Decay Heat Removal System in the Secondary Circuit of the Sodium-Cooled Fast Reactor and Evaluation of its Capacity

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Abstract. Decay heat removal system (DHRS) for the sodium-cooled fast reactor (SFR) by means of implementation of air cooling the outer surface of piping and equipment of heat removal loops of the SFR secondary circuit is proposed. The method of evaluation of the efficiency of such a DHRS and mathematical model of a code developed for this evaluation is described. The results of evaluation of characteristics of this DHRS in application to SFR power units with various power level are presented to determine allowable power range of its application, as well as approaches of optimization of the DHRS characteristics are explained.

Key Words: Sodium-cooled fast reactor, decay heat removal system, pipelines of the secondary heat removal loops.

1. Introduction

A new option of the system for decay heat removal through the walls of pipelines and equipment of main heat removal loops of the reactor facility (RF) is proposed that can be used, for example, in design of liquid metal fast reactors. A similar principle of decay heat removal was considered in the PRISM reactor design [1], where decay heat was planned to remove through the walls of the reactor vessels to the outside air. However, such a design solution for decay heat removal system (DHRS) significantly limits the value of power removed and it can be used only in designs of liquid metal fast reactors with small power size [2].

The paper analyses the DHRS option, where the surface of pipelines and equipment of main heat removal loops of the SFR secondary circuit (DHRS-2C) is used. The optimization of the characteristics of the proposed DHRS-2C is performed in relation of its application in the BN-800 secondary loops. In addition, for evaluation of the allowable power range of application of the DHRS-2C, the computational analysis of decay heat removal modes by this system for large power size SFR, namely for the SFR with electric power 1600 MWe, so-called BN-1600, is carried out. The degree of influence of the DHRS-2C characteristics on its efficiency is studied.

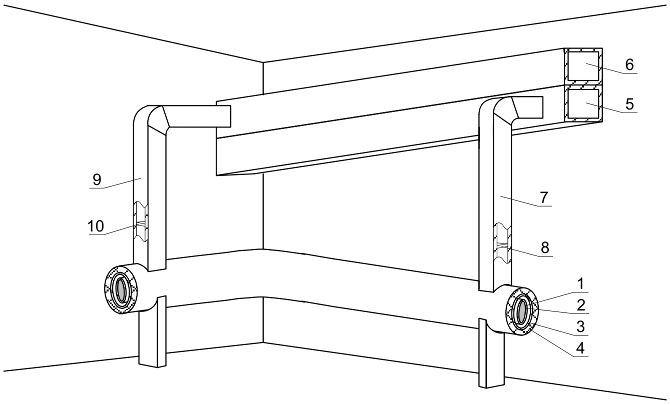
2. Description of the DHRS-2C

The following technical solution to use the external surface of the sodium pipelines and equipment of the secondary loops for emergency decay heat removal is proposed, that provides controllable heat removal from pipelines and equipment of the secondary circuit to the surrounding area.

All equipment and pipelines that are supposed to be used for decay heat removal are placed in safety jacket that is covered with thermal insulation and it is cut off from the surrounding space during normal operation modes of the RF. Thus, the parasitic heat losses from the equipment and pipelines are excluded in normal operation modes. When the modes occur that require to remove decay heat from the reactor after its shutdown, the gap between pipelines, equipment and safety jacket around them connects with surrounding space, providing flow of outside air through the gap and increased heat dissipation from the RF elements accordingly.

Heat transfer in loops of the primary and secondary circuits of the RF is carried out by coolant natural circulation (NC). Conditions for NC occurrence are provided by appropriate elevation of the heat exchange equipment and loop configuration: the core is located below than intermediate heat exchangers (IHX) in the primary circuit, all pipelines of the secondary circuit cooled by external air are placed above IHX. Air flowrate in the gap can be provided both by NC and by forced circulation (fans). The DHRS-2C option with air NC provided by a chimney connected to the mentioned gap is analyzed in the paper.

The section of the pipeline equipped with a similar system of emergency decay heat removal is presented in Figure 1.



