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An Experimental Study on the Performance of Air/Water Direct Contact Air Conditioning System

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Direct contact air conditioning systems, in which heat and mass are transferred directly between air and water droplets, have many advantages over conventional indirect contact systems. The purpose of this research is to investigate the cooling and heating performances of direct contact air conditioning system for various inlet parameters such as air velocity, air temperature, water flow rate and water temperature. The experimental apparatus comprises a wind tunnel, water spray system, scrubber, demister, heater, refrigerator, flow and temperature controller, and data acquisition system. The inlet and outlet conditions of air and water are measured when the air contacts directly with water droplets as a counter flow in the spray section of the wind tunnel, and the heat and mass transfer rates between air and water are calculated. The droplet size of the water sprays is also measured using a Malvern Particle Analyzer. In the cooling conditions, the outlet air temperature and humidity ratio decrease as the water flow rate increases and as the water temperature, air velocity and temperature decrease. On the contrary, the outlet air temperature and humidity ratio increase in the heating conditions as the water flow rate and temperature increase and as the air velocity decreases.

Key Words : Air Conditioning System, Direct Contact, Cooling, Heating, Humidification, Dehumidification

1. Introduction

For energy conservation and the protection of the environment, it becomes increasingly important to design air conditioning systems which save energy as well as make comfortable air. Conventional air conditioning systems generally consist of six components. A refrigerator and cooling coil are needed for cooling and dehumidification ; and a boiler, heating coil and humidifier are used for heating and humidification ; and a filter is often installed to purify polluted air. On the other hand, a direct contact air conditioning system in which heat and mass are transferred directly between air and water droplets has many advantages over conventional indirect contact systems. In this system, cooling, heating, dehumidification and humidification are accomplished without using a cooling, heating coil, dehumidifier or humidifier. In addition, the transport efficiencies of heat and mass are relatively high due to the low thermal resistance and the evaporation effect. Also, the design of this system is relatively simple (Seetharamu and Battya, 1989 ; Tadrist et al., 1987 ; Jacobs, 1988). Therefore, this system can save on installation and operation costs. Furthermore, this system can control air

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quality by absorbing dust and contaminated gases from polluted air.

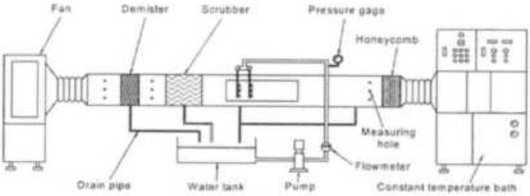
Only a few research papers on the cooling and heating characteristics for direct contact transport systems are found in the literature, and most of them are related to cooling towers. Warrington and Mussulman (1983) used the analytical method to study the effect of drop size variation on cooling tower performance. Lee et al.(1998) have experimentally investigated the effect of the velocity, temperature, and humidity of the entering air on the thermal performance of cooling towers for both counter-flow and cross-flow arrangements. Bohn (1985) has measured the volumetric heat transfer coefficient of direct contact heat exchangers as a function of air and salt flow rate, and conducted economic analysis to compare direct contact heat exchangers with conventional finned-tube heat exchangers. Siqueiros and Bonilla (1999) have performed experiments with pentane as dispersed phases and water as a continuous phase, and calculated the volumetric heat transfer coefficient at various conditions. Cooling performances for different air conditioning systems incorporating air washers were studied by Ismail and Mahmoud (1994). Kang et al.(2002) have numerically investigated the heat transfer characteristics in a spray column direct contact heat exchanger using the two-dimensional axisymmetric two-component flow model. Kim et al.(2001) have suggested the installation of meshes inside a direct contact heat exchanger to improve the performances, and investigated their effects.

In the present study, cooling, heating, dehumidification and humidification performances of a direct contact air conditioning system are evaluated for various inlet parameters such as air temperature, air velocity, water temperature and water flow rate. The droplet size of the water sprays and pressure losses in the system are also measured and compared. Performance analysis for the direct contact air conditioning system is conducted by Yoo et al.(2004) using empirical correlations which are based on this study.

