An Experimental Study in the Fundamentals of Evaporation from Porous Structure

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ABSTRACT

The heat pipe is one of the applications for evaporative heat transfer in porous media. The metal wick in a heat pipe has high thermal conductivity and water as a working fluid has high latent heat of evaporation that enhances the cooling effects. Evaporation rate affects the heat transfer capacity and efficiency of the heat pipe. Therefore, evaporative heat transfer from porous media in heat pipes and vapor chambers plays an important role in determining their overall performance. This paper is to study the fundamental evaporation characteristics and its relationship with regard to the different porosities. Samples with different random configurations, thickness ranging from 5mm to 40mm, and balls sizes of the sizes from 5mm to 20mm were tested at three different (60°C, 80°C and 100°C) heat source temperatures. Experiment results were analyzed at steady state arrangement. It was found that the evaporation rate can be improved by varying the particle size and the porosity. Decreasing the layer thickness could enhance the evaporation rate but it has less effect and could cause the drying out to happen easily. To further validate the capability of evaporation from porous structure, the results were compared with the evaporation from water only. It showed the rate of evaporation was obviously increased for evaporation from porous structures.

Keywords: porous media, wick structure, porosity, evaporation mechanism, heat pipe, vapor chamber

1. INTRODUCTION

The heat pipe is one of the well known thermal solutions and applicable in many applications for both space and terrestrial. The principle of evaporative heat transfer in porous media is especially applied in heat pipes, which are simple but effective heat transfer devices (Cengel, 2006). The inner tube of a heat pipe is lined with porous material called the wick structure. The metal wick in the heat pipe consists of man-made porous media. Porous media is a solid matrix that consists of many pores or voids filled by fluid that permeates in between the solid. The wick in a heat pipe provides a mechanism for the working fluid to return to the evaporator and facilitates the working fluid to distribute evenly over the evaporator surface.

The wick may consist of different types of structures or materials. It creates a porous medium with a different porosity, permeability, thermal conductivity and heat transfer coefficient. Most of the researchers have found that, the heat transfer performance can be enhanced by optimizing the wick characteristics such as pore sizes, porosity, permeability, wick thickness, and wick orientation. Therefore, wick parameters have received by far the most attention in literature.

Hanlon and Ma (2003) developed a two dimensional model and conducted an experimental investigation to predict the effective parameters during evaporation heat transfer in sintered porous media. The results showed that selecting an appropriate particle size, wick porosity, and wick thickness would enhance the evaporation heat transfer coefficient. The effects of the wick’s parameters in sintered loop heat pipe was analyzed by Zan et al. (2004) and got a similar finding as Hanlon and Ma (2003) which combination of optimum parameter of wick structure would enhance the heat transfer performance. Li and Peterson (2006) then investigated the effects of volumetric porosity and mesh size during evaporation/boiling in thin capillary wicks under steady state conditions at atmospheric pressure. The results indicate that, critical heat flux is dependent on both volumetric porosity and mesh size. However, evaporation/boiling heat transfer coefficient is more significantly dependent on mesh size than volumetric porosity. A study by Mahjoub and Mahtabroshan (2008) investigated the effects of wick porosity on heat pipe behavior through numerical simulation. The simulation results showed that when the porosity increases, the temperature difference between the evaporator and condenser is increased due to the decrease in effective thermal conductivity of the wick structures. Sabir et al. (2008) studied the effects of porous layer parameters in evaporators...
experimentally. They found that, there is an optimum particle size for each layer thickness that is associated with maximum heat transfer coefficient and that the particle size has more pronounced effects than layer thickness.

The optimization of wick structure was investigated extensively in order to get the greatest heat transfer performance. However, a study of the evaporation mechanism in porous media remains elusive. In response to this, the purpose of this paper is to study the fundamental evaporative heat transfer in porous media. This study focused on the effects of porosity on evaporation rate as well as the effects of some other factors like particle size, porous layer thickness, and effective thermal conductivity.

2. EXPERIMENTAL SETUP AND PROCEDURE

The experimental apparatus used to study the fundamental evaporation mechanism in porous media and effects of porosity on evaporation rate is shown in Figure 1. It consists of a container, heater used as a heat source, electronic weighing scale, thermal insulation, thermocouples, metal balls, water level indicator, and control system. The operating temperature is maintained below the liquid saturation temperature (for water is 100°C) at atmospheric pressure (101.325 kPa) to avoid the boiling. Water is chosen because it has a greater specific heat capacity and latent heat compared to other common substances.

