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Condensation Heat Transfer Characteristics of Moist Air Outside Hydrophilic and Super-hydrophobic 3D Pin Fin Tube

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Three dimensional pin fin tube is an effective heat transfer element. It has been widely used in industry process. However, condensation heat transfer characteristic of moist air outside it has not been experimentally studied. The wettability of tube surface has an important effect on this process. In this study, experiments were carried out, in which moist air condensing outside three dimensional pin fin tube with different wettability. Smooth tube is also tested to make comparison. Effects of steam mole fraction, moist air temperature, and wall subcooling are analysed in detail. Super-hydrophobic surface is obtained using oxidation and self-assembling monolayer method. The results show that heat transfer coefficient increases with the increase of steam mole fraction, wall subcooling and the decrease of moist air temperature. Heat transfer coefficient ranges from 55 to 2,035 W/m^{2}K within the study of this paper, and hydrophilic three dimensional finned tube can achieve 2 times heat transfer coefficient compared with smooth tube and superhydrophobic three dimensional pin fin tube.

1. Introduction

Condensation heat transfer of moist air plays an important role in industry process, and enhancing its heat transfer coefficient (HTC) is of great importance to energy saving and environment protection. Natural gas has the advantage of clean, so it meets the requirement of environment protection. The main content of natural gas is methane. After burning with air, its exhaust gas contains about 20% volume of water vapor, which have much latent heat (Osakabe et al., 1999). 1 m^3 natural gas contains 1.5 kg water vapor and 3.6 MJ latent heat during burning, and energy efficiency of gas fired boiler can increase about 10 % if the latent heat can be recovered (Wang et al., 2013). However, noncondensable gas in the moist air inhibit the condensation process of vapor greatly. With the process of condensation, noncondensable gas formulate a noncondensable layer near heat transfer surface, and water vapor must get through it to transfer heat with the cooling wall, making heat transfer coefficient decreased greatly. Wang (2018) analysed the market of natural gas in China and pointed out that significantly increasing the proportion of natural gas in the primary energy consumption structure will help China transition to a low-carbon energy structure. Othmer (1929) was the first to carry out experiment to study the effect of noncondensable gas, and found that even 0.5 % noncondensable can reduce heat transfer coefficient more than 50 %. Enhancement of moist air condensation is of great importance.

Finned tube is an effective method to enhance heat transfer process. Fins can increase heat transfer area, and break boundary lay near heat transfer surface. Ali et al. (2012) studied the heat transfer performance of pure water condensation outside integral fined tube and pin fin tube. He pointed out that pin fin tube has less condensate retention compared integral fin tube with identical other parameter. Chen et al. (2018) studied the condensation of hydro-fluoro-olefin (HFO) refrigerant on 3D fins, and found that the HTC of 3D finned tube can achieve 10.8 times as high as smooth tube. Ge et al. (2017) studied gold plating on plain plate and extended surface, she found that when condensate flow rate was low, gold plating surface didn't exhibit higher HTC. Ji et al. (2019) investigated the condensation heat transfer of superhydrophilic-hydrophobic network hybrid surface and obtained 1.7 times higher heat transfer coefficient. Tong et al. (2019) studied the steam-air condensation over a vertically longitudinal finned tube, and found that the longitudinal finned tube can enhance the heat transfer process when air mass fraction in excess of 75 %. Chu et al. (2013) studied the heat transfer and pressure drop characteristic of fin-and-oval-tube heat exchanger using numerical method and found the average

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Nusselt number increases by 16.7 %. Du et al. (2011) experimentally studied the elliptical finned tube heat exchangers inclined towards different air oncoming flow angle and obtained heat transfer coefficient and resistance coefficient of the air side were acquired. Wu et al. (2017) developed an equation based on thermodynamics analysis, which relates the vapor/gas liquid interface parameters and the main stream. Single phase convective heat transfer and flow characteristic has also been studied by many researcher. Zhang et al. (2019) used Taguchi method to study the influence of the structural parameters of 3D pin fin tube on the heat transfer and pressure drop characteristics in the air flow, and found that fin height has the largest effect. Chen et al. (2019) experimentally studied 3D pin fine tube mainly focus on the effect of structure parameters.
3D pin fin tube is an effective method to enhancement heat transfer process, and surface property and operation parameter has an important effect on the condensation process. However, condensation heat transfer of moist air outside 3D pin fin tube has not been experimentally studied. To fulfil this research gap, experiments are carried out to study the condensation heat transfer of moist air outside 3D pin fin tube with different surface wettability. In this paper, moist air flows across a horizontal cooper tube, which has an outer diameter of 20 mm. Its inner diameter is 14 mm and cooling water is flowing inside. Temperature of moist air, tube wall, inlet and outlet temperature of coolant water are measured. Vapor volume fraction is also recorded at the same time. Besides, moist air velocity is kept at 2.4 m/s, and coolant water is kept at a low constant velocity. Besides, the contract angle is 67° for hydrophobic tube and 153° for superhydrophobic tube.

