Thermal parameters of elongated heat conductors of evaporation-condensation type for passive emergency cooling of reactor equipment

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1. Background and goal of the present work

Object of the study relates to passive safety systems of cooling, heat removal and thermal protection that operate as independent evaporation-condensation (EC) systems and could maintain required thermal conditions of the technological systems of nuclear power cycle. Reliability of the passive systems is provided due to both absence of moving parts and operation based on physical laws of nature, i.e., without any intervention of staff, power supply, and control signals.

2. Analysis of heat transport ability of EC systems

One of the main features of these systems is their ultimate heat transferring ability. The authors undertook investigation of various thermophysical factors limiting this ability, determined and analyzed its regularities, which depend upon thermodynamical conditions, transport ability of capillary structures (if any), and the interaction of vapor and liquid flows of heat pipes coolant.

As known, water-water reactors have three safety barriers, which availability depends, in particular, upon efficient and reliable heat removal.

These barriers are fuel element, primary circuit, and containment. To provide integrity of the third safety barrier and thermal conditions of its components, such as vessels, protecting casings, and reactor vaults in operating and emergency modes a passive system of thermal protection, in which heat transferring elements of EC type (heat pipes) are used, could be proposed.

Advantages of these systems over active ones are conditioned by their thermophysical, technological and operating features, which are as follows:

- Heat transfer processes occur in autonomous leakproof shells of the HPs not depending upon availability and operation of other systems and devices;
- Provision of efficient and reliable separation of heat source and sink, as well as of high heat conductivity between heat supply and drainage zones that could be located far from each other and arbitrarily reciprocally oriented;
- Possibility to vary transformation (concentration or deconcentration) of heat flux rate within a wide range in the zone of heat supply with regard to the zone of heat removal;
- Neither power consumption for transportation of inside coolant nor emergency water resources, compressed air systems, valves, etc. are required;
- Implementation of them will increase reliability and safety of main equipment operation and will be cheaper due to design simplification and possibility to refuse backup equipment.

There is a hydrodynamic limitation of heat transferring ability connected with provision of coolant circulation in heat pipe. The equation of pressure balance here includes moving head, pressure drops by friction in liquid and vapor phases. In gravitational EC systems without both capillary structure and organized circulation of coolant the limitations caused by various thermophysical processes could be combined into two groups: 1) the crises depending upon quantity and distribution of liquid phase in evaporation zone; and 2) the crises affected by hydrodynamic interaction of liquid and vapor phases. Under tightness, when evacuation of vapor bubbles is impeded, heat transferring ability is limited by violation of hydrodynamic stability of the interface of counter flows of liquid and vapor phases. This crisis phenomenon is called flow flooding. It is characterized by deceleration, separation, and entrainment of liquid by vapor flow. Such crisis is determined by maximal heat flux Q_{max} or maximal axial density of heat flux q_s.

3. Investigation of elongated heat conductors

Vertical elongated gravitational (without capillary structure) heat pipe manufactured from seamless steel tube was chosen as an example of the element of multi-tube thermal shielding.

The tested HPs were of four designs:

design 1 – straight HP; condensation zone has transverse fins and is cooled due to free air convection;

design 2 – straight HP in condensation zone cooled by water;

design 3 – analogous to design 2 but with longer condensation zone; and

design 4 – HP condensation zone is bent in transportation zone; cooled by water. Designs 2 to 4 are shown in Fig.1.

The main geometrical dimensions of the HPs were:

working length – 8 m;

outer/inner diameter – 25/20.5 mm;

length of evaporation zone L_e – 3 m (volume of coolant - 150; 290; 450; 590, and 730 ml) and condensation zone L_c – 4 m (design 1) and see Fig. 1 for designs 2 to 4.

In the experiments with the HPs of designs 1 to 3 the limitation of heat flux by interaction of the phases was not achieved. According to prediction the ultimate heat flux is much higher than the achieved values.

