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MODELING OF HEAT FLOW THROUGH MULTILAYER INTERNAL SUPPORTS OF CRYOGENIC VESSELS

MODELOWANIE PRZEPŁYWU CIEPŁA PRZEZ WIELOWARSTWOWE PODPORY MIĘDZYPŁASZCZOWE W ZBIORNIKACH KRIOGENICZNYCH

A b s t r a c t

The article presents the issue of heat flow through internal supports of double-walled cryogenic vessels. The influence of the thermal resistance at the contact plane between supports and vessel materials is discussed. A simulation of heat flow through the support multilayer made of plastic is presented. The simulation takes into account the influence of temperature and local contact pressure on the thermal resistance.

Keywords: *cryogenic, double-walled vessel, internal support, contact thermal resistance*

S t r e s z c z e n i e

W artykule przedstawiono zagadnienie przepływu ciepła przez wewnętrzne podpory dwupłaszczowych zbiorników kriogenicznych. Omówiono wpływ oporu cieplnego w miejscu styku materiałów podpór i zbiornika. Przedstawiono symulację przepływu ciepła przez podpory wielowarstwowe wykonane z tworzyw sztucznych. W symulacji uwzględniono wpływ temperatury i lokalnej wartości nacisku powierzchniowego na opór cieplny.

Słowa kluczowe: *kriogenika, zbiornik dwupłaszczowy, podpory wewnętrzne, kontaktowy opór cieplny*

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1. Introduction

Cryogenic vessels have been widely used in the industry and medicine for a long time. Currently, due to the increased interest in the liquefied natural gas LNG, an interest in modern constructions of both fixed and mobile tanks is growing. In the Institute of Applied Informatics, Faculty of Mechanical Engineering at the Cracow University of Technology in cooperation with Works of Chemical Equipment CHEMET SA a number of studies on double-walled cryogenic vessels with vacuum insulation was conducted. Figure 1 shows one of these structures – a tank container for LNG transportation and storage. As part of this work, series of articles on the analysis of heat flow through the insulation fibre [3, 5], as well as on the inner tank mounting structure in the outer tank [4–7] were published. In the further part of the article internal tank mounting elements are referred to as internal supports. This article focuses on the possibility of improving the thermal insulation of internal supports by the use of a multi-layer structure.

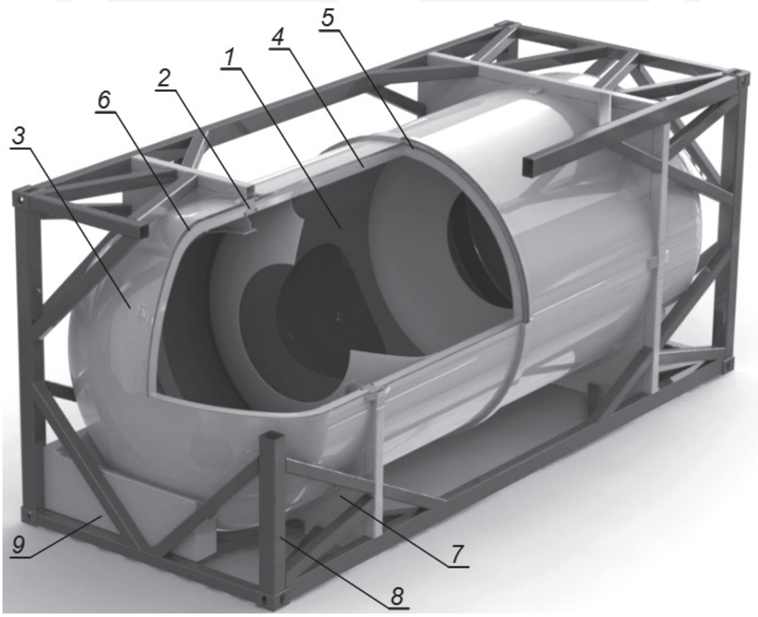


Fig. 1. Model of the LNG tank container for LNG transportation and storage [3]: 1 – inner tank, 2 – inner supports made of plastic materials, 3 – outer tank, 4 – insulation, 5 – radiation shields, 6 – the vacuum, 7 – outer supports, 8 – container frame, 9 – fittings

In general, the amount of heat inflowing the cryogenic tank through internal supports depends on:
– a height and cross-sectional area of the internal supports,
– a thermal conductivity of the internal support material,
– a contact thermal conductivity between internal supports and walls of the tank.

Issues associated with selection of materials for internal supports, their dimensions, and a cross-sectional shape of the supports are widely discussed in the Katarzyna Głowik-Łazarczyk doctoral dissertation [7]. However, issues related to the use of the contact thermal conductivity phenomenon and multi-layer support structures have not been developed in that work.

