Modeling of corium melt cooling during severe accidents at the nuclear power plants

ALI KALVAND AND IVAN KAZACHKOV[1]
Department of Heat and Power, National Technical University of Ukraine “KPI”
Polytekhnichna str., 37, B. 5, 02056, Kyiv, UKRAINE
[1]Also Affiliated Professor at the Royal Institute of Technology, Stockholm, SWEDEN
Ivan.Kazachkov@energy.kth.se
http://researchprojects.kth.se/index.php/kb_7955/pb_1129/pb.html

Abstract: - This paper is devoted to an analysis of the problem of a corium melt interaction with the water and low-melting temperature blocks in the passive protection systems against severe accidents at the nuclear power plants (NPP), which is of high importance for a substantiation of a nuclear power safety, for building and successful operating of the passive protection systems. In the third-generation reactors the passive protection systems against severe accidents at the NPP are mandatory, therefore the topic of this paper is of importance for the nuclear power safety. A few such systems have been considered, which are in different stage of completeness.

An analysis of the unsolved thermal hydraulic problems, which solution might help to an improvement of the current systems or to a development of the new ones, more effective, has been provided. The ways for solution of the stated problems and the methods for their successful elaboration were discussed. The mathematical models developed and analysis performed in the paper might be helpful for a design of the passive systems for the corium melt retention inside the containment after a corium melt eruption from the failed reactor vessel.

In the paper a problem of a mathematical modeling of corium melt coolability with the water and low-melting temperature blocks was considered. A few most successful passive systems and their characteristic thermal hydraulic problems were analyzed and discussed. The paper has shown how a modeling and computer simulation has to improve the constructions of the passive protection systems against severe accidents. The problem statement has been done for a future investigation too.

Key-Words: - Modeling, Corium, Passive System, Melting Blocks, Severe Accident, Nuclear, Coolability.

1 Introduction to the problem

The melt-water, melt-vapour and melt-solid blocks interaction would involve film boiling, intensive evaporation up to a steam explosion, melt fragmentation and solidification, and many other complex problems of the modern multiphase flow dynamics. This is a problem of so-called “hypothetical severe NPP accidents” scenario modeling.

Assuming the high temperature molten core material encountering water and solid block of a low telting temperature material, one can consider the above-mentioned case study scenario. If a vapor film around discrete melt fragments collapse, the interaction with the water can result in steam explosions. Such events are of potential safety concern, partly due to the dynamic loading on reactor (containment) structures, and partly due to a generation of the fine debris particles, which could have a negative impact on the long-term coolability of the core material.

In general, a problem of a corium melt cooling down and controlling nuclear fuel temperature regime is of paramount interest for nuclear power safety and construction of the new third generation nuclear power plants, which have to install mandatory passive protection system against severe accidents. As far as many countries still have interest to develop and use nuclear power plants being not able presently to get alternative energy sources, the problem of NPP safety is really important and a number of world-wide known laboratories pay attention to this problem.

A problem of the fuel cooling down and its fragmentation is also of a great importance for a lot of the modern industry and technology tasks:

metallurgy, chemical technology, energy, and so on. Because of complexity of the real physical systems, which are high-temperature multiphase multicomponent in their nature, there are also considered such processes together with another ones, for example, phase crystallization and flows through porous (granular) media. A studying of such complicated problems came true only in the last decades due to very impressive achievements of a computer science and of a mathematical simulation. It is worthwhile to underline that a number of different problems were studied in touch with the basic features of the severe accidents' progression during the past two decades [1-12].

Ex-vessel melt (debris) coolability revealed as a critical safety issue for the current and for the future NPP with water reactors with respect to stabilization and termination of the postulated severe accidents with a core melt down. Late phases of a severe accident progression are associated with a corium melt discharge from the reactor vessel and further spreading of it on the concrete basemat in the current NPP of the second generation or in a core-catcher in future plants of the third generation. The accident would be considered terminated when the coolability (quenching and solidification) of the melt/debris bed is achieved in the long term.

