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Research Article

Computational simulation of the heat and mass transfer processes occurring in the containment of Novovoronezh NPP II's units 1 and 2*

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Abstract

The paper presents information on the key approaches to the design of the containment ventilation system for units 1 and 2 of Novovoronezh NPP II (NPP-2006 project). The authors have developed a CFD model for the containment of Novovoronezh NPP II's units 1 and 2, which includes the key structural components and the basic equipment installed within the containment. A series of the containment air temperature measurements was undertaken during power operation of the units. Based on the measured temperature values, a series of calculations was undertaken to determine the air temperature field inside the containment. It is revealed that when ensuring the design characteristics of the cooling capacity of the ventilation system stages, the design parameters of the containment air, wall and equipment temperature are achieved. In addition, with proper mixing of the containment air, it is possible to significantly reduce the average air temperature in the most "hot" rooms. Based on the calculation results, causes have been identified for the low efficiency of the ventilation system, and specific measures have been proposed for increasing significantly the system capacity. The proposed approach to determining the characteristics of ventilation systems using modern methods of three-dimensional computational hydro-gas dynamics makes it possible to optimize and modernize existing ventilation systems, as well as to assess the efficiency of ventilation at the design stage of nuclear power plants. The developed and proposed CFD model makes it possible to do this at the modern level without resorting to bench/experimental modeling issues.

Keywords

NPP-2006, ventilation, CFD, modernization, containment, operating experience, numerical simulation, steam generator

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Ventilation system for the containment rooms of the Novovoronezh NPP II units

Ventilation systems for rooms inside the containments of current generation III+ NPPs are intended not only to remove excessive heat and moisture and provide the best possible environmental conditions for normal operation of equipment, create normal climatic conditions for the personnel activities in the process of preventive maintenance and refueling operations in the unit shutdown period, and purify air from active aerosols, but also to create rarefaction of not less than 200 Pa in the unattended area and not less than 150 Pa in the limited access area (Kokorin 1978; Bogoslovsky et al. 1985; Slonimsky 1987; Tikhomirov and Sergeenko 1991; Margulova 1994; NP-036-05 2005; Andrushechko et al. 2010). The resultant pressure difference, as seen by designers, will prevent the spread of air with a content of radioactive aerosols into the personnel limited access rooms via potential looseness during normal operation of the plant.

The fundamental solutions for ventilation of the inner containment rooms have been adopted based on the concept of the room separation into two areas: a limited access area (access and possibility is provided for short-term occupancy by personnel in the process of the unit power operation) and an unattended area (personnel access is allowed only for preventive maintenance).

In accordance with the design of the Novovoronezh NPP II's units 1 and 2 (Novovoronezh NPP, Unit 1 of Novovoronezh NPP II 2016, NPP-2006 2007a, 2007b), the limited access area includes a central hall, the RCP motor rooms, and other rooms (Fig. 1, item 1). The unattended area includes the partitioned volume of the inner containment, including the steam generator (SG) and reactor coolant pump (RCP), compartments the reactor cavity, valve chambers, and other rooms which accommodate the primary circuit components and pipelines (Fig. 1, item 2).

As designed, however, the air temperature in the NPP normal operation mode is:

- up to +60 °C in unattended rooms in the normal operation mode;
- from +20 °C to +40 °C in attended and periodically attended rooms in the controlled access area;
- from +33 °C to +40 °C in the limited access rooms within the inner containment in the normal operation mode.

