Study of thermal-hydraulic processes in the BREST-OD-300 steam generator

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Steam generator (SG) is an essential component of the BREST-OD-300 reactor facility. This is a vertical heat exchanger with coiled tubes immersed in liquid lead. The coolant and working fluid motion is straight-flow in the donwcomer and counter-flow in the riser. Fig. 1 shows the SG design featuring the following major components: a feedwater chamber, steam chambers, a support plate, a tube bundle, and an outer shell. Of interest, in terms of thermal-hydraulics, is the tube bundle that has a water line including a downcomer and a riser. Such hydraulic system may involve flow rate fluctuations and flow reversing in some of the tubes in the bundle. Also of interest is the downcomer thermal insulator which is equivalent to a heat tube.

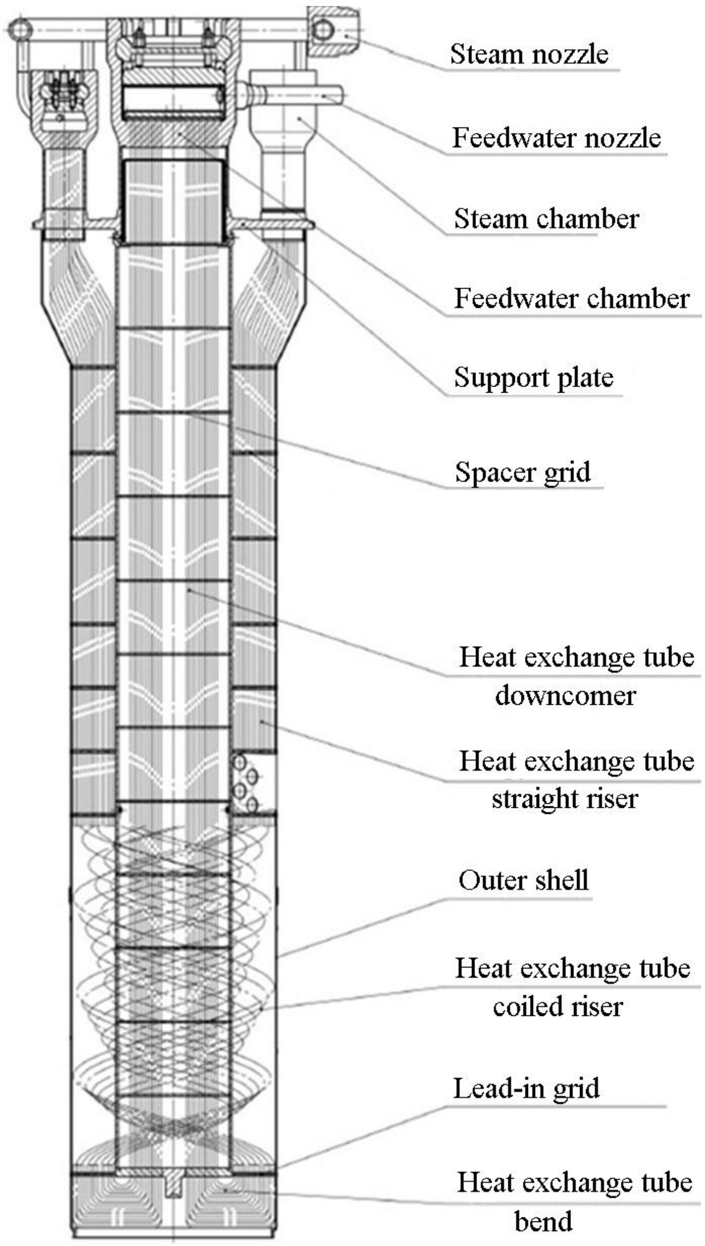


Fig. 1. SG overall view

The design of such a SG requires a thorough understanding of thermal-hydraulic processes typical of various operating conditions. Computational modeling based on dedicated codes offers the simplest and readily available method for thermal-hydraulic studies; specifically, RELAP5, a well-established thermal-hydraulic code, was used for this study.

