

Conduction Heat Transfer on the Porous Media in the Gap with Heater from Below

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ABSTRACT

Conduction heat transfer in gaps containing many porous objects has not been widely discussed, despite several applications. This study aims to determine the mechanism and calculate conduction heat transfer in porous objects and whether there is a change in the thermal conductivity value. The research started from a mathematical model with a horizontal medium, and the results were matched with the simulation results. Porous objects contain water that can evaporate. This study used clove buds stacked with a certain thickness which caused porous between the piles of cloves. So, this research uses several heat transfer formulas related to porous media. The new formula is obtained to get the thickness of cloves pile based on the amount of porosity of objects and the porosity between the piles of objects.

Keywords: Porous Objects, Conduction, Gaps, Heat Transfer.

1 INTRODUCTION

Heat transfer in porous media has become an essential subject in mechanical engineering. This study presents experimental and numerical theory investigations of the effective thermal conductivity in porous media. Porous objects are very numerous, especially in agricultural products that need drying. The purpose of drying agricultural products is to get good quality in heat and mass transfer. Mining material that will be processed usually needs to be drained so that water is not disturbed in the process. This research is about conduction heat transfer in a set of porous objects in the gap to get an equation that calculates the thickness of the cloves pile based on the amount of porosity of objects and the porosity between the piles of objects.

This research starts from the translation of equations related to conduction heat transfer and porous objects. Furthermore, conducting research by heating a set of porous objects in the gap to get the value of energy and conduction requirements of porous objects. The success of this study can be used as a basis for the process of porous heating objects based on conduction.

Research carried out by several researchers, such as research by Zilong et al. (Deng et al. 2017), with the increase in porosity can lead to a smaller effective thermal conductivity. The ratio of thermal conductivity of the solid matrix to the fluid phase is an essential parameter in determining heat conduction. The theory about average volume was developed to estimate both stagnant thermal conductivity and thermal dispersion conductivity within porous media (Yang and Nakayama 2010). Experimental results relating to heat conduction refer to the situation that conduction with liquid is stagnant, normal toward fluid velocity, and in a diagonal parallel to the fluid velocity (Telles and Massarani 1974). It was shown that these observations qualitatively agree with the last item's theoretical criteria of conclusions and enough for the determination of parameters in the tensor function. The study determined the effective stagnant thermal conductivity of Cu-btc and Fe-btc materials and examined the effects of introducing improved heat transfer structures such as aluminium foam or wire (Henriksen 2013). Simulations and experiments with porous medium (pumice stone) bottom and top of the sample are cooled and heated using heat exchangers

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and hot water baths (Salati 2014). The representative base cell of concrete is selected to determine homogenized tensors of heat conductivity numerically. Depending on the geometric properties of the cell, sensitivity analysis has enabled us to highlight the effect of moisture content and material porosity on homogenized heat conductivity tensors (Bennai et al. 2018). Theoretically, predicting the thermal conductivity with the cubic cell model requires the knowledge of the thermal conductivity of the solid particle and the materials atmospheric gas or ice and the porosity of the soil (Gori and Corasaniti 2004). Developed porosity and saturation-dependent thermal conductivity models in porous media using percolation-based effective-medium approximation. Models function the properties, e.g., air, solid matrix, saturating fluid thermal conductivities, a scaling exponent, and a percolation threshold (Ghanbarian and Daigle 2016). When the thermal conductivity of the solid-phase and wet phase is greater than that of the gas phase, the effective thermal conductivity of unsaturated fractal porous media decreases with decreasing degree of and increasing fractal dimension for pore area saturation fractal dimension for tortuosity and porosity (Kou et al. 2009). Developing a heat transfer model in the rule of a mixture of porous objects is necessary to predict thermal conductivity. The development of this mixing rule is based on particle size distribution data for non-combined porous media. Where solid and liquid phases are considered (Evgeny Skripkin 2015). An experimental study with sintered porous media has been employed on mini heat pipes (MHP) in the capillary transport of working fluid from the condenser to the evaporator section. The thermal resistance of the interface showed to be negligible for the determination of the effective thermal conductivity of the porous media composed of layers (Florez et al., 2011).

