Influence study of porous material and diameter on heat transmission from corrugated walls cavity

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Abstract. Experimental study of heat transfer by free convection in a cavity filled with a porous medium. The study carried out on three forms of cavities (a cavity with flat walls, opposite walls, and similar walls), for the wavy wall cavity the (Asp=1), where a regular thermal flux was applied at the bottom with five values ranging between (500-2000) W/m² by using five voltages (8,10,12,14 and 16) W. The side was completely insulated to be adiabatic and the upper surface of the cavity is exposed to free convection. The sand (1 mm and 3 mm) and glass (1 mm and 5 mm) were used as a porous medium of the three forms of cavities that have been studied. The experimental results show that the cavity with opposite walls gives the largest difference in temperature, as this difference is the basis for studying the other parameter. The lower thermal conductivity of the materials gives the greater heat transfer process, and this was demonstrated by the materials used, where sand gave the best heat transfer. When the diameter of the porous material increases, the temperature difference will decrease, and accordingly the heat transfer coefficient of free convection increases.

Keywords: Free convection, Porous media, Wave cavity, Constant heat flux

1. Introduction
A porous material (medium) is a strong containing void space (pores), either continuous or detached, scattered inside the material in either a normal or arbitrary way. These purported pores may contain an assortment of fluids e.g. air, water, oil etc. Many researchers investigated the porous media experimentally and numerically. Salih et al [1] investigated numerically heat transfer natural convection in rectangular porous cavity; the sides were adiabatic and horizontal walls heated to uniform but different temperatures. The study showed that the rates of heat transfer depended on the porous Rayleigh number (Ra) for, based on width of cavity, for the range (Ra≤500), with aspect ratios for layer Ar (height / width) ranging (0.5≤Ar ≤5). Isotherms and streamlines plots showed the action of the temperature distribution and flow. The porous Rayleigh number in this study is based on Nu, and the cavity geometry. Increase Ra due to a change of pattern flow from unicellular to multicellular flow. The correlation of credence of Nu, on the Ra, of porous, and aspect ratio (Ar) was useful in design the thermal insulators system in the engineering applications. Kumar, et al [2] The free convection resulted by a vertical wavy surface with steady heat flux in a porous enclosure analyzed numerically by using the finite element method (FEM). The convection
and flow process were dependent on the flow parameter like (Ra), and wave amplitude (a) as geometrical parameters, the wave number (N) in the vertical of the cavity and wave phase (φ). The small sinusoidal deviation from the vertical wall with 60° as phase angle and high frequency improved the free convection with uniform heat flux from a vertical wall. Ismael [3] numerically studied the heat transfer by natural convection and fluid flow inside a fluid-saturated porous media wavy enclosure heated by an internal circular cylinder. The investigation used Galerkin finite-element method implemented through the software package (Flex PDE). The effect of inner cylinder position ξ (0.45-1.05), Darcy modified Rayleigh number Ram (100-1000), and waviness of wavy walls λ (0-0.35) was studied. The results were presented by visualization of the streamline and isothermal contours, and by the local and average Nu. It was found that for any values of inner cylinder position and wall waviness, the heat transfer was an increasing function of Darcy modified Ra. Higher heat transfer is obtained when the inner cylinder is positioned below the mid enclosure height and whatever the wall waviness the lower position of the inner cylinder (ξ=0.45) was the largest the values of Nu. while the influence of the wall waviness ratio is found to be very small. Abbas [4] studied two-dimensional laminar natural convection model in porous enclosure. The vertical walls were maintained at different warm and cold temperatures. The model was study according to Darcy-Brinkman-Förchheimer. The finite volume method was used to solve four dimensionless numbers; the Darcy number, the thermal Grashof, Prandtl number and the aspect ratio. The results found the following: the Grashof number (Gr=500, 1000, and 3000), and increasing with a constant Darcy number, so the increase in flow velocity and heat transfer as a result of the increasing of convection. The Darcy number, (Da=10-2, 10-3 and 10-4) decreasing at constant of Grashof number of the medium is opaque, which slow motion of the convection phenomenon. Mohammed, et al [5] experimentally studied the effect of mixed convection heat transfer in packed fill with a metallic porous materials for stainless steel beads with spherical shape with average diameter 6 mm, and heated at a constant heat flux in a vertical concentric annulus. The water was the working fluid with Ra range from (122418.92 - 372579.31) and Re was (14.62, 19.48 and 24.36) based on the particles diameter steady state condition effected. The results showed that the local heat transfer coefficient increased with the increasing of the imposed heat flux and Re. Additionally, the mean Nusselt number (Nu_m) increased with increasing Ra and Re. Vanjari et al.[6], The heat transfer by force convection due to the stainless steel ball porous media, in diameter (8, 12 and 16 mm) with different porosity was experimentally studied [6]. The effect of the parameters Re, Pr, convective heat transfer coefficient, porosity and the effect of mass flow rate with porosity on heat transfer rate were investigated. The result appeared that for minimum porosity heat transfer rate raised and it related on mass flow rate.

