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Managing water on heat transfer surfaces: A critical review of techniques to modify surface wettability for applications with condensation or evaporation

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ABSTRACT

Most materials of practical interest are neither completely wetting nor completely non-wetting. "Surface wettability" then refers to the degree that a surface is hydrophilic (i.e. water-loving) or hydrophobic (i.e. water-fearing). Through careful design, it is possible to alter the natural wettability of a surface to be more water-loving or water-fearing. This is principally achieved by modifying the surface chemistry and/or surface roughness. In some cases, modifying the surface may bring operational benefit or advantage. For example, aluminum and copper (which are used in the construction of heat exchangers) tend to retain water in application, which can degrade performance. Modifying the surface however to be superhydrophilic can help to spread out the condensate, reduce the air-side pressure drop, and facilitate drainage. Moreover, by creating a wettability pattern or gradient, it is possible to predetermine the initiating sites for condensation on a surface as well as facilitate droplet motion and/or control the water droplet movement path. In the first part of this review, the current state of the art of surface wettability modification and control techniques are presented, which includes topographical manipulation, chemical modification, as well as methods for creating gradient surfaces and patterned wettability. In the second part of this review, possible applications and the potential impact of these methodologies in energy systems are discussed with a special focus on heating, ventilation, air conditioning, and refrigeration (HVAC&R) systems and components.

1. Introduction

It is well-known that the condensation of a vapor on a surface depends largely on the surface characteristics. By manipulating either the surface chemistry or roughness, the wetting behavior can be favorably altered. For example, the application of a coating to a surface changes the underlying chemistry of that surface (and therefore its wettability) because the interfacial free energies related to the droplet contact angle are altered. In the same way, the micro-scale roughness of a surface can also be used to significantly affect the wetting behavior and/or motion of water droplets on a surface by increasing or decreasing the solid/liquid contact area [1,2].

The topic of "surface wettability" has attracted considerable interest over the past few years. In fact, the number of publications in this research area has seen a significant and sustained increase from 1992 to 2016 according to the Science Citation Index (SCI) source (see Fig. 1). It is also important to point out that this plot only shows journal publications in the areas of engineering and materials science; it does not include conference proceedings. Thus, the actual number of publications is considerably higher. Because of the breadth of the encompassing literature, this review will be divided into the following sections—(1) homogeneous surface wettability manipulation (chemical and topographical), (2) variable and patterned surface wettability, (3) applications in energy systems, and (4) operational challenges and current limitations (i.e. fouling, longevity, adhesion, etc.).

Over the past decade, many researchers have attempted to use surface wettability modification in different types of energy systems. For example, surface wettability modification has been used in air-cooled evaporators as a means of enhancing condensate drainage and improving the overall energy efficiency of these systems. Heat

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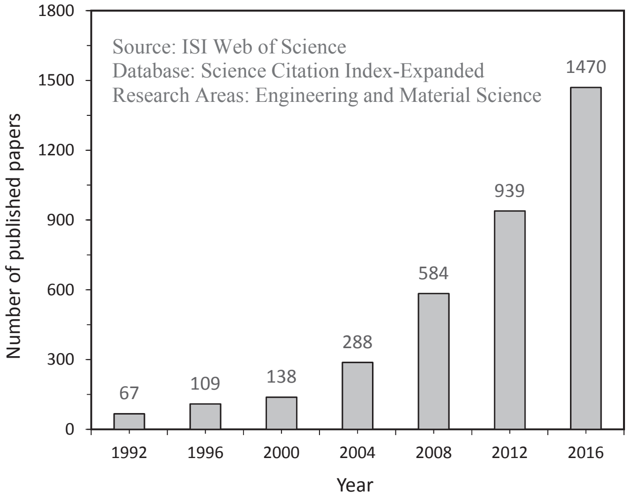

Fig. 1. Plot showing the rapid increase in "surface wettability" research in recent years according to the Science Citation Index-Expanded (SCI).

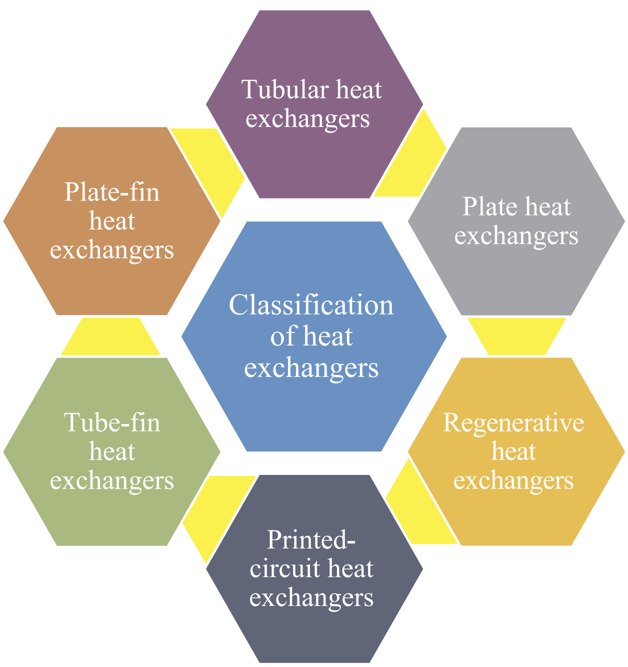

Fig. 2. Classification of heat exchangers with respect to their construction type [4].

