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Innovative Cooling System for a High-Flux Pool-Type Research Reactor

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Abstract:

The present paper introduces the conceptual design of a pool-type research reactor facility with a three-circuit cooling system. The advantages of creating a comprehensive cooling system for the research reactor, based on a combination of forced and natural coolant circulation, are substantiated. The use of "dry" cooling towers for transferring heat from the reactor to the ultimate sink (atmospheric air) eliminates the problem of salt deposits formation in the equipment and significantly reduces operational costs for chemical and mechanical cleaning of heat exchangers. The presence of an intermediate circuit, operating on the principle of a heat pipe (thermosiphon), helps to eliminate the risk of radioactive coolant leakage into the environment. The operation of this circuit ensures high heat transfer efficiency while maintaining a simple design and absence of moving mechanical parts, which ensures the reliability of the system. The utilization of an upward flow for heat removal from the core creates optimal conditions for enhancing thermal reliability in the pool-type reactor, considering the displacement of the maximum neutron flux density to the lower part of the core due to the position of control rod drives and improved heat removal conditions in this area due to increased pressure and minimum coolant temperature. The design of the pool-type

reactor facility and numerical assessments of the cooling circuits' performance at a power of 25 MW, providing a neutron flux exceeding 1×10^{15} $cm^{-2}s^{-1}$, are presented.

Keywords: Research reactors, passive system, reactor cooling system, heat pipe, thermal reliability, nuclear reactor safety, natural convection

Introduction

Research reactors play a key role in the advancement of nuclear science and technology. They are used for various purposes, including radioisotope production, neutron radiography, material research, and education. One of the most critical aspects of their operation is ensuring reliable and efficient cooling of the reactor core. Traditional cooling methods, such as water and air systems, have their limitations and drawbacks, which can affect the safety, efficiency, and economic viability of reactor operation [1]

Thermohydraulics is recognized as a key scientific subject in the development of innovative reactor systems. Innovative nuclear reactor concepts are being explored worldwide, focusing on demonstrating their technical feasibility, economic competitiveness, and improved safety features.

Traditional water cooling systems using wet cooling towers require large amounts of water and special water treatment, which can be problematic in regions with limited water resources. Air cooling systems, on the other hand, are less efficient and require significant investment in their construction to ensure the necessary cooling capacity, although they drastically reduce operational costs.

Modern research reactors require increased power and heat flux density to conduct more complex and diverse experiments. Traditional cooling systems may not cope with the increased thermal loads, which can lead to overheating and potential emergency situations. The problem of inadequate cooling efficiency is particularly acute in reactors used for radioisotope production. In such installations, the high heat flux density requires a reliable and stable cooling system to prevent overheating and ensure stable operating conditions [2].

The use of heat pipes with water under vacuum allows for significantly improved heat removal efficiency by utilizing the phase transitions of water at low pressure. The use of dry cooling towers, which do not require water evaporation for cooling the secondary loop, significantly reduces water consumption and environmental impact. Such systems are also more resilient to external factors and can operate in any climatic conditions.

The proposed innovative cooling system concept for a research reactor facility is based on enhanced safety by maximizing the simplification of heat removal systems from the reactor core and predominantly using passive systems for coolant circulation in the cooling loops [3].

1. Approaches to Innovative Design of Research Reactors

Unlike power reactors, research facilities need to maximize heat removal from the core to achieve optimal efficiency rather than maintaining high coolant temperatures. The use of heat pipes with water under vacuum significantly enhances heat removal efficiency by utilizing the phase transitions of water at low pressure. This helps maintain a stable temperature in the reactor core and reduces the risk of overheating [4].

Using dry cooling towers that do not require water evaporation for cooling the secondary loop significantly reduces water consumption and environmental impact. Such systems are also more resilient to external factors and can operate in any climatic conditions [5].

Introducing new approaches to cooling research reactors, such as using heat pipes and dry cooling towers, is a necessary step to ensure their safe and efficient operation. These innovations will help increase reactor reliability and economic efficiency while reducing their environmental impact, which is particularly important given the growing attention to the ecological aspects of nuclear facility operation.

1.1 Features of Using Water Coolant in Research Reactors

In pool-type reactors, water boils at a relatively low temperature (just over 100°C), which limits the heat removal capabilities from the core, especially if the fuel assembly (FA) manufacturer has provided for the exclusion of surface boiling in the core. To increase the intensity of heat removal, the core is placed in a high-pressure vessel, through which a large volume of water circulates to cool the core. This allows for a significant increase in the saturation temperature of the coolant and ensures heat removal from the high-energy core without boiling the coolant, thereby creating conditions for increasing the specific thermal power in the FA and a corresponding increase in neutron flux density (for example, in the SM-3 research reactor with a power of 100 MW, the maximum neutron flux density in the central trap reaches 5×10^{15} $cm^{-2} \cdot s^{-1}$). However, such a high heat flux in the core of pool-type reactors creates certain problems due to the risk of a heat transfer crisis even when removing residual heat after the reactor is shut down, as it is necessary to ensure forced coolant flow for some time after shutdown. Moreover, depressurization of the cooling circuit carries the risk of transitioning to a heat transfer crisis from the FA and their destruction. Therefore, efforts should be made to achieve high thermal loads in the core using pool-type reactors without the use of high-pressure vessels, as they are considered safer [6].

1.2 Safety

New designs of research reactor facilities should ensure passive safety both at sufficiently high levels of thermal power and during reactor core cooldown. When designing cooling systems for the reactor core and safety-critical systems, preference should be given to systems (elements) whose operation is based on passive principles and self-protecting properties, as well as on the implementation of safe shutdown and single failure principles [7].

These requirements can be most easily implemented in pool-type reactors because:

- With reasonable design, dehydration of the reactor core is practically impossible.
- A natural circulation scheme for residual heat removal from the reactor core can be most easily implemented.
- There is easy access to the channels and cells of the reactor core and reflector for replacing irradiation devices.
- There is a negative reactivity effect in the event of coolant boiling in the reactor core.

It is possible to organize cells with continuous replacement of irradiation devices and transfer them to adjacent pools (for example, using pneumatic tubes) for processing without reactor shutdown.

1.3 Flexibility

The approaches applied to the cooling system allow for various configurations of the reactor's reactor core and irradiation channels in the reflector. Open access to the reflector channels, located in the pool, provides convenience for irradiation and replacement of irradiation devices even during reactor operation.

1.4 Choice of Circulation Scheme through the Reactor core

One of the most critical elements of the design of a pool-type reactor facility is the circulation scheme of the coolant through the reactor core. Despite the simplicity of the hardware design of the downflow circulation scheme, it does not fully satisfy the properties of inherent self-protection. This is because disruptions in normal operation can lead to a reversal of coolant circulation in some channels or in the entire reactor core, causing instability in reactivity effects and heat removal modes from the fuel assemblies (FAs). Additionally, in pool-type reactors, the downward flow imposes restrictions on coolant flow rates due to hydraulic losses in the reactor core. In the lower part of the FAs, pressure (and the corresponding saturation temperature) becomes unacceptably low, which can lead to hydrodynamic instability and decrease thermal-hydraulic reliability.

The preferred circulation scheme through the reactor core is an upward flow of coolant through the FAs, as implemented, for example, in the OPAL reactor. In this case, using a special design of check valves on the "chimney" ensures reliable natural circulation when forced flow through the reactor core ceases and transitions to internal-pool natural circulation. With the optimal height placement of the first circuit heat exchanger relative to the reactor core, a natural circulation loop forms between them, and in emergency situations, heat from the pool is partially transferred to the second circuit and partially removed through evaporation [8,9,10].

The reliability of safety systems for heat removal from the reactor core in any situation should be based on the application of passive action principles (e.g., gravity) and utmost simplicity of design, reducing the likelihood of failure or unauthorized activation. By applying such approaches to facility design, significant reductions in the cost of thermal-hydraulic equipment and operational expenses for its maintenance can be achieved.

1.5 Choice of Heat Transfer System to the Ultimate Absorber

An important factor affecting the operational costs of a research reactor is the heat transfer systems to the ultimate absorber. Atmospheric air or open water bodies can act as the ultimate heat absorber. Heat transfer systems directly to atmospheric air (e.g., "dry" cooling towers) are less efficient than systems that transfer heat to air through water evaporation (cooling towers). However, with water evaporation in cooling towers, there is an accumulation of hardness salts and the growth of scale deposits on all elements of the circuit (on heat exchange tubes, film-type cooling tower sprayers, in the lower part of circulation pipelines) [11,12]. This adversely affects operational costs because:

- Costly water treatment is required before periodic water replacement in the cooling tower circuit.

- Chemical and mechanical cleaning of heating surfaces of heat exchangers from scale deposits is carried out (leading to increased personnel radiation doses).
- With the formation of a large amount of sludge in the cooling tower circuit and the accumulation of sludge in the lower part of the circulation pipelines, expensive replacement work is carried out.

The use of "dry" cooling towers, despite the increased capital costs in the construction of the research reactor facility, solves the problem of high operational costs caused by salt accumulation in the "wet" cooling tower circuit, ensuring high heat dissipation capacity from the first circuit throughout the entire service life.

Reducing the overall construction and maintenance costs of the research reactor will make it possible to consider this neutron source as an effective and economically justified tool in various areas of scientific and industrial activities [13].

2. Implementation of the Research Reactor Cooling System Concept

2.1 Three-Circuit Cooling System Scheme

For medium-power research pool-type reactors, a three-circuit cooling system is proposed for consideration, which includes:

- The first circuit with forced circulation of the coolant, comprising pipelines, the tube space of the heat exchanger-steam generator, a pump unit, a coolant supply header under the reactor core and under the neutron reflector, the reactor core and the neutron reflector, a partially open top chimney tube above the reactor core, a side branch from the chimney tube, and the reactor pool;

- The second circuit, comprising the inter-tube space of the heat exchanger-steam generator, supply steam lines to the "dry" cooling tower heat exchanger, the tube space of the "dry" cooling tower heat exchanger, condensate drain pipes from the "dry" cooling tower heat exchanger, and the vacuum system;

- The third circuit, including the "dry" cooling tower heat exchanger and the cooling tower.

2.1.1 Efficient Heat Removal Implementation from the Reactor core in the First Cooling Circuit

The reactor system design envisages forced circulation only in the first cooling circuit, while natural convection may be exclusively used for coolant circulation in the second and third cooling circuits. This not only reduces equipment costs and maintenance expenses but also ensures high reliability of the research reactor cooling systems during nominal power operation, shutdown cooling, and in abnormal situations [14,15].

The first cooling circuit, designed for removing heat from the reactor core, irradiation channels, and reflector, provides stable circulation in all reactor operation modes at power and during shutdown in a subcritical state. Power supply to the reactor cooling system is only required during reactor operation to maintain the specified flow rate of forced coolant circulation through the reactor core.

2.1.2 Utilization of Natural Convection during Reactor core Shutdown Cooling

During shutdown cooling, the cooling system of the reactor installation operates entirely independent of energy supply, with residual heat removal facilitated by two independent circuits of natural circulation [16]:

- The intrapool natural circulation circuit, comprising downward flow in the reflector and upward flow in the reactor core.
- Through the standard cooling circuits (heating of the coolant in the reactor core and cooling in the heat exchanger), which ensure natural circulation in the first circuit and subsequent heat transfer to the second and third circuits, also functioning through natural circulation.

The intrapool natural circulation circuit is activated immediately after the cessation of forced flow in the first circuit due to increased pressure in the "chimney" pipe and automatic opening, caused by the pressure difference reversal of the plate valves in the natural circulation system. These valves are pressed against the seating surfaces on the "chimney" by hydrostatic pressure in the reactor pool. Therefore, even in the first seconds after the cessation of forced flow through the reactor core, with the residual heat still high in the fuel assemblies, safe heat removal from the fuel rods is ensured by heating the water in the pool. Possible boiling of the coolant in the fuel assemblies in the first seconds after the cessation of forced flow increases the driving head of natural circulation, enhancing heat removal efficiency.

