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Influences of solution subcooling, wall superheat and porous-layer coating on heat transfer in a horizontal-tube, falling-film heat exchanger

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ABSTRACT

An experimental study was conducted to investigate the effects of solution subcooling and wall superheat on both sensible and evaporative heat transfer in a falling-film heat exchanger using both plain and porous-layer coated tubes. By varying the subcooling and wall superheat, it was seen that the portions of sensible and evaporative heat transfers could be controlled. Since the falling-film heat exchanger is limited by the coupled relationship between flooding of the upstream tubes and partial dry-out of the bottommost tubes, the ability to control this evaporation-to-sensible heat transfer ratio is important in system optimization. It was shown that sensible heat transfer can be promoted for the upstream tubes while evaporation heat transfer can be promoted for the downstream tubes. Since sensible heat transfer is enhanced by higher solution Reynolds number and therefore larger film thickness, flooding of the upstream tube rows is no longer detrimental.

1. Introduction

A horizontal-tube, falling-film heat exchanger is typically constructed of an array of horizontal tubes over which a solution fluid is dripped or sprayed and through which a heating fluid flows. This type of heat exchanger or evaporator is widely used due to its high solution side heat transfer coefficient and its relatively small liquid inventory compared to flooded evaporators. Preferably, the solution fluid is distributed uniformly over the entire surface area of the tube array, creating a thin liquid film ideal for evaporation heat transfer. However, in an attempt to facilitate this thin film, an unwetted area on the evaporator tube is unavoidable and it is known that this unwetted area increases as the solution flow rate decreases, the heat flux is increased, and/or the number of tube rows is increased [1–3].

The coupled nature of this phenomenon makes it very difficult to optimize this system strictly for evaporation. It is therefore beneficial to introduce some amount of solution subcooling in order to maximize sensible heat transfer from the upstream tube rows while still maintaining fully-wetted thin-film evaporation conditions on the bottommost rows. Furthermore, an understanding of the effects of wall superheat and solution subcooling on the ratio of evaporation-to-sensible heat transfer is critical to optimizing the falling-film heat exchanger.

Many Studies have been done to improve the solution wetting and heat transfer coefficient of the falling-film heat exchanger. The optimum spacing of the evaporator tubes was investigated by Liu et al. in an attempt to prevent solution loss due to splashing [4]. Also, the performance of this system has been examined using surfactants and nano-particles in the solution fluid as well as mechanically enhanced surfaces such as low-finned or roll-worked tubes [5,6].

Koroğlu et al. [7] studied the tube row effects of a sintered micro-scale porous-layer coating on solution wetting and system-wide heat transfer and found that performance could be enhanced by up to 100% at the lowest solution flow rates due to capillary-driven liquid spreading and the promotion of thin-film evaporation at the menisci created in the porous coating. The same porous-coating is used in this study to investigate the effects of solution subcooling and tube wall superheat on both evaporative and sensible heat transfer. Koroğlu et al. [8] also investigated the effects of a nano/micro-scale surface morphology of copper oxides on heat transfer in a falling-film heat exchanger. Employing a hydrophilic surface morphology, treated copper tubes showed a 50% increase in heat transfer due to the decrease in liquid contact angle brought about by the oxidation layer.

Research has been done confirming the importance of evaporator wall superheat on two-phase heat transfer. Wall superheat refers to the temperature differential between the evaporator surface, which in this case is the tube wall, and the saturation temperature of the system, which is dictated by the pressure within the evaporator chamber. While investigating capillary-assisted evaporation on the outside surfaces of horizontal tubes, Xia et al.

