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Active infrared thermography analysis of porous media PPI 10 and PPI 30 of ZrO_2

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ABSTRACT: Infrared thermography is a non-contact method of measuring and interpreting the surface temperature of the body surface, which is the object of testing and thermographic analysis. In this paper two hollow porous discs made of ZrO2 with different porosity of the open cells, PPI 10 and PPI 30, were thermographically analyzed. Porous disks are heated up to 20 minutes by an external heat source of temperature up to 400 °C in the shape of a flat plate. The active infrared thermographic method determines the thermograms of the system which consists of the heating plate and the hollow porous disk. The mathematical model established by the heat flux exchange between the heat source plate and the porous media. The output heat flux of the porous media is indirectly determined and compared with the contactless direct measurements of the heat flux. The established methodology in this paper can be used in the case of determining the porosity of a porous medium when it is not known.

KEYWORDS: infrared thermography, porous media, open cells, heat flux, hollow disc

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I. INTRODUCTION

The temperature field of the object can easily be visualized by the thermogram obtained using an infrared thermographic camera. The surface temperature of the object and its emissivity are the basic parameters that determine the temperature field of the object of measurement in a qualitative and quantitative sense. The chemical, physical and geometric characteristics of the object surface are influenced by different intensities on the infrared thermographic analysis.

Porous media were successfully used for various industrial applications in the field of heat transfer. The material of the porous media is most commonly metallic or non-metallic, while the structure of the foam cells can be performed as an open cell or closed cell. The porosity can be extremely high, which directly reduces the mass of porous media [1, 2]. Modern technological processes in the production of porous media with open cells enable different shapes and dimensions of cells. Theoretical analyzes and combined experimental tests of the effective conductivity of various metals and non-metallic porosity media were carried out by several authors [3 to 6]. Some investigations showed the correlation between thermal diffusivity and medium porosity using pulsed infrared thermography [7]. Furthermore, any studies, quantitative are testing porosity using active infrared thermography [8]. On the other hand, the research based on this paper aims to directly measure the heat flux of the porous media using non-contact measurements and indirectly determine the heat flux using infrared thermography. Measuring objects are two hollow discs of the porous material with open cells of different porosity and thickness. The bottom of the porous hollow disc is heated by the flat plate heater. Heat transfer by natural convection through the interior of the porous disc as well as the heat radiation are neglected.

II. INDIRECT DETERMINATION OF THE OUTPUT HEAT FLUX OF CERAMIC POROUS MEDIA IN THE FORM OF A HOLLOW DISC

The effective thermal conductivity of the porous medium in the case where the thermal conductivity of the porous media and fluid is small, was established from (Nield 1991b) in the form of an equation (1). A fluid that fills the porous medium ZrO_2 with open cells is air. Certainly, this mathematical expression could not be used if instead of ZrO_2 it was, for example, a metal porous medium. The effective thermal conductivity is

$$\lambda_{ef} = \lambda_p^{\varepsilon_p} \cdot \lambda_f^{1-\varepsilon_p} \tag{1}$$

where combining the effective heat flux through the porous matter of the thickness δ and the effective thermal conductivity λ_{ef}

$$q_{ef} = \frac{\left(T_h - \overline{T}_c\right)}{\delta} \lambda_p^{\varepsilon_p} \cdot \lambda_f^{1-\varepsilon_p} \tag{2}$$

where λ_{ef} effective thermal conductivity, λ_f thermal conductivity of the fluid (air), λ_p thermal conductivity of the porous media, T_h temperature of the heating , flat plate, $\overline{T}_c$ average temperature of the top porosity disc, q_{ef} effective heat flux, and δ porous disc thickness. The heat exchanged of the upper surface of the porous hollow disc consists of the heat of the central hollow part ($\overline{T}_o$, $\dot{\varepsilon}_o$, A_o) and the heat of the porous media ($\overline{T}_c$, $\dot{\varepsilon}_c$, A_c), equation (3). The average temperature of total surface $A_1 = A_c + A_o$ marked with $\overline{T}_1$, while the average emissivity is $\dot{\varepsilon}_1$.

