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MULTIDIMENSIONAL COMPUTER MODEL FOR HEAT EXCHANGE PROCESSES IN POOLS OF THE EXTRACTS OF SPENT NUCLEAR FUEL FROM NPP

A model for estimation of heat and mass transfer processes in the basins of the extracts of spent nuclear fuel from NPP reactor VVER-1200 with varying degrees of filling is presented. For the calculation of transport processes in the racks of basins of the extracts the porous body model is proposed, which allowed carrying out a model description of complex constructions. It is shown that excessive tight pack of "fresh" spent nuclear fuel can lead to a significant temperature rise of the spent nuclear fuel. According to the results of numerical simulation, the filling levels of spent nuclear fuel do not exceed 20% for "fresh" fuel.

Introduction. The obligatory condition for construction and operation of nuclear object is the storage system of the spent nuclear fuel (SNF).

Long-term experience of "wet" storage of SNF in the spent fuel pools (SFP) proved its reliability and convenience, especially for decrease of radiation load level, and thermal radiation of the spent nuclear fuel immediately after defueling from the reactor [1-3].

Development of SFP is accompanied by two tendencies: on the one hand, introduction of various devices and constructions to increase of the safety level of storage process; on the other hand, there is a tendency to decrease expenses for SNF storage that is mainly defined by most dense packing of SNF in racks of SFP (Fig. 1).

Fig. 1. Fastened racks construction to place HRP in the SFP at the nuclear power plant with VVER-1200.

The project of the nuclear power plant with VVER-1200 provides the condensed storage of SNF, it is caused by the economy purposes to store SNF in the pool for not less than 10 years. The common capacity of SFP racks for HRP (heat radiation packs) and pressure-tight cases comprises 756 cells. At such way of storage the heat removal is complicated by a small space for water circulation between six-sided pipes of racks of storage.

Excessive high temperature of water in SFP sections can lead to boiling with the subsequent destruction of a combustion cell or decreasing the density of surrounding HRP of the environment with possibility of spontaneous nuclear reaction.

At emergence of heat exchange crisis the cladding surface of a fuel element (FE) warms up to high temperatures at which there are a chemical reaction of zirconium oxidation when reacting with water. Hydrogen forming explosive mixture with oxygen is thus released. Intensity of this reaction at low temperatures of 0-350 °C is extremely small. At temperatures higher than 400 °C the intensity of this reaction increases and a noticeable zirconium oxidation worsens thermo-mechanical properties of a cladding material.

Besides chemical interactions, temperature increase of the cladding itself leads to the change of thermo-mechanical properties. At the temperature above 350 °C structural cladding behavior worsens a little, and plasticity increases. The cladding properties sharply change in the temperature range from 400 to 500 °C.

Definition of the research problem. As it can be seen from the described above features of zirconium behavior at temperature change, there are three levels of temperature indications of a cladding condition.

The first level – 350 °C – means some deterioration of structural properties.

The second level – 450 °C – means sharp deterioration of structural properties and a noticeable zirconium oxidation while interacting with water.

The third level – 1000–1200 °C – means chain chemical paro-zirconium reaction. This temperature level means fast cladding destruction and taking out of operation one of the main barriers of nuclear safety in VVER reactors.

Thus, there is a problem of safe storage of SNF choosing the optimum design and regime parameters of a cooling system in conditions of most dense packing of SNF in racks of SFP.

During the planned overload of fuel for heat removal from SNF in a reactor SFP there is a cooling system which periodically operates, maintaining water temperature in the pool at 30 °C. The maximal water temperature in SFP should not exceed 70 °C at the complete unloading of SNF to the fuel pool from the nuclear core of the reactor [2].

Thus, cooling of SNF is:

1) due to forced convection of ventilated air over water surface in the upper section of SFP;

2) due to the forced circulation of cooling water.

Analysis method. Numerical 3D model analogues can serve as basis of the analysis of SFP and SNF.

Similar model analogues should be constructed considering complex spatial geometrical arrangements and describe various modes of the heat removal, taking into account both convective transfer, and evaporation effect.

2D and 3D non-stationary conservation equations should constitute the basis for such techniques at the starting and boundary conditions corresponding to actual storage conditions of SNF in SFP.

In this paper, within the formalized software package COMSOL Multiphysics model patterns, the analogue system of spent nuclear fuel temporary storage and cooling in the reactor spent fuel pools is worked out (Fig. 2).

