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MODELING OF HEATMASSTRANSFER PROCESSES IN "WET" AND "DRY" STORAGES FOR SPENT NUCLEAR FUEL

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For time being the countries with developed nuclear power have been chosen the following modes for nuclear spent fuel storage organization:

- short term "wet" storage of the spent nuclear fuel assemblies (SNFA) in near-reactor located water pools after fuel unloading from reactor (during ~ 1 year);
- interim "wet" storage (during decades) inside of longer volume pools after unloading SNFA from near-reactor pools; these "wet" type storages (WTS) are located at nuclear power plants territories (in most cases) or at territories of the plants for nuclear fuel reprocessing, or for long term "dry" storage (up to hundreds of years), or for final dispose;
- interim "dry" storage (DTS) in different types of facilities: cask type, when SNFA are placed in gas-filled casks (containers); vault (modular) type, when SNFA are placed in under ground concrete wells; camera-type, when SNFA are placed (hanged) in large-scale volume cameras and cooled by air-flow, arising due thermogravitational driving.

From thermophysical point of view the main difference between WTS and DTS consists in difference between heat removal processes intensities. The higher levels of heat fluxes from the surfaces of spent fuel rods in WTS are connected with shorter time periods of delays after their unloading from reactor, when its level of radioactivity is higher. It relates mainly to near-reactor pools. At final stages of interim storage (after 10 or more years of delay) the heat flux densities levels in WTS and DTS are close to each other, but temperature regimes are quite different. Due to higher heat transfer coefficients to water medium the maximum fuel temperature in WTS only slightly excess the water temperature (30-50ºC). Because of safety requirements the forced convection in storages of any types must be excluded. The relatively low heat transfer coefficients for air coolant in DTS lead to much higher fuel temperatures. International regulating rules establish their allowed values at level of ~ 350ºC for the mode from circonium alloys claddings of water cooled reactors fuel rods.

The storage process in WTS is accompanied by the evaporation of water to air flow, ventilating the volume above water level in a pool. Especially important is an evaporation process for analysis of probable accident situation, when by some reasons the water circulation in a pool is stopped and significant loss of water is possible (after pool's overheating or due to accident openings of hole in pool's wall).

Specific feature of heat transfer process in DTS is a significant income of thermal radiation in overall heat release, as for normal conditions and as for accidental fire, which also should be considered in safety analyses. Some of above mentioned phenomena are the topics of the given paper.

1. Experimental modeling of co-current and counter-current flows mixed convection in pools with RBMK-1000 reactor fuel

For the additional protection of the pool water from the direct contact with the cladding of highly radioactive fuel rods, the SNFA in these storages are placed in metal cans, which are also water filled (cans are opened from above). Pool water with the temperature of 30-40ºC is pumped from the bottom of pool apartments to the external system of cooling and purification and returns cooled up to 20-30ºC, flowing into the regions near upper water level. Maximum temperatures of pool's water are fixed in its upper part. Fact of temperature stratification leads to conclusion, that the natural convection is a dominant process in mixed convection heat transfer in water volume.

The system of cans with SNFA cooling when pool water would be pumped from the upper volume of a pool is not used in this storage. However it also represents the interest for modeling. In that case from the pool would be pumped warmer and more dirty waters (comparatively with nominal scheme), because of about mentioned stratification effect. As a result the efficiency of outer pool waters cooling and purification systems could be higher.

For these reasons our experiments have been organized for both modes of mixed convection: co-current and counter-current ones. The body of the test section (fig.1, [1]) is manufactured from the organic glass which allowed to observe flow of water, particularly the transition from steady laminar flow to unstable turbulent flow (accompanied with water temperature oscillations) with increasing of Rayleigh number. The cans with SNFA (or fuel rods inside can, when the fuel rods grid has rectangular geometry) are modeled by the electrically heated 56 stainless steel tubes. The stability of water flow through model has been provided with high accuracy (±1 %) due to use of the head tank with constant water level.

