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WATER JACKETS AS EFFICIENT HEAT SHIELDS IN HIGH TEMPERATURE DIFFERENCE CASES – CFD MODELLING OF CONVECTIVE AND RADIATIVE HEAT TRANSFER IN VACUUM SYSTEMS

PŁASZCZ WODNY JAKO EFEKTYWNA IZOLACJA CIEPLNA W APLIKACJACH O DUŻEJ RÓŻNICY TEMPERATUR - MODELOWANIE CFD KONWEKCYJNEJ I RADIACYJNEJ WYMIANY CIEPŁA W SYSTEMACH PRÓŻNIOWYCH

Abstract

Many experimental high-energy installations, e.g. ITER (Cadarache), CERN (Geneva), SOLARIS (Krakow), require an ultra-high quality of vacuum. To meet these requirements, a vacuum void and its adjacent diagnostic systems are exposed to elevated temperatures (baking) after assembly to outgas all volatile surface contaminants. The baking temperature peaks as high as 250°C for up to 24 hours.

Keywords: vacuum systems, heat transfer, water jacket, heat shield

Streszczenie

W eksperymentalnych instalacjach wysokich energii, m. in ITER (Cadarache), CERN (Genewa), SOLARIS (Kraków), istnieje konieczność uzyskania próżni o wysokiej jakości. W tym celu przestrzeń próżniowa oraz znajdujące się w niej urządzenia diagnostyczne wystawiane są na bardzo wysokie temperatury by pozbyć się resztek zanieczyszczeń z układu. Podczas tego procesu wygrzewa się instalację w temperaturze dochodzącej do 250°C przez nawet 24 godziny.

Słowa kluczowe: system próżniowe, wymiana ciepła, płaszcz wodny, izolacja termiczna

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1. Introduction

The concept of a water jacket cooled by water, assumes that it is a sufficiently efficient heat shield. It serves as a thermal barrier between high and low temperature zones. The water jacket should be, as much as possible, thermally isolated from the high temperature structure. The most efficient thermal insulation system is based on a vacuum layer (one or more if needed) enclosed by surfaces characterised by their low thermal emissivity coefficient. In practical applications, the thermal barrier is not fully efficient in steady state conditions and gains heat from the adjacent hot walls. The excessive heat must be removed from the thermal barrier in order to maintain it at the required temperature and this is provided by cooling water circulating along walls of the thermal barrier. For less strict requirements and also for reasonably low temperature differences between hot and cold regions, the heat shield is often designed as a metal shield made of material which is characterised by its high thermal conductivity [1]. The temperature of the heat shield is controlled by water circulating through loops of pipes which are attached to the external or internal surfaces of the heat shield. For more thermally loaded cases and also for high thermal requirements, the only efficient solution is the one based on the water jacket concept.

The aim of proposed paper is to compare the efficiency of the multilayer insulation thermal shield structures, based on the water jacket concept, by the use of 3D CFD simulation in ANSYS Fluent software. The surface-to-surface (S2S) model is applied to simulate heat transfer by radiation. In addition, the paper includes discussion about multilayer solutions, characterised by a high thermal resistance, and particularly dedicated to vacuum transfer lines with high temperature differences.

2. Water Jacket Geometries

The water jacket geometries for the comparison between single- and double-layer vacuum solutions have been modelled in the Autodesk Inventor software. The layout of the single-layer vacuum system is shown in Figure 1.