2 MATHEMATIC MODEL

This mathematical model is intended for derivatives of conduction equation formulas on porous objects in the gap. Conduction that occurs is transient, and the heating temperature remains, but there is a vapor so that there will be a change in the value of the material's heat conductivity.

The porosity of a group of materials:

$$\phi = \frac{V_f}{V_{pm}}$$

The porosity of single material:

$$\phi = \frac{V_w}{V_{sp}}$$

Where V_f is a volume of fluid; V_{pm} is a volume of porous media; V_w is a volume of water; V_{sp} is a solid volume.

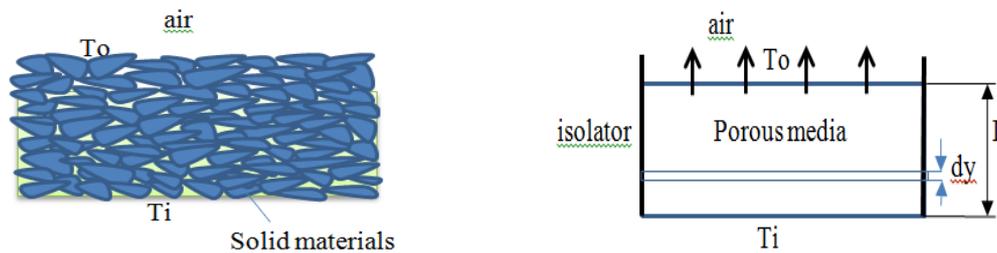


Figure 1. Porosity material

The heat conductivity of materials for porous media, according to (Adrian 2013). If the heat conduction takes place in series:

$$\frac{1}{k_{pm}} = \frac{(1-\phi)}{k_s} + \frac{\phi}{k_f} \quad (1)$$

When viewed from the composition of the solid body, the structure drawn in series is taken; subsequently, the series formula is used.

The heat conductivity of materials for solid objects (k_s) contains water, so this material is also a porous media in which the series is arranged.

$$\frac{1}{k_s} = \frac{(1-\phi)}{k_p} + \frac{\phi}{k_w} \quad (2)$$

This solid material, if exposed to heat energy, the water in the object will evaporate; with water evaporating, the porous media will shrink so that equation (2) will affect equation (1).

If equation (2) is entered into equation (1), it will become a series with the series equation:

$$k_{pm} = \frac{1}{\frac{\phi}{k_f} + \frac{\phi(1-\phi)}{k_w} + \frac{(1-\phi)(1-\phi)}{k_p}} \quad (3)$$

When k_{pm} is the thermal conductivity of porous media; k_s is the thermal conductivity of solid; k_f is the thermal conductivity of fluid; k_p is the thermal conductivity of porosity in single material; k_w is the thermal conductivity of water.

The principle of conservation of energy for the porous media, surface area A , and thickness of dy , Figure 1, can be stated as follows:

The formula for heat transfer of steady conduction is

$$k.A \frac{dT_s}{dy} = h.A.(T_o - T_a) \quad \text{where, } y = 0, T = T_i$$

$$y = L, T = T_o$$

$$k \frac{(T_i - T_o)}{(L_o - L_t)} = h.(T_o - T_a)$$

$$T_o = \frac{h.(L_o - L_t).T_a + k.T_i}{k + h.(L_o - L_t)} \quad (4)$$

In a steady-state, T_o has not changed up and down. With the warming of the porous media, its nature will also change. This change is due to the evaporation of water contained by solid material in the porous media.

With the evaporation of water in solid material, there will be changes in the value of heat conductivity, specific heat, and density, the thickness of porous media, the porosity of solid material, and porous media's porosity. With these changes, the value of T_o will change according to some of these variables' rate of change.

