficient fuel combustion is of high importance.

About 90% of all energy produced in the world is produced by burning hydrocarbon fuels and, according to forecasts of the Energy Information Administration (USA), this share will not fall below 80% until 2040, while global energy consumption will grow by 56%. This is related to such global problems of modern civilization as the depletion of non-renewable energy resources, environmental pollution and global warming.

For environmentally friendly energy production from renewable energy sources, reliable and highly accurate forecasting of related processes is necessary as a basis for developing optimal technical and technological solutions.

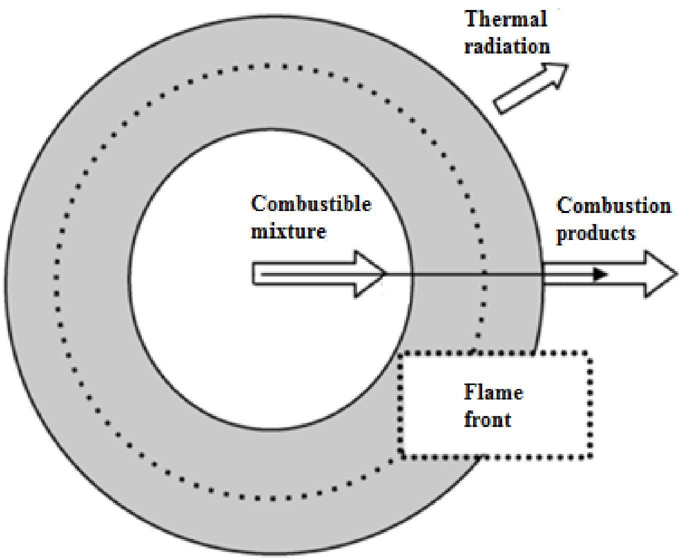
2. Technical Solutions

Combustion of gases in a porous medium has a number of advantages over open combustion of gases, since it allows the use of extremely lean mixtures and obtaining superadiabatic temperatures of combustion products. These effects arise as a result of heat transfer from combustion products to the fresh mixture due to thermal conductivity of the solid frame. A large radiative heat flux is another important feature of gas combustion in a porous medium. The latter circumstance makes it possible to use this process to create effective sources of thermal radiation.

Most models of filtration combustion of gases consider an unbounded porous medium and, as a rule, do not address the issues of flame stabilization in regions close to the boundary of a porous body. At the same time, for practical applications related to the creation of infrared sources of thermal radiation, understanding the mechanisms of flame stabilization and assessing the radiation fluxes from the porous body in which combustion occurs is an important task.

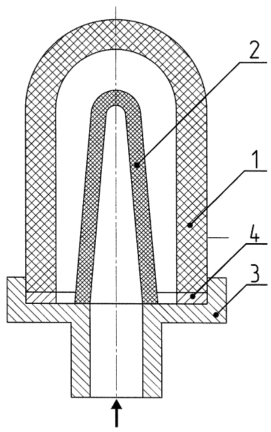
At the Institute of Theoretical and Applied Mechanics named after S.A. Khristianovich SB RAS, Novosibirsk, a model of filtration combustion of gases in a cylindrical porous body was created, which takes into account radiation transfer inside the porous body and the radiation flux from the porous body into the environment (Figure 1).

Figure 1: Scheme of Combustion of a Pre-mixed Mixture of Gases in a Cylindrical Porous Burner



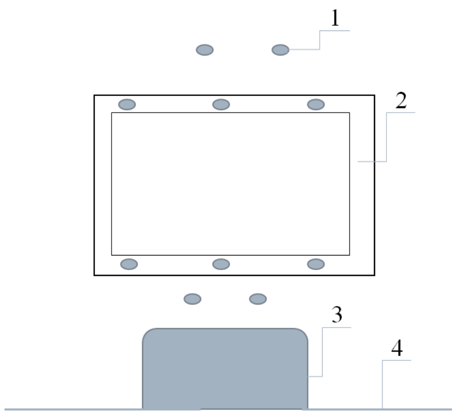
At the Tomsk Scientific Center of the Siberian Branch of the Russian Academy of Sciences, a number of studies were devoted to the study of gas combustion in porous media. A promising approach to the utilization of low-calorie gases is the organization of combustion in porous media, which allows expanding the combustion limits and power control range, increasing the temperature in the combustion zone, reducing the emission of harmful substances, etc. There are two global approaches to organizing the combustion of gases in porous media: conditionally propagating combustion waves and stationary combustion waves. The first include those processes in which a spatially limited zone, a combustion wave, propagates through a certain extended porous medium, for example, a backfill of ceramic granules. The movement of the combustion wave can be either in the direction along the flow of the initial reagents or towards the flow; flame anchoring modes are possible. Depending on the conditions, the temperature in the combustion zone can be up to two or more times higher than adiabatic. Stationary combustion waves include processes in which the combustion zone is stabilized on the surface of some porous material or at the interface between two different porous materials (Figure 2).

Figure 2: Radiation Burner: 1 – Gas-permeable Cylindrical Emitter, 2 – Gas-permeable Flow Distributor, 3 – Burner Body, 4 – Ceramic Fiber Gasket



Another new direction is the use of capillary-porous materials in the external building envelope. Creating conditions for abnormal diffusion of oxygen, carbon dioxide and water vapor from the room through the external building envelope and back seems to be a very promising solution for the effective formation of a microclimate in the room. An example of such a solution is presented in Figure 3.

