Performance characteristic of hybrid cooling system based on cooling pad and evaporator

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Abstract. In South Korea, most of domestic animals such as pigs and chickens might die due to thermal diseases if they are exposed to the high temperature consistently. In order to save them from the heat wave, numerous efforts have been carried out: installing a shade net, adjusting time of feeding, spraying mist and setting up a circulation fan. However, these methods have not shown significant improvements. Thus, this study proposes a hybrid cooling system combining evaporative cooler and air-conditioner in order to resolve the conventional problems caused by the high temperature in the livestock industry. The problem of cooling systems using evaporative cooling pads is that they are not effective for eliminating huge heat load due to their limited capacity. And, temperature of the supplied air cannot be low enough compared to conventional air-conditioning systems. On the other hand, conventional air-conditioning systems require relatively expensive installation cost, and high operating cost compared to evaporative cooling system. The hybrid cooling system makes up for the lack of cooling capacity of the evaporative cooler by employing the conventional air-conditioner. Additionally, temperature of supplied air can be lowered enough. In the hybrid cooling system, induced air by a fan is cooled by the evaporation of water in the cooling pad, and it is cooled again by an evaporator in the air-conditioner. Therefore, the more economical operation is possible due to additionally obtained cooling capacity from the cooling pads. Major results of experimental analysis of hybrid cooling system are as follows. The compressor power consumption of the hybrid cooling system is about 23% lower, and its COP is 17% higher than that of the conventional air-conditioners. Regarding the condition of changing ambient temperature, the total power consumption decreased by about 5% as the ambient temperature changed from 28.7°C to 31.7°C. Cooling capacity and COP also presented about 3% and 1% of minor difference at the same comparison condition.

1. Introduction

The hot and humid air of around 33 °C in the summer of Korea has a negative effect on manufacturing industries and livestock industries. In the livestock industry field, diseases such as reproductive disorders and dyspnea of domestic animals can be caused by the high temperature and humid climate of summer. Similarly, in the manufacturing industry, the production efficiency declines due to the increased labor's discomfort index. Especially if the production amount during the summer occupies a large portion from the entire production amount, it will have more fatal effect. Even though these symptoms are usually
caused by high air temperature, in fact, the influence of high humidity which is often seen in regions having hot climate is larger. In terms of characteristics of summer climate of the West United States, Mexico and Spain, their climate condition appears slightly different from Korea's climatic conditions; summer climate of those countries is usually high and dry, otherwise that of Korea appears high and humid. Therefore, problems coming from summer climate of Korea that mentioned above are hardly occurred in those countries. This is because the absorbed heat can be dissipated more rapidly and its amount is also larger if the humidity is low in the hot summer climate. Many researches on ‘Evaporative coolers’ which utilizes a cooling pad for space cooling have been conducted in countries with high and dry climate. The related researches are as follows.

Huang et al. [1] analyzed the heat and mass transfer between air and water film in an evaporative cooler. The flow speed of the air flowing into the cooling pad and the thickness of the pad have a large influence on the cooling effect of the evaporative, and the optimum air flow rate according to the experimental result is 2.5 m/s according to the author.

Ramin et al. [2] compared performance of the air-cooled condenser and the evaporative condenser, and found that the performance of the evaporative condenser was about 51% higher than that of the air-cooled condenser.

Abdollah et al. [3] conducted experimental analysis on pressure drop, humidity distribution, efficiency, etc. on the cellulosic evaporative cooling pad. The pressure drop and the amount of water evaporated are increased as the flow rate increases, and as the thickness of the cooling pad increases. On the other hand, efficiency and humidity tended to decrease as the flow rate increased.

Wasim et al. [4] listed types and features of evaporative coolers and recorded the difference of direct, indirect, and direct or indirect evaporative coolers.

Sarker et al. [5] analyzed performance improvement of cooling capacity by dry-air and moist-air in the case of the hybrid closed circuit cooling tower. The difference of evaporation capacity between the cases that dry air circulates and moist air circulates the cooling tower was about from 26% to 260%.

However, in the case of Korea, there is no research or development of the “evaporative coolers” at all. Therefore, in this paper, the performance characteristics of a hybrid cooling system combining evaporative cooler targeting Korea's hot and humid climate.

2. Evaporative cooler

As mentioned above, the structure of the evaporative cooler used in the country with high and dry climate is shown in figure 1. When outside air flows through the inlet part at the left and right side, the outside air is cooled by the cooling pad where water flows through the form of waves of it. Then, the cooled air is taken out by the blower. Sensible heat exchange, evaporative latent heat exchange and substance exchange occur in the process of contact between outside air and water.