$$\dot{\varepsilon}_c A_c \sigma\left(\overline{T}_c^4 - T_{am}^4\right) = \dot{\varepsilon}_1 A_1\left(\overline{T}_1^4 - T_{am}^4\right) - \dot{\varepsilon}_o A_o\left(\overline{T}_o^4 - T_{am}^4\right) \tag{3}$$

If the emissivity of the material of the porous media and the surface of heat plate are approximately equal, i.e. $\dot{\varepsilon}_c \approx \dot{\varepsilon}_1 \approx \dot{\varepsilon}_o$, then the average temperature of the top porosity disc $\overline{T}_c$ is

$$\overline{T}_c = T_{am}\left[1 - \frac{\left(\dfrac{\overline{T}_1}{T_{am}}\right)^4 - 1}{1 - \left(\dfrac{d_o}{d_1}\right)^2} - \frac{\left(\dfrac{\overline{T}_o}{T_{am}}\right)^4 - 1}{\left(\dfrac{d_1}{d_o}\right)^2 - 1}\right]^{0.25} \tag{4}$$

where ambient temperature T_{am} , internal diameter of the hollow porous disc d_o , while the outer diameter of the hollow porous disc is d_1 , Fig. 1.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Two hollow porous discs of material ZrO_2 and various porosity, PPI 10 and PPI 30, were heated at a heat source of uniform surface temperature. The temperature of the heating surface increases from the ambient temperature to the maximum during the heating time of 20 min. The characteristic dimensions of the hollow disks are shown in Table 1. Porous media of ZrO_2 and open cells have a significant potential to be applied to chemical reactions since they enable turbulent flow and radial mixing which enhance mass and heat transfer.

Table1. The characteristic dimension of the porous discs, material ZrO_2

$d_o\,[\mathrm{mm}]$	$d_1\,[\mathrm{mm}]$	$\delta_1\,[\mathrm{mm}]$	$\delta_2\,[\mathrm{mm}]$	$\lambda_p\,[\mathrm{W\,m^{-1}K^{-1}}]$	$\lambda_f\,[\mathrm{W\,m^{-1}K^{-1}}]$
35	95	24	15	6	0.04
		PPI 10	PPI30		

The disc A has a porosity of PPI 10, while disc B has a porosity of PPI 30. During the heating of hollow discs ambient temperature is 23.5 °C, while the relative humidity is 27.5%. A thin layer of conductive paste was coated between the heat source (heating plates) and hollow porous disc. The role of the conductive layer is to prevent the appearance of the contact resistance between the heater plate and the porous disc. Infrared imaging of the porous hollow disc and the heated flat surface is performed after 20 minutes from the beginning of the heating of the disc. Infrared thermographic testing is conducted with an infrared camera Fluke Ti32, while the commercial software for processing the thermogram is SmartView 2.3.2.

The accepted emissivity coefficient of the porous material is 0.85. On the other hand, the determination of the heat flux was performed using heat flow meter OS-652, measuring range 0 ÷ 1999 BTU with accuracy and resolution 1 BTU. Heat flow measurement was performed after 20 minutes from the start of the heating of the hollow porous disc, in the same way as the infrared imaging was carried out.