2. Experimental device

The study includes three types of cavities for two types of porous materials (sand and glass) with different diameters 1 and 3 mm for sand, and (1 and 5 mm for glass. The experimental test rig was installed in the laboratory of mechanical engineering department college of engineering, wasit university. This cavity exposed to the constant heat flux ranging between 550 to 2208 W/m². The temperature of the cavity measured by using eleven thermocouples type (K). A data logger was used to collect the data reads. After working the calculation, we show the effect of some parameter on the heat transfer current by free convection.
3. Calculations of parameters

To calculate the amount of heat transferred and other parameters from the practically recorded temperatures, they are listed as follows:

1- Power supply to the heater can be calculated as following [7]

\[ Q = I \times V \times \cos \phi \]  

Where, \( Q \) : Electrical power consumed by the heater in Watt
\( \phi \): Phase shift angle (power factor) for three phases.

Note:- \( \cos (\phi) = 1 \) for heater

2- Heat flux equal to heat input the system [8].

\[ \overline{q} = \frac{Q}{A} \text{ W/m}^2 \]  

\( A = \text{Width } \times \text{ depth of cavity } = W \times Z \)

3- The heat losses from cavity to the ambient with the side wall, front and back wall.

- \( q_\text{fr} \) = The front wall heat losses (W/m²).
- \( q_\text{ba} \) = The back wall heat losses (W/m²)
- \( q_\text{si} \) = The sides wall heat losses (W/m²).

By using the Fourier law equation the simple conduction heat transfer take example the case of 16V and total heat flux 2074(W/m²).

\[ q_\text{losses} = q_\text{fr} + q_\text{ba} + q_\text{si} = \text{Total heat losses} \]  

\[ = 101.6 + 67.3 + 19.3 = 188.27 \text{ W/m}^2 \]

And then calculating the out heat flux:

\[ q_\text{in} = q_\text{out} - q_\text{losses} \]

\[ 2074 = q_\text{out} + 188.27 \]

\[ q_\text{out} = 1885.7 \text{ W/m}^2 \]

After of determinations of the net heat flux these steps explain the calculation of other parameters,[9].

- \( \Delta T \): is the difference between average base temperature and average bulk temperature

- \( \Delta T = T_{\text{base}} - T_{\text{bulk}} \)
• $T_f$ is the average of base and bulk temperature and from it take all properties of water that is needed in determinations: $T_f = \frac{T_{base}+T_{bulk}}{2}$.

Calculate the heat transfer coefficient by divided the net heat flux on the temperature difference. $h = \frac{q_{net}}{\Delta T}$

• $K_{eff}$ at $T_f$ calculate the thermal conductivity for both fluid and solid and from below equations determine the effective thermal conductivity.

$$K_{eff} = \varepsilon \times k_f + (1 - \varepsilon) \times k_{solid}$$ (5)

• Permeability $K$: the porosity is calculated by equations from [7].

$$K = \frac{D_p \times \varepsilon^3}{150(150-\varepsilon)^2}$$ (6)

• Calculation of porosity: the porosity is calculated by two ways. The first way depending on the empirical equations from [10]

$$\varepsilon = 0.3454 + 11.6985 (D_p)$$ (7)

The second ways using the experimental procedure, by taking a 300ml of sand with 3mm diameter in a glass beaker, and 300 ml of water. Then we add the water to the beaker that contains the sand. We will notice that a part of the water penetrates into the spaces between the sand and fill it up, and after the water is saturated, the remaining part will rise above the saturated sand the portion above is subtracted from the total volume of water and then divided by the total volume to calculate the porosity.

$$V_o = V_{total} = 300 ml$$
$$V_{wa1} = 300 ml$$
$$V_{wa2} = 185 ml$$
$$V_{po} = V_{wa1} - V_{wa2} = 300 - 185 = 115 ml$$
$$\varepsilon = \frac{V_{po}}{V_{total}} = \frac{115}{300} = 0.383$$

This value for sand porosity and glass equals to the value which find from the first way show in Table 1.