There are recirculating air cooling systems inside the containment (Fig. 2) to provide for heat removal from process equipment and pipelines, and for maintaining the preset air temperature in the containment rooms:

1. Recirculating cooling system for the unattended area. The system cools the main circulation circuit and the steam generator rooms, the pressurizer, the support truss, and the thrust truss. The system comprises four plants of which two are in operation and the other two are standby (Fig. 2, item 1);
2. Recirculating system for purifying air inside the containment rooms. The system is designed to purify air from radioactive contaminants and keep the radiation situation in the containment rooms at the predefined acceptable level, and comprises two identical plants one of which is in operation and the other is standby (Fig. 2, item 2);
3. Recirculating system for cooling the control and protection system (CPS) drives. The system is designed for air cooling of the CPS drives, and comprises three plants two of which are in operation, and the third one is standby (Fig. 2, item 3);
4. Recirculating system for cooling the limited access area. Consists of two independent systems. One of the systems (Fig. 2, item 4.1) serves to cool the annulus area, the adjacent rooms, and the equipment they accommodate. Comprises three plants of which two are in operation, and the third one is standby. The second system (Fig. 2, item 4.2) serves to cool the central hall rooms. Comprises three plants of which two are in operation, and the third one is standby;
5. Exhaust ventilation system (Fig. 2, item 5);
6. Plenum ventilation system (Fig. 2, item 6) which creates rarefaction inside the containment rooms jointly with the exhaust ventilation system. Plenum air is fed into the annulus from where it is bypassed, via pressure relief valves, into potentially contaminated unattended and periodically attended rooms at the expense of the rarefaction created by the exhaust plant fans. Such layout prevents air from flowing out of dirty rooms and creates the directed air flow towards them.

The water used in the essential consumer intermediate circuit and in the normal operation consumer intermediate circuit is the cooling agent for the ventilation and air conditioning systems. These systems have a closed circuit, and the essential service water systems are used for their heat removal (heat removal by the compressor-type refrigerator is added for the summertime).

Experience of operating the Novovoronezh NPP II containment ventilation systems

It was found in the course of operation that the containment air temperature for units 1 and 2 of the Novovoronezh NPP II exceeds the design values independent of the season and the outdoor air temperature t_{oa} (Fig. 3). Moreover, the temperature value in the rooms that accommodate the control and protection system (CPS) drives is close to the limit setpoint temperature of 120 °C.

The temperature in the central hall reaches 55 °C, the design value being 40 °C, and that in the SG compartment room reaches 80 °C, which is 20 °C as high as the design value, this leading potentially to the loss of the concrete strength