The liquid-vapour and liquid-solid interfaces are prone to different types of instabilities being subjected to the influence of diverse physical factors and parameters, e.g. temperature of the phases and their physical properties (viscosity, surface tension – for the liquid phase, heat conductivity and its dependence of temperature, latent heat, heat capacity of the phases, etc.).

For example the sizes of a melt frangments and surface tension predetermine the regime of vapour flow and a character of instabilities at the interface. Drop with surfactants will also be subjected to the additional surface forces strongly depending on changeable physical properties of the melted fuel (corium – melt with diverse additing being involved during a melt spreading inside the reactor vessel and in a containment after reactor vessel destroy).

The processes considered may vary from a point-to-point in a domain being, strictly speaking, chaotic. The intensity of vapour flow depends on the plate temperature and drop properties (size, density, capillary forces and viscosity), which, in turn, are also subjected to the temperature variation.

A most convenient management measure for the severe NNP accident is a controlled cooling of the corium melt and debris, therefore one of the many different proposals was to establish a water layer on a top of the melt pool. This coolability scheme has been investigated extensively in the MACE experiments (Sehgal *et al.* 1992 and Merilo *et al.* 1997) where was found a crust formed on the upper surface of the melt pool, which limits an access of a water to a melt pool.

An understanding of the peculiarities of the interaction phenomena of the melt corium-water-vapour and solid blocks of low melting temperature, e.g. numerical models of molten core spreading processes [1, 2], ex-vessel coolability of a molten pool by coolant injection from submerged nozzles and other scenario [3-5, 10, 12], cooling the particles of corium after their solidification [6, 8, 9, 10, 12], cooling the corium melt layer by injection of water jets [7, 10, 12], etc. are highly important for nuclear power safety problems.

The melt-water interaction phenomena important for the conditions governing behaviors of corium coolability inside containment during severe accidents at the NPP, as well as their modeling are analyzed and the basic modeling approaches are studied. The problem may be of interest for many other industrial and technological situations where interaction of high-temperature melts and solid materials with liquids and vapours mainly predetermine the character of the processes.

2 Modelling of a corium cooling inside the NPP containment

The issues of safety and reliability are critical to the design of the future reactors of the third and forth generation. The third generation reactors started already implementing into the operation and they have to substitute the existing reactors completely during the next two decades.

Except the increased nuclear power safety requirements, the reactors' designs must also be thermodynamically competitive and cost effective. Thus, the use of materials which can withstand higher temperatures (in a harsh radiation and chemical environment), which are operable in the environments other than water and steam will likely be very important to consider in the future perspectives.

These materials must also be highly reliable, and their reliability must be understood and well documented. A large amount of operational data related to component and system performance already exists, and these data will need to be extended, reviewed, and consolidated into reactor designs. Advanced monitoring techniques which enable timely operator intervention, along with passively-safe system and component designs will also be important for the future scientific investigations and engineering designs.

Ability to accurately model the fluid flow and heat transfer capability of the reactor coolants is vital to an understanding the margins to a nuclear power safety in any reactor plant. Continued improvement of the analytical tools in a design-basis accident (DBA) have already resulted for some cases in elimination of these events from establishing limiting conditions for a normal operation (e.g., peak fuel rod power, power shape, etc.) in the currently-operating water reactors. This trend is expected to continue as more utilities turn to so-called "best-estimate LOCA" codes. As a result of such situation, the transient events and the local thermal-hydraulic (TH) conditions likely establish the limiting operating conditions.

The above important feature is expected to be true for the future water reactor designs too. For another reactor types (for example the liquid-metal reactors or the gas-cooled reactors), the local TH models are essential for analyzing the core TH performance. Improvements in smaller-scale, local thermohydraulics models, e.g. subchannel TH models, computational fluid dynamics models could lead to a reduced conservatism and to an improved economics in the nuclear power plant operations.