1 – main sodium pipeline, 2 – gap between main pipeline and safety jacket, 3 – safety jacket, 4 – thermal insulation, 5 – inlet air collector, 6 – exit air collector, 7 – sectional air delivery pipe, 8 – damper in sectional air delivery pipe, 9 – sectional air return pipe, 10 – damper in sectional air return pipe

FIG. 1. Layout of the DHRS-2C section for main pipeline of the SFR secondary circuit.

The exit air collector receiving air from the gap is connected to the chimney in considered DHRS-2C option. Air heated in the gap is removed through the chimney outside, thus providing NC draught in air circuit created by inlet air collector, sectional air delivery pipe, gap between main pipeline and safety jacket, sectional air return pipe, exit air collector and chimney.

Obviously, creating a large gap between the pipeline and jacket is inexpedient for the following reasons. First, it is necessary to minimize volumes of premises. Second, the reduction of gap width leads to increase of air velocity in the gap and, consequently, to increase of the heat transfer coefficient to the air. However, this also increases the hydraulic resistance of the gap that leads to decrease of air flowrate. If you do the gap of acceptable width for the whole secondary loop with one inlet and one outlet for air flow, hydraulic resistance of the gap would be significant and would not allow to organize the removal of the necessary amount of heat.

To increase the efficiency of described DHRS-2C it is proposed to divide mentioned gap into several parallel on air side sections connected to common chimney providing air draught in these gaps. In this case the inlet and outlet ducts of the sections are recommended to be placed in the upper part of the premises to exclude congestion in zone of personnel actions.

Note that the safety jackets used in this system perform localizing functions during normal operation of the RF, thus, improving the SFR fire safety.

3. Approach to substantiation of the DHRS-2C characteristics

The DHRS-2C efficiency depends on many parameters:

- Surface area available for heat removal;
- Width of the gap affecting both the value of the heat transfer coefficient to the air and the value of its hydraulic resistance;
- Number of parallel sections that the gap is divided into;
- Height of exhaust chimneys;
- Value of thermal emissivity of materials of pipelines and equipment of the secondary loops and safety jackets;
- Value of the coolant NC in the RF circuits.

Existing experience on similar systems (reactor vessel air cooling system in PRISM reactor, air cooling systems of tube bundles of steam generators in Phenix and BN-350 reactors) shows that the value of power removed by such systems is limited primarily by the capabilities of the air heat removal. Meanwhile, heat transport in the RF circuits by the coolant NC does not represent fundamental difficulties and, as noted above, it is provided by appropriate elevation of heat exchange equipment and loop configuration, which is the subject of a separate study. In this paper main attention is directed to substantiation of the possibility of removal of required value of power in this DHRS by air flow. And we assume that transport of decay heat in the RF circuits is provided by the coolant NC. Therefore, a SARB code was developed for analysis of the DHRS-2C that models in details phenomena occurring in the DHRS-2C air circuit specially.

As noted above, evaluation of the DHRS-2C efficiency has been conducted for two SFR of different power – BN-800 and BN-1600.

Analysis of the DHRS-2C is performed under the following basic assumptions:

- Surface of the main pipelines of the secondary circuit is only used for heat removal (surface of the steam generators and other equipment of the secondary circuit is not used for heat dissipation, we also neglect heat losses from the reactor vessel);
- Heat losses through insulation of safety jackets are neglected, it is only taken into account heat removed by air flow in the gap;
- Integral RF heat capacity takes into account heat capacity of the coolant and steel structures of the primary circuit and heat capacity of the operating secondary loops, including all their equipment;
- All parallel sections that the gap between sodium pipelines and safety jackets is divided into are considered as identical (to simplify calculation);
- Option without special increase of the heat transfer surface to air in the gap is analyzed.

4. Mathematical model of the SARB code

As noted above, the DHRS-2C efficiency, first of all, is limited by the capacity of the air heat transfer system and by the characteristics of the air circuit. Therefore, the developed SARB code provides the most detailed modeling of transient thermal hydraulic modes in the air circuit of the DHRS-2C and heat transfer conditions to the air flow in it, while the dynamics of sodium circuits is simulated by a rather simplified way. This approach permits to do a large volume of computational studies on optimization of the characteristics of the air circuit of these systems and demonstration of their potential capabilities.

A maximum value of average coolant temperature in the reactor vessel achievable during emergency decay heat removal mode is selected as a criterion for optimization of the DHRS-2C parameters.