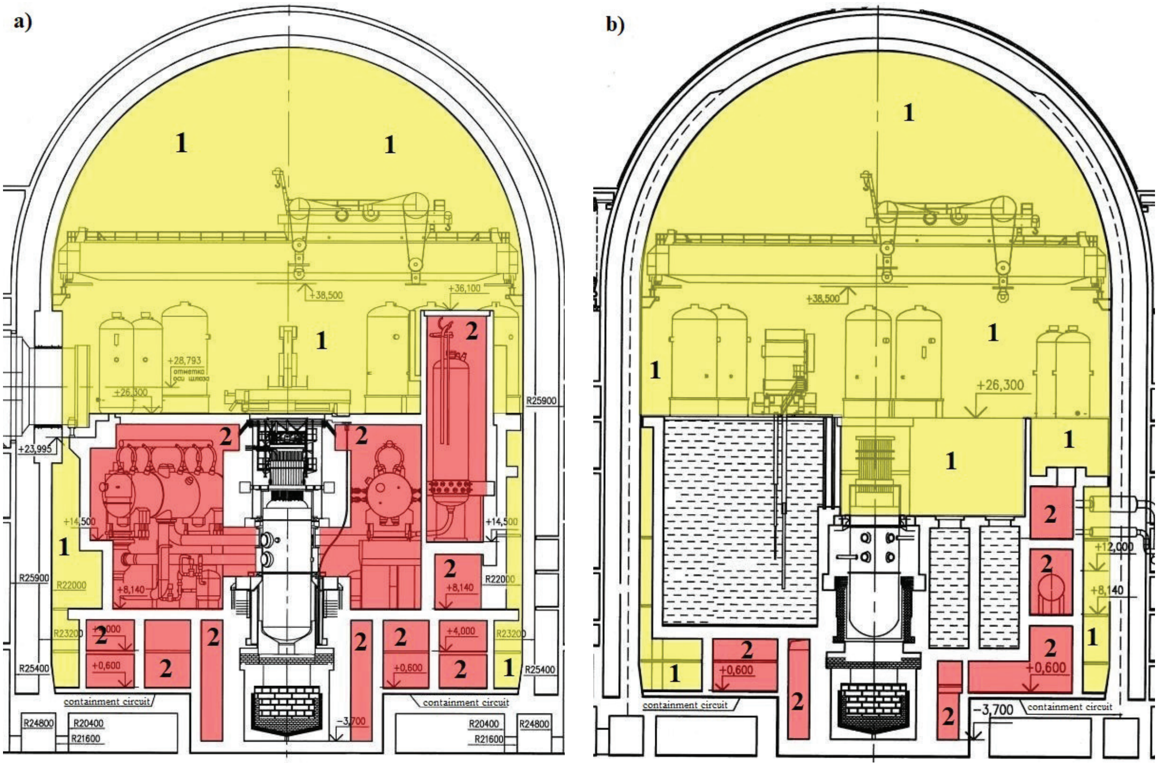

Figure 1. Containment room separation concept (1 – limited access area; 2 – unattended area): **a**) containment cross-sectional cut; **b**) containment longitudinal cut.

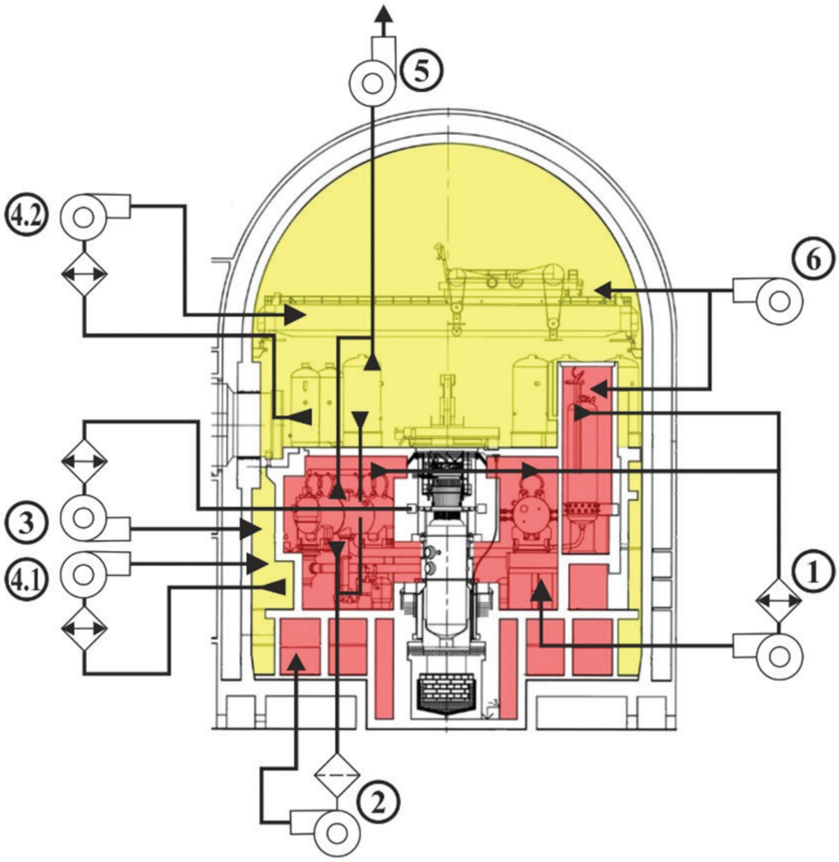

Figure 2. Flow diagram of the containment cooling and ventilation system: 1 - recirculating system for cooling the unattended area; 2 - recirculating system for purifying air inside the containment rooms; 3 - recirculating system for cooling the control and protection system drives; 4.1 - recirculating system for cooling the annulus area, adjacent rooms and equipment they accommodate; 4.2 - recirculating system for cooling the containment central hall; 5 - exhaust ventilation system; 6 - plenum ventilation system.

