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Experimental investigation of sodium boiling heat exchange in fuel subassembly mockup for perspective fast reactor safety substantiation

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Abstract

Numerical modeling of ULOF-type accident development in sodium-cooled fast reactor carried out using the COREMELT code indicate the development and spreading of sodium boiling in the core accompanied with fluctuations of reactor technological parameters lasting over a period of several tens of a seconds. Significant influence on the calculation results is produced by two-phase coolant flow regime so the code boiling models requiring experimental confirmation. Design solution that includes the "sodium cavity" above the reactor core was suggested in order to exclude reactor accidents resulting in the destruction of reactor core elements. As the result of experimental studies on heat exchange during sodium boiling in the fast reactor fuel subassembly mockup with "sodium cavity" conducted on the AR-1 test facility under natural circulation conditions it was demonstrated possibility of long-term fuel pins simulators stable cooling. Schematic map of two-phase liquid metal flow regimes in fuel pin bundles is presented, data on the heat transfer during liquid metal coolant boiling in the fuel assembly are presented and analyzed. The obtained experimental data are used for further elaboration of the calculation model of sodium boiling in the fuel assembly and for COREMELT computer code verification.

Keywords: Fact reactor; Sodium; Fuel subassembly mockup; Experimental studies; Boiling; Two-phase flow regime map; Heat transfer.

Introduction

Experience of fast reactors operation (BN-350, BN-600, Phenix and PFR) confirms convenience of their operation due to favorable intrinsic self-control properties and stability [1].

Undertaken design and technological solutions pertaining to perspective reactor facilities must exclude development of emergency situations and accidents resulting in the destruction of reactor core elements. Thus, reactor design must prevent potential development of boiling crisis followed by destruction of fuel pin cladding.

Calculation studies implemented with application of COREMELT code [2] for the most unfavorable scenario of beyond design-basis accident associated with simultaneous interruption of electricity supply to all main circulation pumps accompanied by failure of the reactor emergency shutdown system (ULOF type accident) confirmed the efficiency of arrangement in the fuel subassembly of the so-called "sodium cavity" located above the reactor core before the upper blanket to ensure in sodium-cooled high-power reactor self-protection [3]. Presence of "sodium cavity" allows compensating the sodium void reactivity effect (SVRE) due to the increased contribution of neutron leakage in the overall reactivity balance in case of penetration of steam phase from the upper part of the reactor core into the "sodium cavity",

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as the result of which reactor power starts to reduce that in its turn lead to the reduction of steam generation intensity.

Calculation studies implemented using COREMELT code indicate the presence of reactor technological parameters fluctuations in the process of ULOF accident development with emergence of sodium boiling in the reactor core which can proceed during several tens of seconds [3]. In this case exist the possibility of stable residual heat removal regime establishment without boiling crisis. Since the results of calculations depend on a significant extent on the model of two-phase flow applied in the code, experimental substantiation of the model is required.

Studies of liquid-metal coolant boiling using classical design subassemblies mockups (without "sodium cavity") were carried out in the 1970–1980, for instance, in Japan [4,5], in Germany [6], in the USA [7], in France [8] and, in the 1990-ies and at the beginning of 2000-s, in Russia [9–13]. Results of experimental studies of sodium boiling under natural circulation conditions at low coolant velocities typical for ULOF-type accidents are of special interest. There are no data available on sodium boiling for the case of "sodium cavity" arranged in fuel subassemblies for such circulation regimes.

Thus, the tasks for the present study were the investigation of specific features of development of sodium boiling, determination of boundaries of stable sodium two-phase flow in the regimes with low velocities typical for the ULOF-type accidents using the mockup fast reactor fuel subassembly with "sodium cavity" and obtaining data for verification of the COREMELT code.

Experimental equipment

Experiment measurement and control system

Experimental facility consists of the following two circulation loops: the main circulation loop with sodium coolant and auxiliary circulation loop with sodium–potassium coolant [14]. The main loop is represented by the coolant rising section with mockup fuel subassembly and upper blanket, expansion tank, downcoming section, electromagnetic induction pump and direct heater installed at the riser inlet. Beside the above components the loop is equipped with parallel shortened leg with low hydraulic resistance bypassing the direct heater. Conductive electromagnetic pump on the basis of permanent magnet is envisaged for this bypass. Auxiliary loop serves for cooling down the coolant in the sodium loop. Heat removal from sodium loop is performed via the heat exchanger installed on the outer surface of the expansion tank. Sodium is inlet in the expansion tank from the experimental mockup facility, after which it is cooled down to 550 °C and supplied to the downcoming section. Thermal energy from sodium–potassium loop is removed by air-cooled heat exchanger.

Seven fuel pin simulators with electric heating packed in triangular lattice with relative pin pitch equal to 1.11 and fuel pin spacing made using winding wire. Pins bundle is placed in the hexagonal duct made of heat-resistant steel and serving as the external casing. Its outer surface is equipped with potentiometric probes, thermocouples and protective heater, and is covered by thermal insulation layer.

Fuel pin simulator consist of cylindrical cladding with external diameter of about 9 mm and length equal to 1200 mm inside which a spiral made of high melting point metal with length equal to 600 mm is installed. Space between the spiral and the cladding is filled with temperature resistant electrical insulation powder and with helium. The cladding consists of two coaxial pipes made of heat resistant steel. Longitudinal slots are arranged in the pipe with smaller diameter for installation of four thermocouples distributed along the length of heat generation section.

Sodium is preheated before entering the mockup subassembly and during its propagation along the forced circulation line within the direct heater of loop type. After heating sodium first penetrates the inlet chamber of the experimental section and, following this, it passes to the heated area of the mockup fuel subassembly. "Sodium cavity" with length equal to 430 mm is located above the reactor core mockup; after passing through it sodium goes through the area oppressed with upper blanket mockup with length equal to 700 mm which forms with cladding of the section a annular gap with 4 mm width.

Sodium boiling in the oppressed fuel subassembly flow channels is a complex and highly dynamic high-temperature process (sodium saturation temperature at atmospheric pressure is equal to 883 °C). Dynamics of formation of steam phase can have explosive character, especially taking into account possible overheating of sodium as related to the saturation temperature during sodium boiling. Operational control of the facility, data recording and processing are performed at high speed continuously and in real time.

National Instruments Compact RIO platform was applied in the development of the software and measurement complex. Programmable controller Compact RIO represents multifunctional and universal system for data collection, control and management of technological processes ensuring high productivity, accuracy and reliability of operation of measurement systems.

Analog and digital signals including fuel pin imitators power, temperature of technological elements and pipelines of circulation loops, coolant flow temperature, mockup fuel pin wall temperature, pressure of cover gas, coolant temperature in the loop, pressure drop in the fuel subassembly mockup, pressure pulsations at the fuel assembly mockup outlet, coolant flow rate in the loop, pressure pulsations at the mockup outlet, registration of steam phase presence in different sections of the mockup, sodium level in the volume control tank, acoustic emission signal, electric voltage on heaters, coolant leakage signals, operability of electrical equipment and control circuits, control of heating power for elements of the loop, working section, loop air cooling system, control of coolant flow rate and emergency switching off of electric power supply to mockup fuel pins are recorded and processed.