

A METHOD FOR EVALUATING THERMAL TRANSFER THROUGH CONVECTION AND CONDUCTION IN LAYERED COMPOSITES

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Abstract. This paper presents the mathematical expressions for calculating the temperatures between the layers of a plan, tubular or spherical composite, by natural or forced conduction and convection or under the influence of stationary heat flow. Here there are taken into account two possibilities of contact between the layers: one is the perfect contact or the other acknowledges the existence of casual imperfections. The expressions also take into consideration the influence of added protection on the wall surface or the possible deposits of solids materials that can occur during the operation of the structure.

Keywords: layered composite, thermal conduction, thermal convection

1. INTRODUCTION

At this moment of time there is an increasingly stringent need of finding cheaper and more reliable replacements for materials used in the industrial equipment areas (process industries [1-5], aerospace [6-9], above ground or underwater transport industry [10-12], military industry [13-15], medical domain [16, 17] etc.) due to the economical crises but also because our material resources are limited. These replacements have to take into consideration the functional parameters which are increasing in intensity more and more but also that the working environment is sometimes very aggressive. It is expected of these new materials to have a higher bearing capacity while reducing the masse of the structure. In this category of materials the laminated composites and plated structures have an important place due to their success in complying with the above requirements.

In operation in this type of structures thermal processes occur and they can create extra loadings on the system. In this case, it is important to know the temperatures developed during operation between the layers of the material in either perfect or imperfect contact between layers. This paper addresses, in the current context, the thermal transfer determined through convection and conduction in plane, tubular or spherical layered walls. Among this study the case of added protection or random deposits it is also analyzed because of the negative impact it has on the heat transfer through the wall.

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Here, this method offers the possibility of deciding the geometry of the layers, the number of layers and the nature of the chosen material for the specific layer to determine the inside temperature and also the outside temperature of the wall. Another way of studying these materials is by knowing the inside temperature and the thermal flow value for a specific layered wall and then to determine the outside wall temperature or the temperature of the outside environment convenient for the given technological process.

2. EXPRESSIONS OF THE TEMPERATURES BETWEEN LAYERS

The practical situations show that the mono-or multilayer walls are subjected on the inner and outer surface to the influence of convection. The convection coefficients, on the warm side, α_i , and on the cold side, α_e will be introduced in the mathematical expressions.

Knowing that T_i, T_e , are the temperatures near the wall, on each side of the limit layers (from the warm and the cold zone), in stationary regime, the expressions for the temperatures can be deduced from the wall surfaces.

2.1. Plane wall

2.1.1. Monolayer plane wall – Figure 1a

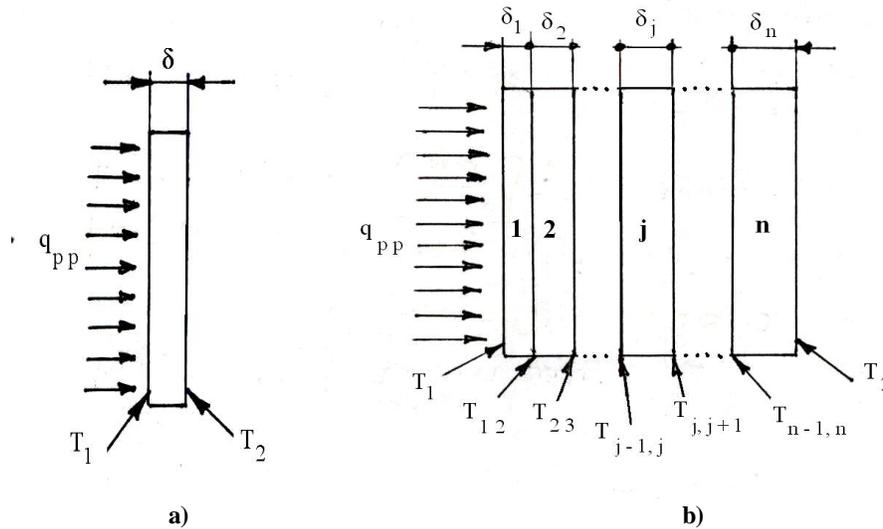


Fig. 1. Thermal transfer in a plane wall: a - monolayer wall; b - multilayer wall.

