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Research Paper

Experimental investigation of convective condensation heat transfer on tube bundles with different surface wettability at large amount of noncondensable gas

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HIGHLIGHTS

- Air–vapor condensation on tube bundles with various wettability is studied experimentally.
- The discrete droplet flow of the condensate among bundles is observed.
- Average condensation heat transfer improves as the tube-row number increases.
- Condensation enhancement of bundle effect reduces with increase of water vapor fraction.

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ABSTRACT

Surface modification technology provides the potential to further enhance condensation heat and mass transfer. The water vapor convective condensation heat transfer of condensing heat exchanger assembled by plain, 2D-finned and 3D-finned tubes with different surface wettability was investigated experimentally, when the volume fraction of noncondensable gas was more than 75%. The condensation behaviors and flow patterns of the condensate among bundles were also recorded visually. It was found that the discrete droplet flow of condensate formed among tube bundles in the presence of large amount of noncondensable gas. Typical factors including the cooling water flow rate, air–vapor mixture flow rate, and the volume fraction of water vapor on convective condensation heat transfer coefficient were discussed in detail. The experimental results showed that the average condensation heat transfer coefficient of superhydrophobic plain tubes with 9 rows was 1.53 times of one single row for the water vapor volume fraction of 11% while it reduced to 1.34 times of one single row when the vapor volume fraction reached 23%.

1. Introduction

The condensation heat transfer enhancement promises high efficient energy saving for various industries. If the temperature of vapor/noncondensable gas mixture is reduced below the dew point, the water vapor in the mixture will condense accompanied by release of the sensible heat and latent heat. Improvements in heat and mass transfer during this phase change process can result in a considerable conservation of energy and economic resources. Condensing heat exchanger is the key device in such applications. However, condensation heat transfer of vapor/noncondensable gas mixture in the condensing heat exchanger is not yet well understood due to the complexity of both the geometric structures and partial condensation. Significant efforts have been devoted to develop the enhancement technologies of condensation heat transfer, and there has been a lot of research reported on the performance of condensing heat exchangers applied in various industries under dehumidifying conditions.

Condensation heat transfer of exhaust gas from a natural gas boiler on horizontal heat exchanger to recover latent heat was experimentally investigated by Osakabe et al. [1,2]. Experimental research was reported for condensation of water vapor on a tube bank in the presence of air [3,4]. It was found that the heat transfer coefficients of the vapor side for the integral-fin tubes were 2.5–3.5 times higher than those for plain tubes. Condensation heat transfer of vapor–noncondensable gas mixtures in horizontal tubes was experimentally studied [5], and the effects of local mass fraction of noncondensable gas, local liquid flow and local turbulent mixing on local heat transfer coefficient were also presented. The condensation experiments on wire-wrapped enhanced tubes and horizontal finned tubes were carried out, and the effects of inundation and condensate retention were reported [6,7]. Experimental

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investigation of forced convective condensation heat transfer on the bank of horizontal smooth tubes was reported for the mass fraction of water vapor ranging from 3.2 to 12.8% [8]. Their experimental results showed that the convection condensation heat transfer coefficient was 1–3.5 times of the forced convection without condensation. Hwang et al. [9,10] investigated the heat and mass transfer characteristics of a latent heat recovery (LHR) heat exchanger with crushed titanium tubes and evaluated the pressure drop and convective heat transfer coefficient of the LHR heat exchanger with/without condensation. They found that the convective heat transfer coefficient with condensation was 3–5 times higher than the case without condensation. Shi et al. [11] designed a compact heat exchanger of plain finned tubes for a heat recovery steam generator to recover both sensible and latent heat. And the convective condensation heat transfer performance was investigated theoretically and experimentally. Tang et al. [12] developed a double boundary layer model and numerically investigated film condensation heat transfer outside a horizontal tube in the presence of noncondensable air. Ma et al. [13] experimentally studied the inundation effect on the film condensation heat transfer coefficient outside 5-row tube bundle.

It is known that the dropwise condensation exhibits much higher heat transfer character than the film condensation [14]. Recently, with the increasing research on fabrication of non-wetting surface using various surface modification techniques, promoting dropwise condensation on hydrophobic or superhydrophobic surface has become a promising technique to enhance the condensation heat transfer.