Heating the water in the pool during reactor core shutdown cooling, without forced circulation, intensifies evaporation from the surface and creates a natural circulation loop in the pipelines of the first circuit due to the higher position of the steam generator relative to the reactor core. In this scenario, stable passive heat removal from the reactor is ensured by the energy-independent operation of the second circuit, working on the principle of gravitational heat pipe, and the energy-independent operation of the third circuit, functioning as a "dry" cooling tower with natural circulation of atmospheric air.

2.1.3 Implementation of the "Heat Pipe" Principle in the Intermediate Circuit

To create an additional barrier preventing the release of radioactive substances from the first circuit into the environment, an intermediate circuit is utilized, designed on the principle of a gravitational heat pipe. Water at low pressure (vacuum) serves as the coolant in the second circuit. To induce water boiling at a relatively low temperature, such as 54°C, the pressure in the steam generator heat exchanger must be reduced to 15 kPa. The resulting steam flows through large-diameter pipes to the air-cooled heat exchangers of the "dry" cooling tower, where it condenses and the condensate flows back by gravity into the inter-tube space of the steam generator heat exchanger. The vacuum in the second circuit is maintained by a vacuum system that removes the air-steam mixture from the circuit, cools it, removes non-condensable gases, and returns the resulting condensate back to the second circuit. The vacuum system operates only during the period of non-condensable gas removal and is then switched off after reaching the required vacuum level, making the operation of the second circuit independent of energy sources [4].

The high efficiency of heat transfer from the first circuit to the second through the steam generator heat exchanger is ensured by:

- High coolant velocity in the heat exchange tubes, resulting in a high convective heat transfer coefficient.
- Good thermal conductivity of the heat exchange tube material and thin tube walls.
- High heat transfer coefficient during water boiling in the inter-tube space.

The absence of hardness salts in the coolant of the first and second circuits prevents deposits on the heat exchange tubes. Therefore, even with a developed tube surface, there is a small mean logarithmic temperature difference during the transfer of high thermal power through the steam generator heat exchanger.

The low mean logarithmic temperature difference in the air-cooled heat exchanger of the "dry" cooling tower is achieved by a high heat transfer coefficient during steam condensation (in the absence or low content of non-condensable gases), high thermal conductivity of the heat exchange tubes (preferably made of aluminum), and the presence of extensive finning on the external surface of these tubes. Increasing the circulation velocity of the cooling air through the air-cooled heat exchanger is achieved either by the presence of fans or by the presence of a tall "dry" cooling tower, or by a combination of having a tower and fans.

2.1.4 Avoiding the problem of salt accumulation in circulating water

The efficiency of cooling the coolant in a "wet" cooling tower is associated with the evaporation of pure water into the atmosphere; however, this simultaneously creates issues with the accumulation of hardness salts in the second circuit, leading to the deposition of these salts on the heat exchange tubes, on the fills of the cooling tower, and the accumulation of sludge in the circulation pipelines. This results in a dire situation where maintaining the required temperature in the first circuit becomes impossible, and restoring the operability of the water supply circuit requires enormous expenses. Based on the operational experience of research reactors at the RIAR facility (Russia), water supply circuits of reactor installations with "wet" cooling towers pose significant challenges and substantially increase operational expenses due to the need for frequent chemical and mechanical cleaning of heat exchangers, as well as the requirement for mechanical cleaning or replacement of fills in film or film-type splash cooling towers. Therefore, when designing new research reactors, it is advisable to abandon "wet" cooling towers in favor of "dry" ones.

2.1.5 Using a "dry" cooling tower for heat transfer to the ultimate heat sink

Despite significant drawbacks of a "dry" cooling tower, such as low cooling efficiency (cooling is only possible to the ambient air temperature), high construction cost (it is 5 times higher compared to a fan-type cooling tower of the same capacity), and inconvenience in periodic cleaning of the heat exchanger, it possesses advantages that make its application preferable for transferring heat from the reactor installation to the ultimate heat sink – the atmospheric air [5]:

- The closed circuit ensures no moisture carryover, eliminating the need for coolant replenishment (water).
- No possibility of foreign impurities entering the coolant.
- Ability to operate at negative temperatures.

- Due to the closed loop of the coolant, there is no need for water purification during circuit operation (although initially, clean prepared water – distillate – is required as the coolant).

With high efficiency of the air heat exchanger, fans may not be required or may only be activated during hot periods, so the third circuit can be considered conditionally energy-independent. In the mode of cooling the reactor's reactor core with relatively low heat dissipation, the first, second, and third circuits operate in natural circulation mode, providing safe passive heat removal from the reactor installation without electricity supply. This achieves a high level of safety in all operating modes of the research reactor.

2.2 Enhancing Nuclear and Radiation Safety of the Reactor Installation

Radiation safety and environmental protection are among the most critical factors when designing new research reactor installations. No equipment failure or malfunction should pose a risk of significant radioactive release into the environment.

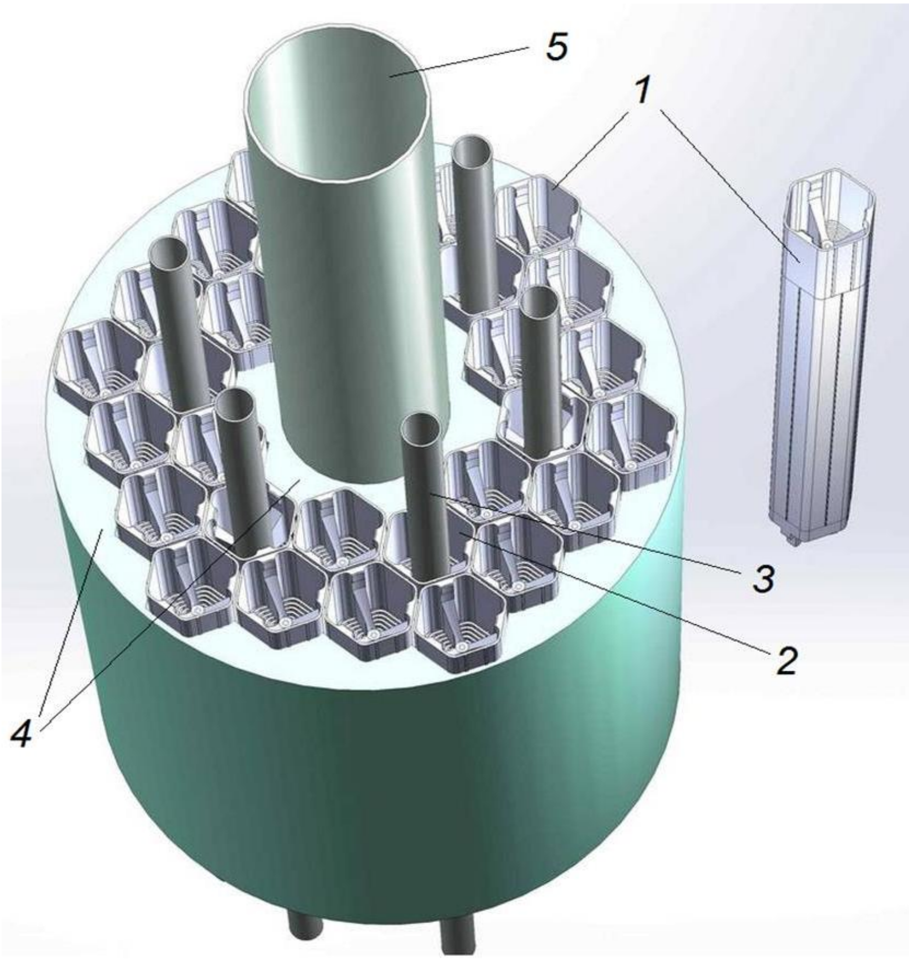
Technical solutions ensuring the impossibility of radioactive substances escaping from the reactor installation into the environment provide a significant competitive advantage in the design of research reactor installations. Pool-type reactors, due to the low pressure in the active zone, have substantial limitations on the coolant temperature in the primary circuit [17]. Therefore, a two-loop cooling system is typically used for such reactors, where the secondary loop is the coolant circulation loop, cooled directly by atmospheric air. Loss of hermetic integrity in the heat exchanger between the loops threatens the release of radioactive coolant into the secondary loop and subsequently into the environment. The proposed three-loop heat removal scheme solves this problem.

The absence of high pressure in the cooling systems of pool-type reactors minimizes the risk of equipment and pipeline failures, and the negative reactivity effect caused by the coolant density in water-cooled research reactors ensures nuclear safety [15].

3. Calculations and design solutions to confirm the feasibility of the proposed concept

3.1 Reactor core

To assess the feasibility of the proposed concept for a 25 MW research reactor, a core configuration with a central moderator region (Figure 1) is chosen, comprising 30 VVR-KN fuel assemblies with low-enriched fuel - 19.7% U-235 [19].



1 - 8-tube VVR-KN fuel assembly; 2 - 5-tube VVR-KN fuel assembly; 3 - control rod channel; 4 - displacer; 5 - neutron trap

Fig. 1. Three-dimensional model of the reactor core

The core comprises twenty-four 8-tube VVR-KN fuel assembly (1) and six 5-tube VVR-KN fuel assembly (2) with centrally located control rods (3). Zirconium alloy can be used as the material for the displacer (4) in the reactor core and the central channel (5).

Table 1 presents the characteristics of the VVR-KN fuel assemblies used for the analytical calculations:

Table 1. Characteristics of VVR-KN fuel assemblies in the core [8]

Parameter	**Value**
U-235 Enrichment, %	19,7
Uranium Density, g/cm^3	2,8
Mass of U-235 in Fuel Assembly, g	
8-pipe fuel assembly	250
5-pipe fuel assembly	199
Number of Fuel tube, pcs	
8-pipe fuel assembly	8
5-pipe fuel assembly	5
Fuel element thickness, mm	1,6
Core Thickness, mm	0,7
Cladding Thickness, mm	0,45
Heat Transfer Surface Area of 5-pipe fuel assembly, m^2	1,045
Heat Transfer Surface Area of 8-pipe fuel assembly, m^2	1,274
Total Heat Transfer Surface Area of all Assemblies, m^2	36,86

3.2 Neutron-physical calculation of the reactor core

Neutron-physical calculation of the reactor is carried out for the geometry presented in Figure 2 using the MCU program [18] for a reactor power of 25 MW. Heavy water is adopted as the reflector. The positions of the 4 control points are indicated by numbers in the figure, and the calculation parameters of the neutron flux for these points are specified in Table 2.

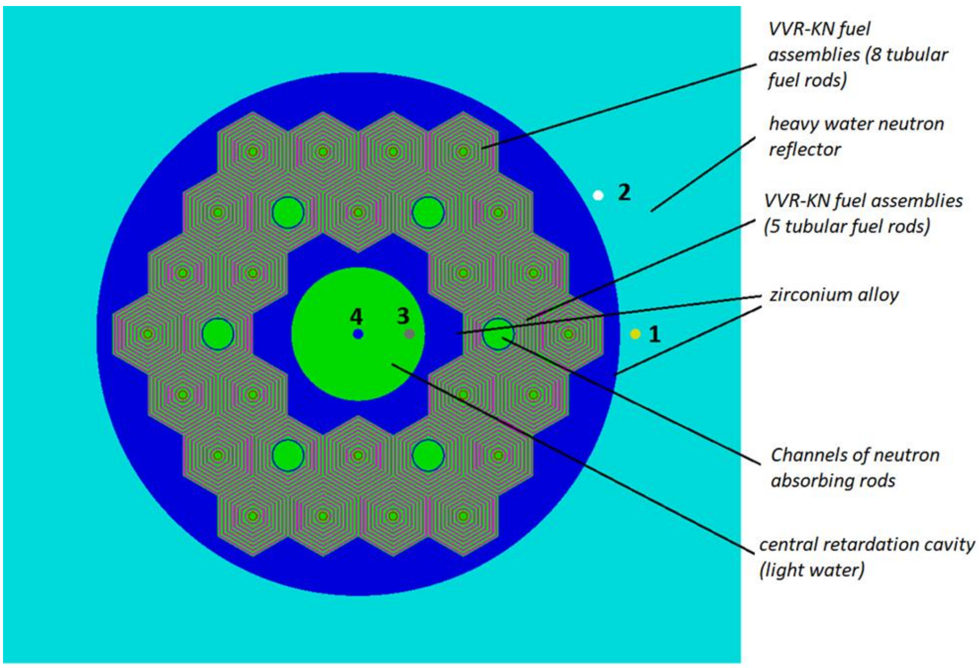


Fig. 2. Geometry schematic of the reactor core with indication of materials for neutron-physical calculation.