For a wall with δ thickness and λ thermal conductivity, unprotected and without industrial deposits, with T_i temperature at the inner surface, respectively T_e at the outer surface, we can write the following:

$$q_{pp} = \alpha_i \cdot (T_i - T_1) = \alpha_e \cdot (T_2 - T_e) = \frac{\lambda}{\delta} \cdot (T_1 - T_2) = k_1 \cdot (T_1 - T_2) = k_1 \cdot \Delta T \tag{1}$$

or:

$$q_{pp} = \frac{T_i - T_1}{\frac{1}{\alpha_i}} = \frac{T_1 - T_2}{\frac{\delta}{\lambda}} = \frac{T_2 - T_e}{\frac{1}{\alpha_e}} = \frac{T_i - T_e}{\frac{1}{\alpha_i} + \frac{\delta}{\lambda} + \frac{1}{\alpha_e}} = \frac{T_i - T_e}{\mathfrak{R}_{T_1}} \tag{2}$$

by using the proportions property. The wall surfaces temperatures are derived as:

$$T_1 = \left(1 - \frac{1}{\alpha_i \cdot \mathfrak{R}_{T_{12}}}\right) \cdot T_i + \frac{1}{\alpha_i \cdot \mathfrak{R}_{T_{12}}} \cdot T_e ; T_2 = \frac{1}{\alpha_e \cdot \mathfrak{R}_{T_{12}}} \cdot T_i + \left(1 - \frac{1}{\alpha_e \cdot \mathfrak{R}_{T_{12}}}\right) \cdot T_e \quad (3)$$

2.1.2. Multilayer plane wall, without imperfections between layers – Figure 1b

For such a wall, with **close (perfect) contact** between the n layers, with δ_j thicknesses and λ_j thermal conductivities, similar to the previous case, we can write:

$$q_{pp} \cdot = \frac{T_i - T_1}{1/\alpha_i} = \frac{T_1 - T_{1,2}}{\delta_1/\lambda_1} = \frac{T_{1,2} - T_{2,3}}{\delta_2/\lambda_2} = \dots = \frac{T_{j-1,j} - T_{j,j+1}}{\delta_j/\lambda_j} = \dots$$

$$\dots = \frac{T_{n-1,n} - T_2}{\delta_n/\lambda_n} = \frac{T_2 - T_e}{1/\alpha_e} = \frac{T_i - T_e}{\mathfrak{R}_{T_2}} \quad (4)$$

where T_1 and T_2 are the characteristic temperatures of the wall, so, based on the proportions property, it can be established that:

$$\mathfrak{R}_{T_2} = (1/\alpha_i) + \sum_{j=1}^n (\delta_j/\lambda_j) + (1/\alpha_e) \quad (5)$$

The following correspondence can be easily distinguished [23]:

$$\alpha_i = \lambda_{s11} / \delta_{s11} ; \alpha_e = \lambda_{s12} / \delta_{s12} \quad (6)$$

where $\lambda_{s11}, \lambda_{s12}$ [19 - 26] represent the thermal conductivity coefficients of the fluid/fluids of the limit layers from the inside (1) and the outside (2) of the wall; $\delta_{s11}, \delta_{s12}$ - are the thicknesses/widths of the limit layers, which are characterized by free /natural convection or forced convection, on one side or on both sides.

The equalities (11) provide an opportunity to assess the intermediary surface temperatures, T_i and T_e being known values then:

$$T_1 = \left(1 - \frac{1}{\alpha_i \cdot \mathfrak{R}_{T_2}}\right) \cdot T_i + \frac{1}{\alpha_i \cdot \mathfrak{R}_{T_2}} \cdot T_e \quad (7)$$

$$T_{1,2} = T_1 - \frac{\delta_1}{\lambda_1 \cdot \mathfrak{R}_{T_2}} \cdot (T_i - T_e) \quad (8)$$

.....

