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Simulation of Natural Convection in DEMO Cryostat During Helium Ingress Accident

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ABSTRACT

For proper work conditions, superconducting magnets have to be actively cooled by helium at cryogenic conditions. During a helium ingress accident, the cryostat in a DEMO fusion reactor is filled with helium gas. The loss of helium into the cryostat is studied at normal and baking conditions of the vacuum vessel, whereas the temperature of magnet coils is preserved at 59 K. The temperature difference between warm and actively cooled structures establishes the natural convection inside the cryostat. The ANSYS CFX code was used to run the steady-state simulations of the natural convection at different pressures and temperatures to assess the temperature distribution, heat fluxes and heat transfer coefficients on the cryostat inner wall.

1 INTRODUCTION

One of the hypothetical accident scenarios in the DEMO fusion reactor considers ingress of helium into the cryostat due to the break of the cryogenic cooling line, which is used to cool down the superconducting magnets. The atmosphere inside the cryostat is normally kept at very low pressure (vacuum) to minimize heat transfer between cold structures (superconductive magnets and thermal shields) and warm structures (vacuum vessel and cryostat) [1, 2].

During the postulated accident, the helium at cryogenic temperatures is released inside the cryostat, and since the cryostat is surrounded on the outside by air at room temperature, the heating of the released gas inside is the main cause of the pressure increase. Since the cryostat is designed as a thin-walled vacuum vessel, it could rupture due to the overpressurization.

The steady-state simulations of natural convection are performed using the ANSYS CFX computational fluid dynamics code. A numerical model including a 22.5° sector of the interspace between vacuum vessel and the cryostat inner wall was developed. The computational model contains the vacuum vessel (VV) with port structures, the superconducting magnet coils, the vacuum vessel thermal shield (VVTS), the cryostat thermal shield (CTS) and the cryostat. The aim of this study is to determine temperature distribution, heat fluxes, and heat transfer coefficient at different pressures and temperatures. Namely, these parameters, especially the heat transfer coefficient, are needed to properly assess the heating of the helium gas and the pressure increase inside the cryostat in the future studies. The temperature of the magnet coils in this study is preserved at 59 K and the cryostat wall is cooled by the outside air at 293 K.

2 SIMULATION MODEL

A steady state numerical simulation of the natural convection of helium gas were performed using ANSYS CFX code. The normal and baking conditions were taken into consideration, where vacuum vessel is actively cooled to 40 °C (313 K) or 180 °C (453 K), respectively. Cryostat was passively cooled by the outside air at temperature 20 °C.

2.1 Computational mesh and boundary conditions

In this study a 2018 CAD geometry of DEMO tokamak and the cryostat with 16 equatorial sectors was used (Figure 1 left), which was already used in a similar work by Draksler et al. [1]. Due to the toroidal symmetry, only one sector of the VV, the thermal shields, the magnet system, and the cryostat is used in the simulation model (Figure 1 right). Cryostat thermal shield (CTS) and vacuum vessel thermal shield (VVTS), both shielding the magnets from the radiation heat transfer, are modelled as a thin wall structures with a thickness of 3 cm [1]. The VVTS completely surrounds the VV and VV ports up to the CTS [3].