2. Heat flow through supports

If a permanent contact between the internal supports and the walls of the tank and between the individual layers of the multi-layer is assumed, as well as thermal insulation of the side walls with the use of radiation shields and vacuum insulation, some simplifications in the heat flow model can be made. Considering the typical heat transfer mechanisms such as conduction, convection and radiation, in this case convection and radiation are insignificant.

2.1. Conductive heat transfer

The basic, essential for the internal support, heat flow method is the conduction described by the Fourier equation. Due to the large temperature differences and an analysis of a three-dimensional model, the full form of the equation [1, 2] is assumed:

$$\mathbf{q} = -\lambda \nabla T \tag{1}$$

where:

- $\mathbf{q}$ – the local heat flux density,
- λ – the material's conductivity,
- ∇T – the temperature gradient.

2.2. Contact conductivity

The heat flow through the element consisting of two parts of the same material causes a temperature difference at the contact surface. The difference does not exist if there is no parting plane. This temperature difference is a result of the contact thermal conductivity phenomenon (or its inverse which is the contact thermal resistance). The contact conductance of a single gap decreases with the decrease of pressure forces, and it is also dependent on the hardness of the contact pair materials and the medium which fills the gap in the contact surface. A general relationship presented by Furmański and others [2] has the following form:

$$R_c = \left(\left[1.25 \cdot k_s \cdot \frac{m}{\sigma} \left(\frac{P}{H} \right)^{0.95} + \frac{k_g}{Y + M} \right] \cdot A_\alpha \right)^{-1} \tag{2}$$

where:

- k_s – harmonic mean of the thermal conductivity of the two contacting bodies,
- m – total contact area,

σ – effective contact surface of solids,
P – contact pressure,
H – hardness of the softer of the materials in contact,
k_g – thermal conductivity of the medium filling the gap,
Y – the distance between the surface of solids in the cross-section slot,
M – parameter characterising the gas in the gap in terms of its density.

The equation (2) is difficult in practical use. Part of the parameters set out in equation (2) as k_s, k_g, H, M varies with temperature changes. Thus, due to large temperature differences which occur in the cryogenic constructions, these changes must also be taken into account. The article considers a case based on the structures of polyamide supports cooperating with shells made of stainless steel and carbon steel. Because of the similarity of the structure to simulation studies of the multi-layer internal supports, contact conductivity coefficients determined in papers [5 and 7] are applied. Figure 2 shows dependence of the contact conductivity on the contact surface average temperature.

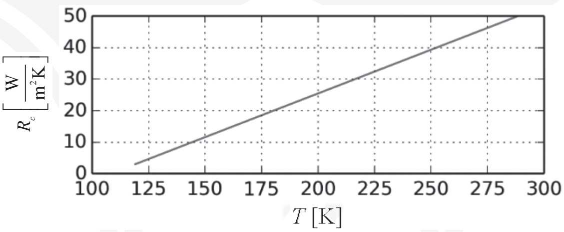


Fig. 2. Dependence of the contact conductivity against the average temperature of the contact surface determined on the basis of [5, 7]

3. Geometrical model

Due to the weakening of the structural stability of the support caused by division into multiple layers, it was assumed, that the shape of the support will be simple, with a constant section. As demonstrated in [7], in the case of such supports, the difference between different shapes may reach 4%, and a rectangular cross section with an aspect ratio of 1:4 is the most preferred one. This shape was adopted to study the multilayer supports.

Dimensions of the support (Fig. 3) were set to 50 × 200 × 100 mm (WxLxH) as stated in [7]. The minimum thickness of the polyamide layer was set to 4.75 mm, the layers were separated from each other by the stainless steel 0.25 mm thick plates. In the version with a maximum number of layers (15), a monolithic block with a thickness of 25 mm is left. The block is designed to hide the heads of the bolts.

At the beginning of the heat flow analysis the following assumptions were made:
– cryogenic medium: liquid nitrogen,
– the temperature of the cryogenic medium in the container 73 K,
– the ambient temperature of 293 K,
– cryogenic tank material: stainless steel 1.4301,

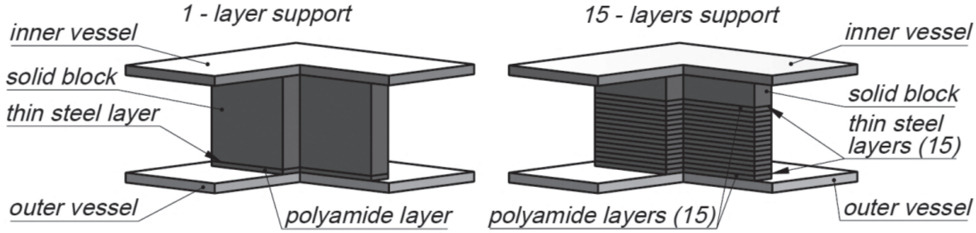


Fig. 3. Simplified simulation model to study the multi-layer support (section without quarter). On the left model with a single layer, on the right model with a maximum number of layers – 15

– shielding container material: constructional steel P355NL1,
– internal support material: PA6,
– omitted details of attachment of the support to the reservoir,
–omitted thin steel spacers in the FEM model, replaced by the appropriately defined contact surface.

