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MODELING OF PASSIVE HEAT REMOVAL SYSTEM OF NUCLEAR POWER PLANT CONTAINMENT IN THERMAL CONVECTION MODE

The modeling analogue of system of passive heat removal from a protective cover is developed within the limits of the formalized templates of COMSOL Multiphysics software package. The method of final elements in COMSOL Multiphysics system interpretation was used for numerical realization of modeling analogue of system of passive heat removal from a protective cover. The heat exchanger of system of passive heat removal from a protective cover is presented in calculations in the form of flat surfaces because of a great number of settlement cells. The non-stationary problem in establishment is solved in calculation. By the results of numerical modeling it is received that the heat exchanger and condenser of system of passive heat removal from a protective cover works in a pulse mode. Recurrence of jumps of the expense of the heat-carrier in computing experiments made size of an order 150–200 s. The specific thermal stream and total thermal stream per one section of the heat exchanger of system of passive heat removal depending on temperature conditions under a dome of a protective cover of NPP was received.

Key words: emergency emissions of NPP, transfer processes, modeling, computing template.

Introduction. The main security problem of NPP is a reliable removal of residual heat release. Accident cooling system of a reactor is the most complex and responsable and it is largely determined by the construction of ideology-guide structure of NPP in general.

The priority of passive means and ways to protect plants is determined by their fundamental advantages as compared with active systems: functioning without electricity consumption, no need for the use of governing signals of instrumentation and operating personnel intervention [1, 2].

Currently, broad search for new approaches to the problem of creation of passive systems cooling down the reactor, as well as passive systems to overcome the consequences of the beyond design basis accidents with depressurization of the primary circuit, such as systems of heat removal from containment are conducted in the world. Usually the task is solved by the use of water storage in reservoirs. The systems operate at natural circulation of the heat-carrier, and the energy of the residual heat is removed by heating and evaporation of definite amount of water reserve. It is considered that the conditions for the emergence and development of accidents allow through certain intermediate-current time (about 72 hours) to regain control, power supply, cooling water supply and so on.

To manage the beyond design basis accidents the systems of passive heat removal from the steam generators (SPOT PT) and from the containment (SPOT ZO) are foreseen.

A passive heat removal system provides a long (at least 24 h) removal of heat from the scope of protective cover during the beyond design basis accidents involving loss of heat-carrier at the first contour, blackout and failure of the sprinkler system. SPOT ZO (Fig. 1) includes heat exchangers, condensers placed in the upper part of the containment volume and connected by pipelines with emergency heat removal tanks (BAOT).

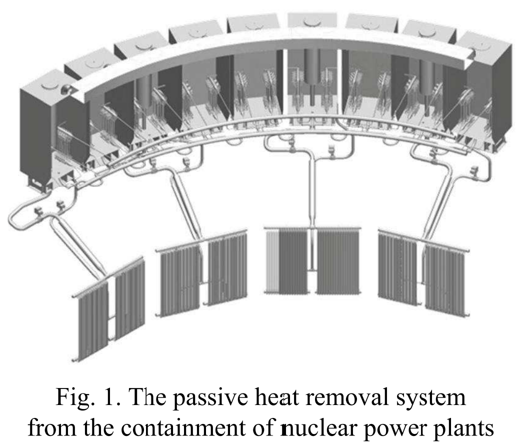

Fig. 1. The passive heat removal system from the containment of nuclear power plants

Heat removal to heat exchanger-condensers starts due to the processes of natural convection and condensation in accidents involving steam entering in containment and increase in temperature. At the same time there is a natural circulation in the circuit of SPOT ZO and the removal of body to water in emergency tanks.

Main part. Objective of the study:

– development of methodical basis of simulational modeling of thermohydraulic processes in the heat exchange machines and circuits of passive residual heat removal systems from the reactor plant and containment to the ultimate absorber of the "NPP-2006" project;

– creation of a simulation software package to calculate the passive safety systems of the "NPP-2006" project;

– a fulfilment of series of computational experiments to determine the optimal operating conditions of passive safety systems of the "NPP-2006" project and the development of control algorithms;

– basis of design characteristics of the passive security systems of the project "NPP-2006" with regard to the conditions of the Republic of Belarus.