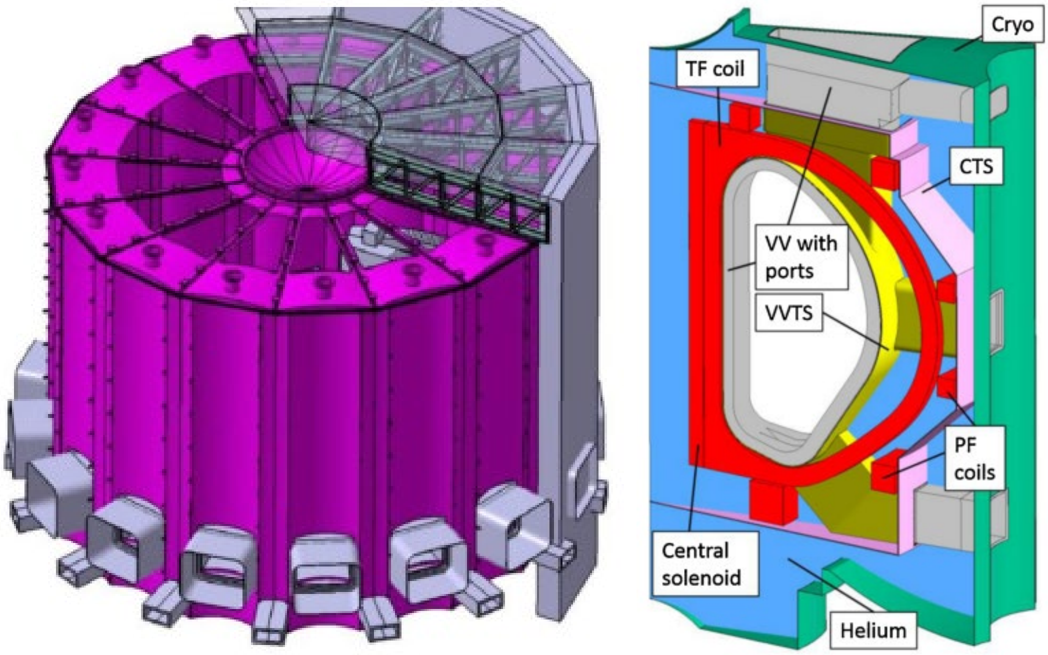

Figure 1: DEMO cryostat and bioshield structure (left) and sector used in the simulation (right) [1].

Numerical meshes used in this study were taken from Draksler et al. [1]. The numerical mesh consists of tetrahedral elements in the centre of the fluid domain and prism layer elements clustered on the domain interfaces and boundaries. The similar meshing approach was used for solid domains. The simpler geometries were meshed using only the hexahedral elements. The full model consists of approximately 85.5 Mio mesh elements and 21.2 Mio nodes. Majority of the elements are located in the fluid domain [1].

The simulation of a single sector considers the event of helium ingress into the cryostat at different reference pressures. The magnets are assumed to be at constant temperature of 59 K. That enables a strong natural convection inside the cryostat due to the high temperature differences. The heat transfer through the cryostat wall to the outer environment is controlled by the heat transfer coefficient between the outer cryostat surface and air at 20 °C and was set to the value of 4 W/m^2K [1].

2.2 RESULTS

Simulation results for normal and baking DEMO operating conditions at different reference pressures are presented and discussed.

Temperature differences between warm and cold structures of the reactor cause a natural convection to occur inside the cryostat. As seen in Figure 2a, showing the case with reference pressure 100 kPa, the warmer and lighter helium gas accumulates in the top part, while the colder and heavier helium lingers at the bottom part of the cryostat. The complexity of a natural convection inside our cryostat, at same conditions, is represented by velocity vectors across velocity contour located on the central plane in Figure 2b. Many recirculation zones, caused by natural convection, can be observed.