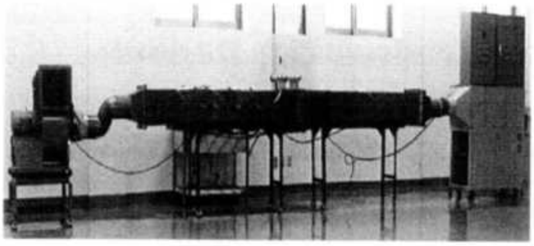
2. Experimental Apparatus and Procedure

2.1 Experimental apparatus

The experimental apparatus, shown in Fig. 1, comprises a wind tunnel, water spray system, scrubber, demister, heater, refrigerator, flow and temperature controller and data acquisition system. A suction type wind tunnel is used, which is made of PVC and has a square test section of 300 mm×300 mm. Maximum air speed in the wind tunnel is 4.2 m/s and the air flow rate is controlled by an inverter. The air temperature, which is induced into the air conditioning system from the unconditioned room, is controlled by a constant temperature bath which is equipped with a cooling and also a heating system. The water spray system consists of a tube bank, spray nozzles, a circulation pump, water tank, flowmeter and pressure gage. The water supplied by a circulation pump is sprayed through two rows of tube banks and each tube bank has 16 nozzles, and the water flow rate is controlled by the inverter. The water droplets after making contact with blowing air are returned into the water tank through the drain pipe. The circulated water temperature is controlled by an electric



(a) Schematic



(b) Photo

Fig. 1 Schematic and photo of air/water direct contact air conditioning system

Table 1 Operating ranges of experimental parameters for cooling and heating

Parameters	Cooling	Heating
Inlet air temperature	24~38℃	15~16℃
Air velocity	1~3 m/s	1~3 m/s
Inlet water temperature	4~16℃	25~53℃
Water flow rate	0.1~0.35 kg/s	0.1~0.35 kg/s

heater in heating experiments, and by a vapor compression refrigerator in cooling experiments, respectively. A scrubber made of corrugated PVC and a demister made of stainless-steel mesh eliminate the remaining water droplets from the exhaust air after contact with the water spray.

2.2 Experimental procedure

To investigate the cooling and heating performances, inlet and outlet conditions of air and water are measured when the air contacts directly with water droplets as a counter flow in the spray section of the wind tunnel. The operating ranges of experimental parameters for cooling and heating are determined by considering those of conventional air conditioning systems, and are given in Table 1. Water is cooled below the inlet air temperature in cooling experiments, and water is heated above the inlet air temperature in heating experiments. The flow rate of air and water is then set by the inverter. The air velocity is measured by a pitot tube and the water flow rate is measured by a rotameter. In order to measure dry and wet bulb temperatures, T-type thermocouples are inserted through the measuring holes which are located far upstream of the spray section, downstream of the scrubber and downstream of the demister.

3. Results and Discussion

3.1 Droplet size of water spray

Heat and mass transfer in air/water direct contact air conditioning systems are dominated by droplet size. If water of constant volume is dispersed into a lot of small droplets, heat and mass transfer are enhanced by the increase of the total contact area between air and water droplets.

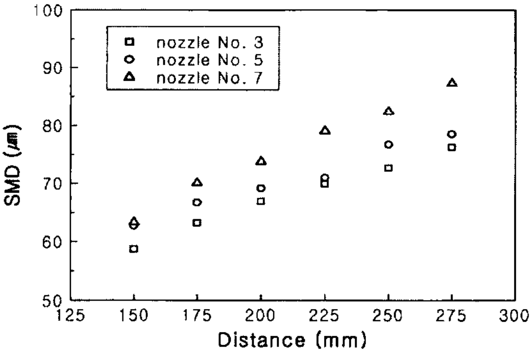


Fig. 2 Variation of SMD with distance

In the present study, the Malvern Particle Analyzer is used to measure the size of water droplets. The droplet size is usually expressed by means of SMD, which stands for sauter mean diameter. Variations of SMD for three different nozzles are presented in Fig. 2. When the nozzle number increases, the droplet size tends to increase due to the increase in the orifice diameter of nozzle. As the distance between the spray nozzle and measuring point increases, the size of the water droplets increases. It can be explained by the fact that the small droplets are agglomerated by the velocity gradient and the large droplets are agglomerated by gravitational settling. From this result, the size of the droplets sprayed from the nozzle is assumed to be around 50~90 μm.