There has been significant interest in developing a combination method of chemical functionalization and roughness to create superhydrophobic surface for dropwise condensation and enhance the condensation heat transfer. The self-assembled monolayer approach as a mature chemical functionalization method to create the nonwetting surfaces has the advantage without introducing a significant thermal resistance. Vemuri et al. [15,16] used self-assembled monolayers of n-octadecyl mercaptan to promote the dropwise condensation and they found that the n-octadecyl mercaptan coated surface improved the condensation heat transfer rate by about eight times when the pressure was 101 kPa. The self-assembled monolayer treatment was employed to investigate the effects of surface free energy and nanostructure on dropwise condensation by Lan et al. [17]. A new condensate sinkage mode for the dropwise condensation on the superhydrophobic roughed surface in the presence of noncondensable gas was proposed [18]. Droplet departure frequency on the $Cu(OH)_2$ superhydrophobic surface was investigated using the environmental scanning electron microscopy [19], and the higher surface renewal frequency improved the condensation heat transfer coefficient by a factor of 2 during dropwise condensation.

In comparison to the thiols, the silanes are more stable for the practical application. The superhydrophobic nanostructured surface was achieved by the silane self-assembled monolayer treatment [20,21], and it was observed that the condensate droplets could jump from the condensing surface of low super-saturation. Xiao et al. [22] experimentally found that the oil-infused micro- and nanostructure surface had approximately 100% improvement in condensation heat transfer coefficient compared to the typical hydrophobic surface. Subsequent studies [23–25] reported the impact of micro- and nanoscale topography of hierarchical superhydrophobic surface on the droplet coalescence dynamics and wetting states during dropwise condensation. Rykaczewski et al. [26] described a novel droplet coalescence mechanism during dropwise condensation on the superhydrophobic surface, and they also explained the contribution of the three-dimensional aspect of droplet coalescence to the dropwise condensation heat transfer process. Recently, Preston et al. [27] provided the ultrathin scalable chemical vapor deposited (CVD) graphene coatings with robust chemical stability and low thermal resistance to promote dropwise condensation on copper tube. And they demonstrated experimentally that the condensation heat transfer coefficient of copper tube with graphene CVD coatings was approximately 4 times larger than that of the film condensation on bare tube.

Although lots of works were reported on the condensation heat transfer enhancement by using various surface extension technologies and by promoting the dropwise condensation with wettability modified technologies, the investigation on condensation heat transfer enhancement technologies of extended surface combined with wettability modification was rarely presented. Furthermore, there was no report about the experimental research of convective condensation heat transfer outside different wettability bundles in the presence of a large amount of noncondensable gas. In the present study, we demonstrated the convective condensation heat transfer characteristics of plain, 2D-finned and 3D-finned horizontal tube bundles with different surface wettability at a large amount of noncondensable gas. The rest of the paper was organized as follows. In Section 2, we detailed the experimental system and testing process of condensation heat transfer outside different wettability bundles, and the geometries of both the condensing heat exchanger and three types of heat transfer tubes were also presented. In Section 3, the employed surface modification and characterization methods were described. In Section 4, the condensation behaviors and flow patterns of the condensate among bundles were visually presented. In addition, the influences of operating parameters and bundle effect on the convective condensation heat transfer were discussed in detail, when the volume fraction of the noncondensable gas was more than 75%. Finally, a brief conclusion was given in Section 5.

2. Experiment facility and procedure

2.1. Experiment facility and test method

The experimental apparatus is schematic in Fig. 1. The air at room temperature supplied by a centrifugal fan was heated to the same temperature as the water vapor through the first stage electric heater with the maximum input of 90 kW. The water vapor of 0.1–0.7 MPa was generated by a 72 kW electric boiler. The water vapor and air at the same temperature were mixed in the mixing chamber. Then the air–vapor mixture flowed into the second stage electric heater with the maximum input of 30 kW and was heated to a required temperature. The volume flow rates of air, water vapor and air–vapor mixture were measured by vortex flowmeters (LUGB-150, China) with uncertainty of ±1.0% in the ranges of 0–1000, 0–250 and 0–1000 m^3/h. The inlet and outlet temperatures of air–vapor mixture were measured by four K-type thermocouples positioned upstream and downstream of the test section with uncertainty of ±1.5 K, respectively. To minimize the effect of flow misdistribution and improve measurement accuracy, the data signals of temperature were recorded individually and averaged. During the experiment, the air–vapor mixture temperature, the volume fraction of water vapor and the mixture velocity were set to desired values at the entrance of the tested condensing heat exchanger.

In the tested condensing heat exchanger, the heat released from the hot air–vapor mixture was taken away by the cooling water inside the tube bundles. The flow rate of cooling water was measured by an electromagnetic flowmeter (ZFG-50, China) with uncertainty of ±0.5%. To obtain the mixed average temperature of cooling water accurately, the mixers assembled by baffles with holes alternately near the center and perimeter were installed at the inlet and outlet of the cooling water line [28]. And four K-type thermocouples with uncertainty of ±1.5K were installed in the mixers to collect the inlet and outlet temperatures. The condensate fell down into the bottom container due to gravity and the mass flow rate of condensate was measured and determined by the precision elec-