18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18-P02-4

RADIATIVE HEAT EXCHANGE MODEL FOR LATE PHASE OF SEVERE ACCIDENT AT VVER-TYPE REACTOR

A.E. Kiselev
Phone: +7(095)955-2273
Fax: +7(095)958-1151
E-mail: ksv@ibrae.ac.ru

G.V. Kobelev
Phone: +7(095)955-2273
Fax: +7(095)958-1151
E-mail: kgv@ibrae.ac.ru

V.F. Strizhov
Phone: +7(095)955-2218
Fax: +7(095)958-1151
E-mail: vfs@ibrae.ac.ru

A.D. Vasiliev
Phone: +7(095)955-2269
Fax: +7(095)958-1151
E-mail: vasil@ibrae.ac.ru

Nuclear Safety Instutute, Russia,
Moscow 113191, B.Tulskaya 52

ABSTRACT

In the course of a hypothetical severe accident at VVER-type reactor the temperatures inside the reactor vessel reach high values at which taking into account of radiative heat exchange between the structures of reactor (including core and other reactor vessel elements) gets important. Radiative heat transfer dominates the late phase of severe accident because radiative heat fluxes (proportional to T^4, where T is the temperature) are generally considerably greater than convective and conductive heat fluxes in a system. In particular, heat transfer due radiation determines the heating and degradation of core and surrounding steel in-vessel structures both at the initial stage and at the stage of melt retention in the reactor vessel lower head and finally influences the composition, temperature and mass of materials pouring out of the reactor vessel after its loss of integrity.

The purpose of this work is to develop a universal module which is able to model radiative heat exchange in VVER-type reactor vessel both inside the core and between the core and in-vessel structures under severe accident conditions. The approach presented in this paper for radiative heat exchange problem is developed on the basis of classical principles and special methods which allow to evaluate radiation heat fluxes in steam-noncondensables medium in cases of intact geometry, partial and total degradation of structures including the appearance of porous debris and liquid pools in the core region and the reactor vessel lower head.

The main differences between the model developed in this paper and existing radiative heat exchange models (implemented to severe accident codes such as ICARE, SCDAP/RELAP, MELCOR) include special logic for calculation of view factors and mean beam lengths taking into account significant change of geometry; application to the geometry of VVER; non-stationary heat transfer on the basis of effective radiative thermal conductivity (proportional to T^3) in the core layers with considerable temperature gradients; principal taking into account of axial radiative heat transfer along with radial transfer (tensor approach to radiative thermal conductivity); using of exact analytical values of view factors and mean beam lengths (which are a good tool in radiative heat transfer concerning gas media) for a number of “standard” geometries.

This model is implemented to the Russian best estimate code RATEG/SVECHA/HEFEST and is used for the calculation of radiative heat exchange during a hypothetical loss-of-coolant accident at VVER-1000.

Keywords: Severe accident, reactor, effective radiative conductivity, view factor, mean beam length.

1. INTRODUCTION

Radiative heat transfer inside the vessel of VVER-type nuclear reactor plays very important role during a hypothetical severe accident. Radiative heat exchange between different structures of reactor (radiative heat transfer in the core, between the core periphery and the baffle, between the core and the block of protective tubes (BPT), the support grid, the plates of BPT, the corium surface in the lower plenum etc., Fig. 1) in much extent governs the core center and periphery heat-up dynamics, the heat-up and the extent of degradation of surrounding in-vessel steel structures both at initial and late phases of severe accident and finally influences the output of mass, energy and hydrogen after the reactor vessel loss of integrity.

It is necessary to note that the exact solution of radiative heat exchange problem in the reactor vessel is very complicated due to the following circumstances:

- the construction of reactor core and in-vessel structures itself is rather complicated for rigorous statement and solution of radiative heat exchange problem;
- non-uniform, non-stationary temperature field spatial distributions arise in the course of an accident; the calculation of these temperature fields should be fulfilled self-consistently with radiative heat exchange problem;
- severe accident evolution is accompanied by change of emissivity of surfaces and the dramatic change of geometry of construction elements up to their total degradation;
- surrounding gas absorption and emission has considerable effect to radiative heat exchange problem; the parameters of steam-noncondensables medium (density, temperature, concentration of noncondensables) change also considerably during an accident.

This is why some approximate methods are generally used to estimate the radiative heat transfer inside the reactor vessel. These methods are based on different approximation approaches to model geometry of elements inside the reactor vessel and to describe temperature distribution in them. The approaches and the extent of detailed description of core and in-vessel structures accepted for numerical modeling of the accident scenario has a considerable impact on methods of radiative heat exchange problem solution. The thing is that in numerical modeling of severe accidents the number of calculational elements modeled is limited and determined by the general requirement to numerical codes – ensuring of acceptable computational speed in the course of joint solution of several problems including the thermal hydraulics, the physical and chemical processes description, the core and in-vessel structures degradation dynamics and the radiative heat exchange.

Beside that, radiative heat exchange module should ensure:

- sufficient accuracy of the radiative heat exchange problem's solution when the extent of detailed description of core and in-vessel structures is given by external thermal hydraulic code;
- high computational speed and stability of running in the integral code designed for severe accident description;
- some universality which would allow to apply the module to different types of reactors and to different nodalizations within the bounds of one type of reactor.

The purpose of this work is the development of a universal module MRAD which is able to model radiative heat exchange in VVER-type reactor vessel. The main application of the module MRAD is its using as part of best estimate codes for modeling of severe accidents at nuclear power plant with VVER.

Radiative heat exchange in the reactor vessel is computed in this model using dividing on zones (zonal method) as in existing radiation models implemented to severe accident numerical codes such as ICARE (Gonzalez *et al*., 1993), SCDAP/RELAP (Siefken *et al*., 2000), MELCOR (Summers *et al*., 1994). The zonal method means that thermal elements are divided into zones (surfaces) with uniform temperature within the bounds of one zone. The interaction of radiation with participating medium is an important part of calculations.

The main differences of modeling methods taken in the model MRAD in comparison to above-mentioned models are summarized below:

- the special logic for computation of view factors and mean beam lengths taking into account the complicated character of changing of these parameters as far as geometry is changed in the course of an accident;

- the precise analytical expressions were derived for view factors and mean beam lengths for complex systems of interacting surfaces;
- the geometrical distinctive features of VVER-type reactor are taken into account (for example, triangular set of fuel rods in the core);
- the principal taking into account of axial radiative heat transfer along with radial transfer which corresponds to tensor character of radiative thermal conductivity;
- the non-stationary heat transfer is modeled in the core periphery (where large temperature gradients are present) which makes possible to estimate more adequately the radiative heat fluxes from the core periphery to surrounding structures.