Thermal hydraulic modeling in the systems of high-temperature corium melt-water-vapour-solid blocks with low melting temperature is one of the most complex problems in the modern multicomponent multiphase flow dynamics and heat transfer. Thermal hydraulics in a volumetrically heated porous layer has been reported recently in many publications, e.g. [5, 6, 8, 9, 12]. The linear energy equation for the solid/gas mixture was solved numerically by Choudhary M.V. and El-Wakil N.M (1970). Volumetrically heated porous layer cooled with forced flow evaporation was studied by Polyaev V.M. with co-workers (1988) and Naik A.S. and Dhir V.K. (1982).

One-dimensional energy equations for the particles and coolant solved by Naik and Dhir under assumption of no differences in solid/liquid temperatures showed reasonable correlation for a water-steam flow at atmospheric pressure. The experimental and analytical study of dryout heat flux in the inductively heated beds showed no satisfactory correlation of data obtained by a few researchers, e.g. Hofmann G. (1984).

Based on equations derived by Nigmatulin R.I. (1978) for saturated monospherical particle layer in heterogeneous non-thermal equilibrium approach, a 2-D model and numerical algorithm were developed by Kazachkov I.V. (1986) for a steam flow in a particle layer surrounded by an impermeable medium.

First the model was used for geothermal system in numerical simulation of a non-stationary non-isothermal filtration and then the model was modified to describe dryout location by introducing the initial thermodynamic perturbations, which may lead to abnormal temperature escalation in a local subdomain [6, 8, 9].

Sözen and Vafai presented [13] a general set of the volume-averaged governing equations for the non-thermal equilibrium condensing forced flow through a latent heat storage porous media. And a comprehensive numerical study of the phenomenon has been done.

Kuznetsov [14] performed such analysis of the full energy equations for incompressible fluid and solid phases using the perturbation technique and showed that the temperature difference between fluid/solid phases in a semi-infinite packed bed forms a spatially localized wave. Then he investigated a thermal behavior of a three-dimensional porous bed in a non-thermal equilibrium flow through it assuming the constant thermal, physical and transport properties.

3 The non-linear model of a jet penetration into the liquid pool

A detail study of a two-dimensional non-stationary non-isothermal gas (steam) filtration through a monospherical particle layer under internal heat generation with an emphasis on the non-thermal gas/particle local equilibrium and non-linear properties of media has been performed by Kazachkov I.V. and Konovalikhin M.J. [6].

Fig. 1 presents schematically the physical problem considered.

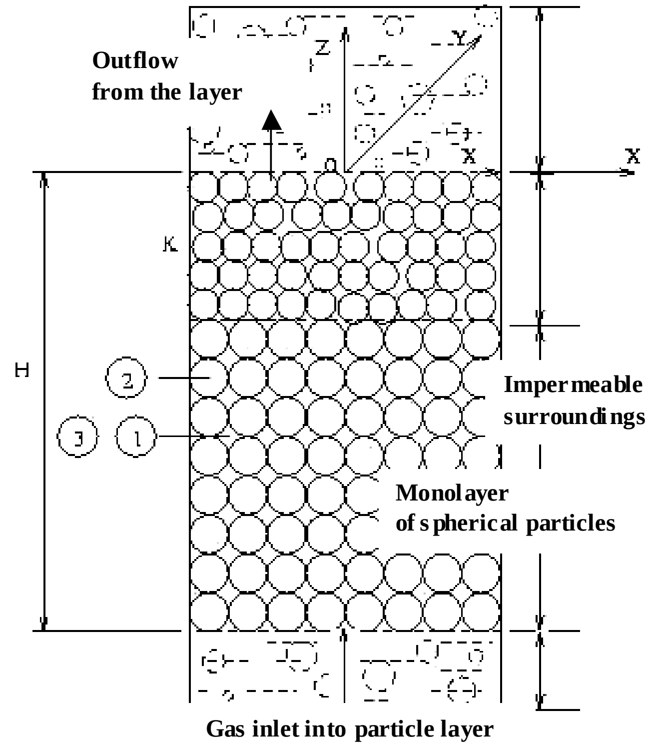

Fig. 1. Scheme of heterogeneous particle-gas medium.