Table 1. The porosity and permeability for porous material.

| Diameter (m) | 0.001 | 0.003 | 0.005 |
|-------------|-------|-------|-------|
| Porosity $\varepsilon$ | 0.36  | 0.38  | 0.4   |
| Permeability (m$^2$) | $7.593 \times 10^{-10}$ | $8.56 \times 10^{-9}$ | $3.22 \times 10^{-8}$ |
Figure 2. The experimental measurement of porosity for sand.

Table 2. The physical properties for the porous materials used in the study

| Porous materials       | T,K  | \( \rho, kg/m^3 \) | \( C_p, J/Kg.k \) | K.W/m°C |
|------------------------|------|---------------------|------------------|---------|
| Silica-sand            | 300  | 2300                | 1170             | 0.197   |
| Soda lime(glass)       | 300  | 2500                | 750              | 1.4     |

- Effective Nusselt Number.
  \[ Nue = \frac{h \cdot D_h}{K_{eff}} \]  
  Where; H is the high of cavity.

- Modified Rayleigh Number based with hydraulic diameter.
  \[ Ra_m = (Gr \times Pr) \times Da \]  
  Where, Da, is the Darcy number
  \[ Ra_m = \frac{g \times \beta \times \Delta T \times K \times D_h}{\sigma \times \alpha} \]  
  Where, \( D_h \) is the hydraulic diameter.

4. Result and dissections

The experiments study carried out to cover a range of heat flux varies from (450 w/m²) to (2000 w/m²), porosity between (0.36 – 0.4) and Rayleigh number from (14) to (1010).

4.1. The Effect of sand particle diameter on temperature distribution

Figures (3 to 8) show the temperature profiles for different thermal flux and types of packing with vary in the diameter full of the three types of cavities using silica sand and glass as saturated porous medium. These figures show in general that the amount of temperature difference increased with the increasing in the thermal flux for the diameter 1 and 3mm for sand, and 1 and 5 mm for glass. The amount of temperature difference increased with diameter decreasing; 1 mm was much higher than the diameter 3 mm and 5 mm for all levels of thermal flux and for the various cavity that have been studied. This is due to the fact that the increase in thermal flux leads to an increase in the growth of the thermal layer, which in turn causes increasing in the buoyancy strength for all cavities.
**Figure 3.** Temperature difference distribution versus heat flux for sand as porous media in reverse cavity.

**Figure 4.** Temperature difference distribution heat flux for sand as porous media in flat cavity.

**Figure 5.** Temperature difference distribution versus heat flux for sand as porous media in similar cavity.

**Figure 6.** Temperature difference distribution versus heat flux for glass as porous media in reverse cavity.

**Figure 7.** Temperature difference distribution versus heat flux for glass as porous media in flat cavity.

**Figure 8.** Temperature difference distribution versus heat flux for glass as porous media in similar cavity.
4.2. Effect of heat flux with modified Ra*  
The relationship between the amount of thermal flux impose to the cavity filled with saturated porous medium with the modified Rayleigh number calculated basis on the hydraulic diameter for all the models tested is shown in figures (9 and 10). It appears that the modified Rayleigh number increased with the increasing in the thermal flux and is the highest value at the opposite wave walls cavity, flat walls cavity and finally with symmetric wave walls cavity. Through the saturated porous sand medium with diameter of 3 mm, the values of the modified Rayleigh number were higher than the porous medium with a diameter of 1 mm. In the porous medium with small particle 1mm diameters, causes narrow passage through the pore, low velocity, so the heat transfer path is narrow. In porous materials with a diameter of 3 mm, the contact surface area is less, which leads to an increase in the velocity of the fluid, thus increasing the number of Rayleigh.

4.3. Effect of the heat flux on the modified Rayleigh number for glass.  
Figures (11 and12) explain the relation between the modified Rayleigh number with the impose heat flux for the glass saturated porous media. In general form the modified Rayleigh number increases with the thermal flux increase for 1 mm and 5mm diameter with the same behavior of the sand. The value of the modified Rayleigh number for 5 mm diameter of glass porous media, the cavity with similar walls is the highest value, followed by the opposite, and the minimum values for the flat walls, this attributed to the permeability as well as the decrease in the contact surface porous media.