Table 2. Calculation parameters of the neutron flux at control points

Detector number	Neutron flux density					Calculation error			
	over 0,1 MэB	0,1MeV.. to 1 keV	1 keV to 0,5 eV	less than 0,5 eV	General flow	over 0,1 MeV	0,1MeV to 1 keV	1 keV to 0,5 eV	less than 0,5 eV
1	1,09E+14	1,07E+14	1,16E+14	3,04E+14	6,37E+14	1,5%	1,5%	1,5%	1,0%
2	9,53E+13	1,01E+14	1,16E+14	3,02E+14	6,14E+14	1,6%	1,6%	1,5%	1,0%
3	1,78E+14	8,47E+13	1,38E+14	6,30E+14	1,03E+15	1,1%	1,5%	1,2%	0,9%
4	1,23E+14	6,01E+13	1,09E+14	8,78E+14	1,17E+15	1,3%	1,8%	1,4%	0,8%

In Figure 3, the calculated distribution of specific energy release along the height of the most thermally stressed fuel rod is presented, used to determine the maximum temperatures in the fuel assemblies. The displacement of the maximum neutron flux values to the lower part of the reactor core is caused by the partial insertion of the control rod mechanisms into the central channels of the fuel assemblies with five tubular fuel rods.

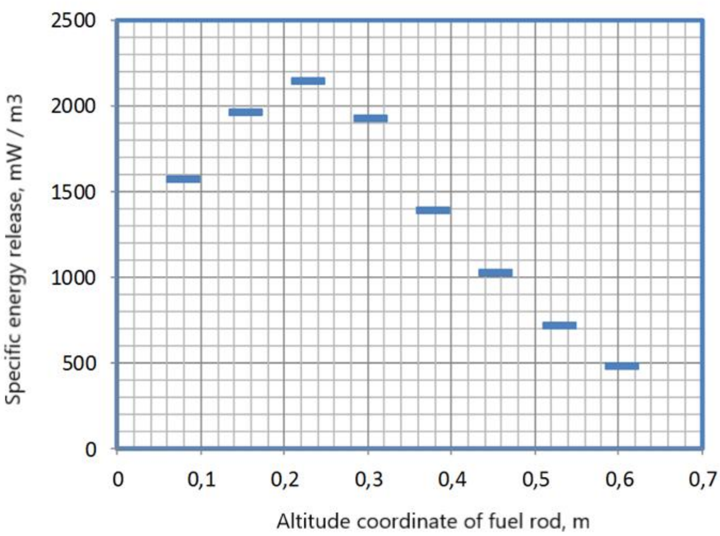


Fig. 3. Calculated distribution of specific energy release along the height of the most thermally stressed fuel rod.

For such a height wise distribution of neutron flux, the upward flow of coolant in the reactor's pool-type reactor core is optimal and provides maximum margin before boiling for two reasons:

- In the lower part of the reactor core, the coolant temperature is minimal.
- In the lower part of the reactor core, the coolant pressure is maximal.

Thermal-hydraulic calculation of the reactor's reactor core is performed for the geometry of the VVR-KN type fuel assembly, using the CAD/CAE software suite SolidWorks/FlowSimulation [20]. The calculated hydraulic characteristic is provided in Fig.4.

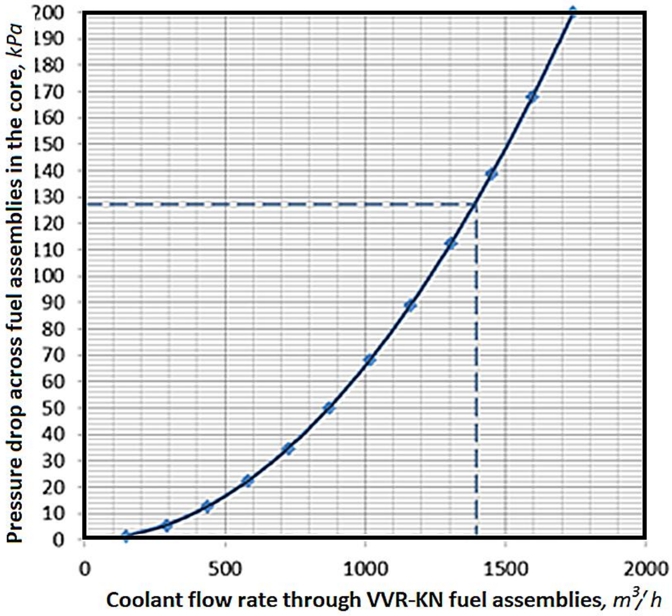


Fig. 4. Hydraulic characteristic of the reactor core.

3.3 Main Parameters of the Reactor Core

The main thermal and neutron-physical parameters of the considered research reactor facility with a power of 25 MW, along with the justified calculated characteristics, are provided in Table 3.

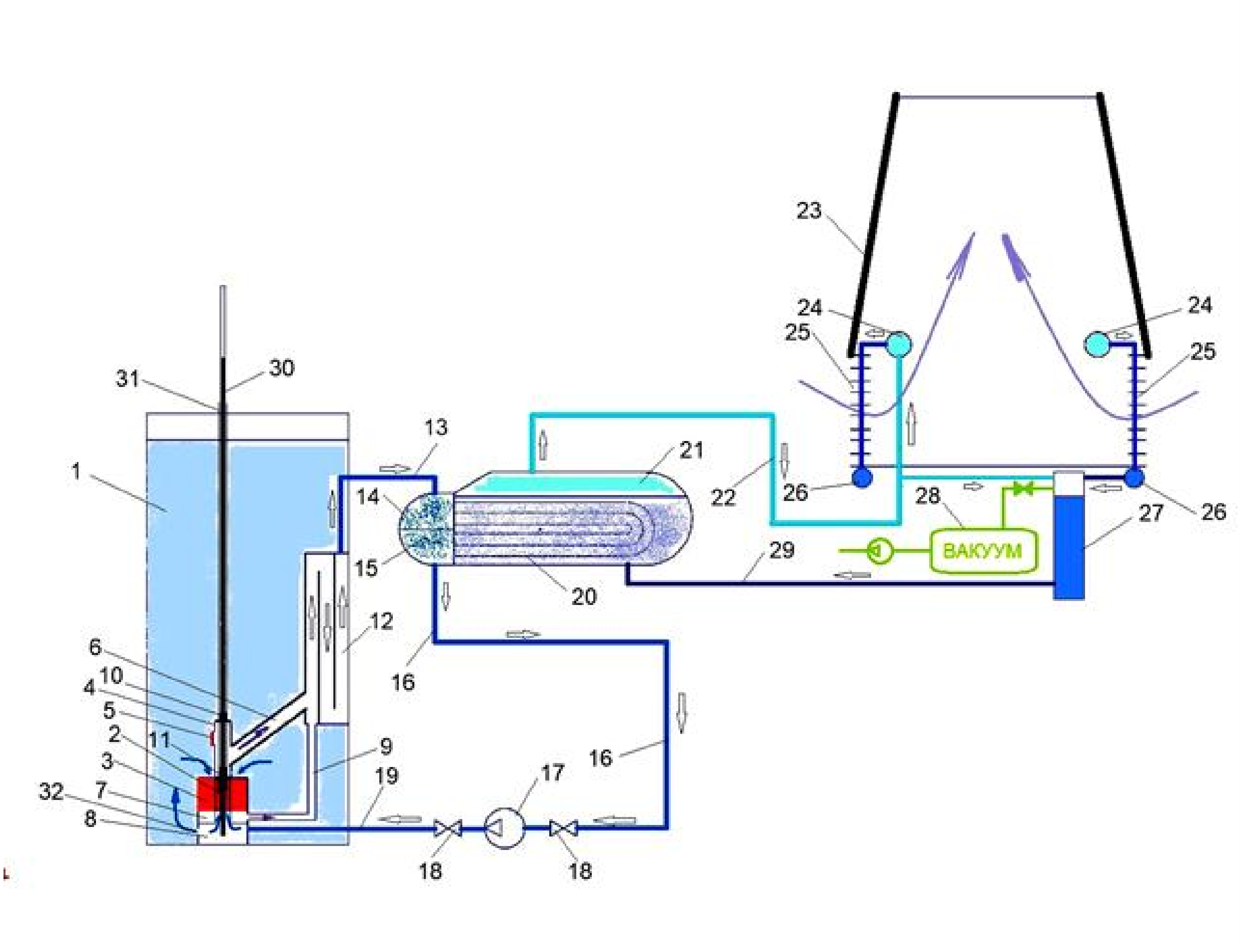
Table 3. Main Parameters of the Pool-type Reactor Core with Forced Coolant Circulation

Reactor Characteristics	**Value**
Type of Reactor	Pool-type reactor with water cooling, intermediate neutron spectrum, and central trap
Power, MW	25
Maximum Heat Flux Density, $cm^{-2}s^{-1}$	1.17×10^{15}
Fuel	Uranium dioxide, 20% enrichment in U-235
Reactor Core Geometry	Shape, close to cylindrical with a neutron trap in the center
Number of Fuel Assembly Cells, pcs	30
Type of Fuel Assembly, pcs	VVR-KN
of which:	
5-tube, pcs	6
8-tube, pcs	24
Coolant	Light water

Core Diameter, mm	Ø480
Core Height, mm	600
Coolant Flow Rate, [t h^{-1}]	1400
Temperature at the Fuel Assembly Inlet, [°C]	60
Temperature at the Fuel Assembly Outlet, [°C]	75,8
Coolant Temperature Rise in the Core, [°C]	15,8
Coolant Velocity in the Fuel Assembly, [m s^{-1}]	6,1
Reynolds Number *Re* (average)	57745
Nusselt Number *Nu*	233,4
Heat Transfer Coefficient α [W m^{-2} $°C^{-1}$]	38704
Heat Removal Surface Area of Fuel Elements, [m^2]	36,86
Average Heat Flux Density, [kW m^{-2}]	678,3
Maximum Heat Flux Density, [kW m^{-2}]	1356,6
Maximum Temperature Difference Between Wall and Coolant, [°C]	35,1
Maximum Fuel Element Temperature, [°C]	110
Pressure Loss in the Core, [kPa]	130
Pressure at the Core Outlet Above the Retainer, [kPa]	150
Pressure at the Core Outlet Below the Retainer, [kPa]	200