2. Experimental system and procedure

2.1 Experimental system

Air and steam were mixed to monitor exhaust flue gas. The test rig consists of four main part, which are circulation line, steam generator system, cooling water system and measuring system, as shown in Figure 1. All the heated facilities were wrapped with insulating layer except the test tube. Steam came from boiler was mixed with hot air inside the mixing box, and then moist air was transported into the test section to transfer heat with 3D pin fin tube. Inside the 3D pin fin tube was the cooling water from water tank. After heat transfer, the condensates was collected in the bottom of the test section and exhaust moist air was transmitted into the mixing box to replenish water vapor. Pipeline from the mixing box to the pressure gauge were wrapped with heater band. The heating band and the boiler has a power of 2 kW and 6 kW respectively.
At the beginning of the experiment, the circulating fan was turned on to circulating air inside the pipeline. Then the heater band was turned on to heat the air. It needs about 2 h to heat the system above 100 °C. After that the boiler was turned on and it needs about 3 min to produce steam. Mixture was transported to the test section to transfer heat with 3D pin fin tube. The velocity of moist air is measured by pilot tube and differential pressure gauge.
Clean tap water was pumped into the water tank in the higher position of the test facility. Cooling water's flow rate was measured by the metallic rotor flow meter and temperature increase was measured by the T type thermocouples.

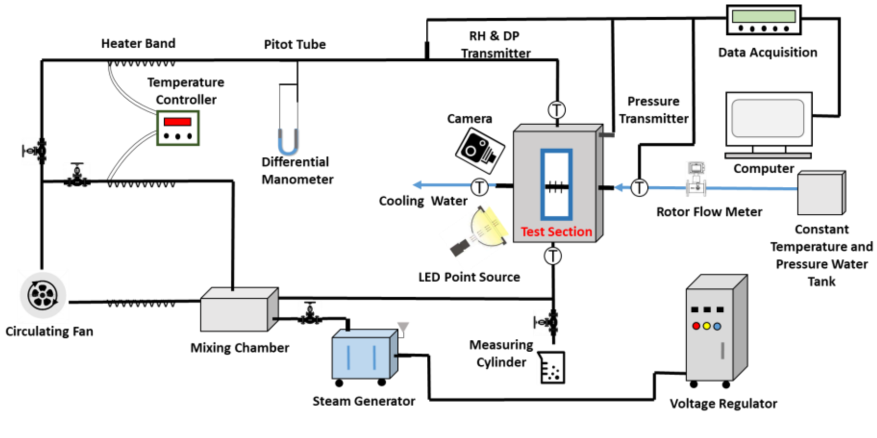


Figure 1: Schematic diagram of the experimental system

The test sectional size is 400 mm in height, 400 mm in length and 80 mm in width. Smooth tube or 3D pin fin tube was placed horizontally in the middle of the chamber. The length of the tube is 495 mm, and its effective heat transfer length is 400 mm. The test section is connected with a transition connection to make the moist air flow uniformly before entering it. All the test was well thermal insulated to prevent heat loss to the environment.

The heat transfer tube was made of cooper, and it has an outer diameter of 19 mm and inner diameter of 13 mm. Its thermal conductivity is 397 W/ (m K). Tube's both ends were wrapped with a 47.5 mm long nylon tube, which inner diameter is a little bit larger than the outer diameter of heat transfer tube, preventing heat conduct with the steel chamber wall. Eight T type thermocouples were used to measure the tube wall temperatures, as shown in Figure 2. Before and after the heat transfer area were two mixing chambers to make water flow uniformly in it. Three 1.0 mm diameter thermocouple were fixed in the chamber to measure the average coolant temperature. Superhydrophobic surface treatment method is similar with the lecture (Hu et al. 2015). For the etching method was exactly the same. After that procedure, trimethoxy (1H, 1H, 2H, 2H-heptadecafluorodecyl) silane methanol solution, which volume fraction was 1%, was used to formulate an organic layer at temperature 75 °C for 1 h. The organic layer is obtained with self-assembly of molecules attached to the oxide surface of copper.