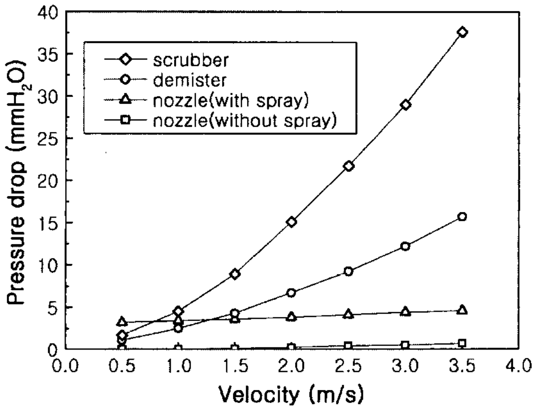


Fig. 3 Pressure loss versus air velocity at each section

3.2 Pressure loss

Pressure loss as well as heat and mass transfer characteristics is very important factor in the design of air conditioning systems. Figure 3 shows variations of pressure loss with air velocity at the spray section, scrubber and demister. When the water is not sprayed, the pressure loss in the spray section is negligible. But when the water is sprayed with a flowrate of 0.23 kg/s, the pressure loss jumps up because water droplets obstruct the air flow. At the scrubber and demister, the pressure loss increases with increasing air velocity, and the pressure loss at the scrubber is more than twice that of the demister.

3.3 Cooling performance

Variations of outlet air temperature, humidity ratio and effectiveness are investigated as a function of water flow rate, air velocity, air temperature and water temperature. Figure 4 shows the effect of cooling water flow rate on outlet air conditions such as temperature and humidity ratio. In this experiment, inlet air flow rate is constant at 0.221 kg/s, inlet air temperature is between 30 and 31℃, and cooling water temperature ranges from 9 to 10℃. The outlet air temperature and humidity ratio decrease as the cooling water flow rate increases. The reason for this is that the contact area between air and water droplets increases as the cooling water flow rate increases, and thereby heat and mass transfer are augmented. In these experimental conditions, the humidity ratio of the inlet air is higher than that of saturated air at cooling water temperature, so mass is transferred from air to water.

The variation of outlet air conditions as a function of air velocity is shown in Fig. 5. In this case, the cooling water flow rate is fixed at 0.221 kg/s, the cooling water temperature is between 9 and 11℃, and the inlet air temperature ranges from 30 to 31℃. The outlet air temperature and humidity ratio increase, as the air velocity increases. Nevertheless heat and mass transfer coefficients between air and water droplets increase with increasing air velocity, differences in air temperature and humidity ratio between inlet and outlet become smaller with increasing air velocity. This can be explained by the fact that the mass flow rate of inlet air is proportional to the air velocity.