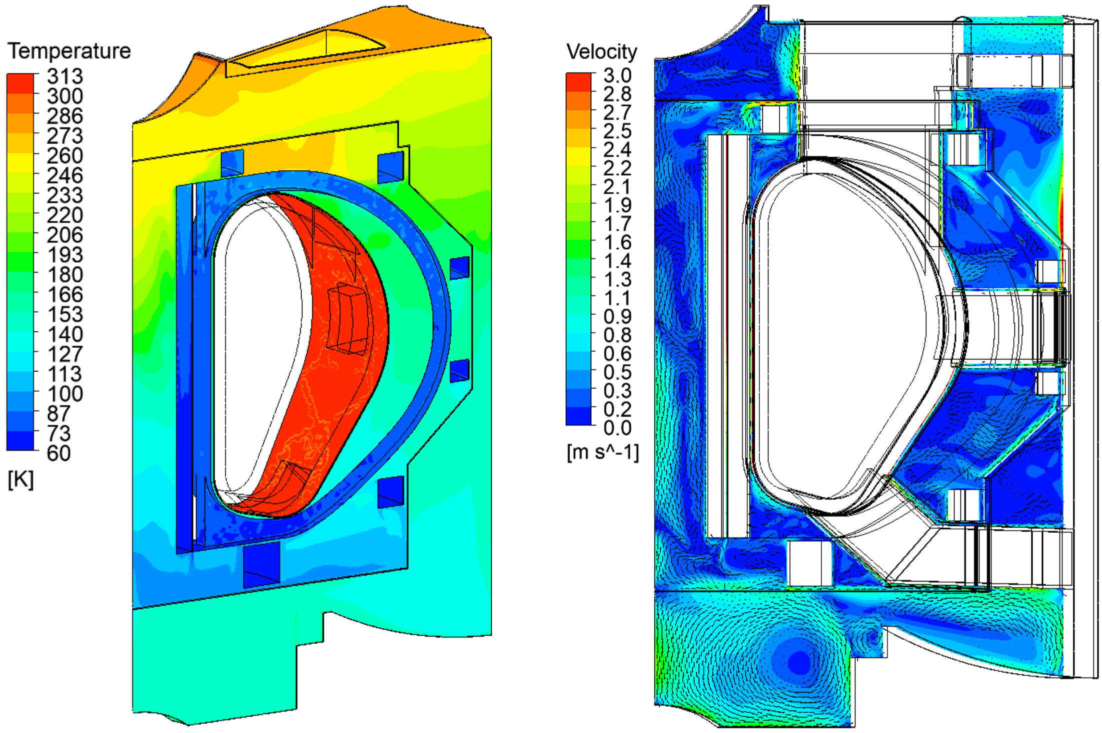

Figure 2: Contour of helium gas temperature at symmetry planes (a). Velocity vectors across a velocity contour on the central plane (b).

Figure 3 shows volume-average temperature of the fluid domain for different reference pressure values and operating conditions (VV temperatures). The temperatures at baking conditions are obviously higher, since the VV is kept at higher temperatures. It can be observed that the volume average temperature is decreasing with increasing pressure. Namely, increased pressure means higher density of helium gas inside the cryostat which increases the ability of helium to transfer heat. However, an exception at 30 kPa may be observed, where we see a rise of temperature. This anomaly at 30 kPa should be furtherly investigated. At $p = 3$ kPa, however, the highest temperature difference for the majority of the helium gas (not considering helium next to heated and cooled structures) is only around 10^{-4} K. Furthermore, the average temperatures in the entire fluid domain for normal and baking conditions are 294 K and 297 K, respectively, which is higher than the environmental temperature (293 K). As furtherly discussed, at such low pressure the natural convection did not establish.

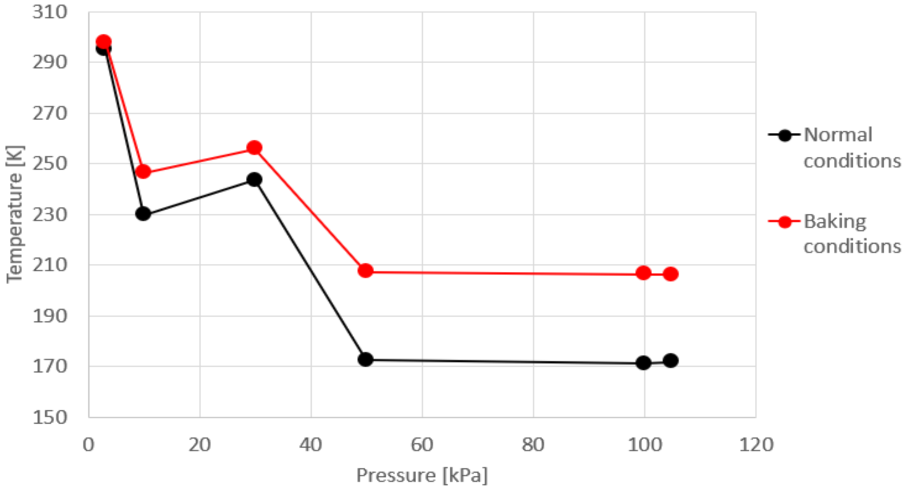

Figure 3: Volume-averaged temperature values of the helium gas for different reference pressures and operating conditions.

Rayleigh dimensionless number (*Ra*) is directly associated with natural convection. Low *Ra* means weak natural convection with little to no movement of the fluid and the heat is mainly transferred by conduction, while at higher *Ra* heat is mainly transferred by natural convection. Rayleigh number is defined as:

$$Ra = \frac{g\beta(T_s - T_{bulk})L^3}{\nu\alpha} \tag{1}$$

where g is the gravitational acceleration, β is the thermal expansion coefficient of gas, T_s is the temperature of the surface, T_{bulk} is bulk temperature, ν is the kinetic viscosity, α is the thermal diffusivity and L the characteristic length scale, which is calculated as a ratio between the volume of the interspace between cryostat wall and CTS and area of the cryostat wall.

