Characterization of the External Thermal Resistance of the Condenser Using the Evaporative Cooling with Porous Medium

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*Abstract*— In this study, we theoretically and experimentally analyzed the effect of evaporative cooling using a screen mesh that is attached to a condenser surface on the external thermal resistance of a condenser. The evaporation rate of water filled into the screen mesh was theoretically calculated using the Lewis number which can convert heat transfer to mass transfer. In addition, the maximum flow rate absorbed by the screen mesh was determined by the capillary limit condition, considering liquid pressure drop through the screen mesh with Brinkman-Extended Darcy Equation. Especially, the super hydrophilic screen meshes with mesh number M100, M150, and M200 were manufactured and attached to an aluminum plate simulating the condenser surface. The external thermal resistance of the condenser was measured according to varying input power, air velocity, and mesh number. Based on the results, it is shown that the theoretical results were well matched with experimental results. Finally, we presented when using evaporative cooling with screen mesh, the external thermal resistance of the condenser was reduced by an average of 92% and the maximum heat transfer rates varied depending on the mesh number.

Keywords—External Thermal Resistance, Evaporative Cooling, Hydrophilic screen mesh

# Introduction

As energy consumption increases rapidly in various industries, high heat fluxes (>1 kW/cm2) are expected in high-power systems. So, the volume of conventional cooling systems will increase exponentially with the expected heat load. Especially, the condenser volume typically accounts for more than 50% of the total volume of the thermal management system for high-power applications. Therefore, it is important to reduce the volume of the thermal management systems, enhancing the cooling performance of the condenser. An analysis results using a simple condenser thermal resistance model clearly showed that external condenser resistance accounts for over 70% of the total resistance. Moreover, most previous results have been focused on reducing internal thermal resistance of a condenser. So, in this study, we theoretically and experimentally analysed the external thermal resistance on a condenser surface using evaporative cooling with hydrophilic screen mesh to reduce the external condenser resistance dramatically.

# Theoretical Approach

## External Thermal Resistance

Figure 1 is a schematic diagram of the external condenser surface using evaporative cooling with a porous medium. The external thermal resistance of the condenser was composed of the thermal resistance of the porous medium

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Fig. 1. Schematic model of condenser surface

layer filled with water and the thermal resistance generated by evaporation, since the thermal resistance of the condenser wall is very small and can be ignored. The external thermal resistance equations of a condenser using evaporative cooling using a porous medium can be defined as in (1) to (3).

 (1)

 (2)

 (3)

where, *A*, *k*eff, *k*f, *k*s, *q*in, *R*evap, *R*external, *R*porous, *T*∞, *T*w, and *t* represent the area of ​​the condenser surface, effective thermal conductivity, thermal conductivity of water, thermal conductivity of the porous medium, heat amount, thermal resistance due to evaporation, external thermal resistance of the condenser, thermal resistance of the porous medium layer, air temperature, water temperature, thickness of the porous medium, and porosity of the porous medium. In order to obtain the external thermal resistance of the condenser using Equations (1) to (3), the temperature of the water must be known. It was assumed that the heat is dissipated from the condenser wall under a constant heat flux condition, and the temperature of the porous medium and the temperature of the water are the same. It was also assumed that the thickness of the porous medium is very thin and the temperature is constant in the thickness direction. Therefore, as shown in Fig. 1, the energy equation for finding the temperature of water in the x direction is expressed as (4), and the boundary conditions at this time are as (5).

 (4)

, (5)

where *h*fg, *L*, and represent the latent heat of water, the width of the condenser, the amount of evaporation, and the amount of heat transfer due to evaporation.

The water required for evaporative cooling is absorbed from the reservoir at both ends of the condenser, so the water temperature at both ends is assumed to be ambient temperature. Especially, in order to obtain the analytical solution of (4), the amount of heat transfer due to evaporation must be known, and in order to know the amount of heat transfer due to evaporation, the amount of water evaporation must be obtained. To calculate the amount of water evaporation, the Lewis number [1], which changes heat transfer into mass transfer, is used, and the amount of evaporation is expressed using the convective heat transfer coefficient as in (6).

 (6)

where *c*p, *h*conv, *k*air, Le, Nu, Pr, and Re are the specific heat of air, convective heat transfer coefficient, thermal conductivity of air, Lewis number, Nusselt number, Prandtl number, Reynold’s number, and density of water vapor. Klopper et al. [2] defined the effective Lewis number as 0.5–1.3 due to various factors such as air flow pattern (counterflow, parallel flow, etc.) and air condition (air velocity, relative humidity, etc.). If water vapor is assumed to be an ideal gas in (6), the evaporation amount could be expressed in terms of relative humidity and water temperature as in (7).

