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Heat Transfer in Inverted Annular Mode of Steam–Water Flow

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Abstract—A modified version of Hammouda's model for heat transfer in the inverted annular flow mode region is proposed, central to which is the use of temperature factor in calculating the Nusselt number and a new approximation of the influence coefficient θ. As a result, good agreement with experimental data for steam–water flow is obtained. Criteria for selecting the length integration step in computation codes are suggested.

Keywords: modified version of Hammouda model, inverted annular flow mode, heat transfer, temperature coefficient, steam–water flow

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A numerical analysis based on simulation of thermophysical processes in loop elements is the most accessible tool for analyzing unsteady thermal-hydraulic processes in the circulation loop of a nuclear reactor [1]. The safety of a nuclear reactor during its further operation depends in many respects on how valid the processes typical for the emergency situations postulated at the design stage are mathematically simulated.

At present, especially after the accident at the Fukushima nuclear power station, we are witnessing increased interest in description of physical processes in the post-burnout region for water-cooled reactors.

The modern ideas about post-burnout heat transfer are based on recognition of two fundamentally different mechanisms governing the onset of a situation in which a change occurs in the conditions of heat removal from a surface ("poor" removal of heat by steam emerges instead of "good" removal of heat by liquid, which leads to a growth of wall temperature), namely, burnout and dryout. Burnout is connected with a transition from bubble boiling of liquid to its film boiling, and dryout involves disappearance of liquid film on a heating surface and transition from dispersed-annual to purely dispersed flow structure.

Since burnout is observed at high heat flux densities typical for the cores of water-cooled reactors, the increase of fuel rod cladding temperature may be very high, up to burn-through of the cladding. It should be noted that the bulk temperature of coolant flow may in this case be well below the saturation temperature. Burnout conditions in heat removal may occur in a nuclear reactor also at surface heat loads lower than q_{cr} when the faulty core is flooded with cold water. In this case, with comparatively low heat flux, which is nonetheless sufficient for the wall temperature to exceed the minimal temperature at which the liquid wets the surface, the occurrence of inverted annual flow mode (also called inverted annual film boiling, IAFB) is also possible. Despite the increased attention paid by researchers to the problem of post-burnout heat transfer [2], there is still insufficient amount of experimental data on heat transfer for steam–water flows in the post-burnout region, which are required for confirming the validity of recommendations derived from the results of calculations. This is due to certain difficulties of setting up experiments on steam and water at high heat flux densities (several megawatts). In view of this circumstance, the majority of investigations for the region of parameters beyond the burnout of inverted annular flow mode in a channel are usually carried out with cryogenic liquids or using the hot spot technique when the above-mentioned flow mode is obtained at relatively moderate heat flux densities (a few hundred kilowatts).

Thus, post-burnout heat transfer flow mode involving the occurrence of inverted annular flow mode is possible in the following two cases:

(i) in an emergency situation without loss of coolant at heat fluxes above the critical one (a classic burnout); and

(ii) in reflooding the reactor core with water during which the heat fluxes are below the critical values and the wall temperature is above the Leidenfrost temperature.

Both these cases differ from each other, apart from thermal load values, in the flow motion velocity. At normal flowrates of medium through the core, the mass flow velocity is around 10^3 kg/(m^2 s), and during core reflooding it is around 10^2 kg/(m^2 s).

We believe that consideration of heat-transfer matters for these cases is of much importance.

In our opinion, the Hammouda model [3] is the one using which heat transfer under the conditions of