The water jacket layout is based on two axisymmetric cylinders made of stainless steel, one inserted into the other forming a thin layer between the walls which is filled with circulating water. An internal space, within the internal cylinder (1) is allotted for the installation of diagnostic instruments. It is assumed that the inner wall (0) of the internal cylinder (1) is ideally thermally connected with diagnostic instruments; thus, their temperatures are considered to be the same. The temperature of the internal cylinder is regulated by the temperature of the circulating water (2). It is assumed that all diagnostic instruments are thermally connected with the internal cylinder (1) and the entire thermal load is absorbed by the water (2) through the internal cylinder (1). The middle cylinder (3) absorbs the heat by radiation, through the vacuum (4) layer, emitted by the adjacent surfaces of the external shell (5). Moreover, the supporting elements (6) are indispensable to fix the water jacket, however they constitute additional thermal bridges. In the proposed solution, the supporting elements are formed in a pattern of full length rectangular rods, parallel to the axis of the water jacket cylinders. To ensure thermal resistance of the proposed solution, the emissivity coefficient of walls adjacent to the vacuum should be as low as possible and the number, size and thermal conductivity of the supporting elements should be minimised. It is conservatively assumed that four full-length supporting elements (6) is the maximum number and size and in the final design phase, it would be reduced. The double-vacuum layer water jacket layout is presented in Figure 2.

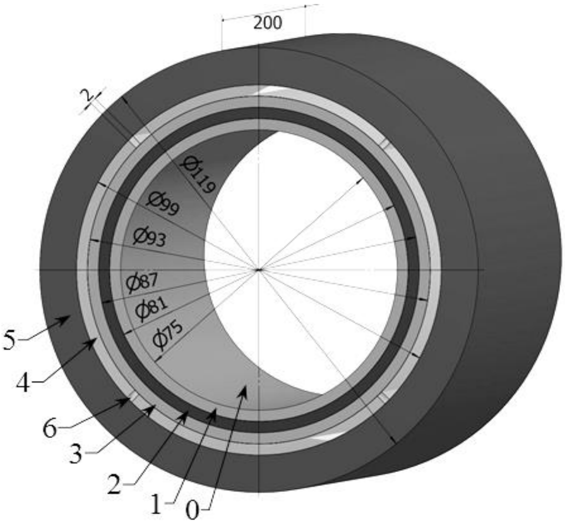

Fig. 1. Concept of the water jacket with single-layer vacuum

The water jacket zone names and basic dimensions are presented in Table 1.

Table 1

The water jacket with single-layer vacuum - zone names and basic dimensions

No	Name	Dimension [mm]	Description
0	Inner Wall	75	Diameter
1	Internal Cylinder	3	Thickness
2	Water	3	Thickness
3	Middle Cylinder	3	Thickness
4	Vacuum	3	Thickness
5	External Shell	10	Thickness
6	Supporting Element	2	Width

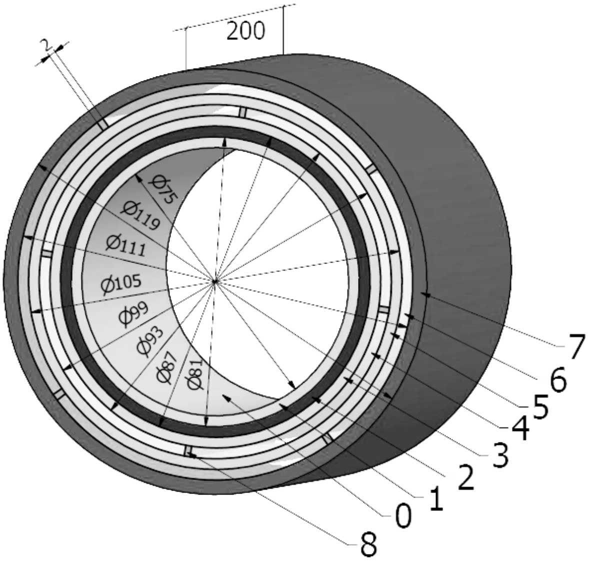

Fig. 2. The water jacket with double-layer vacuum

The double-layer solution is founded on the single-layer water jacket concept. Zone names and basic dimensions are presented in Table 2.