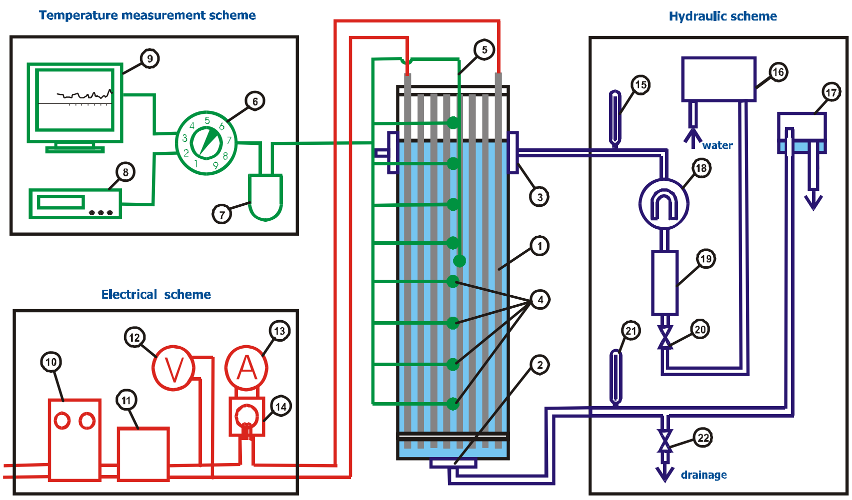


Fig. 1. Scheme of test section and experimental facility

1 – heated tubes; 2 – outlet collector; 3 – water supply collector with flow uniform distribution nozzle device; 4 – moved thermocouples for water temperatures measuring along and across of test section; 5 – moved thermocouple for measuring temperature of tubes; 6 – thermocouples switch; 7 – Dewar with constant temperatures of "cold" contacts of thermocouples; 8 – digital millivoltmeter for thermocouples signals registration; 9 – computer equipped with ADT card; 10 – primary controlled power supply transformer; 11 – secondary transformer; 12 – voltmeter of electrical power supply system; 13 – amperemeter of that system; 14 – transformer of electrical current; 15,21 – thermometers for water inlet and outlet temperatures measuring; 16 – tank-damper for water deaeration and flow rate stabilization; 17 – moved water vessel, providing necessary level of water in test section and supplied by electrical heater of water; 18 – reversed U-type reometer for water flow rate measurements; 19 – filter for water purification; 20 –valve for water flow rate adjustment; 22 – drainage valve

In accordance with methodic, proposed in Petukhov B.S. et al. works [3] for the turbulent mixed convection regime, the dependence between dimensionless criteria was searched in a form

$$Nu/Nu_0 = f(Gr_q/Re^n \cdot Pr^m). \qquad (1)$$

For the scale Nusselt number Nu_0 the dimensionless heat transfer coefficient by "pure" forced turbulent convection was chosen from [4]:

$$Nu_0 = \frac{(\lambda_{fR}/8)\cdot Re\cdot Pr}{k + 4{,}5\sqrt{\lambda_{fR}}\left(Pr^{2/3}-1\right)}, \text{ where} \qquad (2)$$

$$k = 1 + A/Re;\ \lambda_{fR} = (1{,}82\cdot \lg Re - 1{,}64)^{-2}. \qquad (3)$$

It was found that best correlation for co-current regime was provided with exponents n = 2 and m = 1 in (1) and with constant A = 200 in (3). Correspondingly for counter-current regime n = m = 1 and A = 100.

This methodic has been applied by us for low Reynolds numbers convection (in our case Re = 25-65, which corresponds to WTS operation), because in all our experiments the water temperature oscillations have been observed.

Eventually:

$$\frac{Nu}{Nu_0} = 1{,}16 \cdot \left(\frac{Ra_q}{Re^2}\right)^{0{,}31} \qquad (4)$$

(co-current mixed convection)

and

$$\frac{Nu}{Nu_0} = \frac{1}{3} \cdot \left(\frac{Ra_q}{Re}\right)^{0{,}33} \qquad (5)$$

(counter-current mixed convection).

These correlations have been obtained for the model of WTS pool with parameters:

$$s/d = 1/4;\ Ra_q = (3{,}5\text{-}30)\cdot 10^5.$$

The comparison between co-current and counter-current convection (fig.2, in coordinates Nu/Nu_0, Ra_q/Re) shows:

- heat transfer intensity for co-current regime is in average by 40% lower, which can be explained by earlier turbulization of counter-current flow;
- larger scattering of data for counter-current regime, probably, reflects not only instabilities, arising with meeting of "cool" liquid (from above) and "warm" liquid (from below), but also lack of criteria describing the process.