In Table 1 the results of test at 290 ml of coolant for design 4 HP are given (t_{we}, t_{wt} – wall temperatures in evaporation and transport zones; w_v, q_e, α_e – vapor velocity, heat flux rate and heat transfer coefficient in evaporation zone). Within the whole range of heat flux up to 7 kW the heat pipe functioned steadily and reliably but at 8 kW the crisis took place.

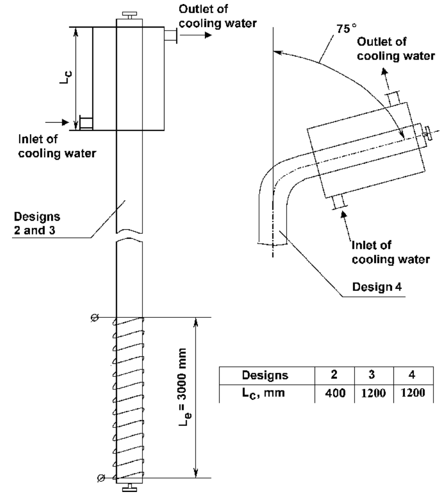

Fig. 1. Experimental heat pipe (designs 2 to 4)

Table 1. Experimental results (design 4)

Q, W	2000	3000	4000	5000	6000	7000	8000
t_{we}, °C	49.5	61.9	72.5	81.3	93.3	107.1	120.7
t_{wt}, °C	42.0	55.3	66.4	73.9	85.6	98.0	101.4
q_e, W/m^2	10363	15544	20726	25907	31089	36270	41452
α_e, W/(m^2·K)	1382	2355	3398	3501	4037	3985	2148
w_v, m/s	45.1	38.4	30.1	28.3	21.4	16.7	17.1

The temperatures of HP casing in the zones of evaporation and transportation, of radiator fins in condensation zone, heat flux, and the temperatures of cooling air or water were measured. The critical heat power was achieved, when thermal resistance of the tested elongated HP had reached the value that made steady heat removal impossible since vapor flowing up disrupted condensate flowing down under the given operational conditions.

The calculations based on the developed models of ultimate heat transfer under interaction of the phases show that for the tested HP at saturation temperature of 98°C the predicted values of the ultimate heat flux resulted in flow flooding satisfactorily agrees with the experimental data that were used for assessment of maximal heat transferring ability of the HP as an element of heat removal and thermal shielding. For example, at 3-m length evaporation zone and saturation temperature or temperature in transportation zone of about 200 °C value of Q_{max} is given in Table 2.

Table 2. Ultimate thermal load for HP

d, mm	25	32	38	51
d_{in}, mm	20.5	26	32	45
Q_{max}, kW	13.8	22.1	33.5	65.9
q_s, kW/cm^2	2.8	2.8	3.0	3.2

The comparison of experimental data with the prediction based on the model of ultimate heat transfer rate taking into account interaction of vapor and condensate phases has demonstrated their quite satisfactory agreement. As a result, assessment of the maximal heat transfer ability of the HPs as the elements of the system of heat removal and thermal shielding has been performed. The values of ultimate heat flux and of axial heat flux rate related to the area of HP cross-section depending upon its outer diameter are presented.

These results certify that heat transferring ability of the tested HPs corresponds to the level of heat removal enough to maintain an emergency operation and integrity of the vital NPP equipment.

Thus, analysis of the obtained experimental data and calculations made by the authors proved the possibility to create efficient elongated passive EC systems of passive heat removal and thermal protection for various facilities and stages of nuclear power technologies, such as reactor equipment, systems of storage and cooling of spent fuel, systems of fire and thermal shielding of both bearing structures and power equipment.

Further development and investigations aimed to increase heat transferring ability of the EC systems and to make them the main means of NPP's passive safety system are needed.

4. Conclusions and Acknowledgements

- The performed investigation widens scientific and experimental base for designing and manufacturing passive systems of heat transfer, heat removal, and thermal shielding of the reactor equipment.
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