Thermal-hydraulic processes occurring while working in the heat exchangers and circuits of SPOT PT and SPOT ZO, take place in a natural circulation and phase transitions of a heat exchanger and are sufficiently complex for their analytical solution. Experimental studies are expensive and require a lot of time to create the stand and holding a large number of experiments to set statistics. The best in this case is to create a computer simulation model and to carry out numerical experiments.

The study of passive systems with natural cooling requires co-simulation of the following transient processes:

– steam condensation from the steam-gas mixture under the protective cover on the outer surface of the heat exchange of tube bundles of heat exchanger-condensers of SPOT ZO;

– heat and mass transfer processes in the containment of a protective cover;

– condensation of a heat-carrier (taking into account accumulation of non-condensable gases) in a heat exchanger tube bundles of emergency cooling of SPOT PG;

– boiling regimes on the outer surfaces of the tube bundles of heat exchangers of emergency cooling of SPOT PG, possibilities of rise of a film boiling regime;

– mixing of cooling water in a tank of emergency cooling at heat removal from the heat exchangers of emergency cooling of SPOT PG associated with thermal convection and boiling;

– stability of work of the cooling circuits of SPOT PG and SPOT ZO.

In this paper, in the framework of formal templates of COMSOL Multiphysics software package the model analogue of SPOT ZO was developed.

A description model of transfer processes is based on the solution of universal equations of conservation of momentum, mass and thermal energy [3]:

$$\rho\frac{\partial U}{\partial t}-\left[\eta(\nabla U+\nabla U)^{T}\right]+$$
$$+\rho U\nabla U+\nabla P(T-\bar{T})\cdot\gamma\cdot\rho\cdot\beta_{\text{liq}}=0;$$

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

where ρ – density of the medium; U – flow rate; η – coefficient of dynamic viscosity; P – hydrostatic pressure; T – temperature; β_{liq} – coefficient of compressibility; C_p – specific heat; $\vec{u}$ – velocity vector; λ – coefficient of thermal conductivity; Q_v – volumetric heat source. The superscript T – turbulent component determined according to the k–ε turbulence model in interpretation of COMSOL Multiphysics.

In addition, the following equation of conservation of mass vapor above the evaporation mirror (to calculate the heat flux due to evaporation) was solved:

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

where c'' – vapor concentration; D'' – coefficient of diffusion of vapor in the air.

The total heat flow through the surface of the interface is as follows:

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

where q_{ev} – the heat flux due to evaporation; q_{con} – the heat flux due to convection.

The total heat flow in the approximation of the reduced film method near the surface is defined as [4, 5]

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

where Nu – Nusselt number; L – characteristic linear scale of processes at the surface; λ_{mix} – thermal conductivity coefficient of vapor and air mixture; T_{sf} – saturation temperature (at the surface); T_{∞} – temperature at a distance from the surface); D''– vapor diffusion coefficient in air; ρ_{mix} – density of the steam-air mixture; k – latent heat of vaporization; m_{mix}– mass of vapor and air; c''– vapor concentration.

Analogue of SPOT ZO the method of finite elements in the interpretation of COMSOL Multiphysics system was used (Fig. 2).

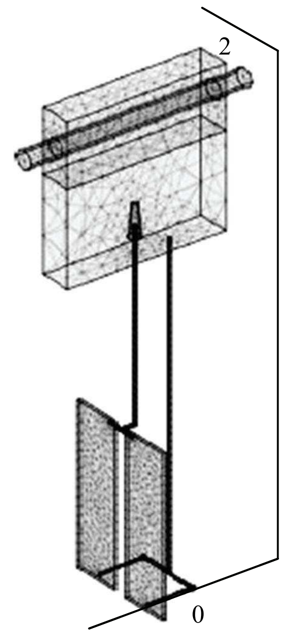

Fig. 2. The model analogue of SPOT ZO element with the partition of finite elements in the interpretation of COMSOL Multiphysics system
For the numerical implementation of the model

As the object of the simulation modeling shown in Fig. 2 SPOT ZO basic element consisting of two heat exchanger-condensers and an emergency heat removal tank was considered.

