The Effect of Surface Modification on Heat Transfer of Heat Exchanger

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Abstract. This study mainly discussed the influence of different surface properties, namely an unmodified copper fin surface and a modified hydrophobic fin surface, on the heat transfer effect of heat exchangers with air velocity ranging from 0.5 m/s to 2.5 m/s and relative humidity of 60% and 90%. The researchers established the following conclusions based on the experiment results. The heat transfer and water removal rates of the two heat exchangers increased with an increase in wind velocity. When the inlet air velocity was increased from 0.5 to 2.5 m/s, the heat transfer and water removal rates of both heat exchangers were increased by approximately 90%. Under similar air velocity conditions, heat exchangers with hydrophobic surfaces constantly removed the condensed water droplets, thereby preventing the water droplets from causing surface thermal resistance. As a result, the condensation heat transfer effect of hydrophobic surfaces was greater than that of unmodified copper surfaces. Compared with heat exchangers with unmodified copper fin surfaces, heat exchangers with hydrophobic surfaces exhibited a 5.56% higher heat transfer efficiency.

1. Introduction

The advancement of technology has resulted in substantial energy consumption worldwide. Therefore, environmental protection and energy-related issues are of considerable concern. In current dry system designs, heat exchangers are commonly employed to transfer thermal energy. With the aim of improving energy use efficiency, researchers worldwide have continued to pursue the development of high-efficiency heat exchangers. As mechanical equipment and factories produce waste heat during operation, the effective use of high-efficiency heat exchangers to recover energy can substantially improve energy use efficiency. Consequently, those in the dry system industry and academia have endeavored to improve the heat transfer ability of heat exchangers.

Therefore, the optimal heat transfer model should base on the highest heat transfer capacity under minimal temperature difference. This characteristic is demonstrated in the phase change process, during which a substantial amount of heat is transferred through latent energy changes while a constant temperature is maintained. Therefore, heat transfer systems with phase changes
exhibit a considerably higher heat transfer rate than heat transfer systems that do not adopt phase changes. According to the principle of condensation heat transfer, when air passes over a low-temperature surface, the air temperature drops below the humid air dew point temperature and cause condensed water to form on the surface. During this process, latent heat is transferred to surface of condensed water. During the condensation process, the amount of condensed water increases with process duration and is characterized by Filmwise condensation (FWC) or Dropwise condensation (DWC) according to the surface composition. This is mainly due to the condensation surface exhibiting different levels of surface tension. Hydrophilic surfaces exhibit a high level of wetness, resulting in FWC. With time, the condensation surface of the water film increases in thickness, which in turn increases heat transfer resistance. By contrast, hydrophobic surfaces exhibit a low level of wetness, which results in DWC. As DWC does not produce a water film on the surface, the heat transfer resistance is relatively lower than that of FWC. In summary, because FWC produces a water film over the condensation surface, which directly lowers the heat transfer rate, DWC has a higher heat transfer rate than FWC. Furthermore, condensation and drainage speed are key factors influencing the heat transfer rate during the condensation process. Therefore, changes in the surface properties of heat exchanger fins can improve the heat transfer rate during the condensation process.

In previous studies have indicated that DWC has a higher heat transfer rate than FWC. Additionally, numerous following studies discussed DWC mechanisms and employed surface modification to increase the condensation heat transfer capacity. Furthermore, scholars have discussed hybrid wettability surfaces and revealed that droplet drainage frequency increased in accordance with surface tension gradient. In this study, the researchers employed surface designs with different levels of hydrophilicity and hydrophobicity to improve the heat transfer rate of the heat exchanger.

The type of condensation on surface determined by the dimension of contact angle. Hydrophilic surfaces exhibit smaller contact angles, which increases the possibility of the condensation process creating a water film. By contrast, hydrophobic surfaces have a larger contact angle, which increases the possibility of the condensation process producing droplets. Because hydrophobic surfaces have higher contact angles and smaller rolling angles, droplets cannot remain on hydrophobic surfaces. Therefore, hydrophobic surfaces exhibit droplet resistance. For example, the surface of lotus leaves is a primary example of natural hydrophobic materials. By constructing a simulation model and comparing experiment results, revealed that surfaces with larger contact angles exhibited higher heat transfer coefficients [1]. Developed a mathematical model to estimate the heat transfer rate of superhydrophobic surfaces with contact angles larger than 150° [2]. The results revealed that the heat transfer rate of water film and droplets were significantly influenced by the surface contact angle, and a larger contact angle enhanced condensation heat transfer.

