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NUMERICAL ANALYSIS OF NATURAL CONVECTION OF CORIUM IN A SEMI-CYLINDRICAL CAVITY WITH ISOTHERMAL WALLS

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ЧИСЛЕННЫЙ АНАЛИЗ ЕСТЕСТВЕННОЙ КОНВЕКЦИИ КОРИУМА В ПОЛУЦИЛИНДРИЧЕСКОЙ ПОЛОСТИ С ИЗОТЕРМИЧЕСКИМИ СТЕНКАМИ

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Аннотация. *В настоящей работе проводится моделирование естественной конвекции кориума в полуцилиндрической полости с изотермическими стенками в ламинарном приближении. Для описания влияния выталкивающей силы внутри тепловыделяющей среды используется модель Буссинеска. Для реализации задачи, сформулированной на основе преобразованных переменных, применяется метод конечных разностей. Полученные результаты отражают влияние определяющих параметров на структуру течения и теплоперенос, а также на эволюцию интегральных характеристик.*

Introduction. Natural convection is a heat and mass transfer mechanism where the fluid motion is generated only by density differences in the fluid due to the buoyancy forces influence. Natural convection of corium can be realized during the severe accident in reactor [1]. Therefore, it is very important to study the heat transfer performance for such severe accidents [1–3].

Mathematical model. Natural convection of heat-generated corium in a cooling horizontal cylindrical cavity of a radius R_c is studied (see Fig. 1). Walls of this region are maintained at a constant low temperature T_0. At the initial moment, the corium is motionless, and its temperature at all points is equal to initial temperature T_0, the volumetric heat generation density of the corium is constant in this case [4].

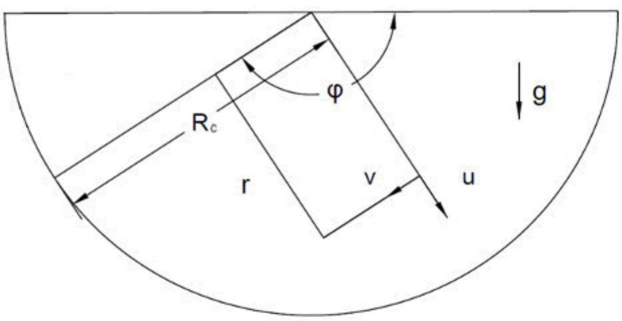

Figure 1. The domain of interest

Governing partial differential equations formulated using non-primitive variables [4, 5] have the following non-dimensional form:

$$R\frac{\partial^2\Psi}{\partial R^2}+\frac{\partial\Psi}{\partial R}+\frac{1}{R}\frac{\partial^2\Psi}{\partial\varphi^2}=\Omega \tag{1}$$

$$\frac{\partial\Omega}{\partial\tau}+\frac{\partial(U\cdot\Omega)}{\partial R}+\frac{1}{R}\frac{\partial(V\cdot\Omega)}{\partial\varphi}+U\frac{\partial V}{\partial R}=\sqrt{\frac{Pr}{Ra}}\left(\frac{\partial^2\Omega}{\partial R^2}-\frac{1}{R}\frac{\partial\Omega}{\partial R}+\frac{1}{R^2}\frac{\partial^2\Omega}{\partial\varphi^2}+\frac{\Omega}{R^2}\right)+ \\ +R\frac{\partial\theta}{\partial R}\cos(\varphi)-\frac{\partial\theta}{\partial\varphi}\sin(\varphi) \tag{2}$$

$$\frac{\partial\theta}{\partial\tau}+U\frac{\partial\theta}{\partial R}+\frac{V}{R}\frac{\partial\theta}{\partial\varphi}=\frac{1}{\sqrt{Ra\cdot Pr}}\left(\frac{\partial^2\theta}{\partial R^2}+\frac{1}{R}\frac{\partial\theta}{\partial R}+\frac{1}{R^2}\frac{\partial^2\theta}{\partial\varphi^2}+1\right) \tag{3}$$

It should be noted that the used non-primitive variables stream function Ψ and vorticity Ω can be defined as

$$U=\frac{1}{R}\frac{\partial\Psi}{\partial\varphi},\ V=-\frac{\partial\Psi}{\partial R},\ \Omega=\frac{\partial U}{\partial\varphi}-V-R\frac{\partial V}{\partial R} \tag{4}$$

Initial and boundary conditions for these governing equations can be written as follows

$$\tau=0:\ \Psi=0,\ U=V=0,\ \Omega=0,\ \theta=0 \tag{5}$$

$$\begin{aligned} &\tau>0:\ \Psi=0,\ \Omega=0,\ \theta=0 \quad \text{at } R=0,\ \varphi\in[0,\pi];\\ &\Psi=0,\ \Omega=\frac{\partial^2\Psi}{\partial R^2},\ \theta=0 \quad \text{at } R=1,\ \varphi\in[0,\pi];\\ &\Psi=0,\ \Omega=\frac{1}{R}\frac{\partial^2\Psi}{\partial\varphi^2},\ \theta=0 \quad \text{at } \varphi=0,\pi,\ R\in(0,1)\end{aligned} \tag{6}$$

Definition of all parameters used in equations combined with conditions (1)–(6) can be found in [4, 5].