2. Mathematical modeling of accident progression in "wet" storage after loss-of-flow

The scheme of a thermal two-dimensional computational model, pertaining to this problem was developed and is shown in fig.3. In this scheme, a spent fuel pool is, in fact, reduced to one "microstorage" unit, which has all elements of an actual storage facility that participate in heat-mass transfer, e.g. fuel rods, canisters with SNFA, pool water, and pool structures (walls, bottom, metal deck-plates above the water level). So, one can expect that after the determination of specific parameters of the nonstationary process, namely the amounts of heat removed and water evaporated from one cell, and after the subsequent multiplication of these parameters by the number of SFAs in storage, the values for the entire facility can be determined.

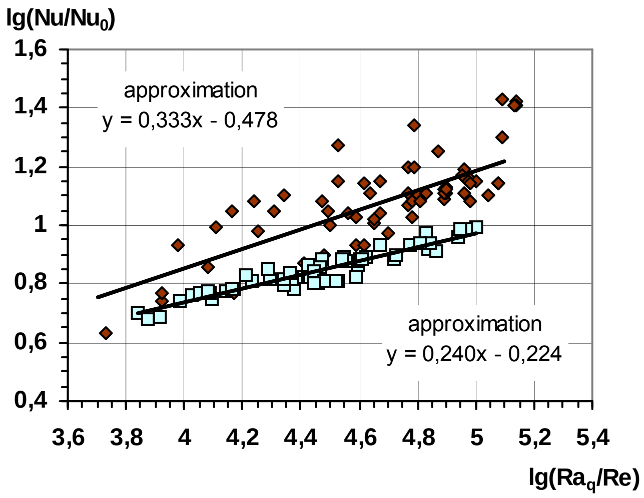
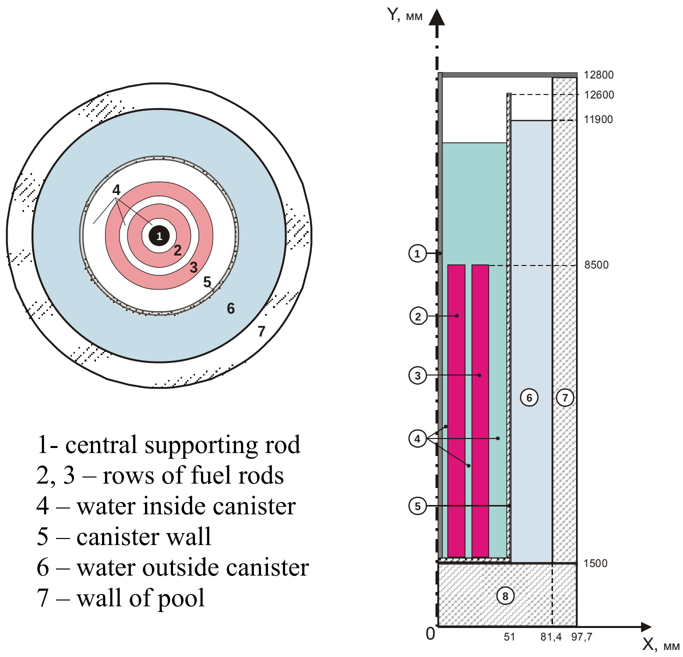


Fig.2. Experimental data for co-current (◘) and counter-current (◆) mixed convection



1- central supporting rod
2, 3 – rows of fuel rods
4 – water inside canister
5 – canister wall
6 – water outside canister
7 – wall of pool

Fig.3. Elementary pool cell used to model loss-of-flow in storage

In this model all sizes of the canisters are assumed to be real ones. However, the intercanister spaces are modeled in the form of annular channels, which is simpler compared to real geometry, but similar with regard to heat-mass transfer processes development. All sizes of the volumes external in relation to a single canister are chosen in a way that all the intercanister space cross-section dimensions and concrete walls restrictions of the model are the same as the real ones. The width of two heat-generating rings, modeling two rows of fuel rods inside a SFA (such is geometry of the RBMK-type reactor SFA), is chosen in a way that the evaporation mirror inside the canister of the model is equal to that in a real-life storage. The conditions of thermal modeling are satisfied by the equality of the meanings of the Bio criterion of the model and that of the real object and in recalculation of the Fourier criterion, taking into account the difference between concrete walls restrictions of the model and ones for the real pool. In the above model the water-air boundary is mobile and moves downwards in the course of evaporation from the pool and canisters.