In accordance with these objectives, it is selected two-parametric model of the sodium circuits – 1) sodium in the reactor vessel and cooling loops, and 2) metal structures in the reactor vessel and cooling loops:

$$C_{Na} \cdot \frac{dT_1}{d\tau} = W_{ocm} + K_S \cdot F_S \cdot (T_S - T_1) - q_0 \cdot F_R \tag{1}$$

$$C_S \cdot \frac{dT_S}{d\tau} = K_S \cdot F_S \cdot (T_1 - T_S) \tag{2}$$

where $T_1(\tau)$ – the average sodium temperature, $T_S(\tau)$ – the average temperature of metal structures, C_{Na} – the integral heat capacity of the coolant in the reactor vessel and heat removal circuits, W_{ocm} – power of the decay heat release in shutdown reactor, C_S – the integral heat capacity of the metal structures in the reactor vessel and cooling loops, F_S – the surface area of the heat transfer between sodium and metal structures, F_R – the surface area of heat exchange with air, K_S – integral coefficient of heat transfer from sodium to metal structures, q_0 – the heat flux density to air. The dependence of power of the decay heat release on time is set either analytically or in tabular form.

The heat transfer from sodium to air and thermal hydraulics of the air circuit is described by the following equations:

$$q_0 = q_1 + q_2 \tag{3}$$

$$q_0 = K_R \cdot (T_1 - T_2) = \frac{\lambda_S}{\delta_R} \cdot \left(T_2 - T_3\right) \tag{4}$$

$$q_1 = \alpha_1 \cdot (T_3 - T_B) \tag{5}$$

$$q_2 = \frac{\sigma_0}{\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right)} \cdot \left[(T_3 + 273)^4 - (T_4 + 273)^4\right] = \alpha_2 \cdot \left(T_4 - T_B\right) \tag{6}$$

$$c_B \cdot G_B \cdot (T_{B_K} - T_{B_0}) = q_0 \cdot F_R \tag{7}$$

$$T_B = \frac{T_{B_K} - T_{B_0}}{2} \tag{8}$$

$$\Delta p_t = \Delta p_h^{\Sigma} \tag{9}$$

$$\Delta p_t = \left(\gamma_{B_0} - \gamma_{B_K}\right) \cdot g \cdot H \tag{10}$$

$$\Delta p_h^{\Sigma} = \Delta p_h^{in} + \Delta p_h^{T} + \Delta p_h^{out} = \xi_0 \cdot \frac{G_B^2}{2 \cdot \gamma_{B_0} \cdot f_0^2} + \xi_R \cdot \frac{G_B^2}{2 \cdot \gamma_B \cdot f_R^2 \cdot N^2} + \xi_K \cdot \frac{G_B^2}{2 \cdot \gamma_{B_K} \cdot f_K^2} \tag{11}$$

