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Monitoring of Coolant Flow Rate and Velocity in the Hot Channel of the IPR-R1 TRIGA Reactor Core

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1. Abstract

The IPR-R1 TRIGA research reactor of the Center of Nuclear Technology Development (CDTN) at Belo Horizonte is a pool type reactor cooled by light water under natural circulation. The core channels extend from the bottom grid plate to the top grid plate. The cooling water flows through the holes in the bottom grid plate, passes through the lower unheated region of the element, flows upwards through the active region, passes through the upper unheated region, and finally leaves the channel through the differential area between a triangular spacer block on the top of the fuel element and a round hole in the grid. In the natural convection, the driving force is supplied by the buoyancy of the heated water in the core channels. A forced heat removal system is provided for removing heat from the pool water. Direct measurement of the flow rate in a coolant channel is difficult because of the bulky size and low accuracy of flow meters. The flow rate through the channel may be determined indirectly from the heat balance across the channel using measurements of the water inlet and outlet temperatures. This paper presents the experiments performed in the TRIGA IPR-R1 reactor to monitoring some thermohydraulic parameters at the hot channels, with the forced cooling system switched off and on.

Key words: TRIGA nuclear reactor, research reactor, hot channel.

2. Resumen (Monitoreo del flujo y la velocidad del refrigerante en el canal caliente del núcleo del reactor nuclear TRIGA IPR-R1)

El reactor de investigación TRIGA IPR-R1 del Centro de Desarrollo de la Tecnología Nuclear (CDTN) en Belo Horizonte (Brasil) es un reactor tipo piscina refrigerado por agua leve en régimen de circulación natural. Los canales del núcleo se extienden desde la placa de fondo a la placa superior. El flujo de agua de refrigeración fluye a través de los orificios de la placa de fondo, pasa a través de la región inferior del elemento combustible, pasa a través de la región activa y posteriormente en la región fría de la parte superior y, finalmente, deja el canal a través del área diferencial entre un bloque espaciador triangular en la parte superior del elemento combustible y una abertura redonda en la placa. En la convección natural la fuerza del movimiento es suministrado por la flotabilidad del agua caliente en los canales. Se construyó un sistema de refrigeración forzada para el agua del pozo. La medición directa del caudal en un canal de refrigeración es difícil debido al volumen de los canales y a la baja precisión de los medidores de flujo. El flujo a través del canal se puede determinar indirectamente mediante un balance de calor en el canal midiendo la temperatura del agua a la entrada y salida. Este artículo presenta los experimentos realizados en el reactor TRIGA IPR-R1con la finalidad de supervisar algunas propiedades termohidráulicas del canal caliente del núcleo, con el sistema de enfriamiento forzado apagado y encendido.

Palabras clave: reactor nuclear TRIGA, reactor de investigación, canal caliente.

3. Introduction

The IPR-R1 TRIGA reactor at CDTN, as shown in Fig. 1, was started up on November 11th, 1960 with a maximum thermal power of 30 kW. The present forced cooling system was built in the 70th when the power was upgraded to 100

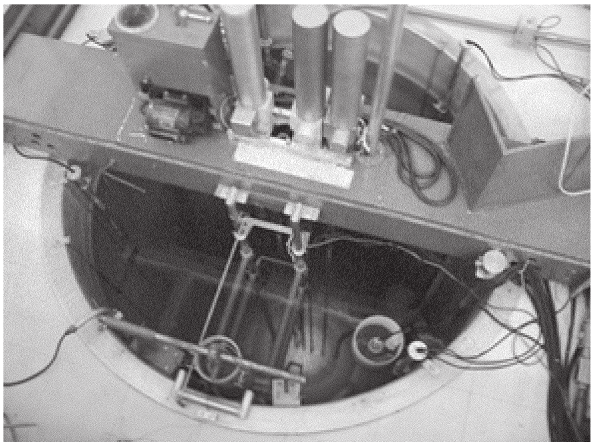

Fig. 1. IPR-R1 TRIGA reactor.