exchangers are important to the overall efficiency, cost, and compactness of many thermal management and energy systems including solar heating applications and heating, ventilation, air-conditioning and refrigeration (HVAC&R) systems. According to a 2015 Department of Energy study, HVAC&R systems are responsible for nearly 30% of all the energy used in U.S. commercial and residential buildings and are the single largest energy end-use in buildings, consuming approximately 14 quads (or, 1.5×10^{19} J) of primary energy annually [3]. Heat exchangers are devices responsible for the transfer of heat between two or more fluids (liquid or gas) by a combination of conduction, internal/external convection, and/or radiation. Various types of classifications have been introduced for categorizing heat exchangers; however, a popular one is based on their construction type (see Fig. 2) [4,5]. It is important to also point out that aluminum, copper, and stainless steel which are widely used in the construction of heat exchangers are naturally hydrophilic. This affinity for water makes it difficult for these materials to drain water effectively, which in turn leads to increased condensate retention, which can degrade the overall performance of the heat exchanger. More specifically, this retention of water on the heat exchanger is problematic because it increases the air-side core pressure drop, creates the possibility of corrosion, provides a site for biological activity, and perhaps most importantly can reduce the air-side heat transfer rate. In air conditioning systems, water that does not drain from the evaporator will eventually return to the air as vapor and therefore, must be recondensed which increases the latent load of the system. As a result, the heat exchanger is often oversized and/or a higher rate of refrigerant flow is required to attain the same sensible cooling and coefficient of performance (COP). Moreover, the retention of water on the heat transfer surface not only decreases the rate of heat transfer, but it also provides a site for biological growth and activity that can be detrimental to human health [6–8].

In refrigeration systems, due to the periodic requirement for defrosting (and thus downtime), refrigerator evaporators tend to be rather inefficient. Furthermore, heat exchanger fin spacing is often quite large in these systems to mitigate frost blockage, and thus convective heat transfer coefficients are typically low which further reduce their energy efficiency. Thus, the management and control of water droplets on heat-transfer and air-handling surfaces is vital to the overall energy efficiency, functionality, and maintenance of these systems. Wettability manipulation has also been widely used in other energy systems such as the aerospace, automotive, renewable energy, and biomedical industries where water retention techniques have proved helpful in mitigating surface drag, improving wing de-icing, manufacturing more intelligent lab-on-a-chip devices, etc.

The purpose of this review then is to present the current state of the art in surface wettability manipulation and control, which includes a discussion of homogeneous surface wettability manipulation (Section 2) as well as gradient surfaces and patterned wettability (Section 3). Following that, the application of these methodologies and their potential impact in energy systems are discussed with a special focus on HVAC&R systems (Sections 4.1 and 4.2), although applications in other systems are also briefly addressed (Section 4.3). The review then finishes with some basic discussion about the challenges of using these approaches and future work (Section 5). Although other review articles exist [9–13], this review provides both a summary of recent developments in the field as well as the fundamental science behind surface wettability modification and gradient surfaces. The information presented here has been systematically gathered and critically analyzed in the context of their potential application in energy systems including HVAC&R systems. In this way, this review seeks to fill an important gap in the field by examining the current state of the art in terms of both recent developments and future opportunities.

2. Homogeneous surface wettability manipulation

Although the earliest observations of wetting can be attributed to Galileo Galilei in 1612, he did not formally recognize the concept of surface tension (i.e. surface wettability) when he observed an ebony wood chip floating slightly below the surface of a water bath [14,15]. Rather, it was Thomas Young, an English physicist, whose equation and work revived discussions on the topic of surface wettability in 1805. His well-known equation in its contemporary form (see Fig. 3a) can be written as:

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv}\cos\theta \tag{1}$$

in which γ is the surface tension (or surface free energy), θ is the static contact angle (CA), and the subscripts s, v, and l denote solid, vapor, and liquid, respectively [16]. By proposing this physical relationship, he is widely regarded as the father of scientific research on wetting and contact angles.

The contact angle property shown in Fig. 3(a) is generally determined by the attraction of the droplet molecules towards the surface (adsorption force) and the attraction of the droplet molecules towards