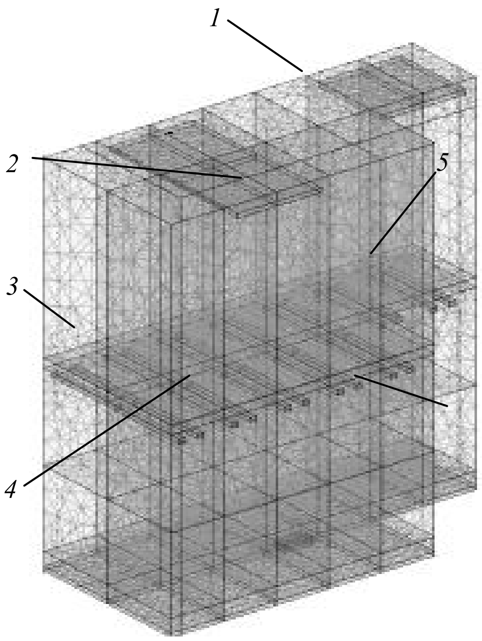


Fig. 2. Model analogue and calculated network of SFP (geometrical parameters – 6×13×17 m):
1 – inlet air ventilating duct; 2 – outlet air ventilating duct; 3 – cooling water manifold; 4 – water discharge manifold; 5 – water level line; 6 – HRP location.

In the calculated SFP model the following main assumptions are accepted:

1) gas phase movement is described within the bi-component gas vapor mixture;

2) physical properties of water and solid environments are accepted by constants, and properties of gas vapor mixture – as temperature-, pressure-, and air relative humidity - dependent;

3) bottom and walls of the SF pool o are considered to be heat isolated, and heat transfer is carried out, respectively, only via ventilating ducts.

Thus, two mechanisms of heat removal were considered:

1) due to forced convection of ventilated air over water surface in the upper section of SFP;

2) due to the forced injection and a water intake through a drainage collector and service water intake at the top level of liquid. Radiation heat exchange was not considered.

The common transfer processes description model was based on the solution of non-stationary movement, weight and thermal energy conservation equations [4]

$$\rho\frac{\partial U}{\partial t}-\nabla\left[\eta\left(\nabla U+(\nabla U)^{T}\right)\right]+\rho U\nabla U+\nabla P=0,$$

$$\nabla U=0,$$

$$\rho C_p\left(\frac{\partial T}{\partial t}+\vec{u}\cdot\nabla T\right)=\nabla\left(\lambda\nabla T\right)+Q_V,$$

where ρ – environment density; U – flow rate; η – dynamic viscosity coefficient; P – hydrostatic pressure; T – temperature; Cp – specific heat capacity; u – speed vector; λ – a thermal conductivity; Q_V – a volume thermal source. T superscript is turbulent constituent, defined according to the turbulence model in COMSOL Multiphysics interpretation.

To describe transfer processes in SFP sections (fig. 3) with various extent of construction filling, the following Brinkman's equation was accepted:

$$\rho\frac{\partial U}{\partial t}-\frac{1}{(1-\varepsilon)}\nabla\left[\eta\left(\nabla U+(\nabla U)^{T}\right)\right]+\frac{\eta}{k}U+\nabla P=0,$$

where $(1-\varepsilon)$ – the extent of construction filling in SFP sections at the average fraction of a throat ε; k – permeability coefficient, in calculations k = 0,01.

Introduction of porosity concept allowed considering transfer processes by a uniform method in the composite HRP rack design in a wide extent range of construction filling (1 – ε). Racks and sections for HRP storage can be considered as heterogeneous environments with a plenty of inhomogeneities in the form of changing throats. It is apparent that analysis of each separate inhomogeneity is not possible. To solve this problem, it is necessary to simulate an actual heterogeneous section with various level of HRP filling (1 – ε), replacing it with the efficient homogeneous environment, possessing the same macroscopic properties and behavior under external influence, as actual object.

In the analyzed method the macroscopic transport properties and behavior of a material of SFP section for HRP storage are removed, considering its structural spatial filling. The possibility to distinguish the representative porous volume is extremely essential for arranging computational experiments at various extents of SFP filling.

Additionally, the mass of a vapor phase conservation equation was solved:

$$\frac{\partial c''}{\partial t} + \vec{u} \cdot \nabla c'' = \nabla \left(D'' \nabla c'' \right),$$

where c'' – a vapour concentration; D'' – a vapour diffusion in air coefficient.

The total heat flux through the surface phase separation was assumed

$$q_{sum} = q_{ev} + q_{con},$$

where q_{ev} – evaporation heat flux; q_{con} - convection heat flux.

Sum heat flux in an approximation of a method of the given film near a SFP surface was defined as [6]

$$q_{sum} = \frac{Nu}{L} \left[\lambda_{mix} \left(T_{sf} - T_\infty \right) + D'' \rho_{mix} k \ln \left(\frac{\left(m_{mix} \left(1 - c'' \right) \right)_\infty}{\left(m_{mix} \left(1 - c'' \right) \right)_{sf}} \right) \right],$$

where Nu – Nusselt number; L – the typical distance scale of processes at a surface; λ_{mix} – a gas vapor mixture thermal conductivity coefficient; T_{sf} – saturation temperature (at a surface); T_∞ – temperature at a surface distance); D'' – a vapour diffusion in air coefficient; ρ_{mix} – a gas vapor mixture density; k – evaporation latent heat; m_{mix} – the mass of a gas vapor mixture.

