Desalination 280 (2011) 363–369

Contents lists available at ScienceDirect

Desalination

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

Experimental investigation of dropwise condensation on hydrophobic heat exchangers. Part II: Effect of coatings and surface geometry

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ARTICLE INFO

Article history:
Received 9 March 2011
Received in revised form 11 July 2011
Accepted 12 July 2011
Available online 9 August 2011

Keywords:
Dropwise condensation
Electroless Ni–P–PTFE
Hydrophobic heat exchangers
Vertical-grooved heat exchanger sheets
Vapor-compression desalination

ABSTRACT

This is Part II of an experimental investigation of hydrophobic heat exchangers. Two plates were studied: (a) 0.127-mm-thick titanium grade 2 and (b) 0.203-mm-thick copper. Titanium plate had round-dimpled spacers. Copper had either round-dimpled spacers or round-shaped vertical-grooved spacers. Titanium was bare but copper had electroless Ni–P–PTFE hydrophobic coating. Two chemical compositions of the hydrophobic coating were employed: lead-containing and lead-free. For some studies, the coating thickness was varied from 0.635 to 127 µm. To measure the overall heat transfer coefficient, the plates were mounted in a sealed two-chamber apparatus with condensing saturated steam on one side and forced-convective boiling liquid water on the other. The best overall heat transfer coefficient was $U = 240$ kW/(m^2·°C) (0.203-mm-thick copper plate, round-shaped vertical grooves, 2.54-µm-thick lead-free Ni–P–PTFE, $P = 722$ kPa, $T = 160$ °C, $\Delta T = 0.20$ °C, saturated liquid velocity $v_{liq} = 1.57$ m/s, shearing steam $v_{steam} = 0.23$ m/s, and flow ratio $R \approx 0.6$ kg shearing steam/kg condensate).

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1. Introduction

Part I of this study [1], used a variety of heat transfer enhancement techniques such as dropwise condensation, forced convective boiling, roughening on boiling surface, boiling stones as nucleation agents, and condensation with shearing steam. Condensation on a hydrophobic surface using shearing steam and forced-convective boiling with nucleation agents produced very efficient heat transfer.

The low surface energy of titanium promotes dropwise condensation, which increases the heat flux [2]. Furthermore, titanium resists abrasion, corrosion, and fouling. Over time, the resulting overall heat transfer rate of titanium surfaces is often comparable to metals that have higher thermal conductivity.

The literature [3] suggests that compared to flat surfaces, vertical grooves deliver about 25% higher overall heat transfer coefficients. For dropwise condensation, liquids form microscopic droplets on the condensation surface, followed by droplet growth, coalescence/growth, and downflow. The thermal resistance of liquids attached to the metal surface dominates dropwise condensation [4]; rapidly shedding liquid droplets is an important factor that increases heat flux [5,6]. Round-shaped vertical grooves on the condensing surface help channel the condensing steam so it sheds quickly, which increases the heat flux [3,7,8]. This study measures the effects of shearing steam on the overall heat transfer coefficient of hydrophobic surfaces of thin copper plates. Electroless Ni–P–PTFE is employed as an economical and robust hydrophobic coating.

Table 1 exhibits a literature review of previous work with electroless Ni–P–PTFE hydrophobic coatings on vertical plates. Past studies focused on characterizing the coating resistance to corrosion and fouling [9–17]. The overall heat transfer coefficients reported were very low compared to the results of the present study. None of the experiments reviewed was conducted with high-pressure steam. In this review, the highest measured overall heat transfer coefficient was $U = 17$ kW/(m^2·°C) at comparatively large ΔT (2 to 7 °C) and low P (200 kPa) for a corrugated plate-and-frame heat exchanger coated with electroless Ni–P–PTFE.

Desalination technologies for municipal drinking water must meet NSF STD 61 certification. Lead is a common contaminant in most Ni–P–PTFE hydrophobic coatings. To overcome this problem, lead-free chemistry should be employed in systems that produce drinking water [18].

In this paper, the first study quantifies heat transfer in titanium plates with round dimples. The second study uses copper with round dimples; the thickness of the lead-containing Ni–P–PTFE coating was varied. The third study uses copper with vertical grooves with lead-containing Ni–P–PTFE coatings. The fourth study is similar to the third, but it employs lead-free Ni–P–PTFE.

2. Materials and methods

Experiments were conducted using bare 0.127-mm-thick titanium grade 2 and 0.203-mm-thick copper coated with either lead-containing or lead-free electroless Ni–P–PTFE coating.

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0011-9164/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.desal.2011.07.017

Table 1
Literature review of Ni–P–PTFE hydrophobic coatings.