 (7)

where *P*sat, , andrepresent the saturation pressure of water vapor, the relative humidity of air, and the relative humidity above the water surface. The relative humidity above the water surface is assumed to be 100%. The water temperature obtained from (4) and the amount of evaporation mass obtained from (7) interact with each other.

## Maximum Wicking Flow Rate

​​ The amount of evaporation cannot be more than the amount of water absorbed by the capillary force of the porous medium, and the amount of water absorbed into the porous medium is determined by the capillary force of the porous medium and the pressure drop of the water. The capillary force of the porous medium can be expressed as in (8), and the pressure drop of the water in the porous medium was analyzed using the Brinkman-Extended Darcy Equation, and the analytical solution of (9) was used [3]. In order for water to be absorbed, the capillary force must be greater than the pressure drop of the water within the porous medium. When (8) and (9) are equal, the maximum flow is determined. When water is absorbed into the porous medium, the maximum flow rate of the water is as in (10), and finally, the maximum flow rate can be expressed as in (11).

 (8)

 (9)

 (10)

 (11)

where *A*c, *K*, , *P*c, *P*f, *r*eff, and *U*d represent the cross-sectional area of ​​the porous medium, permeability, flow rate absorbed by the porous medium, capillary pressure, pressure drop of the water in the porous medium, effective pore radius, water velocity in the screen mesh, and surface tension of water.

# Experimental approach

## Hydrophilic Screen Mesh

A copper screen mesh with high thermal conductivity was used. In the case of general copper screen mesh, it has hydrophobic characteristics. Huang et al. [4] showed the research result that when copper is immersed in 2.5 mol/L NaOH + 0.1 mol/L (NH4)2S2O8 aqueous solution for 10 minutes, the surface of the copper becomes hydrophilic. Therefore, in this study, a hydrophilic copper mesh was fabricated using the method used by Huang et al. [4]. The effective pore radius and permeability of the fabricated hydrophilic mesh were measured using the Rate-of-rise method [5] developed by our research team, and the results are shown in Table 1.

1. The effecitv pore radius and permeability of super hydrophilic mesh

|  |  |  |
| --- | --- | --- |
|  | *reff* [m] | *K* [m2] |
| M100 | 1.53×10-4 | 1.86×10-10 |
| M150 | 1.30×10-4 | 1.37×10-10 |
| M200 | 8.43×10-5 | 5.06×10-11 |

## Experimental Apparatus and Process

The National Research Foundation of Korea (NRF) grant funded by Korea government (MSIT).

In order to experimentally measure the change in the external thermal resistance of a condenser with a porous medium using evaporative cooling, an evaporative cooling experimental device was constructed as shown in Fig. 4, and the detailed specifications of the experimental device are shown in Table 2. Figure 2(a) is a experimental apparatus. A honeycomb was used to create a uniform air flow, and a thermo-hygrometer (Testo 635-2) was installed in front and behind the test section to measure the temperature and relative humidity of the air. An anemometer (Testo 425) was used in front of the test section to measure the air speed. The uncertainty of the measurement device is shown in Table 3. Figure 2(b) is a schematic diagram of the test section. As shown in Fig. 2(b), the condenser wall was modeled as an aluminum plate, and a film heater was attached under the aluminum plate to model the amount of heat transferred to the condenser wall. In addition, five thermocouples were attached to the bottom of the aluminum plate in the direction of air flow to measure the temperature of the aluminum plate. The external thermal resistance was calculated using the average temperature of the measured aluminum plate and the air temperature. Based on the measurement results, the uncertainty of the experimental device at the 95% confidence

1. Wind tunnel diemsnion

|  |  |
| --- | --- |
| Wind tunnel dimensions (m)  (W×L×H) | 0.3×2.3×0.45 |
| Honeycomb Length (m) | 0.11 |
| Honeycomb cell size (m) | 0.00317 |
| Test section dimensions (m)  (W×L×H) | 0.2×0.2×0.225 |
| Aluminum plate area (m2) | 0.01 |
| Aluminum plate thickness (m) | 0.0015 |

1. specification of probs

|  |  |  |
| --- | --- | --- |
| Measurement | Model | Accuracy |
| Air temperature | Testo 635-2 | 0.2±0.5% oC |
| Air humidity | Testo 635-2 | 0.1±2% RH |
| Air flow velocity | Testo 425 | 0.03±5% m/s |
| Plate Temperature | T-type thermocouple | 0.5 or ±0.4% oC |

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(a) Wind tunnel

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(b) Test section

Fig. 2. Experimental apparatus

level in the T distribution with n-1 degrees of freedom was analyzed, and it was confirmed that it had an error range of ±3.37%.

