Heat transfer in mixed convection of molten salt in the presence of magnetic fields

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Abstract. This paper discusses the results of an experimental study and numerical simulation of a down flow of heat exchange of molten salt in a uniformly heated pipe under the action of a high transverse magnetic field. This article also presents a comparison of the results of the experiment and numerical simulation. The impact of transverse magnetic field on a flow structure and heat transfer in a vertical pipe was studied. Experimental studies were performed in the Reynolds number range (Re = 4000–20000) under the influence of a magnetic field (Ha = 13–14). Numerical calculations were estimate in the same ranges of Reynolds numbers and Hartman numbers which were 13–30. The paper is about comparison of results.

1. Introduction

One of the perspective areas of nuclear power development is the creation of reactors on molten salts and the development of hybrid thermonuclear facilities [1,2,3]. The creation of such systems is related with the solution of many technical and scientific problems. [4]. The operating temperature of the reactor is in an enough narrow range because the molten salts have a high melting point, and structural materials have a limitation in their applicability. The working range is about one hundred degrees. Therefore, the problem of heat hydraulic justification of projects is actual [5]. The exact significance of the medium and local characteristics of heat transfer is need for solve this problem.

The movement of molten salts will take place in high magnetic fields in the case of the use of molten salts in hybrid reactors which based on tokamak reactors. The existing experimental and numerical information [6, 7, 8, 9] suggests that their influence can be significant even with relatively small Hartmann numbers, and this influence cannot be neglected. Reconstruction of these conditions in scientific experiments is too expensive, that is why research are conducted by means of numerical modelling and using model fluids. For the first time investigation is being done in a range of significant heat loads. Experimental studies are carried out using the RK-3 facility (HELMEF), which consists of several separate loops of a closed type, which can be placed into a powerful electromagnet. RK-3 was used to recreate conditions similar to those of the TNS (thermonuclear neutron source). 30% solution of potassium hydroxide is employed as a molten salt simulator. RK-3 is the third generation Mercury Circuit [10] which originally was created for the study of liquid metal flow. In parallel with the experimental study [11], numerical modelling is performed using the DNS method. Further, experimental data and numerical simulation data are verified.

2. DNS Calculations

Direct numerical simulation (DNS) in our case means the solution of the complete non-stationary three-dimensional Navier-Stokes equations, the continuity equations and the energy equation (1)
taking into account the various components which responsible for the influence of mass forces. In this work, the flow in a vertical pipe with uniform heating was investigated.

![Figure 1. Geometry of pipe.](image)

Method is based on the approach described in detail in [12,13]. The main advantage of this numerical simulation method is that, by solving a system of equations of the form (1), we simulate hydrodynamics and heat transfer in a flow without using any additional assumptions or approximations. At the same time, statistical data calculated by averaging DNS results can be used to test and calibrate turbulence models. At the most fundamental level, DNS can be used to gain an understanding of the turbulence structure and turbulent transfer processes, which can be valuable in the development of turbulence management or prediction methods. DNS can also be considered as an alternative to physical experiment.

Continuity equation:

\[ \nabla \cdot \vec{v} = 0 \]  \hspace{1cm} (1)

Equations of motion (Navier-Stokes):

\[ \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} = -\nabla P + \frac{1}{Re} \nabla^2 \vec{v} + \vec{F}_A + \vec{F}_{EM} \]  \hspace{1cm} (2)

Energy equation:

\[ \frac{\partial \bar{\theta}}{\partial t} + \vec{v} \cdot \nabla \bar{\theta} = \frac{1}{Pe} \nabla^2 \bar{\theta} - \frac{\bar{v}_x}{dx} \frac{dP_b}{dx} \]  \hspace{1cm} (3)

Continuity equation In the equation of motion (2) \( \vec{F}_A \) is the buoyancy force, \( \vec{F}_{EM} \) is the electromagnetic force.

\[ \vec{F}_A = -\frac{Gr \bar{\theta} \bar{\theta}}{Re^2} \]  \hspace{1cm} (4)

\[ \frac{\partial \bar{\theta}}{\partial t} + \vec{v} \cdot \nabla \bar{\theta} = \frac{1}{Pe} \nabla^2 \bar{\theta} - \frac{\bar{v}_x}{dx} \frac{dP_b}{dx} \]  \hspace{1cm} (5)

Energy equation In equation (4), \( \bar{g} = \frac{g}{9815 \text{ (m/s}^2) \text{)} \) is the unit vector of the direction of the gravity vector. Ohm's law:

\[ \vec{j} = -\nabla \vec{\phi} + \vec{v} \times \vec{B} \]  \hspace{1cm} (6)

where the electric potential field \( \vec{\phi} \) is calculated from the Poisson equation

\[ \nabla^2 \vec{\phi} = \nabla \cdot (\vec{v} \times \vec{B}) \]  \hspace{1cm} (7)

In this work, we compared the experimental data obtained for an aqueous solution of KOH (30%), which is used as a model fluid in a physical experiment, and the results of DNS calculations. For these
calculations, the effect of free convection and magnetic field on the flow and heat transfer was taken into account.

An approximation of quasistationary turbulent motion was used to process the results of numerical calculation. The solution of the equations system together with the boundary conditions were three-dimensional fields (actual values) of velocity $u(x,y,z,t)$, temperature $\theta(x,y,z,t)$, pressure $p(x,y,z,t)$, and electric potential $\Phi(x,y,z,t)$. To obtain the averaged values of current values, averaging was used for a period of time, which was rather large compared with the period of turbulent fluctuations, but small compared with the time interval which characteristic of averaged motion:

$$\xi(x,y,z) = \frac{1}{T} \int_{0}^{t_0 + T} \xi(x,y,z,t) dt$$  \hspace{1cm} (8)

The system of equations is discretized on an inhomogeneous grid using the methods of finite-difference approximation (table 1). The grid for spatial discretization is formed in the nodes of a cylindrical coordinate system with center on the axis of the pipe. The grid points thicken along the radius as they approach the walls. Grid clasterisation to the wall is described using the converted radius $\xi = \frac{d \tanh(Ar)}{2 \tanh(A)}$, where A is the parameter that determines the degree of clasterisation.