System of heat-mass transfer equations including equations of movement in cylindrical coordinates taking into account the temperature dependence of the media physical properties (x – radial coordinate, y – axial coordinate) is presented as follows:

$$c \cdot \rho \cdot \frac{\partial T}{\partial \tau} = \frac{1}{x} \cdot \frac{\partial}{\partial x}\left(x\lambda \frac{\partial T}{\partial x} - c\rho UxT \right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y} - c\rho VT \right) + Q_v ;$$

$$\frac{\partial C}{\partial \tau} = \frac{1}{x} \cdot \frac{\partial}{\partial x}\left(xD \frac{\partial C}{\partial x} - UxC \right) + \frac{\partial}{\partial y}\left(D \frac{\partial C}{\partial y} - VC \right);$$

$$\rho \cdot \left(\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} \right) = -\frac{\partial P}{\partial x} + 2\mu \frac{1}{x}\left(\frac{\partial U}{\partial x} - \frac{U}{x} \right) + 2\frac{\partial}{\partial x}\left(\mu \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y}\left[\mu \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \right] + \rho F_x ; \quad (6)$$

$$\rho \cdot \left(\frac{\partial V}{\partial \tau} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} \right) = -\frac{\partial P}{\partial y} + \frac{2\mu}{x}\left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right) + 2\frac{\partial}{\partial y}\left(\mu \frac{\partial V}{\partial y} \right) + \frac{\partial}{\partial x}\left[\mu \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \right] + \rho F_y ;$$

$$\frac{1}{x}\frac{\partial (xU)}{\partial x} + \frac{\partial V}{\partial y} = 0 ; \qquad \vec{F} = \vec{g} \cdot \beta \cdot (T_a - T).$$

System (6) is solved by the finite difference numerical method under the following boundary conditions:

- At solid surfaces "sticking" conditions apply: U = 0, V = 0.
- At the boundary "water–moist air" the normal velocity components are equal to zero (V = 0) and tangential stresses are absent ($\partial U / \partial y = 0$); this corresponds to no ventilation in the space above the water (conservative evaluation); if ventilation is included, the flow rate and velocity of ventilating air should be specified.
- At the boundary line "water–steam-air mixture" and near the upper metal floor, which is cooled by the natural air convection inside the storage building, the vapor is saturated, but at the final stages of accident process the steam pressure near floor may be lower than saturation pressure.
- At the outer boundary of a concrete wall of the pool the boundary condition of the third type is specified:

$$-\lambda \cdot \frac{\partial T}{\partial x} = \alpha_{env} \cdot (T - T_{env}) .$$

- Temperature at the lower boundary of a computational region is constant and is equal to the annual average soil temperature under the bottom (foundation) of the pool.

At fig.4 are shown the typical examples of the system (6) solution for the specific stages of accident process (partial evaporation of water from the can and from pool after loss-of-flow event).

In computational practice it is impossible to get reliable results for temperatures, velocities and concentrations profiles in any type SNF-storages without so-called closing correlations, which are usually empirical ones: for heat-mass transfer and pressure drops; for physical properties, including emissivity of heat exchanging by radiation fluxes surfaces.