The important parameters of view factor and mean beam length are a good tool in radiative heat transfer concerning gas media in a system of surfaces. These parameters are used in the system of equations for radiation fluxes. Moreover, the evaluation of these parameters is also necessary to determine the radial and axial effective radiative thermal conductivities in the core region.

The fundamental contribution to the development of theoretical basis and computation of radiative heat exchange in the system of bodies was given in classical works of Hottel and Sarofim (1967) and Surinov (1975). These made the basis for development of modern engineering zonal methods of radiative heat transfer phenomena in complicated systems of bodies surrounding by participating media.

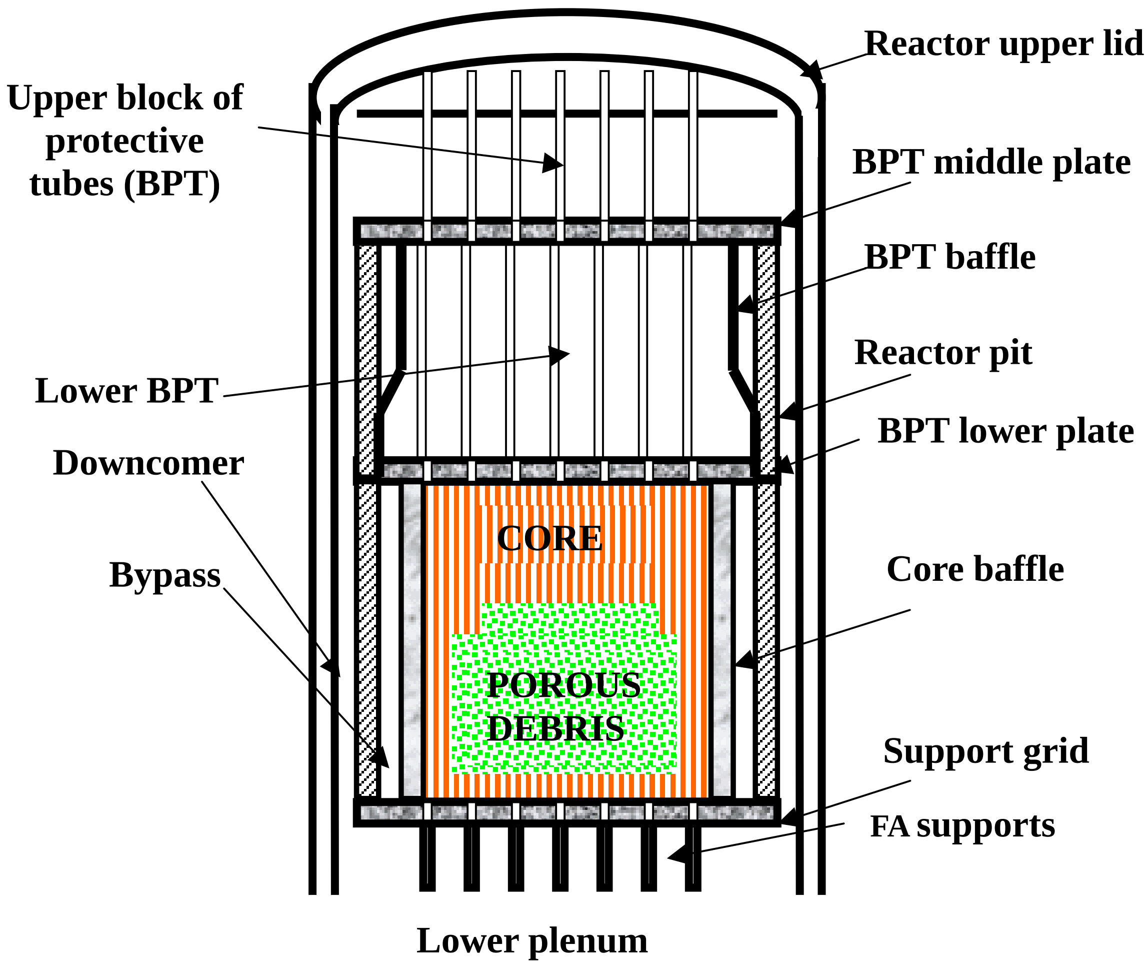

Fig. 1. Schematic picture of VVER-1000 basic elements which take participation in radiative heat exchange at in-vessel-stage of hypothetical severe accident.

Some limiting assumptions are generally made to determine analytically view factors and mean beam lengths. Hottel's method of strings (Hottel and Sarofim, 1967), for example, is valid when interacting bodies have infinite length in one dimension. Another case is the evaluation of mean beam length from geometric mean beam length, which is only valid for the optically thin limit. For example, the geometric mean beam length between two coaxial cylinders of infinite length was obtained by Andersen and Hadvig (1989).

Some examples of view factor and mean beam lengths evaluation for structures of pressurized water reactor are given in the literature (Vasiliev and Kobelev, 2003). The geometry of LWR is characterized by a large number of surfaces participating in radiative heat exchange and a considerable role of participating medium (especially steam) in absorption and emission of radiation.

New analytical expressions for view factors and mean beam lengths for a number of "standard" axial symmetry geometries, including rings of arbitrary finite thickness located on cylinder sides and coaxial cylinders of finite length are used in the module MRAD. These expressions do not use the assumption of infinite length in one dimension, also, they allow to estimate the mean beam length for arbitrary optical thickness.

The radiative heat exchange problem is solved in the module MRAD both for intact (initial) geometry and for new geometry which is changed from initial one as a result of thermal expansion, melting, flowing, degradation, slumping of elements in the course of an accident which is described by following means:

- All participating surfaces are included in the system of equations for heat fluxes from the very beginning of computation (even if some surfaces do not participate in the radiative exchange yet);
- At every time step new view factor and mean beam lengths are estimated taking into account modified dimensions during thermal expansion, melting and candling;
- If, as a result of degradation or relocation, some radiation surface disappears and the visibility arises between two other surfaces then non-zero view factors are calculated for these surfaces;
- If some surface has disappeared (relocated) then view factors of this surface get equal to zero.

The distinctive feature of the model presented in this paper is taking into account of the principally non-uniform temperature profile in the core periphery. The non-stationary heat transfer problem is solved in the core region using the energy equation with effective radiative thermal conductivity. The radiative thermal conductivity is a tensor value with different axial and radial components.

High computational speed is ensured due to using of effective iteration method of solving radiative heat exchange system and due to using of analytical expressions for view factors and mean beam lengths for a broad range of geometries.