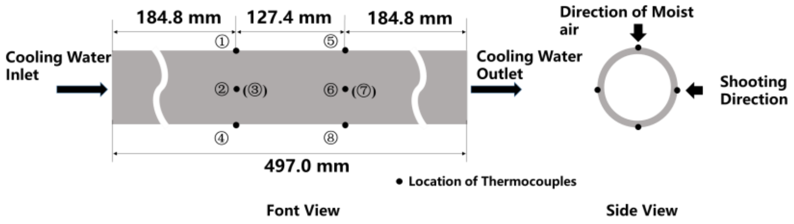


Figure 2: Schematic diagram of thermocouple arrangement.

2.2 Data reduction and system validation

The amount of heat convection of 3D pin fin tube and smooth tube was considered equal to the heat transferred in coolant side. Hence it can be calculated by coolant water mass flow rate and its temperature rise, as shown in Eq(1), i.e.,

$$Q = q_m c_{p,w}(t_{c,out} - t_{c,in}) \tag{1}$$

, where q_m is coolant water mass flow rate measured and calculated by the metallic rotor flowmeter, $c_{p,w}$ is thermal capacity of water, $t_{c,out}$ and $t_{c,in}$ are the average outlet and inlet temperature measured by six T type thermocouples, as shown in Eq(2) and Eq(3),

$$t_{c,\mathrm{out}} = \sum_{i=1}^{3} t_{c,out,i} \tag{2}$$

$$t_{c,\mathrm{in}} = \sum_{i=1}^{3} t_{c,\mathrm{in},i} \tag{3}$$

Outside HTC can be obtained by heat transfer rate, average temperature of moist air and tube outer wall temperature, and heat transfer coefficient is calculated by Eq(4),

$$h_o = \frac{Q}{A(t_f - t_w)} \tag{4}$$

, where t_f is moist air inlet average temperature, A is heat transfer area calculated based on base tube outer diameter for smooth tube and 3D pin fin tube. In our study, A is almost the same. For 3D pin fin tube is fabricated based on smooth tube, using special cutting tools. This kind of fabricating method has the advantage of easy operating and avoid contract thermal resistance between fins and base tube.

Table 1: Uncertainties for measurements.

Parameter	Instrument	Uncertainty
Temperature	Thermocouples	± 0.1 %
Coolant mass flow rate	Rotor flow meter	± 0.5 %
Relative Humidity	Humidity and temperature transmitter	± 1 %
Moist air velocity	Pitot tube	± 1.6 %
Heat transfer coefficient	/	± 15 %

3. Results and discussion

3.1 Effect of surface property and vapor mole fraction

Effect of water vapor mole fraction (X_v) is studied. Moist air temperature (t_m) is kept 90 °C, and X_v is ranging from 5% to 50 %. As can be seen from Figure 3. Superhydrophobic 3D pin fin tube (SFT) have smaller condensates below compared with hydrophilic 3D pin fin tube (HFT) and hydrophilic smooth tube (HST). Contract angle remains almost constant before and after heat transfer experiment. Besides, refreshing frequency is smaller in superhydrophobic tube compared with hydrophilic surface. This makes heat transfer capacity weaker for superhydrophobic tube. Heat flux (q) and outside heat transfer coefficient (h_o) changing with vapor volume fraction (X_v) can be seen in Figure 4. q and h_o both increase with the increment of vapor mole fraction, and HFT can achieve 0.3 times higher heat flux than HST. When vapor mole fraction is less than 7 %, 3D pin fin tube's heat transfer coefficient is larger than smooth tube, for 3D pin fin helps increase heat transfer area and break thermal and flow boundary layer. Single phase heat transfer is the mean form in this condition. But when vapor mole fraction becomes larger than 7 %, condensation heat transfer starts to appear, and hydrophobic surface is getting to have larger heat transfer coefficient. Due to higher surface refreshing frequency, hydrophilic tube has higher heat transfer coefficient.