Basic formula from (Kreith, Raj M., and Mark S. 2011), a simple equation can be based on changes in energy from porous media as follows:

Change in internal energy of the porous media during dt = heat flow from the porous media to the air during dt

$$\begin{aligned} dm.C_p. dT &= h. A dT_a.dt \\ \rho.dy.A.C_p dT &= h.A dT_a.dt \\ \rho.C_p \int dy dT &= h \int dt dT_a \\ \rho.dy.C_p (T_r - T_a) &= h.(T_o - T_a).dt \quad \text{if } L = 0 \quad T = T_i \text{ and} \\ & \quad L = y \quad T = T_o, \\ & \quad L \gg y \quad T = T_a \\ \rho.(L-0).C_p (T_r - T_a) &= h (T_o - T_a)(t_i - t_o) \quad \text{if } t = 0 \quad T_o = T_a \\ & \quad \text{if } t > 0 \quad T_i > T_o > T_a \\ & \quad \text{if } T_r = (T_i + T_o)/2 \quad \text{if } t_o = 0 \quad t = t_i \\ t &= \frac{\rho.L.C_p.\{(T_i + T_o)/2 - T_a\}}{h(T_o - T_a)} \quad (5) \end{aligned}$$

When there is no heating $T_o = T_a$, after T_i temperature is present, the temperature of the T_o will continue to rise and stop after stability. Starting from increasing T_o to stop time can be calculated by equation (5); the temperature of this T_o will continue to rise following the change in variables described above.

The energy absorbed by the fluid in the gap will decrease, considering the object's volume decreases with time.

$$Q = m_f.C_f.dT \quad (6)$$

Please note that the specific heat depends on the porosity of the material. The equation can be made as follows,

$$C_{pm} = \phi C_f + (1-\phi)C_s \quad (7)$$

The specific heat of porosity of solid objects can be made as follows:

$$C_s = \phi C_w + (1 - \phi) C_p \quad (8)$$

Equation (8) substitutes to equation (7) will become

$$C_{pm} = C_p + \phi (C_f - C_p) + \phi (1 - \phi)(C_w - C_p) \quad (9)$$

This C_{pm} value continually changes because the water contained in the object evaporates, whereas C_f is considered unchanged because the temperature change is not too high.

The density also depends on the material porosity

$$\rho_{pm} = \phi.\rho_f + (1 - \phi)\rho_s \quad (10)$$

The density of solids is,

$$\rho_s = \phi.\rho_w + (1 - \phi)\rho_p \quad (11)$$

Equation (11) is entered into equation (10), then it will be:

$$\rho_{pm} = \rho_p + \phi (\rho_f - \rho_p) + \phi (1 - \phi) (\rho_w - \rho_p) \quad (12)$$

The porosity of the media is considered unchanged, but the solid object's porosity depends on time. The longer the porosity decreases so the above equation will change.

The change in porosity of a solid body depends on the speed of change in porosity. An equation can be made as follows:

$$\begin{aligned} d\phi &= \nu_\phi.dt \\ (\phi_i - \phi_{(pin)}) &= \nu_\phi.(t_i - t_o) \\ \phi_{(pin)} &= \phi_i - \nu_\phi t. \quad (13) \end{aligned}$$

Reducing the material's porosity depends on the speed of evaporation of the liquid contained in a solid body. The higher the temperature, the faster the evaporation of water. So, the reduction in porosity of a solid object can be calculated by the equation:

$$\begin{aligned} (\phi)_{n+1} &= (\phi)_n - a.(\phi)_n^b \\ (\phi)_{n+2} &= (\phi)_{n+1} - a.(\phi)_{n+1}^b \quad (14) \end{aligned}$$

Reduction of porosity of material can be calculated by the equation:

$$\begin{aligned}
 (\varphi)_{n+1} &= (\varphi)_n - c(\varphi)_n^d \\
 (\varphi)_{n+2} &= (\varphi)_{n+1} - c(\varphi)_{n+1}^d
 \end{aligned}
 \tag{15}$$

With the known reduction of porosity of solid objects, the thickness of porosity of the material can be calculated by the equation:

$$L = \frac{Lp}{(1-\varphi)(1-\varphi)}
 \tag{16}$$

From the elaboration of these formulas, it is known that the porosity of a single material and the porosity of the media stack can affect the value of L (thickness). It should be noted that the drying of agricultural products is very different from that of non-agricultural products. In the drying process, water evaporation occurs, which causes the cloves to shrink so that the volume decreases and the porosity in the clove decreases. Then this causes a reduction in the porosity of the clove pile because the stacked cloves are more tightly arranged so that the air gap narrows.

