The Effect of Porosity on The Temperature Spectrum Area and Heat Transfer in Chamber with Porous Media Under the Saturated Vapour Flow

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Abstract. This study aims to determine the porosity effect on the temperature spectrum area and heat transfer in chamber containing porous media. Porous media is modelled in a chamber and fluidized tangentially. The porosity value of porous media is varied by 10%, 20%, 30%, 38%, and 40%. Fluid flowed and at the same time used as a heat source is saturated vapour with a temperature of 323 K with an entry speed into the chamber of 2.5 m/s. The ambient temperature outside the chamber is kept constant at 298 K, while the chamber bottom plate temperature, which is also the heat-sink is kept constant at 283 K. The porous media material is aluminium. This research was carried out using ANSYS Workbench 14.5, which solve the equation for mass, momentum, and energy conservation. The results of the study show that porosity affects the temperature spectrum area in the vapour channel and inside the porous media layer. The smaller porous media porosity, further expanding the high-temperature spectrum in the vapour channel, but constricting the low-temperature spectrum in both the vapour channel and porous media layer. Together with convection heat, porosity plays an important role in forming three patterns of temperature distribution along the vapour channel. In the heat transfer in the porous media layer, even though the conduction effect is stronger than convection, but the effect of temperature difference between porous media surfaces is greater than the effect of porosity.

1. Introduction
To control the heat transfer rate in the internal flow, such as fluid flow in the pipe, duct, etc., there are several ways, including changing the fluid flow turbulence level and / or changing the contact surface area [1]. This study focused on efforts to control the heat transfer rate through changing the contact surface area between fluids and solid particles using porous media variations in porosity. Porous media is a continuous solid phase in which there are many empty spaces or pores. For example: sponges, cloths, paper, sand, bricks, rocks, some packing used in the distillation column, adsorption, catalyst, etc. Empty space (void fraction) contained in porous media may or may not be interconnected. Holes that are spread in porous media create cavities that cause fluid to pass through it. This results in greater heat transfer surface area in porous media materials compared to solid material.

In 2000 research was performed on porous media to find out heat transfer simulated using random porosity on the channel and in laminar flow state. The random porosity applied in porous media aims to increase heat transfer, and use the Kinderman-Ramage method to obtain its random porosity. The results
obtained from the study show that greater porosity in porous media can provide higher heat dissipation [2].

In 2011 an experimental study of laminar condensation on porous media was conducted to find out the ambient temperature treatment effect on dynamic flow lateral migration of condensate on porous media with different humidity. The experimental results prove that the condensate flow observed was not only uniform (periodic dominant), but also found non-uniform flow (non-periodic dominant), even chaotic-propagation in some cases of condensate flow were found [3]. Then in 2015 a simulation study was conducted on the effect of porous media porosity on hot fluids and cold fluids mixture. The results show that the smaller porous media porosity results in decreasing temperature fluctuations and greater effective thermal conductivity [4].

For temperature differences that are not too large, there are two types of heat transfer that occur in porous media, namely conduction heat transfers and convection heat transfer. $Q_{\text{cond}}$ conduction heat transfer that occurs in this study is formulated as follows [5].

$$Q_{\text{cond}} = -kA \frac{T_1 - T_2}{\Delta x} \quad (1)$$

Where $k$ is thermal conductivity, $A$ is the area penetrated by heat, $(T_1 - T_2)$ is the temperature difference, and $\Delta x$ is the thickness of the layer penetrated by heat.

Whereas $Q_{\text{conv}}$ convection heat transfer is as follows [6],

$$Q_{\text{conv}} = -hA(T_w - T_\infty) \quad (2)$$

Where $h$ is the convection heat transfer coefficient, $A$ is the area penetrated by heat, $T_w$ is wall temperature, and $T_\infty$ is the saturated vapor temperature. Meanwhile, in porous media, the $K_{\text{eff}}$ effective thermal conductivity value of porous media with voids filled with saturated vapor can be determined by equation [3]:

$$K_{\text{eff}} = \left[ \left( \frac{1 - \varepsilon^{2/3}}{\left(1-\varepsilon^{2/3}\right) + \varepsilon^{1/3}(kp/k_a)\varepsilon^{1/3}} \right) \right] kp \quad (3)$$

Where $\varepsilon$ is porosity, $k_p$ is the porous media particles thermal conductivity, and $k_a$ is the saturated vapor thermal conductivity.

2. Method

This research was performed using the CFX software package contained in ANSYS 14.5 Workbench. The modeling and test section of the porous media installation in the chamber and the ambient conditions used in this study can be seen in Figure 1.