A two-dimensional self-heated porous packed bed, which consists of homogeneous spherical particle layer is filled with a gas (steam), which moves from the bottom to the top, and is initially at the known temperature distribution. The following assumptions were employed by a development of a mathematical model:

- The flow is single phase and is compressible (gas, steam)
- The particles' sizes are significantly greater than molecular-kinetic scales, but significantly less than the characteristic scale of the system
- The physical properties of the media such as thermal conductivity, viscosity, density, etc. are temperature dependent
- Solid particles are immovable and porosity is constant in each monolayer.

The mathematical model of gas filtration in a spherical particle monolayer is presented as [6]

$$w_1 = (1-\alpha_1)\left[\mathbf{Pe} - \kappa_\rho \mathbf{Ra}^*(T_2 - T_{20}) - \mathbf{Re}_*^2 \frac{p_1}{T_1}\right]\left(\frac{T_{10}}{T_1}\right)^m,$$

$$\frac{\partial \rho_1^0}{\partial \mathbf{Fo}} = -\rho_1^0\left(\frac{\partial u_1}{\partial x} + \frac{\partial w_1}{\partial z}\right), \quad u_1 = -\frac{\partial p_1}{\partial x}\left(\frac{T_{10}}{T_1}\right)^m,$$

$$\frac{\partial p_1}{\partial z} = \mathbf{Pe}(\alpha_1 - 1)\left[1 - \Delta_2(T_2 - T_{20})\right] - \mathbf{Re}_*^2 \frac{\alpha_1 p_1}{T_1},$$

$$\frac{\partial T_1}{\partial \mathbf{Fo}} = (1-\gamma_1)T_1\left(\frac{\partial u_1}{\partial x} + \frac{\partial w_1}{\partial z}\right) - \left(u_1\frac{\partial T_1}{\partial x} + w_1\frac{\partial T_1}{\partial z}\right) +$$

(1)

$$+(\gamma_1 - 1)(u_1^2 + w_1^2)\left(\frac{T_{10}}{T_1}\right)^m \frac{T_1}{p_1} + \frac{\gamma_1 \mathbf{Pe}(T_1/T_{10})^m}{\alpha_1 \kappa_a \kappa_\rho \mathbf{Re}_*^2 p_1}\cdot$$

$$\cdot\left\{T_1\left(\frac{\partial^2 T_1}{\partial x^2} + \frac{\partial^2 T_1}{\partial z^2}\right) + m\left[\left(\frac{\partial T_1}{\partial x}\right)^2 + \left(\frac{\partial T_1}{\partial z}\right)^2\right] + \xi \mathbf{Nu}_1 T_1(T_2 - T_1)\right\},$$

$$\frac{\partial T_2}{\partial \mathbf{Fo}} = \frac{(1-\alpha_1)^{-1}}{1-\Delta_2(T_2 - T_{20})}\left[\frac{\partial^2 T_2}{\partial x^2} + \frac{\partial^2 T_2}{\partial z^2} + \xi\frac{\mathbf{Nu}_1}{\kappa_k}\left(\frac{T_1}{T_{10}}\right)^m (T_1 - T_2)\right] + \mathrm{Q_V},$$

$$\frac{\partial T_3}{\partial \mathbf{Fo}} = a_{32}\left(\frac{\partial^2 T_3}{\partial x^2} + \frac{\partial^2 T_3}{\partial z^2}\right).$$

The equation array (1) is represented in a dimensionless form with the following length, time, velocity, pressure and temperature scales introduced, respectively: H, H^2/a_2^0, a_2^0/H, $\mu_{10}a_2^0/K_0$ and ΔT, where ΔT is a characteristic temperature in the system, a_2^0 is heat diffusivity for the particles, μ_1 is gas viscosity and K_0 is permeability of the particle layer. Bottom zero index depicts the values taken by initial temperature.

Here the first two equations describe the gas filtration velocities by x and z, respectively. Then the other two equations represent mass conservation (continuity equation) and momentum conservation equation. Further there are three energy equations for the gas, permeable particles of the layer and impermeable surrounding medium, respectively.