4. FEM model and simulations

FEM model was prepared in the Abaqus CAE system. A fully coupled thermal-stress analysis was chosen. Elements of type C3D8T (*an 8-node thermally coupled-hexadron-brick, trilinear displacement and temperature*) were used.

A simplified model is characterized by the symmetry in two directions, also the load and the boundary conditions are symmetrical in these directions. Therefore, the analysis was carried out using a quarter of an appropriate model. On the section walls were inserted the corresponding symmetry conditions. The outer tank was fixed on the sides and loaded from the outside by the atmospheric pressure. The inner wall of the inner tank was loaded by the internal pressure and the force coming from the weight of the load. These loads correspond to the real load values of the supports under typical operating conditions. Referring to the thermal boundary conditions, the following assumptions were made [7]:
– on the walls in contact with the cryogenic liquid on the natural convection of transmittance values 337 W/(m^2 K) at a constant fluid temperature 73 K is presented,
– on the walls in contact with the air the natural convection of with a transmittance values 8.98 W/(m^2 K) at a constant ambient temperature of 293 K is presented,
– adopted vacuum insulation, heat exchange by radiation and convection is omitted.

Between the layers of the inner support, mechanical and thermal contact was defined. Coefficient of contact conductivity was made dependent on the temperature and contact pressure (Abaqus options: *Surface to surface contact, thermal conductance, Use only pressure-dependency data, temperature-dependent Use date*). The temperature dependence was created using the data shown in Fig. 2. It was also assumed that the full value of the contact conductance is achieved for contact pressure of 15 MPa, and it disappears in the absence of contact pressure. Spatial distributions of temperature for 1-layer and 15-layer models are shown in Fig. 4.

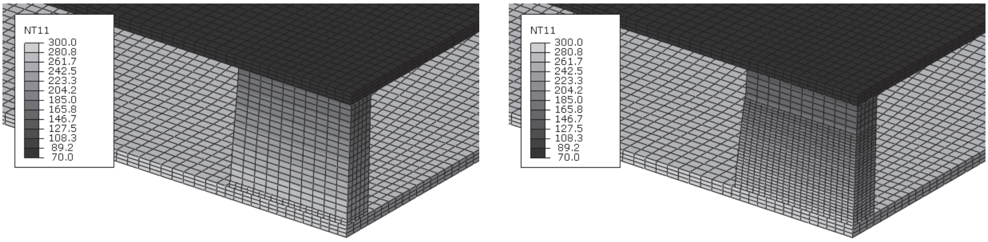
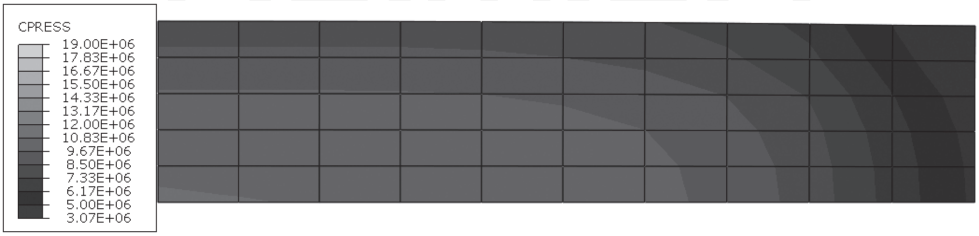


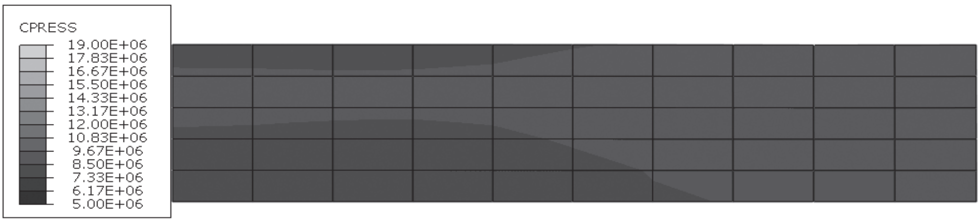
Fig. 4. Spatial distribution of temperature (*NT11 parameter*) on 1-layer support (left) and 15-layer support (right)

It was noted that an additional advantage of the multi-layer supports is a more uniform distribution of contact pressures on the support pillars and the max value decreases when the layer number is increasing (Fig. 5a and b). This fact allows to reduce their cross sections. Therefore, a reduced support version was created. The support length was decreased from 200 mm to 160 mm. This version 15 lay min for calculation was named.