In 1805, proposed an equation for calculating the contact angle for water films and droplets [3]. However, Young’s theory is only applicable for flat homogeneous surfaces; it cannot be employed for rough or heterogeneous surfaces. Therefore, proposed a theory, termed Wenzel’s theory, which states that all solid surfaces consist of a certain degree of roughness and that droplets that make contact with rough surfaces often create wetted surfaces [4]. According to the Wenzel equation, surface hydrophobicity can be enhanced by increasing surface roughness. The rolling condition of droplets is considerably influenced by water droplet coming into full contact with solid surfaces. Extended Wenzel’s theory and proposed the Cassie theory, which states that droplets do not make full contact with rough surfaces, but that a layer of air exists between the contact surface of the liquid droplet and solid surface [5]. This composite surface
is created because the droplet is partially supported by air and the solid surface, thereby giving the surface a higher hydrophobicity than general rough surfaces.

Another method of surface modification involves designing and inlaying shapes mixing hydrophobic and hydrophilic materials on the condensation surface to create surface differences, thereby inducing droplet movement and increasing droplet drainage frequency. A horizontal hydrophilic–hydrophobic surface structure was designed [6]. The study revealed that if the hydrophobic surface structure was thicker than 2 mm, the heat transfer enhancement effect of the surface structure was negligible because the effect of the thickened water film was more prevalent. Therefore, the enhancement effect, during which falling droplets interfere with the water film, is only significant at the border of the condensation surface. The enhancement effect was reduced with an increase in the hydrophilic surface area, thereby implying the existence of an optimal width design. Designed a vertical striated hydrophilic–hydrophobic hybrid surface [7]. When a hybrid surface was used for a condensation experiment, droplets moved from the hydrophobic area to the hydrophilic area. Due to differences in surface energy, such droplets are influenced by both gravity and imbalanced surface energy, thus accelerating droplet accumulation and sliding mechanisms. Employed the wetness of gradient slopes to create differences in front- and back-end droplet contact angles, making the front-end contact angle smaller than the that of the back-end and inducing droplets to be transferred along the condensation surface [8]. The experiment results demonstrated that gradient surfaces exhibited greater droplet drainage efficiency than normal hydrophobic surfaces did. When the condensation surfaces were positioned vertically, gradient surfaces exhibited 35% more droplet drainage than normal hydrophobic surfaces, thereby proving that droplets are movable and can be drained, even on horizontal surfaces.

Designed two hydrophilic–hydrophobic surfaces, namely the island pattern and tree pattern [9]. The hydrophilic island patterns of different sizes had hydrophilic–hydrophobic areas on a scale of 1:3. The study revealed that in the tree pattern, water droplets were trapped in the hydrophilic area. In the island pattern, smaller hydrophilic island areas resulted in a smaller maximum droplet radius, thereby increasing the condensation rate, droplet dropping frequency, and thermal convection coefficient. Furthermore, hydrophilic condensation surfaces with the island pattern and a thickness of 0.25 mm exhibited higher heat transfer coefficients than normal hydrophilic surfaces did. Compared the droplet condensation performance between a condensation surface with superhydrophilic and hydrophilic sections that were parallel to each other and an entirely hydrophilic copper surface [10]. The results indicated that the superhydrophilic–hydrophilic condensation surface exhibited a smaller maximum droplet size and higher drainage frequency than the hydrophilic copper surface did. Additionally, when droplets on the hydrophilic section gradually enlarged and came into contact with the superhydrophilic area located on both sides of the hydrophilic section, the droplets were sucked over to the superhydrophilic area due to differences in capillarity force. Thus, the water catchment rate of the superhydrophilic–hydrophilic condensation surface was 17.4% higher than that of the hydrophilic copper surface.

The influence of hydrophilic, hydrophobic, superhydrophilic, and superhydrophobic hybrid surfaces on condensation heat transfer [11]. The results indicated that the heat transfer coefficient of hydrophilic–hydrophobic hybrid surfaces was greater than that of hydrophilic surfaces. Furthermore, the heat transfer coefficient of hydrophilic–hydrophobic hybrid surfaces was 9% and 16% greater than that of hydrophobic and hydrophilic surfaces, respectively. The study revealed that hydrophilic–hydrophilic hybrid surfaces induce the accumulation of droplets from hydrophobic and hydrophilic areas, thereby accelerating droplet sliding.
Additionally, the study tested the performance of condensation surfaces in which hydrophilic and hydrophobic areas were reversed. The results indicated that the heat transfer coefficient was reduced in the reversed condensation surface, thereby indicating the importance of hydrophilic and hydrophobic structure design.