For numerical implementation of SFP model, a method of finite elements in COMSOL Multiphysics system interpretation was used. Thus, the problem of maintaining the non-stationary process was solved.

Results of computational experiments. Numerical model of heat-mass exchange processes at SNF storage in the SF pool was defined for three cases:

- minimum porosity (the maximal filling) – 20% at drainage through the bottom drainage collector;
- minimum porosity – 20% at water intake through a branch pipe in the upper section;
- alternative calculations at various values of porosity (percentage ratio) and at water intake through a branch pipe in the upper section for monitoring that the maximal temperature of HRP do not reach a boiling point.

The described above computational experiments allowed qualitative and quantitative assessing of heat-mass exchange processes in the HRP storage system. Results of model experiments are presented in Fig. 3-5.

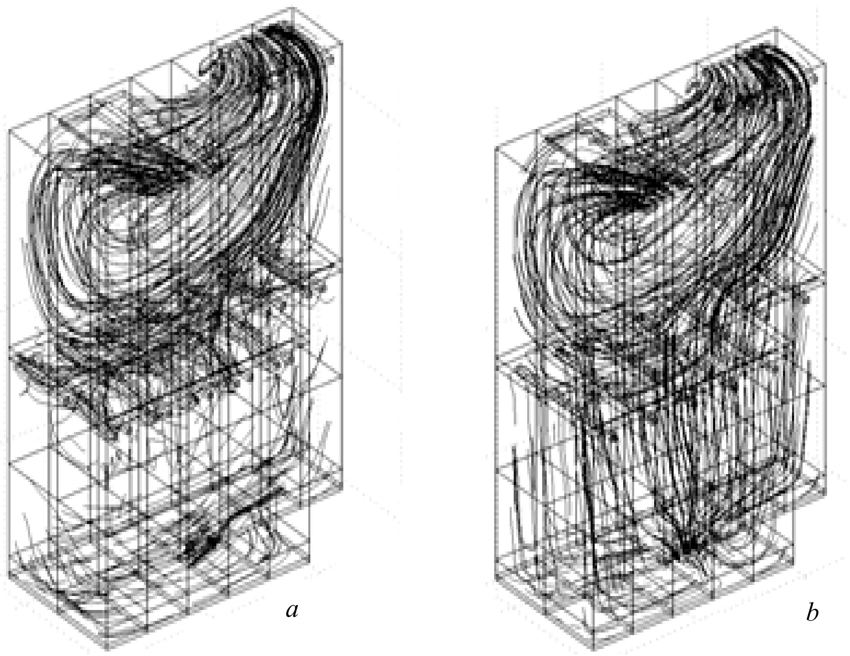


Fig. 3. Spatial distribution of vectors and flow functions in a liquid layer and SFP gas area (geometrical parameters according to fig. 2):
a – at a water intake only through the top branch pipe;
b – at a water intake only through the bottom drainage pipe.

The main heat HFR removal is carried out in a liquid layer with the subsequent heat transfer or through the bottom drainage collector, or through in taking branch pipes. Thus, the first option (Fig. 3, a) is a backup one according to the safety requirements. However such option of heat removal is the most effective and sufficient one as there is a forced water circulation through HFR racks. In the second option (Fig. 3, b) the subsequent heat transfer goes through in taking branch pipes and external airflow. This option is more heat-stressed for HFR as heat removal from HFR is carried out through natural convection in the constrained area.

According to the thermal processes calculation in SFP, it is possible to distinguish 3 typical temperature zones (Fig. 4):

– top cold zone with airflow circulation;

– intermediate zone;

– bottom hot zone with HFR afterheat.

The interlayer of water serves as a zone of the mixed heat exchange between external cold air and hot HFR. Besides, in this layer there is a water blending from the external cooling system.

As model computational experiments showed, the top water drainage from SFP is not always a sufficient option of HFR cooling (Fig. 5).

So, in case of the complete filling of SFP section (a flow open section is only 20%, and an initial heat transfer is 1 kW/m^3), it is obviously not enough space for a safe HFR temperature (Fig. 5, b) reaching.

In this case, the free area of 80% is sufficient for heat removal from natural convection.