Table 2

The water jacket with double-layer vacuum - zone names and basic dimensions

No	Name	Dimension [mm]	Description
0	Inner Wall	75	Diameter
1	Internal Cylinder	3	Thickness
2	Water	3	Thickness
3	Middle Cylinder	3	Thickness
4	First Vacuum layer	3	Thickness
5	External Cylinder	3	Thickness
6	Second Vacuum layer	3	Thickness
7	External Shell	3	Thickness
8	Supporting Element	2	Width

Most of the features and components of the double-layer vacuum solution are the same as in the single-layer concept. As an additional component, it contains the external cylinder (5), separating two vacuum layers (4 and 6), all located outside of the water layer (2). The external cylinder (5) and the second vacuum layer (6) are inserted by removing the internal fragment of the external shell (7). The external cylinder (5) is supported on both sides by two sets of four evenly distributed supporting elements (8). The second set of supporting elements is orientated at an angle of 45° relative to the first set in order to minimise heat transfer by thermal conduction.

3. Boundary conditions and numerical model

All CFD simulations have been performed with the ANSYS Fluent software. Numerical meshes in both geometries were generated by the sweep method. The 3D mesh of the single-layer vacuum model is presented in Figure 3. The global boundary conditions and material properties are listed in Table 3.

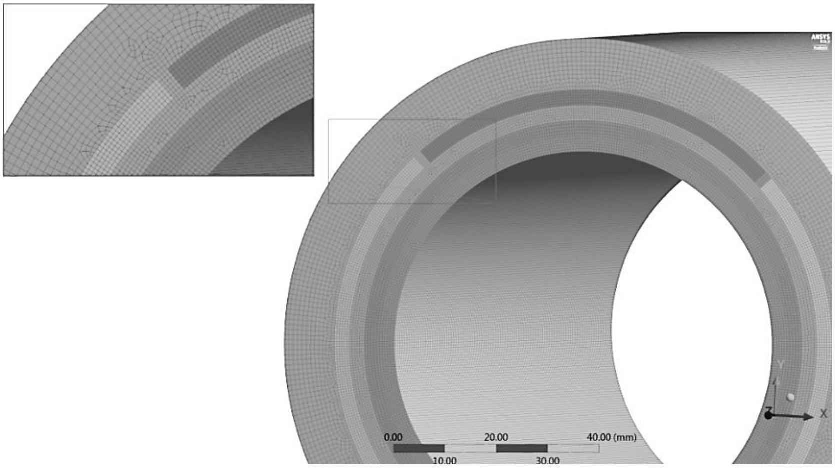

Fig. 3. 3D structural mesh

Table 3

Global boundary conditions and material properties

Boundary condition	Value
Inlet Water Temperature	293 K
External Shell Temperature	513 K
Heat load from diagnostic instruments	2 W
Water Inlet Velocity	0.5 [m/s]
Internal radiation emissivity coefficient	0.5
Material of all structural components	Stainless Steel 316L
Thermal conductivity (316L)	16.27 W/mK
Cooling Water properties	Demineralised water, reference pressure 1 atm
Vacuum properties	Vacuum: air at constant density, max. 10 Pa

The major heat transfer rate to the water jacket is transferred from the external shell to the external cylinder, by radiation, surface to surface, and locally by thermal conduction through the supporting elements. It is assumed that the contribution of thermal conduction and convection effects to the overall heat transfer through the vacuum layer is negligible [2], this is mainly due to the extremely low density of the gas and the thin vacuum gap.

The additional minor heat load, generated by diagnostic instruments during their operation is a maximum of 2 watts. Diagnostic instruments are located in the space within the inner wall (0). In the simulation, it is defined as a constant heat flux boundary condition on the inner wall of the internal cylinder.

According to ANSYS Fluent Documentation [3], the recommended optimal numerical models are as follows:

- pressure based, steady-state model for flow calculations;
- k-ε realisable turbulence model;
- surface-to-surface radiation model.

4. Simulation results comparison

Preliminary calculations indicate, assuming that layout and dimensions are constant, that the influence of three parameters is dominant: water flow rate, internal emissivity and the thermal conductivity of solid materials. The above mentioned parameters are defined in the simulation task as constant boundary conditions and material properties.

Steady-state simulation results are very promising and indicate that the idea of the heat shield by the water jacket is very effective in both cases. Temperature contours on the symmetrical (in the middle of the length) cross-sections and selected walls are shown in Figure 4. The temperature of the internal cylinder (1) is, in both cases, uniformly maintained at a low level, close to the temperature of the water. The high temperature gradient, particularly in the supporting elements (6) of the single-layer vacuum layout, may generate thermal stress problems. This effect should be studied later, during the final design stage.