$$\xi_R = \xi_{R_0} + \lambda_R \cdot \frac{L_R}{2 \cdot d \cdot N} \tag{12}$$

where q_1 – the heat flux density removed from the outer surface of the pipelines due to air convection, q_2 – the heat flux density removed from the inner surface of the safety jackets by air convection, T_2 – the temperature of the inner surface of the pipelines, T_3 – the temperature of the outer surface of the pipelines, T_4 – the temperature of the inner surface of the safety jackets, T_B – the average temperature of the air flow in the heat exchange section, δ_R – thickness of the main pipeline of the secondary loop, K_R – the heat transfer coefficient from sodium to the inner surface of the pipelines, α_1 – the heat transfer coefficient from the outer surface of the pipelines to air, α_2 – the heat transfer coefficient from the inner surface of the safety jackets to air, λ_S – the thermal conductivity coefficient of wall material of pipelines and safety jackets, σ_0 – the Stefan-Boltzmann constant, ε_1 – the thermal emissivity coefficient of the wall material of the pipelines, ε_2 – the thermal emissivity coefficient of the wall material of the safety jackets, T_{B_0} – the temperature of outside air (at inlet to heat exchange section), T_{B_K} – the temperature of air flow at the exit from the heat exchange section, G_B – mass air flowrate in the air circuit, N – the number of the DHRS-2C parallel heat exchange sections, Δp_t – the NC pressure head created in the air circuit due to air heating, Δp_h^{Σ} – the overall hydraulic resistance of the air circuit, Δp_h^{in} – the hydraulic resistance of the inlet section of the air circuit, Δp_h^{T} – the hydraulic resistance of the heat exchange section of the air circuit, Δp_h^{out} – the hydraulic resistance of the outlet section of the air circuit, γ_{B_0} – the density of outside air, γ_B – the average air density in the heat exchange section, γ_{B_K} – the air density at the exit from the heat exchange section, c_B – the specific heat of air, H – the height of the chimneys, L_R – the total length of pipelines at the heat exchange section, ξ_0 – the total hydraulic resistance coefficient of the inlet section of the air circuit, ξ_R – the total hydraulic resistance coefficient of the heat exchange section of the air circuit, ξ_{R_0} – the total coefficient of local hydraulic resistance in the heat exchange section of the air circuit, ξ_K – the total hydraulic resistance coefficient of the outlet section of the air circuit, λ_R – the Moody friction factor at the heat exchange section, f_0 – the cross-section area of the inlet section of the air circuit, f_R – the cross-section area of the heat exchange section of the air circuit, f_K – the cross-section area of the outlet section of the air circuit, d – the width of the gap between the pipeline and the safety jacket, g – the free fall acceleration.

5. Input data for the DHRS-2C analysis

Input data presented in Table I are used for studying the DHRS-2C characteristics in application to the BN-800 and BN-1600 reactors.

TABLE I: INPUT DATA FOR COMPUTATIONAL ANALYSIS OF THE DHRS-2C.

Parameter	BN-800	BN-1600
Reactor thermal power, MW	2100	4200
Coolant volume in the reactor vessel, m^3	950	3090
Coolant volume in the secondary loop, m^3	300	535
Length of the secondary pipelines cooled by air, m	270	240
Temperature of the outside air, ° C	30	30
Initial average coolant temperature in the RF circuits, ° C	450	450

Number of the operating loops during decay heat removal mode, pcs	2	2–6

The values of the Moody friction factors for elements of the air circuit are defined in accordance with selected geometrical sizes.

The following parameters of the DHRS varied in calculations:

- Width of the gap between main sodium pipeline and safety jacket;
- Thermal emissivity coefficient of materials of main sodium pipeline and safety jacket;
- Height of exhaust chimneys;
- Number of parallel sections that the gap between sodium pipeline and safety jacket is divided into in each secondary loop;
- Number of operating loops of the secondary circuit in emergency decay heat removal mode.

We assume that material of the main pipeline and safety jacket has the same value of the thermal emissivity coefficient and set two basic values of 0.25 and 0.85 for this parameter. Choice of these values of the thermal emissivity coefficient for wall materials of the secondary pipelines is done due to the following reasons. The value of 0.25 corresponds to stainless steel 1Kh18N10T [3] without any special treatment, the second value equal to 0.85 corresponds to the one achievable as a result of special processing of the metal surface. We consider two values of 30 m and 60 m for height of chimneys.

We studied the dependence of the maximum value of average coolant temperature achievable during emergency decay heat removal mode on thermal emissivity of pipeline material and height of exhaust chimneys.

The width of the gap between main sodium pipeline and safety jacket ranged from 1.5 to 7 cm, number of sections that DHRS-2C in each loop is divided into varied from 6 to 80 sections. It is obvious it will be difficult to provide a large number of sections due to both limit for minimum possible length of individual section and large number of sectional inlet and outlet air pipes. However, at the stage of preliminary analysis of this system the aim is to identify the dependence of its efficiency on different parameters in a wide range of their variation.

6. Optimization calculations of the DHRS-2C for the BN-800

There are no data on key characteristics for this DHRS-2C and their influence on its efficiency. Therefore, parametric studies were performed in application to the BN-800 for deeper understanding the relationship between different characteristics of the DHRS-2C and the degree of their influence on its efficiency.

In accordance with the requirement of the regulatory documents to take into account a single failure during operation of safety systems, we postulate the most unfavorable event associated with failure of one cooling loop, for example, due to the closure of the check valve in the MCP-1. Thus, the decay heat from the reactor shutdown after its long-term operation at nominal power level is removed by two secondary loops.