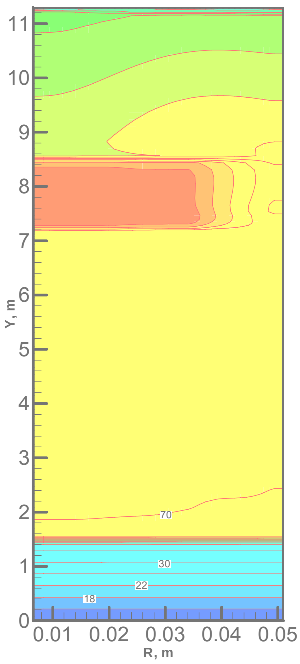


Fig.4a

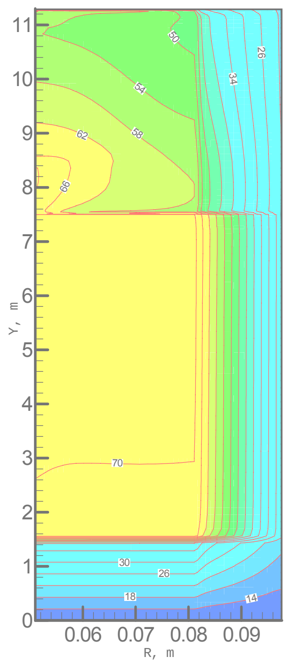


Fig.4b

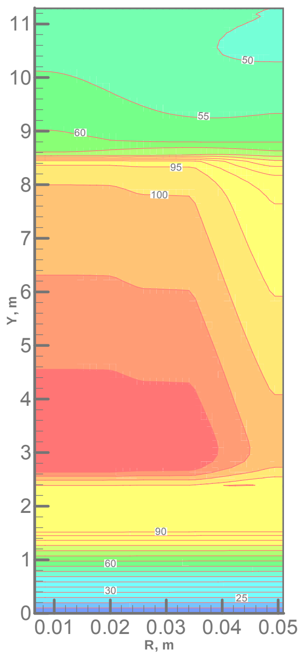


Fig.4c

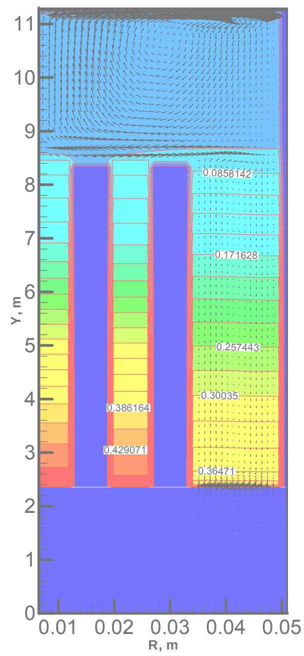


Fig.4d

Fig.4. Examples of the system (6) solution for the specific stages of accident process: temperature field in canister (a), velocities and moisture concentration fields in pool (b) at the moment when water level in canister is 7.2 m; temperature field in canister (c), velocities and moisture concentration fields in canister (d) at the moment when water level in canister is 2.4 m

3. Empirical correlations for the heat-mass transfer in the WTS and DTS components

3.1. Natural convection in a vertical fuel-rod bundle (or SFA canister)

This kind of small-scale, cell-type convection taken place in a canister with SNFA, in a pool with stopped circulation of water, inside of fuel assembly in a gas-filled cask, but only in situation, when vessel with liquid (gas) has a "deaf bottom", i.e. the directed circulation is impossible. Fig.5 presents experimental data [5] for this type natural convection in the absence of circulation with geometry close to that of an RBMK FA. The data are given in the form of correlation between relative heat conductivity of water or air (ratio of λ_{eff} – effective heat conductivity of convective medium to molecular conductivity λ) and Rayleigh number, defined by the distance (gap) between rods.

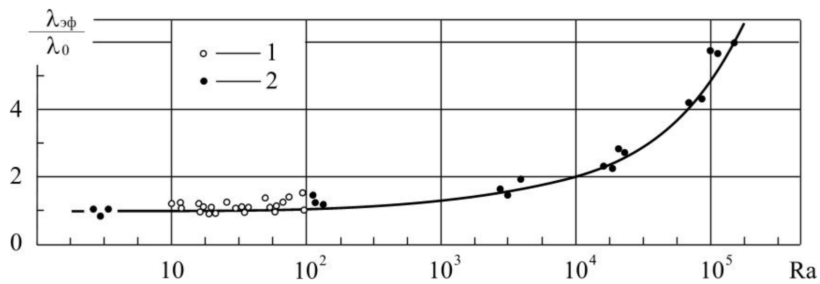


Fig.5. Results from experiments with different shell geometries (1, 2)
on small-scale "vortex-cell" type natural convection