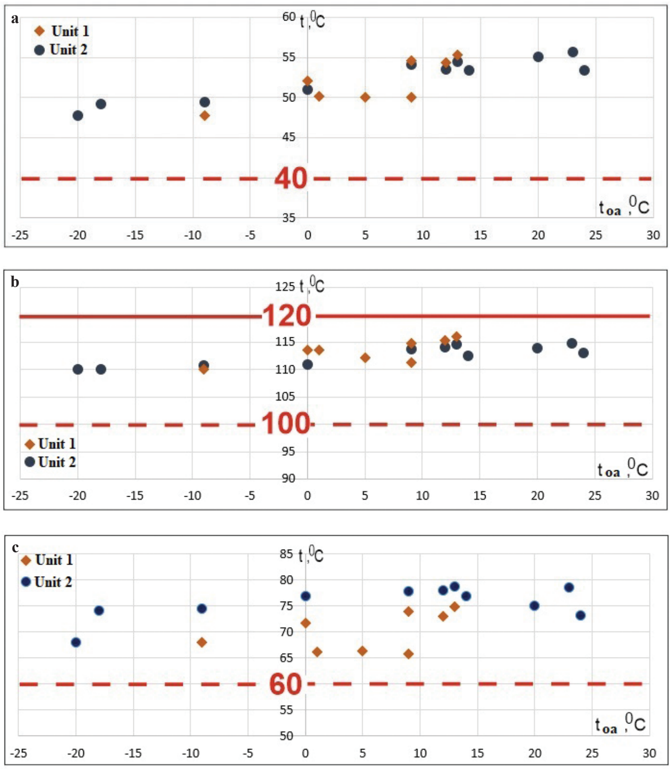

Figure 3. Measured air temperature values for the containment rooms in units 1 and 2 of the Novovoronezh NPP II as a function of the outdoor air temperature (toa): **a**) temperature in the containment's central hall (design temperature value 40 °C); **b**) temperature in the region of the CPS control members and the upper unit (design temperature value 100 °C, scram setpoint temperature value 120 °C); **c**) steam generator compartment temperature (design temperature value 60 °C).

properties and, possibly, to a shorter NPP life. Standard thermocouples were used for the temperature measurement (the measurement accuracy is not more than ± 2.0%).

It was also observed that air was not sufficiently mixed in the containment due to the complicated development of free convection inside the containment as the result of the internal space constraints.

An analysis of the data obtained as part of the commissioning activities and in the course of the unit operation has shown that the potential causes for the temperature increase are:

- low efficiency of the ventilation plants (as compared with the design values);
- increased heat loss from the primary circuit pipeline and equipment surfaces;
- inefficient mixing of air flows inside the containment.

Development of the containment calculation model

To estimate the relative effect of the causes for the deviation of temperatures from their design values, 3D thermo-hydraulic calculations were undertaken for the containment air temperature distribution during rated operation modes using a Rostekhnadzor-certified code, CFD (Computational Fluid Dynamics), of the STAR-CCM+ class (Kirillov et al. 1984; Patankar 1984; Peire and Taylor 1986; Lapin and Strelets 1989; Samarsky and Gulin 1989; Fletcher 1991; Chui and Raithby 1993; Ferziger Peric 1999; Bystrov et al. 2005; Denisikhina 2013).

To this end, CFD models of the containment rooms were developed, including the key components and the ventilation plants (Fig. 4).

Specific to the ventilation unit heat exchanger design is that the heat-exchange tubes have fins on their outside. The external diameter of the tubes is 22 mm, the wall thickness is 2.5 mm, and each fin represents a helical band with a width of 9 mm and a thickness of 1 mm coiled about the tube with a spacing of 5 mm, which, in turn, causes certain complications for simulation using the developed CFD model.