Figure 2 illustrates dependences of maximum value of average coolant temperature in the BN-800 circuits during emergency decay heat removal on number of sections for different values of gap width, thermal emissivity coefficient of wall materials (ε) and height of exhaust chimneys (H). The obtained dependences indicate the presence of a strong minimum in investigated range of numbers of the DHRS-2C sections. Note that minimum of maximum value of average coolant temperature with decreasing gap width shifts towards larger number of sections.

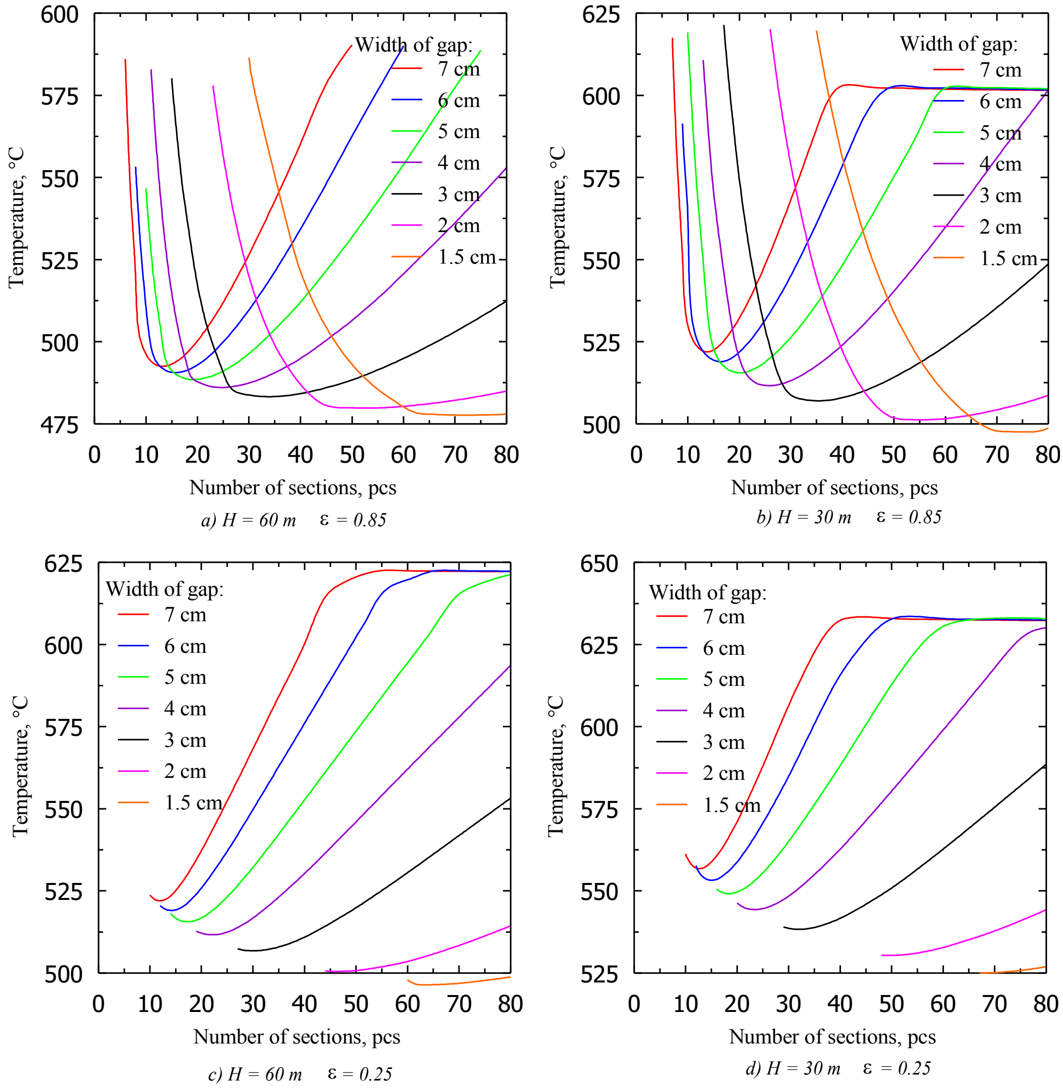


FIG. 2. Dependence of maximum value of average coolant temperature in the BN-800 on number of the DHRS-2C sections.