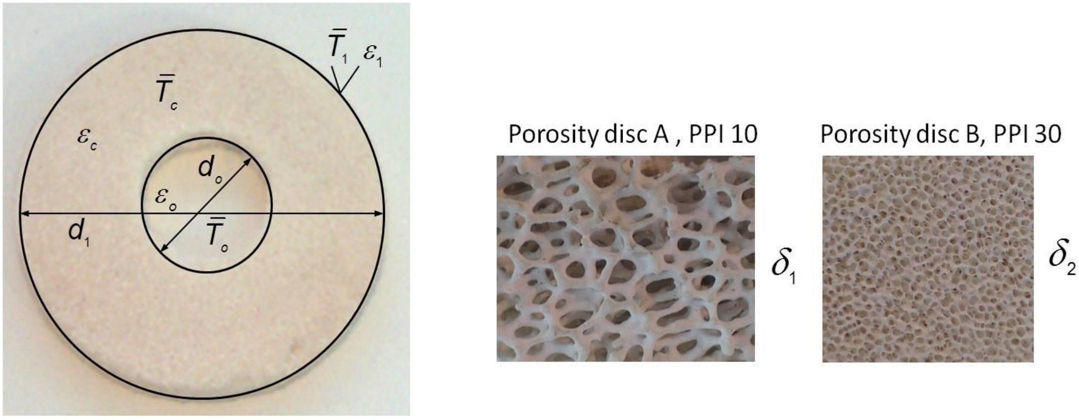

Fig.1.The hallow porous disc – ZrO_2 foam structures, porosity PPI 10 and PPI 30

The method of non-contact measurement of the heat flux is based on two steps. First is measured the heat flux of the central part of heating plate (the diameter is 35mm) located in the hollow part of the porous disc. The distance of the measured device is consistent with the performance of the measuring instrument and has a value of 630mm, Fig.2. After the first measurement, the heat flow meter is placed at a distance of 1710mm from the top surface of the porous media. At this distance, the heat flux was measured from the total surface of the hollow porous disc (the diameter is 95mm). The results obtained are shown in Table 2. According to Fig. 2, the heat flux from the porous disk is equal to the difference between the total q_1 and the central flux rate q_o .

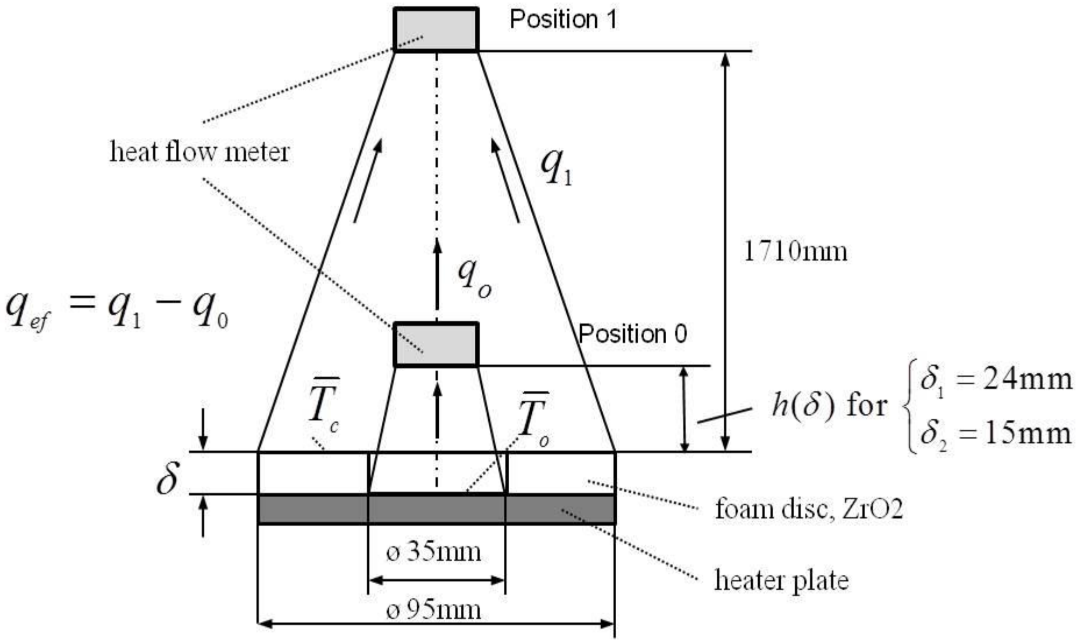

Fig.2. Direct measurement of the effective thermal flux of the porous hollow disc