The values of *Ra* number for different reference pressures and operating conditions are presented on Figure 4. It can be observed, that the value of *Ra* rises with pressure, which promotes the establishment of the heat transfer due to the natural convection. For baking conditions (VV temperature of 180 °C), *Ra* has lower values in comparison to normal conditions (VV kept at 40 °C). Namely, higher VV temperature increases the bulk temperature and lowers the temperature difference between the fluid and cryostat wall (Eq.1). The calculated bulk temperature is lower than the temperature of surface, since the atmosphere inside the cryostat is being cooled down by the magnets, which are kept at constant temperature of 59 K. For the case with 3 kPa, it can be assumed that natural convection had not yet been established, since the *Ra* value is low.

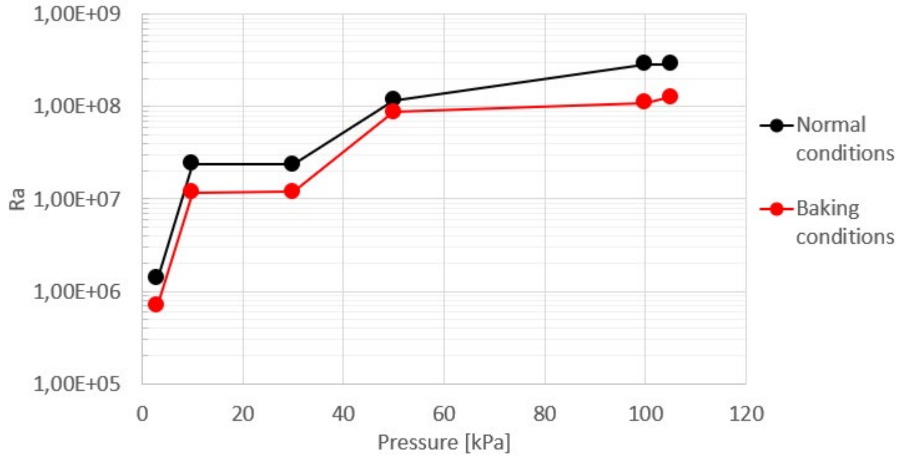

Figure 4: Values of Rayleigh number for different reference pressures and operating conditions.

The temperature distribution on the inner cryostat wall also varies depending on the reference pressure and the VV temperature. Figure 5 shows a comparison between temperature distributions on inner cryostat wall for different pressures and operating conditions. It can be observed, that higher temperatures at cryostat wall occur when the reference pressure is lower. The cause is lower natural convection and therefore lower heat transfer for those cases. The middle VV ports are the closest to the cryostat (of all ports). For this reason, the highest values occur here in all cases, and the cryostat temperature is close to the temperature of the VV. On the other hand, away from middle VV port the temperature value is close to average value.