The aforementioned studies explained the critical influence of hydrophilic and hydrophobic designs on condensation heat transfer. However, most studies have only discussed the performance of single-surface condensation heat transfer. Few studies have applied hydrophilic and hydrophobic designs in complete heat exchanger sets. Therefore, this study employed surface processing technology to create a hydrophobic surface on the copper fins of heat exchangers to effectively induce condensation and remove air with a high temperature and humidity. This study also discusses the influence of hydrophobic surfaces on changes in condensation heat transfer efficiency, droplet condensation conditions, and latent heat changes. Unlike most studies that have discussed the condensation heat transfer of single-surface fins, this study adopted different hydrophobic–hydrophilic hybrid fins to create a heat exchanger and determined the influence of fin surface modification on the condensation heat transfer of a heat exchanger. Additionally, this study adopted visualization experiments to observe the influence of different condensation surfaces on the condensation process and pressure drops.

2. Research method
This study mainly analyzed copper fins and the influence of surface property on the condensation heat transfer function of such fins. Whereas most related studies have discussed the condensation heat transfer ability of single-surface fins, this study designed and constructed a heat exchanger with copper fins and discussed the influence of fin surface modification on the comprehensive condensation-related heat transfer ability of a heat exchanger. Additionally, visualization experiments were adopted to observe the influence of different condensation surfaces on the condensation process. The researchers reviewed the relevant literature and research on condensation heat transfer, metal surface modification, and condensation heat transfer enhancement technologies to identify experiment variables applicable for the research proposed. By analyzing the influence of different condensation surfaces on condensation heat transfer, this study established a parameter-based experiment to identify related variables for optimal condensation heat transfer.

3. Experiment planning and framework
This study analyzed the condensation heat transfer properties of a heat exchanger fin with a chemical surface coating. While maintaining similar environmental temperatures and humidity, this study focused on the influence of different air velocities and heat exchanger surface properties on the condensation heat transfer of the heat exchanger. The experimental setup of this study comprised an environment control room, centrifugal blower, anemometer, thermometer, hygrometer, and differential manometers (see Figure 1).
This study contained three parts. In the first part, a dry coil–related condensation heat transfer experiment was conducted to ensure that the two heat exchangers had consistent heat transfer properties in accordance with temperature changes. After this process was complete, an experiment was conducted in an environment with high temperature and humidity. The second part of the study involved a condensation heat transfer analysis of the copper fins of heat exchangers. In the third part of the study, the researchers coated the surface of copper fins with chemical substances and compared the influence of condensation heat transfer properties with copper fins that had or had not modified surfaces. Additionally, to ensure the creditability of the experiment results, this study conducted uncertainty analysis and evaluated the experiment reproducibility.

In the first part of this study, the two heat exchangers with different surface properties were subjected to a dry-coil heat transfer experiment to determine whether the heat exchangers exhibited similar heat transfer rates under suitable temperature changes and to establish a fiducial value. The experiment was conducted under 30°C and 60% RH. The temperature of water output from the thermostatic water bath output was set to 50°C, and the air velocity at the heat exchanger entrance ranged from 0.5 to 2.5 m/s.

The second part of this study employed a condensation heat transfer system to discuss the influence of humidity-related air conditions on the condensation heat transfer of heat exchangers with general copper fins. The experiment was conducted at 30°C and 90% RH, with the thermostatic water bath output water temperature set at 10°C and the air velocity at the heat exchanger entrance ranging from 0.5 to 2.5 m/s.

In the third part of this study, chemical substances were employed to modify the surface property of the copper fins of heat exchangers. The modified copper fins were subjected to experiments using similar experiment parameters and conditions to determine the condensation heat transfer enhancement rate of the chemical coating. The experiment was conducted under 30°C and 90% RH, with the thermostatic water bath output water temperature set as 10°C and the air velocity at the heat exchanger entrance ranging from 0.5 to 2.5 m/s.