Hot air with water steam of heat carrier condenses and gives off heat to the exchanger-condenser of SPOT. Accordingly the heating of inner heat carrier occurs. Because of the density difference convection inside the contour of SPOT is organized. The heated heat-carrier rises up through the pipes and enters into the BAOT through a chipper and cold liquid from BAOT moves down and through the lower collector enters into the heat exchanger-condenser. In BAOT liquid is heated and through the outer opened surface relates to the external environment. Communication with the external environment through a water trap is installed (in this paper is not considered). Heat removal from the dome area occurs until a total water evaporation in BAOT takes place.

Due to the large number of computational cells the heat exchanger-condenser is presented in calculations in the form of flat surfaces.

In terms of the computational experiments a non-stationary problem on the establishment was being carried out. Initial data for the calculation are given in the Table.

Initial data for calculation

Parameter	Value
Temperature under the shell, K	375
Initial temperature in the cooling tank, K	293
Compressibility coefficient for water (1/K)	0.005
Ambient pressure, Pa	102,350
Heat transfer coefficient, W/(m² · K)	22
Geometric size of the section, m	5×1.5×0.1
Geometric size of pipelines, m	0.1
Geometric size of BAOT, m	5×5×1

At the initial time the temperature equal to 293 K is assumed. In the event of emergency the temperature under the dome is taken equal to 375 K. On the border of the heat transfer surfaces the boundary condition of the second kind is assumed.

In these variant calculations, the coefficient of heat transfer was assumed to be 10 to 22 W/(m² · K). Low water level in the tank of BAOT is 3 m.

The results of the experiment are shown in Fig. 3–5.

For the numerical modelling was chosen the initial period of operation of the SPOT ZO when entering the quasi-stationary mode. The highest temperature jump of height is observed in two symmetric sections of the heat exchanger-condenser. The most developed convective flow in BAOT takes place on water surface in vapor volume, which can be seen from the intensity of the current function (Fig. 3).

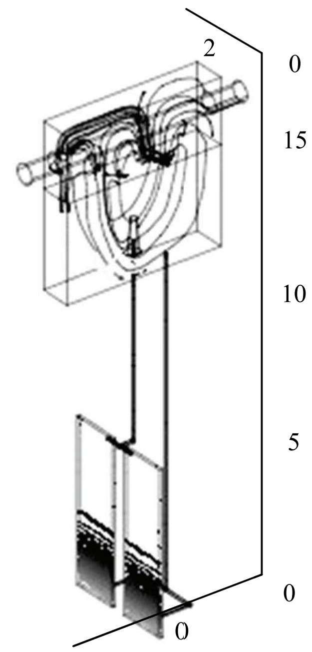

Fig. 3. Computing values of isosurfaces of temperature and current functions during the operation of SPOT ZO – temperature scale changes from 293K (light tone) to 303K (dark tone)