One of the stages in thermo-hydraulic calculations for the containment temperature and air flow distribution is validation of the base CFD model developed.

In the course of the model validation, key uncertainties were identified which include the estimated heat loss into the containment air from the system pipeline and equipment surfaces, the properties of insulating materials from particular manufacturers and delivery batches, and the quality of manufacturing and installation of fast replaceable thermal insulation.

An inverse problem was solved to estimate this effect: such heat loss was chosen based on results of in-service temperature measurements at predefined points using the

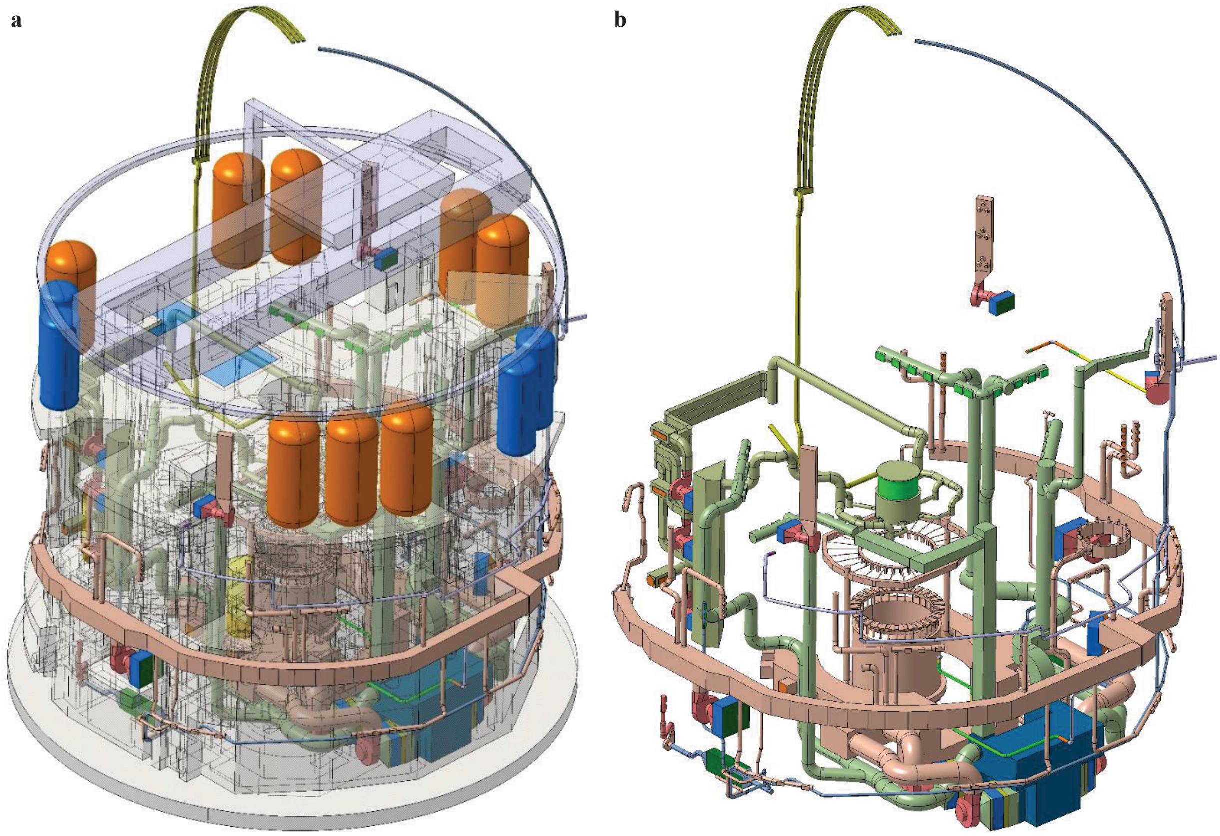

Figure 4. Containment CFD models: **a** key components; **b** ventilation plants.

