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Research Article

Regulation of the temperature in the ampoule channel with natural circulation of coolant*

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Abstract

It has been shown by calculations that it is possible to extend considerably the capabilities for control of temperature conditions in an ampoule channel with natural coolant circulation, using the proposed hydraulic circuit layout, on samples during irradiation in the SM-3 reactor reflector cell by changing the circulation circuit geometry through the arrangement of a bypass heat removal line formed in the upper part above the flow limiter as compared to control only by changing the thermal conductivity of the gas gap in the channel body (through changing the gas pressure or composition). The ampoule channel test conditions, layout and simulation model for thermal-hydraulic analysis using the RELAP5/MOD3.2 code are presented. An investigation was conducted to study the effects of the bypass cooling circuit on the temperature conditions during irradiation of samples in an ampoule channel. The bypass flow rate change is achieved by varying the passage area of the flow limiter orifice. Options have been considered for filling the channel body gas gap with helium and a helium mixture. The calculation showed that the heat removed by the bypass line could reach 40% of the total heat released in the channel. With helium used in the channel body gap, the temperature conditions during irradiation are adjusted in a broader range (200–330 °C) than with a gas mixture of a lower thermal conductivity (279–330 °C), the major temperature variation taking place with the flow limiter orifice area being less than 0.2–0.3 cm^2. Any further increase in the flow limiter orifice area does not lead to a major temperature change in the coolant flowing about the samples.

Keywords

SM research reactor, natural-circulation ampoule channel, investigation results, irradiation temperature conditions, power density.

Introduction

Reactor tests in an experimental channel with natural circulation are often accompanied by the coolant (and sample) temperature deviations from the calculated values. This may happen due to:

- inaccuracies in determination of the power density distribution;
- inaccuracies in the values of the material's thermophysical properties specified in the simulation model;
- manufacturing tolerances in the fabrication of devices that affect the thermal-hydraulic parameters during irradiation, and so on.

In addition, sample tests often require the irradiation conditions to be changed according to a certain program. Therefore, the experimental device design stage requires

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considering the engineering and design solutions to enable adjustment of the irradiation temperature conditions directly in the process of the experiment.

To solve this problem, a double-body ampoule channel design with a gas gap and natural coolant circulation has been proposed. The temperature conditions in the channel can be adjusted by changing:

- the gas gap between the channel bodies through changing the gas pressure or composition;
- the circulation circuit geometry.

This paper investigates an additional mechanism for the sample temperature regulation through the arrangement of a bypass cooling circuit above the coolant flow limiter.

Ampoule channel layout

The ampoule channel (Fig. 1) is intended for the structural material testing in the SM-3 reactor reflectors cells (Bychkov 2009, Zvir et al. 2009, Arkhangelsky and Izhutov 2013) during irradiation at the temperature $T \sim 300$ °C and the pressure $P \sim 13–16$ MPa. The channel tests require the ratio of the corrosive fluid (water) mass to the sample surface area to be observed and no water composition to change substantially during long-term irradiation (Tsykanov and Samsonov 1973, Samsonov and Tsykanov 1991). A detailed description of the channel design is presented in (Seredkin et al. 2013, Osipova 2014, 2015, 2016, Osipova et al. 2015a, b, Uzikov and Osipova 2015).

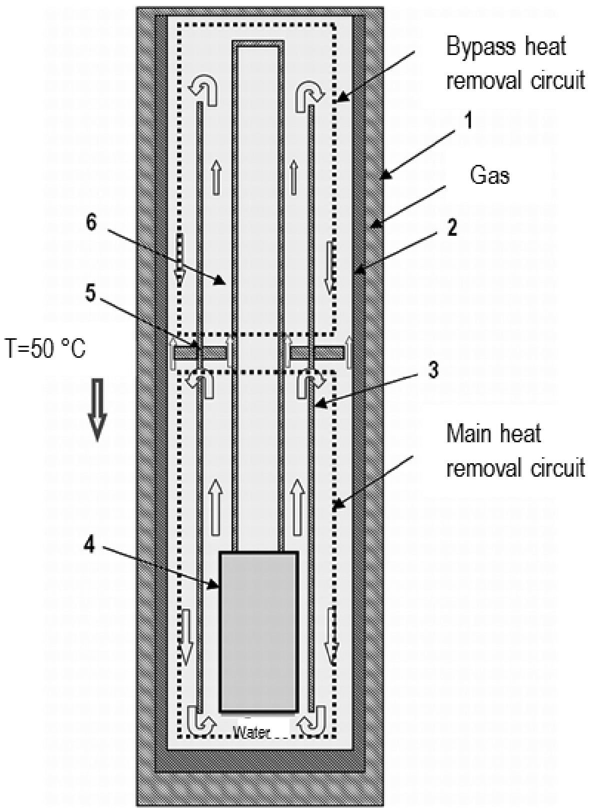


Figure 1. Layout of a natural-circulation channel: 1 outer body 2 inner body 3 separator 4 dummy holder with samples 5 flow limiter 6 bar

For the coolant temperature adjustment, the gap between the inner and the outer channel bodies may contain helium, nitrogen or a mixture thereof making it possible to change the gas gap thermal conductivity. Alternatively, temperature can be adjusted with the use of a bypass heat removal line formed above the flow limiter.