Here, sensible heat means the exchanged heat amount caused by difference of a dry-bulb temperature between water and air flowing through the cooling pad. And the evaporative latent heat refers to the amount of heat delivered to the water from the air, occurred by the evaporation of water as it contacts the air. Lastly the mass transfer is a phenomenon which molecules of water move from water to air by evaporation of water. In short, the outside air passing through the cooling pad of the evaporative cooler is cooled by sensible heat exchange and evaporative latent heat exchange. However, due to the mass transfer phenomenon, its humidity at the outlet increases. Therefore, it is possible to improve the cooling capacity which is lowered by high humidity by combining evaporative cooler and general air conditioners. The combined system lowers the takeout temperature from the evaporative cooler and reduces the power consumption compared to a general air conditioner. Therefore, this paper attempts to demonstrate economical cooling performance through performance analysis of coupled systems under hot and humid operating conditions.
3. Hybrid cooling system

Figure 2 is a schematic diagram of an experimental apparatus of a hybrid cooling system. In order to combine the evaporative cooler and the general air conditioner, a fan and a water pump were used. And cooling pads were attached at the front part of the evaporator and the condenser, respectively. The refrigerant in the system absorbs the heat from the air, which is precooled at the cooling pad, in the evaporator, and then compressed by the compressor. After that, it releases heat to the cooling air, which is also precooled by the cooling pad, in the condenser, and then is expanded by the expansion valve. Finally, the refrigerant circulates the system to complete the cycle. In the hybrid cooling system, the cooling pad copes with a part of the cooling heat capacity of the air conditioner, so more economical cooling is possible compared to the general air conditioner with the same cooling capacity. In this study, the performance of the hybrid cooling system with respect to the ambient temperature is experimentally analyzed, and the effect of installation of the cooling pad at the condenser inlet is reviewed. The experimental working conditions of the system are shown in table 1.

![Figure 1. Schematic diagram of evaporative cooler.](image1)

![Figure 2. Schematic diagram of hybrid cooling system.](image2)
### Table 1. Operating conditions of hybrid cooling system.

| Parameter                          | Value       | Unit |
|------------------------------------|-------------|------|
| Ambient temperature                | 28–32       | ℃    |
| Relative humidity of Ambient       | 65          | %    |
| Air velocity                       | 2.42        | m/s  |
| Circulating water temperature      | 25          | ℃    |
| Refrigerant                        | R-22        |      |

| Case                                                                 |
|---------------------------------------------------------------------|
| Case 1: Without a cooling pad at the condenser inlet                |
| Case 2: With a cooling pad at the condenser inlet                    |

※ In both cases, a cooling pad is installed at the evaporator inlet

### 4. Data reduction

The values of the physical property values of refrigerant and air applied in this study were calculated using the EES (Engineering Equation Solver) program, and the following equations were used to analyze the experimental data. First, in order to compare the hybrid cooling system with and without a cooling pad to a general air conditioner, mathematical equation of cooling capacity ($Q_{TCC}$), consumption power ($W_{total}$), COP of the whole system ($COP_{total}$) were used. And in terms of hybrid cooling system, the formula of cooling heat ($Q_{HCS}$), consumption power ($W_{HCS}$), COP ($COP_{HCS}$) were used. Each of equations are as followings.

\[
Q_{TCC} = Q_{evap} + Q_{CP} \tag{1}
\]

\[
W_{total} = W_{comp} + W_{fan} \tag{2}
\]

\[
COP_{total} = \frac{Q_{TCC}}{W_{total}} \tag{3}
\]

\[
COP_{ref} = \frac{Q_{evap}}{W_{comp}} = \frac{m_R \cdot (h_{evap, out} - h_{evap, in})}{W_{comp}} \tag{4}
\]

\[
Q_{HCS} = Q_{evap} + Q_{CP} \\
= m_{R-22} \cdot (h_{evap, out} - h_{evap, in}) + g_{air} \cdot (h_{CP, in} - h_{CP, out}) \tag{5}
\]

\[
W_{HCS} = W_{comp} + W_{fan} \tag{6}
\]

\[
COP_{HCS} = \frac{Q_{HCS}}{W_{HCS}} \tag{7}
\]

In equation (1), $Q_{evap}$ and $Q_{CP}$ denote the cooling capacity of the evaporator and the cooling pad, respectively. $M_{R-22}$ and $G_{air}$ represent the mass flow rate of the refrigerant and the supplied air. $h_{evap, in}$ and $h_{evap, out}$ in equation (4) represent the enthalpy of refrigerant at the inlet and outlet of the evaporator, respectively. $h_{CP, in}$ and $h_{CP, out}$ in equation (5) depict the enthalpy of air at the inlet and outlet of the cooling pad, respectively. Also, $W_{comp}$ and $W_{fan}$ in equation (6) show the power consumption of the compressor and that of the fan, respectively. In addition, uncertainty of data is shown in table 2.
Table 2. Uncertainty of analysis data.

| Parameter                  | Deviation(\(\)) | Uncertainty(%) |
|----------------------------|------------------|----------------|
| Cooling capacity           | 15.02±0.014      | 0.44           |
| Power consumption of       | 2.6±0.016        | 0.506          |
| compressor                 |                  |                |
| Power consumption of Fan   | 0.7±0.029        | 0.93           |

5. Experimental Results and Discussions.
When the cooling pad is installed at the front of the condenser, the temperature of the cooling air flowing into the condenser decreases, and the condensation temperature decreases due to its influence.