Heat was applied to the container by cast aluminium heater with a built in K-type thermocouple placed under the container. The heater has an effective heating area the same as the container base. When the container is pressed against the heater, imperfection of contact surface inherently arises from limitations in manufacturing technology, causing a less efficient conduction of heat (i.e. contact resistance). The contact resistance between heater and container is reduced by applying a metal plate in between them. This metal plate is Tin/Lead solder and its melting point is at 188°C. Tin/Lead solder is slowly heated prior its melting point in order to soften it, then filled the air gap to form a much better contact surface. To avoid heat losses from the side wall, all the external walls of container, heaters and piping tube were insulated with Superwool thermal insulation.

The porous medium was created using the metal balls. The metal balls were chosen as they have a better thermal conductivity than non metallic balls. For cooling purpose, higher thermal conductivity would increase the heat removal rate. The porosity can be measured experimentally and calculated by:

\[
\phi = \frac{V_v}{V_B}
\]

where \(V_B\) is the bulk volume and \(V_v\) is the volume of void space.

The experimental procedure is as follows:

Metals balls are placed in the container until it reaches a certain height with random arrangement as shown in Figure 2. The bulk volume can be calculated using the container inner length and width multiplied by the height of the porous medium that is created by the metal balls. Water is filled until it fully permeates in between the voids and the water level reaches the top of metal balls surface. The volume of filled water, which denotes the volume of the void space, is recorded. A variety of porosity can be created by altering the ball arrangements. The parameters of the tested samples are listed in Table 1.

![Figure 1: Schematic diagram of the experimental set up](image)
The weighing scale is placed under the insulated heater to measure the mass changes of water during evaporation. The water evaporates as it gains enough kinetic energy to escape into the vapor phase. This causes the water level to drop as well as to decrease the mass of water. In order to determine the water evaporation rate at different temperatures, the mass changes are recorded at each predetermined time interval at each constant temperature. The energy loss from evaporation can be determined by

\[ Q_{\text{evap}} = \dot{m} \cdot \Delta H \]  \hspace{1cm} (2)

where \( \dot{m} \) is the evaporation rate and \( \Delta H \) is the enthalpy change in vaporization.

A dehumidifier is used to set the room humidity in order to achieve the results consistency. The room humidity is set at 65% and temperature of air-conditioner is set at 18°C. An ambient temperature-relative humidity logging system is installed to read the room temperature and room humidity.

When heat is applied, the temperatures of container, metal ball and water are increased gradually. The heat is transferred through the conduction and convection until the water surface temperature is above liquid saturation temperature. Once the water surface temperature reaches the liquid saturation temperature, evaporation occurs. The temperature of container, metal balls and liquid will continuously increase until it reaches a steady state where metal balls and water remain at an equivalent temperature. All the data readings will be taken during steady state. The experiment is run for minimum 3 hours in order to achieve the steady state. The evaporation rate is calculated during the first hour of steady state. During steady state, the temperature does not change with respect to time and can be expressed as

\[ \frac{\partial T}{\partial t} = 0 \]  \hspace{1cm} (3)

where \( \partial T \) is the change in temperature and \( \partial t \) is the change in time.

The water level is measured and recorded before the evaporation begins. The water temperature is measured using the Omron K-type thermocouple. The temperature signal is monitored every second. The data is generated by NI USB 9211A data acquisition with NI LabView SignalExpress software.

A control system with temperature controller, solid state relay (SSR) and pulse width modulation (PWM) shown in Figure 1 is installed to achieve steady state by setting heater temperature to a desired control temperature or setpoint. Temperature controller accepts heater built-in thermocouple as input and compares its actual temperature to the setpoint and provides an output

<table>
<thead>
<tr>
<th>Table 1. Specification of Test Samples</th>
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<tr>
<td><strong>Heater Temperature</strong></td>
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<td><strong>Random Arrangement</strong></td>
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<tr>
<td><strong>Metal balls size (mm)</strong></td>
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<td><strong>Porosity (%)</strong></td>
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<tr>
<td><strong>Water thickness (mm)</strong></td>
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to SSR control element. The SSR will then turn on the heater when the temperature is below and turn off the heater when temperature is above the setpoint. The PWM is used to control the fluctuation of heater’s temperature within ±0.5°C.