The hydrophobic chemical coating process consisted of soaking the copper fin of a heat exchanger in an ethanol solution with 0.1 wt% of 1H, 1H, 2H, 2H-Perfluorodecytriethoxysilane for 10 minutes. After the soaking process was complete, the
coated copper fin was rinsed with ethanol and prepared for volatilization. Subsequently, the copper fin was baked at 120°C for 12 hours before cooling and extraction, thereby completing the hydrophobic chemical coating process.

This experiment employed two experiment samples with similar fin structures of heat exchangers but with different surface materials. The heat exchanger fins were composed of copper and had a thickness of 0.5 mm. The fins were penetrated by copper pipes with a 10-mm diameter and positioned in a staggered arrangement with a 1.6-mm space between each fin. The test section consists of five copper pipes arranged in two rows, thereby constituting 10 circuits. This structure enabled the copper pipes to conduct energy exchange with the surrounding air. Figure 2 displays the copper fins of a heat exchanger without modification. Figure 3 displays the copper fins with surfaces that were coated with chemical substances to bestow them with hydrophobic properties.

4. Experiment results and discussion

After the input air temperature was set at 30°C and the RH was set at 60%, and the thermostatic water bath output water temperature was set at 50°C, the experiments were conducted under different air velocities. The experiment was conducted for 60 minutes, during which time the researchers recorded the heat transfer rate per minute and constructed a line chart based on the recordings to analyze the heat transfer rate and the input and output pressure differences. Figure 4 indicates that the two heat exchangers exhibited similar heat transfer rates. Additionally, Figure 5 presents the changes in input and output pressure differences, thereby demonstrating that under similar air velocity conditions, the pressure differences of the heat exchangers did not change. However, the pressure difference increased with an increase in air velocity. Figure 6 shows that the two heat exchangers exhibited consistently similar Reynolds numbers and Fanning friction factors. This is because the dry coil pressure is not affected by the condensation liquid. The fiducial values acquired in this study enabled the researchers to proceed with the wet coil condensation heat transfer experiment.
Figure 4 Heat transfer rates of the two heat exchangers with different surface properties and under different air velocities (T = 30°C, RH = 60%)

Figure 5 Pressure differences of heat exchangers under different air velocities (T = 30°C, RH = 60%)
Figure 6 Reynold numbers and Fanning friction factors of the heat exchangers with different surface compositions (T = 30°C, RH = 60%)

After the input air temperature was set at 30°C, the RH was set at 90%, and the output water temperature of the thermostatic water bath was set at 10°C, the experiment was conducted under different air velocities for 60 minutes. The researchers constructed a line chart of the data recorded every minute to analyse the heat transfer rate, condensation moisture content removal (hereafter referred to as water removal), and the condensation condition. Figure 7 indicates that the water film condensed on general copper surfaces increased in thickness over time. This creates a water film layer that reduces heat transfer capacity (see Figure 9). By contrast, droplets grew on hydrophobic surfaces due to their low surface wetness properties (see Figure 8). Figure 10 indicates that when a water droplet grows to its maximum radius, the gravitational force of the droplet will exceed the adhesive force between the droplet and condensation surface, thereby causing the droplet to slide downwards and remove other droplets beneath it.

Figure 7 Condensation condition of unmodified copper surfaces under a air velocity of 2.0 m/s

(a) (b) (c)
Figure 8. Condensation conditions of the hydrophobic surface under a air velocity of 2.0 m/s:
(a) 10 minutes (b) 20 minutes (c) 30 minutes
(d) 40 minutes (e) 50 minutes (f) 60 minutes

Figure 9. Surface condensation and droplet removal process for unmodified copper fins

Figure 10 Surface condensation and droplet removal process for hydrophobic surfaces

Figure 11 displays the total water removal quantity of the two heat exchangers subjected to different air velocities for 60 minutes. The figure indicates that the quantity of water removed by both heat exchangers increased accordingly to increases in air velocity. Further analysis revealed that the surface droplet removal and condensation speed of the hydrophobic surface was faster than that of unmodified copper surfaces; the average water removal rate of hydrophobic surfaces was 6.8% higher than that of unmodified copper surfaces.
Figure 11. Comparison between water removal of two surfaces under different air velocities (T = 30°C, RH = 90%).