Basic technical characteristics of the SG

SG thermal power, MW	90
Average mixed lead coolant temperature, ºC	
– SG inlet	535±5
– SG outlet	420±5
SG inlet feedwater temperature, ºC	340±5
SG outlet steam temperature, ºC	505±5

SG outlet steam pressure, MPa	17.00±0.05
SG lead coolant flow rate, kg/s	4950
Lead coolant speed, m/s, not more than	2
Steam-water line flow resistance, MPa, not more than	1.6
Lead coolant flow resistance, MPa, not more than	0.08
Steam output, kg/s	51.30±0.25

No new RELAP5 version including liquid metals was available at the time the study was started. So the RELAP5/MOD3.2 code version with no option for the liquid lead selection as the coolant was chosen for the SG model generation. This did not however hamper the analysis. Since a numerical lead circuit model requires only a fit between the model and full-scale system temperatures and heat exchange coefficients, superheated steam was used instead of lead in the numerical model with the flow rates adjusted proportionally with the lead and steam heat capacity ratio. The steam pressure in the "lead" circuit was assumed to be equal to 2.738 MPa, a pressure leading to the average value of the steam heat capacity, with the preset temperature range, being equal to 2238.7 J/(kg·K) and the deviations from the average value not exceeding ± 0.25%. Since the heat capacity of lead is equal to 147.3 J/(kg·K), then the steam flow rate in the analytical model needs to be 2238.7 / 147.3 ≈ 15.2 times as small as the lead flow rate to have the model steam temperature fitting the lead temperature. It does not matter for steady-state conditions if the volume of the model's circuit and the real volume of the lead circuit fit. The correct simulation of transients was achieved by increasing the circuit volume by the coefficient found by the formula

$$k = \frac{\rho_{Pb} \cdot c_{Pb}}{\rho_{steam} \cdot c_{steam}} \tag{1}$$

where ρ_{Pb} and ρ_{steam} are the density of lead and steam respectively; and c_{Pb} and c_{steam} are the heat capacity of respectively lead and steam. Since the steam density and heat capacity change fairly noticeably in response to a temperature change, the coefficient value was assumed to be such that to have the volumes fit error not exceeding ±1.6% in the downcomer and ±8% in the riser for the preset temperature range. These deviations affect the lead heat-up and cooldown time when transients are modeled. Such accuracy was enough for the calculations performed, still, where required, it was possible to give the numerical model a better fine-tuning and to reduce the deviations.

A table was used to set the coefficient of heat transfer from lead to the steam generating tubes. It was found using the following formulas [1].

For the longitudinal flow about the tube bundle in the downcomer

$$Nu = 7.55 \cdot x - 20 \cdot x^{-13} + 0.041 \cdot x^{-2} \cdot Pe^{0.56+0.19 \cdot x}, \tag{2}$$

where x is the relative pitch of the triangular tube sheet, and the Pe number is found from the bottleneck lead velocity.

For the coiled riser transverse flow

$$Nu = Pe^{0.5} \cdot \sin^{0.4} \varphi, \tag{3}$$

where φ is the angle between the tube axis and the lead flow direction. The Pe number is found from the bottleneck lead velocity.

The heat exchange is worsened by an oxide film formed on the heat exchange tube surface in the process of operation. This film has a heat resistance calculated from relation [2, 3]:

$$R = 0.0002 \cdot C^{0.1514} \tag{4}$$

where R is the heat resistance; and C is the concentration of oxygen. The lead heat transfer coefficient was adjusted using this data.

Such modeling strategy required a check, so the numerical model of the lead-water heat exchange was verified based on results of experiments at the SPRUT test bench at IPPE [4]. The bench's test section is formed by a three-tube lead-heated steam generator (Fig. 2).

The initial experimental stage modeled conditions with a water flow of 80 to 120 % of the rated value, both for the SG working pressure and for the supercritical pressure. Stage 2 modeled partial conditions of the SG operation, and stage 3 modeled the startup conditions.

The experiments were numerically modeled using two RELAP5 versions, namely: RELAP5/MOD3.2 and RELAP5.3D. Unfortunately, the available version of the code RELAP5.3D had limitations on the size of the input data and could not be used to model the processes in the steam generator. Superheated steam was used instead of liquid lead in RELAP5/MOD3.2 with the model having been respectively adjusted. RELAP5.3D supports the use of lead-bismuth eutectic as the coolant. Eutectic and pure lead have slightly differing thermal properties, so lead-bismuth eutectic can be used as the coolant in RELAP5.3D instead of pure lead after the thermal diameter is reduced by a factor of 1.2 in the analytical model.