III.1 Porous disc A, PPI 10

The hollow porous disc A (material ZrO2 and porosity PPI 10) is located on a flat heat source (heating plate) of uniform temperature in the central part about 350 °C. The average temperature of the peripheral part of the heating plate is about 310 °C, Fig. 3, while the average temperature of the entire disc is about 330 °C. On certain sections of the porous disc and heating plate, marked Lo, L1, and L2, are shown the temperature profiles. The temperature gradually grows from the periphery to the center of the square heating plate. At the hollow porous disc, the temperature profiles (L1 and L2) suddenly drop to 160 °C. The temperature profile Lo, within the hollow part of the disc, has the highest temperature of about 350 °C.

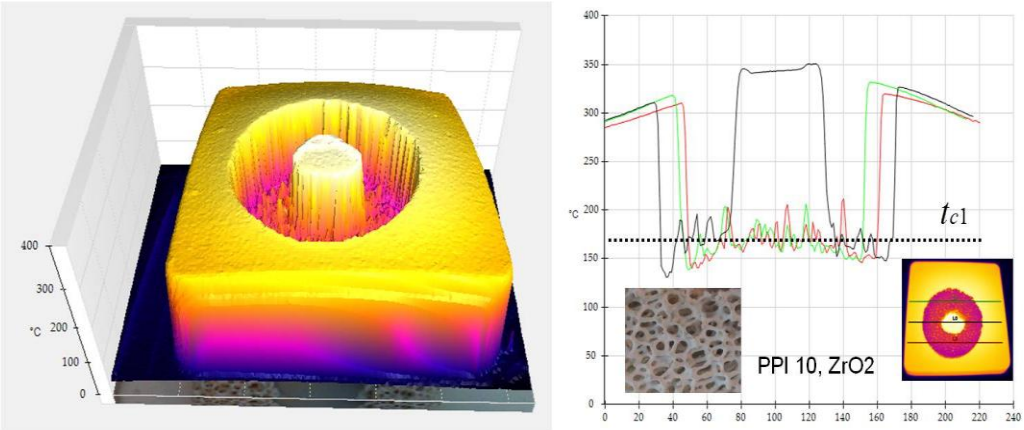

Fig.3. The thermogram and temperature profiles of the porous disc surface A, PPI 10

The greater porosity of the hollow disk generates a rough temperature profile shown in the thermogram in Fig. 3. The three selected profile lines Lo, L1, and L2 show vertical temperature profile, from top to bottom of porous disk A, Fig. 3 on the right. A large number of local maxima within the average temperature t_{c1} are the temperatures of the inner walls of the porous medium, while the local minima are the outer walls of the porous medium. The outer walls of the porous media are the closest to the thermographic camera lens and are exposed to more intense heat transfer exchange with the environment. The walls of the porous media are thin and different shape and only thermal radiation emitters with porous media. Thermal radiation of air within the porous media is neglected. Due to the higher porosity of porous media PPI 10, deeper sections of porous media are also thermal radiation, visible at higher temperatures than external ones, Fig. 4.

