International Journal of Heat and Mass Transfer 71 (2014) 675–681

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Enhancement of condensation heat transfer with patterned surfaces

Abhra Chatterjee [a,*], Melanie M. Derby [a,b], Yoav Peles [a], Michael K. Jensen [a]

[a] Department of Mechanical, Aerospace, and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, United States
[b] Mechanical and Nuclear Engineering Department, Kansas State University, United States

ARTICLE INFO

*Article history:*
Received 29 July 2013
Received in revised form 22 December 2013
Accepted 28 December 2013
Available online 25 January 2014

*Keywords:*
Condensation
Pattern
Hydrophilic
Hydrophobic
Feature size

ABSTRACT

An experimental study of condensation heat transfer on surfaces with patterns of distinct hydrophilic and hydrophobic regions has been carried out. The patterned surfaces of 25.4 mm diameter comprised of 25% hydrophilic region and 75% hydrophobic region by area. Experiments were performed on surfaces with several feature sizes and shapes of the patterns. The feature sizes varied from 0.25 mm to 1.50 mm. Two types of pattern shapes were studied: circular hydrophilic regions on an otherwise hydrophobic surface (island-patterns), and hydrophilic region resembling a tree on a background of hydrophobic region (tree-pattern). Depending on the type of pattern on the condensation surface, the heat transfer coefficients were either higher or lower than that of the completely hydrophobic surface. For the range of inlet vapor velocities (about 0.05 m/s to 5 m/s), among all the surfaces, the highest heat transfer coefficient was observed for the patterned surface with the feature size of 0.25 mm, which was higher than that of a completely hydrophobic surface.

## 1. Introduction

Among the most relevant areas of application of two-phase heat transfer are in the power generation industry, air-conditioning systems, cooling of electronic devices, and the distillation industry. For power generation the Rankine cycle, which evaporates and condenses the working fluid, is one of the most widely employed processes. In the electronics thermal management industry, devices are often cooled by boiling a fluid in a closed loop; after boiling the evaporated working fluid then has to be condensed back to liquid. In the distillation industry liquid is evaporated and then condensed back into liquid to remove dissolved salts and other impurities. Thus, in all the above mentioned industries condensation is an important process and enhancement of heat transfer coefficients will benefit a wide range of industries.

One of the most popular methods to enhance condensation heat transfer coefficients is through the modification of physical and chemical properties of the condensation surface [1–3]. For surfaces whose chemical and physical properties are modified, the interaction of the condensate with the condensation surface is also altered [2].

Condensation modes can be classified as *filmwise condensation (FWC)* and *dropwise condensation (DWC)* [1]. If the condensate forms a film on the condensation surface, it is termed *FWC* and if it is in the form of droplets, it is said to be *DWC* [1]. *FWC*, observed for surfaces with high surface energy, is associated with lower heat transfer coefficients when compared to that of *DWC*. Heat transfer coefficient is also enhanced with increasing mobility of the droplets [4]. The mobility of the condensate for *DWC* is better than for *FWC* which is partly attributed to higher heat transfer coefficient for *DWC* when compared to *FWC* [5]. Droplet mobility can be improved by having a surface energy gradient on the condensation surface [4]. When a surface with a wettability gradient is used, droplets move from the region of lower wettability to regions of higher wettability [4].

Although hydrophobic surfaces promote *DWC*, resulting in higher heat transfer coefficients than hydrophilic surfaces [1], hydrophilic surfaces show higher rates of condensation when compared to hydrophobic surfaces [6]. To benefit from both surface characteristics, a pattern of hydrophilic and hydrophobic surfaces can be utilized on a single condensation surface, which would result in better mobility of the condensate than a uniform surface [4,7]. Therefore, to achieve high heat transfer coefficients, patterns of distinct hydrophobic and hydrophilic regions on the condensation surface can be used [8]. While some patterns can result in higher heat transfer coefficients than that of a hydrophobic surface, others can result in lower heat transfer coefficients [7]. Therefore, patterns with distinct hydrophobic and hydrophilic regions must be carefully designed with due importance to the shape and size of the pattern features. In the present study, condensation heat transfer on patterns with distinct hydrophobic and hydrophilic regions has been studied.

---

[*] Corresponding author.
*E-mail address:* abhramech@yahoo.com (A. Chatterjee).

0017-9310/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.12.069

**Nomenclature**

| | |
|---|---|
| $A$ | area of cross section of the copper block |
| $A_c$ | area of cross section of vapor chamber across which vapor flowed |
| $D$ | hydraulic diameter of the vapor chamber |
| $h$ | heat transfer coefficient |
| $k_{cu}$ | thermal conductivity of oxygen free copper |
| $\dot{m}$ | vapor mass flow rate |
| $P_c$ | perimeter of cross section of vapor chamber across which vapor flowed |
| $Q$ | heat flux |
| $dT/dy$ | temperature gradient along the copper cooling block |
| $T$ | absolute temperature |
| $T_w$ | calculated wall temperature |
| $T_1$ | temperature of the thermocouple closest to the condensation surface |
| $\dot{V}$ | volume flow rate of the condensed steam |
| $y$ | distance of thermocouple |

## 2. Experimental apparatus and procedure

To obtain condensation heat transfer coefficients on a flat vertical surface, a flow loop (Fig. 1) was constructed to supply steam to a vapor chamber.