Figure 3 shows the dependence of optimal number of parallel sections in the DHRS-2C on width of the gap. Figure 4 presents the dependences of maximum value of average coolant temperature in the BN-800 on the following DHRS-2C parameters – thermal emissivity of wall materials of pipeline and safety jacket, height of exhaust chimneys and width of the gap.

Figure 4 a demonstrates that dependence of maximum value of average sodium temperature on thermal emissivity coefficient is not dramatic in achievable range of values. This allows us to say that there is no need to require selection of special materials for walls of the secondary pipelines and safety jackets with high thermal emissivity coefficient.

Analysis of the obtained results shows that it is reasonable to set width of the gap between pipeline and safety jacket equal to about 5 cm. It permits us to choose a reasonable number of sections that the gap in each secondary loop is divided into – not more than 20 (that corresponds to length of each section approximately equal to 14 m). The height of chimneys should not be less than 30 m (Figure 4 b).

The calculations show that proposed DHRS-2C permits to remove decay heat from the BN-800 reactor shutdown from nominal power level without exceeding design temperatures even with failure of one secondary loop.

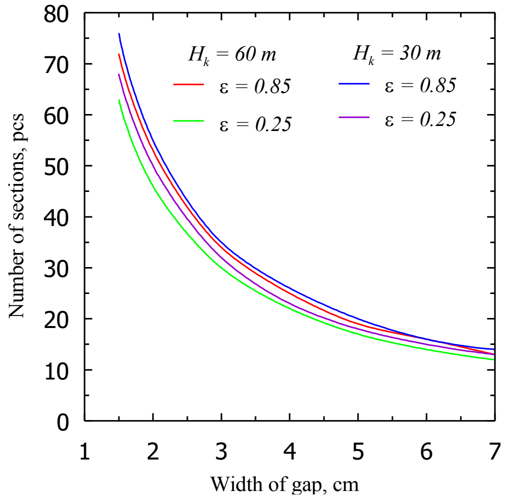


FIG. 3. Dependence of optimal number of the DHRS-2C sections on width of the gap for the BN-800.