Figure 6 shows the variation of outlet air

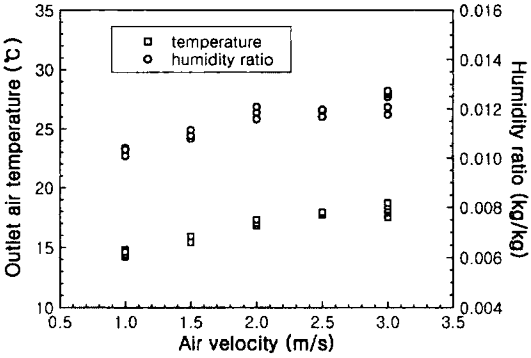


Fig. 5 Variation of outlet air conditions with air velocity for cooling

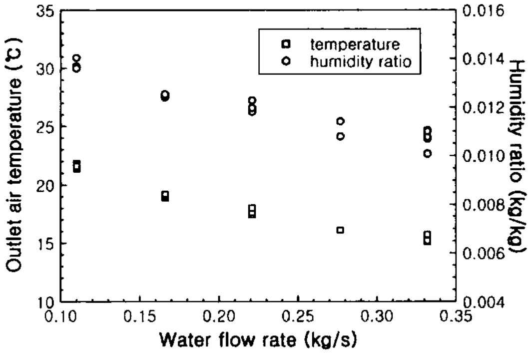


Fig. 4 Variation of outlet air conditions with water flow rate for cooling

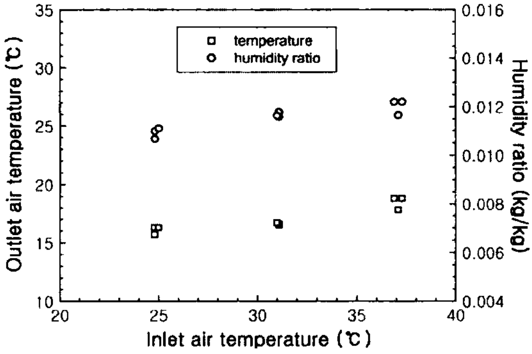


Fig. 6 Variation of outlet air conditions with inlet air temperature for cooling

conditions with inlet air temperature. These results are obtained under the conditions that the cooling water flow rate is 0.184 kg/s, the air flow rate is 0.221 kg/s, and the cooling water temperature is between 8 and 10℃. The lower the inlet air temperature is, the lower the outlet air temperature and humidity ratio are. Considering the inlet and outlet air temperature, decrement becomes higher as inlet air temperature increases. So cooling efficiency becomes higher with increasing inlet air temperature.

The effect of inlet water temperature on outlet air conditions is shown in Fig. 7. In this case, the flow rate of the water and air is 0.221 kg/s, and the inlet air temperature varies from 31 to 32℃. As the inlet water temperature decreases, the outlet air conditions tend to decrease because the temperature difference between air and water droplets becomes larger. However, the decrement of the outlet air temperature is not higher than that of the inlet water temperature.

In order to compare direct contact heat exchange with indirect contact heat exchange, effectivenesses are defined by two ways as below.

$$\varepsilon_{sensible}=\frac{(\dot{m}c_p)_{air}\Delta T_{air}}{(\dot{m}c_p)_{min.}\Delta T_{max.}}=\frac{\Delta T_{air}}{\Delta T_{max.}} \qquad (1)$$

$$\varepsilon_{sensible+latent}=\frac{\dot{m}_{air}\Delta h_{air}}{(\dot{m}c_p)_{min.}\Delta T_{max.}} \qquad (2)$$

The effectiveness considering only sensible heat is defined in Eq. (1), and the effectiveness taking into account sensible and latent heat is defined in Eq. (2). In both cases, the denominator is the maximum possible sensible heat transfer rates. Figure 8 shows the variation of effectiveness with cooling water flow rates. As seen in the figure, both effectivenesses increase, as a result of the enhancement of heat and mass transfer, when the cooling water flow rate increases. Increasing the water flow rate from 0.1 kg/s to 0.35 kg/s results in an increase of 92% in the effectiveness for sensible heat and 92% for total heat, respectively. And the effectiveness of sensible and latent heat is increased by 31% compared to that of pure sensible heat. From these results, we can conclude that cooling and dehumidification are accomplished at the same time. In fact, to control the temperature of inlet air, the inlet air passes through the cooling coil of the constant temperature bath installed at the inlet part of the air conditioning system, and the air is thereby dehumidified before making contact with water droplets. Consequently, the effect of dehumidification is not high at spray section. If the inlet air is not dehumidified at the constant temperature bath, the cooling performance as well as effectiveness will be improved.

The variation of effectiveness with cooling water temperature is shown in Fig. 9. The effectiveness of sensible and latent heat is higher than that of pure sensible heat when the cooling water temperature is lower than 11.6℃, and the effectiveness of pure sensible heat is higher than

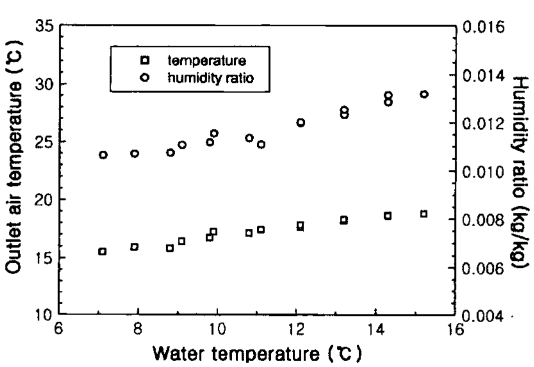


Fig. 7 Variation of outlet air conditions with inlet water temperature for cooling