# results and disscussion

The change in external thermal resistance was experimentally analyzed by changing the input power, air speed, and mesh number, and the experimental results and theoretical results were compared, and it was confirmed that the two results were well matched within 3% when the Lewis number was 0.5. Figure 3(a) shows the results of the experiment in which the heat amount was changed from 60 W to 220 W at the same mesh number (M100). As the input power increases, the temperature of the water rises, which increases the evaporation mass. Therefore, in (2), the increase in the water temperature becomes smaller compared to the increase in the input power, and the thermal resistance gradually decreases as the heat amount increases. In addition, it was confirmed that the external thermal resistance was reduced by an average of 92% when evaporative cooling was used compared to when cooling with air. Fig. 3(b) shows the results when only the air speed was changed. As the air speed increases, the convective heat transfer coefficient in (7) increases, which increases the evaporation amount. Therefore, the external thermal resistance gradually decreases as the evaporation amount increases according to the same principle as the change in the heat amount. Fig. 4(c) shows the results when the mesh number is changed. The mesh numbers used in the experiment are three types: M100, M150, and M200. When the mesh number changes, the geometric shape of the porous medium (effective pore radius, permeability, porosity, etc.) changes. However, as can be seen in (1) to (3), the factor affecting the external thermal resistance of the condenser is the mesh porosity, and the respective porosities are 0.6858, 0.7089, and 0.6564, so the change in porosity is small and does not have a significant effect on the overall thermal resistance change. Therefore, the change in the external thermal resistance was very minimal depending on the mesh number. However, it was experimentally confirmed in Fig. 6 that the maximum heat transfer amount was different depending on the mesh number. When the mesh number is M200, the pressure drop of the water flowing inside the mesh is greater than that of other meshes (M150, M200), so the flow rate flowing by capillary force becomes relatively smaller.



(a) Input power



(b) Air velocity



(c) Mesh number

Fig. 3. External thermal resistance



Fig. 4. The maximum heat transfer rate

# conclusion

In this study, the change in the external thermal resistance of the condenser was analyzed theoretically and experimentally through the evaporative cooling method using a screen mesh, which is a porous medium. A theoretical model was established to analyze the characteristics of the external thermal resistance of the condenser using the energy equation, evaporation amount prediction model, and porous medium approach. In order to verify the theoretical model, the change in the external thermal resistance was experimentally performed according to the heat amount, air speed, and mesh number. The experimental results were compared with the theoretical results, and it was confirmed that the two results were consistent within 3% when the Lewis number was 0.5. In addition, from the experimental results, it was confirmed that the external thermal resistance was reduced by an average of 92% when the mesh (M100, M150, M200) presented in this study was attached to the surface of the condenser and evaporative cooling was used compared to the case of air cooling. In particular, as the heat amount increases, the evaporation amount increases significantly, which increases the heat transfer due to evaporation. Therefore, as the heat amount increases, the increase in the temperature of the water becomes smaller compared to the increase in the heat amount, which reduces the external thermal resistance. Due to the same principle as the increase in heat capacity, the external thermal resistance decreases as the air velocity increases under the same heat capacity conditions due to the increase in evaporation. Finally, the change in external thermal resistance according to the mesh number was experimentally analyzed. Among the geometric shapes of the screen mesh, the only factor affecting the external thermal resistance is the porosity, and the change in the porosity of the screen meshes used in the experiment was small, so the change in the external thermal resistance was minimal. However, it was experimentally analyzed that the maximum heat transfer amount differs depending on the effective pore radius and permeability among the geometric shapes of the screen mesh. As the mesh number increases, the pressure drop due to the permeability increases more significantly compared to the increase in the capillary force caused by the effective pore radius, and the amount of water flowing through the mesh decreases. Therefore, as the mesh number increases, the evaporation limit condition, where the flow rate flowing through the mesh becomes less than the evaporation amount, is reached quickly, and the maximum heat transfer amount changes.For papers with more than six authors: Add author names horizontally, moving to a third row if needed for more than 8 authors.

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