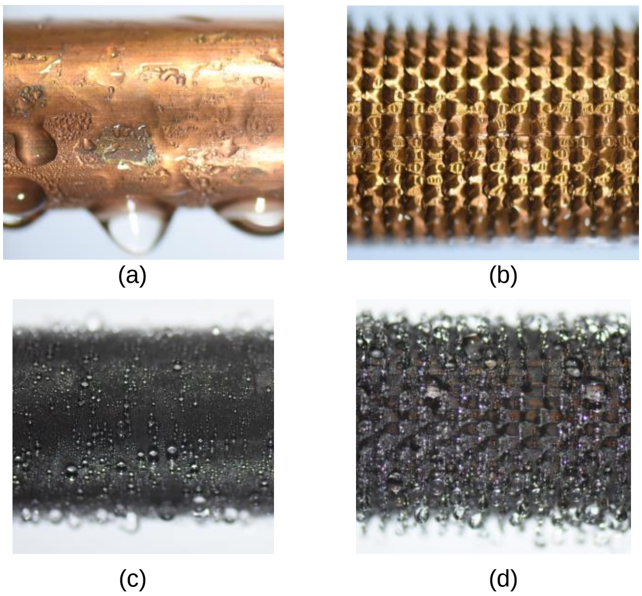


Figure 3: Photo of moist air condensing on heat transfer tube, (a) hydrophilic smooth tube, (b) hydrophilic 3D finned tube, (c) superhydrophobic smooth tube, (d) superhydrophobic 3D pin fin tube.

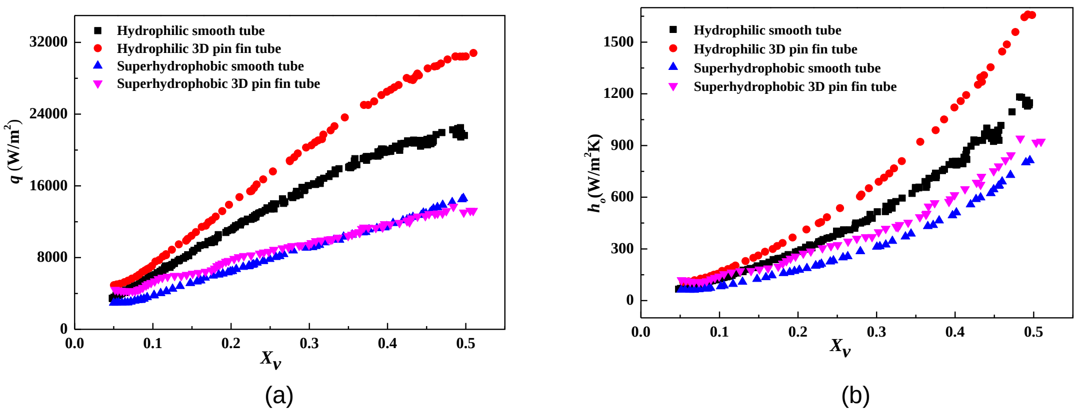
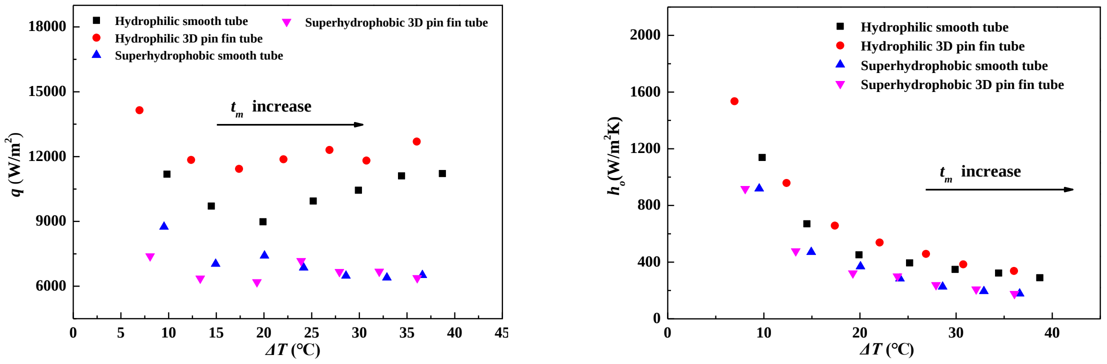


Figure 4: Effect of moist air mole fraction, (a) heat flux changing with wall subcooling, (b) outside heat transfer coefficient changing with wall subcooling.