The term Q_V in the energy equation for particles is intensity of internal heating. Actually internal heating can be ogranized in a gas flow as well or in the both phases. The other two important peculiarities of the mathematical model (1) are connected to an account of the non-linear properties of the both phases (the most important among them is a non-linear heat conductivity of a gas, which depends on its temperature variation substantially, in some temperature range - dramatically) and local heat transfer between the phases (gas/particle).

Here the following dimensionless criteria are introduced: $\mathbf{Pe} = w_0 H / a_2^0$, $\mathbf{Ra}^* = \mathbf{GrPr}^*\mathbf{Da}$, $\mathbf{Gr} = g\Delta_2 H^3 \nu_{10}$, $\mathbf{Pr}^*$, $\mathbf{Fo} = a_2^0 t / H$ and $\mathbf{Da} = K / H^2$ - the Peclet, Rayleigh, Grasshoff, Prandtl, Fourier and Darcy numbers, respectively, $\mathbf{Re}_*^2 = gH/(R\Delta T)$. Then $w_0 = \rho_{20}^0 Kg / \mu_{10}$ is a characteristic filtration velocity, a is a heat diffusivity, e.g. $a_1^0 = k_1^0/(c_{p1}\rho_{10}^0)$. The other parameters are: $\kappa_a = a_2^0 / a_1^0$, $\kappa_\rho = \rho_{20}^0/\rho_{10}^0$, $\kappa_k = k_2 / k_1^0$, $k_{32} = k_3 / k_2$, $\gamma_1 = c_{p1}/c_{v1}$, $a_{32} = a_3 / a_2^0$, $\xi = s_{12} H^2 / b_1$ (parameter of a granular layer structure), s_{12} is a specific interfacial area, $b_1 = b\sqrt{2(2-\pi/3)\pi}$ is the characteristic radius of the pores, b - particle's radius (constant in the each monolayer), $\Delta_2 = \Delta T \beta_{T2}$, β_{T2} is a particle's thermal expansion coefficient.

4 Statement of the initial and boundary conditions

The dimensionless initial and boundary conditions for the equation array (1) are stated as follows:

$$\mathbf{Fo} = 0, \quad p_1 = p_1^0(x,z), \quad T_j = T_j^0(x,z), \quad \text{j=1, 2, 3;}$$

$$z = 0, \quad p_1 = p_1^{top}, \quad \frac{\partial^2 T_1}{\partial z^2} = 0, \quad \frac{\partial T_j}{\partial z} = N_j^{top}(T_j - T_{top}), \quad \text{j=2, 3;}$$

$$z = -1, \qquad T_j = T_{jH}, \qquad \text{j=1,2,3;}$$

(2)

$$x = 0, \quad \frac{\partial T_1}{\partial x} = \frac{\partial T_2}{\partial x} = 0; \qquad x = x_\infty, \quad \frac{\partial T_3}{\partial x} = 0;$$

$$x = x_L, \quad u_1 = 0, \quad T_j = idem, \quad \frac{\partial T_2}{\partial x} = k_{32}\frac{\partial T_3}{\partial x}.$$

If the gas state equation is used, the initial gas pressure spatial distribution $p_1 = p_1^0(x,z)$ in (2) can be identically replaced by a gas density distribution $\rho_1^0 = \rho_{10}^0(x,z)$. The initial surrounding's temperature distribution $T_3 = T_3^0(x,z)$ was chosen uniform, at least by one coordinate, or constant in the whole domain.

The surroundings may do the heat release from the saturated particle layer or perform the thermal isolation of the layer. In the last case, the energy equation for the surroundings is omitted with the sidewall′s temperature kept constant.

The system is considered symmetrical relatively to the vertical axis. The normal velocity is zero at the non-permeable boundary, where the continuity of the temperature profiles and heat fluxes must be satisfied.

Equation array (1) coupled with the initial and boundary conditions (2) represent the mathematical model of the heterogeneous system considered.