3.2. Natural circulation in vertically oriented casks

Usually the circulation circuit is formed inside the vertical cask interspace with up-flow in its central part and down flow in the annular channel between the basket, containing NSFAs, and the cask body. Experimental data, obtained in [6], provides a possibility to perform the calculation of heat transfer coefficients by up-flow in rod bundles, round tubes and annular channels:

$$\frac{Nu}{Nu_{lam}} = [1 + 0.065\,(\frac{Gr}{Re})^{3/2}]^{1/3}, \qquad (7)$$

where Nu_{lam} – Nusselt number corresponding to the laminar flow regime without natural convection influence (this value, which is defined experimentally or theoretically, can be found in literature). Another correlation is presented in the [6] for down flow in the annular channel around the basket

$$\frac{Nu}{Nu_{lam}} = [1 + (0.125\sqrt{Gr \cdot Re}\,)^{4}]^{1/4}. \qquad (8)$$

Both correlations (7) and (8) are valid for the ratio Gr/Re in range from 10 to 10^4.

This type of flow is usually called "viscous-gravitational flow"-regime. The experimental data for hydraulic resistance coefficients in this regime, obtained in [6], or calculated from the textbooks on hydraulic resistances for another geometries, allow the possibilities to determine Re number through iteration process. In these calculations the gas flow rate (usually the casks are filled with inert gases) in a closed system of the circuit "SNFAs-180° turn-annular channel-180° turn" should be defined.

The temperatures and velocities fields inside and outside of a cask (in ambient air) are defining in contemporary works on base of computer codes (FLUENT et al). The simulation model should take into account thermal radiation heat fluxes. The attempts of cask's developers to increase the capacity of these units and, consequently, the thermal loads of its internals, lead to necessity to analyze the thermal behavior of the finned outer cask surfaces. In come cases (temporary storage of SNFAs with the shorter delay times) they use the water filled casks. For them the thermal analysis additionally includes the evaluation of pressure in gas volume above the water level.

4. Dry large-capacity storage of the chamber type

The dry storage facility that is now under construction in Russian Federation (fig.6) is intended for containing more than 30'000 SNF elements. The main storage elements are chambers of about 9 m high, in which metal sockets being pipes with the outer diameter of 0.72 m are installed on a square net pattern with the cell size of 1 m. Cylindrical canisters with spent fuel are placed in the sockets in two tiers. The holes with the diameter of 310 mm for cooling air inflow into the chamber are made in the chamber floor at the centre of cells, formed by the sockets. From the upper part of the chamber air is emitted outside through the exhaust vertical shaft with the height of about 20 m. So the SNF cooling is carried out by means of combined (mixed) convection (natural convection plus organized circulation of air flow) along side with heat radiation.

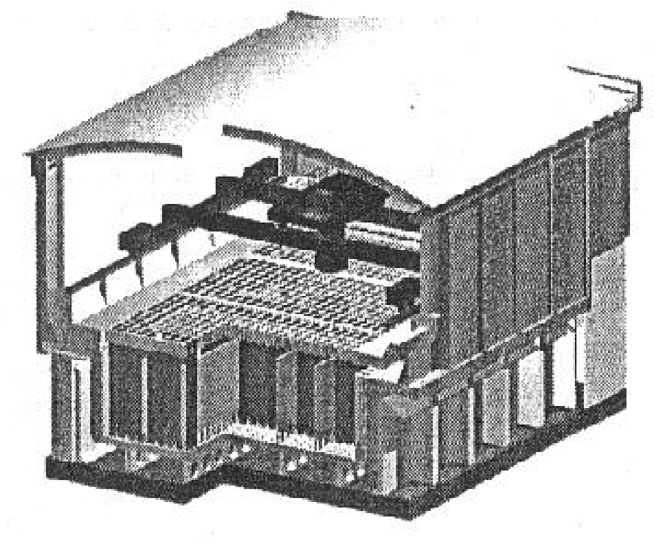


Fig.6. Ground level large capacity dry storage facility (Russian Federation)

The aim of experimental (with 1:4 scale of model) and computational simulation [7] consists in the determination of heat transfer intensity, air temperatures and velocities profiles in cells and airflow rate through the cell. These data are necessary not only for finding SNF cooling efficiency, but for determination of operation conditions for materials and structures of DTS (example – level of operation temperature of concrete, which influences strongly on storage life time).
At fig.7 [7] are shown numerically founded flow rates and fields of characteristics for the cell (with comparison between calculated and experimental data).