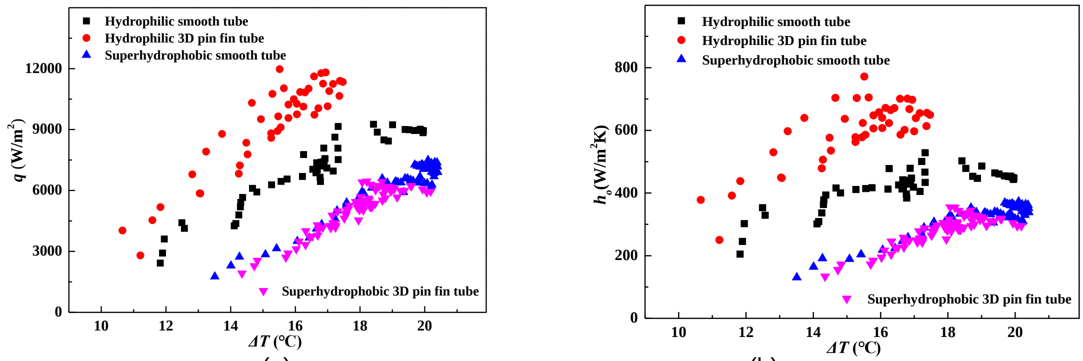
3.2 Effect of moist air temperature

In this section, effect of moist air temperature is studied. Moist air ranges from 60 °C to 90 °C. Moist air velocity and coolant water inlet temperature ($t_{c,i}$) remains constant. As can be seen in Figure 5, when t_m increases, heat flux of HFT decrease from 15 kW/m^2 at the beginning, but then remains almost constant around 12 kW/m^2. Superhydrophobic surface is 6 kW/m^2 lower than hydrophilic surface. When ΔT or t_m becomes larger, h_o decreases. This is because when t_m becomes larger and X_v remains 20 %, dew point becomes lower. Condensation becomes more difficult, heat transfer coefficient also becomes lower.



(a) (b)

Figure 5： Effect of moist air temperature, (a) heat flux changing with wall subcooling, (b) outside heat transfer coefficient changing with wall subcooling.



(a) (b)

Figure 6: Effect of wall subcooling, (a) heat flux changing with wall subcooling, (b) outside heat transfer coefficient changing with wall subcooling.

3.3 Effect of wall subcooling

ΔT has an important influence on condensation process. In this section, ΔT is adjusted through changing $t_{c,i}$. Moist air is kept at 70 °C. Coolant water temperature is adjusted from 30 °C to 50 °C, and its mass flow rate remains constant. As shown Figure 6 (a), heat flux both increase when ΔT getting larger. Hydrophilic surface tube has a smaller ΔT. When $t_{c,i}$ increases from 30 °C to 50 °C, heat flux of HFT increased from 3 kW/m^2 to 10 kW/m^2, which increases from 0.5 time to 0.8 times larger compared with HST. The h_o of SFT and SST increase from 2 kW/m^2 to 6 kW/m^2. This trend is different from Figure 5. Because in this experiment, ΔT increased due to tube wall average temperature decreased. Lower average wall temperature makes more vapor condensate outside tube wall, which means higher HTC. HFT has a larger h_o than hydrophilic smooth tube. Superhydrophobic surface tube show almost the same heat transfer performance, both are lower than hydrophilic surface tube.

4. Conclusions

3D pin fin tube has the advantage of higher heat transfer performance than smooth tube both for hydrophilic and superhydrophobic surface. Within the parameter of this paper, 3D pin fin tube can achieve higher heat flux than smooth tube. Superhydrophobic surface helps eliminate condensate retention below heat transfer tube, but does not exhibit higher heat transfer performance compared with hydrophilic 3D pin fin tube or smooth tube. Hydrophilic tube performs better in lower moist air temperature and lower coolant water inlet temperature. Heat transfer coefficient decrease with increase of moist air temperature, and increase with the decrease of inlet cooling water temperature.

Heat flux and heat transfer coefficient increases from 4 kW to 32 kW and 120 W/m^{2}K to about 1,650 W/m^{2}K for hydrophilic 3D pin fin tube when water vapor fraction increases from 0.05 to 0.50. For superhydrophobic surface, heat flux only increases about 50 %. As the moist air temperature increases, heat flux of hydrophilic 3D pin fin tube decreased about 20 %, and 30 % for superhydrophobic 3D pin fin tube.

The present findings confirm that 3D pin fin tube with hydrophilic surface is an effective element to enhance the condensation process of moist air. And it has a promising usage in the waste heat recovery of gas fired boiler. Future research should consider the effects of pin fin parameter on the heat transfer process, in which sensible heat and latent heat transfer occurs at the same time. Simpler and more accurate model needs to be developed to predict heat transfer process of 3D pin fin tube.

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