International Journal of Heat and Mass Transfer 75 (2014) 381–398

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Results for high heat-flux flow realizations in innovative operations of milli-meter scale condensers and boilers

M.T. Kivisalu, P. Gorgitrattanagul, A. Narain *

Department of Mechanical Engineering-Engineering Mechanics, Michigan Technological University, Houghton, MI 49931, United States

ARTICLE INFO

Article history:
Received 23 November 2013
Received in revised form 17 March 2014
Accepted 19 March 2014

Keywords:
High heat-flux boiler
High heat-flux condenser
Phase-change flows
Annular boiling flows
Annular condensing flows
Pulsatile shear-driven flow boiling
Pulsatile shear-driven flow condensation

ABSTRACT

This paper defines the nature of high heat-flux innovative boiler and condenser operations that keeps these devices functional for many critically needed thermal management applications where gravitational force is negligible (naturally or made to be so) relative to other forces (shear, pressure, etc.). These applications include heat removal from narrow spaces to address electronic cooling needs (i.e. mm-scale boilers and condensers with μm-scale flows), gravity insensitive aircraft operations, and zero-gravity applications. Further, the paper presents fundamental condensing and boiling flow results that describe the physics that needs to be utilized to achieve significantly enhanced heat-flux values within the context of these applications.

Reported experimental results demonstrate: (i) the ability to replace ineffective and problematic liquid–vapor configurations (plug-slug, etc.) with annular flows where a flowing thin liquid film covers the entire heat-exchange surface, (ii) the ability to use pulsation-induced interfacial wave phenomena in conjunction with sub-micron thin film phenomena (such as contact line physics) to achieve very high heat-flux during boiling and condensation, and (iii) the ability to desensitize these flows that would otherwise be highly sensitive to inadvertent but ever present flow fluctuations (due to sensitive coupling between vapor and liquid motions, as well as sensitivity of these micro-meter scale thick liquid films to minuscule transverse vibrations of the heat-exchange surface) when flow channel hydraulic diameters reduce to milli-meter or sub milli-meter scales.

Innovative realizations of shear-driven boiling and condensing flows have been investigated within horizontal channels (with condensation or boiling on the bottom, horizontal surface). Results from boiling and condensing flows of FC-72 fluid in horizontal rectangular cross-section (2 or 6 mm gap height and 15 or 24 mm width, respectively) ducts of 1 m length are presented. Utilizing a controlled presence of pulsatile mass flow rates, significant enhancements in heat-transfer rates are obtained for these innovative devices at a location within the device length – these enhancements (relative to non-pulsatile conditions) are sometimes >860% for condensing flows and >190% for boiling flows. The paper reports representative time-varying heat-flux values at this location in support of the understanding that this phenomena can potentially be used (in future experiments) to significantly enhance average heat-flux value over the entire length of an innovative boiler/condenser. The reported phenomena arises from superposing relatively fast time-scale (2.5–30 Hz) flow rate pulsations on otherwise steady-in-the-mean flows to beneficially change certain flow variable averages – over the longer time-scale (<0.01 Hz) of practical interest – relative to their values obtained in the absence of externally imposed pulsations. Such externally imposed pulsations may cause standing waves to form on the thin film interface. The observed asymmetric reduction in the mean film thickness (associated with high heat-flux values) is likely due to "stickiness" of wave-troughs resulting from interaction of phenomena associated with several length scales (namely nano-scale, micro-scale, and continuum length scales) and two different time scales – short (less than 0.5 s) and long (greater than 1 min). That is, associated micro-scale flows at wave-troughs interact with and, possibly, de-stabilize the local adsorbed layer (whose thickness may be <200 nm and is exposed to phenomena such as disjoining pressures) on the wetting heat-exchange surface.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

This paper presents some new fundamental results from experimental investigations of shear/pressure driven internal flow

---

* Corresponding author.
E-mail addresses: mtkivisa@mtu.edu (M.T. Kivisalu), pgorgitr@mtu.edu (P. Gorgitrattanagul), narain@mtu.edu (A. Narain).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.03.056
0017-9310/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature:

Accent notations

$\overline{\mathrm{X}}$	time-averaged value of variable ‘$X(t)$’
X'	fluctuations in variable ‘$X(t)$’ with $X(t) \equiv \overline{X} + X'(t)$
$a_{X\|Y}(f)$	magnitude of the FFT of variable ‘$X_Y(t)$’ taken at frequency ‘f’, also known as the amplitude of variable ‘$X_Y(t)$’ at frequency ‘f’