2. BASIC EXPRESSIONS FOR ZONAL METHOD

2.1 Basic Assumptions Made

We deal with homogeneous, absorbing, emitting and non-scattering gas in a system of surfaces. When the radiation exchange from one surface to another is considered the gas between these surfaces is assumed to have uniform temperature, pressure and concentrations of mixture components. The gray medium model is used that is absorption coefficient is averaged on spectrum and independent of wave length or only wave length interval with constant absorption coefficient is considered. The emissivities of surfaces are also averaged on spectrum. The radiation exchange between surfaces takes a diffusive character.

2.2 Governing System of Equations

For outgoing radiation flux q_i^- from an area S_i the following expression is valid:

$$q_i^- = \sigma\varepsilon_i T_i^4 + (1-\varepsilon_i)q_i^+, \qquad (1)$$

where q_i^+ denotes incoming radiation flux to an area S_i. In equation (1) the first term in right-hand side is the emmitance of an area and the second term is responsible for flux scattered by this surface. Let us present the incoming flux as in a following manner:

$$q_i^+ = \sum_k q_{ik}^+ \quad , \qquad (2)$$

that is as sum of incoming fluxes from individual areas q_{ik}^+.

The net balance of radiation fluxes for an area S_i is written as

$$q_{ik}^{+} S_i = q_k^{-} S_k \varphi_{ki} \exp(-a_{gki} L_{ki}) + \varepsilon_{gki} \sigma T_g^4 S_k \varphi_{ki} \quad , \tag{3}$$

where

$$\varepsilon_{gki} = 1 - \exp(-a_{gki} L_{ki}) = 1 - \exp(-\tau_{gki}) \quad , \tag{4}$$

is the absorptivity of a medium; a_{gki} is the absorption coefficient of a steam-noncondensables medium between areas considered taking into account the chemical composition of the medium; L_{ki} is the mean beam length between areas S_i and S_k (precise determination of this parameter is given in Chapter 2.3). The parameter $\tau_{gki} = a_{gki} L_{ki}$ is called as the optical thickness of medium between area elements S_i and S_k. In particular, the medium is considered as optically thin as τ_{gki} <<1.
Remember that for view factors the reciprocity law is valid:

$$\varphi_{ik} S_i = \varphi_{ki} S_k \, . \tag{5}$$

Combining (1-5) we will come to the following system of equations to determine the outgoing radiation fluxes:

$$q_i^{-} - (1-\varepsilon_i) \sum_k \varphi_{ik}^{\mathrm{mod}} q_k^{-} = \varepsilon_i \sigma T_i^4 + (1-\varepsilon_i) \sigma T_g^4 \sum_k \varepsilon_{gik} \varphi_{ik} \quad . \tag{6}$$

2.3 View Factor and Mean Beam Length

We proceed from a classical determination of view factor and reduced view factor in the presence of gas between two areas. For any two areas S_i and S_k the reduced view factor φ_{ik}^{red} is determined in general case as fourfold integral on areas considered

$$\varphi_{ik}^{red} = \frac{1}{\pi S_i} \int_{S_i} \int_{S_k} \frac{\cos \beta_i \cos \beta_k}{r_{ik}^2} \exp\left[-a_{g,ik} r_{ik}\right] ds_i ds_k \quad , \tag{7}$$

where β_i and β_k are the angles between the normal vectors $\overline{n}_i$ and $\overline{n}_k$ to the surface and the direction to another surface (Fig. 2), r_{ik} is the distance between points on the surfaces S_i and S_i. The integration is performed on the surfaces S_i and S_k. The view factor φ_{ik} is equal to φ_{ik}^{red} when $a_{g,ik} \equiv 0$ (non-absorbing medium).

The mean beam length $L_{m,ik}$ between areas S_i and S_k is evaluated from

$$\varphi_{ik}^{red} = \varphi_{ik} \exp(-a_{g,ik} L_{m,ik}) \quad , \tag{8}$$

which leads to the expression for mean beam length as follows

$$L_{m,ik} = -(1/a_{g,ik}) \ln(\varphi_{ik}^{red} / \varphi_{ik}) \quad . \tag{9}$$

3. VIEW FACTORS AND MEAN BEAM LENGTHS FOR SOME CASES WITH AXIAL SYMMETRY

Original expressions for view factor and mean beam length are used in the module MRAD. Different cases of geometries with axial symmetry were considered including:

- The ring on lateral side of a cylinder and the ring on bottom side of a cylinder;
- Two rings on top and bottom sides of a cylinder;
- Two rings on lateral side of a cylinder;
- Two coaxial cylinders.

The special method was developed to estimate analytically mean beam lengths (Vasiliev, 2004). The view factor and mean beam length for the first geometry from abovementioned cases is given below for example.

3.1 Circular Ring on Inner Surface of a Vertical Cylinder and Circular ring on Horizontal Surface

This geometry is presented in Fig. 3. The view factor and the mean beam length are expressed by the following way:

$$\varphi_{ik} = \frac{1}{4R_b(z_u - z_d)}(f(z_u) - f(z_d)) \quad , \qquad (10)$$

$$\varphi_{ik}^{red} = \varphi_{ik} + \frac{1}{\pi(z_u - z_d)}\delta \quad , \qquad (11)$$

$$\delta = \delta_0 + \delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 + \delta_6 + \delta_7 + \delta_8 + \delta_9 + \delta_{10} + \delta_{11} \quad , \qquad (12)$$

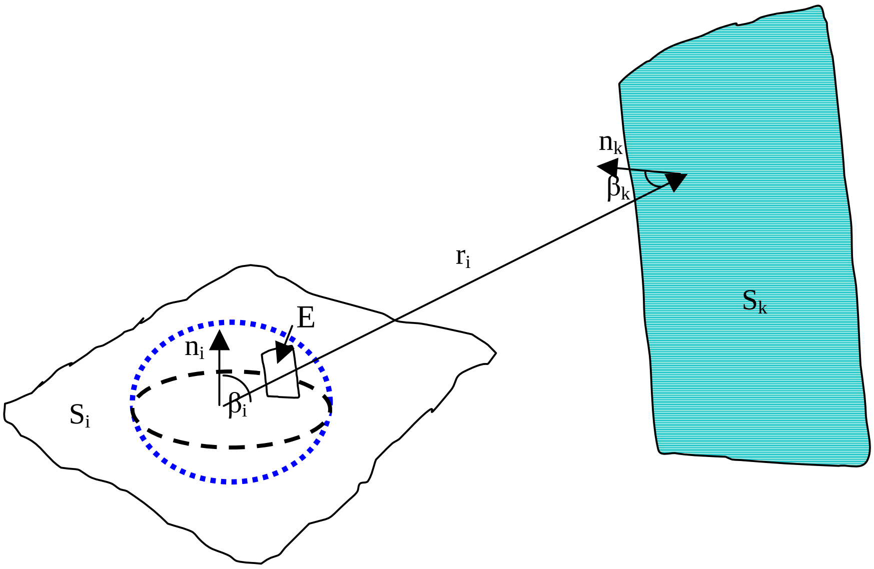

Fig. 2. The basic definitions.

