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NUMERICAL MODEL OF FREE CONVECTION IN THE SPACE OF SCREEN-VACUUM INSULATION UNDER THE THERMAL EXPOSURE

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Abstract. The objective of the study is to find the patterns of the conjugate heat transfer process in a closed space of a coaxial cylinder’s pair under the influence of an external source of thermal radiation within the framework of the free convection model. It is assumed that the priority type of heat transfer in the gas filling the coaxial space is turbulent free convection, and thermal conductivity in the external thermal insulation of the pipeline. A model of the free convection process in a coaxial gas cavity in the presence of local heating in the form of a system of differential equations is created. Comparative results of a full-scale and numerical experiment on measuring the effective coefficient of thermal conductivity of screen-vacuum insulation are presented.

Keywords: liquefied natural gas, coaxial double-walled pipeline, screen-vacuum insulation, free convection, coaxial space

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Introduction

Modern technological processes usually involve the movement of liquefied natural gas (LNG) from its reception points to production workshops through in-plant pipelines, the design of which assumes the ability to maintain LNG in a liquid state. In [1, 2], the influence of thermal insulation on the LNG evaporation during pipeline transportation was analyzed. One of the technical solutions to minimize thermal inflows while maintaining the permissible amount of pressure losses is the use of a coaxial double-walled pipeline with screen-vacuum insulation [3, 4]. One of the possible design solutions is shown in fig. 1.

Structurally, screen-vacuum insulation has become a further development of high-vacuum insulation to reduce the intensity of the radiant component of the thermal inflow and limit the productivity of the LNG boiling process during its transportation [5].

It should be noted that relevant sources regarding this topic have not been found. Theoretical and experimental works aimed at creating physical models of heat transfer processes in a closed space with significant local sources of thermal radiation in conjugate formulations that would take into account the specific shape of the studied space and other most significant factors are still very few in number.

Fig. 1. **Section of cryogenic pipeline with screen-vacuum insulation**

There are several solutions, for example, in [6, 7] similar problems of free convection are considered on the basis of taking into account heat perception along the outer contour of the cylindrical volume under study. However, these results were obtained for conditions that have significant differences with the conditions of thermal perception under the external influence of combustion products in a fire. This is largely due to the difficulties in finding the results of an analytical or numerical solution of the Navier-Stokes equation for rarefied gases and the lack of empirical and semi-empirical patterns in determining the values of heat transfer coefficients at the interface of media in boundary conditions of the third kind [8].

Main part

The objective of this work is finding the patterns of the conjugate heat transfer in a closed space of a pair of coaxial cylinders process (fig. 2) under the influence of an external source of thermal radiation within the framework of the free convection model.

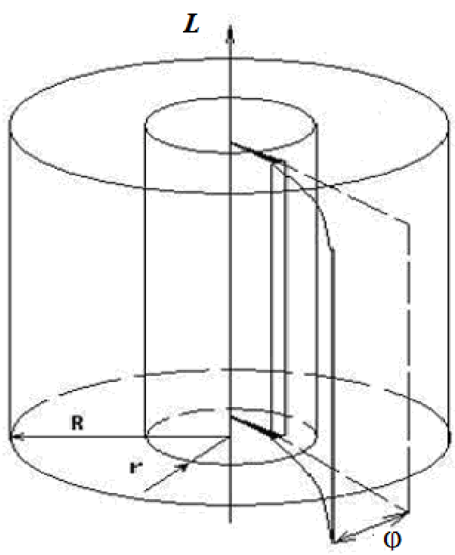

Fig. 2. **The scheme of the investigated coaxial space**

The area under study is a cavity with low gas pressure, bounded from the external environment by thermally conductive walls of finite thickness and known radiation parameters. The intensity of thermal radiation is assumed to be evenly distributed along the outer contour of the screen-vacuum insulation of the pipeline. The priority type of heat transfer in the gas filling the coaxial space is turbulent free convection, and thermal conductivity in the external thermal insulation of the pipeline.

To describe the process of free convection in the analyzed area, a mathematical model is used. This model is a system of differential equations developed to describe mixed convection in locally heated areas [9].