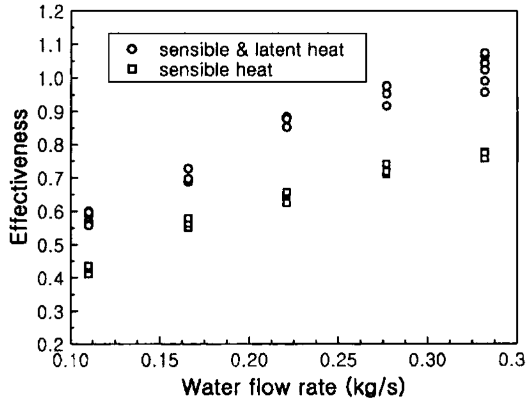


Fig. 8 Effectiveness versus water flow rate for cooling

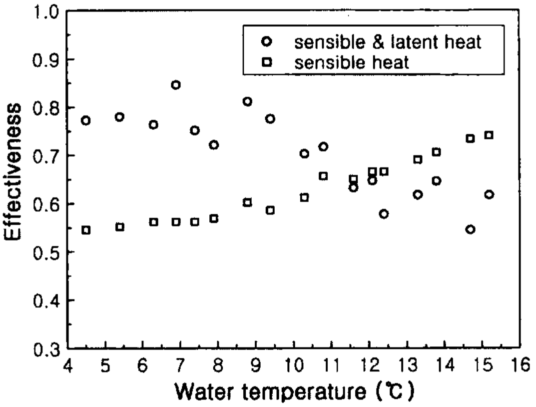


Fig. 9 Effectiveness versus inlet water temperature for cooling

that of sensible and latent heat if cooling water temperature is higher than 11.6℃. If the cooling water temperature is lower than 11.6℃, which is the dew point of inlet air, the concentration of water vapor in the cooling water is lower than that of the inlet air. Therefore, water vapor is transferred from air to cooling water, and cooling and dehumidification occur simultaneously. On the contrary, if the cooling water temperature is higher than 11.6℃, water vapor is transferred from cooling water to air, so cooling and humidification occur. Consequently, it is necessary to have cooling water whose temperature is lower than the dew-point temperature of the inlet air in order to accomplish cooling and dehumidification simultaneously in summer using direct contact air conditioning systems.

3.4 Heating performance

In the heating experiments, the same experimental conditions as the cooling are applied except for the inlet water temperature. Figure 10 shows the outlet air temperature and humidity ratio as a function of water flow rate. In this experiment, the air flow rate is kept at 0.221 kg/s, and the inlet air temperature varies from 15 to 16℃. As the water flow rate increases, the outlet air temperature and humidity ratio increase due to the augmentation of heat and mass transfer caused by the increase in contact area between air and water droplets. Scattering is relatively large when the water flow rate is 0.277 kg/s. It can be explained by the fact that sprayed water temperature is not constant because of the limitation of the heater.