The effects the above-listed factors had on the coolant temperature in the ampoule channel with heat removed from the samples by natural circulation were calculated using the RELAP5/MOD3.2 code (Fletcher and Schultz 1995, RELAP5/MOD3 1995).

The use of RELAP5/MOD3.2 for simulation of the natural intercell convection is described in (Gataullina et al. 2012).

Calculation model

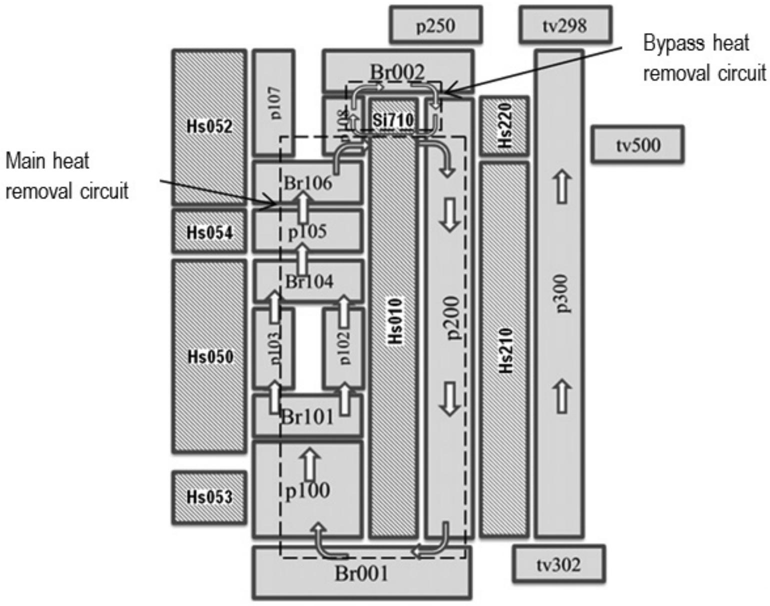
The nodalization pattern of the ampoule channel and downcomer simulation model for the thermal-hydraulic analysis in RELAP5/MOD3.2 is shown in Fig. 2. To describe the heat exchange processes in the simulation model, the following heat structures are used:

- case holder, samples, cases, holder tail (Hs050);
- lower tantalum radiation heater (Hs053);
- upper tantalum radiation heater (Hs054);
- flow separator (Hs010);
- bar (Hs052);
- channel body (Hs210, Hs220).

The hydrodynamic structures describing the coolant circulation line include:

- the circulation circuit riser inside of the flow separator at the lower heater level (p100);
- the circulation circuit riser inside of the flow separator at the sample case holder level fictitiously separated into two flows: the central one flowing about the samples as such (p103) and the peripheral one flowing about the sample cases along the outside perimeter (p102);
- the circulation circuit riser inside of the flow separator at the upper heater level (p105);
- a segment simulating the coolant inside of the bar (p107);
- a segment simulating the coolant between the bar and the flow separator (p108);
- a ring downcomer of the circulation circuit between the flow separator and the inner body (p200);
- the ampoule channel pressurizer (p250);
- the outer flow about the channel (p300);
- the outside channel cooling boundary conditions (tv298, tv302, tv500).

The coolant flow rate under natural circulation conditions inside of the channel is determined from the transient analysis of the coolant heat-up under the action of the heat



Figrue 2. Ampoule channel and downcomer nodalization pattern

generated in the heat structures at the reactor core level (±300 mm), as well as with regard for the heat transfer through the flow separator and the heat losses through the hollow body of the channel.

After the required power is reached, the total power density in the channel's structural materials, in the downcomer components and in water is ~ 19 kW.

To maintain the specified pressure in the ampoule channel during the coolant heat-up, a pressurizer was simulated. The hydraulic parameters of the downcomer and riser flow areas were specified in accordance with the initial design of the ampoule channel and the downcomer components.

Due to heat structures with a complex geometry being impossible to simulate in the RELAP code, the case holder, the cases and the samples were replaced by an equivalent cylindrical structure with the same heat-exchange surface area. The heat structures of the upper and lower heating units were simulated in the same manner.

The bar, flow separator and channel body heat structures are described in a standard way using a cylindrical geometry, with the bar and flow separator heat structures being single-layered, and the channel body heat structure being three-layered.