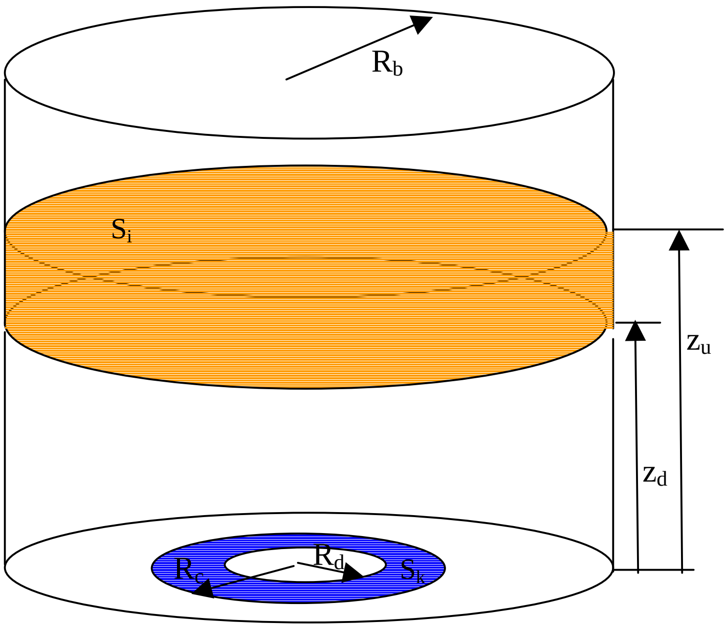

Fig. 3. The ring on lateral side of a cylinder and the ring on bottom side of a cylinder.

$$\delta_0 = \frac{a_g^2}{2(z_u - z_d)R_b}(g(z_u) - g(z_d)) \quad , \qquad (13)$$

$$\delta_1 = -\frac{a_g^2 R_b}{2}\int_0^\infty dx \cdot \frac{\sin x}{x}(f_1(z_u) - f_1(z_d)) \quad , \qquad (14)$$

$$\delta_2 = -\frac{1}{4R_b}\int_0^\infty dx \cdot x \sin x (f_1(z_u) - f_1(z_d)) \quad , \qquad (15)$$

$$\delta_3 = \frac{1}{2R_b}\int_0^\infty dx \cdot \cos x (f_1(z_u) - f_1(z_d)) \quad , \qquad (16)$$

$$\delta_4 = \frac{1}{2a_g^2 R_b}\int_0^\infty dx \cdot \left[\frac{\sin x}{x} + 2\cos x\right](f_2(z_u) - f_2(z_d)) \quad , \qquad (17)$$

$$\delta_5 = -\frac{1}{4a_g^2 R_b}\int_0^\infty dx \cdot x^3 \sin x (f_2(z_u) - f_2(z_d)) \quad , \qquad (18)$$

$$\delta_6 = -\frac{1}{4R_b}\int_0^\infty dx \cdot x \sin x (f_3(z_u) - f_3(z_d)) \quad , \qquad (19)$$

$$\delta_7 = \frac{1}{2R_b}\int_0^\infty dx \cdot \cos x (f_3(z_u) - f_3(z_d)) \quad , \qquad (20)$$

$$\delta_8 = \frac{1}{2a_g^2 R_b}\int_0^\infty dx \cdot \left[\frac{\sin x}{x} + \frac{3}{2}\cos x\right](f_4(z_u) - f_4(z_d)) \quad , \qquad (21)$$

$$\delta_9 = \frac{R_b}{4}\int_0^\infty dx \cdot \frac{\sin x}{x}(f_4(z_u) - f_4(z_d)) \quad , \qquad (22)$$

$$\delta_{10} = \frac{1}{4a_g^2 R_b}\int_0^\infty dx \cdot x \sin x (f_4(z_u) - f_4(z_d)) \quad , \qquad (23)$$

$$\delta_{11} = \frac{1}{8R_b}\int_0^\infty dx \cdot \frac{\sin x}{x}(f_5(z_u) - f_5(z_d)) \quad , \qquad (24)$$

$$f(z) = \sqrt{(z^2 - R_b^2 + R_c^2)^2 + 4zR_b^2} - \sqrt{(z^2 - R_b^2 + R_d^2)^2 + 4zR_b^2} \quad , \qquad (25)$$

$$g(z) = g_1(z) - g_2(z) \quad , \qquad (26)$$

$$g_1(z) = -\frac{(R_b^2 + R_c^2 + z^2)}{8}\sqrt{(R_b^2 + R_c^2 + z^2)^2 - 4R_b^2 R_c^2} + \frac{R_b^2 R_c^2}{2}\operatorname{arccosh}\left[\frac{R_b^2 + R_c^2 + z^2}{2R_b R_c}\right] \quad , \qquad (27)$$

$$g_2(z) = -\frac{(R_b^2 + R_d^2 + z^2)}{8}\sqrt{(R_b^2 + R_d^2 + z^2)^2 - 4R_b^2 R_d^2} + \frac{R_b^2 R_d^2}{2}\operatorname{arccosh}\left[\frac{R_b^2 + R_d^2 + z^2}{2R_b R_d}\right] \quad , \qquad (28)$$

$$f_1(z) = R_c^2 \operatorname{arccosh}\left[\frac{x^2 + a_g^2(R_b^2 + R_c^2 + z^2)}{2a_g^2 R_b R_c}\right] - R_d^2 \operatorname{arccosh}\left[\frac{x^2 + a_g^2(R_b^2 + R_d^2 + z^2)}{2a_g^2 R_b R_d}\right] \quad , \qquad (29)$$

$$f_2(z) \quad \operatorname{arcsinh}\left[\frac{x^2 + a_g^2(R_c^2 - R_b^2 + z^2)}{a_g R_b \sqrt{x^2 \quad a_g^2 z^2}}\right] \quad \text{arcsi} \quad \left[\frac{x^2 + a_g^2(R_d^2 - R_b^2 + z^2)}{R_b \sqrt{x^2 \quad a_g^2 z^2}}\right] \quad , \qquad (30)$$

