AN ELECTRICAL SIMULATOR OF A NUCLEAR FUEL ROD COOLED BY NUCLEATE BOILING

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ABSTRACT

This study investigates an electrical heated test section designed to simulate a nuclear fuel rod. This simulator comprises a stainless steel vertical tube, with length and outside diameter of 600 mm and 10 mm, respectively, inside which there is a high power electrical resistor. The heat generated is removed by means of enhanced confined subcooled nucleate boiling of water in an annular space containing 153 small metal inclined discs. The tests were performed under electrical power and pressure up to 48 kW and 40 bar, respectively. The results show that the experimental boiling heat transfer coefficients are in good agreement with those calculated using the Jens-Lottes correlation.

INTRODUCTION

The safety and economical operation of a pressurized water nuclear reactor are dependent, in great part, on the fuel rod behavior. Even under the severe operation conditions of a commercial nuclear power reactor the performance of the fuel rods can be considered excellent, and a reduced number of failures take place during standard operation.

Experimental qualification tests are required in new designs for fuel rods and they include tests in a research reactor, an irradiation circuit and a laboratory post-radiated analysis.

The irradiation circuit comprises an irradiation capsule and its operational systems. The irradiation capsule constitutes a safety barrier, in cases of a loss of integrity of the fuel rod prototype during the irradiation tests, and its function is to place the prototype in the core of the research reactor to subject it to the neutron flow required for its qualification. The role of the irradiation circuit operational systems is to create, inside the irradiation capsule, more precisely in the zone of the capsule where the rod prototype is installed, the chemical and physical conditions required for the execution of the irradiation tests.

The irradiation tests conducted in research reactors using irradiation circuits for the qualifying of combustible rods are known as nuclear experiments because they involve contamination risks from the research reactor, and the liberation of radioactive material to the environment. These hazards are consequences of the liberation of radioactive material due to a loss of the integrity of the combustible rod prototype and the irradiation capsule at some stage of the tests.

For safety reasons, the design of an irradiator circuit must be validated by an extensive experimental program, conducted in stages: in the first, known as *preliminary experiments*, the irradiation circuit must have its design and manufacturing processes evaluated outside the research reactor, with the nuclear combustible rod replaced by an electrical simulator. This stage aims to avoid the irradiation circuit operating directly with the presence of radiation, which would hinder repairs or changes to its structure and result in prohibitive costs.

Once the preliminary experiments are concluded, the installation of the irradiation circuit capsule in the core of the research reactor will be possible, and the second stage of the experimental program can be carried out, to validate of the design and manufacturing processes in the presence of ionizing radiation. Only after the conclusion of the extensive experimental program is the use of the circuit for effective irradiation tests possible. More information on irradiation circuits can be found in COSTA (2004).

This paper reports on the thermohydraulic testing of a fuel rod consisting of a vertical electrical tube cooled by enhanced subcooled boiling.

EXPERIMENT

Irradiation circuit

The heat source of nuclear reactors, using pressurized light water, is provided by several fuel rods, grouped close together, in order to maintain the reaction of controlled and self-sustained fission. The rod is formed of the combustible material and the metal cladding tube. The nuclear rod is the consumable part of the rod, comprising a column of uranium dioxide ceramic pastilles encapsulated in a cladding tube. The design of the combustible rod must ensure the maintenance of its integrity for its safe functioning, even considering that its components will undergo to elevated values of temperature, pressures and neutron flow, which results in severe mechanical and thermal efforts, accentuated corrosion and significant changes on the properties of materials employed in its manufacturing.

The main safety function of a combustible rod is to prevent the dispersion, in the cooling water of the reactor, of the highly radioactive products generated by the fission reactions that take place in the nuclear fuel. The two operational conditions which can determine the failure or breaking of the rod are the fusion by excess of temperature and breaking of the cladding by excessive pressure upon its inner surface. The loss of structural integrity of fuel rods in nuclear reactors leads to the leaking of radioactive products to the cooling water of the reactor.

Experimental capsule

The experimental device consists of an experimental capsule, operational systems and instrumentation for measuring and acquisition of data. The experimental capsule was designed with its two extremes adapted to the passing of the electrical simulator, so as to enable its electrical feeding by direct current. These modifications did not interfere with the objectives defined for the preliminary experiments of the irradiation circuit.