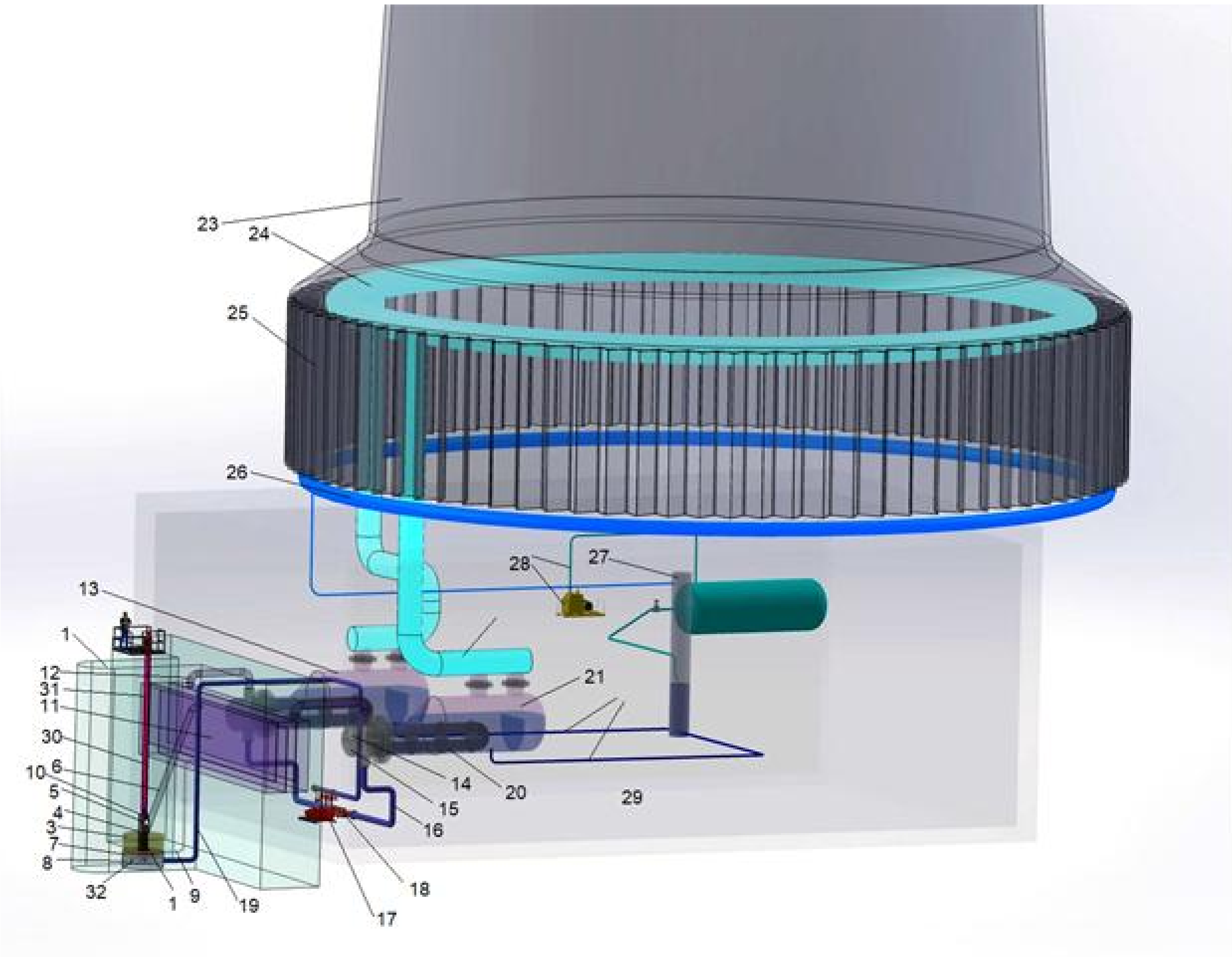
3.4 Reactor Plant Cooling System

To demonstrate the feasibility of the proposed heat removal system concept, a reactor plant is considered, the schematic diagram of which is shown in Figure 5, and the three-dimensional design is presented in Figure 6.



1 - reactor pool; 2 - reactor core; 3 - neutron reflector; 4 - "chimney" above the core; 5 - natural circulation valve; 6 - outlet (hot) piping from the core; 7 - suction chamber under the reflector; 8 - pressure chamber under the core; 9 - outlet hot piping from under the reflector; 10 - chimney cap; 11 - fuel assembly lift preventer; 12 - oxygen activity damper; 13 - hot water supply piping to the steam generator; 14 - steam generator hot water inlet chamber; 15 - steam generator cooled water outlet chamber; 16 - steam generator cooled water piping; 17 - circulation pump; 18 - circulation pump cut-off valve; 19 - cooled water supply piping to the pressure chamber under the core; 20 - steam generator tubing; 21 - steam generator steam space; 22 - steam supply piping to the "dry" cooling tower manifold; 23 - "dry" cooling tower; 24 - air heat exchanger steam supply manifold; 25 - air heat exchanger; 26 - air heat exchanger condensate collection manifold; 27 - condensate collection tank; 28 - condensate collection tank vacuum system; 29 - condensate return piping to the steam generator; 30 - central channel of the core; 31 - control rod drive mechanisms; 32 - pressure chamber throttle orifice

Fig. 5. Schematic diagram of the cooling system for a 25 MW research reactor.



1 - reactor pool; 2 - reactor reactor core (core); 3 - neutron reflector; 4 - "chimney" above the reactor core; 5 - natural circulation valve; 6 - outlet (hot) piping from the reactor core; 7 - suction chamber under the reflector; 8 - pressure chamber under the reactor core; 9 - outlet hot piping from under the reflector; 10 - chimney cap; 11 - oxygen activity damper; 12 - hot water supply piping to the steam generator; 13 - steam generator; 14 - steam generator hot water inlet chamber; 15 - steam generator cooled water outlet chamber; 16 - steam generator cooled water piping; 17 - circulation pump; 18 - circulation pump cut-off fittings; 19 - cooled water supply piping to the pressure chamber under the reactor core; 20 - steam generator tubes; 21 - steam generator steam space; 22 - steam supply piping to the "dry" cooling tower manifold; 23 - "dry" cooling tower; 24 - air heat exchanger steam pressure manifold; 25 - air heat exchanger; 26 - air heat exchanger condensate collection manifold; 27 - condensate collection tank; 28 - condensate collection tank vacuum system; 29 - condensate return piping to the steam generator; 30 - central channel of the reactor core; 31 - control rod drive mechanisms (CRDM); 32 - pressure chamber throttle orifice.

Fig. 6. Three-dimensional design of the cooling system for a 25 MW research reactor

The use of "dry" cooling towers instead of "wet" ones significantly increases the capital costs of creating heat exchangers that have a much more developed heat exchange surface with atmospheric air. In addition, to create the draft for pumping large volumes of air through the heat exchanger, it is necessary to use either large fan systems or ensure natural convection of atmospheric air using tall towers or ventilation pipes.

The proposed three-circuit heat removal scheme from the reactor core to the external heat sink not only provides efficiency but also radiological safety. The mechanism of coolant circulation in the second and third circuits is based on the passive principle of natural circulation, using gravity. In the first circuit, the transition to natural circulation occurs automatically in case of cessation of forced flow through the reactor core (loss of integrity or stopping of circulation pumps). Furthermore, the heat removal system ensures a minimal number of pumps and shut-off and control valves, which significantly reduces the number of possible emergency situations and operational costs. The description of the following circuits is presented in more detail below:

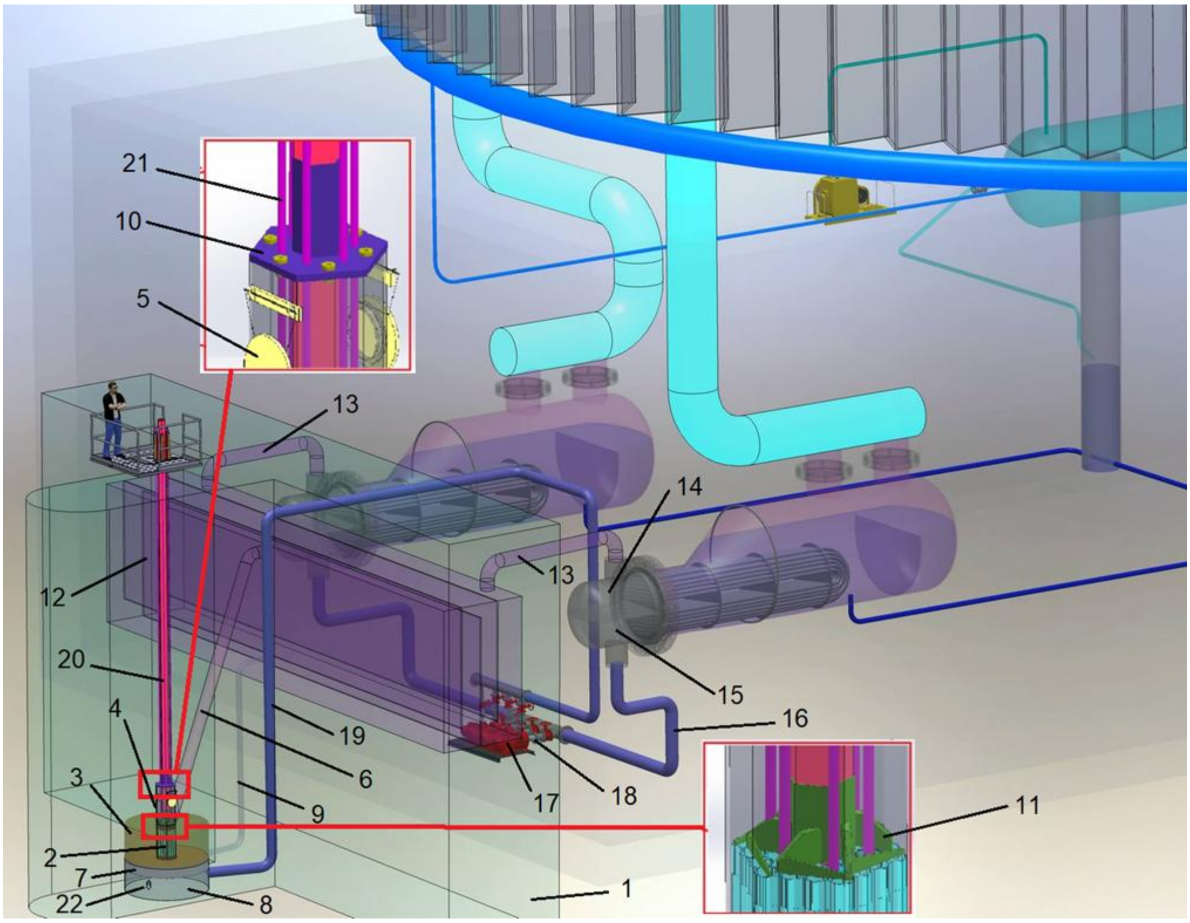
• The heat removal circuit from the reactor core with forced circulation;

• The intermediate low-pressure circuit (heat pipe);

• The heat transfer circuit to the final heat absorber (atmospheric air).

3.4.1 The heat removal circuit from the reactor core with forced circulation (primary circuit)

To ensure the most efficient heat removal from the reactor core in a pool-type reactor to the primary circuit coolant, the optimal scheme is one with forced upward flow of the coolant and a "chimney" located above the reactor core with a lateral outlet piping for the heated coolant (similar to the OPAL reactor scheme). Such a scheme allows for maximum thermal load on the fuel elements due to the possibility of increasing the coolant flow in the primary circuit, which results in not only a high heat transfer coefficient from the fuel elements and, accordingly, a minimal temperature difference between the wall and the liquid, but also reduces the heating of the coolant in the reactor core, increasing the margin to the onset of boiling. The use of circulation pumps ensures the stability of safe heat removal from the reactor core under high thermal loads (Figure 7).



1 - reactor pool; 2 - reactor core; 3 - neutron reflector; 4 - "chimney" above the core; 5 - natural circulation valve; 6 - outlet (hot) piping from the core; 7 - suction chamber under the reflector; 8 - pressure chamber under the core; 9 - outlet hot piping from under the reflector; 10 - chimney cap; 11 - fuel assembly lift preventer; 12 - oxygen activity damper; 13 - hot water supply piping to the steam generator; 14 - steam generator hot water inlet chamber; 15 - steam generator cooled water outlet chamber; 16 - steam generator cooled water piping; 17 - circulation pump; 18 - circulation pump cut-off fittings; 19 - cooled water supply piping to the pressure chamber under the core; 20 - central channel of the core; 21 - control rod drive mechanisms; 22 - pressure chamber throttle orifice

Fig. 7. Coolant circulation scheme of the primary circuit during reactor operation at nominal power.