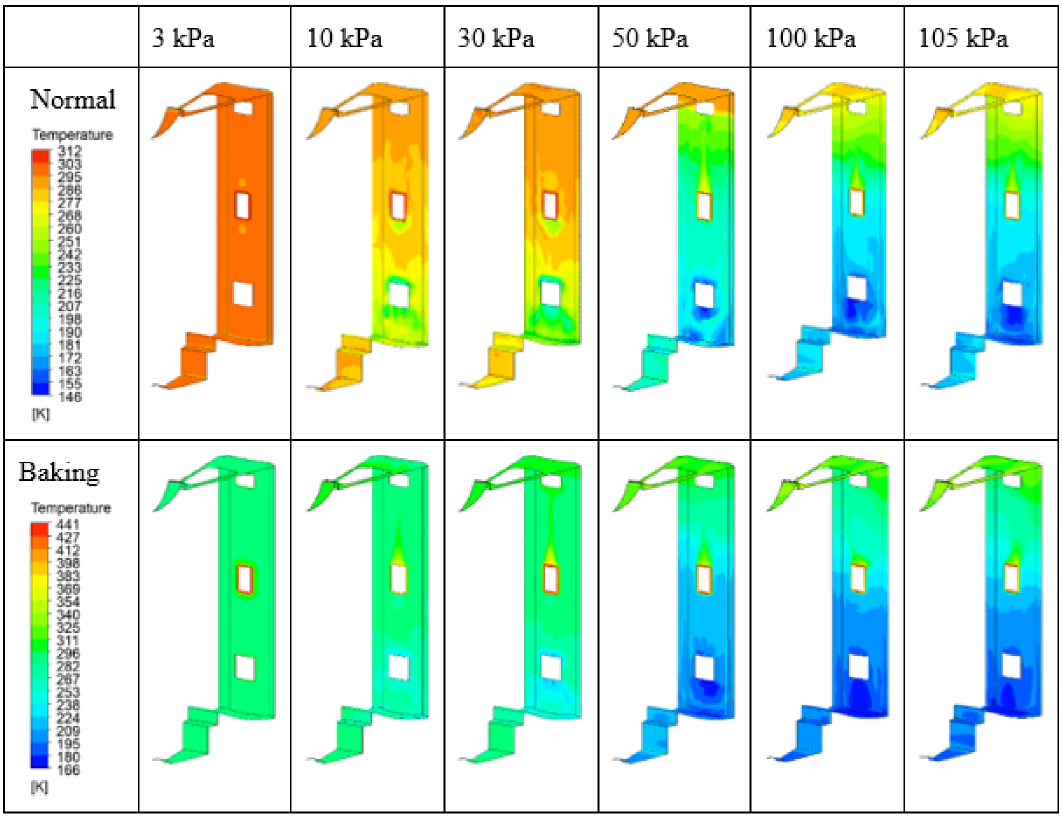

Figure 5: Temperature distribution on the cryostat inner wall for different reference pressures and operating conditions.

Figure 6 reports surface-averaged, maximum and minimum temperatures on the inner cryostat wall for different reference pressures and operating conditions. We can clearly see the effect of weaker natural convection in the case of 3 kPa result. For normal conditions, the difference between minimum, maximum and surface-averaged values of temperature is very low, as an effect of no natural convection at that case. For baking conditions, the maximum value around 440 K is seen. This value occurs only locally around middle VV port, while away from it the temperature value is close to average value.

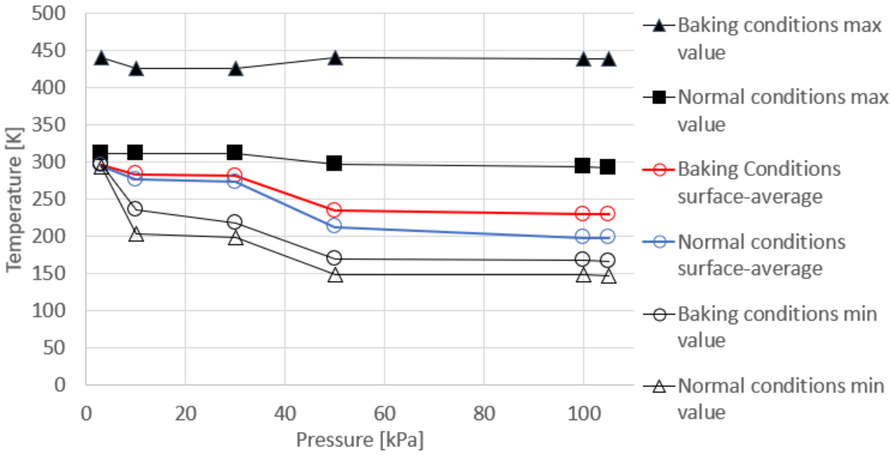

Figure 6: Inner cryostat wall average, minimum and maximum temperature values for different reference pressures and operating conditions.

Heat flux can be defined by Fourier's law of heat conduction as:

$$q = -k\frac{dT}{dx} \tag{2}$$

where k is the thermal conductivity and dT/dx is the thermal gradient in the direction of heat flow.

Figure 7 presents values of wall heat flux on the inner cryostat wall for different reference pressures at different operating condition. Positive wall heat flux denotes the heat is transferred from the cryostat wall towards the colder helium gas, while the areas of colder cryostat wall (close to the temperature of the surrounding air) have negative values. Negative values in Figure 7 are clipped out to better represent boundaries between the opposite wall heat flux directions.

The surface-average and maximum values of the wall heat flux are presented on Figure 8. It can be observed, that the maximum value of wall heat flux increases with pressure, with a slight drop at the case with 105 kPa. The average values increase with pressure and the highest increase is seen between 30 kPa and 50 kPa. This corresponds with Figure 3, where the highest temperature difference of the volume-averaged value between values 30 kPa and 50 kPa can be observed. In respect to Eq.2, lower helium temperatures at higher pressure, increase the value of dT, which consequently increases the absolute value of wall heat flux. However, negative average wall heat flux values for both operating conditions in the case of reference pressure 3 kPa can be seen.