$$T_{j,j+1} = T_{j-1,j} - \frac{\delta_j}{\lambda_j \cdot \mathfrak{R}_{T_2}} \cdot (T_i - T_e) ; j \in \{1, \dots, n-1\} \quad (9)$$

$$T_{n,n+1} = T_2 = \frac{1}{\alpha_e \cdot \mathfrak{R}_{T_2}} \cdot T_i + \left(1 - \frac{1}{\alpha_e \cdot \mathfrak{R}_{T_2}}\right) \cdot T_e \quad (10)$$

2.1.3. Multilayer plane wall, with imperfections between layers

In the case of **imperfections** existing between the layers of the wall, the equality (12) becomes:

$$\mathfrak{R}_{T3} = \frac{1}{\alpha_i} + \sum_{i=1}^n \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_e} + \sum_{j=1}^{m_i} \mathfrak{R}_{c,j} \quad (11)$$

and when there are **additional deposits** on the initial wall surfaces then:

$$\mathfrak{R}_{T4} = \frac{1}{\alpha_i} + \sum_{i=1}^n \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_e} + \sum_{j=1}^{m_i} \mathfrak{R}_{c,j} + \mathfrak{R}_{p,i} + \mathfrak{R}_{d,i} + \mathfrak{R}_{p,e} + \mathfrak{R}_{d,e} \quad (12)$$

$\mathfrak{R}_{c,j}$, $\mathfrak{R}_{p,i}$, $\mathfrak{R}_{p,e}$, $\mathfrak{R}_{d,i}$, $\mathfrak{R}_{d,e}$ being the thermal resistances of the area with imperfections, of the protections to the inside and the outside, but also the thermal resistances of the deposits; $1 \leq m_i \leq (n - 1)$, m_i represents the number of imperfections found in the wall.

$$\sum_{j=1}^{m_i} \mathfrak{R}_{c,j} = \sum_{j=1}^{m_i} \frac{h_{r,e,j} + h_{r,i,j+1}}{\lambda_{j,j+1}}; \quad \sum \mathfrak{R}_p = \mathfrak{R}_{p,i} + \mathfrak{R}_{p,e} = \delta_{p,i} / \lambda_{p,i} + \delta_{p,e} / \lambda_{p,e} \quad (13)$$

$$\sum \mathfrak{R}_d = \mathfrak{R}_{d,i} + \mathfrak{R}_{d,e} = \delta_{d,i} / \lambda_{d,i} + \delta_{d,e} / \lambda_{d,e} \quad (14)$$

with: $h_{r,e,j}$ – the maximum size of the roughness on the outer surface of the layer j ; $h_{r,i,j+1}$ – the maximum size of the roughness from the inner surface of the layer $j + 1$; $\lambda_{j,j+1}$ – the thermal conductivity of the area with imperfections; $\delta_{p,i}$, $\delta_{p,e}$ – the thicknesses of the protection layers; $\lambda_{p,i}$, $\lambda_{p,e}$ – the thermal conductivities of the protection layers; $\delta_{d,i}$, $\delta_{d,e}$ – the thicknesses of the deposited layers; $\lambda_{d,i}$, $\lambda_{d,e}$ – the thermal conductivities of the deposited layers.

Note: The equalities (7) - (10) can also be used in the case of imperfections between layers or protection layers and/or deposits, in which case \mathfrak{R}_{T2} the total thermal resistance is replaced with \mathfrak{R}_{T3} or \mathfrak{R}_{T4} .

2. 2. Tubular/cylindrical wall

2. 2. 1. Monolayer tubular/cylindrical wall – Figure 2a

Taking into account the equality of **the thermal power**, q_{pc}^* , [W / m] in the layers where the convection occurs and on the thickness of the monolayer cylindrical wall, we can write [27]:

$$q_{pc}^* = \frac{T_i - T_1}{\frac{1}{\pi \cdot \alpha_i \cdot d_{i1}}} = \frac{T_1 - T_2}{\frac{1}{2 \cdot \pi \cdot \lambda} \cdot \ln \frac{d_e}{d_i}} = \frac{T_2 - T_e}{\frac{1}{\pi \cdot \alpha_e \cdot d_e}} = \frac{T_i - T_e}{\mathfrak{R}_{T5}} \quad (15)$$

where:

$$\mathfrak{R}_{T5} = \frac{1}{\pi \cdot \alpha_i \cdot d_i} + \frac{1}{2 \cdot \pi \cdot \lambda} \cdot \ln \frac{d_e}{d_i} + \frac{1}{\pi \cdot \alpha_e \cdot d_e} \quad (16)$$

d_i and d_e representing the inner and the outer diameter of the sphere.