The reactor core, central channel, vertical experimental channels (VEC – not shown in the figure), and reflector in the reactor pool dissipate heat using a unified forced cooling system of the primary circuit (Figure 8). The direction of coolant flow in all elements of the core is upward, and in the reflector it is downward. The warmed coolant from the core and central channel enters from below directly into the "chimney" – a section of the vertical piping located above the core with a lateral outlet. The heated coolant from the chimney and the chamber under the reflector first enters the oxygen activity suppressor, and then is sent for cooling to the heat exchanger-steam generator. The cooled coolant, after passing through the pump block, enters the pressure chamber, which is common to both the core and the reflector.

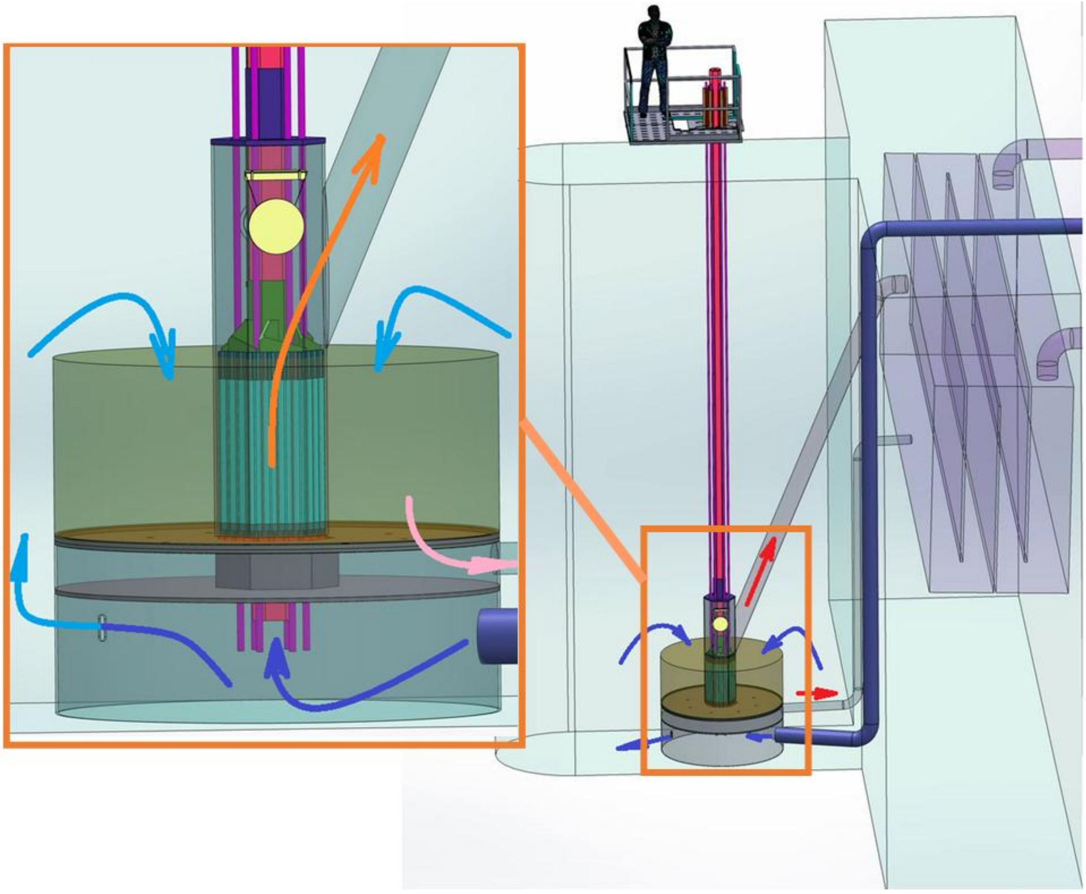
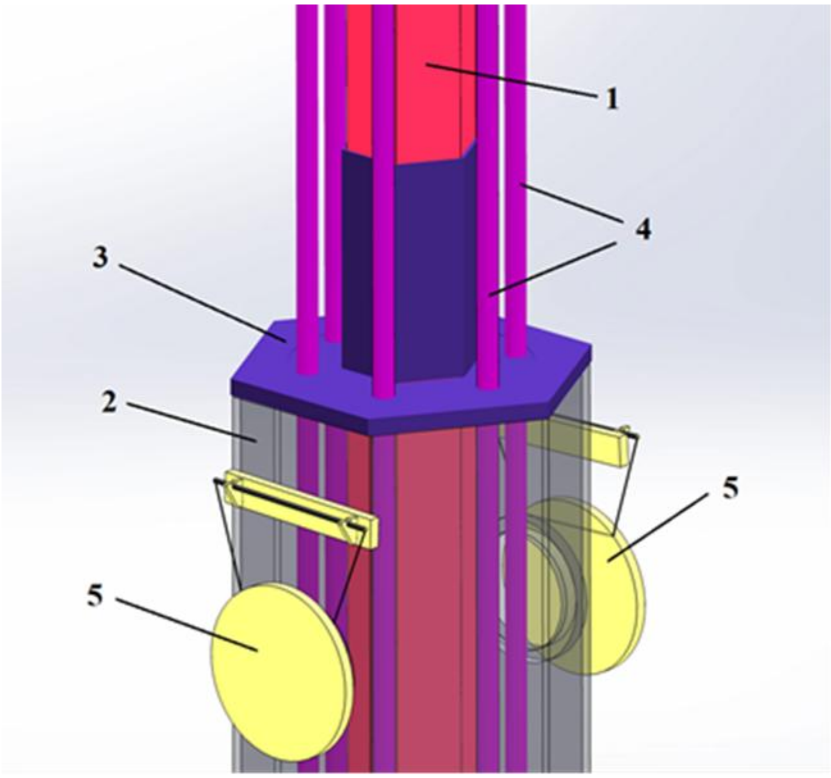


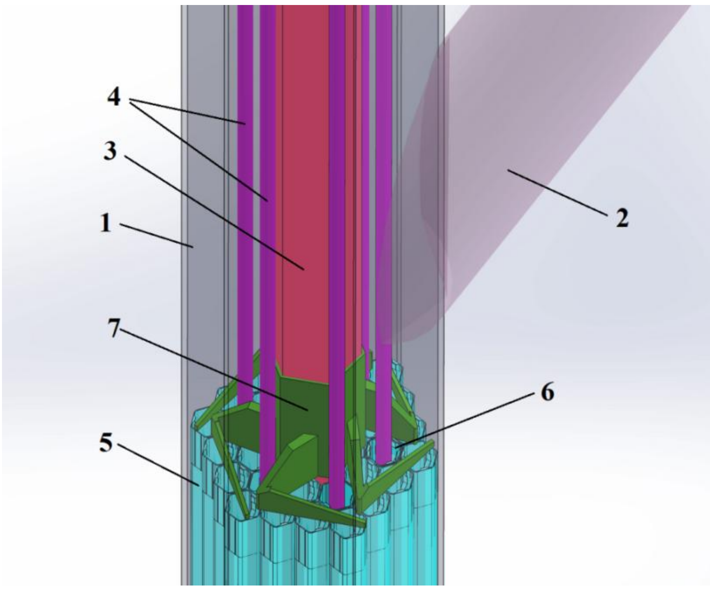
Fig. 8. Coolant circulation scheme in the pool with forced flow in the reactor core.

The distribution of coolant flows through the reactor core with the central channel and through the reflector with VEC is determined by the distribution of hydraulic resistances in different design elements along the coolant flow path. Important elements in the flow distribution are the throttle orifice (22, Figure 7) located in the pressure chamber under the core to regulate the passage of coolant from the reactor tank into the reflector, disc check valves serving as natural circulation valves (Figure 9), and the fuel assembly lift preventer structure located at the bottom of the "chimney," protecting them from lift-off (Figure 10).



1 - hexagonal casing of the central channel; 2 - "chimney" casing; 3 - "chimney" cap movable up the central channel; 4 - channels of CPS working elements; 5 - disc check valves, sealed by the hydrostatic pressure in the tank at nominal coolant flow and opening during natural circulation

Figure 9. Design of the upper part of the "chimney" with throttle sleeves and natural circulation valves



1 - "chimney" casing; 2 - lateral coolant outlet from the "chimney"; 3 - hexagonal casing of the central channel; 4 - channels of CPS working elements; 5 - eight-tube fuel assemblies of VVER-KN type; 6 - five-tube fuel assemblies of VVER-KN type with central channels for control rod drive mechanisms; 7 - retainer

Fig.10. Design of the lower part of the "chimney" with a device for securing fuel assemblies against lift-off

Increasing the hydraulic resistance at the retainer that protects the fuel assemblies from floating up allows for an increase in pressure in the reactor core, which raises the saturation temperature and, accordingly, the margin to boiling in the core. These additional hydraulic losses are easily compensated for by the pump head. The specified flows through the core and the reflector and their ratio are regulated by selecting the hydraulic resistance of the sleeves.

3.4.2 In-pool natural circulation circuit

Following the principles of designing heat removal systems from the core and systems important to safety [7], the proposed design favors systems (elements) whose devices are based on the passive principle of action and properties of inherent self-protection, as well as on the implementation of the principles of safe failure and single failure (Figure 11).