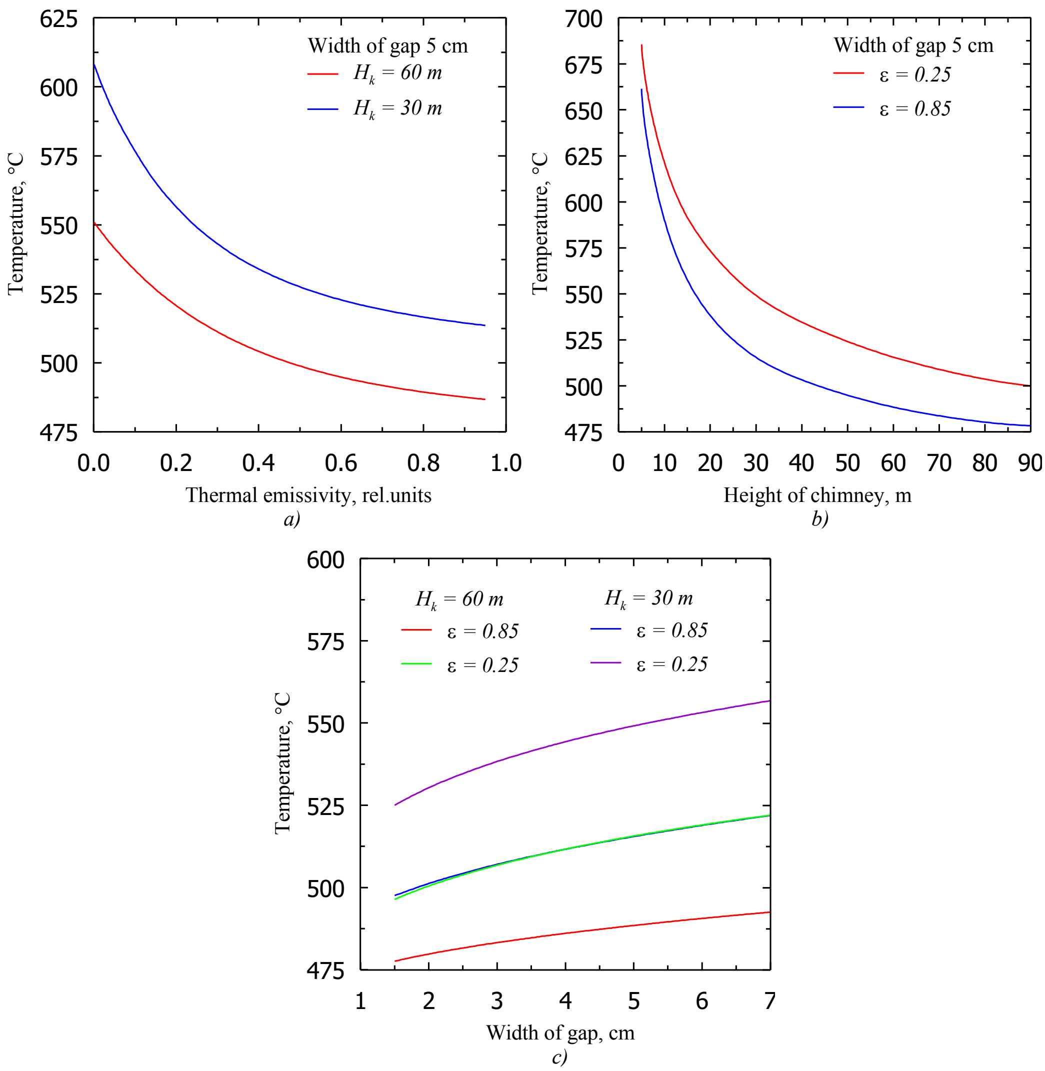


FIG. 4. Dependence of maximum value of average coolant temperature in the BN-800 on the DHRS-2C parameters.

7. Analysis of the DHRS-2C for the BN-1600

The analysis of possibility of the DHRS-2C application in large power size SFR was implemented on example of the BN-1600 taking into account results of parametric optimization of this system obtained for the BN-800.

Width of the gap between the secondary pipelines and safety jackets was selected equal to 5 cm. Number sections that gap is divided into was selected in accordance with obtained optimal values (in the range from 15 to 20).

Dependences of maximum value of average sodium temperature achievable in the BN-1600 during emergency decay heat removal on thermal emissivity, height of exhaust chimneys and number of operating secondary loops are obtained (Figure 5).

These results demonstrate that decay heat in the BN-1600 reactor shutdown from nominal power level may be removed without exceeding design temperatures even in case of failure of two of six secondary loops. Safe limits for the BN-1600 can be provided even with failure of three of six loops.

Figure 6 shows dependence of power removed by one secondary loop on coolant temperature.