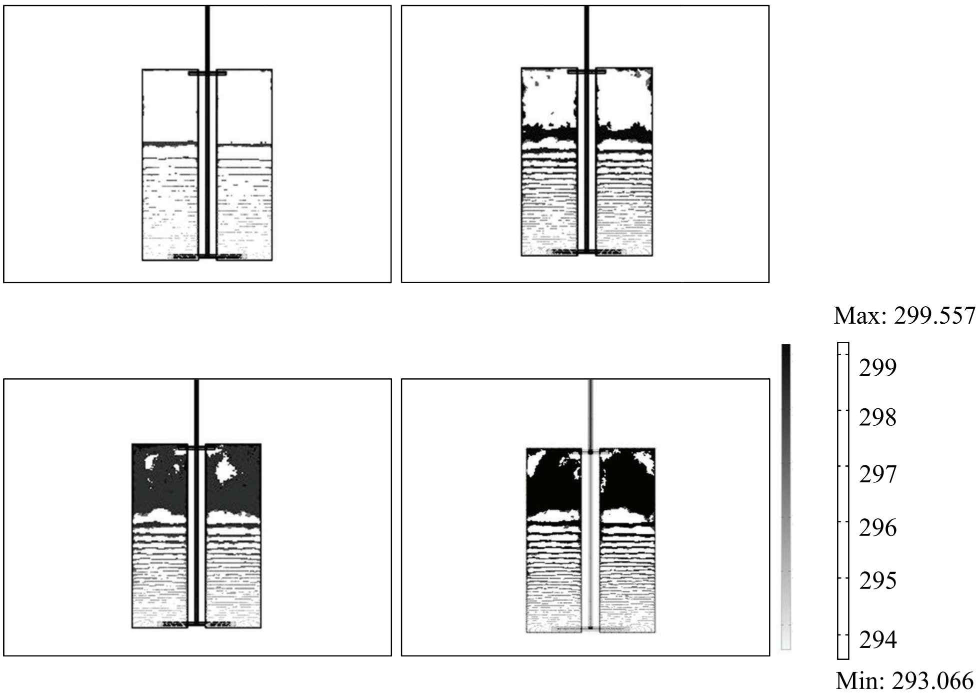

Fig. 4. Gradient view of the dynamics of iso-surfaces of temperature at moments of time of 0; 50; 150; 200 s from the beginning of discharge (gradient of temperatures is as shown in Fig. 3)

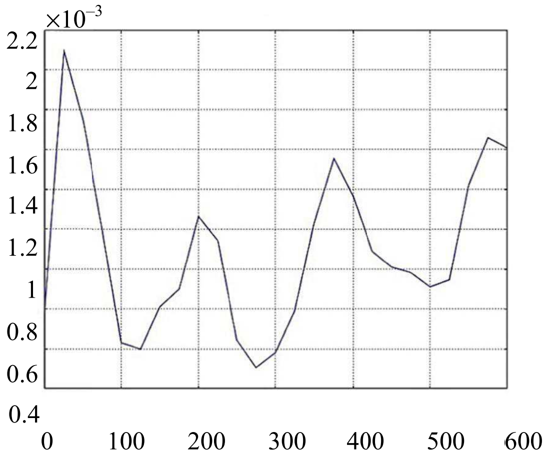

Fig. 5. Periodic changes of speed of a heat-transfer in the middle part of the section of the heat exchanger-condenser

However, the driving force along the contour is low and respectively the circulation rate along the contour is also low. When the warm-up of the sections of the heat exchanger increases, the lifting force, driving the heat carrier along the contour increases too. Simultaneously with this process the input of cold water from the BAOT to the bottom of the heat exchanger takes place which reduces the driving force. Such processes have a periodic character.

The frequency of fluctuation rate of the heat-carrier (and respectively flow rate) in the middle part of the section of a heat exchanger-condenser in terms of computing experiments is.

Pulse character of the movement is in all modes from the initial start-up period to the transition to a quasi-stationary regime illustrated in Fig. 5.

Conclusion. Within the limits of formal templates of COMSOL Multiphysics software package was developed a spatial model analogue of processes of thermal mass transfer into passive heat removal systems from a protective cover of NPP.

It is shown that the intensity of the circulation of the heat-carrier in the contour of a passive heat removal system is cyclical. This computational result agrees with the findings of experimental investigations on the natural samples of SPOT ZO. In this paper possible physical reasons for this phenomenon at the initial stage of the work of SPOT ZO are given. However, during the heat transfer processes in the boiling medium of heat carrier the pulsed character of the work of spot can be associated with the phenomenon of dynamic instability of a cooling system due to the crisis of boiling of the second kind.

It was found in the calculations that depending on the temperature conditions under the dome and on the heat removal on the heat exchange surface the specific heat flow is from 2 to 5 kW/m^2 per one section (64 sections) that corresponds to the total heat flow from 60 to 150 kW.

A designed computational template and the results of this study can be used to analyze the safety of the Belarusian nuclear power plant.

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