The temperatures at the inner and the outer surface level of the wall are dependent on the T_i and T_e (assumed as known) so then their expressions are:

$$T_1 = \left(1 - \frac{1}{\pi \cdot \alpha_i \cdot d_i \cdot \Re_{T5}} \right) \cdot T_i + \frac{1}{\pi \cdot \alpha_i \cdot d_i \cdot \Re_{T5}} \cdot T_e \tag{17}$$

$$T_2 = \frac{1}{\pi \cdot \alpha_e \cdot d_e \cdot \Re_{T5}} \cdot T_i + \left(1 - \frac{1}{\pi \cdot \alpha_e \cdot d_e \cdot \Re_{T5}} \right) \cdot T_e \tag{18}$$

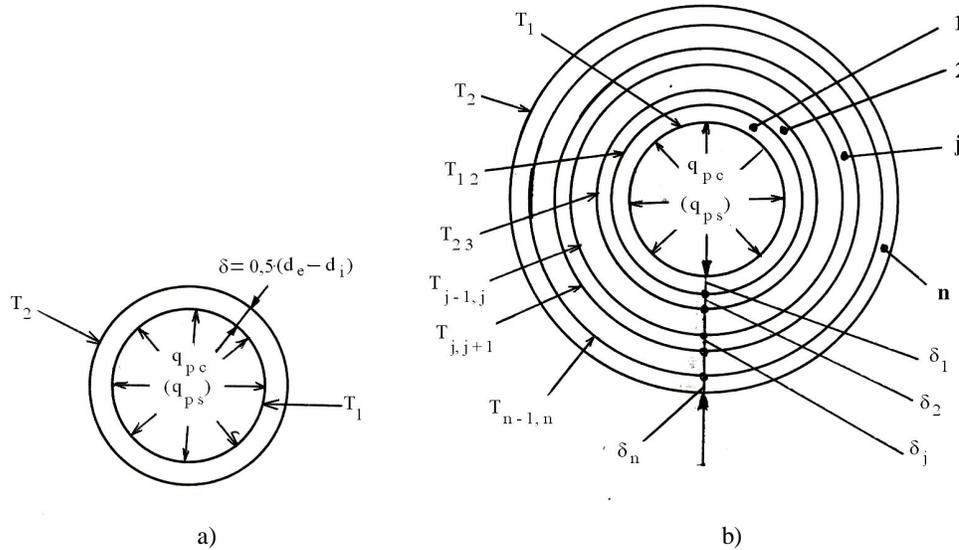


Fig. 2. Thermal transfer in cylindrical or spherical wall: a – monolayer wall; b – multilayer wall.

2. 2. 2. Multilayer tubular/cylindrical wall - Figure 2b, without imperfections between layers

For this type of wall, subjected to the action of a stationary thermal field and characterized by T_i interior temperature and T_e the exterior temperature of the environment, the **thermal power** can be estimated by the equalities:

$$\begin{aligned} q_{pc} \dots &= \frac{T_i - T_1}{1} = \frac{T_1 - T_{1,2}}{2 \cdot \pi \cdot \lambda_1 \cdot \ln \frac{d_{e1}}{d_{i1}}} = \frac{T_{1,2} - T_{2,3}}{2 \cdot \pi \cdot \lambda_2 \cdot \ln \frac{d_{e2}}{d_{i2}}} = \dots = \\ &= \frac{T_{j-1,j} - T_{j,j+1}}{2 \cdot \pi \cdot \lambda_j \cdot \ln \frac{d_{ej}}{d_{ij}}} = \dots = \frac{T_{n-1,n} - T_2}{2 \cdot \pi \cdot \lambda_n \cdot \ln \frac{d_{en}}{d_{in}}} = \frac{T_2 - T_e}{\pi \cdot \alpha_e \cdot d_{en}} = \frac{T_i - T_e}{\Re_{T6}} \end{aligned} \tag{19}$$

with:

$$\Re_{T6} = \frac{1}{\pi \cdot \alpha_i \cdot d_{i1}} + \sum_{j=1}^n \frac{1}{2 \cdot \pi \cdot \lambda_j} \cdot \ln \frac{d_{ej}}{d_{ij}} + \frac{1}{\pi \cdot \alpha_e \cdot d_{en}} \tag{20}$$

keeping the significance of the previous notations, j indicates the number of the component layer of the wall ($d_{i1} = d_i$; $d_{en} = d_e$, represents the inner diameter/ the outer diameter of the wall).