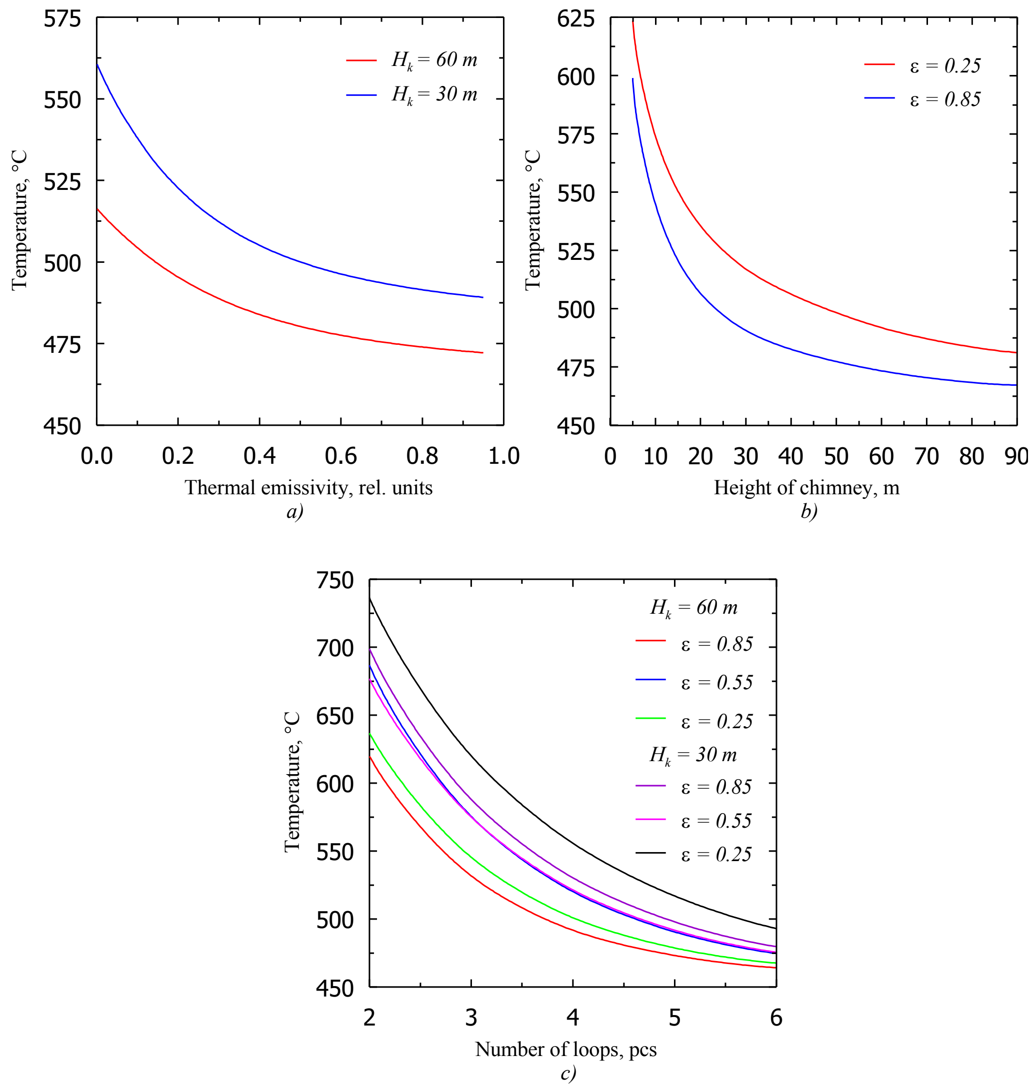


FIG. 5. Dependence of maximum value of average coolant temperature in the BN-1600 on the DHRS-2C parameters (width of the gap 5 cm).

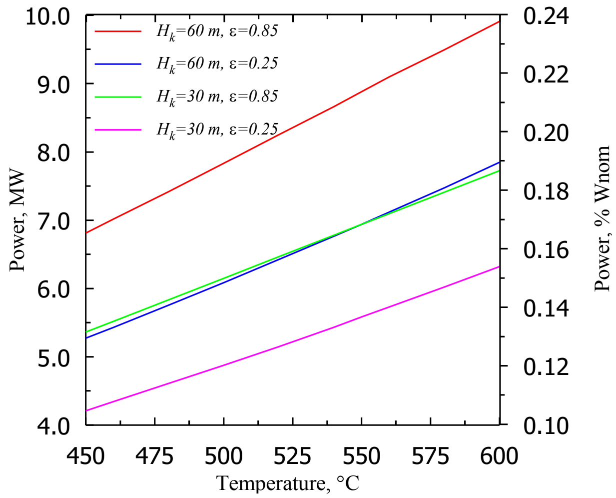


FIG. 6. Dependence of power removed by one secondary loop of the BN-1600 on coolant temperature.

8. Conclusion

The paper is dedicated to analysis of the efficiency of proposed decay heat removal system through the SFR secondary loops and identification of ways to improve its efficiency that allow using such DHRS in SFR of any power without exceeding design temperatures during emergency decay heat removal mode.

Maximal use of the main RF equipment is one of the advantages of this DHRS concept that allows to abandon the special heat exchange equipment for emergency decay heat removal and, thus, to reduce significantly capital costs for NPP construction. In addition, refusal of special "sodium-air" heat exchangers (AHX) permits to exclude danger of sodium freezing in the AHX heat-exchange tubes both in transients related to putting DHRS into operation and in its standby modes.

It should be noted that this DHRS performs additionally localizing functions in SFR that allows greatly to improve their safety against sodium leaks.

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