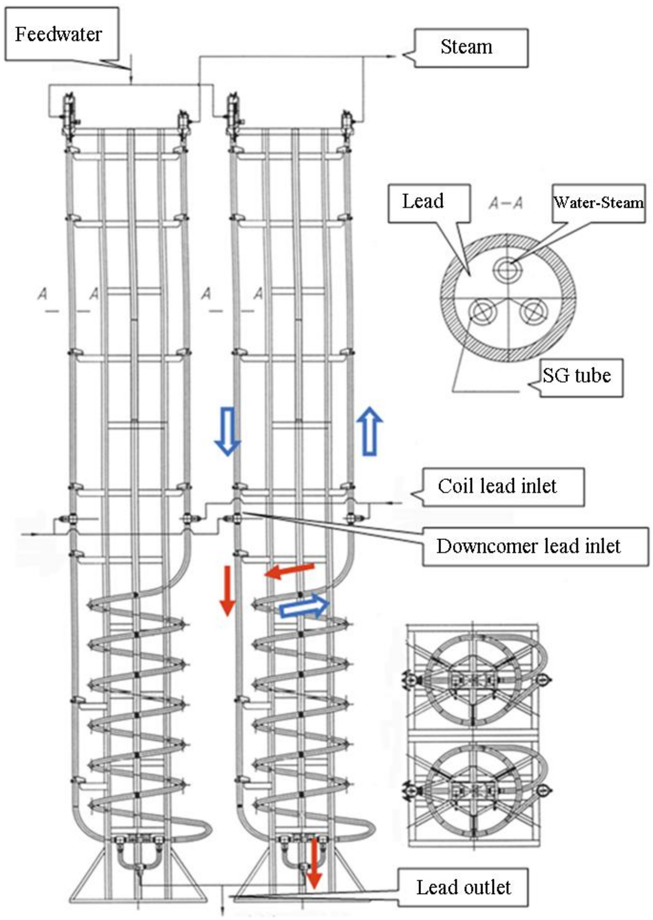


Fig. 2. SPRUT test bench test portion

One can see from Fig. 3 that the results of the calculation using the two codes are practically identical. The diagrams show the measured vessel temperatures which differ slightly from the calculated temperature of lead in the coil. The calculation results were compared with experimental data. The water enthalpy variation and the power on the water and lead side, calculated based on the two codes, differ by less than 1 % for all conditions. The lead calculated and measured temperatures in the coil agree well for practically all conditions. The caculated enthalpy increase values obtained based on both codes deviate from the experiemental values by not more than 10 % for most of the conditions, with only four experimental points drop out but the error in this case does not exceed however 25 %.

The properties of the SG downcomer thermal insulator were studied at a test bench manufactured and installed at NIKIET. The bench’s test section consists of two parallel channels separated by the thermal insulator under investigation. Water was fed into one of the channels, and heating steam was fed into the other. The water and heating steam temperatures were measured along the circuit in different conditions of the test bench operation. Fig. 4 shows the arrangement of detectors. The test bench and the experiment results are described in detail [5 – 9].