The heat transfer by thermal radiation is neglected in the calculations, since the He is transparent, i.e. its absorption coefficient is equal to zero [5]. Furthermore, the heat flux due to thermal radiation is in the range of 10 W/m^2, which is an order of magnitude lower than the values obtained in the present study [4].

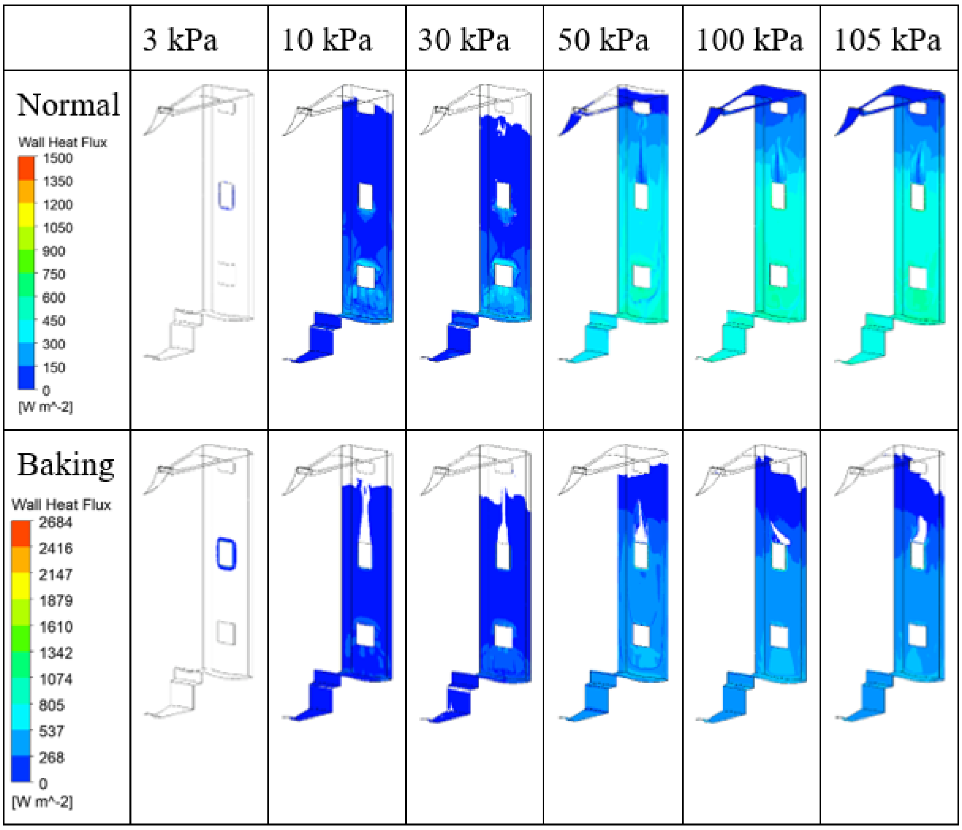

Figure 7: Wall heat flux on the cryostat inner wall for different reference pressures and operating conditions with negative values clipped out. Positive wall heat flux denotes that the heat is transferred from the cryostat wall towards the colder helium gas.

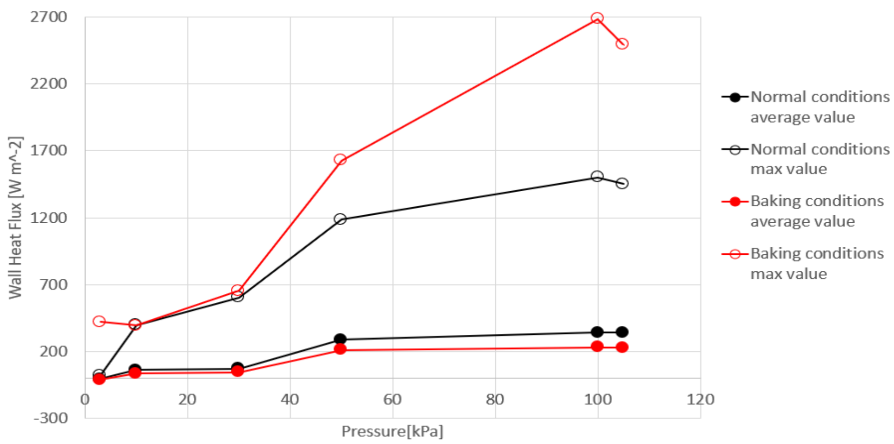

Figure 8: Surface-averaged wall heat flux values for different reference pressures and operating conditions.

