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Experimental investigation of dropwise condensation on hydrophobic heat exchangers part I: Dimpled-sheets

Jorge R. Lara *, Mark T. Holtzapple

Department of Chemical Engineering, Texas A&M University, 3122 TAMU, College Station, TX 77843-3122, USA

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ABSTRACT

Vapor-compression desalination is a reliable and robust desalination technology that benefits from high heat transfer coefficients in evaporators/condensers. In this study, heat transfer coefficients were measured in vertical dimpled-sheet heat exchangers (0.762-mm-thick naval brass 464 or 0.203-mm-thick copper), some of which were bare (filmwise condensation) and others were coated with a thin layer of passive electroless Ni–P–PTFE (dropwise condensation). The heat exchanger sheets were mounted in a sealed two-chamber apparatus with condensing saturated steam on one side and boiling saturated water on the other. Shearing steam on the hydrophobic condensing surface enhanced the overall heat transfer coefficient by 1.6 times and forced convection on the boiling side increased it by an additional 1.4 times. Adding a 0.635-μm-thick layer of hydrophobic Ni–P–PTFE coating to naval brass 464 that was roughened on the boiling-side surface with sand-blasting increased the heat transfer coefficient by 4.3 times. Adding PTFE boiling stones to the boiling side of the hydrophobic copper plates increased the heat transfer coefficient by 1.15 times. The maximum overall heat transfer coefficient measured was $U = 184\ \text{kW/(m}^2\cdot{}^\circ\text{C)}$, which occurred with 0.203-mm-thick copper ($k = 400\ \text{W/(m}\cdot{}^\circ\text{C))}$ coated with 0.635-μm-thick Ni–P–PTFE and PTFE boiling stones as a dynamic nucleation agent in the bulk liquid ($P = 722$ kPa, $T = 166$ °C, $v_{steam} = 0.49$ m/s, $R \approx 1$ kg shearing steam/kg condensate, $v_{liq} = 1.57$ m/s, $\Delta T = 0.20$ °C).

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1. Introduction

1.1. Heat transfer enhancement techniques

Active and passive heat transfer enhancement techniques for heat exchangers have been investigated intensively [1]. Fourth-generation heat transfer technology involves simultaneous application of several techniques to produce an enhancement larger than the individual techniques operating separately. Dropwise condensation has been studied for the past 60 years [2]. Experiments with brass tubes show dropwise condensation has heat transfer coefficients 1.6–28.6 times greater than filmwise condensation [3].

In pool boiling, heat flux across the plate evaporates micro and macro layers of the vertical surface during bubble growth [4]. The level of turbulence imposed by forced convection [5] helps coalesce small bubbles with large bubbles carrying upwards the maximum possible amount of latent heat [6,7]. In the boiling side, the total heat transfer coefficient increases by adding forced convection. Trends for forced convective boiling of water [8] indicate that operating at high pressure increases the critical heat flux (CHF) (i.e., the maximum heat flux attainable) compared to low-pressure operation. It is well known [9] that increasing surface roughness is a cost-effective way to enhance nucleate boiling compared to other more sophisticated techniques.

1.2. Dropwise condensation

During dropwise condensation, the heat transfer process is controlled by the developed intermolecular force field, which is composed of surface tension, gravity, and free surface energy [10]. Drops form at nucleation sites on the condensing vertical surface and grow by direct condensation and coalescence. When a drop cannot be sustained by surface tension forces, it slides down leaving a free nucleation site where a new drop forms. The positive influence of sweeping steam on the condensing surface has been studied [10–12].

An electroless Ni–P–PTFE composite plating coating resists fouling, corrosion, and friction while promoting dropwise condensation. Perkins [13] studied Ni–P–PTFE as a promoter of dropwise condensation of steam at 21 kPa on nickel–copper vertical disks, but concluded the coating was not practical. Later tests [14,15] were conducted on conventional plate-and-frame heat exchangers. The overall heat transfer coefficients were about 17 $\text{kW/(m}^2\cdot{}^\circ\text{C)}$, which is low because the experiments were conducted with large ΔT (2 to 7 °C) and low P (200 kPa). Hydrophobic heat exchangers perform best at high pressures, and their heat transfer coefficients increase remarkably with small temperature differences between the condensing and the boiling chambers [2].

* Corresponding author.
E-mail address: jorge.lara@chemail.tamu.edu (J.R. Lara).

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The thickness (h) of electroless Ni–P–PTFE hydrophobic coating is governed by the deposition rate (δ) and deposition time (t) by the expression: $h = \delta \cdot t$ [16]. Therefore, a thin coating can be obtained by using a short deposition time. Because of the high thermal resistance of PTFE ($k = 2.44$ W/(m·°C)) [17], a very thin hydrophobic coat is desired.

1.3. Forced-convective boiling

Forced-convection enhances heat flux by introducing turbulence in the boundary layer. Calculation of heat transfer coefficients should be performed locally at specified heights of the vertical plate. In a vertical channel, upward forced convection of liquid has well-established boiling regions along the height of the vertical plate [18]. In regions of the boiling liquid channel with saturated nucleate boiling and two-phase flow boiling, the variable characterizing the heat transfer mechanism is the thermodynamic mass quality, which represents the ratio of the vapor mass flow rate to the total mass flow rate [18].