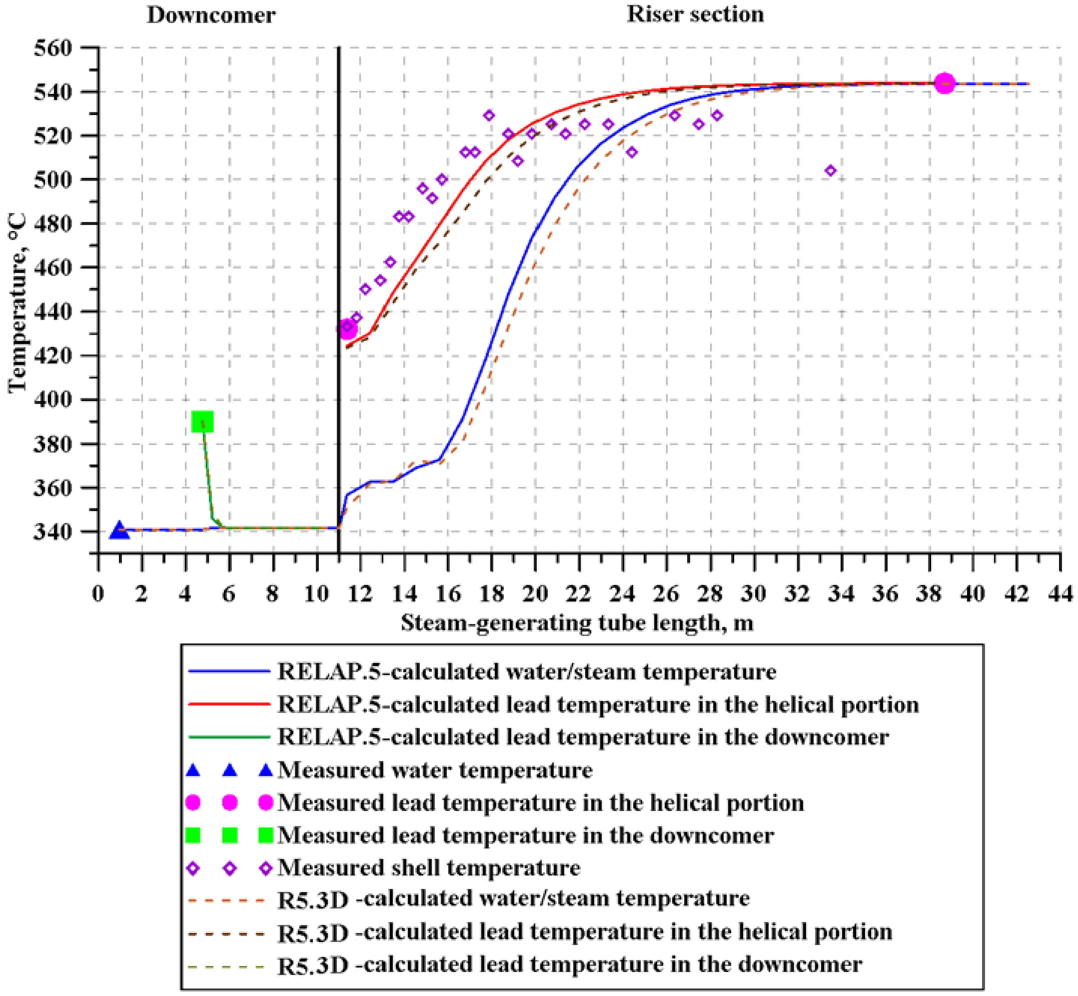
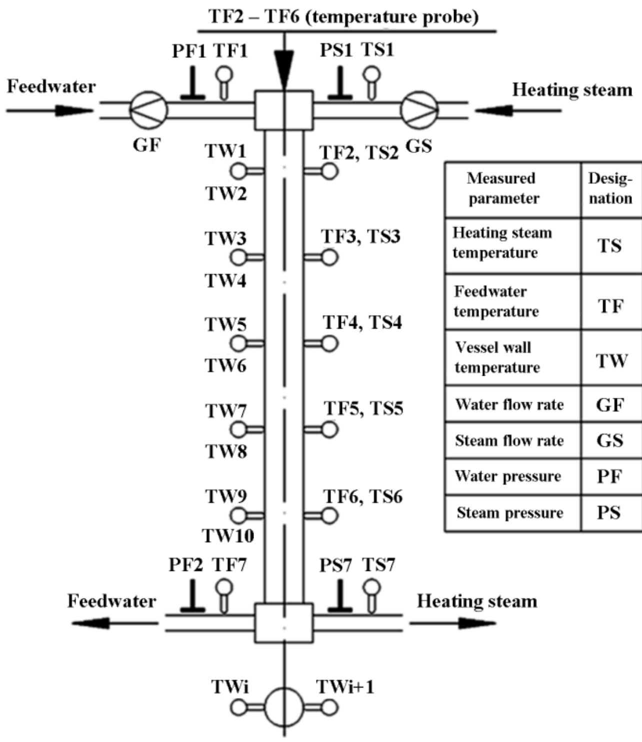


Fig. 3. Temperature distribution along the model length, the water flow rate is 80% of the rated value



Measured parameter	Desig-nation	Number of check points
Heating steam temperature	TS	7
Feedwater temperature	TF	7
Vessel wall temperature	TW	10
Water flow rate	GF	1
Steam flow rate	GS	1
Water pressure	PF	2
Steam pressure	PS	2

Fig. 4. Thermal insulator test setup

An analysis into the experiment results has shown that the SG downcomer thermal insulator is an analog of a heat tube which required a special approach to the generation of the SG numerical model. Experimental data helped with the numerical model tuning. Fig. 5 shows the comparison results for the test section water calculated and measured heat-up. The deviation of the calculation from the experiment lies in an acceptable range with about 95% of points having a deviation of ±15 %.