kW. Recently the power was upgraded again to 250 kW at steady state. TRIGA reactors, developed by General Atomics (GA), are the most widely used research reactor in the world. They are cooled by light water under natural convection and are characterized by being inherently safety. The reactor core consists mainly of a lattice of fuel elements, graphite dummy elements and control rods surrounded by a graphite reflector and water. The fuel is an alloy of zirconium hydride and uranium enriched at 20% in 235U. Under full power conditions, the reactor coolant is constrained to flow in parallel to the fuel elements through the active zone of the reactor core. The gradient of fluid density produces a buoyancy force that drives the fluid upward through the reactor core. Countering this buoyancy force are the pressure losses due to the contraction and expansion at the entrance and exit of the core as well as the acceleration and friction pressure losses in the flow channels. Since each flow channel provides its own driving force, it is possible to consider flow channel independently. A forced heat removal system is provided for removing heat from the reactor pool water (Fig. 2). The water is pumped through a heat exchanger, where heat is transferred from the primary to the secondary loop. The forced cooling system acts in opposition to the natural circulation, and its main purpose is to create a standing water volume at the pool top in order to improve the biological shield. This paper presents the experiments performed in the IPR-R1 reactor for monitoring some thermohydraulic parameters like coolant velocity, mass flow rate and Reynolds's number at the hot channels, with the forced cooling system switched off and on. Two probes with thermocouples were used in the experiments to measure the bulk temperature of the coolant in the coolant channel. The results were compared with the calculations performed by theoretical analyses. A data acquisition system (DAS) was developed to monitor the operational parameters in real-time. Information displayed was recorded on hard disk in a historical database [1].

4. Development

4. Description of the IPR-R1 TRIGA instrumentation

Three type K thermocouples and one resistance thermometer (PT-100) were positioned inside the reactor pool, at different heights, to measure the water pool temperatures. Two type K thermocouples were placed in the core, one at the channel exit and another at the channel entrance. A type K thermocouple was placed just above the pool surface to measure the air temperature at the reactor room and another in a hole in the reactor room floor to measure the soil temperature (Fig. 2).

Two platinum resistance thermometers (PT 100) were positioned at the inlet and at the outlet pipes of the primary cooling loop, just above the water surface of the reactor pool (see Tin and Tout in Fig. 2). These thermometers, together with a flow-measuring device at the loop, give the power dissipated through the primary cooling loop. The flow-measuring device consists of an orifice plate and a differential pressure transmitter. This pressure transmitter was calibrated and an adjusted equation was obtained and added to the data acquisition system. The temperature measuring lines were calibrated as a whole, including thermometers, cables, data acquisition cards and computer. The adjusted equations were also added to the data acquisition system.

For the measurement of the power dissipated in the secondary cooling loop, two resistance thermometers (PT 100) were

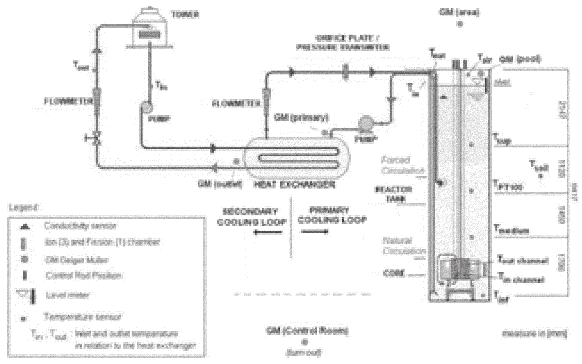

Fig. 2. IPR-R1 TRIGA reactor cooling system diagram and instrumentation distribution.

also positioned in its inlet and outlet pipes. The water flow rate at this loop was maintained constant and was also measured.

The sensor signs were sent to an amplifier and multiplexing board, which also makes the temperature compensation for the thermocouples. These signs were sent to a data acquisition card that makes the analog/digital conversion. This card was installed together in a computer where the data were calculated, registered and recorded. All data were obtained as the average of 120 readings and were recorded together with their standard deviations. The data acquisition system registers these data once a second [1].

4.2. Methodology

The mass flow through the core hot channel was determined indirectly from the heat balance across the channel using measurements of the water entrance and exit temperatures. The channel heating process is the result of the thermal fraction contributions of the perimeter of each fuel around the channel. Inlet and outlet coolant temperatures in hot channel were measured with two rigid aluminum probes (7.9 mm of diameter), each one provided with a 0.13 mm chromel-alumel k-type thermocouple. The probes penetrated axially the channels through small holes in the core upper grid plate. The probes were positioned in diametrically opposite channels, so that when a probe measured the channel entrance temperature, the other one registered the channel exit temperature. In a subsequent run, the probe positions were inverted (Fig. 3). The thermocouples were calibrated to obtain measurements within the experimental resolution of ± 0.5 oC. The temperatures were monitored in real time on the data acquisition system computer screen. The water expansion in the pool and the radiation level were also evaluated, both with the forced cooling system on and off. The maximum power of the IPR-R1 TRIGA is 250 kW, but it is licensed to operate at just 100 kW, so the experiments were performed at 100 kW.