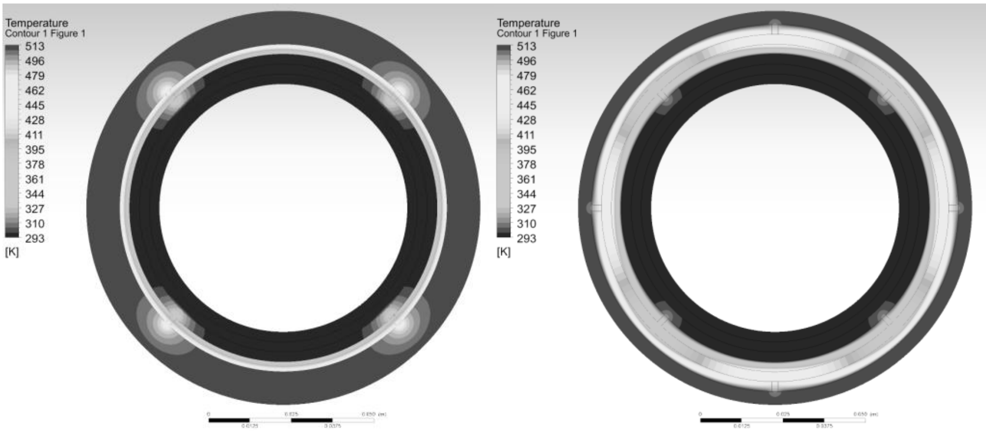

Fig. 4. Temperature contours at cross section: a) single-layer Vacuum layout, b) double-layer Vacuum layout

For more strict thermal requirements, e.g. narrow range of acceptable temperature, the impact of the supporting elements may cause problems with thermal uniformity. Contours of temperature along the inner wall (0) are shown in Figure 5.

The entire water jacket is of almost uniform temperature, with the exception of regions with direct solid-to-solid contacting areas by the supporting elements. The temperature rise is 0.6 K in the single-layer vacuum layout and 0.3 K in the double-layer vacuum layout.

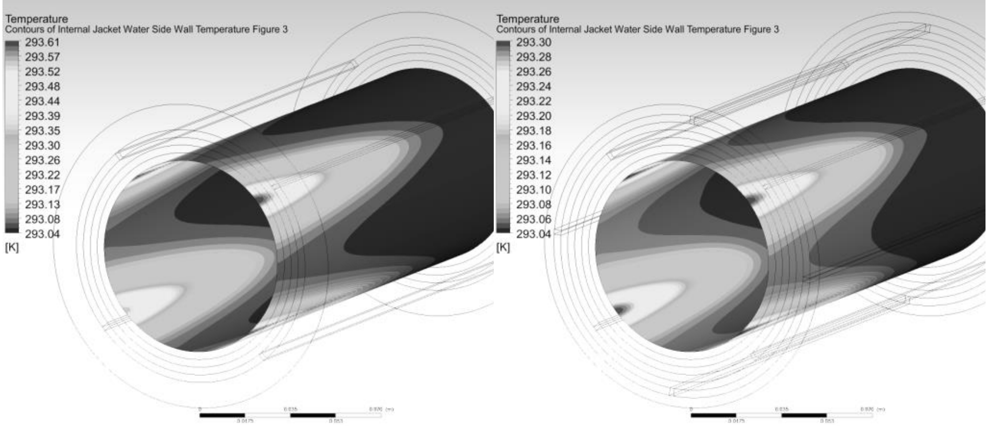

Fig. 5. Temperature contours on the inner wall (0) of: a) single-layer vacuum layout, b) double-layer vacuum layout

There are two possible ways to limit heat transfer by conduction through the supporting elements – by using insulating materials with low thermal conductivity and/or by limiting the thermal contact area; for instance, the quantity and length of the supporting elements can be limited.

