TEKA Kom. Mot. i Energ. Roln. – OL PAN, 2010, 10A, 218-222

CONVECTIVE HEAT EXCHANGE IN OPTOPNEUMATIC CELL

Gennady Kaljuzhnyj, Alim Kovalenko, Ellen Lyshtvan

Volodymyr Dal East-Ukrainian National University, Lugansk, Ukraine

Summary. The paper deals with the results of mathematic simulation of convective heat transfer in optopneumatic cell. It is shown that obtained results will allow to improve methods of computation of time characteristics of optopneumatic cells in automatic control systems.

Key words: convective heat exchange, optopneumatic cell, mathematical simulation

INTRODUCTION

Optopneumatics is one of the modern directions in automatics. Its basic element is an optopneumatic cell (OPC) [2]. This cell represents a hermetic gas-filled cylindrical container (fig. 1). The modulated luminous energy from a laser enters the inner gas-filled cavity 2 of the cell through transparent cover 1 (in our experiments the cover was made of acrylic resin). The cavity is located in the control channel of a fluidic amplifier. The luminous energy falls onto absorption layer 3 of black carbon deposited on the back wall of the cell. This layer absorbs the radiant energy converting it into the thermal one. Its temperature increases and, due to thermal diffusion, so does the temperature of the gas layers adjoining the absorption layer and the whole gas in the cell. The increase of the temperature in the confined space results in the rise of the pressure. In the case of pulse input of the radiant energy, there arises a pressure pulse in the optopneumatic cell.

The pressure pulse propagates in the control channel through membrane 4 to the power jet resulting in its deviation.

The temperature field in the cell changes due to the action of several mechanisms – thermal radiation, thermal conduction, and convection. Under the real conditions, all the three mechanisms are realized simultaneously, and the process is called a complex energy exchange. However, the contribution of separate mechanisms of energy exchanges into the common process is different, and in individual cases some of them can be neglected. Previous investigations [3] demonstrated that, considering heat exchange in an OPC filled with diatomic gas, one can omit the radiant energy, as its contribution into the energy exchange is negligibly small.

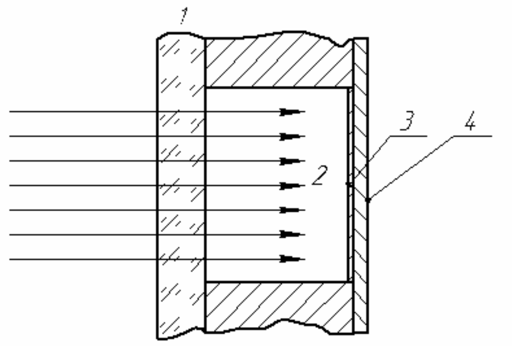

Fig. 1. Optopneumatic cell

The purpose of the present paper lies in the determination of the role of convection in the process of heat exchange in an OPC.

OBJECTS AND PROBLEM. MATHEMATICAL MODEL OF THERMAL PROCESSES IN OPC

Studying complex phenomena depending on several time- and space-varying physical parameters, their interrelation can be expressed by a system of differential equations. Most often, especially in the case of nonlinear equations, such a system must be solved numerically.

The set of equations for thermogravitational convection of incompressible liquid in the Boussinesq approximation includes: the Navier-Stokes equation with regard for the buoyancy force, the heat conduction equation, and the continuity equation under the condition of incompressibility of the gas [4]. The physical meaning of the Boussinesq approximation consists in neglecting density variations caused by the change of the temperature everywhere, except for the expression describing the buoyancy force:

$$\rho_0\left[\frac{\partial\vec{v}}{\partial t}+(\vec{v}\cdot\nabla)\vec{v}\right]=-\nabla P+\eta\Delta\vec{v}+\rho_0\beta T\vec{g},$$

$$\frac{\partial T}{\partial t}+(\vec{v}\nabla)T=\chi\nabla^2 T, \tag{1}$$

$$\operatorname{div}\vec{v}=0 \ .$$

Here: ρ_0 denotes the gas density, $\vec{v}$ is the velocity, P is the pressure, η stands for the dynamic viscosity, β is the temperature coefficient of volumetric expansion, T is the temperature, and $\vec{g}$ is the free fall acceleration. The temperature and pressure are reckoned from the initial values.

The system must be supplemented with initial and boundary conditions. They are presented by the initial gas temperature, the increase of the pressure induced by the former, the temperature of the OPC walls, and the requirement of gas adhesion at the walls.

In the cylindrical coordinate system (ρ, φ, z), the axis z coincides with the OPC axis, while the origin is located in the middle of the axis. In view of the axial symmetry of the problem, it is sufficient to solve it for the two-dimensional region formed by one half of the cylinder cross section $\varphi = \text{const}$. Moreover, one must specify at the axis the conditions of the absence of a thermal flow for the temperature and slip for gas. In this case, the boundary conditions will have a form:

$$v(t,R,z) = v\left(t,\rho,\frac{h}{2}\right) = v\left(t,\rho,-\frac{h}{2}\right) = 0\,;$$
$$v_\rho(t,0,z) = 0\,; \qquad (2)$$
$$\frac{\partial T}{\partial \rho}(t,0,z) = 0\,.$$

(where: R and h are OPC radius and height, correspondingly), and the initial conditions are presented as:

$$T(0,\rho,z) = T_0, \qquad (3)$$
$$P(0,\rho,z) = \rho_0 \frac{R_g}{M} T_0.$$

Here: T_0 is the initial temperature, R_g is the universal gas constant and, M is the molar mass of the gas.