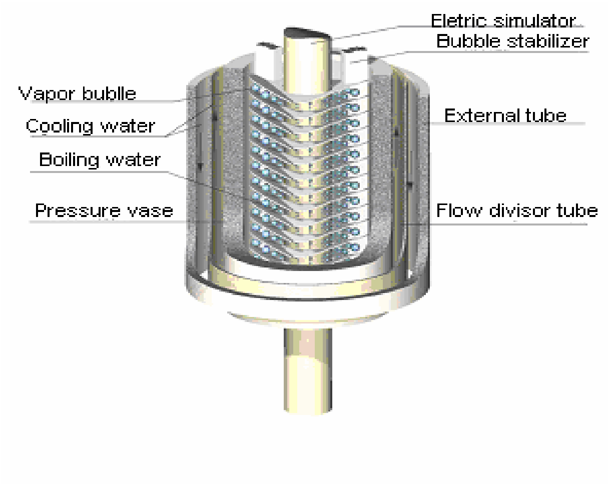
Inside the experimental capsule the electrical simulator of the fuel rod was mounted for the production of heat during the preliminary experiments. The operational systems are used to reproduce, inside the experimental capsule, the conditions of temperature, pressure and flow of pressurized light water to which a nuclear fuel rod is exposed during its utilization in reactors. The experimental device comprised an instrumentation and data acquisition system for control, monitoring and registering of the experimental parameters. Experimental results on temperature profiles in the electrical simulator, temperature profiles in the pressure vessel and coefficients of heat transfer by boiling for the electrical simulator were obtained. Table 1 shows the materials, dimensions and conditions of the design for the electrical simulator and for the experimental device.

Table 1: Table 1: Materials and dimensions of the experimental device

Component (material)	Outer/inner diameters (mm)	Design temperature (°C)	Design pressure (bar)
Simulator cladding (SS)	10 / 8	500	133
Pressure tank (SS and AA)	35.4 / 27	122	133
Flow division tube (SS)	42.2 / 38.9	122	10
External tube (SS)	60.3 / 57	50	10
Guide discs (SS)	26 / 11	122	133
Pressurizer (SS)	60.3 / 49.22	50	133
Pressure taps pot (SS)	60.3 / 49.22	50	133
Primary circuit pipe (SS)	6 / 4	50	133
Secondary circuit pipe (SS)	54 / 50	190	10

SS: Stainless Steel; AA: Aluminum Alloy

The irradiation capsule is composed of three concentric metal tubes, which are identified, from inside to outside, as pressure vessel, flow divider tube, and external tube. The combustible rod prototype is installed inside the first tube, and the external wall of the rod is surrounded by an ensemble of inclined (almost horizontal) small metal discs. This set is called the steam bubble stabilizer. The space inside the first tube is filled with pressurized water. The heat generated is removed from the rod by nucleate boiling. The bubble stabilizer optimizes the natural convective radial heat transfer, caused by the motion of the steam bubbles. Externally to the pressurized water, water flows in two annular spaces, which allows the cooling of the pressure vessel by forced convection. Figure 1 shows a sketch of this tube system (a) and a photograph of the bubble stabilizer (b).



(a)

(b)

Figure 1: (a) Tube system of the irradiation capsule; (b) Photograph of bubble stabilizer

The heat is dissipated by the Joule effect inside the simulator and removed by the nucleate boiling of the pressurized water inside the pressure vessel. Inside this vessel, in the space between the discs of the bubble stabilizer, the heat is transferred in the radial direction by the motion of the steam bubbles towards the inner surface of the pressure vessel, where condensation of the steam bubbles occurs. Between the external tube and the flow divider tube water moves downward through forced circulation imposed by the cooling water system. When this water reaches the bottom of this channel, it changes direction and moves upward along the external surface of the pressure vessel, thus removing the heat generated at the simulator from the experimental capsule.

The upper part of the pressure vessel, including the flanges, is manufactured in AISI-304 stainless steel, whereas the bottom part is made of $AlMg_3$ aluminum alloy. The pressure vessel has an external diameter of 35.4 mm, wall thickness of 4.2 mm and total length of 1092 mm. The pressure vessel lies inside a flow divider tube around which there is an external tube, manufactured in stainless steel AISI-304. The flow divider tube has diameters of 42.2 / 38.9 mm and the external tube has diameters of 60.3 / 57 mm.

The steam bubble stabilizer comprises 153 guide discs, three vertical regulators in the shape of a comb and two guides at the extremities, one on the top and the other on the bottom. The whole assembly was manufactured in stainless steel. The guide discs must not touch the external surface of the electrical simulator nor touch the internal surface of the pressure vessel. The convection cells formed in the space between each couple of guide discs are employed to limit the size of the bubbles, avoid the formation of natural convection streams inside the pressure vessel and the coalescence of vapor bubbles in the superior region to be cooled, ensuring uniform conditions for high values of heat flux.