The independent variable used in this study was porous media porosity which was equal to 10%, 20%, 30%, 38%, and 40%. While the dependent variable was a spectrum of temperature profiles and heat transfer in porous media. The controlled variable in this study was that the ambient temperature for the upper wall of the chamber was maintained at 298 K and the porous media bottom plate, which at the same time for the heat sink, was maintained at 283 K. Saturated vapor was exhaled through the inlet chamber with a velocity of $V_{in}$ 2.5 m/s and a $T_{in}$ temperature of 323 K. With this blowing then the saturated vapor toward porous media and is flowing tangentially.

The steps sequence this research was that after the porous media chamber installation design has completed, meshing was performed on each domain of the porous media chamber and then the boundary condition needed was determined. After execution, the spectrum of temperature profiles on porous media was obtained.
3. Results and Discussions

Based on five temperature spectrum types above, i.e. Figures 3, 4, 5, 6, and 7, it can be seen in each temperature spectrum of the porous media chamber, both in the vapor channel and in the porous media itself, with different porosity. For ease of analysis, in this discussion the temperature spectrum was divided into two parts, namely the high temperature spectrum, which consists of red and brown, and a low temperature spectrum, which consists of yellow, green, and light blue.

When viewed in the porous media section, the greater the porosity visible for each color spectrum (low), namely yellow, green and light blue, the more widespread. This is because the greater the porosity, the easier the saturated vapor, which also carries heat, penetrates the porous media layer, so that this easier penetration results in the wider spectrum of the yellow, green and light blue temperatures.
Figure 2. Cross section of the Porous Media Chamber

Figure 3. Temperature Spectrum at 10% Porosity

Figure 4. Temperature Spectrum at 20% Porosity

Figure 5. Temperature Spectrum at 30% Porosity
Then if viewed from the saturated vapor channel part, or inside along the fluid channel above the porous media. It can be seen that the smaller the porosity will form a high temperature spectrum area, i.e. red and brown, which are increasingly widespread, while the low temperatures area spectrum is getting smaller. This is because the smaller porous media porosity will make it more difficult for saturated vapor fluid to enter into porous media, so that convection heat transfer in the porous media gets weaker, or heat transfer that occurs only takes place by conduction. Therefore, the high temperature spectrum in the vapor channel becomes more 'stuck' on the porous media surface. This is what causes the high temperature area spectrum to grow with the decreasing porous media porosity.

As shown in figure 8, the evaluation points in this study were 11 points, where the eleven points were in each segment-1 or along the saturated vapor channel, segment-2 or above along the porous media surface, and segment-3 or in the middle along the porous media layer.
Figure 9 shows the temperature distribution along segment 1 or the vapor channel. It can be seen globally, that the graph formed shows the same tendency which is the farther the saturated vapor distance from the inlet, the more it decreases the temperature value. This is due, globally, the heat transfer occurrence from saturated vapor as heat source passes through the porous media vertically to the copper plate heat sink, along the channel, so that the decrease in temperature value occurs with increasing channel length due to heat release occurring continuously at each evaluation point, towards the heat sink on the porous media base.

Then, in each porosity, can be seen in figure 9 that the temperature distribution pattern can be classified into 3 pieces. That is, the pattern due to small porosity, namely 10% and 20%; medium porosity, which is 30%; and large porosity, which is 38% and 40%. In small porosity, namely 10% and 20% can be seen in areas with a distance of 40 mm - 60 mm there is an increase in temperature, i.e. to be positive, the temperature gradient value or means a decrease in the temperature deceleration value. This can be caused by two things, namely, the saturated vapor that passes through the inlet has a sudden expansion of hydraulic diameter from 8 mm to 20 mm so that the saturated vapor flow is not fully developed. Secondly, this small porosity results in more difficult saturated vapor fluid penetrating porous media voids, and this also contributes to the positive temperature gradient value on the vapor channel at this distance. In this small porosity, a decrease in the value of temperature deceleration also occurs again at a distance of 160 mm - 180 mm. This is suspected to be caused by a change in influence from the inlet with sudden expansion of the hydraulic-diameter toward the effect of the outlet with sudden hydraulic-narrowing of the vapor channel.

For medium porosity, which is 30%, it can be seen that at a distance of 40 mm - 60 mm the deceleration value of the temperature drop is present, but not as large as small porosity. This can be caused by the void loosening from porous media to be able to be passed by saturated vapor, so that the heat transfer that occurs is not only dominated by conduction between media particles, but also by saturated vapor convection directly to the heat sink on the porous media base. At a distance of 160 mm - 180 mm there is also a decrease in the temperature deceleration value. This is similar to that which occurs in small porosity, so that, at this medium porosity, this is also thought to be caused by a influence change from sudden hydraulic-diameter expansion to the effect of the outlet with sudden hydraulic-diameter constriction in the channel, not from porosity influence.