The simplified thermal resistance network for experimental setup shown in Figure 1 is composed of 4 different resistances (interface resistance, wall resistance, porous structure resistance, and convection resistance) arranged in series as illustrated in Figure 3.

All the four resistances could be described as

\[ R = \frac{l}{kA} \]  

(5)

where \( l \) is the effective thickness between two fixed temperature points, \( k \) is the thermal conductivity between the same two temperature points, and \( A \) is the surface area.

The overall system thermal resistance can be expressed as

\[ R_s = \frac{(T_{\text{set}} - T_{\text{ambient}})}{Q} \]  

(6)

where \( T_{\text{set}} \) is the setpoint temperature, \( T_{\text{ambient}} \) is the ambient temperature, and \( Q \) is the heat transfer rate.

The temporal temperature distribution of the water temperature for different heaters temperature is shown in Figure 6. As shown in Figure 6, for higher heater temperature, the time taken to reach the steady state is substantially longer. As can be seen there, it is about 2400s for 60°C and 80°C setpoint to reach the steady state. It took about another 1500s for 100°C. This is because the heater is supplied with the same power input. Thus, with greater mass and temperature difference, the time taken to reach the steady state is longer.

All the data were taken and analyzed after the system had reached its steady state. Sample with single and mix size balls were analyzed separately as they give a different scenario of results.

At 60°C setpoint (or heater temperature), the water temperature was in the range of 41°C to 45°C as shown in Figure 7, which is 15°C to 19°C lower than the setpoint temperature. This is due to the thermal resistance between the heater and the top surface of water. The thermal resistance will decrease when the heat transfer rate is increasing and reach a constant value when heat transfer rate is more than a certain value.

For balls that arranged randomly, the effective thermal conductivity can be determined by using following equation for packed sphere.

\[ k_{\text{eff}} = \frac{k_l\left[(2k_i + k_j) - 2(1 - \phi)(k_i - k_j)\right]}{(2k_i + k_j) + (1 - \phi)(k_i - k_j)} \]  

(7)

where \( k_l \) is the liquid thermal conductivity, \( k_w \) is the wick thermal conductivity, \( \phi \) is the porosity.

3. RESULTS AND DISCUSSION

Two basic modes of heat transfer during evaporation (Faghri, 1995) are shown schematically in Figure 4 and 5 respectively. There are conduction-convection mode, where the water is just saturating the porous structure, and receding liquid mode, where the liquid layer recedes into the porous structure.
network is shown in Figure 3.

Typical test results are shown in following Figure 6 and 7. The results are presented in terms of porosity and evaporation rate.

Figure 6. Transient temperature response of the water temperature.

Figure 7. The water temperature for the first hour at steady state.

3.1 Comparison of evaporation rate

First, the evaporation rate on each sample is investigated. The porous medium is created by the metal balls that are arranged randomly as shown in Figure 2. The experiments were run and analyzed at three different heater (or heat source) temperatures (60°C, 80°C, and 100°C).

From the results shown in Figure 9, evaporation rate is greater at higher setpoint. Therefore, higher heat input increases the evaporation rate but it also increased the dryout rate. Also, room humidity and temperature are two main factors that will influence the evaporation rate. Lower humidity and higher ambient temperature will increase the evaporative heat transfer rate. As seen in Figure 8, 5&10mm balls size gives the highest evaporation rate among the mix size samples. This is because the room humidity is particularly lowest and the room temperature is relatively high compared to other samples as shown in Figure 8 and Figure 9 respectively.

Figure 8. The relation between evaporation rate and relative humidity.

Figure 9. The relations between evaporation rate and room temperature.

3.2 Effects of particle size on evaporation rate

The water temperature of the each sample was taken at the bottom part of the container due to receding liquid mode. The samples were tested with various particle sizes and arrangements, thus creating different porous layer thicknesses. Bigger particle size gives thicker layer thickness. This prolonged the time of dry out happening. Also, the water temperature is higher for bigger particle sizes as shown in Figure 7.

Particle size affects evaporation rate too. As seen in Figure 8 above, bigger particle size gives higher evaporation rate. This is because the temperature difference between water in Figure 7 and room temperature in Figure 8 is greater for bigger particle size as it has a thicker layer thickness. When the temperature difference is greater, it increases the heat transfer rate and hence improves the evaporation rate.
However, bigger particle size with thicker layer thickness would have greater thermal resistance hence giving a lower heat transfer rate but it could be affected by the porosity which may increase the heat transfer rate. This will be later discussed in Section 3.3.