Taking into account the cylindrical coordinate system adopted for solving the problem, the outer radius of the coaxial gas cavity R_{max} and the full circle 2π were chosen as the scale of the considered solution range. To transform variables in a system of differential equations to a dimensionless form, the following relations were applied:

$$\left\{\begin{aligned} & R=\frac{r}{R_o};\varphi=\frac{\varphi}{2\cdot\pi};\tau=\frac{t}{t_o};U=\frac{u}{V_o};V=\frac{v}{V_o};\Theta=\frac{T-T_o}{\Delta T};\psi=\frac{\psi}{\psi_o}; \\ & \Omega=\frac{w}{w_o};V_o=\sqrt{g\cdot\beta\cdot\Delta T\cdot L};\Delta T=T_{it}-T_o;\psi_o=V_o\cdot L;w_o=\frac{V_o}{L} \end{aligned}\right\},$$

where r, φ – cylindrical coordinates; u, v – velocities in cylindrical coordinates; R, φ – dimensionless cylindrical coordinates; τ – dimensionless time coordinate; t – time coordinate; t_o – the scale of the time coordinate; U, V – dimensionless velocities in cylindrical coordinates; θ – dimensionless temperature; T – current temperature; T_o – the temperature of the air in the space before the start of the fire; T_{it} – current temperature scale; ψ – gas current indicator; ψ_o – the scale of the gas current indicator; w – vortex velocity value; w_o – the scale of the vortex velocity value; Ω – the dimensionless value of the gas current velocity.

The system of differential equations describing the process of free convection in a coaxial gas cavity in the presence of local heating has the form:

$$\left\{\begin{aligned} & \frac{1}{Sh}\cdot\frac{\partial\Omega}{\partial\tau}+U\cdot\frac{\partial\Omega}{\partial r}+V\cdot\frac{\partial\Omega}{\partial\varphi}=\frac{\partial^2}{\partial r^2}\left[\left(\frac{1}{\sqrt{Gr}}\cdot\Omega\right)\right]+\frac{\partial^2}{\partial\varphi^2}\left[\left(\frac{1}{\sqrt{Gr}}\cdot\Omega\right)\right]+\frac{1}{2}\cdot\frac{\partial\Theta}{\partial r}; \\ & \frac{\partial^2\psi}{\partial r^2}+\frac{\partial^2\psi}{\partial\varphi^2}=-2\cdot\Omega;\quad \frac{1}{Fo}\cdot\frac{\partial\Theta}{\partial\tau}=\frac{\partial^2\Theta}{\partial r^2}+\frac{\partial^2\Theta}{\partial\varphi^2}; \\ & \frac{1}{Sh}\cdot\frac{\partial\Omega}{\partial\tau}+U\cdot\frac{\partial\Omega}{\partial r}+V\cdot\frac{\partial\Omega}{\partial\varphi}=\frac{\partial}{\partial r}\left[\left(\frac{1}{\Pr\cdot\sqrt{Gr}}\cdot\Theta\right)\right]+\frac{\partial}{\partial\varphi}\left[\left(\frac{1}{\Pr\cdot\sqrt{Gr}}\cdot\Theta\right)\right] \end{aligned}\right\}. \quad (1)$$

Following definitions are used in the (1) equation:

$$\left\{\begin{aligned} & \textit{Struhal's number}\ : Sh=\frac{V_o\cdot t_o}{l_o};\quad \textit{Grashof number}\ : Gr=\beta\cdot\frac{g\cdot l_o^3}{\nu^2}\Delta T; \\ & \textit{Fourier number}: Fo=\frac{a\cdot t_o}{l_o^2};\quad \textit{Prandtl's number}\ : \Pr=\frac{\nu}{a} \end{aligned}\right\}.$$

The solution of the system of differential equations (1) describing the process of free convection presupposes the setting of boundary conditions. In this case, the initial conditions are represented by equations (2):

$$\psi(r,\varphi,0)=\Omega(r,\varphi,0)=0; \quad \Theta(r,\varphi,0)=0. \tag{2}$$

For the range of solutions (3) on the outer perimeter of the coaxial space of the screen-vacuum insulation, the boundary conditions are represented by equations (4):

$$\frac{\partial\Theta(r,\varphi,\tau)}{\partial\varphi}=0; \tag{3}$$

$$\left\{\begin{matrix} \varphi=0, \quad 0<r<R, \quad 0<\tau<\dfrac{t}{t_o}; \\ \varphi=\dfrac{\varphi}{2\cdot\pi}, \quad 0<r<R, \quad 0<\tau<\dfrac{t}{t_o} \end{matrix}\right\}. \tag{4}$$

For the range of solutions (5) on the outer perimeter of the coaxial space of the screen-vacuum insulation, the boundary conditions are represented by the equations (6):

$$\frac{\partial\Theta(r,\varphi,\tau)}{\partial r}=0; \tag{5}$$

$$\left\{\begin{matrix} r=0, \quad 0<\varphi<\dfrac{\varphi}{2\cdot\pi}, \quad 0<\tau<\dfrac{t}{t_o}; \\ r=1, \quad 0<r<R, \quad 0<\tau<\dfrac{t}{t_o} \end{matrix}\right\}. \tag{6}$$