$$f_3(z) = z^2 f_2(z) \quad , \tag{31}$$

$$f_4(z) = \sqrt{\left[x^2 + a_g^2(R_b^2 + R_c^2 + z^2)\right]^2 - 4a_g^4 R_b^2 R_c^2} - \sqrt{\left[x^2 + a_g^2(R_b^2 + R_d^2 + z^2)\right]^2 - 4a_g^4 R_b^2 R_d^2} \quad , \tag{32}$$

$$f_5(z) = e_c - e_d \; . \tag{33}$$

$$e_c = (R_c^2 + R_b^2 - z^2)\sqrt{\left[x^2 + a_g^2(R_b^2 + R_c^2 + z^2)\right]^2 - 4a_g^4 R_b^2 R_c^2} \quad , \tag{34}$$

$$e_d = (R_d^2 - R_b^2 + z^2)\sqrt{\left[x^2 + a_g^2(R_b^2 + R_d^2 + z^2)\right]^2 - 4a_g^4 R_b^2 R_d^2} \quad . \tag{35}$$

4. RADIATION ABSORPTION COEFFICIENT IN STEAM-NONCONDENABLES MEDIUM

The basic feature of absorption (and emission) of gases is the selective character of their radiation as lines and bands. The location and form of lines and bands depend on temperature and concentration of each gas phase in the mixture. The major impact to the absorption coefficient is brought by tri-atomic molecules (steam) in comparison to diatomic molecules (hydrogen H_2, nitrogen N_2 etc.) due to the presence of vibration and rotational bands.

The integral absorptivity ε_g is determined by

$$\varepsilon_g = \frac{1}{\sigma_B T_g^4}\int_0^\infty u_\lambda(T_g)\varepsilon_{g\lambda}\, d\lambda \quad . \tag{36}$$

Here the spectral density of radiation is

$$u_\lambda(T) = \frac{C_1\lambda^{-5}}{e^{C_2/\lambda T} - 1} \quad , \tag{37}$$

$$C_1 = 2\pi hc^2 \, , \;\; C_2 = hc/k \, , \tag{38}$$

and $\varepsilon_{g\lambda}$ is the spectral absorptivity

$$\varepsilon_{g\lambda} = 1 - \exp(-a_{g\lambda} L_m) \quad , \tag{39}$$

where L_m is mean beam length (Chapter 2.3).

The absorption spectrum of steam in infrared range is characterized by six absorption bands. The absorption bands are characterized by parameters $\lambda_{a,i}$ (characteristic wavelength of absorption band *i* at center) and $\Delta\lambda_{a,i}$ (characteristic width of absorption band *i*) (see Table 1).

Table 1. The characteristics of steam absorption bands (Hottel and Sarofim, 1967, Penner, 1963).

According to data (Hottel and Sarofim, 1967)			
Number of absorption band *i*	$\lambda_{a,i}$, µm	$\Delta\lambda_{a,i}$, µm	Averaged on band spectrum specific absorption coefficient of vapor $K_{g\lambda_{a,i}}^{H_2O}$, $1/(MPa \cdot m)$
1	1.1	0.079	0.523
2	1.38	0.116	13.4
3	1.87	0.214	16.4
4	2.7	0.447	204
5	6.3	2.51	284
6	20	38.7	95

According to data (Penner, 1963)			
Number of absorption band *i* (first three bands are collected to one)	$\lambda_{a,i}$, μm	$\Delta\lambda_{a,i}$, μm	Integrated on band spectrum specific absorption coefficient of vapor $S_{g\lambda_{a,i}}^{H_2O} = \int_0^\infty K_{g\lambda}^{H_2O} d\left[\frac{1}{\lambda}\right]$, $1/(bar \cdot cm^2)$
1	1.625	0.25	18.72
2	2.75	0.5	126.0
3	6.4	3.2	175.0
4	18.75	12.5	58.4

Let us consider the method of determination of radiation absorption coefficient on the basis of data (Hottel and Sarofim, 1967).

From equation (36) we can get the approximation for integral absorptivity in the form:

$$\varepsilon_g = \frac{1}{\sigma_B T_g^4} \sum_{i=1}^{6} u_{\lambda_{a,i}} \varepsilon_{g\lambda_{a,i}} \Delta\lambda_{a,i} \quad , \qquad (40)$$

$$\varepsilon_{g\lambda a,i} = 1 - \exp(-a_{g\lambda_{a,i}} L) \quad , \qquad (41)$$

where L is the mean beam length. The integrated on bands spectrum absorption coefficients in steam with pressure p and temperature T are estimated as

$$a_{g\lambda_{a,i}} = K_{g\lambda_{a,i}}^{H_2O} \cdot \frac{T_0}{T} \cdot \frac{p}{p_0} \quad , \qquad (42)$$

where T_0 =300 K, p_0 =1 MPa.

The expressions above determine integral absorptivity and, hence, integral absorption coefficient via the equation (4).

The differences in integral absorptivity obtained by two methods presented above (Hottel and Sarofim, 1967, and Penner, 1963) is not more than 5 percent.

In infrared range of spectrum the hydrogen (H_2) has one absorption band with the following parameters (Kamenshchikov *et al.*, 1971): characteristic wavelength of absorption band at center $\lambda_{a,i}$ =2.22 μm, integrated on band spectrum specific absorption coefficient of hydrogen

$$S_{g\lambda_{a,i}}^{H_2O} = \int_0^\infty K_{g\lambda}^{H_2O} d\left[\frac{1}{\lambda}\right] = 629 \frac{p_{H_2}}{T} \quad 1/(bar \cdot cm^2) , \qquad (43)$$

where p_{H_2} is the partial pressure of hydrogen, bar; T is its temperature, K.

For pressure p_{H_2} = 1 bar, tempearature T = 1000K and mean beam length L = 0.0085m the integral absorptivity of hydrogen will be

$$\varepsilon_{H_2} \approx \frac{c}{\sigma_B T_g^4} u_{\nu_a} S_{g\lambda_a}^{H_2} L \approx 5 \cdot 10^{-5} \quad , \qquad (44)$$

while for steam at the same parameters we obtain from the equation (40)

$$\varepsilon_{H_2O} \approx 1.9 \cdot 10^{-2} \quad . \qquad (45)$$

5. EFFECTIVE RADIATIVE THERMAL CONDUCTIVITY APPROACH

The distinctive feature of temperature field distribution in the core is the existence of large temperature gradients in the vicinity of core boundaries (top, bottom and side). Indeed, in the course of core heat-up the considerable heat fluxes arise from the core periphery to surrounding structures. At these conditions the strong temperature drop on some characteristic distance is inevitable from the centre to the periphery. This local temperature profile at the core boundary will result in the lowering of radiative heat fluxes to surrounding structures and to rising heat-up rate of the core itself.