4.3. Monitoring of the coolant mass flow rate and velocity in the hot channel

The two hottest channels in the core are Channel 0 and Channel 1' (Fig. 4 and Fig. 5). Channel 0 is located the closest to the core centre, where there is the largest density of neutron flux. There is no hole in the top grid plate in the direction of the Channel 0; so it was not possible to measure its temperature. The inlet and outlet temperatures in Channel 0 were considered as being the same of Channel 1'. Table 1 gives the geometric data of Channel 0 and Channel 1' and the percent contribution of each fuel element to the channel power.

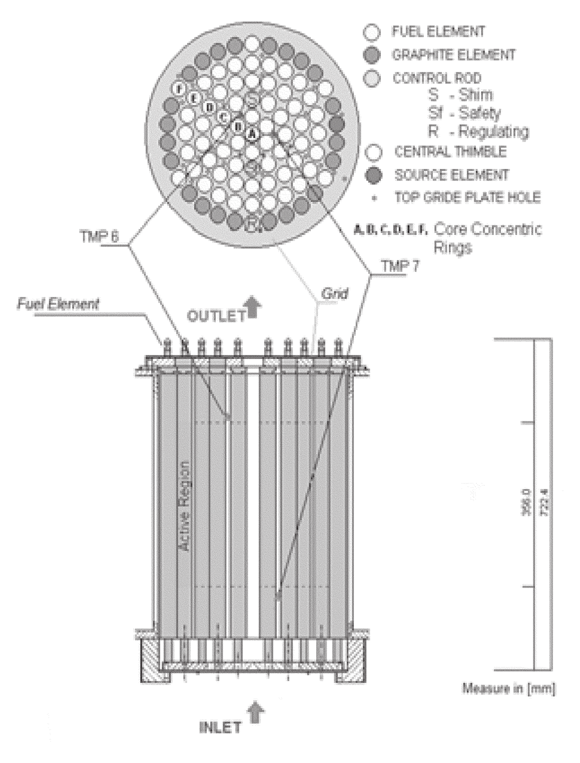

Fig. 3. Top and side view of the core and temperature probe position.

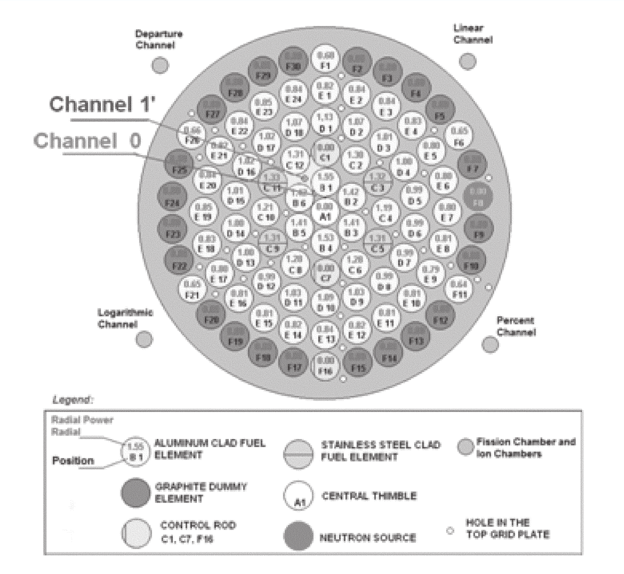

Fig. 4. Present core configuration of IPR-R1 TRIGA research reactor.

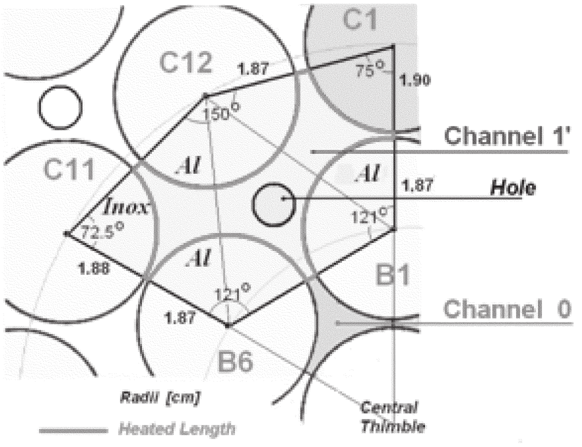

Fig. 5. TRIGA IPR-R1 hot channel.

The channel heating is a result of the contributions of each fuel perimeters fraction around the channel. The core total power in the experiment was 112 kW (corrected by the thermal power calibration result). So there was an average power of 1.909 kW dissipated in each stainless steel cladding fuel element and 1.765 kW dissipated in each aluminum cladding fuel element. The values are multiplied by the core radial power distribution factors calculated by Dalle [2] using WIMSD4 and CITATION codes (Fig. 4), and by the power axial distribution factor in the fuel (1.25), shown in Figure 6 [3]. The products are multiplied by the fractions of the perimeters of each fuel in contact with the coolant in each channel.