The loop consisted of a steam supply line, a filter, a steam separator, a valve, an electric immersion heater, a test section, a heat exchanger, a flow meter, and a drain. The entire flow loop was insulated to minimize heat loss.

The test section (Fig. 2) consisted of a vapor chamber, a piston, a vertical condensation surface, the test section, and a visualization window. Insulation was applied on the vapor chamber to reduce the heat loss. The vapor chamber was 124 mm long and 45.7 mm wide, and the depth of the chamber could be varied between 2 mm and 25 mm. By varying the depth of the vapor chamber, the hydraulic diameter of the vapor chamber could be varied. The hydraulic diameter of the vapor chamber is defined as:

$$D = 4A_c/P_c \tag{1}$$

where, $D$ is the hydraulic diameter of the chamber, $A_c$ is the area of cross-section of the vapor chamber across which vapor flowed and $P_c$ is the perimeter of the same cross section.

The condensation surface was comprised of a 25.4-mm diameter, 7-mm thick cylindrical coupon made of oxygen-free copper (Alloy 101). One of the two flat sides of the cylindrical coupon served as the condensation surface and the other side was soldered to a copper block, which was cooled at the opposite end through a bath circulator, which maintained the cooling water temperature at a specified value.

Experiments were performed on various kinds of patterned surfaces. The patterned surfaces consisted of distinct hydrophilic and hydrophobic regions. For all the surfaces the proportion of the hydrophilic and the hydrophobic regions was maintained at 25% and 75% by area, respectively (Fig. 3). The only difference between the surfaces was in the feature sizes and in the shape of the patterns.

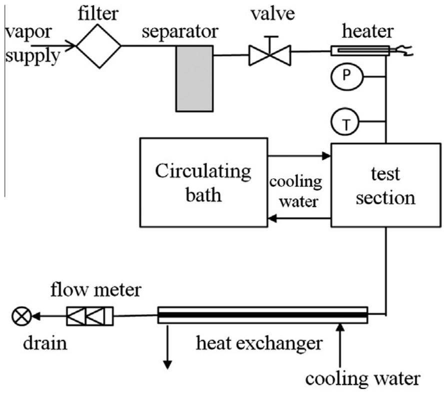

**Fig. 1.** Schematic of the loop.

Experiments were performed on the following feature sizes and shapes of the patterns:

1. Pattern shape: *island-patterns*:
   The *island-patterns* consisted of hydrophilic circular islands of different sizes on an otherwise hydrophobic surface. The various island diameters studied were:
   (a) Hydrophilic circular islands of 1.50 mm diameter.
   (b) Hydrophilic circular islands of 0.75 mm diameter.
   (c) Hydrophilic circular islands of 0.50 mm diameter.
   (d) Hydrophilic circular islands of 0.25 mm diameter.

2. Pattern shape: linear and connected hydrophilic regions, *tree-pattern*:
   The branches in the *tree-pattern* were 1.50 mm wide.

Details of the procedures for the preparation of the patterned surfaces have been described in [9].

For all the surfaces with *island-patterns*, the circular hydrophilic islands were arranged in concentric circles with equal spacing between the neighboring islands in the radial and the azimuthal directions. The distance between the edges of two neighboring hydrophilic islands for each of the feature sizes of the *island-patterns* is given in Table 1.

## 3. Data reduction

To obtain data, the cooling water bath circulator was set to a temperature of 30 °C, so that a constant temperature was maintained at the cooling end of the copper block. The mass flow rate of the cooling water was about 0.2 kg/s and the change in the temperature of the cooling water was less than 0.3 °C. Followed by the bath circulator, the steam supply was turned on, and the valve upstream of the test section was adjusted to obtain the desired mass flow. The immersion heater was then switched on and the heating power was adjusted with the help of a variable power supply to obtain a stable and small superheat of approximately of 0.5 °C before the steam entered the test section. The superheat was necessary to obtain the exact state at which the vapor entered the test section and to calculate the quality of the steam leaving the test section through a heat balance. After steady state was reached, the temperature and pressure were recorded using a computer controlled data acquisition system of National Instruments signal chassis (SCXI-1000) and LabVIEW software. The flow parameters were then altered, and the entire procedure was repeated. The same steps were carried out for several positions of the piston with the hydraulic diameter of the vapor chamber ranging between 4.5 mm and 32.5 mm. The data were reduced and analyzed with the help of computer programs written in Engineering Equations