Whereas in large porosity, that is, 38% and 40% can be seen in 40 mm - 60 mm there is no longer a decrease in the temperature deceleration value, as occurs in small and medium porosity. This means that in large porosity, the saturated vapor penetration into voids is not a problem anymore. So
that the influence of the convection heat transfer that occurs is greatest among the varied porosity, besides the conduction heat transfer between the media particles still continues. A greater difference from the influence of this large porosity than on the small and medium porosity is seen at a distance of 60 mm - 160 mm. In addition to large porosity, the temperature deceleration gradient tends to decrease, or at a constant minimum. However, what occur in large porosity is instead showing deceleration in the decreasing temperature value which increases. This is due to the large porosity of heat transfer from saturated vapor to heat sink that penetrates the porous media per unit length, which is greater than other porosity. This causes the heat flow to the heat sink along the channel to be more rapid. Therefore, the decrease in temperature along the channel in this porosity is to show a high deceleration.

From the above review it can be concluded that there are three patterns for the temperature deceleration curve along the channel. That is, first, the curve pattern due to small porosity which shows the temperature deceleration along the channel with the channel temperature gradient acceleration and stagnation still occurring. Second, the curve pattern due to medium porosity, which shows temperature deceleration along the channel with decelerations stagnation still occurring, without acceleration, channel temperature gradient. Third, the curve pattern due to large porosity, which shows the highest temperature gradient deceleration along the channel without acceleration and only once there is a decelerations stagnation in the channel temperature gradient.

Figure 10. Temperature distribution along Segment 2

Furthermore, Figure 10 shows the correlation between the distribution value or temperature gradient to the increase in distance in segment 2, or the porous media upper face, with different porous media porosity. It can be seen in Figure 10, globally, that the graph formed shows the same tendency, namely an increase in temperature at a distance of 20 mm - 40 mm, a gradual decrease in temperature at a distance of 40 mm - 180 mm, and a sharp decrease in temperature at a distance of 180 mm - 220 mm. If it is assumed that the porous media presence influence is the same along the surface, it can be assumed that the porous media influence dominance at the porous media surface temperature is at a distance of 40 mm - 180 mm. This can be understood because at the distance range the decreases in temperature is quite smooth and gradual. Alias the porous media conduction effect to control the heat transfer is more dominant than convection.

However, the opposite occurs at a distance of 20 mm - 40 mm, and also at a distance of 180 mm - 220 mm. at both of these distances, where a drastic increase in temperature at a distance of 20 mm -
40 mm and a drastic decrease in temperature at a distance of 180 mm - 220 mm, is due to the more dominant role of convection from saturated vapor than conduction from porous media. At a distance of 20 mm - 40 mm, the drastic increase in temperature can be caused by the dominant influence of turbulence that occurs in the saturated vapor flow, which also penetrates into the porous media. This turbulence occurs due to the vapor channel sudden change above the porous media surface along this distance. As is known, the sudden change of this channel due to changes in hydraulic channel inlet diameter, by 8 mm, became suddenly large on the vapour duct channel, by 20 mm. This change in diameter causes the pressure in the saturated vapour flow to change suddenly, so that vortex and turbulence rise. Then, the porous media surface that was first penetrated by this turbulence is a surface that is about 40 mm apart, so that at this distance the porous media surface temperature has the highest temperature than the other surface.

**Figure 11.** Temperature distribution along Segment 3

The opposite condition of the 20 mm - 40 mm distance, is the change in temperature at a distance of 180 mm - 220 mm. at this distance a drop temperature occurs. It can be understood that if the conduction effect of porous media is fixed as at previous distances, then at this distance the convection effect from saturated vapour decreases dramatically. This reduction is caused by the sudden shrinking of the vapour channel, which originally had a hydraulic diameter of 20 mm on the duct turned into a hydraulic diameter of 8 mm at the outlet. So that at this distance there is no turbulence flow. What happens instead is the saturated vapour flow, which carries the vapour temperature in the porous media and on the porous media surface, pulled out of the porous media to the outlet channel that is above the porous media surface. This convection heat pull event makes the temperature on the porous media surface drastically decrease.

Furthermore, Figure 11 shows the correlation between the distribution value or temperature gradient to the length increment in the porous media, or in segment 3, with different porosity. It can be seen in Figure 11, that the graph formed shows the same tendency that is the farther the saturated vapor distance from the inlet, the lower the temperature will be. Where the temperature decreases linearly at a distance of 20 mm - 60 mm, while at a distance of 60 mm - 220 mm the decrease in temperature takes place logarithmic. There is no surge in temperature increase or a drastic drop in temperature in the porous media layer, or segment 3, this can be explained as follows. At a distance of 20 mm - 40 mm in the porous media the temperature decreases linearly, although on the porous media surface (segment 2) also on the vapour channel (segment 1) both show an increase. This proves that the conduction heat transfer
influence in porous media is more dominant, compared to the convection heat transfer from saturated vapour. Compared with a distance of 60 mm - 220 mm, the convection influence at a distance of 20 mm - 60 mm is still there but weak. While at a distance of 60 mm - 220 mm, the convection effect weakens to a distance of 180 mm, then the peak is weak at a distance of 220 mm or at the end of the porous media layer. This discussion can conclude that in this segment, or in porous media, the effect of convection from saturated vapour is the weakest compared to other segments, the porous media particles conduction has the largest dominance compared to other segments.