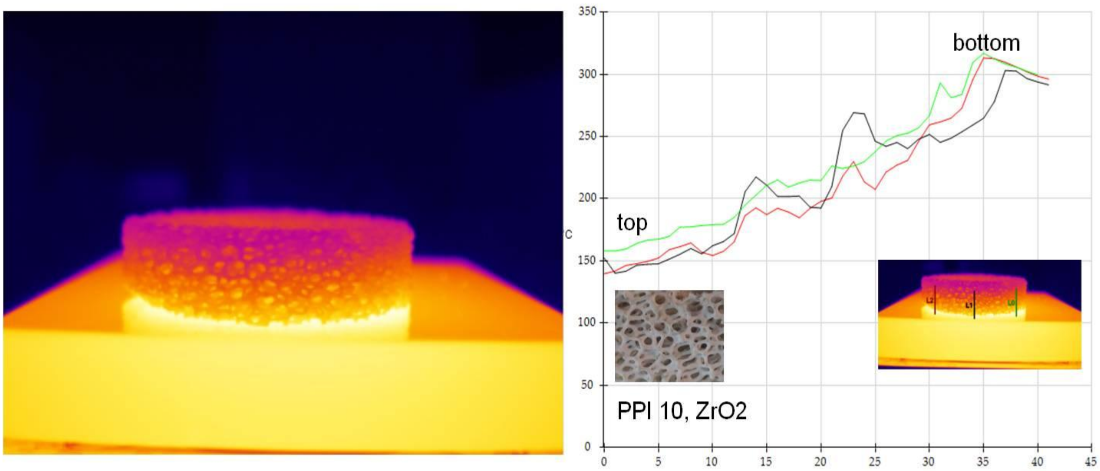

Fig.4. The vertical thermogram and temperature profiles of the surface of the porous disc A, PPI 10

The inner surface of the hollow porous disc has an average temperature of $\overline{T}_o$, which in the case of a porous media PPI 10 is about 311 °C. On the other side, the average temperature of the total surface area of the diameter d_1 is approximately of 186 °C, Fig. 5. By combining the equations (2) and (4) and in accordance with the values obtained from the previous thermograms, the output heat flux of the porous media PPI 10 can be obtained.

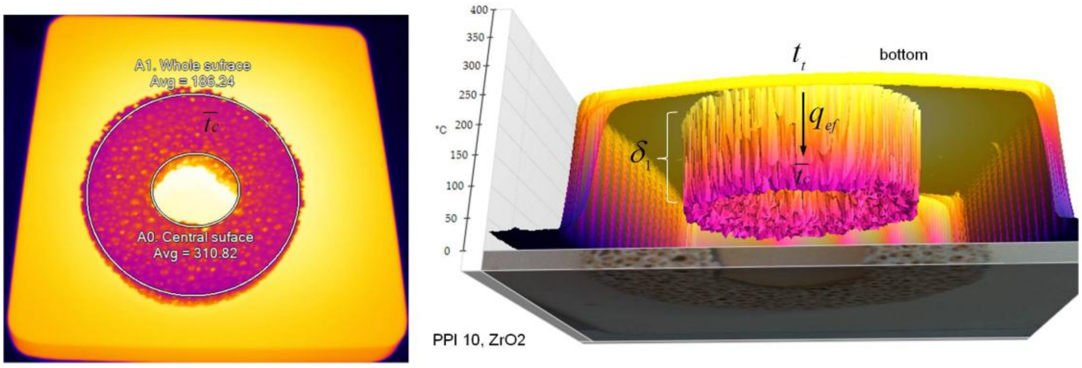

Fig.5.The characteristic physical and geometric characteristics of the porous disc A, PPI 10

Although porous disk A cannot be optically seen, however, the thermal radiation of the porous walls near to the heating plate is more clearly visible than the small bright spots, Fig. 5 on the left.

III.2 Porous disc B, PPI 30

The hollow porous disc B (material ZrO_2 and porosity PPI30) as in the previous case placed on the same heating plate and heated 20min. The starting temperature of the porous hollow disc B and the heating plate are 23 °C. The internal diameter of the hollow cylinder is 35mm, the outer diameter is 95mm while the height of the disc is 24mm. The temperature of the central part of the heating plate is about 380 °C, while the peripheral temperature of the heating plate ranges from 330 °C to 360 °C, Fig. 6. On the other hand, the temperature profiles Lo, L1, and L2 on the upper surface of the disk B are smoother and have a value of 170 °C to 200 °C.