Contours of temperature along the middle cylinder (3) and the supporting elements (6, 8) are shown in Figure 6.

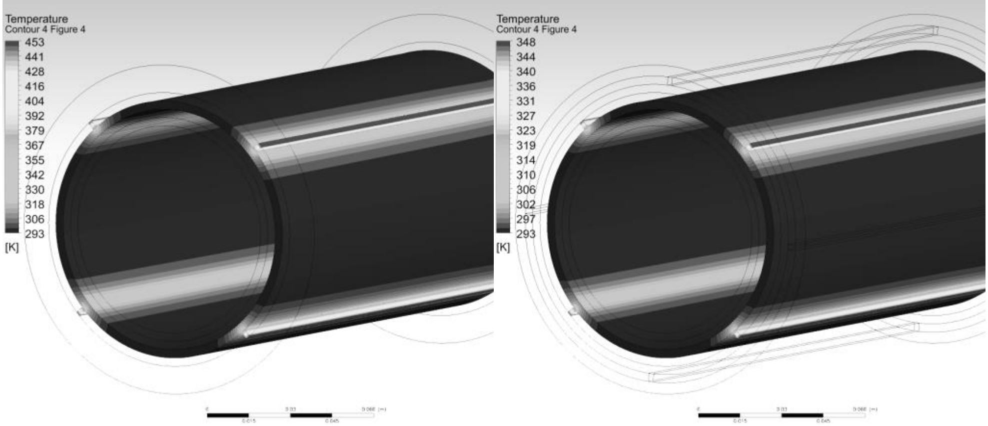

Fig. 6. Temperature contours on the middle cylinder (3) of: a) single-layer vacuum layout, b) double-layer vacuum layout

The analysis of both cases in Figure 6 shows that the influence of the intermediate element – the external cylinder (5) is extremely positive and the double-layer vacuum layout may be chosen as a final solution. The double-layer vacuum layout in principle solves the problem of high temperature gradient, decreasing temperature by around 100 K. Moreover, it allows the decreasing of the overall heat transfer by around three times. The final results are shown quantitatively in Table 4.

Table 4

Final quantitative results – comparison both layouts

Name	**Single-layer Vacuum layout**	**Double-layer Vacuum layout**
Water Mass flow Rate [kg/s]	0.000396	0.000396
Increase of Water Average Temp. [K]	0.5	0.2
Increase of Inner Wall (0) Average Temp. [K]	0.6	0.3
First Vacuum (4) – Radiative Heat Transfer Rate W]	63.5	24.6
First Vacuum (4) – Conductive Heat Transfer Rate through the Supporting Elements [W]	691	242
Total Heat Transfer Rate [W]	756.5	268.6

A particularly important conclusion derived from Table 4 is that it is strongly recommended to restrict the heat transfer by conduction through the supporting elements since their contribution to the overall heat transfer is dominant.

5. Conclusions

The double-layer vacuum layout is significantly more effective as a thermal barrier. The overall heat transfer dropped from 691 W in the single-layer layout to 242 W in the double-layer layout. Additionally, the temperature of the inner wall (0) can be better controlled and maintained more uniformly in the narrow range. However, there is the possibility of further limitation of heat transfer through the water jacket and in consequence the cooling demand. There are several possible ways to decrease the heat transfer occurring as a result of conduction through the supporting elements by:

1. using low-thermal-conductivity insulating materials;
2. limiting the thermal contact area;
3. limiting the number and length of the Supporting Elements.

It is strongly recommended to take into consideration the above mentioned recommendations, since their influence on the overall heat transfer is dominant. Moreover, the contribution of the radiative heat transfer (see Table 4) to the overall heat transfer should be limited by applying a special surface finish.

References

[1] Kantor, R., *Optimization of the LUCID detector heat shield cooling*, 20th International Conference of Process Engineering and Chemical Plant Design, Berlin 2014, 165-177.

[2] *VDI Heat Atlas Second Edition*, Springer-Verlag, Berlin-Heidelberg 2010.

[3] ANSYS Fluent Documentation, v. 16.0.