5 Peculiarities of the mathematical model obtained

In the multiphase system considered above the interactions of the following three different processes occur: non-thermal equilibrium between the gas flow and solid particles in the layer, non-linear processes′ mutual influence and non-linearity of the physical properties of the gas and particles. Properties of a gas are strongly depend on the temperature and pressure.

The first above-mentioned peculiarity is touched with the term $\xi(T_1 - T_2)$, which describes the local heat transfer between the particles and the gas flow through it. From a mathematical point of view it causes some limitation on a parameter ξ because the term $\xi(T_1 - T_2)$ in the energy equations for solid particles and gas flow becomes huge in case of the very small particles.

Thus, the energy equations have terms of a type “∞□0” because by the small particles of a layer a temperature difference $(T_1 - T_2)$ is going to zero while *H/b* is growing. Therefore as the temperature difference between particles and gas flow is going to zero, there is the homogeneous mixture in limit. In such case the heterogeneous system considered should be replaced with the homogeneous one to avoid this peculiarity causing numerical inaccuracy. Therefore the only heterogeneous case is considered here.

The other new phenomenon supposed to be in the system due to localization of the dissipate processes caused by a non-linear heat conductivity. This phenomenon was studied at first by Samarskii et. al. [15] for the quasilinear parabolic equations, e.g. 1-D equation with a non-linear heat conductivity $k = k_0 T^m$ (m=0.5–1.0). Some gas and steam conductivities follow this power law under certain range of the temperature and pressure distributions. In our case all these phenomena are interconnected that makes the problem especially complex and interesting for the numerical simulation and analysis of the severe accidents' scenario.

6 Heat transfer between coolant and corium melt

Heat transfer between the coolant and the melt pool which undergo to a phase change (solidification) is analysed with the objective to quantify the effect of the pool physical properties and the initial conditions on the possible crust formation in the boundary layer of the coolant path which could prevent further pool-coolant mixing. Several studies have been made in the mathematical modelling of binary metal or oxides solidification.

A few studies try to perform quantitative comparison with the experimental data. The problem is difficult because a number of different properties of the process and corium affect the results and not all of them are well known and easy to control. Even with the computer codes that agree with experiments well enough it is hard to gain a deeper insight into the phenomena.

The results of computer simulations by model (1), (2) allow precise studying the spatial and temporal distribution of parameters in general dimensionless form (Fig. 2). But in many cases due to a lack of data in a range of parameters the experimental data are presented in dimensional form for the particular systems, and it is difficult to draw any general conclusions.

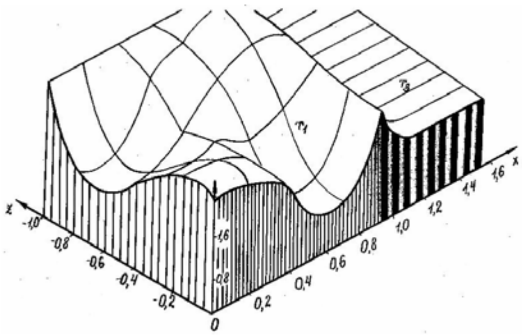

Fig. 2. Calculated temperature distribution in a layer.

During the solidification three regions are distinguishable in the mold containing solid (at the boundary of the coolant flow path) mush and liquid melt respectively. The experimental data obtained for the diverse melt simulants and also for comparison with corium in order to obtain a clearer picture on the effect of material properties and initial conditions on the solidification mechanisms of a hot melt cooled by injecting water were got by a number of authors, e.g. [1-5, 10,11].

Depending on the combination of the physical properties of corium and melted sacrificial blocks one can identify different cooling behaviours. The heat flux should be assessed between the coolant and the melt contacting it. Expressing the heat transfer as $q = h \cdot \nabla T$, where h is the local heat transfer coefficient and ∇T is the melt-coolant average temperature difference.

7 Conclusions

Modeling of a corium melt cooling during the severe accidents at the nuclear power plants is a complex problem of a modern dynamics of the multiphase systems.

It is important for the design and operation of the passive protection systems against the severe accidents at the NPP that corresponding passive system without any help from the personal and automatics are able to effectively remove all collected and permanently produced by nuclear fuel heat.