Equality (19), knowing T_i and T_e temperatures, provides the surface temperatures values available at the separating level of the layers, as follows:

$$T_1 = \left(1 - \frac{1}{\pi \cdot \alpha_i \cdot d_{i1} \cdot \Re_{T6}} \right) \cdot T_i + \frac{1}{\pi \cdot \alpha_e \cdot d_{e1} \cdot \Re_{T6}} \cdot T_e \quad (21)$$

$$T_{1,2} = T_1 - \frac{2 \cdot \pi \cdot \lambda_1}{\Re_{T6} \cdot \ln \frac{d_{e1}}{d_{i1}}} \cdot (T_i - T_e) \quad (22)$$

$$T_{j,j+1} = T_{j-1,j} - \frac{2 \cdot \pi \cdot \lambda_j}{\Re_{T6} \cdot \ln \frac{d_{ej}}{d_{ij}}} \cdot (T_i - T_e); \quad j \in \{1 \dots, n-1\} \quad (23)$$

$$T_{n-1,n} = T_{n-2,n-1} - \frac{2 \cdot \pi \cdot \lambda_{n-1}}{\Re_{T6} \cdot \ln \frac{d_{e(n-1)}}{d_{i(n-1)}}} \cdot (T_i - T_e) \quad (24)$$

$$T_2 = T_{n-1,n} - \frac{2 \cdot \pi \cdot \lambda_n}{\Re_{T6} \cdot \ln \frac{d_{en}}{d_{in}}} \cdot (T_i - T_e) = \frac{1}{\pi \cdot \alpha_e \cdot d_{en} \cdot \Re_{T6}} \cdot T_i + \left(1 - \frac{1}{\pi \cdot \alpha_e \cdot d_{en} \cdot \Re_{T6}} \right) \cdot T_e \quad (25)$$

2. 2. 3. Multilayered tubular/cylindrical wall, with imperfections between layers

Assuming the existence of some imperfections ($1 \leq m_i \leq (n - 1)$) between the component layers of the wall, and the presence of deposits or protection on the free surfaces of wall, the equality (20) is adapted accordingly:

$$\Re_{T7} = \frac{1}{\pi \cdot \alpha_i \cdot d_{i1}} + \sum_{j=1}^n \frac{1}{2 \cdot \pi \cdot \lambda_j} \cdot \ln \frac{d_{ej}}{d_{ij}} + \frac{1}{\pi \cdot \alpha_e \cdot d_{en}} + \sum_{j=1}^{m_i} \Re_{c,j} + \Re_{pi} + \Re_{di} + \Re_{pe} + \Re_{de} \quad (26)$$

maintaining the same meanings for the notations. The equalities (21) - (25) can be used to evaluate the temperatures between layers, where \Re_{T6} will be replaced with \Re_{T7} . Because $\Re_{T6} < \Re_{T7}$ it is observed that the temperatures between layers, in case of imperfections, have lower values than those when the wall have an perfect contact.

2. 3. Spherical wall

2. 3. 1. Monolayer spherical wall – Figure 2a, without protections and/or deposits