The concepts employed in this design have previously been used successfully in other countries (Reichardt, 1968 and Whitehouse, 1992). Guide discs for boiling bubble orientation were first used by M. Neumann and collaborators at the Nuclear Research Centre, Jülich – Germany, in 1968.

Electrical simulator

One of the most important characteristics of nuclear fuel is its high heat flux. Thus, the electrical simulator used in this study was designed to assure the density level. The simulator is fed by electrical current and, through heating via the Joule effect, must reproduce the thermal and mechanical behavior of the cladding of the nuclear fuel rod.

The electrical simulator used employs an indirect method of heating and was built with the geometry, dimensions and materials specified for the cladding of the nuclear fuel rod to be tested. The simulator comprises, from the inside to outside, a central core of ceramic material, tubular resistive element, electrical insulator core and metal cladding tube. In the manufacturing of the electrical simulator, the alloy Inconel-600 was employed for the resistive tubular element, encapsulated in a cladding tube of AISI-304 stainless steel, which is insulated by compact bore nitrate. The heated length of the simulator is 600 mm and the maximum power is 48 kW. Inside the experimental capsule, the entire heated length of the electric simulator is encapsulated by the steam bubble stabilizer. The Inconel-600 tube is fed by direct current from a solid state thyristorized rectifier by means of a copper bus connected to both extremities of the simulator. Figure 2 represents a schematic drawing of the simulator with indirect heating.

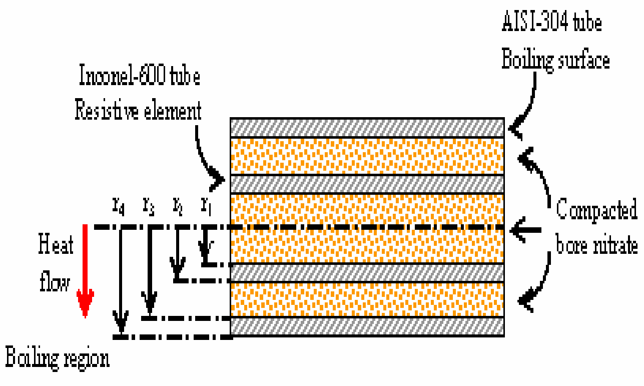


Figure 2: Sketch of the electric simulator.

Operational systems

The operational systems of the irradiation circuit are permanently connected to the inside of the irradiation capsule by means of stainless steel pipes. The operational systems are responsible for reproducing the pressure and temperature conditions, defined for the irradiation test, inside the pressure vessel, where the rod being tested is located.

These systems are also responsible for the cooling of the capsule, by the monitoring of the evolution of the rod inner pressure, caused by the formation of gaseous fission products, and by the storage of radioactive liquid and gaseous wastes, produced during the irradiation tests. The main operational systems of the irradiation circuit and their main functions are listed in Table 2. A detailed explanation of the three first systems is then presented.

Pressurized water system. This system is comprised of the pressure vessel of the capsule, pressurizer, pressure tap pot, manual valves and safety valves, temperature, flow and pressure meters and stainless steel tubes. Its role is to maintain the specified value of pressure for each experiment. In normal operation, 2/3 of the pressurizer volume contains demineralized water and, remainder, is filled with gaseous nitrogen.

Table 2: Operational system of the irradiation circuit

System	Main function
Pressurized Water	Heat transfer from the rod by nucleate boiling.
Cooling Water	Heat transfer from pressurized water by forced convection.
Gaseous Pressurization	Pressurization of the confined water.
Gaseous Counter Pressure	Rod pressure control (increased by fission gas).
Liquid waste and Gaseous	Collection of the fluid waste in case of rod breakage
Protection and Control	Irradiation circuit operation control

Cooling Water System. This system is composed of the centrifugal pump, tubular channels for secondary cooling of the simplified capsule, heating tank, heat exchanger, manual valves, pressure and flow meters and rigid metal tubes. The cooling water removes the heat from the electrical simulator and transfers it to the pressurized water by boiling. The centrifugal pump promotes the circulation of the cooling water, which transfers the heat removed from the capsule to the water of a refrigeration tower.

Gaseous pressurization system. This system consists of a 200 bar nitrogen cylinder, a manual pressure controller, a manual valve and stainless steel tubes. The inside of the pressure vessel is connected to the pressurizer, allowing the adjustment of the system pressure and automatic adjustment of any water expansion (or contraction) due to the formation (or condensation) of vapor bubbles. This pressure control occurs via emission of nitrogen, which is carried out by means of a pressure controller placed at the nitrogen cylinder.