NUMERICAL SOLUTION OF THE MODEL EQUATIONS

As a numerical method, we chose the control volume approach that represents one of the modifications of the conservative methods. Its basic idea can be directly interpreted. The calculation region is divided into some number of nonoverlapping control volumes in such a way that each node is located in one control volume. The differential equation for the sought quantity F is integrated over each control volume. The integrals are evaluated using piece profiles that describe the variation of F between nodes. As a result, one obtains a discrete analogue of the differential equation that includes the values of F in several nodes.

The discrete analogue obtained in such a way expresses the law of conservation of F for a finite control volume the same way as the differential equation expresses the conservation law for an infinitesimal control volume.

Thus, the control volume approach ensures the exact integral conservation of such quantities as mass, momentum, and energy for any group of control volumes and, consequently, for the whole calculation region. This property is valid at any number of nodes, and not only in the limiting case of their very large number. Thus, even the solution at a rough mesh satisfies accurate integral balances.

INVESTIGATION RESULTS

The mathematical model allowed us to obtain rather complete information on the thermal processes taking place inside the OPC. Figure 2 demonstrates the isotherms and characteristics of the gas stream caused by convection (a half of the OPC cross-section is shown). These data allow one to obtain qualitative information on the character of gas motion and temperature distribution. One can see a pronounced convective nature of gas motion. An ascending gas stream moves along the cell axis, a descending one – along its walls.

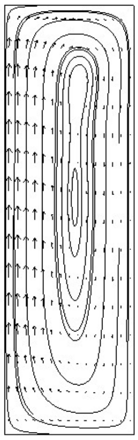

Fig. 2. Gas flow inside the OPC and isotherms (a cell 30 mm in diameter and 60 mm in length)

The question of practical interest is the effect of convection on the heat exchange process in an OPC shown in Fig. 3. One can see that, at the beginning of the process of cell cooling, the effect of convection on the general process is negligibly small and heat exchange is determined only by the thermal conduction mechanism. Such a situation conserves until the gas temperature in the cell decreases approximately twofold as compared to the initial value. It can be explained by the fact that the establishment of convective gas motion requires a finite time, i.e. the convection process is inertial. It is worth noting that the obtained data are in good agreement with experiment [1].

After that, the steady-stated convective gas motion results in a considerable increase of the cooling rate. Due to this fact, the total time of gas cooling in the cell decreases approximately twice.

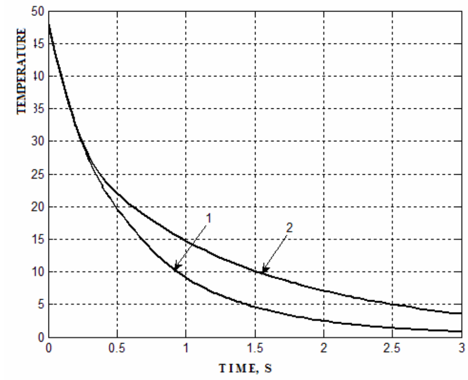

Fig. 3. Variation of the mean gas temperature in the cell (a cell 30 mm in diameter and 60 mm in length with regard for convection (1) and thermal conduction (2)

CONCLUSION

1. The mathematical model of heat exchange in an OPC with regard for mechanisms of thermal conduction and convection is considered.
2. The performed calculations have shown that the contribution of convection at the beginning of the process of gas cooling in the cell is inessential, but it increases with time. Due to this fact, the total time of gas cooling in the cell can decrease approximately twice.
3. The obtained results will allow one to improve methods of computation of time characteristics of OPCs in automatic control systems.

REFERENCES

1. Aamodt L.C., Murphy J. C., Parker J.G., 1977: Size Considerations in the Design of Cells for Photoacoustic Spectroscopy. Journal of Applied Physics, Vol. 48, # 3, March 1977, p.p. 927-933.
2. Kovalenko A.A., Lyshtvan E. Yu., Soroka S.I., 2008: Optopneumatika in Industry: monograph (in Russian). Lugansk: Publisher EUN Dall's University,– 184 p.
3. Landau L.D., Livshits E.M., 1988: Hydrodynamics (in Russian) / Moscow: Science, 1988 – 733 p.
4. Lyshtvan E. Yu., 2007: Dynamics of Radiant Heat Exchange in Optopneumatik Cell (in Russian). Visnik of EUN Dall's University, №4 (110), 2007. – pp.149-156.

КОНВЕКТИВНЫЙ ТЕПЛООБМЕН В ОПТОПНЕВМАТИЧЕСКОЙ ЯЧЕЙКЕ

Калюжный Г.С., Коваленко А.А., Лыштван Е.Ю.

Аннотация. В статье приведены результаты математического моделирования конвективного теплообмена в оптопневматической ячейке.

Ключевые слова: конвективный теплообмен, оптопневматическая ячейка, математическое моделирование.