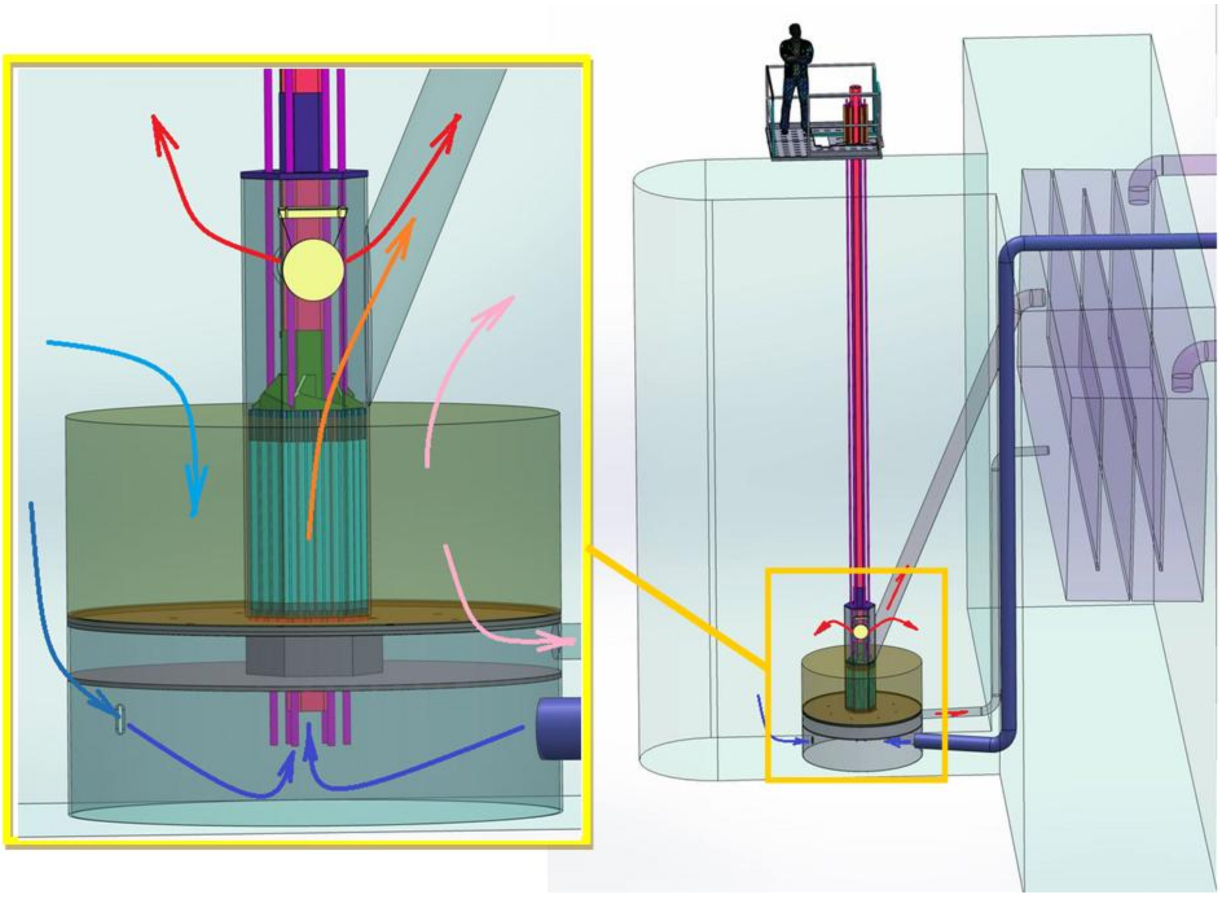
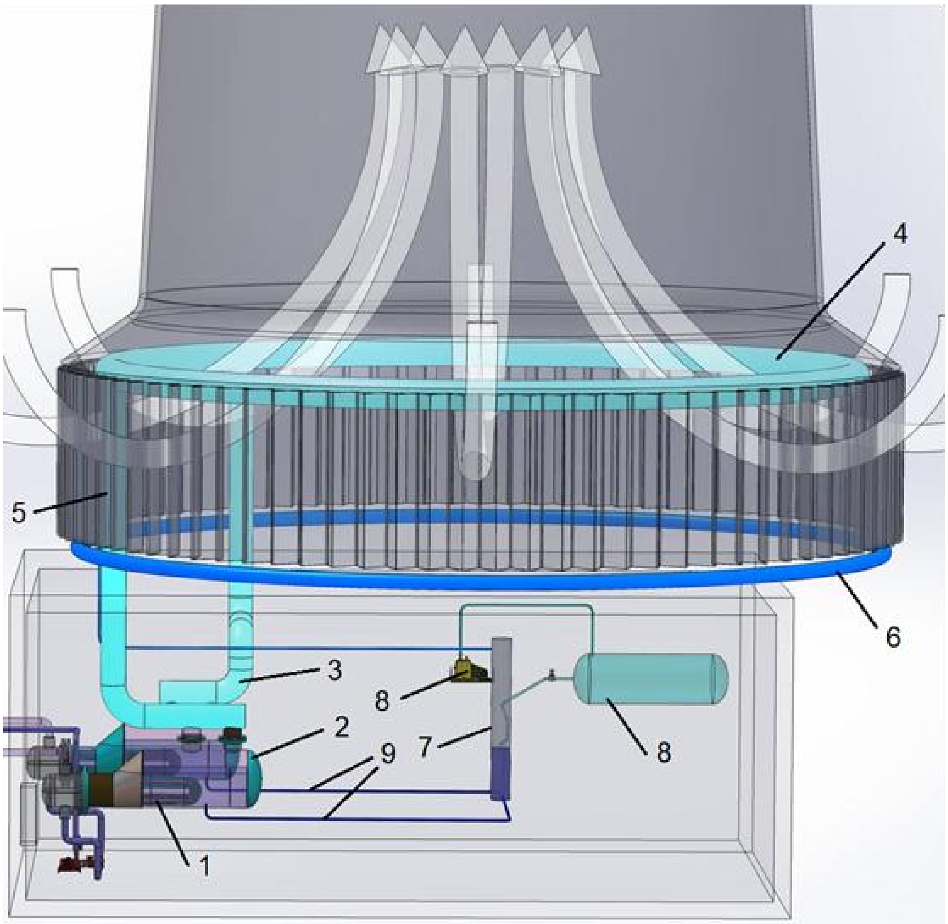


Fig. 11 Natural circulation scheme of the coolant in the pool during reactor cooldown

In the reactor cooldown mode, heat removal across all cooling circuits is performed exclusively due to the natural convection of the coolant and does not require the presence of power sources. Furthermore, the reliability of safe heat removal from the core is guaranteed even in the event of a rupture of the circulation piping and, accordingly, the failure of all heat removal system circuits. This is a consequence of the presence of natural circulation valves in the upper part of the "chimney," which open immediately after the forced flow stops, and the insignificance of the residual heat generation in the reflector, which provides a reverse circulation of the coolant in it, thereby closing the in-pool circulation circuit through the core (Figure 11).

The inevitable heating of the water in the pool in this case (approximately up to 64°C) leads to intensive evaporation from the surface and a gradual decrease in the water level in the tank. At the same time, the temperature of the fuel elements is maintained at a safe level, which completely eliminates the risk of their depressurization and destruction. If the cooling circuits maintain integrity, and the heat exchanger-steam generator is located above the level of the core, then in addition to the in-pool circulation in the tank and evaporation from the water surface, heat is removed to the atmosphere through the standard cooling circuits in the mode of natural convection.



1 – steam generator tubing; 2 – steam generator casing; 3 – steam line; 4 – heating steam manifold; 5 – air heat exchanger-condenser; 6 – condensate collection manifold; 7 – vacuumized condensate collection tank; 8 – vacuum system; 9 – condensate return pipeline

Fig. 12. Intermediate circuit (heat pipe) scheme

The heat pipe is a heat transfer device capable of transferring large amounts of heat with small temperature gradients. It is a sealed structure, partially filled with a liquid coolant. In the heated part 1 (in the heating zone, or evaporation zone), the liquid coolant evaporates, absorbing heat 2, and in the cooled (cooling zone, or condensation zone 4) – the vapor, flowing through the steam line 3 from the evaporation zone, condenses, releasing heat at the air heat exchanger. The movement of steam occurs due to the pressure difference of the saturated steam, determined by the temperature difference in the zones. The return of the liquid to the evaporation zone is carried out through the pipeline 5 due to gravity.

In the considered design, the thermal power from the first circuit is removed using two steam generators. Taking into account the possible additional heat generation from irradiation devices in the reflector, the calculated thermal power is increased from 25 to 26 MW, and considering the flow of coolant through the reflector, the flow in the first circuit is increased to 1650 m^3/h (the flow through the core is 1400 m^3/h).

Calculated estimates of the parameters of one of the two steam generators show that to ensure heat transfer, it must have 500 U-shaped tubes Ø18×1 with a length of 12 meters in a horizontal casing Ø1.4 meters with a length of 9 meters. The generation of low-pressure steam (15 kPa) amounts to 55 m^3/s (Table 4).

The volume of steam produced every second in two steam generators (110 m^3) must be condensed in an air heat exchanger of a "dry" cooling tower or dry cooler. For the condensation surface area of 250 m^2 adopted in the analysis, the heat power removed depending on the temperature of the surface is shown in Figure 13.

From the graph provided, it can be seen that to remove through steam condensation 27 MW of thermal power, it is sufficient to have a condensation area with a temperature of 45°C. Such a surface temperature in the air heat exchanger is quite achievable even in warm weather, provided that there is a developed surface contact with the air and its sufficient flow.

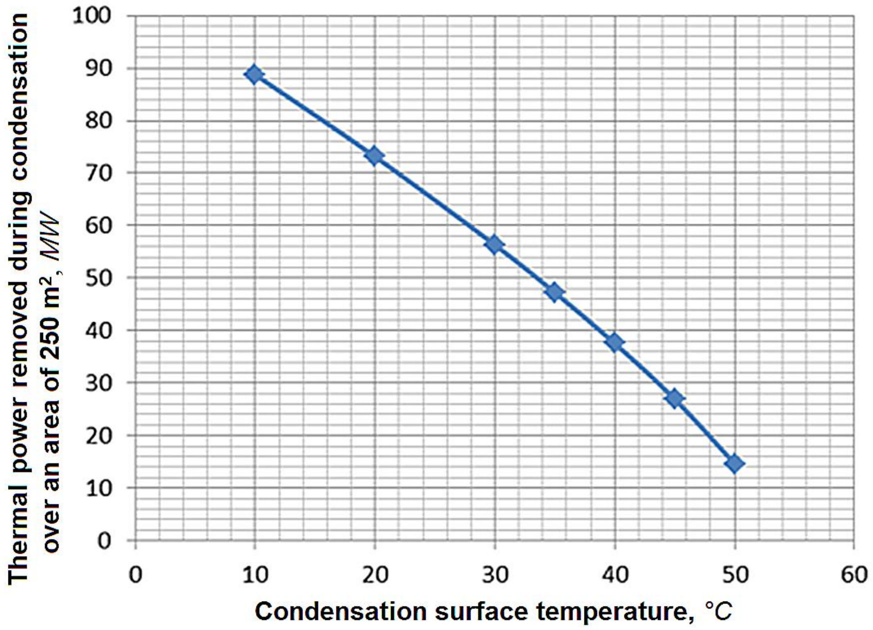


Fig. 13. The dependence of the heat power removed by condensation on a surface area of 250 m^2 on the surface temperature

Table 4. Calculated parameters of the heat exchanger-steam generator

Parameter	Value	Unit of Measurement
coolant flow rate in the first circuit	1650	m^3/h
	0,46	m^3/s
number of steam generators	2	pcs.
coolant flow rate through the steam generator	0,23	m^3/s
	227,79	кг/с
power removed in the steam generator	13000	kW
coolant temperature at the outlet of the steam generator	60	°C
heat capacity	4,188	kJ/(kg K)
cooling of the coolant temperature in the first circuit	13,6	°C
coolant temperature at the inlet of the steam generator	73,6	°C
pressure in the second circuit	15	kPa
saturation temperature in the second circuit	53,9	°C
temperature at the outlet of the steam generator	60	°C
maximum temperature difference on the tube wall Δt_{max}	19,7	°C
minimum temperature difference on the tube wall Δt_{min}	6,1	°C

logarithmic mean temperature difference	11,59	°C
outer diameter of the heat exchange tube	0,018	m
wall thickness	0,001	m
inner diameter of the heat exchange tube	0,016	m
cross-sectional area of the heat exchange tube	0,000254	m^2
number of tubes	500	pcs.
total cross-sectional area of all tubes	0,12723	m^2
velocity in the tube	1,8	m/s
average temperature of the first circuit coolant	66,8	°C
kinematic viscosity	0,00000043	m^2/s
Reynolds number	66736,8	
Prandtl number	2,68	
Nusselt criterion	246,7	
heat transfer coefficient in the heat exchange tube	10222,7	$W/(m^2K)$
heat transfer coefficient on the external surface of the heat exchange tube during boiling	8000	$W/(m^2K)$
wall thermal conductivity	16	W/(m K)
average length of the heat transfer tube	11,98	m
heat transfer coefficient	3504,82	W/m^2K
heat transfer area	319,9	m^2
power transferred by the steam generator	13	MW
pressure in the second circuit	15	kPa
heat of vaporization	2372,4	kJ/kg
steam generation in the steam generator	5,48	kg/s
steam density at 15 kPa	0,0998	kg/m^3
volumetric steam flow rate	54,91	m^3/s
friction factor in the tubes	0,023	
local resistance coefficient in the steam generator	2	
pressure loss in the steam generator along the first circuit	30,99	kPa

3.4.5 "Dry" Cooling Tower Circuit (Third Circuit)

In the presented design of the reactor installation, the problem of water resource scarcity and scale formation in heat exchangers during the transfer of low-potential heat to the final heat sink is solved by using "dry" natural draft cooling towers for these purposes. Despite higher capital costs for their construction, they become cost-effective over time due to lower operational expenses, reduced water consumption, and harmful emissions. The latter is especially important in regions with water resource scarcity. In these systems, the coolant passes through and is cooled within the cooling tower inside surface aluminum coolers, which are externally bathed by air. The cooling columns are located around the perimeter at the bottom of the tower in the windows for the inlet of cooling air. If the movement of air in the cooling tower is to occur due to natural draft, then the cooling tower is constructed in the form of a tower (Figure 14).

Fig.14 “Dry” cooling towers made of structural steel and aluminum (Iran)

To remove 27 MW of thermal power, the required volumetric air flow rate through the "dry" cooling tower, taking into account the slightly varying specific heat of air with temperature, depends on the degree of air heating. The higher the air heating, the lower the air flow rate required for this (Figure 15).