Figure 3: External Building Envelope (View from the Room): 1 – Air Exchange Valves, 2 – Double-glazed Window, 3 – Heating Radiator, 4 – Floor Level



3. Diffusion in Capillary-porous Bodies

The differential diffusion equation (Fick's 1st law) is usually written as:

$$J = - DS\ (\partial C/\partial x) \qquad (1)$$

Where S is the surface area of the area through which diffusion occurs.

Fick's first law is also written as:

$$J = Cv_m \quad (2)$$

Where C is the diffusant concentration; v_m – its average speed, provided that the system under consideration (i.e. the diffusion medium) is at rest.

Fick's law for three-dimensional diffusion is written as:

$$j = -D_{grad}C \quad (3)$$

Anomalous diffusion processes are characterized by a power-law dependence of the width of the diffusion packet on time:

$$\Delta t \propto D_\alpha t^\gamma \quad (4)$$

Where D_α – is the diffusion coefficient.

Depending on the value of the index γ, different diffusion modes are distinguished:

$\gamma > 1/2$ – superdiffusion, $\gamma < 1/2$ – subdiffusion, $\gamma = 1/2$ – normal diffusion.

The anomalous diffusion model is based on a continuous-time random walk model. This model describes the wandering of a particle using a hopping-trap mechanism.

The random walk process is described by the anomalous diffusion equation:

$${}_0D_t^\beta \rho(x,t) = D\frac{\partial^\alpha \rho(x,t)}{\partial |x|^\alpha} + \frac{t^{-\beta}}{\Gamma(1-\beta)}\delta(x) \quad (5)$$

Where $0 < \beta \le 1$, $0 < \alpha \le 2$.

The solution to this equation is:

$$\rho(x,t) = (Dt^\beta)^{-1/\alpha} q(x(Dt^\beta)^{-1/\alpha}; \alpha, \beta) \quad (6)$$

The density estimate for the interval Δi is given by the expression:

$$\tilde{\rho}(\Delta_i, t) = \frac{1}{N}\sum_{j=1}^{N} h_j(\Delta_i) \quad (7)$$

Where the summation is performed from N independent trajectories.

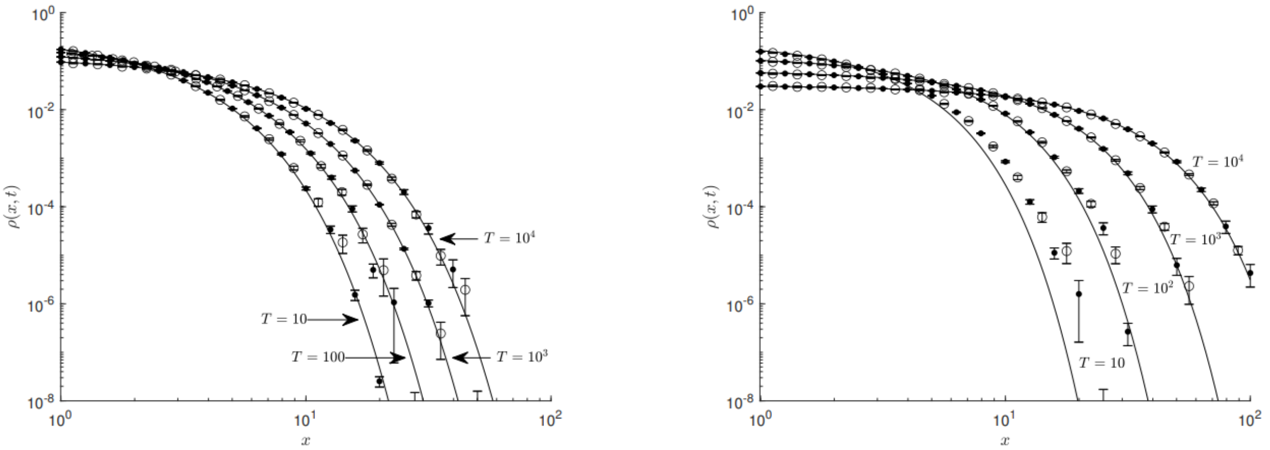
The density estimate takes the form:

$$\tilde{\rho}(x*,T*)=\frac{1}{N}\sum_{j=1}^{N} h_j(x*,T*) \qquad (8)$$

Where the summation is performed from N independent trajectories.

The results of solving equation (5) are shown in Figure 4.

Figure 4: Solution of Equation (5) for the Case of Exponential Distribution of Free Trajectories and β = 0.3 (Left) and β = 0.6 (Right)



From Figure 4 it is clear that for the value of the parameter β = 0.3, the results of the local estimate and the histogram coincide with solution (5) at time T∗ = 10. This means that by this time the wandering process has already entered the asymptotic mode. Thus, for given values of the parameter, estimate (8) can be used to solve equation (4) at times T∗ > 10.

4. Conclusion

- Studying the patterns of filtration combustion of porous materials taking into account the theory of anomalous diffusion seems very relevant.
- A promising approach to the utilization of low-calorie gases is the organization of combustion in porous media, which allows expanding the combustion limits and power control range, increasing the temperature in the combustion zone, reducing the emission of harmful substances, etc.
- Studying the patterns of formation of the indoor microclimate taking into account the theory of anomalous diffusion seems very relevant.
- The use of anomalous diffusion theory is at an early stage of research.
- The anomalous diffusion model is based on the continuous-time random walk (CTRW) model, which describes the wandering of a particle using a hopping-trap mechanism.

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