Therefore, it is necessary to analyze the performance of the hybrid cooling system with respect to the condensation temperature change. Two cases of working conditions are analyzed; when the cooling pad is not installed in front of the condenser (case 1), and when it is installed (case 2). In both case 1 and case 2, the cooling pad is installed at the inlet of the evaporator since the precooling process obviously increased the cooling capacity and improved the performance. Figure 3 presents a performance characteristic of the refrigerator of the hybrid cooling system with respect to the presence or absence of the cooling pad at the front of the condenser.

During the experiment, the evaporation capacity was kept relatively constant by controlling the mass flow rate of the refrigerant through the expansion valve to compare each case. In fact, when the condensation temperature decreased due to precooled cooling air from the cooling pad, the cooling capacity of the evaporator was constantly increased. That is because increased subcooling degree resulted in the enlarged enthalpy difference of the evaporator inlet and outlet. Thus, the mass flow rate of the refrigerant was decreased to maintain the constant cooling capacity. Compressor power consumption of case 2 was measured lower than case 1, due to not only the decreased amount of mass flow rate of the refrigerant, but also lowered condensation pressure. COP(ref), which means COP of only refrigerator, tended to increase in case 2. The reason is that the power consumption of the compressor decreased when the evaporation capacity is kept constant.

Figure 4 depicts performance characteristic of the hybrid cooling system with respect to the presence or absence of the cooling pad at the front of the condenser. The same parameters as in figure 3 were analyzed in figure 4, and all parameters presented the same tendency as figure 3 when comparing case 1 and case 2. \(Q_{HCS}\) showed about 54-62% higher value than \(Q_{evap}\) due to additional cooling capacity obtained from the cooling pad (\(Q_{CP}\)). \(W_{HCS}\) included power consumption of the fan (\(W_{fan}\)), thereby showing about 26-31% higher value than \(W_{comp}\) from figure 3. Therefore, COP(HCS) was about 22-23% higher than COP(ref). In short, even though additional power consumption of the fan was needed in the hybrid cooling system, additionally obtained cooling capacity from the cooling pad occupied the higher portion in the hybrid cooling system.

Figure 5 represents the cooling capacity of the hybrid cooling system and the temperature of supplied air to the space, according to changing ambient temperature. As the ambient temperature rose, the temperature of supplied air increased due to the limited amount of obtainable cooling capacity at the cooling pad. Increase of the ambient temperature resulted in enlarged temperature difference between the ambient and the water that flows the cooling pad. Also, the one between the ambient temperature and evaporation temperature increased. Thus, the cooling capacity of the cooling pad (\(Q_{CP}\)) showed slight increase, and the cooling capacity of the evaporator (\(Q_{evap}\)) presented increase as well. As a result, the cooling capacity of the hybrid cooling system (\(Q_{HCS}\)) slightly increased as the ambient temperature rose.

Figure 6 depicts analysis about the total power consumption and the COP of the hybrid cooling system as ambient temperature changes. First, the total power consumption amount showed slight
increase as the ambient temperature rose. This was because the mass flow rate of the refrigerant and the pressure difference at the compressor increased, resulted from risen condensation pressure. Based on the experimental data of figure 5 and figure 6, the cooling capacity of the hybrid cooling system at the ambient temperature of 28.7 ºC was about 3% higher than when it was 31.7 ºC. On the other hand, the total power consumption at the ambient temperature of 31.7 ºC showed about 5% higher value compared to that of 28.7 ºC. Considering these two values, the COP of the hybrid cooling system decreased about 1% as the ambient temperature changed from 28.7 ºC to 31.7 ºC.

Figure 3. COP of refrigerator, compressor power consumption and cooling capacity of evaporator with respect to presence or absence of cooling pad in front of condenser.

Figure 4. COP, power consumption and cooling capacity of hybrid cooling system with respect to presence or absence of cooling pad in front of condenser.
Figure 5. Cooling capacity of hybrid cooling system and temperature of supply air with respect to ambient temperature.

Figure 6. COP and power consumption of hybrid cooling system with respect to ambient temperature.

6. Conclusion
In this study, performance analysis on the hybrid cooling system was analyzed with respect to presence and absence of the cooling pad at the condenser inlet. Also, the effect of the ambient temperature on the hybrid cooling system was studied. As the result, applying the cooling pad at the condenser inlet made the compressor power consumption about 23% lower and COP of the refrigerator about 17% higher than that of the case without the cooling pad. On the other hand, effect of changing ambient temperature on the system was minor. The total power consumption decreased about 5% as the ambient temperature changed from 28.7 °C to 31.7 °C. Cooling capacity and COP also presented about 3% and 1% of minor difference at the same comparison condition. In summary, it was experimentally proved that the more economical space cooling is obtainable with the hybrid cooling system applied to the cooling pad, compared to a conventional cooling system.
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