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Experimental estimation of the effect of contact condensation of steam–gas mixture on VVER passive safety systems operation

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Abstract

Results of experimental study of the effects of contact condensation of steam–gas mixture on the operation of VVER passive safety systems and steam generator in emergency condensation mode are presented. Contact condensation takes place when subcooled liquid is supplied in the accumulator tank of VVER reactor auxiliary passive core flooding system (the HA-2 system) in the presence of accumulated non-condensable gases. Water supplied to hydro accumulators can be used for increasing the operating time of VVER steam generator in the emergency condensation mode and for ensuring core cooling during longer time. Low liquid outlet velocity (less than 1 m/s) caused by the necessity to ensure safety systems operation in passive mode constitutes the distinguishing feature of the investigated processes.

Experiments were conducted on the test facility with parameters typical for the primary cooling loop of the reactor facility 24 h after the accident initiation for different concentrations of gas in the steam–gas mixture. Nitrogen and helium, which replaces hydrogen for the purposes of safety assurance, were used as the non-condensable gases. It was established according to the results of experiments that the increase of concentration of non-condensable gas within the volume of HA-2 hydro accumulator model up to 45% leads to the reduction of intensity of contact condensation of steam from the steam–gas mixture by ~29% in the experiment with nitrogen and by ~57% in the experiment with helium. The obtained experimental data can be used for numerical simulation of emergency processes in the VVER reactor facility during operation of passive safety systems taking into account the removal of steam–gas mixture from steam generator by supplying the subcooled liquid jet into the volume HA-2 accumulator tanks.

Keywords: VVER; Steam generator; Condensation mode; Contact condensation; Non-condensable gases; Steam–gas mixture.

Introduction

Availability of both active and passive safety systems is incorporated in many modern foreign and national designs of reactor facilities. For instance, passive residual heat removal systems intended for cooling down the reactor facility in the cases of emergency situations when active systems cannot be engaged because of some reasons (for example, because of the loss of external electric power supply sources) can be attributed to such systems.

Passive safety systems incorporated in the national design project "AES-2006" allow removing residual heat from the reactor core during 24 h after initiation of the emergency situation caused by the guillotine rupture of the main circulation pipeline with simultaneous loss of all electric power supply sources [1,2]. Passive heat removal system (PHRS) removes heat from steam generator (SG) by switching it to the operational mode of condensation of steam supplied from the reactor core. Notably, when steam generator is operated in the condensation operational mode its tube bundle assembly is filled with non-condensable gases penetrating from the reactor which results in the gradual decrease of condensation capacity of the SG. In the process of operation of system of hydro accumulators of the second stage

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(HA-2) non-condensable gases are spontaneously removed during the first 24 h after initiation of the accident from the steam generator tube bundle assembly in the volume of HA-2 hydro accumulator tanks of the system [3]. As the result of emptying of hydro accumulator tanks of the second stage and their filling with steam–gas mixture (SGM) part of steam from SGM is condensed on internal walls of HA-2 accumulator tanks. The above process continues until the hydro accumulator tanks are heated to reach the ambient temperature existing inside the containment. After draining water accumulated in the hydro accumulator tanks spontaneous removal of steam–gas mixture from steam generator stops, which, as the final result, may lead to the deterioration of heat exchange in the tube bundle assembly and interruption of supply of condensate in the reactor [4]. In connection with above the task emerges of increasing the time of steam generator operation in condensation operational mode and, consequently, increasing the duration of operation of passive safety systems as well.

Several technical solutions were suggested in order to increase the time of SG operation in condensation mode. In particular, use of system of hydro accumulator tanks of the third stage (HA-3) is suggested in the VVER-TOI project for ensuring long-term heat removal from the reactor core [5]. Technical solution according to which removal of SGM from steam generator tube bundle assembly is ensured by reducing pressure in HA-2 hydro accumulator tanks by supplying in their volume of cold water from additional tanks arranged above the HA-2 system is also examined [6]. However, in order to achieve this, it is necessary to ensure that hydro accumulator tanks of the second stage would contain not only non-condensable gases but steam as well. The above condition is satisfied because by the end of the first 24 h of accident development mean mass concentration of gas in steam–gas mixture will not exceed 20% in the real HA-2 hydro accumulator tank which is confirmed by calculations performed using the results of experiments conducted on GE2M-SG test facility [7]. It is suggested using high quality thermal insulation of additional accumulator tanks to maintain relatively low temperature of supplied liquid (not more than 50 °C). When water is supplied in the HA-2 volume it is difficult to create using passive methods head pressure sufficient for water atomization with formation of small water droplets, because water velocity will not exceed 1 m/s. Additional advantage of the discussed technical solution is associated with the fact that water penetrating hydro accumulator tanks one day after the initiation of the accident ensures additional feed of the reactor with coolant.

Direct contact of steam with liquid jets and droplets occurs in numerous heat exchange devices and, therefore, investigation of heat exchange during contact condensation of multi-component mixtures has significant practical and theoretical importance. At the same time, the implemented review of publications demonstrated that heat exchange processes during contact condensation of steam–gas mixture on jets and droplets of subcooled liquid at low outlet velocities are not sufficiently enough investigated. E.g., results of experiments with supply of water in "pure" steam and in steam with added nitrogen are represented in [8]. Water supply was achieved through the atomizer. Formula for calculation of dimensionless temperature averaged over the mass derived by the authors of [8] is applicable for very low nitrogen concentrations in steam (less than 1%). Measured values of temperature of turbulent jet during its discharge are presented in [9] for velocities starting from 0.4 m/s. Results of calculations for jets discharged with initial velocity up to 2 m/s from cylindrical holes with diameters up to 7 mm are also provided in this paper. For the above ranges of diameters and velocities the jet can be regarded as continuous along the section with length equal to 300–450 mm. However, presence of non-condensable gases significantly reducing efficiency of condensation as the result of which the process of condensation is not completed within the continuous part of the jet, is nor accounted for in [9].

Expressions for calculation of dispersed jets in the presence of steam–air mixture are provided in references [10–12]. The presented formulas are applicable to droplets with sizes not exceeding 4 mm. Heat removal during condensation of steam and steam from steam–gas mixture on continuous liquid jets was addressed in [13], but, however, condensation on atomized liquid jet is not examined in this paper. Processes of condensation of steam–gas mixture emerging as the result of operation of sprinkler systems applied on NPPs equipped with VVER-1000 reactor are examined in [14]. Authors of [15] conducted studies for the purpose of investigation of operation of sprinkler systems of PWR reactor as the means for reducing pressure and temperature inside containment and for reducing local concentration of hydrogen as the result of condensation of steam on droplets formed during water atomization. Experiments on the investigation of heat exchange during steam condensation on the surface of hollow cone of atomized water are presented in [16]. Role of non-condensable gases was not addressed in [16].

The conclusion can be reached based on the analysis of studies of steam condensation on water jets [8–16] that the investigated processes significantly differ from the processes taking place during condensation of steam–gas mixture penetrating the volume of hydro accumulator tanks of the second stage. The necessity to implement experimental studies of contact condensation of steam–gas mixtures as applicable to the conditions of operation of passive safety systems of VVER reactor follows from the above discussion.

Methodology of experiments on test facility

Test facility for investigation of process of contact condensation of steam–gas mixture was constructed at the JSC «SSC RF-IPPE». Main equipment and process lines of the test facility are presented in Fig. 1.

Test facility consisted of the measuring section and auxiliary systems. Composition of auxiliary systems included steam generator with capacity equal to 300 l with internal controlled electrical heating with maximum power of 12 kW; condenser of the pressure maintenance system; steam ac-