Due to large number of rods in the core the very fruitful approach for radiative transfer seems to be the model based on effective radiative thermal conductivity. The non-stationary energy equation for temperature T is written as

$$E + \overline{\nabla} \cdot (\hat{\kappa} \overline{\nabla} T) = c \frac{\partial T}{\partial t} \quad , \qquad (46)$$

where $E=E(t)$ is the volumetric energy source; $\hat{\kappa}$ is the effective thermal conductivity tensor which is a function of temperature; c is the heat capacity of unit volume. The effective thermal conductivity is the effective value depending on radiative thermal conductivity κ_{rad} (proportional to T^3) and the solid thermal conductivity κ_s of rods. Analogously, the heat capacity of unit volume is determined by heat capacity of rod material taking into account the porosity, that is, it is necessary to take into account the empty space between the rods.

Consider first the steady-state ($\partial T/\partial t \equiv 0$) one-dimensional case (only radial heat transfer) and constant thermal conductivity in the ring with the internal radius $r=r_{in}$ and the external radius $r=r_{out}$:

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} = -\frac{E}{\kappa} \quad . \qquad (47)$$

$$\left.\frac{dT}{dr}\right|_{r=r_{in}} = -\alpha \qquad T\big|_{r=r_{in}} = T_{in} \quad . \qquad (48)$$

The solution of (47-48) is the following temperature profile:

$$T = T_{in} - \frac{E}{4\kappa}(r^2 - r_{in}^2) + \left[\frac{E}{2\kappa} r_{in}^2 - \alpha r_{in}\right] \ln \frac{r}{r_{in}} \quad . \qquad (49)$$

The equation (49) shows that the temperature difference $\Delta T=T_{in}-T_{out}$ takes place at the layer width $\Delta r=r_{out}-r_{in}$:

$$\Delta r \approx \sqrt{\frac{2\kappa \Delta T}{E}} \quad . \qquad (50)$$

If the effective thermal conductivity is proportional to T^3, that is $\kappa \propto T^3$, then the solution will be

$$T^4 = T_{in}^4 - \frac{E}{A}(r^2 - r_{in}^2) + \left[\frac{2E}{A} r_{in}^2 - \alpha r_{in}\right] \ln \frac{r}{r_{in}} \quad . \qquad (51)$$

The temperature field at the core periphery as a rule does not reach the steady-state solution. Indeed, the estimate for characteristic time to reach the steady-state is

$$\tau \approx \frac{(\Delta r)^2}{\chi} \quad . \qquad (52)$$

At given periphery layer width $\Delta r \approx 0.1$m, the thermal diffusivity $\chi=\kappa/c \approx 10^{-6}$ m^2/s the time τ will be of the order 10^4 s which is comparable to accident evolution time, which is of the order 10,000 s for large break and 30,000 s for small break loss of coolant accident.

In the non-stationary case the solution of (46) under the assumption that the periphery layer width is mush less than the characteristic core radius is written as follows (Arutyunyan *et al.*, 1990):

$$T = \frac{\chi}{\kappa}\int_0^t E(\tau)d\tau - \frac{\chi^{1/2}}{\kappa \pi^{1/2}}\int_0^t q_{out}\big|_{t-\tau} f_1(\tau)\frac{d\tau}{\tau^{1/2}} + \frac{\chi^{1/2}}{\kappa \pi^{1/2}}\int_0^t q_{in}\big|_{t-\tau} f_2(\tau)\frac{d\tau}{\tau^{1/2}} \quad , \qquad (53)$$

$$f_1(\tau) = \sum_{n=0}^{\infty}\left[\exp\left[-\frac{(2(n+1/2)d - x)^2}{4\chi\tau}\right] + \exp\left[-\frac{(2(n+1/2)d + x)^2}{4\chi\tau}\right]\right] \quad , \qquad (54)$$

$$f_2(\tau) = \sum_{n=0}^{\infty}\left[\exp\left[-\frac{(2(n+1)d - x)^2}{4\chi\tau}\right] + \exp\left[-\frac{(2nd + x)^2}{4\chi\tau}\right]\right] \quad , \qquad (55)$$

where $d=r_{out}-r_{in}$, x is the coordinate directed from the center and equal to zero at the internal layer boundary, q_{in} и q_{out} are heat fluxes at the internal and external boundaries correspondingly.

The expressions obtained allow to estimate the temperature at the external boundary of the core periphery zone and, hence, to calculate the radiative heat flux to surrounding structures.

As mentioned above, the energy equations with tensor value of effective thermal conductivity should be solved in general case. Let us illustrate a conception of effective radiative thermal conductivity in the case of regular grid of circular cylinders (Fig. 4). This geometry is typical for the core of VVER-type pressurized water reactors.

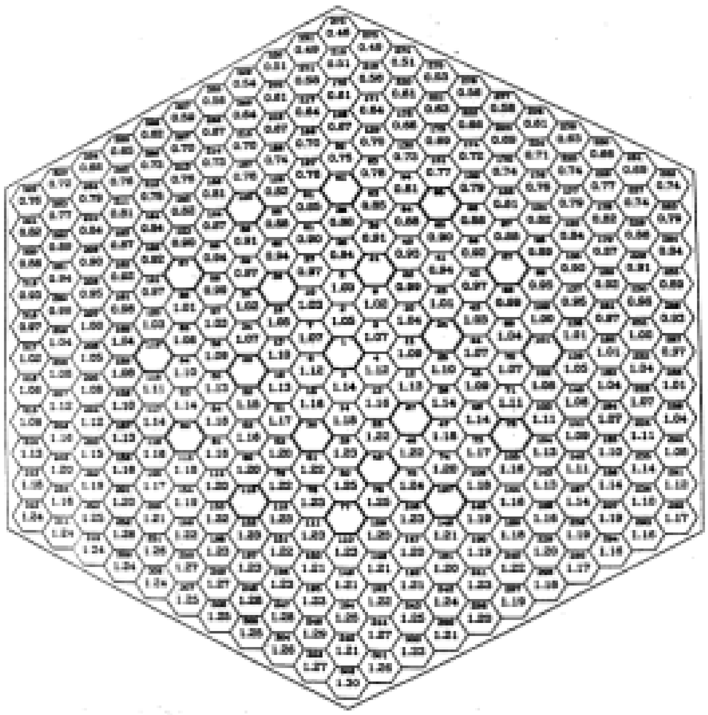

Fig. 4: Triangular set of rods in VVER-1000 fuel assembly.