Table 1. Channel 0 and Channel 1' characteristics [4].

	Channel 0	Channel 1	Unit
Area (A)	1.574	8.214	cm^2
Wetted Perimeter (P_w)	5.901	17.64	cm
Heated Perimeter (Ph)	3.906	15.15	cm
Hydraulic Diameter (D_w)	1.067	1.862	cm
C11 Fuel Diameter	3.760	3.760	cm
B1, B6, C12 Fuel Diameter	3.730	3.730	cm
C1 Control Rod Diameter	3.800	3.800	cm
Central Thimble	3.810	3.810	cm
Core Total Power (q_n)	100.000	100.000	%
B1 Fuel Contribution	0.540	1.110	%
B6 Fuel Contribution	0.460	0.940	%
C11 Fuel Contribution	-	0.570	%
C12 Fuel Contribution	-	1.080	%
Channel Total Power	1.00	3.700	%

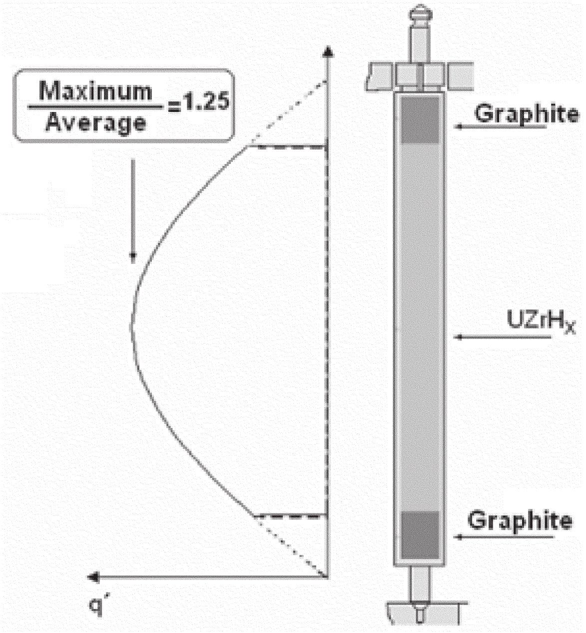

Fig. 6. Axial power distribution within the fuel rod.

The mass flow rate in the hydraulic channel (m) in [kg/s]; is given indirectly from the thermal balance along the channel using measurements of the water inlet and outlet temperatures:

$$\dot{m} = \frac{q_c}{c_p \Delta T} \qquad (1)$$

where q_c is the power supplied to the channel [kW], c_p is the isobaric specific heat of the water [J/kgK] and ΔT is the temperature difference along the channel [°C]. The values of the water thermodynamic properties are obtained as function of the bulk water temperature at the channel for the pressure 1.5 bar.

The graph in Figure 7 shows the temperatures evolution at the entrance and exit of Channel 1' (Figs. 4,5) and their differences. The difference is greater at the beginning of the operation (first 2 hours) when the cooling system was turned off.

The pertinent parameters required for the analysis of Channel 1' and Channel 0 are tabulated in Table 2. In the table, the mass flow G is given by: $G = m/channel\ area$. The velocity u is given by $u = G/\rho$, where is ρ the water density (995 kg/m^3). The values of the water thermodynamic properties at a pressure of 1.5 bar, as a function of the fluid average temperature of in the channel were estimated by interpolation from, the table

Table 2. Properties of the coolant in the core hot channel.

	Core Power q_n [kW]	Channel Power q_c [kW]	$T_{out}-T_{in}$ (average) ΔT [°C]	Specific Heat c_p [kJ/kgK]	Flow Rate $\dot{m}$ [kg/s]	Mass Flux G [kg/m²s]	Velocity u [m/s]	Dynamic Viscosity μ [10^{-3}kg/ms]	Reynolds Number Re -
Channel 1'									
Cooling off	112	4.15	4.15	4.1793	0.150	182.62	0.18	0.620	5485
Cooling on	112	4.15	4.15	4.1793	0.198	241.05	0.24	0.620	7239
Channel 0									
Cooling off	112	1.12	1.12	4.1793	0.041	340.52	0.34	0.620	5860
Cooling on	112	1.12	1.12	4.1793	0.054	343.07	0.35	0.620	5904

provided by Wagner and Kruse [5]. Reynolds number is given in the last column of Table 2 and was obtained by:

$$Re = \frac{GD_w}{\mu} \qquad (2)$$

Where G is the mass flow in [kg/m²s], Dw is the hydraulic diameter in [m] and μ is the dynamic viscosity [kg/ms]. Note that the natural convection flow is turbulent. The evolution of the coolant mass flow and velocity in Channel 1' and Channel 0 is shown in the graphs of Fig. 8 and Fig. 9. The results confirm the theoretical analysis did by Veloso in 2005 [6].