1.4. Theoretical calculations

Theoretical calculation of the overall heat transfer coefficient can be performed from

$$U = \frac{1}{\frac{1}{h_{cond}} + \frac{1}{h_{boiling}} + \left(\frac{x}{k}\right)} \quad (1)$$

where

U	overall heat transfer coefficient (kW/(m^2·°C))
X	plate thickness (m)
K	thermal conductivity (kW/(m·°C))
h_{cond}	condensation heat transfer coefficient (kW/(m^2·°C))
$h_{boiling}$	boiling heat transfer coefficient (kW/(m^2·°C))

Using data from the literature, Lara [19] estimated the heat transfer coefficient of an innovative sheet-shell heat exchanger with a hydrophobic coating. On the steam side, he estimated $h_{cond} = 324$ kW/(m^2·°C) for gravity-controlled dropwise condensation of steam. On the liquid side, he estimated $h_{boiling} = 1022$ kW/(m^2·°C) for natural-convection pool boiling. Using 0.18-mm-thick naval brass plate with hydrophobic coating, he estimated an overall heat transfer coefficient $U = 179$ kW/(m^2·°C), which is very similar to values documented in this paper.

1.5. Calculation of heat transfer coefficients

Measured heat transfer coefficients U are obtained from

$$U = \left(\frac{q}{\Delta T}\right) \quad (2)$$

and

$$q = \left(m h_{fg}\right) / A \quad (3)$$

where:

q	heat flux (kW/m^2)
m	condensate collected from the apparatus (kg/s)
h_{fg}	latent heat of condensation (kJ/kg)
A	effective heat transfer area = 0.0645 m^2
ΔT	temperature differential across the plate (°C)

In this experimental investigation, heat transfer coefficients were measured in coated and uncoated dimpled vertical heat exchanger plates. Two different square, thin-sheet plate substrates were tested (naval brass 464 and copper). For naval brass 464, the steam-side heat transfer mechanism was condensing saturated steam with either filmwise (bare surface) or dropwise (coated surface) condensation; for copper plates, it was dropwise condensation. In both cases, the experimental plates were mounted in a sealed two-chamber apparatus with condensing saturated steam on one side and boiling liquid water on the other (Fig. 1).

The experiments reported herein enhanced heat transfer by simultaneously employing the following: (1) passive electroless Ni–P–PTFE thin hydrophobic coating to promote dropwise condensation on the steam side and to inhibit fouling in the boiling side, (2) active forced convection circulating saturated liquid in the boiling chamber, and (3) active shearing steam on the condensing surface. In some experiments, nucleate boiling was enhanced by roughening the heat exchanger surface or including boiling stones in the bulk liquid. The following factors were investigated: (a) saturated steam pressure, (b) temperature differential ΔT across the plate, and (c) shearing steam velocity.

2. Materials and methods

2.1. Test surfaces

The first plate was round-dimpled 0.762-mm-thick naval brass 464 (Cu 59.62 wt.%, Zn 39.2 wt.%, Sn 0.5–1.0 wt.%, Fe 0.1 wt.% max, Pb 0.2 wt.% max) with thermal conductivity $k = 116$ W/(m·°C) [20], which was roughened via sand-blasting on the liquid side to promote nucleation. The condensing metal surface was either bare (filmwise condensation) or coated with 0.635-μm-thick layer of Ni–P–PTFE (dropwise condensation) by Micro Plating, Inc. (Erie, PA). The 0.635-μm-thick hydrophobic Ni–P–PTFE coating ($k = 5.44$ W/(m·°C)) has negligible thermal resistance ($x/k = 4.6 \times 10^{-6}$ m^2·°C/W) [21]. In addition to its non-wettability property, Ni–P–PTFE hydrophobic coating also provides surfaces that resist abrasion (0.03 mg loss per 1000 cycles using CS Wheel Taber Abrasion) and corrosion (>1000 h, ASTM B 117 5% salt water at 35 °C) [16,22–24]. Experiments on heat exchangers show that the coating prevents chemical fouling and biofouling on the boiling surface [25].

The second plate was round-dimpled 0.203-mm-thick copper ($k = 400$ W/(m·°C)). The plate surfaces in both chambers were modified with a 0.635-μm-thick Ni–P–PTFE hydrophobic layer by Micro Plating, Inc. (Erie, PA).

The plates were 305 mm × 305 mm. One hundred equally distributed round dimples (19.1-mm diameter and 3.18-mm deep separated by 25.4-mm centers) were formed on each plate. Because the mounting mechanism blocked some of the plate, the effective heat transfer area was 254 mm × 254 mm or 0.0645 m^2.

2.2. Apparatus and procedure

The experimental apparatus is tailored to observe and manipulate key heat transfer variables. The apparatus (Fig. 1) consists of two sections: (1) a boiling water chamber and (2) a condensing steam chamber. Both chambers are made of stainless steel 304 and are divided by the test plate. The whole assembly is bolted together. To prevent leakage, a gasket is placed between each side of the test plate and frame. Data were collected only after steady state was achieved.

High-pressure steam enters valve V1 into cyclone C1 where liquid is separated, thus ensuring the steam quality entering the apparatus is 1.0. Pressure regulator V2 sets the condenser pressure, which is measured by pressure gage P. The steam enters the condenser, which has a 3.17-mm gap that is set by the thickness of the aluminum plate inserted into the condenser. At the bottom of the condenser, condensate flows into sight glass S2. By manually opening valve V4, the liquid level in sight glass S2 can be maintained constant. The drained liquid is collected in graduated cylinder G1 and is measured over a 90-s interval. (Note: this