With regard for the radiation heat exchange through the channel body gas gap (Osipova et al. 2014), an equivalent model with the effective thermal conductivity of the gas layer and a correction for radiation was used (Mikheev and Mikheeva 1977, Kutateladze 1990, Kirillov et al. 1990).

To test the method described in this paper, the calculation results were compared with the results of a procedural experiment with irradiation of heat-resistant steel samples. The test results showed a satisfactory agreement and were reported in (Osipova et al. 2015a). The discrepancy in the estimated and experimental temperature values at the sample level does not exceed 3%.

Results of computational studies

To analyze the influence of the bypass heat removal circuit formed above the flow limiter on the ampoule channel temperature conditions, a series of calculations was performed with the constant initial conditions, channel geometry and thermal conductivity of the gas layer in the body. The flow rate through the bypass line was selected as the variable parameter. The bypass flow rate is changed by changing the flow area of the flow limiter orifice. Helium and a helium-nitrogen mixture were used as the channel body gas environment (Chirkin 1968).

The computational studies were performed with the following initial data:

- material of the separator, the channel body and the downcomer with samples – 12Kh18N10N steel;
- conditions of heat removal from the ampoule channel:
  - primary coolant temperature and pressure of 50 °C and 5 MP respectively;
  - downward flow rate inside of the central reactor shell of 1400 m3/h;
  - upward flow circulation rate of 1.5 m/s at the core level in the annulus with a gap width of 1 mm.

As a result of calculating the natural circulation with heat removal from the downcomer in the ampoule channel using the RELAP5/Mod3.2 code, dependencies of the main circulation circuit power (Q_{main}) and the bypass circuit power (Q_{byp}) on the flow limiter orifice area at a constant total power (Q_{tot}) (Fig. 3) were obtained, where Q_{tot} is the power released in the channel's structural components, in the downcomer and in water; Q_{main} is the power removed through the body in the lower part of the channel upstream of the flow limiter; and Q_{byp} is the power removed through the bypass circuit.

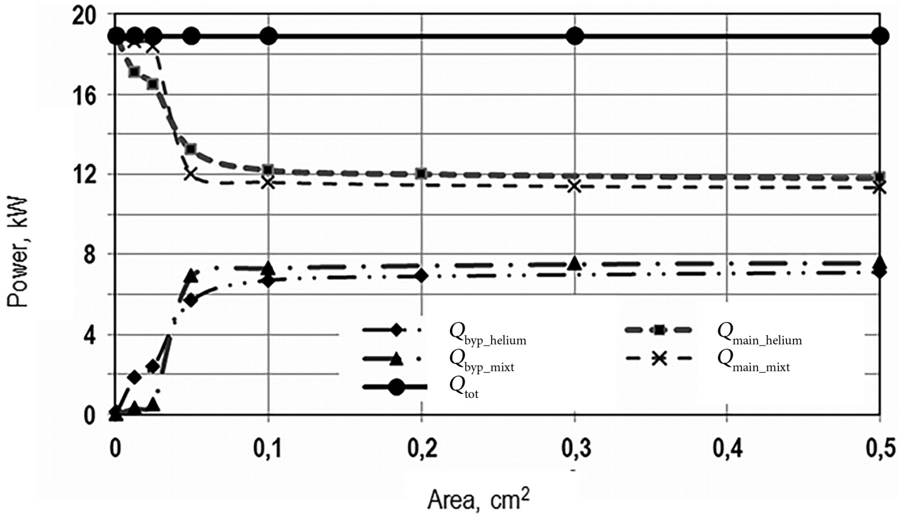


Figure 3. Total power ($\mathbf{Q}_{tot}$), main circulation circuit power ($\mathbf{Q}_{main}$) and bypass power ($\mathbf{Q}_{byp}$) as functions of the flow limiter orifice area

With the flow limiter orifice area values being less than 0.1 cm^2, the power removed by the main circulation circuit decreases to 60%, and the power removed by the bypass circuit increases, accordingly, by 40%. When the orifice area values are less than 0.03 cm^2 and a helium-nitrogen mixture (the thermal conductivity of which is approximately two times as low as that of helium) is used, the coolant boils throughout the length at the sample casing level. When the channel body gas gap is filled with helium and the values of the flow limiter orifice area are below 0.01 cm^2, the sample temperature also reaches the boiling point at a given pressure. Fig. 4 shows the sample inlet and outlet temperatures as functions of the flow limiter passage area.