Labels

h	gap height of flow channel in test-section (instrumented condenser or boiler used in the reported experiments) [mm]
L	length of flow channel of interest for flow measurements within the test-section [m]
FC-72	working fluid used in experiments, trade name for 3M Corp. perfluorohexane (C_6F_{14}) Flourinert™ electronic liquid.
DPT	differential pressure transducer: measures pressure-differences directly
APT	Absolute Pressure Transducer: used for direct measurement of absolute pressure at a location of interest
HFM-40	heat flux meter used to measure heat flux directly at a location 40 cm downstream from the inlet
$\mathrm{P_V}$	vapor pulsator used to induce fluctuations in vapor pressure and flow rate supplied to the test-section
$\mathrm{P_1}$, $\mathrm{P_2}$	pumps used to circulate liquid working fluid in experimental flow loop
OM	orifice-plate flow meter for estimating instantaneous dynamic flow rate
TEC	Thermoelectric cooler. These are solid state heat pumps which use electrical current to transfer heat in either direction.
L/V Separator	liquid–vapor separator
DC	direct current, as of electrical potential and current
PID	proportional-integral-derivative, as in the feedback control method
N-IF	no-Imposed fluctuation, referring to cases in which the vapor pulsator was not used
L-IF	low amplitude-imposed fluctuation
T-IF	transition amplitude-imposed fluctuation
H-IF	high amplitude-imposed fluctuation

Variables

f	frequency [Hz]
$f_{P:V}$	(same as f_P) primary frequency associated with imposed vapor phase flow pulsations [Hz]
$f_{P:L}$	primary frequency associated with imposed liquid phase flow pulsations [Hz]
x	distance downstream of the start of the region of interest in the test-section [cm]
$\dot{m}$	mass flow rate [g/s]
p	pressure [kPa]
v	average velocity over a reference area [m/s]
T	temperature [°C]
q''	heat flux [W/cm^2]
Δp_{a-b}	pressure difference between locations $x = a$ and $x = b$, each in units of cm (see Subscripts below) [Pa or kPa]
t	time [s]
ΔT	temperature difference between a representative saturation temperature and a representative heat-exchange surface temperature [°C]

Subscripts

0	at the $x = 0$ cm location
10	at the $x = 10$ cm location
40	at the $x = 40$ cm location
90	at the $x = 90$ cm location
I	associated with the inlet of the test-section or another flow loop component
E	associated with the exit of the test-section or another flow loop component
R	associated with re-circulating vapor flow
P	associated with imposed pulsations or the vapor pulsator
L	liquid
V	vapor
AC	associated with the auxiliary condenser
B	associated with the pool boiler of Figs. 4 and 5
Sat	saturation, as of temperature
Avg	representative of an average value with respect to distance ‘x’ within the test-section

boiling and flow condensation. The study is both comparative and unifying in nature. Traditional condenser (all vapor flow at inlet and all liquid flow at exit) and boiler (all liquid flow at inlet and all vapor flow at exit) operations are shown in Figs. 1(a) and 2(a), respectively. Operations for realizing the innovative condensing and boiling flow conditions are schematically represented in Figs. 1(b) and 2(b).

The rationale for using recirculating vapor flows in the innovative arrangements of Figs. 1(b) and 2(b) is to arrange an appropriate through flow of vapor that does not undergo phase-change in the condenser or in the boiler. The innovative boiler operation also has a desired liquid flow rate at the inlet (which may be held at close to saturation temperature) – with or without a left-over recirculating liquid flow rate at the exit. A left-over recirculating liquid flow rate at the exit of the boiler is preferred if the boiler is heated by a specified heat-load (as in cooling of electrical or electronic devices) – as it is desirable to avoid critical heat-flux phenomena associated with dry-out conditions. As seen from the representative flow visualization photographs in Figs. 1 and 2, the innovative arrangements allow effective control of liquid–vapor morphology – restricting them to the efficient annular regime while avoiding complex non-annular condensing and boiling flow regimes (nucleate, bubbly, plug/slug, dry out and critical heat-flux related film boiling regions, etc.) discussed in [1–10]. The term *annular* flow regime as used in this paper relates to the same regimes which are called, in many popular gas-liquid flow regime terminologies [3], as smooth/wavy and annular/stratified regimes. For horizontal flow boilers of larger than mm-scale hydraulic diameter, nucleate boiling may persist within the annular film and such nucleation could even be beneficial for increasing heat-transfer rates. This paper's focus, however, is to restrict itself to mm and sub-mm scale flow boilers with micro-m scale liquid film thicknesses – which are of interest to applications which require heat removal from small areas or relate to space-based or aircraft-based thermal management. The annular liquid film thicknesses are achieved because nucleation, growth, and detachment of vapor bubbles have been suppressed to varying degrees – depending on flow conditions and the location within the boiler. Ways of suppressing undesired bubble nucleation and growth within most of the annular regime are suggested for these flows. This suppression is observed here and is known [11] to occur when liquid film thickness values are small (film Reynolds

Download English Version:

https://daneshyari.com/en/article/7056997

Download Persian Version:

https://daneshyari.com/article/7056997

Daneshyari.com