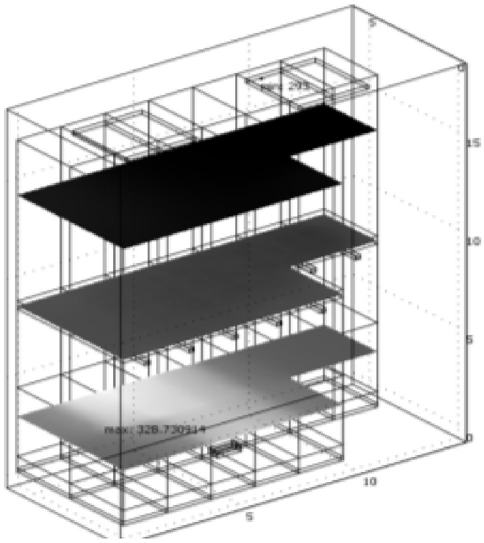
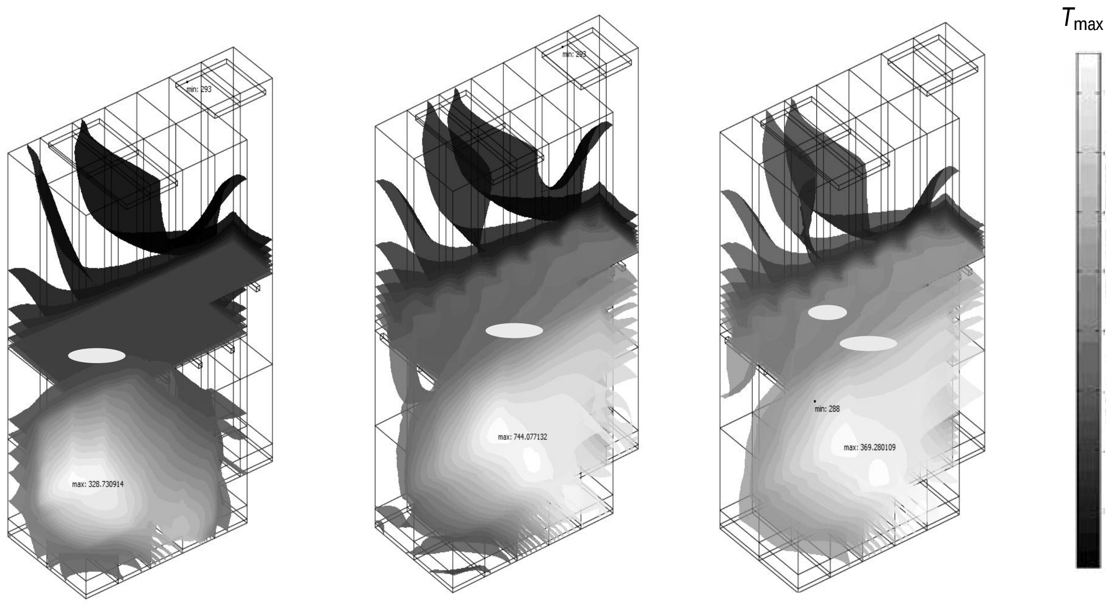


Fig. 4. Typical SFP temperature zones (temperature range 288-328 K)

In the course of arranging the nominal system of cooling through water in taking branch pipes the admissible HFR temperature can be reached only when the section with HFR racks filling is not higher than 20% (Fig. 5, c).



a *b* *c*

Fig. 5. Spatial temperature field distribution in SFP (geometrical parameters according to fig. 2): *a* – minimum porosity (the maximal filling) 20% at drainage through bottom drainage collector; maximal HFR temperature; temperature range 288-328 K; *b*– minimum porosity of 20% at water intake through a branch pipe in the upper section; the maximal HFR temperature is anomalously high; temperature range 288-806 K; *c* – alternative calculations at various values of porosity (percentage ratio) and at water intake through a branch pipe in the upper section for monitoring that the maximal HFR temperature do not reach a boiling point; temperature range 288-369 K.

Conclusion. Within the computing COMSOL programs the computer module of heat transfer processes in SFP calculation was worked out, taking into account non-uniform filling and non-uniform thermal HFR emission.

For calculation of hydrodynamic characteristics in sections with heat-producing assemblies the porosity model is offered. The calculated values of speed fields and temperatures in spent fuel pools are received.

Alternative calculations to compare the assessment of various refrigerating conditions and the maximal HFR temperature are carried out. It is defined that the forced pumping of water through racks significantly reduces the maximal HFR temperature even at its maximal filling. At the same time, the intake and input of water through the upper HFR section leads to the fact, that heat HFR removal is only due to natural convection in the constrained rack construction.

As a result of alternative calculations the maximal degree of filling ((1 – ε) = 20%) of section HFR racks in SFP which does not raise temperature above a boiling point at the least effective heat removal option was defined.

The developed computational template and the results of this research can be used for carrying out safety SNF storage examination at pre-reactor spent fuel pools, and, in particular, at the Belarusian nuclear power plant.

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