Description of the numerical methods. The formulated boundary-value problem was solved using the finite difference method [4–6]. The second order difference schemes were used for an approximation of derivatives relative to the space coordinates, while for the unsteady term the first order difference schemes was used. The obtained difference equations for the vorticity and temperature were solved by the Thomas algorithm, while for the stream function the successive over relaxation technique was used. It should be noted that for transformation of two-dimensional problem to the set of one-dimensional problems the locally one-dimensional Samarskii scheme was used.

Results. In the present work, numerical analysis was conducted to study the heat transfer performance of the corium in a semi-cylindrical cavity with Prandtl number that was taken at the melting point of uranium dioxide, $Pr = 0.8202$, and Rayleigh number which varies from 10^3 to 10^6. To represent the work, distributions of streamlines and isotherms were used as was mentioned before to analyze the structure of the convective flows. These results are represented in Figure 2. As shown, two symmetric convective cells of different rotations are formed within the cavity. When the Rayleigh number increases, the cores of both cells shift closer to the curvilinear wall of the cavity.

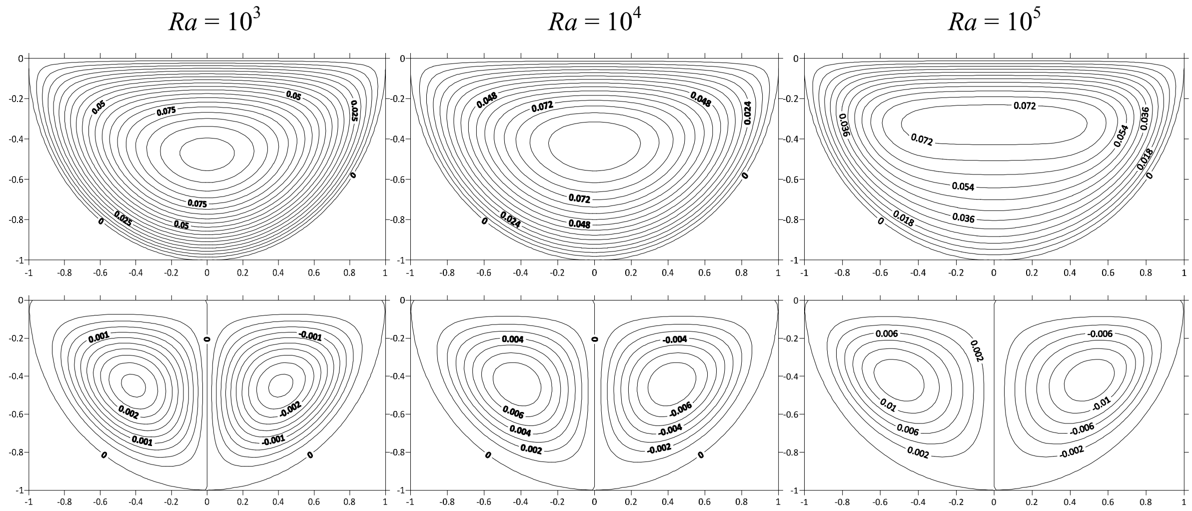

Fig. 2. Distributions of isotherms (top row) and streamlines (bottom row) at various Rayleigh numbers for $\tau = 100$

Conclusions. In this research, the numerical experiments for corium natural convection study in a semi-cylindrical cavity were performed using the Java programming language to show the influence of the Rayleigh number on streamlines and isotherms. It was found that a rise of the Rayleigh number illustrates a formation of two convective cells within the cavity and a uniform temperature field reflects an appearance of temperature maximum in a central part of the cavity due to an internal volumetric heat generation. Moreover, the average Nusselt number at the bottom and top walls have an opposite dependence on the Rayleigh number due to a displacement of the temperature maximum in the cavity to the upper wall with *Ra*.

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REFERENCES

1. Zhang L., Zhou Y., Zhang Y., Tian W., Qiu S., Su G. Natural convection heat transfer in corium pools: A review work of experimental studies // Progress in Nuclear Energy. – 2015. – V. 79. – P. 167–181.
2. Refaey A.M., Abdel-Latif S.H., Wasfy S.A. Thermal hydraulic and mechanical behaviour of VVER-1000 reactor lower plenum in the late phase of severe accident // Progress in Nuclear Energy. 2021. – V. 139. – P. 103833.
3. Hengra N.H., Ilyas M., Inayat M.H. Severe accident analysis of the Qinshan Nuclear Power Plant and evaluation of boundary conditions for ex-vessel heat transfer // Progress in Nuclear Energy. 2022. – V. 143. – P. 104032.
4. Kudrov A.I., Sheremet M.A. Numerical simulation of corium cooling driven by natural convection in case of in-vessel retention and time-dependent heat generation // Computer Research and Modelling. – 2021. – V. 13(4). – P. 807–822.
5. Sheremet M.A. Interaction of two-dimensional thermal “plumes” from local sources of energy under conditions of conjugate natural convection in a horizontal cylinder // Journal of Applied Mechanics and Technical Physics. 2012. – V 53(4). – P. 566–576.
6. Roache P.J. Computational Fluid Dynamics. – Hermosa Publishers, 1976. – 446 pp.