Instrumentation and data acquisition

The experimental device uses an assemblage of an electrical transducer and transmitters installed in the experimental capsule and in the operational systems for measuring the physical variables investigated or controlled during the tests. The electrical signals of these devices are sent to a group of data acquisition electronic plates, installed in a microcomputer and processed by the operator of the experimental device using graphical software. This system allows real time monitoring and the registering of the measurements taken by the instrumentation for subsequent processing and analysis of the results representing the measured variables. The physical variables measured are: external temperatures of the simulator cladding (4 type-K thermocouples); external temperatures of the pressure vessel (4 type-K thermocouples); input and output cooling water temperatures (2 type-K thermocouples); cooling water flow (Coriolis meter); pressurized water pressure (PT16 transmitter); electrical current and voltage at the simulator (TRUE RMS meters).

The four simulator thermocouples are distributed along the heated length and positioned in the radial direction at angles of 90°, being more concentrated in the upper part of the heater element, where the probability of the occurrence of a critical heat flux is higher.

The Data Acquisition uses electronic plates for processing electrical signals and a microcomputer to obtain and process the signals of the thermocouples and the associated transmitters. There are 16 data input channels, representing temperature, absolute and gauge pressures, flow, voltage and electrical current. Each channel obtains and registers 2 to 3 electrical signals per second of the respective physical variables measured in the experimental device. The graphical interface program transforms the electrical signals into physical units, allowing the operator to make decisions in real time.

Experimental procedures

The experimental procedures in this study are similar to those of Baird (1995) and Figliola (2000). Before the tests, the system was heated for 30 min at a pressure of 1 bar and under boiling operation conditions in order to remove air from the experimental capsule. The tests were then started according to the following procedure: (1) set the cooling mass flow rate of the water and the water temperature to values of 0.39 kg/s and 30°C, respectively; (2) set the water confined pressure to 1 bar, 5 bar, 10 bar or 40 bar (for each experiment); (3) reset the three variables above; (4) adjust the electric current rectifier (thermal power) until the thermal power is 20% lower than the value of the critical heat flux (determined by classical correlations); (5) reset the values above; (6) register the data for a period of 2 minutes. In these experiments, pressures of up to 110 bar should have been used, but this was not possible due to failures in the welded thermocouples. For this reason, complementary preliminary experiments will be conducted using simulators with direct heating, in order to achieve the necessary temperatures and pressures.

The uncertainty theory used in this study was based on Coleman (1999). All of the measurement instruments were checked with standard calibrators. The global uncertainty of each measurement is comprised of the standard uncertainty used in the measuring chain, the uncertainty of the adjusted calibration curve and the statistical uncertainty associated with the average of the measurements carried out over approximately 2 min by the data acquisition system. The calibration curves of the meters were determined by the least square method for n points. The uncertainties of the primary physical variables measured, such as temperature, pressure, and water properties, were obtained from literature [Wagner and Kruse, 1998], and the uncertainties of the thermal power and heat transfer coefficient were obtained using the expression below [Kline and McClintock, 1953]:

$$w_f = \sqrt{\sum \left(\frac{\partial f}{\partial x_i} w_i \right)^2} \tag{1}$$

where f is a function of i independent variables x_i, w_f is the absolute uncertainty associated with the function f determined by the partial derivates of f and the uncertainties w_i associated with the independent variables. by boiling.

Analysis of the uncertainty of the experimental results showed that it is dependent mainly on the power delivered to the electrical simulator, and the maximum uncertainty of the heat transfer coefficients, as a function of the pressure, are: 29% (1 bar), 16% (5 bar), 10% (10 bar) and 7.5% (40 bar).

RESULTS AND DISCUSSION

Figure 3 shows the internal temperature of the pressure vessel versus the heat flux. According to Fourier's law, in the radial direction the internal temperature can be calculated using the following equation:

$$T_{\text{int}} = T_{ext} + q'' R \tag{2}$$

where T_{ext} and q'' represent the external temperature of the pressure vessel and the heat flux, respectively, and both are obtained through measurement. R represents the thermal conduction resistance of the wall. Note that the highest internal temperature occurs for a pressure of 40 bar, and it is close to 90°C. This value is lower than the maximum permissible temperature for the steel pressure vessel.