Figure 12. The heat transfer rate in porous media to distance

Figure 12 shows a correlation graph between the heat transfer rates with different distances on porous media with different porosity. At a glance, the graph above has a tendency similar to the temperature distribution graph on porous media surfaces or in segment 2. This is due to the calculation of the heat transfer rate in porous media using equation (1) where the heat transfer rate is a function of porous media $K_{eff}$ effective thermal conductivity and the temperature difference between the top surface of the porous media and the lower face or the copper plate temperature which is kept constant, $(T_1 - T_2)$. Here, it can be seen that the upper face temperature difference effect on the porous media $(T_1 - T_2)$ caused by temperature changes dynamics, especially in the upper face, has a greater effect than porous media $K_{eff}$ effective thermal conductivity changes due to changes in saturated vapour $k_a$ thermal conductivity caused by changes in temperature inside porous media itself. So because the effect of changes in temperature difference is more dominant than the effect of changes in effective thermal conductivity, the question why the graph of the heat transfer curve in figure 12 is almost the same as the temperature distribution on the explained porous media surface.

4. Conclusions

Based on the discussion above, it can be concluded that porous media porosity affects the temperature spectrum distribution area; temperature distribution on the vapor channel, and in the porous media layer; and heat transfer on porous media. In the temperature spectrum area, the smaller porous media porosity, further expanding the spectrum of high temperatures in the vapor channel, but narrowing the area of the low temperature spectrum in both the vapor channel and porous media layer. Regarding the temperature distribution on the vapor channel, it can be concluded that there are three temperature deceleration patterns along the vapor channel. Where, all three patterns of temperature distribution are
influenced by organized or a combination of convection from saturated vapor and also conduction from porous media particles which are a function of porous media porosity. That is, first, the curve pattern due to small porosity, which shows the temperature deceleration along the channel with the channel temperature gradient acceleration and stagnation still occurring. Second, the curve pattern due to medium porosity, which shows temperature deceleration along the channel with decelerations stagnation still occurring, without acceleration, channel temperature gradient. Third, the curve pattern due to large porosity, which shows the highest temperature gradient deceleration along the channel without acceleration and only once there is decelerations stagnation in the channel temperature gradient. Against the temperature distribution in porous media. With the fact that the temperature decreases linearly at a distance of 20 mm - 60 mm, and even at a distance of 60 mm - 220 mm, the temperature decrease is logarithmic, and there is no increase in temperature rise or a drastic decrease in temperature in the porous media layer, it can be concluded that the effect of the conduction heat transfer in the porous media layer is more dominating, where porosity is involved in it, compared to the convection heat transfer from saturated vapour. Against heat transfer in porous media. With the evidence that the effect of the upper-face temperature difference on the porous media face is more influential, than the \( K_{eff} \) effective change in thermal conductivity as a function of porosity \( \varepsilon \) and changes in \( k_s \) saturated vapor thermal conductivity, it can be concluded that porosity has a weak effect compared to the temperature difference in heat transfer that penetrates porous media.

REFERENCES

[1] Incropera, F.P., and DeWitt, D.P., 1990. *Fundamentals of Heat and Mass Transfer*. New York: Mc. Graw Hill, Ltd.
[2] Fu, W.S., and Huang, H.C., 1999. *Effect of a Random Porosity Model on Heat Transfer Performance of Porous Media*, International Journal of Heat and Mass Transfer, 42 (1), pp. 13-25.
[3] Siswanto, E., Katsurayama, H., and Katoh, Y., 2011. *Instability on Condensate Propagation in Porous Media*, International Journal of Mechanics, 5(4), pp. 327-335.
[4] Wang, Y., and Lu, T., 2015. *Influence of the Partical Diameter and Porosity of Packed Porous Media on the Mixing of Hot and Cold Fluids in a T-Junction*, International Journal of Heat and Mass Transfer, 84, pp. 680-690.
[5] Cengel, Y.A., 1998. *Heat Transfer; Practical Approach*. New York: Mc. Graw Hill, Ltd.
[6] Holman, J.P., 1993. *Heat Transfer, 6th edition*, New York: Mc. Graw Hill, Ltd