Ref no.	ΔT (°C)	P_{sat} (kPa)	Substrate metal	Base metal thickness (mm)	Coating	Coating thickness (μm)	Shear steam	Liquid side agitation	Nucleation sites	Surface geometry (mm)	Heat transfer coefficient (kW/(m² °C))	Antifouling	Corrosion resistance	Dropwise condensation (DWC)
[8]	NR	Pool boiling 101.3	Cu SS 304	0.35	Ni–Cu–PPTFE	23	No	No	No	15×10 vertical coupon	7	Yes	Superior to Ni-P-PTFE Coating	NR
[9]	NR	Pool boiling 101.3	Cu SS 304 LC steel	0.35	Ni–P–PTFE	0.254–2.54	No	No	No	15×10 vertical coupon	NR	Inhibited formation of CaSO4 scale	Yes	No
[10]	NR	Pool boiling 101.3	Cu SS 304	0.35	Ni–P–PTFE	Various	No	No	No	15×10 vertical coupon	5	Reduced adhesion of CaSO4 scale	NR	No
[11]	2–7	200	SS 316	NR	Ni–P–PTFE	NR	No	Yes (Oil)	No	Corrugated plate-and frame HX	17	Yes	Yes	Yes
[12]	NR	100	SS 304	1.0	Ni–Cu–PPTFE	23	No	No	No	15×10 vertical coupon	NR	Minimized microbial adhesion by over 96–98%	Yes	No
[13]	NR	200	Cu SS 304	0.35	Ni–P–PTFE	NR	No	No	No	Corrugated plate-and frame HX	17	Yes	Yes	NR
[14]	NR	100	SS 304	NR	Ni–P–PTFE	NR	No	No	No	Rotating cylinder	NR	High wear resistance	NR	NR
[15]	NR	100	SS 316	NR	Ni–P–PTFE	1.28–23	No	No	No	Common heat exchangers	Ni-P-PTFE improved processing skim milk and tomato juice	NR	NR	NR
[16]	NR	100	Cu	0.35	Ni–Cu–PPTFE	23	No	No	No	15×10 Vertical coupon	NR	Yes	Yes	NR

2.1. Calculation of heat transfer coefficients

The plates were placed in a two-chamber apparatus described in Part I [1]. Measured overall heat transfer coefficients U are obtained from

$$U = \left(\frac{q}{\Delta T}\right) \quad (1)$$

and

$$q = \left(m h_{fg}\right) \Big/ A \quad (2)$$

where:

U	overall heat transfer coefficient (kW/m^2·°C)
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)

2.2. Test surfaces

The first plate was round-dimpled 0.127-mm-thick titanium grade 2 (k = 22 W/(m·°C)) with chemical composition: carbon 0.80% max., nitrogen 0.03% max., oxygen 0.25% max., iron 0.30% max., hydrogen 0.015% max., titanium balance [19]. The condensing metal surface was bare. 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.

The second plate was 0.203-mm-thick copper (k = 400 W/(m·°C)) with round dimples. Both plate surfaces were modified with lead-containing Ni–P–PTFE hydrophobic coatings of different thicknesses.

The third plate was 0.203-mm-thick copper (k = 400 W/(m·°C)) with round-shaped vertical grooves. The plates were 305 mm × 305 mm. Twenty-seven equally distributed round grooves (8-mm diameter and 3.18-mm deep) were formed on each plate. The effective heat transfer area was 254 mm × 254 mm or 0.0645 m^2. Both plate surfaces were modified with a 0.635-μm-thick lead-containing Ni–P–PTFE hydrophobic coating by Micro Plating, Inc. (Erie, PA).

In this study, two hydrophobic coatings were used; one uses lead acetate as stabilizer in the electroless bath and the other is lead-free. Table 2 shows the chemical composition of lead-containing Ni–P–PTFE [17] compared to lead-free Ni–P–PTFE [18].

The fourth plate was 0.203-mm-thick copper with round-shaped vertical grooves that was coated with lead-free 2.54-μm-thick Ni–P–PTFE.

Table 2
Bath composition for electroless Ni–P–PTFE hydrophobic coating.

Lead-containing Ni–P–PTFE [17]	Lead-free Ni–P–PTFE [18]
$NiSO_4 \cdot 6H_2O$ 25 g/L	$NiSO_4 \cdot 6H_2O$ 30 g/L
$NaH_2PO_2 \cdot H_2O$ 30 g/L	$NaH_2PO_2 \cdot H_2O$ 30 g/L
[a]$Na_3C_6H_5O_7 \cdot 2H_2O$ 18 g/L	Lactic acid 25 mL/L
Sodium acetate 18 g/L	Sodium acetate 10 g/L
(CH_2) CS 1 ppm	Accelerator 4 g/L
Lead acetate (stabilizer) 3 ppm	KIO_3 (stabilizer) 5 ppm
PTFE (60 wt.%) 10 mL/L	PTFE (60 wt.%) 4–50 mL/L
$C_{20}H_{20}F_{23}N_2O_4I$ (FC-4) 0.4 g/L	
pH 4.8	pH 4.6–5
T (°C) 88	T (°C) 90 ± 2

[a] Sodium citrate.