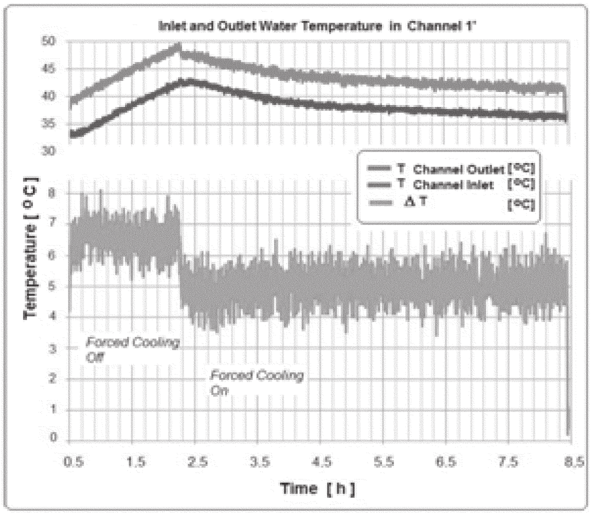

Fig. 7. Evolution of temperatures at the entrance and exit of Channel 1'.

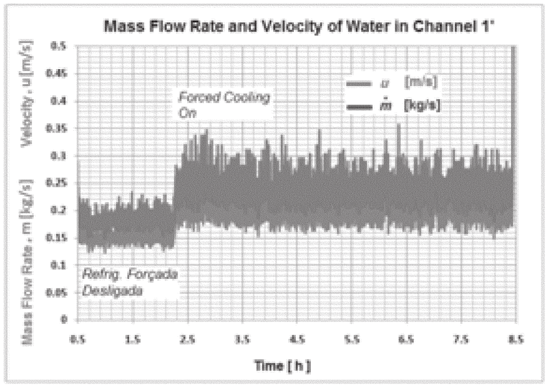

Fig. 8. Evolution of the mass flow rate and velocity of water in Channel 1'.

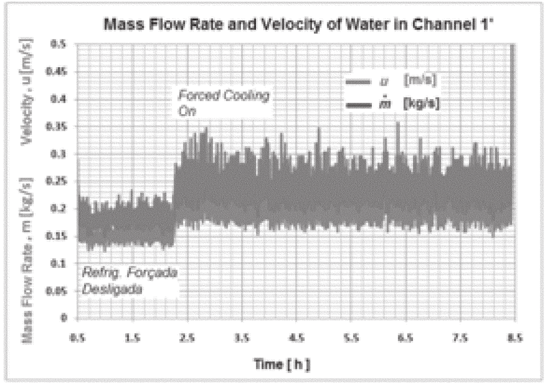

Fig. 9. Evolution of the mass flow rate and velocity of water in Channel 0.

5. Conclusions

Experiments were performed in the IPR-R1 reactor for monitoring some thermohydraulic parameters like coolant velocity, mass flow rate and Reynolds's number at the hot channels, with the forced cooling system switched off and on. The Reynolds number shows that the coolant flow is turbulent, in agreement with the experiments carried out by Mesquita [4], which showed that the heat transfer is subcooled nucleate boiling for operations over 85 kW. The experiments results indicated an increase in mass flow rate and velocity in the hot channel when forced cooling is turned on. Despite the forced cooling being contrary to the natural circulation inside the core, it cooled the pool water and makes the temperature at the entrance of core channels lower, improving the heat removal from the fuel elements.

The IPR-R1 TRIGA core design accommodates sufficient natural convective flow to maintain continuous flow of water throughout the core, which thereby avoids significant bubbles formation and restricts possible steam bubbles to the vicinity of the fuel element surface. The spacing between adjoining fuel elements was selected not only from neutronic considerations but also from thermohydrodynamic considerations.

It is suggested to repeat the experiments reported here, by placing a hollow cylinder over the core, with the same diameter of it, to verify the improvement of the mass flow rate by the chimney effect. These experiments can help the designers of the Brazilian Multipurpose Reactor (RBM), which will be a pool reactor equipped with a chimney to improve the heat removal of from the core [7].

Acknowledgments

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