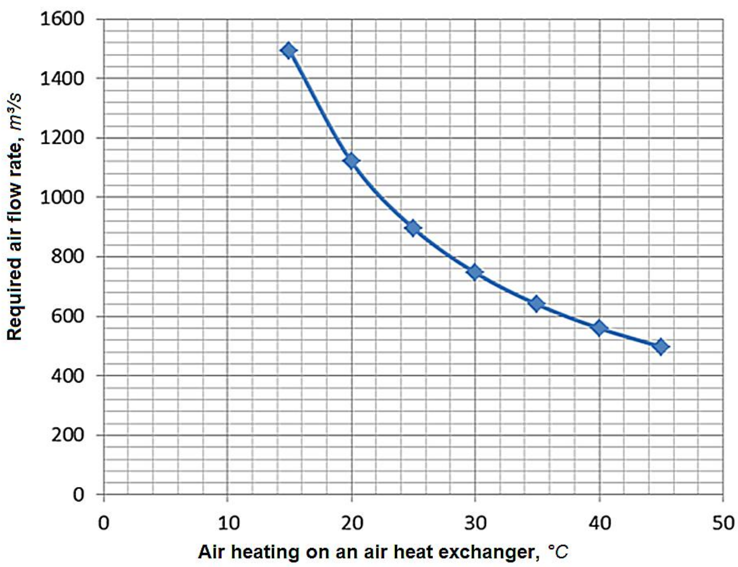


Fig.15 The dependence of the required volumetric air flow rate through the heat exchanger of the "dry" cooling tower on the degree of air preheating

The modules of the heat exchange aluminum columns must meet the requirements of maintenance convenience, tightness, and replaceability. To determine the efficiency of the heat exchange column, it is sufficient to substantiate the heat transfer capacity of an elementary cell of the air heat exchanger and extend this property to all columns. By determining the air heating in an elementary cell with a finite element calculation at a given air flow rate through it and determining the corresponding hydraulic losses, one can easily estimate the parameters of the entire cooling tower by calculating the total number of elementary cells based on the diameter of the column placement at the base of the tower D and their height h (Figure 16).

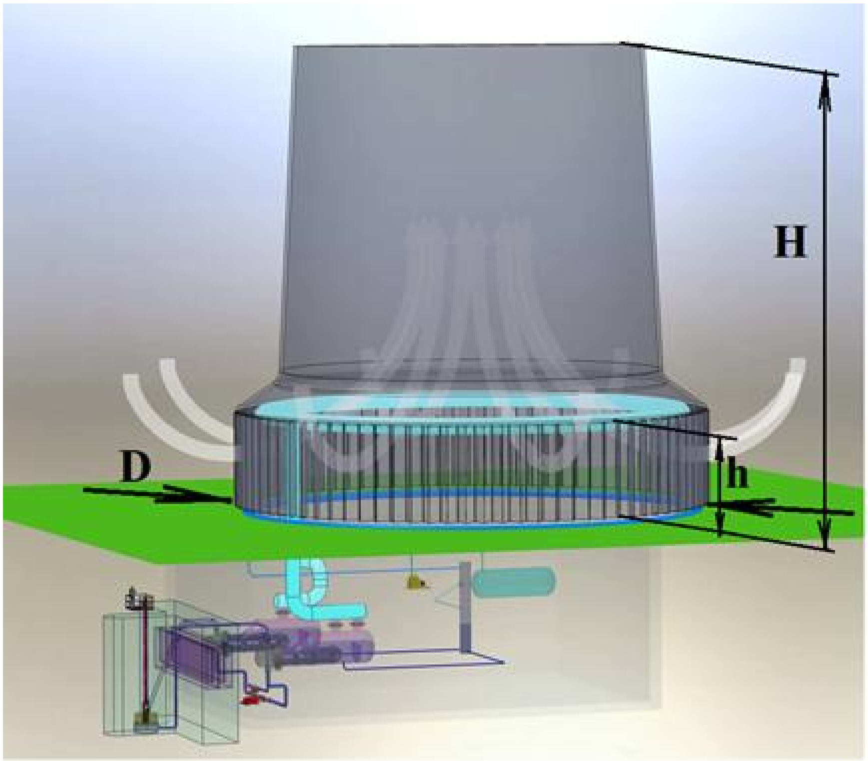


Fig.16 Basic geometric parameters of the "dry" cooling tower

The heat exchange column design consists of a stack of V-shaped horizontal aluminum plates, each 100 mm wide and 3 mm thick, spaced 4 mm apart from each other, serving as fins for twenty vertical aluminum tubes, each with a diameter of 25×4 mm, in a single column (Figure 17).

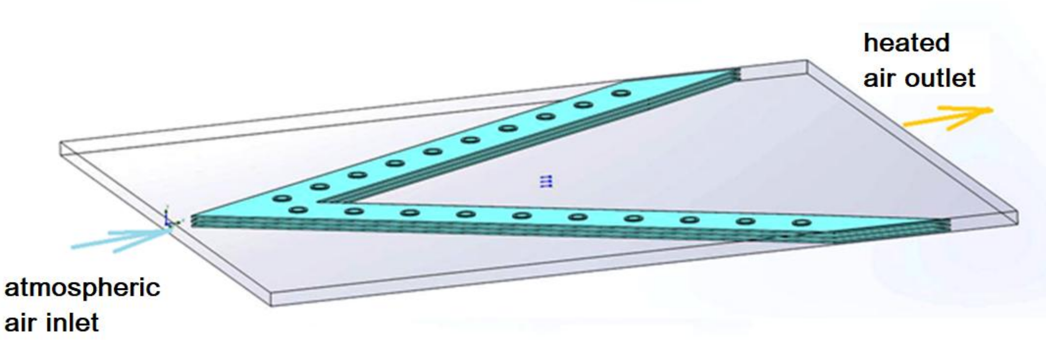


Fig.17 Elementary calculation cell

Elementary calculation cell consisting of twenty vertical sections of aluminum tubes ∅ 25×4 mm and three horizontal aluminum fin plates with a thickness of 3 mm, spaced 4 mm apart from each other (cross-sectional area of the cell $F_{el.cell}$=0.021 m^2)

The vertical tubes ∅ 25×4 mm are connected at the top to the heating steam manifold (Figure 18), and at the bottom – to the condensate collection manifold.

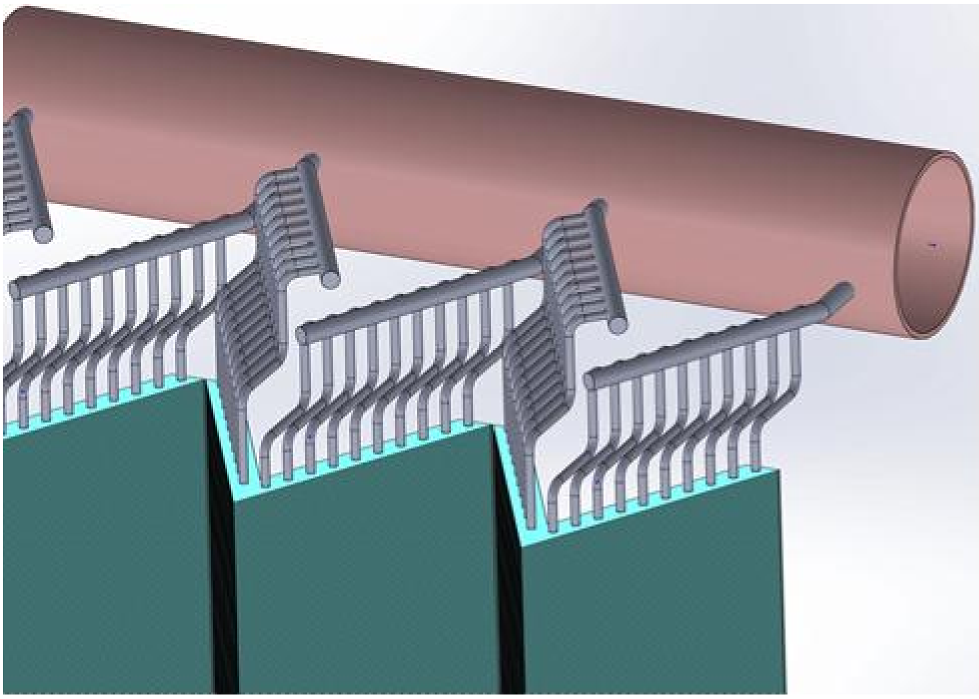


Fig.18. Connection of heat exchange columns to the heating steam manifold

By setting different airflows through the chosen geometry of the elementary cell of the heat exchange column and the temperature on the internal surface of the aluminum tubes ∅ 25×4, corresponding to the steam condensation temperature at a known pressure in the secondary circuit, the air heating was calculated at an ambient temperature of 26˚C using the Flow Simulation module of SOLIDWORKS, as well as the pressure loss when passing through the elementary cell. For the chosen height and diameter of the cooling tower and the adopted height of the heat exchange column, the following were determined:

- Total cross-sectional area of the heat exchange columns;
- Number of elementary cells in the heat exchange columns with the chosen geometry;
- Airflow through the heat exchange columns;
- Based on the air preheating and flow rate, the removed thermal power was determined;
- The driving head of natural circulation was determined by the difference in densities of atmospheric and heated air and the height of the cooling tower.

The power removed by the "dry" cooling tower is determined by the formula:

$$N_{град} = \; G_{m(cell)}^{air} c_p^{air} (t_{heat} - t_{atm}) \frac{\pi D h}{F_{cell}}$$

Where $N_{град}$ – thermal power of the "dry" cooling tower, kW;

$G_{m(cell)}^{air}$ – mass airflow through the elementary cell, kg/s;

c_p^{air} – specific heat capacity of air, kJ/(kg K);

t_{heat} – temperature of the heated air, ˚C;

t_{atm} – temperature of atmospheric air, ˚C;

D – diameter of the "dry" cooling tower at the base, m;

h – height of the heat exchange column, m;

F_{cell} – cross-sectional area of the elementary cell, m^2.

The driving head of natural circulation of the "dry" cooling tower is determined by the formula:

$$\Delta P_{dr} = [\rho(t_{atm}) - \rho(t_{heat})] g H$$

Where ΔP_{dr} – driving head of natural circulation, Pa;

$\rho\left(t_{атм}\right)$ – density of atmospheric air, kg/m^3;

$\rho\left(t_{нагр}\right)$ – density of the air heated in the cooling tower, kg/m^3;

g – acceleration due to gravity, m/s^2;

H– height of the cooling tower, m.

Below are the distribution of the temperature field (Figure 19) and the distribution of the pressure change field (Figure 20) in the calculation cell at air flows of 25, 55, and 75 m^3/s.