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Nomenclature

A	surface area [m^2]
c	specific heat [kJ kg^{-1} K^{-1}]
D	diameter [mm]
d	solution dispenser nozzle hole diameter [mm]
f	friction factor
g	gravitational constant [m-s^{-2}]
k	thermal conductivity [W m^{-1} K^{-1}]
L	length [mm]
$\dot{m}$	mass flow rate [kg s^{-1}]
Nu	Nusselt number
Pr	Prandtl number
Q	heat transfer rate [W]
r	radius [mm]
R	thermal resistance [K W^{-1}]
Re	Reynolds number
S	tube spacing [mm]
s	solution dispenser nozzle hole spacing [mm]
T	temperature [°C]
U	external heat transfer coefficient [W m^{-2} K^{-1}] or uncertainty
V	velocity [m s^{-1}] or volume [kg m^{-3}]
X	measured variable
Y	calculated variable

Greek letters

δ	boundary layer thickness [m]
Δ	variable differential
Δh	latent heat of vaporization [J kg^{-1}]
Γ	solution mass flow rate per unit length and per tube side, $\Gamma = \dot{m}\,(2L)^{-1}$ [kg s^{-1} m^{-1}]
σ	surface tension [N m^{-1}]
μ	dynamic viscosity [Pa-s]
ν	kinematic viscosity [m^2-s^{-1}]
ρ	density [kg m^{-3}]

Subscripts

ave	average
b	bubble
c	column
d	hydraulic diameter
ds	solution dispenser
e	evaporation
ext	external
h	heating
i	inlet or inner or variable index
j	row number index
l	liquid
lv	liquid-vapor
max	maximum
nz	solution dispenser nozzle hole
o	outlet or outer
ONB	onset of nucleate boiling
p	constant pressure or particle
pl	plain
po	porous
r	inner rod
s	solution fluid or sensible
sat	saturated
sc	subcooling
sh	wall superheat
t	tube or thermal
tot	total
v	vapor or void
x	measured variable
y	calculated variable

found that when the superheating temperature is reduced from 5.0 to 1.0 °C, an increase of 30–60% of the evaporation heat transfer coefficient can be obtained [9]. This was said to be because the increasing wall superheat decreases the ratio of the heat flux across the evaporating thin film region to the total heat flux, therefore reducing the evaporation heat transfer coefficient. However, these results only address the heat transfer coefficient and not the actual heat duty of system, since heat transfer is a function of both the heat transfer coefficient and the driving temperature difference between the wall and the cold fluid.

The term subcooling refers to the temperature differential between the saturation temperature of the system and the temperature of the solution fluid. With respect to pool boiling, the natural convection portion of the boiling curve has been shown to shift upward with increased subcooling due to the increase in driving temperature difference between the solution and the hot surface, but subcooling has little, if any, effect on nucleate boiling [10]. Demiray and Kim [11] investigated the effects of subcooing on heat transfer under nucleating bubbles departing from a heated surface. The individual departure diameter and energy transfer were larger with low subcooling, but the departure frequency increased at high subcooling, resulting in higher overall heat transfer. They also found that the bubble growth for both high and low subcooling conditions was primarily due to energy transfer from the superheated liquid layer and relatively little was due to heat transfer from the wall during the bubble growth process.

Cheng and Verma [12] investigated the effect of subcooled liquid and wall superheat on film boiling about a vertical heated surface in a porous medium. They obtained similarity solutions for the buoyancy-induced flow in the vapor and subcooled liquid layers using boundary layer approximations. They found that at a given vapor Rayleigh number, the Nusselt number was dependent on the vapor film's dimensionless thickness, which in turn depends on three dimensionless parameters related to wall superheat, bulk liquid subcooling, and a property ratio of the vapor and liquid phases. From their analysis, they determined that increased subcooling of the bulk fluid works to decrease the vapor boundary layer thickness, increase the liquid boundary layer thickness, and increase the surface heat flux. An increase in wall superheat was found to increase the vapor layer thickness, decrease the liquid layer thickness, and increase the surface heat flux.

The goal of this work is to investigate the duality of these two temperature differentials (solution subcooling and evaporator wall superheat) and how they work together to affect the portions of sensible and evaporation heat transfer in a two-phase system, specifically a horizontal-tube, falling-film heat exchanger. With a better understanding of the overall effects of the inlet temperatures of both the heating and solution fluids, this system can be tuned to maximize sensible, evaporative, or total heat transfer for a given tube array.

2. Experimental setup and procedure

An experimental setup was built to compare the heat transfer performance of a horizontal-tube, falling-film heat exchanger using various solution and heating fluid inlet temperatures. A stainless steel chamber was constructed, housing two solution dispensers and eight horizontal evaporator tubes. Also, plumbing lines for the heating and solution fluids, a stainless steel solution