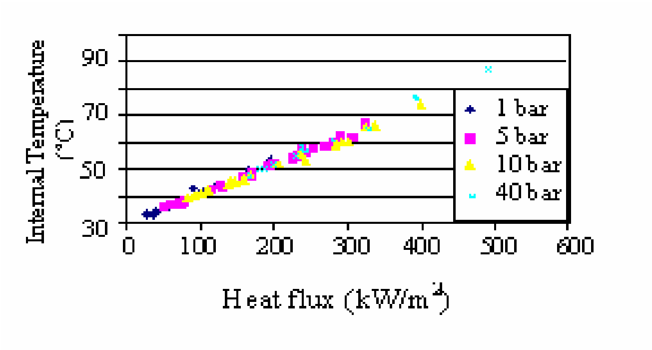


Figure 3: Pressure vessel internal temperature as function of the heat flux

Table 3: Experimental coefficient for heat transfer by boiling

P_{sat} (bar)	q" (kW/m^2)	T_{sim} (°C)	h (kW/m^{2}K)
1	527	123	22
5	872	178	33
10	1075	202	48
40	1325	266	89

Figure 4 shows the graph of the simulator external temperature as a function of the heat flux. In this case, the heat flux range is wider than that of Figure 3 because the pressure simulator surface is smaller than that of the pressure vessel surface. In Figure 4, for each pressure, there are two temperatures represented in the graphs. The first is the experimental temperature and the other is the temperature calculated by means of the Jens-Lottes correlation, which is given below.

$$\Delta T_{sat} = 25(q'')^{1/4} e^{-P_{sat}/62} \qquad (3)$$

where ΔT_{sat} (°C) is the temperature difference between the simulator external wall and the water for the pressure P_{sat} (bar), and the heat flux q'' unit is MW/m^2. The outside wall temperature of the simulator can be calculated by:

$$T_{sim} = T_{sat} + \Delta T_{sat} \qquad (4)$$

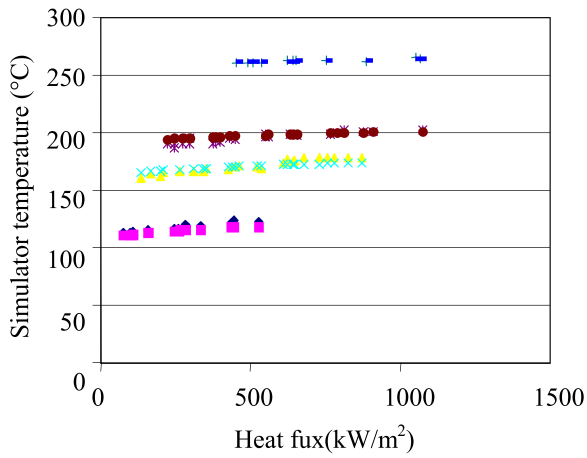


Figure 4: Simulator temperature as a function of the heat flux

◆ Experimental data
■ Jens-Lottes correlation (1 bar)

▲ Experimental data
× Jens-Lottes correlation (5 bar)

✳ Experimental data
● Jens-Lottes correlation (10 bar)

\+ Experimental data
▪ Jens-Lottes correlation (40 bar)

In this study, some correlations for pool boiling, such as those of Rohsenow and Taylor (Carey, 1994), were employed to calculate the simulator temperature. However, the results were not in agreement with the experimental values. Although the Jens-Lottes correlation is for convective boiling, it gave results which were in good agreement with the experimental values, as can be seen in Figure 4.

It should be noted that the highest simulator temperature is close to 270°C, occurring at a pressure of 40 bar. This value is lower than the maximum permissible temperature for simulator cladding which is manufactured in steel.

The experimental boiling heat transfer coefficients for the simulator surface are given in Table 3, along with the values of this coefficient for some simulator temperatures.

CONCLUSIONS

The experimental results show that the cooling process by confined nucleate boiling allows high heat flux and occurs with a reduced temperature difference between the simulator external surface and pressurized water. This difference becomes smaller with an increase in the water saturation pressure. The great efficiency of the heat transfer observed in this system is due to the suction effect induced by the collapse of the vapor bubbles. In addition, as the boiling occurs in a confined region, the thrust from the bubble condensation is amplified, thus further enhancing the process efficiency by nucleate boiling. Thus, the temperature levels of the solid parts of the system were well below the limits of operation.

The experimental results presented good conformity with the values obtained by means of the Jens-Lottes correlation. Thus, this correlation can be used to evaluate the simulator and pressure vessel temperatures for severe operational conditions which were not tested in this study.

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