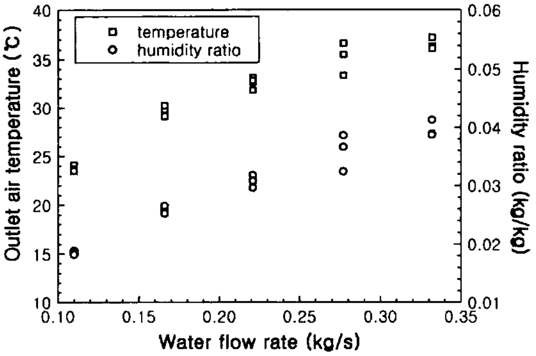


Fig. 10 Variation of outlet air conditions with water flow rate for heating

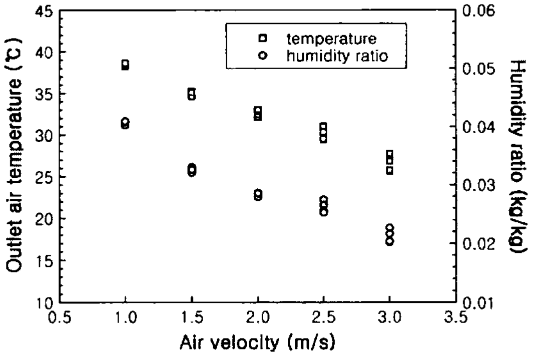


Fig. 11 Variation of outlet air conditions with air velocity for heating

Figure 11 shows the variation of outlet air conditions against air velocity when water flow rate is kept at 0.221 kg/s. As the air velocity increases, the outlet air temperature and humidity ratio decrease rapidly. Although heat and mass transfer rates increase as the air velocity increase, temperature increase of inlet air becomes smaller because mass flow rate of air increase.

The effect of the inlet water temperature on the outlet air conditions is shown in Fig. 12. The outlet air temperature increases as the inlet water temperature increases, because temperature difference between air and water droplets becomes larger. The humidity ratio also increases,

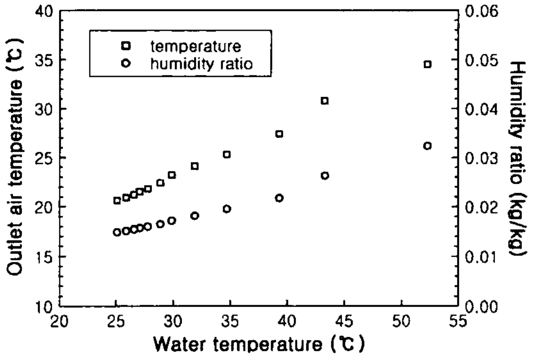


Fig. 12 Variation of outlet air conditions with water temperature for heating

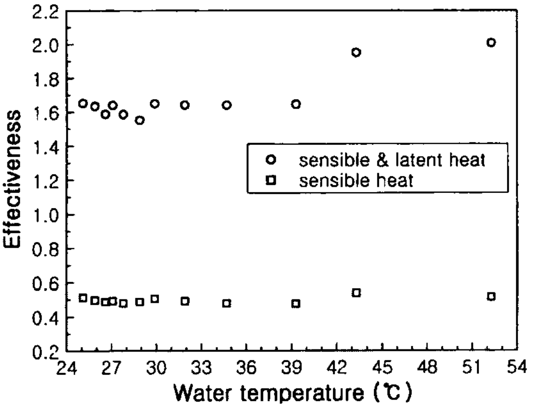


Fig. 13 Effectiveness versus water temperature for heating

because mass transfer is accelerated as saturation concentration of water increases.

Figure 13 shows effect of inlet water temperature on the effectiveness. It can be observed that the effectiveness seems to be affected little by inlet water temperature, and the effectiveness of sensible and latent heat is almost three times higher than that of sensible heat. Consequently, heating and humidification are accomplished simultaneously in the heating experiments, and transfer of latent heat is much larger than that of sensible heat. Because of excessive humidification, it is very difficult to control temperature and humidity at the same time. This is one of the disadvantages of direct contact air conditioning systems, and this problem can partly be solved by mixing of outlet air with indoor circulation air.

4. Conclusions

Cooling and heating performances of direct contact air conditioning system are investigated experimentally for various operating conditions. Major results are summarized as follows :

(1) As the water flow rate increases and air velocity, inlet water temperature and inlet air temperature decrease, the outlet air temperature and humidity ratio decrease in the cooling conditions.

(2) Increasing the water flow rate from 0.1 kg/s to 0.35 kg/s results in an increase of 92% in the effectiveness for sensible heat and 92% for total heat, respectively.

(3) Cooling and dehumidification are accomplished simultaneously if the inlet air is cooled below the dew-point temperature. On the contrary, cooling and undesirable humidification occur if the inlet air is cooled above the dew-point temperature.

(4) As the water flow rate and inlet water temperature increase and air velocity decreases, the outlet air temperature and humidity ratio increase in the heating conditions.

(5) The effectivenesses taking into account sensible and latent heat is almost three times higher than those considering only sensible heat in heating. This is because mass is transferred more vigorously than heat, so it is very difficult to control temperature and humidity simultaneously.

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