3 RESULTS AND DISCUSSIONS

The simulation conditions can be arbitrary, but the example here is made with the following conditions: The initial thickness of the porous object is 3 cm. The average rate of decline in the porosity of solids is made $a = 0.01$ and $b = 3$. The average rate of decrease in the porosity value of the total object is $c = 0.002$ and $d = 2.5; 3; 3.5$. A reduction in average thickness is made. The final temperature at the top of the object depends on the simulation results. The total time required for the drying process depends on the simulation. The constant temperature at the bottom of the porosity material of 70°C . The thermal conductivity of solid materials varies according to the reduced water content in them. The value of the heat conductivity of porous materials varies according to the conductivity of other materials. The effect of the thickness of a porous object on its density, from Figure 3, can be seen that the thicker the object, the smaller the density. Due to the heating of the porous object and the vaporized tone, shrinkage occurs, resulting in the density decreases. The thickness of the material's porosity will affect the specific heat; as shown in Figure 4, the thicker the porous object, the greater the specific heat, but the thicker the specific heat decreases at a certain thickness.

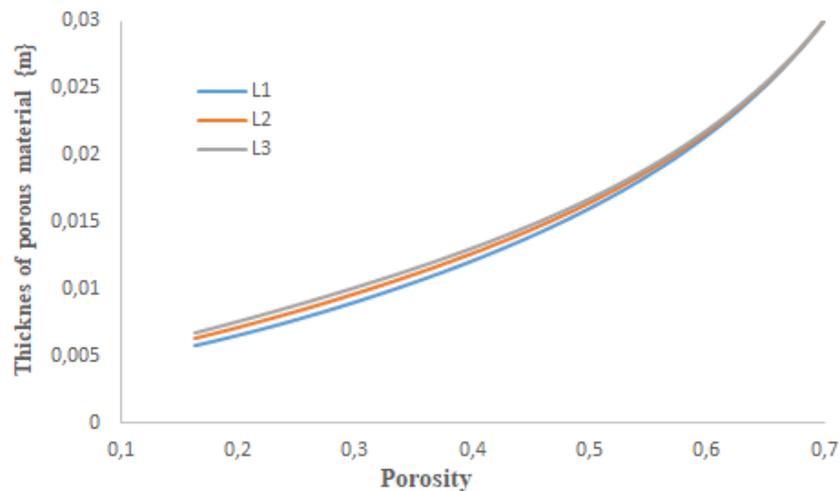


Figure 2. The effect of solid material porosity on material thickness

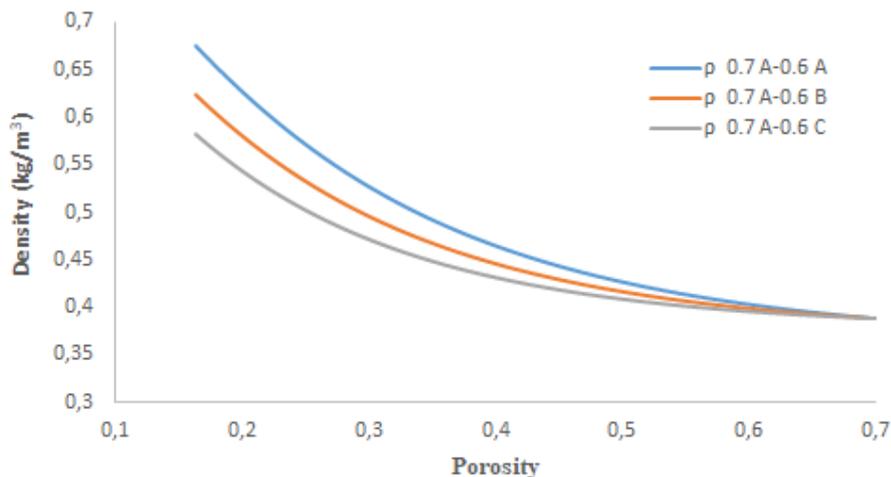


Figure 3. The effect of solid material porosity on density

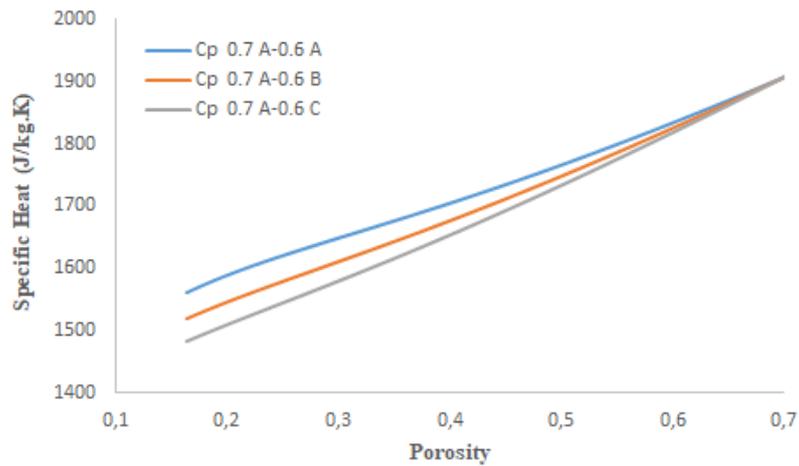


Figure 4. The effect of the thickness of the porosity of the material on the Specific heat

Thermal conductivity for objects whose arrangement is considered parallel is influenced by the thickness of the material's porosity; as shown in Figure 5, the thicker the object, the greater the thermal conductivity. Still, the thicker the thermal conductivity will be at a certain thickness, and the line is not linear. The amount of temperature on the upper surface of a porous object is influenced by the object's thickness. As shown in Figure 6 shows, the thinner the object, the higher the temperature. The relationship between the object's thickness and the temperature is not linear, approaching a hyperbola. The object's thickness will affect the temperature changes on the object's surface, as shown in Figure 7; the thicker the object, the longer the time needed for temperature changes. The relationship between the object's thickness with temperature changes is not linear.