After solving a radiative heat transfer problem in such a geometry with cylinder radius *R* and grid pitch *d* it is possible to derive the following expression for effective radiative conductivity (Vasiliev and Kobelev, 2003):

$$\kappa_{rad} = \sigma_B \frac{\sqrt{3}}{\pi} \frac{d^2}{R} T^3 \quad , \tag{56}$$

where σ_B is Stefan-Boltzmann constant, T is a temperature. Characteristic values of effective radiative conductivity lie in the range 1÷40 W/(mK) depending on a temperature.

The expression mentioned above is valid when parameters *R* and *d* are of the same order. In general case the solid thermal conductivity κ_s is also important. The total effective thermal conductivity when using Imura correlation (Imura and Takegoshi, 1974, Yagi and Kunii, 1957) will be estimated as:

$$\kappa_{eff} = \frac{1-\Phi}{\Theta + \frac{\kappa_{rad}}{\kappa_s}(1-\Theta)} \kappa_{rad} + \Phi \kappa_{rad} \quad , \tag{57}$$

$$\Phi = \frac{\varepsilon - \Theta}{1-\Theta} \qquad \Theta = 0.3\varepsilon^{1.6} \left[\frac{\kappa_s}{\kappa_{rad}} \right]^{-0.044} \quad . \tag{58}$$

6. MODEL VERIFICATION

Due to extremely complicated character of analysis in most general formulation the verification of model was conducted in several directions encompassing separate aspects of the phenomenon considered.

At first, the investigation was made on the basis of simplest configurations allowing the analytical solution. It is necessary to note that within the bounds of assumptions made (diffusive character of radiative exchange, axial symmetry geometry of in-vessel structures but not core zones, approximation of fuel rods as right cylinders) the view factors and the mean beam lengths are estimated well with the good accuracy for the analysis. The use of reciprocity and laws favors the achievement of this goal.

At second, the model was justified on the basis of integral experiments with comparably simple geometries (tests like PHEBUS SFD B9+, CORA W2, QUENCH-06) and the computations of severe accidents at VVER-1000. All integral tests without exception showed extremely high importance of adequate description of radiative heat transfer for thermal behavior analysis. Beside that, these tests simulate in small dimension the geometrical features of VVER-type reactors and their analysis is important for understanding of radiation behavior in the reactor. Severe accident analysis at VVER-1000 was also important from the point of view of "radiation energy" conservation in numerical calculations.

At third, the results were compared with sparse experimental data on thermal behavior of fuel assemblies located in container TK-13 designed for storage and transportation of fuel assemblies. Here the special attention was paid to adequate simulation of effective thermal conductivity parameter and of temperature profile in fuel assembly.

The comparison of the model with the experimental data on effective thermal conductivity is presented below.

6.1 Test on Determination of Effective Thermal Conductivity of Fuel Assembly

Fromzel *et al*. (1997) determined the effective thermal conductivity of VVER-1000 fuel assembly (FA) in the temperature range 280÷450K.

Experimental data were obtained using model consisted of N=127 electrically heated tubes of diameter D=10×1 mm placed in triangular grid with the pitch d=13.4 mm, as shown in Fig. 5. In this figure only 3 from 13 rows of tubes are depicted. Tubes were placed in hexagonal shroud with inner pitch 154 mm. The shroud wall thickness was δ=3 mm.

The total linear energy generation was Q=671 W/m.

From the solution of one-dimensional heat problem in a cylinder we get a temperature difference between the center and the periphery:

$$\Delta T = \frac{Q}{4\pi\kappa_{eff}} \quad . \tag{59}$$

The temperature difference between assembly center and shroud $\Delta T \approx$166K was obtained in the experiment, whereas the temperature in the center was $T_c \approx$446K. From the equation (57) we get the value of effective thermal conductivity $\kappa_{eff} \approx$0.32 W/(mK).

The numerical module calculates the temperature difference $\Delta T \approx$180K which is in good agreement with experimental data. This temperature difference corresponds to effective conductivity $\kappa_{eff} \approx$ 0.30 W/(mK).

The radial distribution of temperature in the case of uniform effective thermal conductivity is described by quadratic profile:

$$T = T_c - \frac{Q}{4\pi\kappa_{eff}} \frac{r^2}{R^2} \quad , \tag{60}$$

where *R* is the effective radius of the shroud chosen from the equality of the length of the circle of radius *R* and the perimeter of the shroud. In Fig. 6 the temperature predicted by the model is presented in comparison with experimental data. It is seen, that the value of effective radiative conductivity obtained in the experiment is larger at the center than at the periphery. It is not surprising because radiative thermal conductivity is proportional to the third extent of temperature.

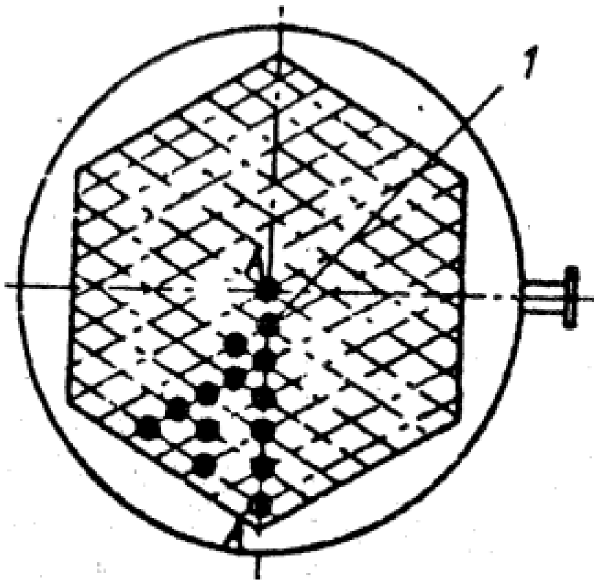

Fig. 5: Cross-section of experimental model: 1 – the tubes with thermocouples.