For a hollow sphere with d_i inner diameter and d_e outer diameter, subjected to the action of a stationary thermal field and taking into consideration the effects of the limit layers from inside and outside, where convection appears, with T_i and T_e enclosures temperatures, assumed known, the continuity of thermal transfer can be expressed by the following equalities[15]:

$$q_{ps} = \frac{T_i - T_1}{\pi \cdot \alpha_i \cdot d_i^2} = \frac{T_1 - T_2}{\frac{1}{2 \cdot \pi \cdot \lambda} \cdot \frac{d_e - d_i}{d_i \cdot d_e}} = \frac{T_2 - T_e}{\pi \cdot \alpha_e \cdot d_i^2} = \frac{T_i - T_e}{\Re_{T8}} \quad (27)$$

with:

$$\mathfrak{R}_{T8} = \frac{1}{\pi} \cdot \left(\frac{1}{\alpha_i \cdot d_i^2} + \frac{1}{2 \cdot \lambda} \cdot \frac{d_e - d_i}{d_i \cdot d_e} + \frac{1}{\alpha_e \cdot d_e^2} \right) \quad (28)$$

From (27), the expressions for calculating the temperatures in the wall surfaces can be established:

$$T_1 = \left(1 - \frac{1}{\pi \cdot \alpha_i \cdot d_i^2 \cdot \mathfrak{R}_{T8}} \right) \cdot T_i + \frac{1}{\pi \cdot \alpha_i \cdot d_i^2 \cdot \mathfrak{R}_{T8}} \cdot T_e \quad (29)$$

$$T_2 = \frac{1}{\pi \cdot \alpha_e \cdot d_e^2 \cdot \mathfrak{R}_{T8}} \cdot T_i + \left(1 - \frac{1}{\pi \cdot \alpha_e \cdot d_e^2 \cdot \mathfrak{R}_{T8}} \right) \cdot T_e \quad (30)$$

2.3.2. Monolayer spherical wall, with protections and/or deposits, without imperfections

As a result of the existence of some protection layers or deposits in the wall, the \mathfrak{R}_{T8} thermal resistance is changed accordingly:

$$\mathfrak{R}_{T9} = \frac{1}{\pi} \cdot \left[\frac{1}{\alpha_i \cdot (d_i - \delta_{pi} - \delta_{di})^2} + \frac{\delta_{di}}{2 \cdot \lambda_{di} \cdot (d_i - \delta_{pi}) \cdot (d_i - \delta_{pi} - \delta_{di})} + \frac{\delta_{pi}}{2 \cdot \lambda_{pi} \cdot (d_i - \delta_{pi}) \cdot d_i} + \frac{d_e - d_i}{2 \cdot \lambda \cdot d_i \cdot d_e} + \frac{\delta_{pe}}{2 \cdot \lambda_{pe} \cdot (d_e + \delta_{pe}) \cdot d_e} + \frac{\delta_{de}}{2 \cdot \lambda_{de} \cdot (d_e + \delta_{pe}) \cdot (d_e + \delta_{pe} + \delta_{de})} + \frac{1}{\alpha_e \cdot (d_e + \delta_{pe} + \delta_{de})^2} \right] \quad (31)$$

and the intermediary temperatures are:

$$T_{id} = \left[1 - \frac{1}{\pi \cdot \alpha_i \cdot (d_i - \delta_{pi} - \delta_{di})^2 \cdot \mathfrak{R}_{T9}} \right] \cdot T_i + \frac{1}{\pi \cdot \alpha_i \cdot (d_i - \delta_{pi} - \delta_{di})^2 \cdot \mathfrak{R}_{T9}} \cdot T_e \quad (32)$$

$$T_{dpi} = T_{id} - \frac{\delta_{di}}{2 \cdot \pi \cdot \lambda_{di} \cdot (d_i - \delta_{pi}) \cdot (d_i - \delta_{pi} - \delta_{di}) \cdot \mathfrak{R}_{T9}} \cdot (T_i - T_e) \quad (33)$$

$$T_1 = T_{dpi} - \frac{\delta_{pi}}{2 \cdot \pi \cdot \lambda_{pi} \cdot (d_i - \delta_{pi}) \cdot d_i \cdot \mathfrak{R}_{T9}} \cdot (T_i - T_e) \quad (34)$$

$$T_2 = T_1 - \frac{d_e - d_i}{2 \cdot \pi \cdot \lambda \cdot d_i \cdot d_e \cdot \mathfrak{R}_{T9}} \cdot (T_i - T_e) \quad (35)$$

$$T_{dpe} = T_2 - \frac{\delta_{pe}}{2 \cdot \pi \cdot \lambda_{pe} \cdot d_e \cdot (d_e + \delta_{pe}) \cdot \mathfrak{R}_{T9}} \cdot (T_i - T_e) \quad (36)$$