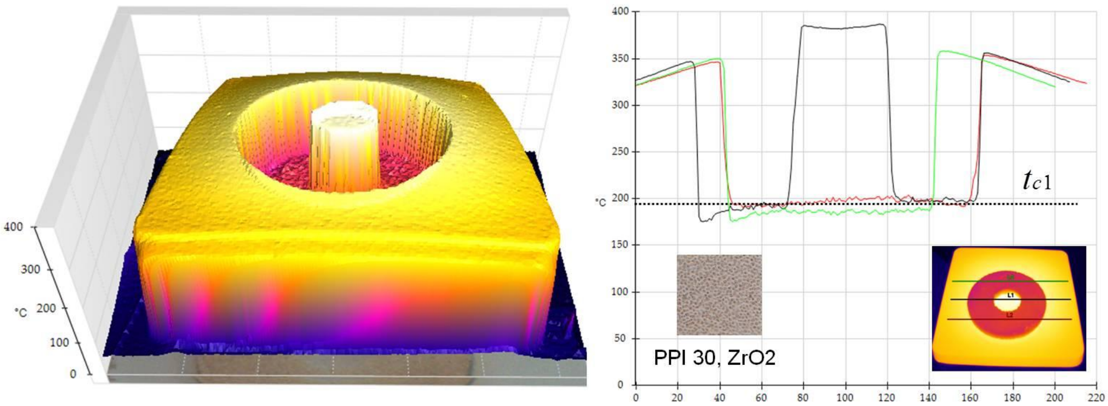

Fig.6. The thermogram and temperature profiles of the porous disc surface B, PPI 30

Less porosity does not cause a greater distance between the walls of the porous medium and their temperature is evenly distributed, as shown within the average temperature t_{c1}, Fig. 6. The small cell size of the porous disc B in relation to the porous disc A causes more uniform temperature profiles in the vertical part of the disk B, Fig. 7.

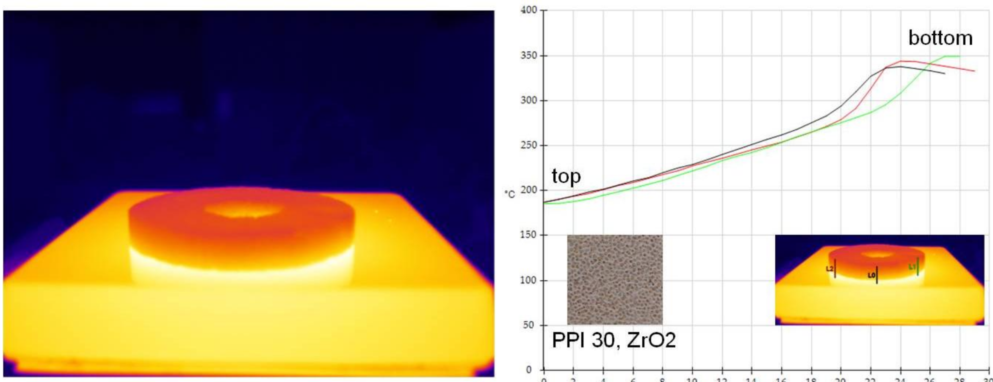

Fig.7. The vertical thermogram and temperature profiles of the surface of the porous disc B, PPI 30

By combining the equations (2) and (4) and according to the values of the temperatures obtained from the previous thermograms, the output heat flux of this porous media can be obtained, Fig. 8.