For the range of solutions (7) on the inner perimeter of the coaxial space of the screen-vacuum insulation, the boundary conditions are represented by equations (8):

$$\frac{\partial\psi(r,\varphi,\tau)}{\partial\varphi}=0, \quad \frac{\partial\Theta_1(r,\varphi,\tau)}{\partial\varphi}=\lambda_{1,2}\cdot\frac{\partial\Theta_2(r,\varphi,\tau)}{\partial\varphi}; \quad \Theta_1(r,\varphi,\tau)=\Theta_2(r,\varphi,\tau). \tag{7}$$

$$\varphi=\frac{\varphi}{2\cdot\pi}, \quad 0<r<R, \quad 0<\tau<\frac{t}{t_o}. \tag{8}$$

For the range of solutions (9) on the inner perimeter of the coaxial space of the screen-vacuum insulation, the boundary conditions are represented by equations (10):

$$\frac{\partial\psi(r,\varphi,\tau)}{\partial r}=0, \quad \frac{\partial\Theta_1(r,\varphi,\tau)}{\partial r}=\lambda_{1,3}\cdot\frac{\partial\Theta_3(r,\varphi,\tau)}{\partial r}; \quad \Theta_1(r,\varphi,\tau)=\Theta_3(r,\varphi,\tau). \tag{9}$$

$$r=\frac{l_o}{R}, \quad 0<\varphi<2\cdot\pi, \quad 0<\tau<\frac{t}{t_o}. \tag{10}$$

The consideration of the radiation component for the range of solutions (5) on the outer perimeter of the coaxial space of the screen-vacuum insulation is described by the differential equation (11) under boundary conditions:

$$\frac{\partial\Theta_1(r,\varphi,\tau)}{\partial\varphi}=\frac{\partial\Theta_2(r,\varphi,\tau)}{\partial\varphi}+\frac{q\cdot l_o^3}{\lambda\cdot\Delta T}. \tag{11}$$

It is shown in [9] that the second term of the right-hand side of equation (11) is the Kirpichev criterion *Ki*.

Consideration of the thermal inflow radiation component, as well as the secondary vortex formations influence, suggests a description of the temperature dependence of the thermophysical characteristics of the gas filling the studied discharged space of screen-vacuum insulation in a temperature range of practical interest for predicting the behavior of a coaxial double-walled LNG pipeline in fire conditions.

The processes of heat and mass transfer in gaseous media associated with the interaction of individual molecules develop depending on the pressure of such a medium. This applies to the processes of diffusion, viscosity, thermal conductivity and does not apply to the processes of radiation heat transfer in the case of the use of multilayer screens in the construction of screen-vacuum insulation of LNG pipelines.

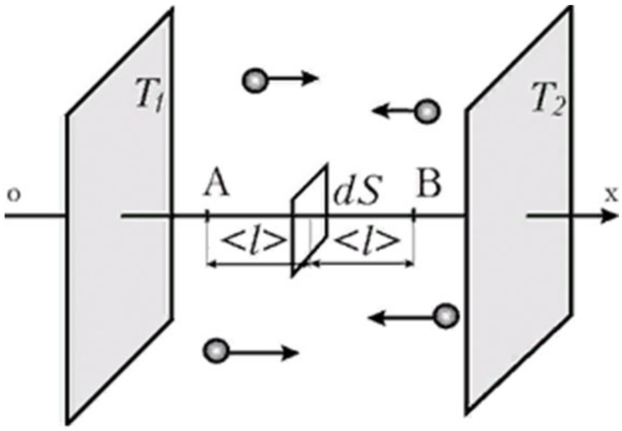

Fig. 3. **Diagram of the heat transfer process in discharged gas mixtures**

Considering that the value of the average free path l_m for all molecules is Roughly equal, and the values of the isochoric molar heat capacities C_v for various gases are also roughly the same, the value of the thermal conductivity coefficient λ at a constant concentration of n gas particles is associated with the value of the average Brownian motion velocities of w_m molecules [10].

$$\lambda=\frac{1}{3}\cdot n\cdot w_m\cdot l_m\cdot\frac{C_v}{N_A}=\frac{1}{3}\cdot\rho\cdot w_m\cdot l_m\cdot c_v;$$

$$w_m=\sqrt{\frac{8\cdot k\cdot T}{\pi\cdot m_o}},$$

where N_a – Avogadro number; ρ – density of the discharged gas mixture; m_o – the mass of the molecule; k – Boltzmann constant.