CFD model with which the estimated temperature at the CFD model geometry points was equal to the measured temperature at the same containment point.

The design values of the heat loss in the period of the rated unit power are 700 kW for the limited access area and 600 kW for the unattended area.

As the result of the calculation, the following heat loss values have been obtained for the rated power of the reactor facility:

- unit 1 – 535 kW for the limited access area, and 1550 kW for the unattended area, the total heat loss being 1.6 times as high as the design values;
- unit 2 – 650 kW for the limited access area, and 1685 kW for the unattended area, the total heat loss being 1.8 times as high as the design values.

The above differences between unit 1 and unit 2 can be explained by the properties of insulating materials from particular manufacturers and delivery batches, as well as by the quality of manufacturing and installation of fast replaceable thermal insulation (FRTI).

The heat loss obtained when solving the inverse problem is used for the calculations to estimate the distribution of temperatures and the air flows inside the containment as part of justifying the ventilation equipment upgrades and achieving the design containment air temperature values. The heat loss from the CPS have been assumed to be equal to the design value of 680 kW. Meanwhile, no inverse problem to determine the actual heat loss from the CPS control rod jackets has been solved due to the absence of design temperature measurement points at the ventilation subsystem inlet.

Calculation results

The calculated containment air temperature for unit 1 of the Novovoronezh NPP II is given in Table 1, and that for unit 2 is given in Table 2. The results obtained in the course of the calculations are rather close to the measured temperature values at the sensor installation points inside the containment. A calculation was further undertaken to estimate the containment air temperature field using the CFD model developed by the authors.

The results of a numerical simulation for the containment air temperature distribution and the operating data for effective unit 1 of the Novovoronezh NPP II for October 15, 2020 are presented in Fig. 5 in a single color scale.

As shown by the calculated data, the temperature in the space beneath the dome and in the annulus exceeds the design characteristics by 20 °C on the average. The minimum temperature areas keep their earlier positions relative to the containment's key components (these are the grade-level rooms). It has been found that the design values of the containment air, wall and equipment temperature are reached when the design cooling capacity is achieved for the ventilation system stages. Besides, with the containment air mixed properly, the average air temperature in the 'hottest' rooms can be reduced considerably.

Table 1. Comparison of the calculated and operating air temperature values inside the containment for unit 1 (T_{CONT} – average containment air temperature, T_{SG} – average SG compartment temperature)

Measurement date	T_{CONT}, °C calculation	T_{CONT}, °C measurement	T_{SG}, °C calculation	T_{SG}, °C measurement
October 15, 2020	55.5	55.3	75.0	74.9
October 25, 2020	54.5	54.4	74.5	73.8
January 03, 2021	52.0	52.1	75.5	71.8

Table 2. Comparison of the calculated and operating air temperature values inside the containment for unit 2 (T_{CONT} – average containment air temperature, T_{SG} – average SG compartment temperature)

Measurement date	T_{CONT}, □C calculation	T_{CONT}, □C measurement	T_{SG}, □C calculation	T_{SG}, □C measurement
October 15, 2020	53.5	54.5	77.0	78.7
July 03, 2020	52.5	55.1	75.0	75.1
January 21, 2021	49.5	49.2	71.0	74.2

Conclusions

It follows from the computational analysis that the containment air temperature is stratified substantially along the containment height reaching 20 °C and more (Fig. 5). To level off the air temperature, it is required to ensure that there is air mixing via directed circulation between individual ventilation systems or in the shared passage between the central hall space beneath the dome and the sump region.

At the present time, the temperature inside the containment is measured at two points: at the level of the polar crane operator cabin in the central hall and in the SG compartments which, as shown by the calculation results, does not reflect in full the air temperature distribution by the NPP rooms. It is therefore proposed that more temperature sensors be installed in the lower and upper parts of the SG compartments, in the annulus and in the central hall.