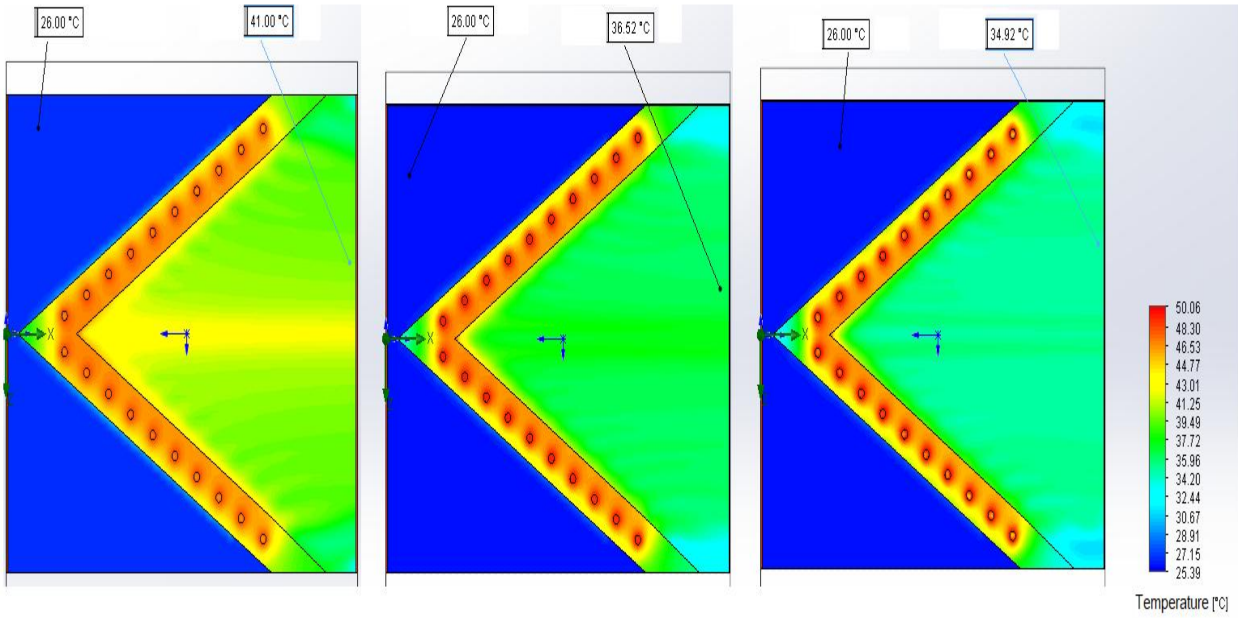


Fig.19. Heating of air in a unit cell at a volumetric air flow of 25, 55 and 75 m^3/s (from left to right), respectively

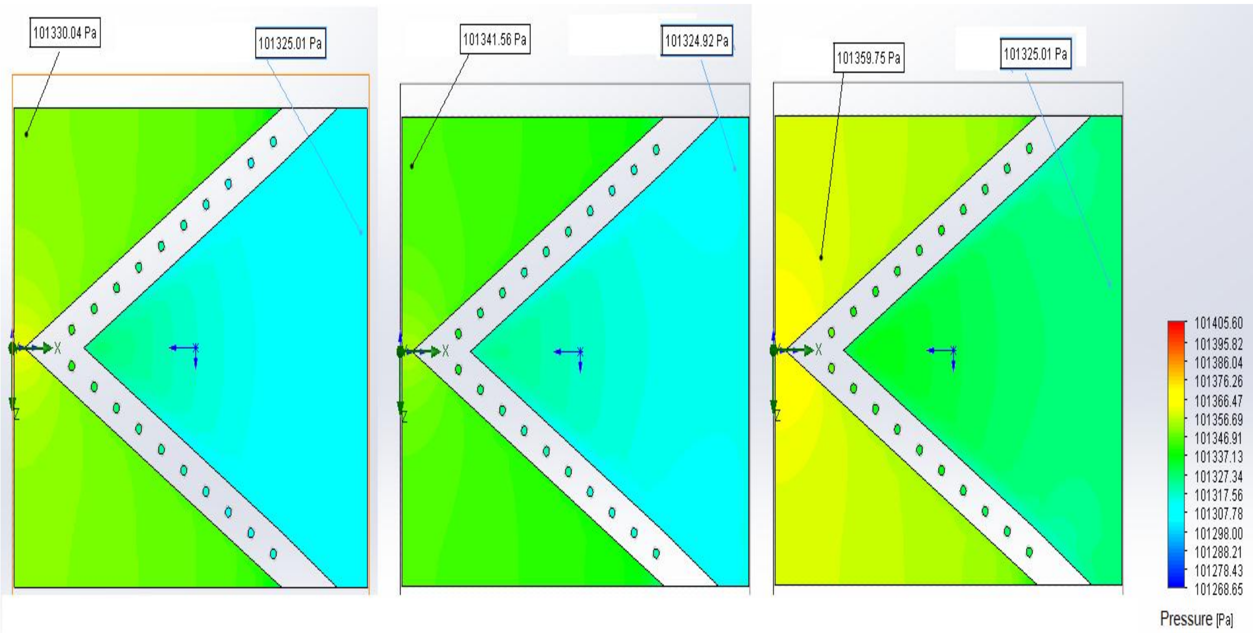


Fig.20. Air pressure drop in the elementary cell at volumetric air flows of 25, 55, and 75 m^3/s (from left to right) respectively

Below are graph for finding the working point of the cooling tower at various geometric parameters with a heat exchange column height of 6 m, an atmospheric air temperature of

26˚C, and a steam temperature in the secondary circuit of 54˚C. The working point is found by intersecting the dependencies of the driving head and pressure loss.

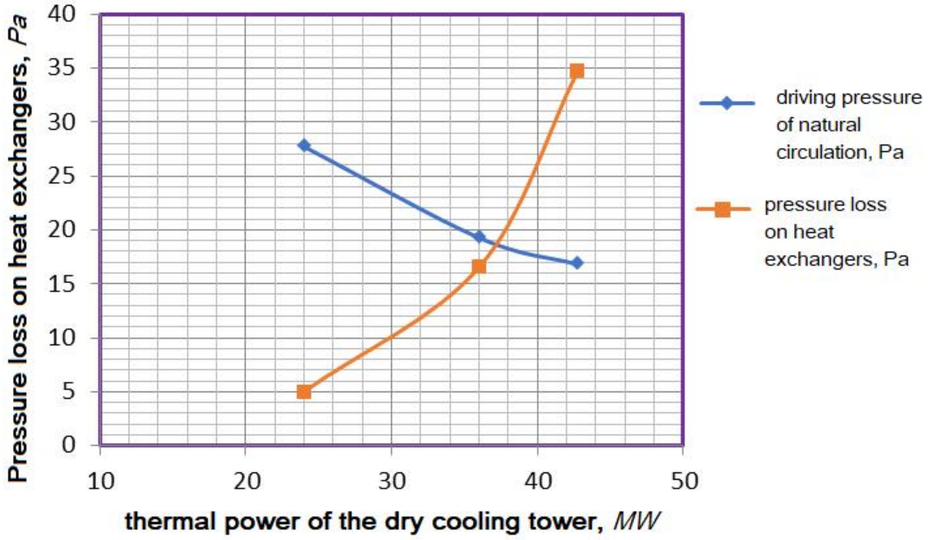


Fig.28 Operating point of a cooling tower 50 m high, 60 m in diameter with a heat exchanger height of 6 m at an ambient air temperature of 26 °C

After processing the calculated data for the selected geometry of the heat exchange equipment, the dependence of the power dissipated by the 'dry' cooling tower on its base diameter and height was obtained at an ambient air temperature of 26°C and a condensing steam temperature of 54°C, corresponding to a pressure of 15 kPa in the second circuit (Figure 30).

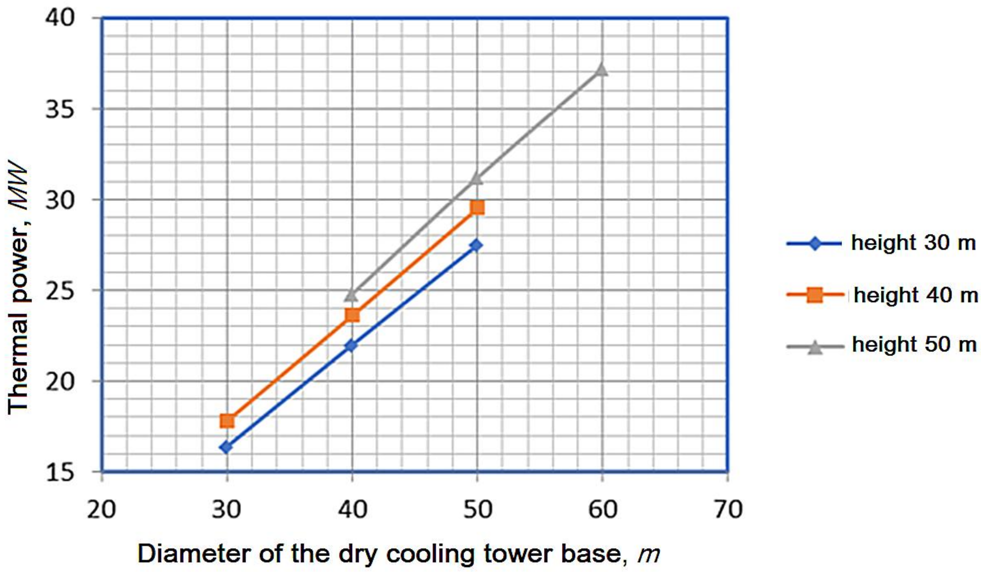


Figure 30. The dependence of the power removed by the "dry" cooling tower on its base diameter and height at an atmospheric air temperature of 26 °C and a condensing steam temperature of 54°C

4. Enhanced protection against blockage of the fuel assembly cross-section

Despite the difficulties in reloading fuel assemblies associated with the presence of the "chimney," such a design virtually eliminates one of the most dangerous situations – the blockage of the fuel assembly cross-section in the core during reactor operation. If with a downward flow scheme in the core, foreign objects accidentally falling into the reactor pool would simply be drawn by the coolant flow into the core, then with the considered flow configuration, the entry of foreign objects is practically excluded, as the coolant flow supplied from below to the core first passes through a mechanical filter.

5. Monitoring the thermotechnical parameters of the reactor

The presented reactor design allows for reliably monitoring the thermohydraulic parameters of heat removal from the core and reflector. The control of the coolant flow rate and temperature through the core (including the central channel with the neutron trap) is carried out through a flow metering device and a temperature sensor installed in the pipeline that removes the coolant from the "chimney". A flow and temperature sensor is also installed in the pipeline that removes the coolant from the suction chamber located under the reflector. By adjusting the hydraulic resistance of the throttle orifice (11, Figure 7), it is possible to redistribute the total coolant flow through the primary circuit between the flow through the core and the flow through the reflector, monitoring them according to the readings of the corresponding flow meters.

Conclusion

• A conceptual design of a pool-type research reactor installation with a three-circuit heat removal system has been presented. The advantages of creating a comprehensive cooling system for a research reactor, based on the combination of forced and natural convection of the coolant, have been substantiated;

• The presence of an intermediate circuit operating on the principle of a heat pipe (thermosiphon) eliminates the risk of radioactive coolant entering the environment. The operation of this circuit provides high heat transfer efficiency with a simple design and the absence of mechanical moving parts, which ensures system reliability;

• The use of "dry" cooling towers for heat transfer from the reactor to the final heat sink (atmospheric air) resolves the issue of scale formation in equipment and significantly reduces operational costs for chemical and mechanical cleaning of heat exchangers;

• The design of the "dry" cooling tower and heat exchange columns has been presented, as well as calculated estimates of the heat power removed depending on geometric parameters: the diameter of the cooling tower base, its height with a height of heat exchange columns of 6 m, and an atmospheric air temperature of 26 °C;

• The design of the cooling circuits ensures continuous natural circulation of the coolant in the cooling circuits during the reactor cooldown mode, creating conditions for the safe heat removal of residual heat generation from the fuel assemblies without the need for electricity supply;

• The use of an upward flow for heat removal from the core creates optimal conditions for improving thermotechnical reliability in a pool-type reactor, considering the shift of the maximum neutron flux density to the lower part of the core due to the position of the control rod drive mechanisms and improved heat removal conditions in this part due to increased pressure and minimal coolant temperature;

• The use of a forced circulation circuit partially separated from the pool through the core not only reduces the release of radioactive gases from the pool surface but also protects against the entry of foreign objects into the fuel assemblies, carrying the risk of blockage of the cross-section and melting of the fuel.

• The placement of the oxygen activity damper at the top of the pool ensures the heating of the coolant in the upper layers of water, which hinders the diffusion of radioactive gases to the surface and reduces their emissions into the atmosphere.

• The presence of a retainer above the fuel assemblies, preventing their flotation under the action of the coolant flow, not only ensures optimal upward movement of the coolant in the core but also creates significant hydraulic losses at the exit from the core, which are compensated by the head of the circulation pump and simultaneously increase the pressure in the core. Otherwise, such an effect in pool-type reactors would be achieved by submerging the core at a greater depth in the pool, thereby complicating transport and technological operations.

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