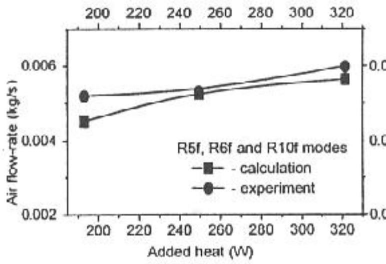


Fig.7a. Relation between the air flow-rate throught the cell and the heat flux added

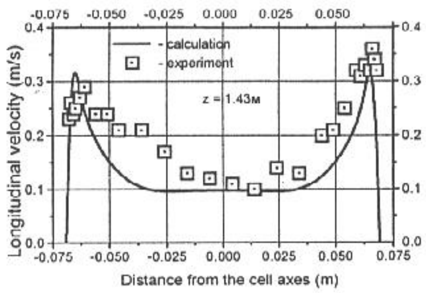


Fig.7b. Comparison of air velocity fields in the cell

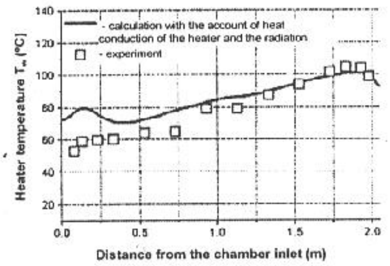


Fig.7c. Heater temperature variation over the height

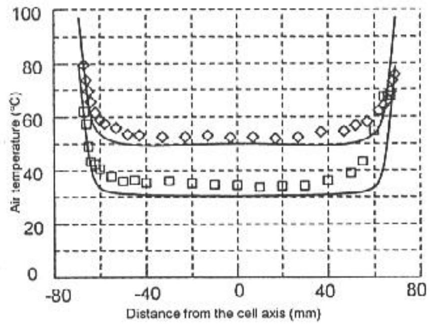


Fig.7d. Comparison of calculated and experimental air temperature fields

Fig.7. Results of numerical modeling of thermohydraulic characteristics of the chamber-type DTS [7]

Conclusion

1. The area of heat-mass transfer processes studies in the different types of storages for spent nuclear fuel is very wide one. It includes a simulation of a storage as a whole system, the solution of partial hydrodynamic and thermophysic problems and experimental modeling that gives necessary boundary conditions and closing correlations for the simulation.
2. For time being designer has possibilities to predict with acceptable accuracy integral characteristics and the temperature regimes for normal operation conditions of all types of storages (water pools, casks, on-ground and under-ground “dry”-type facilities).
3. Nevertheless the way to determine the optimum design and optimal operational regimes of SNF storage has not yet been finalized. There is a lack of experimental data for the local stationary and non-stationary characteristics (local temperatures, especially in critical zones and points of a system, local air (gas) humidity etc).

Particularly, taking into account the expansion of storages number in many countries, connecting with nuclear power usage expansion, the accident situations with storage must be an object of increased attention from investigators and engineers.

Nomenclature

d_{eq} – equivalent (thermal) diameter of the elementary cell of experimental model, defined through heated perimeter of a part of tubes surface, which contacting with water in one cell; in our experiments d_{eq} = 15 mm;

g – gravity acceleration, m/s^2;
w – flow rate velocity, m/s;
α – heat transfer coefficient, W/(m^2·K);
β – thermal expansion coefficient, 1/K;
λ – thermal conductivity, W/(m·K);
μ - dynamic viscosity, kg/m;
ν – kinematic viscosity, m^2/s;
q – heat flux density, W/m^2;
a - thermal diffusivity coefficient, m^2/s;
$Gr_q = \frac{g d_{eq}^4 \beta q}{\nu^2 \lambda}$ – Grashof number;
$Pr = \nu/a$ – Prandtl number;
$Ra_q = Gr_q \cdot Pr$ – Rayleigh number;
$Re = \frac{w d_{eq}}{\nu}$ – Reynolds number;
$Nu = \frac{\alpha d_{eq}}{\lambda}$ – Nusselt number;
Nu_0 – base (scale) Nusselt number for purely forced turbulent convection (see (2)).

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