$$T_{ed} = T_{dpe} - \frac{\delta_{de}}{2 \cdot \pi \cdot \lambda_{de} \cdot (d_e + \delta_{pe}) \cdot (d_e + \delta_{pe} + \delta_{de}) \cdot \mathfrak{R}_{T9}} \cdot (T_i - T_e) \quad (37)$$

where $T_{i d}$, $T_{e d}$ are the temperatures at the inner surface, respectively at the outer of the deposits, and the temperatures between deposits and protections, at interior $T_{d p i}$ and at exterior $T_{d p e}$, have the significances given by (33) and (34).

2. 3. 3. *Multilayered spherical wall – Figure 2b, without protections and/or deposits, without imperfections*

Accepting T_i interior enclosure temperature and T_e exterior enclosure, for a spherical multilayer wall, then the total thermal resistance is:

$$\mathfrak{R}_{T10} = \frac{1}{\pi} \cdot \left(\frac{1}{\alpha_i \cdot d_i^2} + \frac{1}{2} \cdot \sum_{j=1}^n \frac{d_{e j} - d_{i j}}{\lambda_j \cdot d_{i j} \cdot d_{e j}} + \frac{1}{\alpha_e \cdot d_e^2} \right) \tag{38}$$

so the intermediary temperatures between layers have the expressions:

$$T_1 = \left(1 - \frac{1}{\pi \cdot \alpha_i \cdot d_i^2 \cdot \mathfrak{R}_{T10}} \right) \cdot T_i + \frac{1}{\pi \cdot \alpha_i \cdot d_i^2 \cdot \mathfrak{R}_{T10}} \cdot T_e \tag{39}$$

$$T_{1,2} = T_1 - \frac{d_{e1} - d_i}{2 \cdot \pi \cdot \lambda_1 \cdot d_i \cdot d_{e1} \cdot \mathfrak{R}_{T10}} \cdot (T_i - T_e); \tag{40}$$

$$\dots\dots\dots$$

$$T_{j,j+1} = T_{j-1,j} - \frac{d_{e j} - d_{i j}}{2 \cdot \pi \cdot \lambda_j \cdot d_{i j} \cdot d_{e j} \cdot \mathfrak{R}_{T10}} \cdot (T_i - T_e); \quad j = \overline{2, n-1} \tag{41}$$

$$T_2 = T_{n-1,n} - \frac{d_e - d_{i n}}{2 \cdot \pi \cdot \lambda_n \cdot d_{i n} \cdot d_e \cdot \mathfrak{R}_{T10}} \cdot (T_i - T_e) =$$

$$= \frac{1}{\pi \cdot \alpha_e \cdot d_e^2 \cdot \mathfrak{R}_{T10}} \cdot T_i + \left(1 - \frac{1}{\pi \cdot \alpha_e \cdot d_e^2 \cdot \mathfrak{R}_{T10}} \right) \cdot T_e \tag{42}$$

considering that $d_{i1} = d_i$; $d_{en} = d_e$.

2. 3. 4. *Multilayer spherical wall, with protections and/or deposits, with imperfections*

Maintaining the continuity of the thermal flow between layers, the temperatures in these areas have the expressions:

$$T_{i d} = T_i - \frac{T_i - T_e}{\pi \cdot \alpha_i \cdot (d_i - \delta_{p i} - \delta_{d i})^2 \cdot \mathfrak{R}_{T11}} \tag{43}$$

$$T_{d p i} = T_{i d} - \frac{\delta_{d i}}{2 \cdot \pi \cdot \lambda_{d i} \cdot (d_i - \delta_{p i} - \delta_{d i}) \cdot (d_i - \delta_{p i}) \cdot \mathfrak{R}_{T11}} \cdot (T_i - T_e) \tag{44}$$

$$T_1 = T_{0,1} = T_{d p i} - \frac{\delta_{p i}}{2 \cdot \pi \cdot \lambda_{d i} \cdot d_i \cdot (d_i - \delta_{p i}) \cdot \mathfrak{R}_{T11}} \cdot (T_i - T_e) \tag{45}$$