The problem was solved in a cylindrical coordinate system in a dimensionless form. The computational domain was a circular tube with a radius and a length which sufficient to reproduce large-scale flow structures. Characteristic scales and similarity numbers:

Length scale - $r_0$, velocity scale - average velocity $w_0$, magnetic induction scale - external field induction $B_0$, dimensionless temperature - $\Theta = \frac{\theta - \bar{\theta}}{\bar{\theta}}$ (growth-average temperature of liquid which is determined from the heat balance), dimensionless electric field potential - $\Omega = \frac{\Phi}{w_0 dB_0}$, Reynolds number - $Re = \frac{\bar{\omega}d}{v}$, Hartmann number - $Ha = B_0 d \sqrt{\frac{\sigma}{\nu \rho}}$, Grashof number - $Gr = \frac{\bar{\alpha}q_0 d^4}{\nu^2 \lambda}$, Prandtl number - $Pr = \frac{\nu}{\alpha}$ Peclet number - $Pr = \frac{w_0 d}{a} = Re \cdot Pr$.

Periodic boundary conditions on the velocity $u$ and electric potential $\varphi$ at the inlet and outlet are imposed. Periodic condition for temperature and pressure are determined according to approach described in [12].

Boundary conditions in dimensionless form:
for velocity field at $r = r_0$ - $u_r = u_\phi = u_z = 0$

for temperature boundary condition of 2nd kind at $r = r_0$ - $\frac{\partial \Theta}{\partial r} = 1$
electrical wall insulation conditions at $r = r_0$ - $\frac{\partial \varphi}{\partial r} = 0$

| Table 1. Characteristics of the grid. |
|---|---|---|---|---|---|
| Pr | Re | Nx | Ny | Nz | Ar |
| 4.1 | 5000 | 120 | 90 | 120 | 2.5 |
| 4.1 | 7000 | 120 | 90 | 120 | 2.5 |
| 4.1 | 10000 | 250 | 90 | 160 | 2.5 |

3. Results

Results of numerical simulation provided by described above method are compared with results of experiments [11]. Due to experimental possibilities it was much easier to measure temperature fluctuations and then to calculate the temperature fluctuation intensity. Experiments have shown that in area of small Reynolds numbers (7000-10000) in a down flow in a heated pipe transverse magnetic field influence manifests itself in an increase of temperature fluctuations intensity. This result was interesting as it is known and have been shown in works [7,8] that magnetic fields supresses the velocity fluctuations and therefore suppression of temperature fluctuations have been expected.
Results of DNS confirms principal result obtained from the experiment (figure 2 and figure 3). Data was normalised on value of dynamic velocity and temperature determined as:

\[ t^* = \frac{q_w}{\rho \cdot c_p \cdot u^*} \] (9)

\[ u^* = \sqrt{\frac{\tau_w}{\rho}} \] (10)

where; \( \tau_w \) is the tangential stress at the wall; \( u^* \) – dynamic velocity; \( v, \rho, c_p \) is the kinematic coefficient of viscosity, density, fluid heat capacity.

However, by now stronger magnetic field is required to achieve quantitively similar result.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{Profiles of temperature fluctuations intensity, Re = 7000: 1 - calculation, Ha=0, Gr=7.9\cdot10^7; 2 - calculation, Gr = 7.9\cdot10^7, Ha = 30; 3 - experiment, Ha = 0, Gr = 7\cdot10^7; 4 - experiment, Ha = 14, Gr = 7\cdot10^7; 5 - calculation, Gr = 7.9\cdot10^7, Ha = 13.}
\end{figure}
Figure 3. Profiles of temperature fluctuations intensity, Re = 10000, Gr = 7,9·10^7: 1 - calculation, Ha = 0; 2 - calculation, Ha = 20; 3 - experiment, Ha = 0; 4 - experiment, Ha = 14.

At the same time DNS results show changes in velocity fluctuations provided by magnetic field influence (figure 4). Both radial and spanwise components are being suppressed, and verification on experimental data would be useful. However, experimental measurement of velocity components is a difficult task as model fluid is chemically active, strong magnetic fields and heat fluxes are applied.

Figure 4. Profiles of spanwise and radial velocity fluctuations intensity, Re = 7000, Gr = 7,9·10^7: 1 - calculation, Ha = 0; 2 - calculation, Ha = 30.

4. Conclusion
Experimental and numerical studies of the heat transfer characteristics of a molten salt simulator were carried out for a down flow in a vertical pipe with Reynolds numbers (Re=4·10^3-20·10^3) under the influence of a magnetic field (Ha=13-14) and significant values of heat load (Gr up to 10^8). Calculations of heat transfer of the molten salt simulator under the regimes which realize in the experiment were made. Additionally, calculations were carried out with regime parameters that were not possible to implement in an experimental study (Ha=14-30). The results obtained are in qualitative
agreement with experimental data. In the case of a developed turbulent flow, the effect of a magnetic field on the flow structure and turbulence shows itself in a form of suppression of velocity fluctuations but increase of temperature fluctuations without development of periodical peaks [13]. Based on this principal result further numerical and experimental investigation is planned, involving experimental measurements of velocity components and numerical simulations in a wider range of parameters.

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