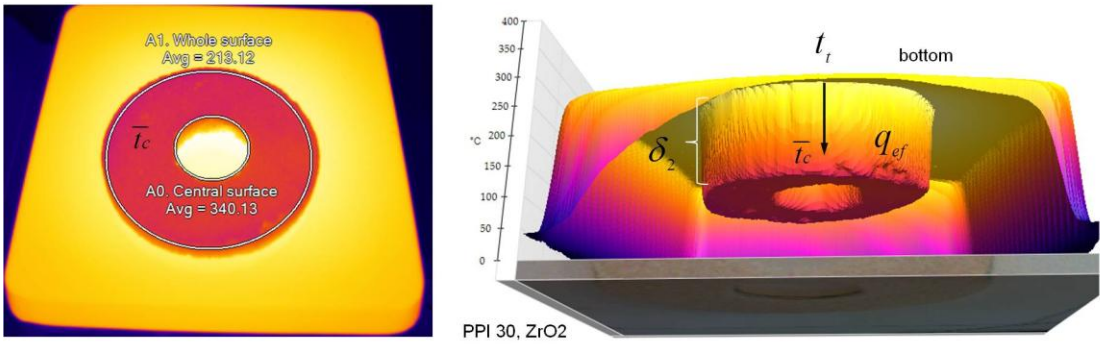

Fig.8. The characteristic physical and geometric characteristics of the porous disc B, PPI 30

IV. THE COMPARISON OF EFFECTIVE HEAT FLUX OF THE POROUS DISC A (PPI 10) AND DISC B (PPI 30)

On the basis of the conducted infrared thermographic analysis of the porous disc A (PPI 10) and the porous disc B (PPI 30), the average temperatures of the total external upper surface $\bar{T}_1$ and the central surface of the heating plate $\bar{T}_o$ is obtained. At constant ambient temperature T_{am}, by combining equations (2) and (4), the effective heat flux on the upper porous surface of disc A and disc B can be determined, using the equation (5).

$$q_{ef.IC} = \frac{\left\{ T_h - T_{am}\left[1 - \frac{\left(\frac{\bar{T}_1}{T_{am}}\right)^4 - 1}{1 - \left(\frac{d_o}{d_1}\right)^2} - \frac{\left(\frac{\bar{T}_o}{T_{am}}\right)^4 - 1}{\left(\frac{d_1}{d_o}\right)^2 - 1} \right]^{0.25} \right\}}{\delta} \lambda_p^{\varepsilon_p} \cdot \lambda_f^{1-\varepsilon_p} \tag{5}$$

By direct measurement of the heat flux of the total upper surface of the annular disc q_1 and the central surface q_o and from their difference $q_{ef} = q_1 - q_o$, the effective heat flux on the upper porous surface of the disc A and disc B can be obtained. The comparative results of the heat flux obtained by infrared analysis and direct thermal contactless heat flux measurements shown in Table 2.

Table 2. Comparative values of the effective heat flux obtained by infrared analysis and direct contactless measurement

Porous disc	$T_1\,[\mathrm{K}]$	$T_o\,[\mathrm{K}]$	$T_{am}\,[\mathrm{K}]$	$T_h\,[\mathrm{K}]$	$q_{ef.IR}\,[\mathrm{W\,m^{-2}}]$	$q_{ef}\,[\mathrm{W\,m^{-2}}]$
A (PPI 10)	460	584	296	575	14850	14122
B (PPI 30)	486	613	296	608	22772	22118

V. CONCLUSIONS

The application of the combined non-contact heat flux measurement and its indirect determination using infrared thermography is shown in this paper. Two porous discs of ZrO_2 material, the same diameter, but different porosity and height, with the same methodology tested. Since active infrared thermography is used, the discs are heated by a heat plate source. The primary heat transfer through the discs was considered conduction, while the ambient conditions were kept constant. Disk porosity A is defined with PPI 10, while disk porosity B is marked with PPI 30. The results obtained by this research confirm the possibility of determining the heat flux of the porous media. Different porosity, PPI 10 with larger open cells and PPI 30 with smaller open cells affect the final appearance of vertical and horizontal temperature profiles of the porous media. Less cell dimensions, as expected, have a smooth shape of the temperature profiles. The rough shape of the temperature profile is expressed in porous media in larger open cells i.e. PPI 10.

On the other hand, direct non-contact measurement of the heat flux confirmed that the results obtained in the indirect thermographic analysis are acceptable. Also, the conclusion is that in this way, the porosity of a porous medium can be indirectly determined when it is not known.

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