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Air-side heat transfer characteristics of hydrophobic and super-hydrophobic fin surfaces in heat exchangers: A review☆

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ABSTRACT

A comprehensive literature review has been carried out to investigate the air-side heat transfer enhancement by different types of heat exchanger fin surfaces. In particular, the characteristics of hydrophobic and super-hydrophobic fin surfaces is compared with uncoated (bare) and hydrophilic fins. A summary of comparative findings under dry/wet conditions and frosting/defrosting conditions for heat exchanger and single plates is provided.

Contents

1. Introduction

Fin-and-tube heat exchangers are widely used in both air-conditioners and heat pumps. In air-conditioning systems, moisture condenses and accumulates on the heat transfer surface of an evaporator or a cooling coil when the surface temperature is below the dew point of the humid or conditioned air. When the amount of water condensed on fin surface increases, some water droplets drain from the fins due to the gravity or airflow forces while some adhere to its surface due to the surface tension [1–4]. Those water droplets that remain on fins are called as the "water hold-up." The water hold-up on fins can lead to unwanted conditions, e.g., (i) bridging between fins which increases

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Nomenclature

DCA	Dynamic contact angle
D_C	Fin collar outside diameter (mm)
D_{in}	Tube inner diameter (mm)
D_{out}	Tube outer diameter (mm)
f	Friction factor
F_P	Fin pitch (mm)
FPI	Fin per inch
h	Average heat transfer coefficient (W/m^2.K)
HE	Heat exchanger
H_f	Heat exchanger core depth (mm)
L_f	Fin length (mm)
m	Mass flow rate (kg/s)
N_r	Number of tube rows
N_t	Number of tubes
ΔP	Pressure drop (N/m^2)
Re	Reynolds number
RH	Relative humidity (%)
S_L	Longitudinal tube spacing (mm)
S_T	Transverse tube spacing (mm)
T	Temperature (°C)
t	Fin thickness (mm)
V_r	Frontal velocity (m/s)
W_d	Width of the heat exchanger (mm)

Greek symbols

θ	Contact angle (degree)

Subscript

a	Air
adv	Advancing
d	Defrosting
dp	Dew point
f	Frosting
in	Inlet
p	Plate
rec	Receding

the air-side pressure drop; (ii) reduction in the air-side heat transfer coefficient; (iii) degrading of the cooling capacity; (iv) leading to corrosion; (v) Providing a moist environment for biological activity [5,6].

On the other hand, under winter conditions, frost layers develop on fin surfaces resulting in an increase of the heat transfer resistance between the fin and air, the blockage of the airflow passages through fins and even the shutdown of heat pumps [7,8]. During this condition, it is necessary to employ a defrosting process to melt the frost layer. Therefore, an innovative design and surface treatment for water hold-up reduction and frost layer retardation is necessary to improve the heat transfer performance of a finned-and-tube heat exchanger. As a result, this could lead to smaller, lighter, quieter, and more energy-efficient systems.

1.1. Objectives and scope

A comprehensive literature study has been carried out to investigate heat transfer enhancement by different types of fin surfaces in heat exchangers. In particular, the performance of hydrophobic and super-hydrophobic fin surfaces is compared with uncoated (bare) and hydrophilic fins. The specific objectives of this paper are (i) to compile main findings from the literature on the heat transfer enhancement and pressure drop characteristics of hydrophobic and super-hydrophobic fin surfaces operated under dry/wet condition (dehumidifying) and frosting/defrosting condition and (ii) to draw out the main findings and conclusions and to give recommendations for future investigations.

1.2. Surface wettability and contact angle

Surface condensation is generally classified either as dropwise condensation or as filmwise condensation [9]. In the former case, the liquid-phase collects as individual droplets, while in the latter case, the condensate forms a film that covers the solid surface. Evaporators used in HVAC systems mostly have hydrophilic coatings. The coating increases the surface wettability (reduces the liquid condensate contact angle) and makes the filmwise condensation thinner, and as a result, the power consumption of the fan decreases. However, although the hydrophilic treatment decreases fan power consumption and causes lower aerodynamic noise level at fixed air velocity for the same pressure drop, it adds to thermal resistance [10].

In contrast, it is argued that a fin surface with dropwise condensation is able to augment both the heat and the mass transfer coefficient as compared to the film condensation condition. The main mechanism responsible for the enhancement is related to droplet mobility [9]. Although an attractive heat transfer rates achievable in dropwise condensation modality are encouraged by a reduced surface wettability, it seems that hydrophobic coating has some drawbacks due to undesired blockage and bridging effects between the fins of a heat exchanger under wet or defrosting conditions.

The contact angle θ is defined as the angle formed by the intersection of the liquid–solid interface and the liquid–vapor interface. Meanwhile, wetting is categorized into three regimes which are wetting (when $0° < \theta < 90°$ and liquid spreads partially over the solid), non-wetting (when $90° < \theta \le 150°$ and liquid spreads partially over the solid), and super-hydrophobic (when $\theta > 150°$ [11,12] and a contact angle hysteresis less than 10° [13]).Types of coatings on aluminum fins as well as their wetting mechanisms for dehumidifying heat exchangers have been well documented by Hong and Webb [14]. Other than hydrophilic coating methods, there are a few studies that explain hydrophobic [5] and super-hydrophobic [13,15,16] coating techniques. Since a substantial decrease was seen in contact angle as the number of wet/dry cycle tests increased [17], it is important to quantitatively investigate the long-term wetting characteristics of various commercial coatings and other surface treatments applied in heat exchangers.

1.3. Contact angle measurement techniques

The most widely used technique of contact angle measurement is a direct measurement of the tangent angle θ on a static drop profile by using "telescope-goniometer." The phenomenon of wetting is more than just a static state. The liquid droplets form on the fin surface move via gravity and also the air going through the heat exchanger (at high airflow rates) [5]. When the droplets start to move, they advance over previously dry surface but recede from previously wet surface. This will create an advancing (θ_{adv}) and a receding (θ_{rec}). Gokhale et al. [18] conducted experimental observations reveal that as the rate of condensation increases, the contact angle increases. This means that a dynamic contact angel (DCA) should be considered in dropwise condensation. Dynamic contact angles are measured by using two common methods; (a) volume changing method and (b) tilted plate. In the first method, water droplets are injected onto the surface of the fin using high-precision micro-syringe. The advancing and receding angles are then measured by increasing or decreasing the volume of water droplets injected on the surface until the maximum or minimum volume is achieved without a change in the droplet contact area. In the second method, the droplet is placed onto the surface, which is then gradually tilted, and the measurement of θ_{adv} and θ_{rec} is performed just before the droplet starts to move. The actual difference between advancing