The passive protection system has to keep controlled cooling of the fuel during the requested temporal interval before the corresponding necessary measures are taken by NPP personal. It is discussed and revealed in the paper all the range of the problems in touch with thermal hydraulic processes leading the features of the passive protection systems. Non-linear physical properties as shown by numerical simulation may cause specific features of the system.

References:

[1] L.A. Bolshov, et al. Numerical models of molten core spreading processes in nuclear reactor safety problems/ *Proc. 4th Int. Topical Meeting on Nuclear Thermal Hydraulics*.- Operations and Safety. April.- Taipei.- Taiwan.- 1994.

[2] V.V. Asmolov. Latest findings of RASPLAV Project/ *Proc. OECD/CSNI workshop on in-vessel core debris retention and coolability*.- 1998.

[3] N.I. Kolev. Verification of IVA5 computer code for melt-water interaction analysis/ *Proc. NURETH-9*.- 1999.

[4] I.V. Kazachkov, D. Paladino, B.R. Sehgal, Ex-vessel coolability of a molten pool by coolant injection from submerged nozzles/ *9th Int. Conf. Nucl. Energy Devel*.- Nice.- France.- 2001.

[5] H. Alsmeyer, B. Spencer, W. Tromm, The COMET-concept for cooling of ex-vessel corium melts/ *Proc. of ICONE-6*.- May 10-15.- San Diego.- 1998.

[6] I.V. Kazachkov and M.J. Konovalikhin. A Model of a Steam Flow through the Volumetrically Heated Particle Bed// *Int. J. Thermal Sciences*.- 2002.- Vol.41.- P. 1077-1087.

[7] H.S. Park, I.V. Kazachkov, B.R. Sehgal, Y. Maruyama and J. Sugimoto. Analysis of Plunging Jet Penetration into Liquid Pool in Isothermal Conditions/ *ICMF 2001*: *4th Int. Conf. on Multiphase Flow*.- New Orleans.- Louisiana, USA.- May 27 - June 1, 2001.

[8] M.J. Konovalikhin, I.V. Kazachkov, and B.R. Sehgal. A model of the steam flow through the volumetrically heated saturated particle bed/ *ICMF 2001*: *4th Int. Conf. on Multiphase Flow*.- New Orleans.- Louisiana, USA.- May 27 - June 1, 2001.

[9] I.V. Kazachkov, M.J. Konovalikhin and B.R. Sehgal, Coolability of melt pools and debris beds with bottom injection// *2nd Jap.-EU Two-Phase Flow Group Meeting*.- Tsukuba.- Japan.- 2000.

[10] I.V. Kazachkov. Modern status and problems of a modeling of severe accidents at NPP// J. Nuclear and Radiation safety.- 2003.- № 1.- P. 25-34 (In Russian).

[11] S.V. Bechta, S.A. Vitol, E.V. Krushinov, V.S. Granovsky et all. Water boiling on the corium melt surface under VVER severe accident conditions// Nuclear Engineering and Design.- 2000.- v.195.- P. 45-56.

[12] I.V. Kazachkov, A. Moghaddam. Modeling of thermal hydraulic processes during severe accidents at NPP.- Monograph.- Kyiv: NTUU "KPI".- 2008.- 172 pp.

[13] M. Sözen and K. Vafai. Analysis of the Non-Thermal Equilibrium Condensing Flow of a Gas Through a Packed Bed// Int. J. Heat Mass Transfer.- 1990.- V. 33.- N 6.- P. 1247-1261.

[14] A.V.Kuznetsov. An Investigation of a Wave of Temperature Difference between Solid and Fluid Phases in a Porous Packed Bed// Int. J. Heat Mass Transfer.- 1994.- V. 37.- N 18.- P. 3030-3033.

[15] A.A. Samarskii, V.A. Galaktionov, S.P Kurdjumov and A.P. Mikhailov. Blowing-up in the Problems for Quasilinear Parabolic Equations.- Moscow: Nauka.- 1987.- 462 pp.