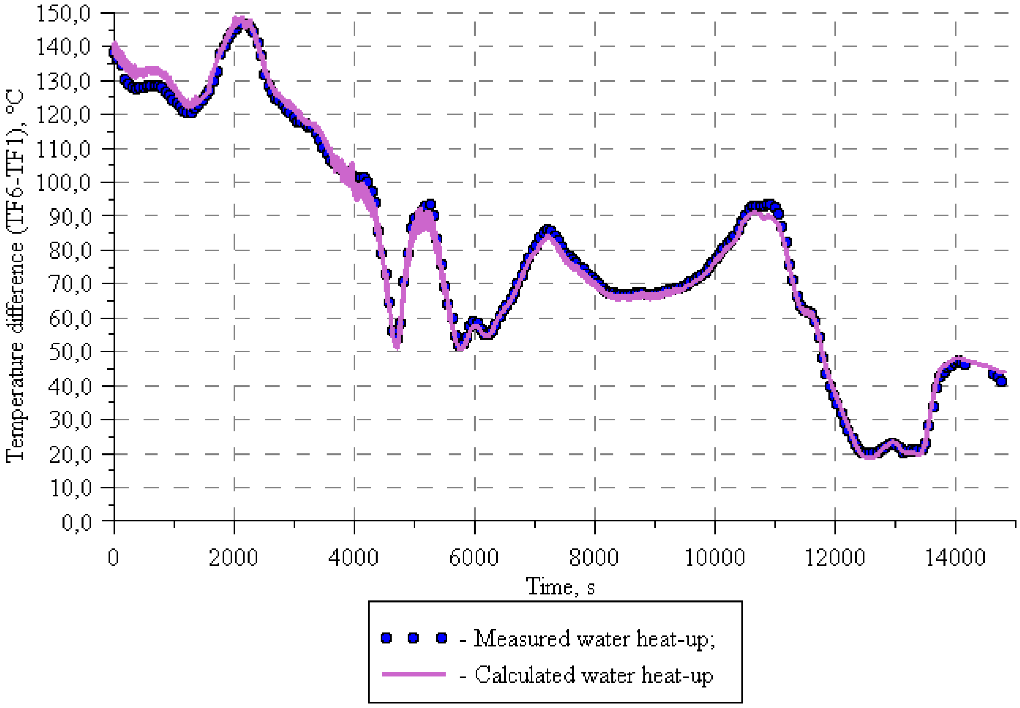


Fig. 5. Test bench calculated and experimental water heat-up

The verification of the numerical SG model based on experimental data has demonstrated the adequacy of the selected modeling procedure. The subsequent stage involved a computational analysis of the different SG operating conditions.

Fig. 6 shows calculation results for the SG nominal operating conditions. It can be seen from the figure that the lead and steam outlet temperatures agree with the design values. Meanwhile, thanks to the downcomer being thermally insulated, it became possible to keep water subcooled throughout the downcomer length, and the lead temperature decreased to below 400°C in the downcomer.

The numerical model helped to estimate the reliability of the circulation in the SG. Fig. 7 shows the hydrodynamic characteristics for the SG initial and final designs. The peculiarity of the SG circuit is that the hydrodynamic characteristics, when the flow rates are small, enter the negative pressure difference regions. This threatens to cause the circulation reversal in some of the tubes and flow rate oscillations. In the initial design, the instability region was over 50% of the rated flow. The optimal value was obtained for the hydraulic resistance of throttle valves based on calculation results, which resulted in the instability boundary shift towards 20%. The calculation for the conditions with a water flow rate of 10% of the rated value (or being, in other words, in the negative pressure difference region) has confirmed the possibility of the circulation reversal in some tubes.