$$\dots\dots\dots$$

$$T_{j,j+1} = T_{j-1,j} - \frac{d_{e j} - d_{i j}}{2 \cdot \pi \cdot \lambda_j \cdot d_{e j} \cdot d_{i j} \cdot \mathfrak{R}_{T11}} \cdot (T_i - T_e); \quad j = \overline{1, n-1} \tag{46}$$

$$T_{n,n+1} = T_2 = T_{n-1,n} - \frac{d_e - d_{in}}{2 \cdot \pi \cdot \lambda_n \cdot d_e \cdot d_{in} \cdot \mathfrak{R}_{T11}} \cdot (T_i - T_e) \quad (47)$$

$$T_{dpe} = T_2 - \frac{\delta_{pe}}{2 \cdot \pi \cdot \lambda_{pe} \cdot d_e \cdot (d_e + \delta_{pe}) \cdot \mathfrak{R}_{T11}} \cdot (T_i - T_e) \quad (48)$$

$$\begin{aligned} T_{ed} &= T_{dpe} - \frac{\delta_{de}}{2 \cdot \pi \cdot \lambda_{de} \cdot (d_e + \delta_{pe} + \delta_{de}) \cdot (d_e + \delta_{pe}) \cdot \mathfrak{R}_{T11}} \cdot (T_i - T_e) = \\ &= \frac{1}{\pi \cdot \alpha_e \cdot (d_e + \delta_{pe} + \delta_{de})^2 \cdot \mathfrak{R}_{T11}} \cdot T_i + \left[1 - \frac{1}{\pi \cdot \alpha_e \cdot (d_e + \delta_{pe} + \delta_{de})^2 \cdot \mathfrak{R}_{T11}} \right] \cdot T_e \quad (49) \end{aligned}$$

where the total thermal resistance is:

$$\mathfrak{R}_{T11} = \frac{1}{\pi} \cdot \left[\begin{aligned} &\frac{1}{\alpha_i \cdot (d_i - \delta_{pi} - \delta_{di})^2} + \frac{\delta_{di}}{2 \cdot \lambda_{di} \cdot (d_i - \delta_{pi}) \cdot (d_i - \delta_{pi} - \delta_{di})} + \\ &+ \frac{\delta_{pi}}{2 \cdot \lambda_{pi} \cdot (d_i - \delta_{pi}) \cdot d_i} + \sum_{j=1}^n \frac{d_{ej} - d_{ij}}{2 \cdot \lambda_j \cdot d_{ij} \cdot d_{ej}} + \frac{\delta_{pe}}{2 \cdot \lambda_{pe} \cdot (d_e + \delta_{pe}) \cdot d_e} + \\ &+ \frac{\delta_{de}}{2 \cdot \lambda_{de} \cdot (d_e + \delta_{pe}) \cdot (d_e + \delta_{pe} + \delta_{de})} + \frac{1}{\alpha_e \cdot (d_e + \delta_{pe} + \delta_{de})^2} + \\ &+ \sum_{j=1}^{m_i} \frac{h_{r,e,j} + h_{r,i,j+1}}{2 \cdot \lambda_{j,j+1} \cdot (d_{ej} - h_{r,e,j}) \cdot (d_{ej} + h_{r,i,j+1})} \end{aligned} \right] \quad (50)$$

Note: By adequate estimations – not taking into account the roughness or the thickness of the protections and/or the deposits - data can be found out in the previous paragraphs.

3. CONCLUSIONS

This paper, addressing structures made of layered composites, but also other types of structures (for example plated structures), show the adequate method for determining the temperatures between layers in the presence of convection and conduction. The mathematical expressions take into account monolayer and multilayer walls, which are plane, tubular and spherical shaped. Also, there are given details both for perfect constructions, perfect contact between layers, but also for constructions that have imperfections between layers or protections and/or functional deposits. In this study the imperfections between the protection layers and/or those which are deposited in operation and the wall are not taken into consideration, because they have reduced thicknesses compared to the thickness of the base layers. As a result, their influences on the temperature fields are insignificant. The results obtained allow appropriate adjustments, when practical situations ask such influences.

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