a)



b)



c)

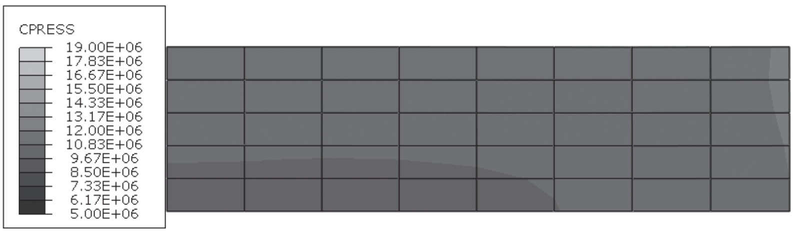


Fig. 5. Contact pressure distribution [Pa]: a) *1 layer* version, b) *15-layers* – before support reduction, c) *15-layers-min* –after support reduction

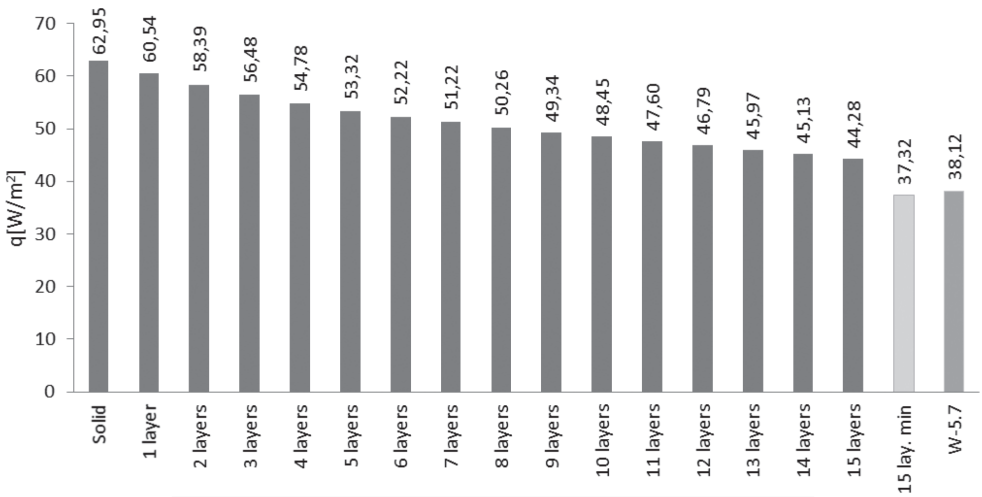


Fig. 6. Heat flux comparison for various number of supports: from *solid* to *15 layers*. Item *15 lay. min* – 15 layer support with reduced length. Item W-5.7 represents a solid support with holes analysed in work [7]

After performing simulations in the Abaqus CAE system, the average values of heat flux on the same parts of the outer wall of the external tank were calculated. The results obtained for both solid and the multi-layered supports are summarized in Fig. 6. Furthermore, the average value of the heat flux obtained on an identical simulation model for the best case presented in [7] (named W-5.7), was added.

The best result was achieved with the largest number of layers, equal to 15. This allows reduction in heat flux of about 30%. It can be seen that the improvement is significant, although it is slightly less than achieved for the best variant in [7], which was 38%. In the case of reduced support, the heat flux decreased to 37.32 W/m^2, which is almost the same value as for W-5.7, and the maximum contact pressure increased to the value of 16.9 MPa (Fig. 5c), which is still less than the maximum value for the W-5.7 variant (20.5 MPa) [7].

5. Conclusion

This paper presents a model of a multi-layer polyamide-metal support designed for supporting an internal tank of a double-walled cryogenic container. These structures are developed by Chemet SA in scientific cooperation with the Institute of Applied Informatics at Cracow University of Technology. As part of the work, strength and thermal calculations of the support were performed. The values of the heat flux between the inner and the outer tank for different support variants were determined. The results were compared to those obtained with monolithic supports with holes as described in [7].

The proposed support is characterized by a similar thermal insulation as a monolithic support with holes. However, the presented solution has several advantages, including a more uniform distribution of contact pressures on the outer surfaces and the possibility of creating a structure comprising different materials in different layers. The latter feature is particularly important because it allows the designer to apply a layer of more expensive material, which has lower thermal conductivity than the polyamide (PVDF, PEEK), without a substantial increase of the total support cost. Also the pressure distribution is more advantageous, which allows reduction of the support cross-section. Thus, it is possible to further improve its insulating properties.

A significant problem in the work carried out on the construction of cryogenic tanks was relatively low availability of material parameters under cryogenic conditions, especially contact thermal conductivity coefficients. Therefore, further studies are needed in order to determine properties of newly constructed structure supports more accurately.

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