Heat transfer coefficient (HTC) was analysed on the inner cryostat wall. It is defined as:

$$HTC = \frac{q}{T_{wall} - T_{bulk}} \tag{3}$$

where q is the wall heat flux, T_{wall} is the wall temperature and T_{bulk} is the characteristic fluid temperature. The average value of the helium gas temperature between cryostat wall and cryostat thermal shield (cryo and CTS on Figure 1) was used. The values for different reference pressures and operating conditions are shown in the Table 1. As before, we see a decrease of average temperature with increase of pressure.

Table 1: Averaged helium gas temperature between cryostat inner wall and CTS for different reference pressures and operating conditions.

Normal		Baking	
Pressure [kPa]	Temperature [K]	Pressure [kPa]	Temperature [K]
3	298	3	298
10	264	10	278
30	268	30	279
50	204	50	227
100	187	100	225
105	188	105	225

Figure 9 shows absolute values of calculated heat transfer coefficients on inner cryostat wall for different reference pressures and operating conditions using values from Table 1 as characteristic fluid temperature. We can observe an increase of HTC with pressure increase, highest again being between reference pressure values of 30 kPa and 50 kPa. The case with reference pressure 3 kPa again stands out especially at baking conditions. The reason for such deviation is the absence of natural convection as discussed before.

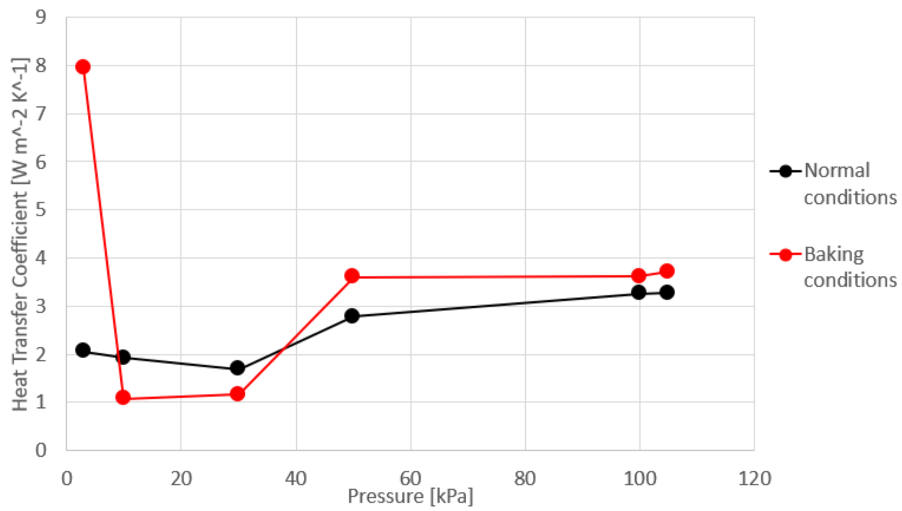

Figure 9: Surface-averaged absolute values of heat transfer coefficient using averaged temperature values of He gas between cryostat inner wall and CTS for different reference pressures and operating conditions.

3 CONCLUSIONS

During helium ingress accident the cryostat is filled with helium gas. Due to temperature difference between warm and cold structures inside the cryostat a natural convection of helium occurs that causes a non-homogeneous distribution of the wall temperatures. Two different operating conditions (normal and baking) with different reference pressures have been analysed. The simulation results show, that pressure increase in both operating conditions causes a decrease of average helium gas temperature and therefore lower average cryostat wall temperature. We noted that at the case with reference pressure of 3 kPa the natural convection did not establish and consequently a temperature profile of the helium gas throughout the fluid domain of the cryostat had almost constant values, slightly higher than the temperature of the surrounding air. The effects of no natural convection at the case with reference pressure 3 kPa are also obvious at the results of the average wall heat flux on the cryostat inner wall, where the negative values of that case stood out (average wall temperature is lower than helium temperature). The highest wall heat flux was noted at the reference pressure 105 kPa and baking condition with a value of 342 W/m^2. For the analysis of the heat transfer coefficient (HTC) the average He gas temperature between cryostat wall and CTS was used. The results showed that the HTC increases with pressure and the highest values for both operating conditions were reached at reference pressure of 105 kPa (3.27 W/(m^{2}K) at normal conditions and 3.71 W/(m^{2}K) at baking conditions). The effect of no natural convection in the case of reference pressure 3 kPa can be seen yet again.

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