The presented model of free convection in the discharged space of the screen-vacuum insulation of an LNG pipeline was implemented using the potential of the MathWorks MATLAB & Simulink software package. The results of numerical simulation for the temperature range, which allows us to assess the correctness of the presented model are shown in fig. 4.

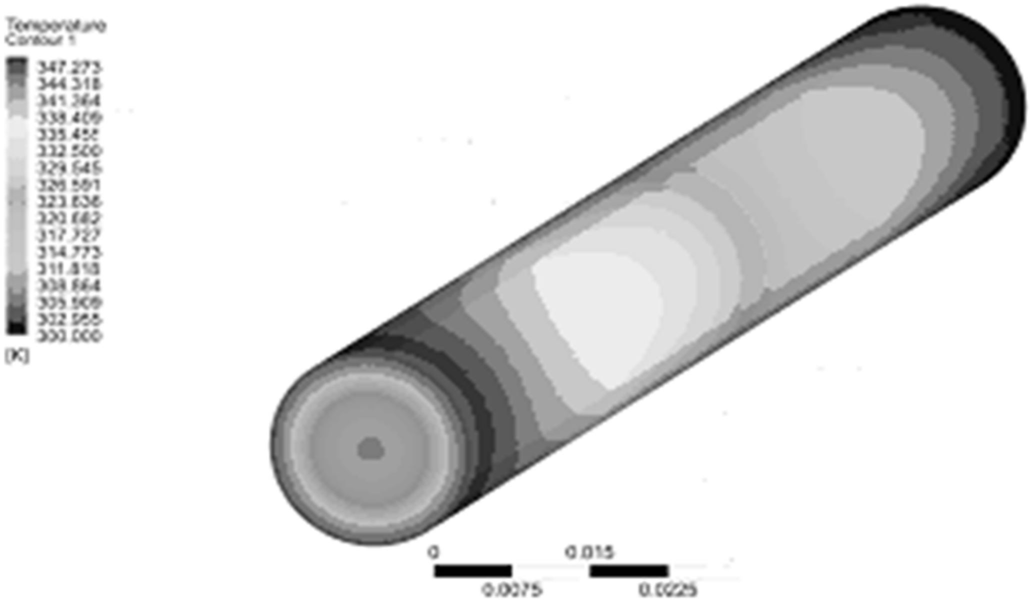

Fig. 4. **Graphical representation of the temperature field under external thermal influence on the screen-vacuum insulation of the LNG pipeline**

To assess the adequacy of the aforementioned model, the process of heat transfer through a 32 mm thick layer and an air pressure of 2 mbar with three layers of 0,1 mm thick aluminum foil with a degree of blackness of 0,2 was contemplated. Fig. 5 shows data on measuring the effective value of the thermal conductivity coefficient of screen-vacuum insulation, given in [11] – curve 1, and data computer simulation – curve 2.

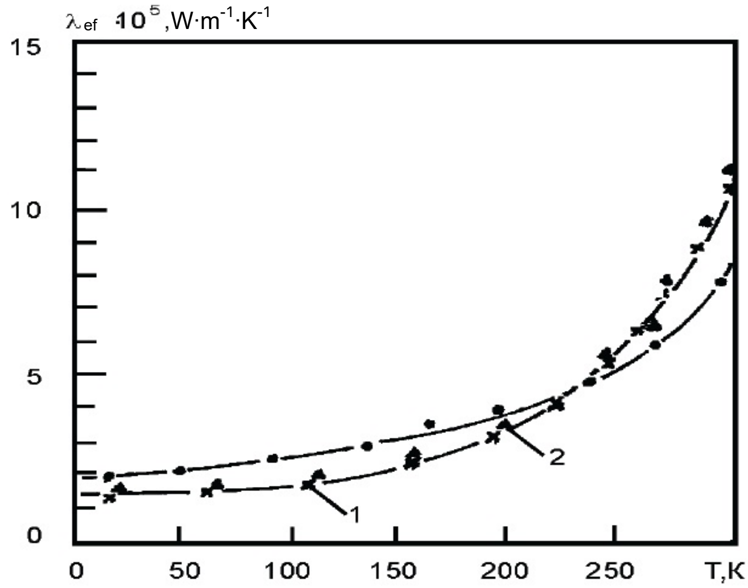

Fig. 5. **The results of full-scale and numerical experiments to study the effectiveness of screen-vacuum insulation**

Conclusion

The results of comparing the on-field and numerical experiments suggest that the created model adequately reflects the physical processes occurring in the screen-vacuum insulation of LNG pipelines when exposed to a heat flow.

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