When the heat-exchange surfaces of the ventilation stages are replaced, full-scale testing is required to confirm the design cooling performance, as well as the possibility for the design cooling water temperature values to be recovered at the ventilation plant stage inlets.

The proposed approach to determining the performance of the ventilation systems using current 3D computational gas fluid dynamics methods makes it possible to optimize and upgrade the existing ventilation systems, as well as to estimate the efficiency of ventilation at the NPP design stage. The CFD model developed and proposed allows doing this at the state-of-the-art level without the need for addressing the bench/experimental simulation issues. At further CFD model optimization stages, it will be reasonable to undertake a series of calculations to estimate the heat-exchange characteristics of the ventilation plant tubes with spiral finning.

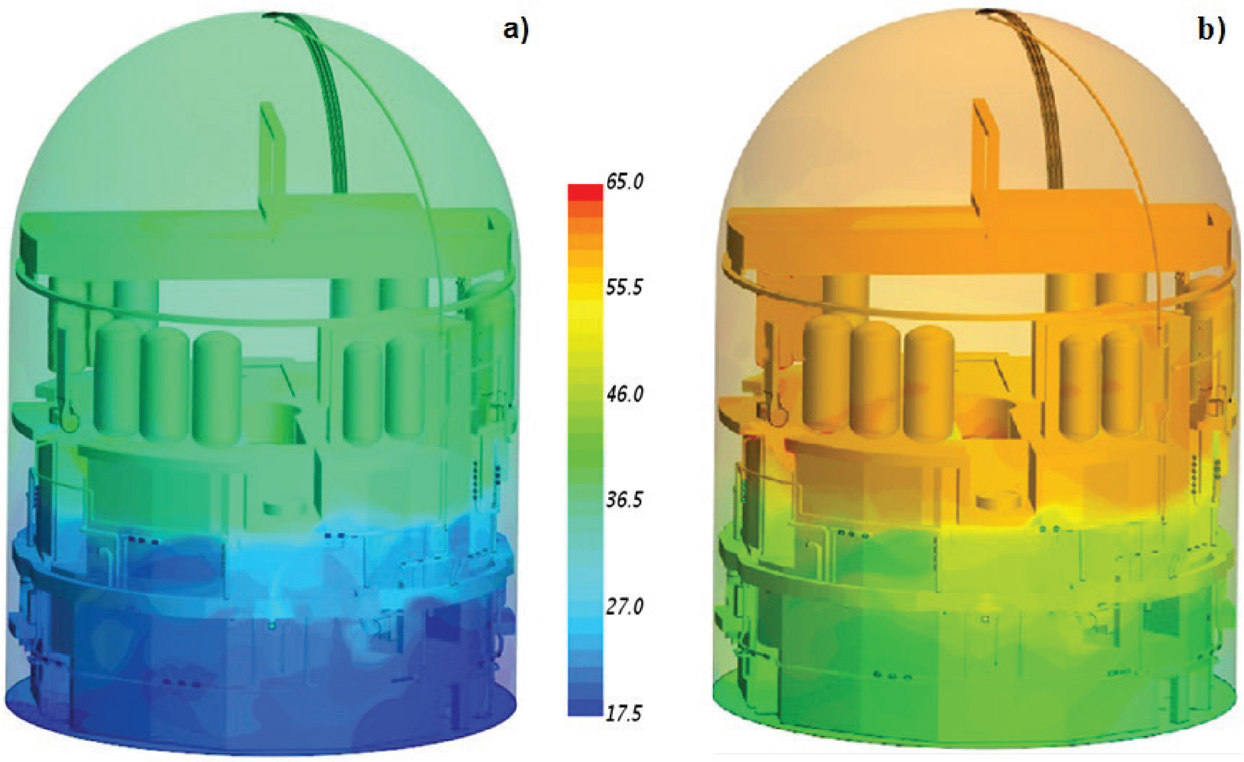

Figure 5. Results of calculating the containment atmosphere temperature: **a**) design data; **b**) calculated data (based on experimental measurement results).

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