**Figure 9.** Modified Rayleigh number against heat flux for different cavity with 1mm sand porous media.  

**Figure 10.** Modified Rayleigh number against heat flux for different cavity with 3mm sand porous media.
4.4. Effect of modified Rayleigh number on the Nusselt number

The effect of the shape cavity on the Nusselt number with different modified Rayleigh number for all cavity and both materials was studied. A comparison between 1 and 3mm sand porous media was made and illustrated in figure (13 and14). We noticed that the values of the Nusselt number in general increased with the increasing the Rayleigh number for all the models tested. However, the symmetric wave cavity gave the highest values of the Nusselt number and the lowest values obtained in the opposite wave cavity. This is due to the fact that the temperature difference in the opposite wave cavity gives the lowest values of the heat transfer coefficient, which in turn is directly proportional to the increase in the Nusselt number.

On the other hand, it can be shown that the effect of the diameter sand porous particles on the influence of values of Nusselt number, as the sand diameter 3 mm gave higher values for the Nusselt number of all cavities due to the decrease porosity and particle diameter decreases the Nusselt number, although the contact area is increased.

The other porous media was studied as a glass with (1, 5) mm diameter, this material has the same behavior for sand, where Nusselt number increases with Rayleigh number increases, except that the cavities with flat surfaces have the highest value of the Nusselt number for both diameters 1 mm and 5 mm, but in the case of 1 mm diameter, the cavity with similar walls is higher than the opposite and vice versa in the case of 5 mm diameter as show in figure (15 to 16).

From figure (5.12 to 5.15) it is clear that the Nusselt number increase with increasing in the heat flux. On the other hand it can be seen that Dp is 3 mm for sand and 5mm for glass gives the highest value of Nusselt number. This is due to the large surface area of contact and high values of porosity which is compared to the porosity for the Dp = 1mm.
4.5. Effect of the porous material on the Ra* 

The effect of the porous materials (sand and glass) with 1 mm diameter on the Rayleigh number for different heat flux and for all cavities which studied experimentally was appear in figure (17 to 19). From this comparison was made between glass and sand for a diameter of 1 mm, as it was observed that the modified Rayleigh number of sand is higher than glass for all cavities. This attributed to the fact that glass has a higher thermal conductivity than sand. Furthermore, it can be seen that the revers wall cavity give great value for modified Rayleigh number than the flat wall and similar wall cavity.
Figure 17. Effect of porous media on the modified Rayleigh number for different heat flux with revers wall cavity.

Figure 18. Effect of porous media on the modified Rayleigh number for different heat flux with flat wall cavity.

Figure 19. Effect of porous media on the modified Rayleigh number for different heat flux with similar wall cavity.

5. Conclusions
Experimental solutions are presented in this work for the constant heat flux for the bottom surface, insulated side wall and the top surface exposed to the convection boundary condition. Glass, and Silica - sand was used as porous media materials, saturated with water. The main conclusions are following:

1. Porous with diameter 1 mm gives the highest temperature difference and lowest values for Rayleigh number and Nusselt number for sand and glass.
2. The cavity with opposite walls gives the highest difference in temperature transfer, and similar walls gives the smallest difference.
3. In the case of 1 mm glass, the opposite walls give the highest value of Rayleigh, and the flat walls give the highest value of 5 mm of similar.
4. In the case of sand with a diameter of 3 mm, the highest value of Rayleigh number is at opposite walls and the highest value of Nusselt number of scales at similar walls.
5. In the case of glass with a diameter of 5 mm, the highest value of Rayleigh number is at similar walls, and the highest value is at flat walls.
6. Generally, sand gives the highest values for Rayleigh number.
Table 3. The meaning of the symbols.

| Symbol | Description               |
|--------|---------------------------|
| A_c    | Cross sectional area      |
| D_a    | Darcy number              |
| D_h    | Hydraulic Diameter        |
| D_p    | Particle diameter         |
| G_r    | Grashof number            |
| H      | high of cavity            |
| h      | heat transfer coefficient  |
| I      | Electrical current        |
| K      | Permeability              |
| K_f    | Water thermal conductivity |
| K_s    | Porous sphere thermal conductivity |
| K_{eff} | Effective thermal conductivity |
| Nu_x   | Local Nusselt number      |
| Pr     | Prandtl number            |
| q      | Heat flux                 |
| Q      | Power supply              |
| Rem    | Modified Reynolds number  |
| ΔT     | Difference between average base temperature and average bulk temperature |
| T_a    | Ambient temperature       |
| T_b    | Base temperature          |
| T_{bulk}| Bulk temperature         |
| Ɛ      | Porosity                  |

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