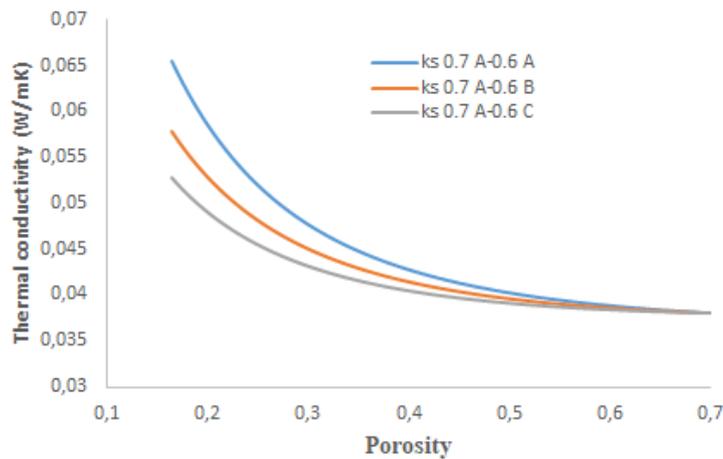


Figure 5. The effect of solid material porosity on combined thermal conductivity

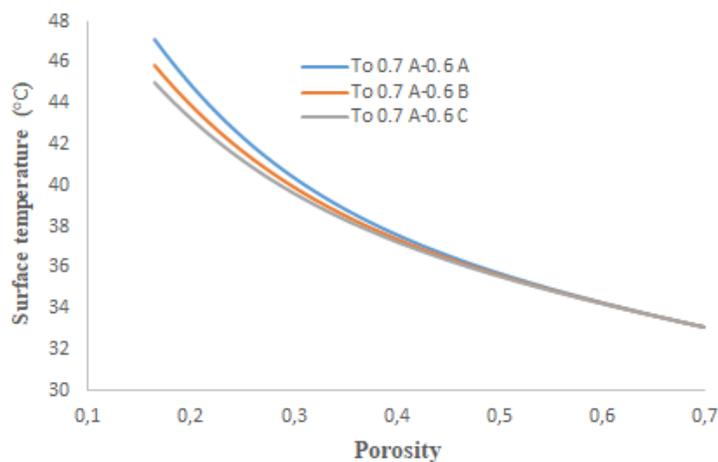


Figure 6. The effect of material porosity on the temperature at the top surface of the material

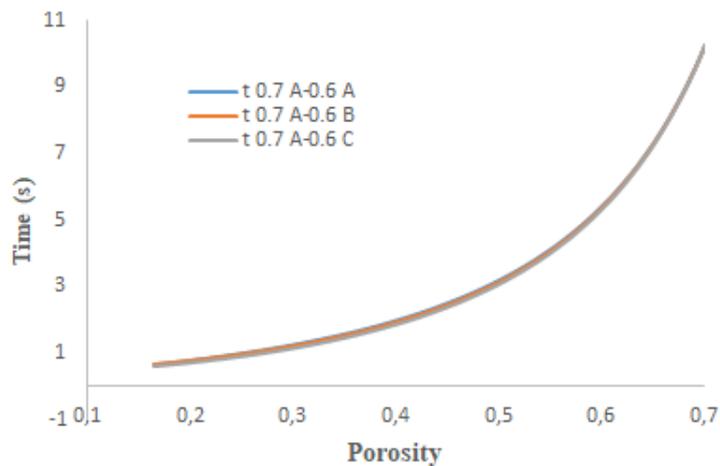


Figure 7. The effect of material porosity on time for temperature change (s)

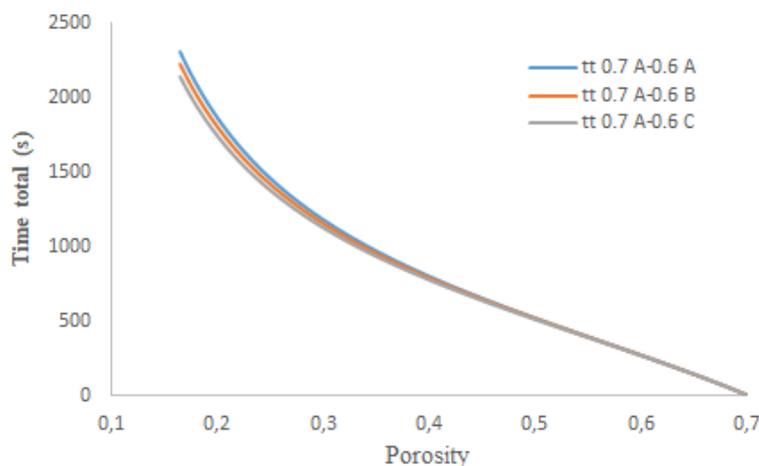


Figure 8. Total Time required to reduce material

The thickness of the object influences the shrinkage time of the object. As shown in Figure 8, the smaller the object, the longer it takes to shrink. The relationship between the thickness of the object and the time required for shrinkage is not linear.

4 CONCLUSIONS

Based on the research and simulation, the following conclusions were down.

1. The porosity of the material (cloves) and the porosity of the clove pile can be used to determine the thickness of the pile during drying process
2. The porosity of the material affects the density, specific heat, heat conductivity, surface temperature of the pile, changes in the surface temperature of the pile, and changes in time during drying process

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