The SG is isolated from the water line and the steam line in conditions of an emergency reduction of reactor power, while steam is simultaneously discharged through a safety valve. This leads to a decrease of pressure and, accordingly, to a decrease of the water saturation temperature. The calculation has shown that this may result in the lead solidification in the downcomer. So, following the numerical modeling, the algorithms for equipment operation in conditions of an emergency power setback were adjusted.

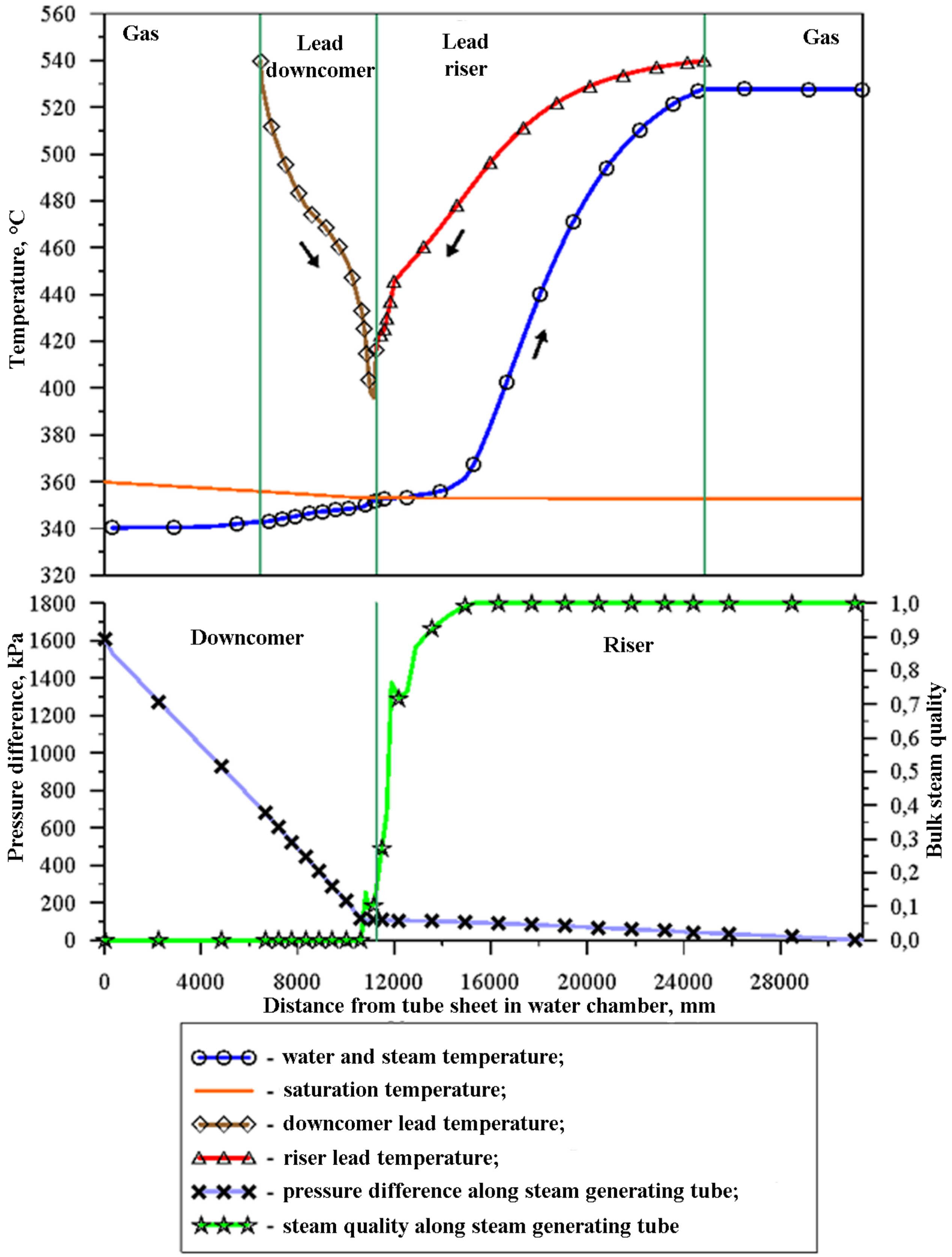


Fig. 6. Thermal-hydraulic parameters of water, steam and lead in the SG in nominal operating conditions