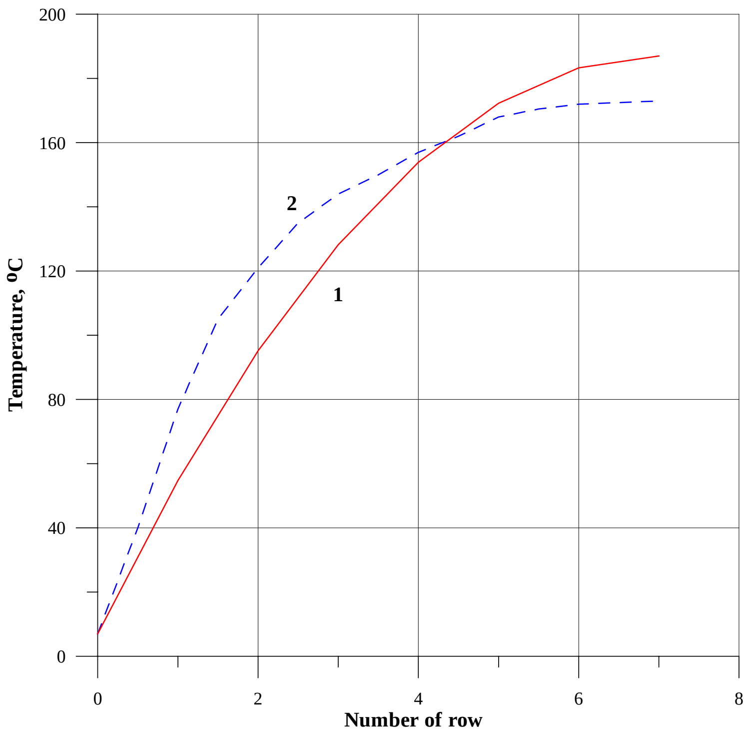

Fig. 6: Temperature distribution in dependence of number of radial row of rods (0th row – shroud, 7th row – central rod: 1 – model prediction, 2 – experiment.

7. CONCLUSIONS

The results of universal module development for numerical modeling of radiative heat exchange in reactor vessel during in-vessel stage of severe accident. The basic purpose of the module is its using in best estimate codes for severe accident analysis at VVER-type reactors.

The application of known classical principles and introducing of some special methods allowed to describe the radiative heat transfer self-consistently in the following cases:

- Intact geometry;
- Partially or totally degraded core and in-vessel structures;
- Energy exchange in the cases of considerable zones of degradation including the exchange with the melt in core and in lower head.

Currently, radiation exchange module MRAD is implemented to Russian best estimate code RATEG/SVECHA/HEFEST. The numerical code RATEG/SVECHA/HEFEST developed for modeling of thermal hydraulics and the late phase of severe accident at nuclear power plant with VVER.

As a part of integral code RATEG/SVECHA/HEFEST the module MRAD was tested on a broad range of problems:

- By comparison with known analytical solutions;
- On the basis of computations of integral experiments and severe accidents at VVER-type reactor;
- On experiments on temperature behavior of fuel assemblies in vertical containers.

NOMENCLATURE

a_g	radiation absorption coefficient, m^{-1}
$d\Omega$	elementary solid angle
h	Plank constant, $J \cdot s$
k	Boltzmann constant, J/K
L_0	geometric optical length, m
L_m	mean beam length, m
p	pressure, N/m^2
q^-	hemispherical outgoing radiative flux, W/m^2
R_i	radius of ring boundary, m
S	arbitrary surface
T	temperature, K
u_λ	spectral density distribution of radiation energy on wavelengths, W/m^3
u_ν	spectral density distribution of radiation energy on frequencies, J/m^2

Greek Symbols

ε	emissivity
λ	wavelength, m
ν	frequency, s^{-1}
σ_B	Stefan-Boltzmann constant, $W/(m^2K^4)$
τ	optical thickness
φ_{ik}	view factor between surfaces S_i и S_k

Indices

a	relevant to absorption
b	relevant to black body
g	relevant to gas
i	number of radiation surface
k	number of radiation surface
red	reduced due to absorption

ACKNOWLEDGMENTS

The authors would like to thank T.Vinogradova, V.Sidorov, D.Tomachik and A.Filippov for valuable

discussions. The work has been performed in the frame of project on severe accident numerical code development.

REFERENCES

[1] Andersen, K.M., Hadvig, S., (1989), J. Heat Transfer, Vol.111, pp.811-813.

[2] Arutyunyan, R.V., Bolshov, L.A., Vassiliev, A.D., Kiselev, V.P. (1990), Soviet technology reviews / Section B: Thermal physics reviews, Harwood Academic Publishers GmbH, United Kingdom., Vol.3, part 1, pp.1-174.

[3] Fromzel, V.N., Fromzel, L.V., Vdovets, N.V., (1997), Proc. "Processes of heat- and mass transfer and hydrodynamics in safety systems of NPP with VVER-640", Saint-Petersburg, SPb AEP-KB "Hydropress"-A.P.Alexandrov NITI, pp.139-150.

[4] Hottel, H.C., Sarofim, A.F., (1967), "Radiative Transfer", NY, McGraw-Hill Book Company.

[5] Gonzalez, R, Chatelard, P. and Jacq, F., (May 1993), Technical note DRS/SEMAR 93/33.

[6] Imura, S., and Takegoshi, E., (1974), Heat Transfer Japanese Research, Vol.3, p.4.

[7] Kamenshchikov, V.A, Plastinin, Yu.A., Nikolaev, V.M., Novitskii, L.A. (1971), "Radiation Properties of Gases at High Temperatures", Moscow, Mashinostroenie, (in Russian.)

[8] Kaviany, M., (1994), "Principles of Heat Transfer in Porous Media", 2nd Edition, Mechanical Engineering Series, Springer-Verlag, 708 pp.

[9] Penner, S.S., (1963), "Quantitative Molecular Spectroscopy and Emissivity of Gases", Moscow, Izd-vo inostr. literatury. (translation in Russian).

[10] Siefken, L.J., Coryell, E.W., Harvego, E.A., Hohorst, J.K., (September 2000), NUREG/CR-6150, INEL-96/0422, Idaho National Engineering and Environmental Laboratory, Idaho Falls.

[11] Summers, R.N., Cole, R.K., Jr., Smith, R.C. *et al*., (September 1994), NUREG/CR-6119, SAND93-2185.

[12] Surinov Yu.A., (1975), Izvestiya AN SSSR. Energetika i Transport, N 4, pp.112-137, (in Russian).

[13] Vasiliev A.D. and Kobelev G.V., (2003), Preprint IBRAE -2003-09, Nuclear Safety Institute, Moscow, 56 pp, (in Russian).

[14] Vasiliev A.D., (December 5-8, 2004), Proc. International Mechanical Engineering Conference IMEC2004, Kuwait, IMEC04-1049.

[15] Yagi, S., Kunii, D., (1957), A.I.Ch.E. Journal, pp.373-381.

