Computational simulation of thermal hydraulic processes in the model LMFBR fuel assembly

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Abstract. The aim of this study was to verify a developed software module on the experimental fuel assembly with partial blockage of the flow section. The developed software module for simulation of thermal hydraulic processes in liquid metal coolant is based on theory of anisotropic porous media with specially developed integral turbulence model for coefficients determination. The finite element method is used for numerical solution. Experimental data for hexahedral assembly with electrically heated smooth cylindrical rods cooled by liquid sodium are considered. The results of calculation obtained with developed software module for a case of corner blockade are presented. The calculated distribution of coolant velocities showed the presence of the vortex flow behind the blockade. Features vortex region are in a good quantitative and qualitative agreement with experimental data. This demonstrates the efficiency of the hydrodynamic unit for developed software module. But obtained radial coolant temperature profiles differ significantly from the experimental in the vortex flow region. The possible reasons for this discrepancy were analyzed.

1. Introduction

One of the possible approaches to description of heat and mass transfer processes in the core and heat-exchange equipment is using of porous body model. Equations of this model are obtained as a result of rigorous mathematical procedure of averaging initial three-dimensional equations of heat and mass transfer processes [1-2].

\[
\frac{\partial}{\partial x_j} \varphi u_i \phi = 0, \quad i = 1, 2, 3, \tag{1}
\]

\[
\frac{\partial}{\partial \tau} \rho u_i \phi + \frac{\partial}{\partial x_j} \rho \phi u_i u_j = \rho \phi g_i \phi - k_{ij} u_j - \frac{\partial \rho P}{\partial x_j} + \frac{\partial}{\partial x_j} \mu_{eff} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \tag{2}
\]

\[
\rho c_v \frac{\partial \phi}{\partial \tau} + \frac{\partial}{\partial x_j} \rho c_v \phi u_j t = \phi q_v - \frac{\partial}{\partial x_j} \lambda_{eff} \frac{\partial t}{\partial x_i} - k_{ij} (t - t_F) \tag{3}
\]

where \( \varphi \) – porosity; \( u_i, u_j \) – components of the velocity vector; \( g_i \) – components of the gravitational acceleration; \( k_{ij} = k_{\xi \xi} \delta_{ij} + \left( k_{\eta \eta} - k_{\eta \eta} \right) n_i n_j \) – tensor components of resistance, where \( k_{\eta \eta} (\beta) \) and \( k_{\xi \xi} (\beta) \) – main components corresponding to the directions along and transverse to rods; \( P = p + cp \nu^2 \) – the...
effective pressure in the flow, the sum of the thermodynamic pressure and the pressure due to the turbulent fluctuations and variations of speeds, where "c" - the pressure coefficient; \( q_V \) – power density in the liquid; \( \lambda_{ij}^{\text{eff}} \) – components of the coolant effective thermal conductivity tensor; \( t, t_F \) – temperature of the coolant and fuel rods, respectively; \( k_{ij} \) – volumetric coefficient of heat transfer from the fuel rods to the coolant; \( \mu_{\text{eff}} \) – the effective viscosity of the coolant flow.

Effective transfer coefficients in the equations (1) - (3) are determined using a specially developed integral turbulence model [3].

Software module APMo is designed to solve equation system by finite element method. APMo is developed for mathematical calculations of heat and mass transfer in the core and heat-exchange equipment of advanced NPP. The aim of this study was verification of software module at computational research of sodium coolant flow in the experimental fuel assembly with partial blockage of the flow section.

2. Experimental assembly

Experimental assembly KNS-Test [4] consisted of 169 smooth cylindrical rod elements, some of which are heated by electric current (Figure 1). The blockade was located at a distance of 40 mm from the entrance and overlapped 21% of flow section. The boundary conditions were specified by the coolant rate at the inlet, outlet pressure and the condition of the sliding cover on the surface. The temperature dependence of thermal properties of sodium [5] was taken into account in calculations.

![Figure 1. KNS-Test.](image)

3. Calculation result

The resulting calculated coolant velocity distribution in a longitudinal section FA is shown on Figure 2a. It is easy to see a vortex produced behind the blockade. The existence of a vortex is also found experimentally by processing of the measured temperature fields.
The observed flow pattern can be quantitatively described by a number of characteristic parameters. The position of the top of the stagnation zone, the center of the vortex, and the reverse flow rate (Figure 2a) could be included to them. In the experiment [4], as a reverse flow velocity relative velocity \( U_{rR} \) was considered. It could be defined by the following expression:

\[
U_{rR} = \frac{u_R}{\bar{u}}
\]

where \( \bar{u} = \left( u_0 + u_B \right)/2 \); \( u_0 \) – the coolant rate at the inlet; \( u_B \) – the coolant rate in the blockade; \( u_R \) – reverse flow rate.

The rates \( u_B \) and \( u_R \) were determined by means of the dependence of the longitudinal component of the velocity from the height of the fuel assembly in the far corner and the central cell. This dependence is also used to determine the top of the stagnation zone.

The position of the vortex center was determined by the minimum coolant velocity in its distribution in the cross section of the fuel assembly (Fig. 2b).

Comparison of the calculated and experimentally obtained parameters is given in Table 1.

**Table 1.** Comparison of the calculated and experimental parameters.

| Parameter                          | Experiment | Calculation |
|------------------------------------|------------|-------------|
| The height of the stagnation zone, mm | 100        | 95          |
| The vortex center position, mm     | 45         | 35          |
| The relative velocity of reverse flow | 0.18       | 0.26        |

Quantitative and qualitative comparison of the velocity fields shows that simulation result corresponds with the experiment. This demonstrates the efficiency of the hydrodynamic unit APMod software module.

Experimentally measured coolant temperature [4] is normalized by the value of the axial temperature gradient, that is determined in the undisturbed portion of the central equivalent cell:

\[
\theta = \Delta t/(dt/dz),
\]
where $\Delta t = t - t_m$ – heating of the coolant at the point of measurement, $dt/dz$ – axial temperature gradient defined by the following formula:

$$dt/dz = 4q/(\rho c_p u_d d_G)$$

In the expression (6) $q$ – heat flux into the liquid on equivalent cell to a boundary, and $d_G$ – its hydraulic diameter.

For comparison with the experimental data, calculated temperature field was normalized in accordance with the formulas (5) and (6). Figure 2 shows a comparison of the radial profile of calculated and experimental normalized temperature at different distances from the blockade.

![Figure 2](image-url)

**Figure 2.** Comparison of the radial profile of the calculated and experimental normalized temperature at different distances from the blockade.

There is a noticeable discrepancy between the obtained results and the experiment in the vortex area. One of the possible reasons for this discrepancy could be that the energy in the computational model was described as voluminous source of energy in the liquid. In experimental setup electrically heating rods was used and thermocouple was placed on the surface of the rods. So the temperature in the vortex axis could vary significantly from fluid temperature. In addition, the porous body model operates by averaged values so calculated temperature profiles will flatten.

### 4. Conclusion

As a result of the research a good quantitative and qualitative agreement between the calculated and experimental characteristics of the sodium coolant flow was received. Calculated radial coolant temperature profiles differ significantly from the experimental in the vortex flow region. The possible reasons for this discrepancy were analyzed.

### References

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