In addition, bubbles forming will slow down the evaporation heat transfer. Samples with smaller pore sizes are more likely to trap the vapor or bubbles.

3.3 Effects of porosity on evaporation rate

Experimental results describing the relationship between porosity and evaporation rate is shown in Figure 10. The results are compared for the samples at three different heater temperatures. The sample with the smallest ball sizes did not necessarily give the lowest porosity as indicated in Table 1. One possible explanation for 5mm balls giving higher porosity than 10mm balls is that the samples were arranged randomly. However, it may be due to the flooded surface for the sample with 5mm balls. This is because of difficulties in accurately controlling the water level in very thin layer.

As stated in Section 3.2, increase in ball sizes will increase the thermal resistance and hence decrease the evaporation rate. But, Figure 10 shows that porosity does affect the evaporation rate. As seen in Figure 10, the greater the porosity, the higher the evaporation rate. It can also be explained theoretically. With lower porosity, the effective thermal conductivity shown in equation (10) is decreased and thus gives lower thermal resistance hence, increasing the heat transfer rate and enhancing the evaporation cooling effects. However some samples did not give the same result due to the effects of layer thickness and the temperature difference stated earlier.

In addition, due to the latent heat of vaporization of water is constant and equal to 2260kJ/kg, so it means that, the greater the amount of water (i.e. the higher the porosity) and more heat can be absorbed by water. But, thermal conductivity of water is lower than thermal conductivity of the rigid structure. Hence, creating a porous structure with high thermal conductivity metal and high porosity will enhance the evaporation cooling effects.

![Figure 10](image1.png)

Figure 10. The relations between porosity and evaporation rate at different heater temperatures.

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![Figure 11](image2.png)

Figure 11. The evaporated water mass for the first hour at steady state. (single sizes samples)

![Figure 12](image3.png)

Figure 12. The evaporated water mass for the first hour at steady state. (mix sizes samples)

3.4 Comparison of evaporation rate between porous media and reference condition

The evaporation rate of water from porous media for single and mix size balls was then compared with that from water only. The results are shown in Figure 11 and 12 respectively. As
seen from Figure 7, the water temperature gives 44°C, 55°C, and 64°C respectively for heater temperature set at 60°C, 80°C, and 100°C.

At 60°C setpoint, evaporation from porous media apparently gives a higher rate compared to evaporation from water only as shown in Figure 11 and 12 for both single and mix size samples.

However, when the heat source temperature was set at 100°C, the evaporation rate of water was higher than the others. One of the possible reasons is high rate of vapor formation at 100°C. This vapor may trap in the porous media and cause the lower evaporation rate.

4. CONCLUSION

In this paper, we have presented the experimental results on evaporative heat transfer characteristics and its relationship with regard to the different porosity heated at atmospheric pressure and below the boiling point. The experimental results show that creating a porous structure with high thermal conductivity metal and high porosity will enhance the evaporation rate. It is also found that the greater the temperature difference between water and room temperature, the better the evaporative cooling effects. Also, porous layer thickness has less significant effects compared to the porosity. However, chrome steel balls used in these experiments are prone to atmospheric oxidation and rusting in humid environment. Therefore, further investigations using non-corrosive materials are mandatory to determine the literal correlation and effects between the porosity and evaporation rate. Maintaining the water at a constant level is essential to simulate the real case application. Also, taking the water surface temperature is essential for results analysis.

NOMENCLATURE

\( A \quad \text{Area, m}^2 \)
\( \Delta H \quad \text{Enthalpy change in vaporization, J/kg} \)
\( k \quad \text{Thermal conductivity, W/m.K} \)
\( l \quad \text{Porous layer thickness, m} \)
\( m \quad \text{Evaporation rate, kg/s} \)
\( Q \quad \text{Heat energy, J} \)
\( R \quad \text{Thermal resistance, K/W} \)
\( T \quad \text{Temperature, K} \)
\( t \quad \text{Time, S} \)
\( V \quad \text{Volume, m}^3 \)

Greek symbols

\( \phi \quad \text{Porosity} \)

Subscripts

ambient \quad \text{Ambient}
B \quad \text{Bulk}
eff \quad \text{Effective}
evap \quad \text{Evaporation}
l \quad \text{Liquid}
o \quad \text{Overall}
s \quad \text{Solid}
set \quad \text{Setpoint}
v \quad \text{Void space}

REFERENCES