With helium used in the channel, the irradiation temperature conditions are adjustable in a broader range (200 to 330 °C) than with a mixture of gases (279 to 330 °C). The biggest temperature change occurs with the flow limiter orifice area being less than 0.2 to 0.3 cm^2. Any further increase of the flow limiter orifice area does not lead to a major temperature change. This is due to the fact that the sample irradiation temperature conditions depend directly on the velocities and, accordingly, the rate of the coolant flow about the samples. Under the natural circulation conditions, the coolant flow rate is determined from the equality of the dynamic pressure and the hydraulic resistance of the circuit. With the flow limiter orifice areas of less than 0.2 to 0.3 cm^2, the greatest contributor to the circuit's hydraulic resistance is the local resistance of the orifices, which influences the flow rate and the temperature. With larger orifice areas, the contribution from the local orifice resistances to the total hydraulic resistance of the circuit becomes negligible and has no effect on the natural circulation flow rate.

Fig. 5 shows the main flow rate and the bypass flow rate as functions of the flow limiter orifice area.

With the flow limiter orifice area values of below 0.5 cm^2, the bypass line flow rate increases with both

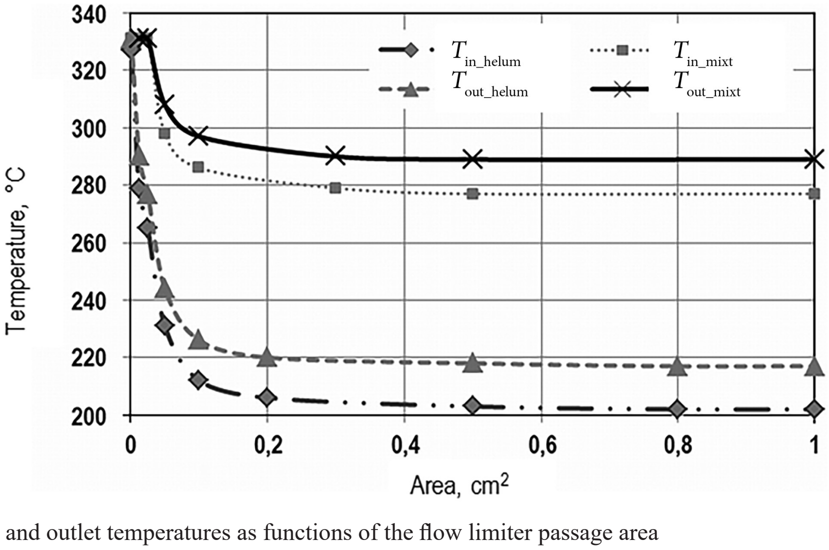


Figure 4. Sample inlet and outlet temperatures as functions of the flow limiter passage area

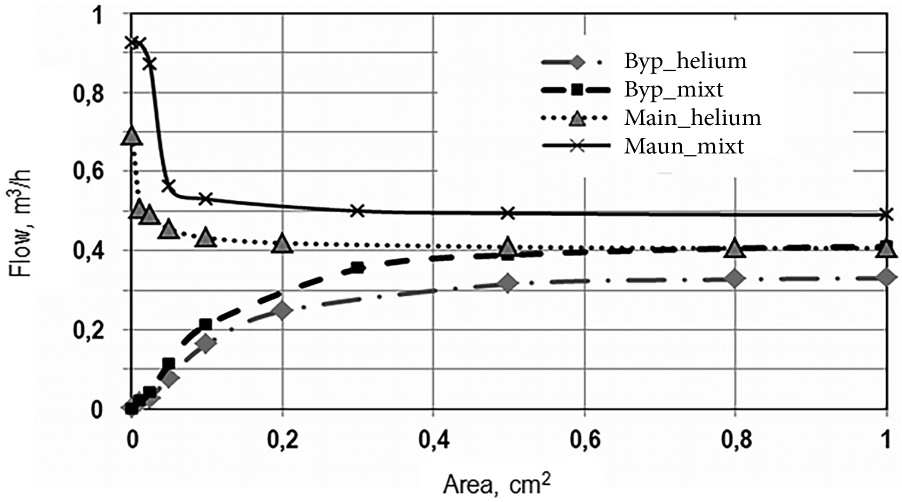


Figure 5. Bypass and main flow rates as functions of the flow limiter orifice area

gas types used in the channel and reaches a constant value. And the flow rate through the bypass line for the gas mixture is higher than for helium. This is due to the helium thermal conductivity being higher than the gas mixture thermal conductivity, which is the reason for the heat removal being predominantly through the main line.

Conclusion

It has been shown by calculations that the proposed coolant circulation pattern in the ampoule channel provides for much greater capabilities for the sample temperature regulation during irradiation, as compared with conventional regulation only through the heat conductivity of the AC body gap thanks to the heat removal by the bypass line in the channel's upper portion by changing the flow limiter orifice area, the share of which may reach 40% of the total heat released in the structural materials. When helium is used in the channel, the sample temperature change in a range of 200 to 330 °C can be achieved by changing the flow limiter orifice area in a range of up to 0.5 cm^2.

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