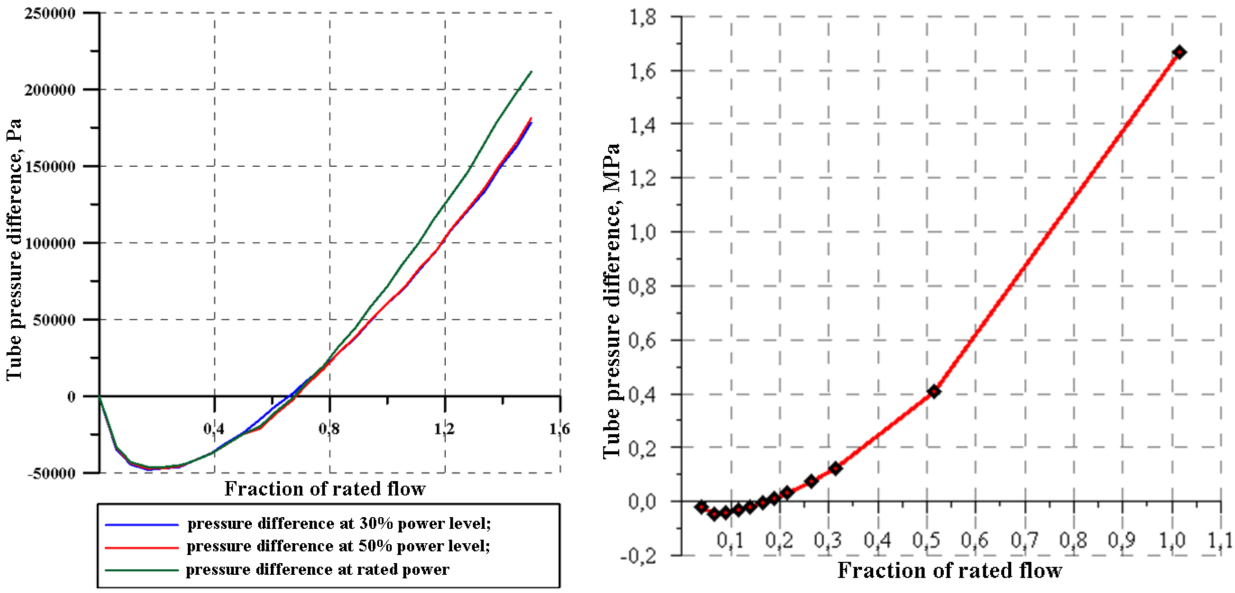


Fig. 7. SG hydraulic characteristics prior to and after the throttle valve flow resistance optimization

One of the situations requiring for an emergency reduction of reactor power and the SG pressure reduction is a steam generating tube rupture. In this case, the tube rupture is the initial event after which the pressure starts to grow in the gas space due to the steam release from the SG. The effects are localized using a special system. The design of this system requires one to know the thermal-hydraulic parameters of the mixture being released. So a rupture of an SG heat exchange tube was numerically modeled which has shown the flow rate dependence on the rupture point. Depending on the rupture location, the rupture flow rate is from 0.8 kg/s to 2.5 kg/s. The nearer to the steam header is the rupture the larger is the leakage, which is because of an increase in the superheated steam flow rate. The feedwater flow rate remains practically invariable due to a throttle valve installed on the downcomer. The mass steam quality of the steam-water mixture also depends on the rupture point, but, in any case, is over 80 %. The mixture temperature is in a range from 360 °C and higher.

To conclude, it can be said that the study of the steam generator thermal-hydraulics is one of the stages in the design and validation of the BREST-OD-300 reactor facility [10-13]. A major result of this stage is the development and verification of the numerical steam generator model. The developed numerical model was used to study the steam generator thermal-hydraulic processes. Specifically, stability was analyzed, and full power, partial power, SG startup, emergency power setback and other conditions were modeled. The SG numerical modeling results have made it possible to formulate recommendations for improving the steam generator design, and were also used to develop other BREST systems. See [14, 15] for more details of the study of the steam generator thermal-hydraulic processes.

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