Figure 12 shows the average heat transfer rate of the two heat exchangers under different air velocities for 60 minutes. The figure demonstrated that the heat transfer rate of both heat exchangers increased with an increase in air velocity. Additionally, the average heat transfer rate of heat exchangers with hydrophobic surfaces was higher than those of unmodified copper surfaces, thereby demonstrating heat transfer efficiency improvements of 3% to 8%. Due to their low surface wetness, dropwise condensation occurred on hydrophobic surfaces. When a droplet grows to its maximum radius, the gravitational pull of the droplet supersedes the adhesive force between the droplet and condensation surface, thereby causing the droplet to slide downwards and remove other droplets beneath it. After water removal was conducted, the droplet condensation process was repeated on the cleared space. Owing to higher water removal and condensation speeds, hydrophobic surfaces exhibit greater heat transfer performance than unmodified copper surfaces.

Figure 12. Heat transfer rates of different condensation surfaces under different air velocities (T = 30°C, RH = 60%)
5. Conclusion

This study mainly discussed the influence of different surface properties, namely an unmodified copper fin surface and a modified hydrophobic fin surface, on the heat transfer effect of heat exchangers. The researchers established the following conclusions based on the experiment results.

The heat transfer and water removal rates of the two heat exchangers increased with an increase in air velocity. When the air velocity was increased from 0.5 to 2.5 m/s, the heat transfer and water removal rates of both heat exchangers were increased by approximately 90%. Under similar air velocity conditions, heat exchangers with hydrophobic surfaces constantly removed the condensed water droplets, thereby preventing the water droplets from causing surface thermal resistance. As a result, the condensation heat transfer effect of hydrophobic surfaces was greater than that of unmodified copper surfaces. Compared with heat exchangers with unmodified copper fin surfaces, heat exchangers with hydrophobic surfaces exhibited a 5.56% higher heat transfer efficiency. Furthermore, the optimal increase in heat transfer efficiency in this study was observed when the air velocity was 2.0 m/s, during which time the heat transfer efficiency of heat exchangers with hydrophobic surfaces was 7.59% higher than that of heat exchangers with unmodified copper surfaces. It was revealed that the pressure differences of both heat exchangers increased with an increase in condensed water droplet sizes and progressively stabilized at higher air velocities.

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References

[1] Ma X, Lan Z, Zhou X-D, Wang M (2009) Theoretical Study of Dropwise Condensation Heat Transfer: Effect of the Liquid-Solid Surface Free Energy Difference. International Journal of Heat and Mass Transfer 16: 61-71

[2] Kim S, Kim K-J (2011) Dropwise Condensation Modeling Suitable for Superhydrophobic Surfaces. International Journal of Heat and Mass Transfer 133: 081502-081507

[3] Young T (1805) An Essay on the Cohesion of Fluids. Philosophical Transactions of the Royal Society of London 95: 65-87

[4] Wenzel R-N (1936) Resistance of solid surfaces to wetting by water. Industrial And Engineering Chemistry. 28: 988-994

[5] Cassie A-B-D., Baxter S. (1944) Wettability of porous surfaces. Transaction of the Faraday Society. 546-551

[6] Kumagai S, Tanaka S, Katsuda H, Shimada R (1991) On the enhancement of filmwise condensation heat transfer by means of the coexistence with dropwise condensation sections. Experimental Heat Transfer 4: 71-82 DOI 10.1080/08916159108946406
[7] Leu T-S, Lin H-W, Wu T-H (2006) Enhancement of phase change heat transfer by using surface energy patterning techniques Nano/Micro Engineered and Molecular Systems, 2006 NEMS'06 1st IEEE International Conference on IEEE, pp. 994-998.

[8] Bonner RW (2009) Dropwise condensation on surfaces with graded hydrophobicity ASME 2009 Heat Transfer Summer Conference collocated with the InterPACK09 and 3rd Energy Sustainability Conferences American Society of Mechanical Engineers, pp. 491-495.

[9] Chatterjee A, Derby MM, Peles Y, Jensen MK (2014) Enhancement of condensation heat transfer with patterned surfaces. International Journal of Heat and Mass Transfer 71: 675-681.

[10] Ghosh A, Beaini S, Zhang BJ, Ganguly R, Megaridis CM (2014) Enhancing dropwise condensation through bioinspired wettability patterning. Langmuir 30: 13103-13115

[11] Yang K-S, Lin K-H, Tu C-W, He Y-Z, Wang C-C (2017) Experimental investigation of moist air condensation on hydrophilic, hydrophobic, superhydrophilic, and hybrid hydrophobic-hydrophilic surfaces. International Journal of Heat and Mass Transfer 115: 1032-1041