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Experimental comparison and visualization of in-tube continuous and pulsating flow boiling

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ABSTRACT

This experimental study investigated the application of fluid flow pulsations for in-tube flow boiling heat transfer enhancement in an 8 mm smooth round tube made of copper. The fluid flow pulsations were introduced by a flow modulating expansion device and were compared with continuous flow generated by a stepper-motor expansion valve in terms of the time-averaged heat transfer coefficient. The cycle time ranged from 1 s to 7 s for the pulsations, the time-averaged refrigerant mass flux ranged from 50 $\text{kg m}^{-2}\text{ s}^{-1}$ to 194 $\text{kg m}^{-2}\text{ s}^{-1}$ and the time-averaged heat flux ranged from 1.1 kW m^{-2} to 30.6 kW m^{-2}. The time-averaged heat transfer coefficients were reduced from transient measurements immediately downstream of the expansion valves with 2 K and 20 K subcooling upstream, resulting in inlet vapor qualities at 0.05 and 0.18, respectively, and covered the saturated flow boiling range up to the dry-out inception. Averaged results of the considered range of vapor qualities, refrigerant mass flux and heat flux showed that the pulsations at low cycle time (1 s) improved the time-averaged heat transfer coefficients by 5.6% and 2.2% for the low and high subcooling, respectively. However, the pulsations at high cycle time (7 s) reduced the time-averaged heat transfer coefficients by 1.8% and 2.3% for the low and high subcooling, respectively, due to significant dry-out when the flow-modulating expansion valve was closed. Furthermore, the flow pulsations were visualized by high-speed camera to assist in understanding the time-periodic flow regimes and the effect they had on the heat transfer performance.

1. Introduction

High heat exchanger performance is crucial to comply with efficiency standards with low cost and environmental impact in various applications such as heat pumps, refrigeration and air-conditioning. In a recent paper [1], we compared in-tube continuous and pulsating flow boiling heat transfer experimentally at low vapor qualities, in order to demonstrate possible heat transfer enhancement by introducing flow pulsations. The experimental setup was designed to mimic a refrigeration, air-conditioning or heat pump system with R134a evaporating at 5 °C and condensing at 32 °C. Time-averaged heat transfer coefficients were obtained immediately after the expansion valve with 2 K subcooling upsteam. The pulsations were introduced by a pulsed flow expansion device and compared with continuous flow from a stepper-motor expansion valve. The cycle time ranged from 1 s to 9 s for the flow pulsations. We presented first results, derived from a prototype evaporator test section (8 mm smooth round tube made of copper), that indicated a small heat transfer enhancement (3.2%) at the lowest cycle times (1 s to 2 s), but also a small penalty at high cycle times and high heat flux due to significant dry-out when the pulsating flow valve was closed. The current paper serves to provide a better foundation for the comparison of continuous and pulsating flow boiling heat transfer. Some important points not addressed in the recent paper, but included in the current paper are: (1) the results cover the whole quality range up to the point of dry-out inception for the continuous flow (and a similar time-averaged quality for the pulsating flow), (2) the results include the effect of larger subcooling (20 K) and thus lower inlet vapor quality, (3) the test sections were improved with four wall temperature measurements circumferentially instead of only two in the recent paper (considered to be enough for the first experimental campaign), (4) since the inlet vapor quality was fixed due to the same boundary condition before the exchangeable expansion valves, the change in quality was interdependent with the change in heat flux. With several test sections, these important variables are no longer correlated or dependent in the data set.

Pulsating flow boiling (or fluid pulsation/vibration) has received little attention in the literature for boiling and condensation

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Nomenclature

Roman

A	cross-sectional area, m^2
Bo	boiling number $[q/(h_{fg}g)]$
Bd	Bond number $[(\rho_f - \rho_g)gd^2/\sigma]$
c_p	specific heat capacity, $J\ kg^{-1}\ K^{-1}$
D	outer tube diameter, m
d	inner tube diameter, m
Fr_g	vapor Froude number based on Mori et al. [20] $[G^2/(\rho_g(\rho_f - \rho_g)gd)]$
G	mass flux, $kg\ m^{-2}\ s^{-1}$
g	gravitational acceleration, $m\ s^{-2}$
h	specific enthalpy, $J\ kg^{-1}$
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$
L	test section length, m
p_r	reduced pressure, –
Pr_f	liquid Prandtl number $[c_{pf}\mu_f/k_f]$
q	heat flux, $W\ m^{-2}$
$\dot{Q}$	heat flow rate, W
R_{adj}	adjusted coefficient of determination, -
Re_f	liquid Reynolds number $[G(1-x)d/\mu_f]$
Re_g	vapor Reynolds number $[Gxd/\mu_g]$
T	temperature, °C
t_{cyc}	cycle time, s
t_{open}	opening time, s
$\dot{V}$	volume flow rate, $m^3\ s^{-1}$
We_f	liquid Weber number $[G^2d/(\rho_f\sigma)]$
We_g	vapor Weber number $[G^2d/(\rho_g\sigma)]$
x	vapor quality, –
x_{de}	dry-out completion quality, –
x_{di}	dry-out inception quality, –
z	axial coordinate, m

Greek

α	heat transfer coefficient, $W\ m^{-2}K^{-1}$
μ	dynamic viscosity, $N\ s\ m^{-2}$
ρ	density, $kg\ m^{-3}$
σ	surface tension, $N\ m^{-1}$

Subscripts

cont	continuous
crit	critical
exp	experimental
f	liquid
g	vapor
pred	predicted
puls	pulsation
r	refrigerant
sat	saturation
w	water
wall	wall
∞	ambient

Abbrevations

MAD	mean average deviation
MRD	mean relative deviation
OD	valve opening degree
SC	subcooling

enhancement [2,3]. It is in fact difficult to find independent studies concerning the same evaporator or condenser type, actuator, and operation conditions, e.g. pulsation frequencies. The reported results are also conflicting, showing that the performance improves, diminish, or result in no appreciable effect. Some earlier findings involving pulsating flow boiling or condensation are summarized in the following, a deeper description of the studies are provided in Kærn et al. [1] and are not repeated herein.

Antonenko et al. [4] studied nucleate boiling enhancement by fluid vibrations at 15 Hz to 100 Hz and argued that the nucleate boiling region was impossible to enhance. Obinelo et al. [5] studied steam pulsations (0.08 Hz to 0.25 Hz) in a reflux condenser and found a several-fold increase in the condensation capacity. Bohdal and Kuczyński [6] investigated pulsating flow in an R134a evaporator coil and found that the superheated region increased with higher cycle times and led to a decrease in the heat transfer performance. Later, the same authors [7] investigated pulsating flow during condensation of R134a in pipe mini-channels (0.64 mm to 3.3 mm hydraulic diameter) and found that the subcooling area in the condenser increased with increasing cycle time, while the condensation area decreased and led to a decrease of the overall condenser effectiveness. Thus, lowest cycle times (highest pulsating frequencies) performed better for both evaporation and condensation. Chen et al. [8] studied pulsating flow with nearly triangular waves with peak-to-peak amplitudes from 10% to 30% of the average flow and large cycle times from 30 s to 120 s. Only a slight impact on the time-averaged heat transfer coefficient and boiling curve was observed at these modest oscillations. Roh and Kim [9] studied flow pulsations in an R410A heat pump and found the coefficient of performance (COP) could be improved by 4%. The authors suggest the enhancement is caused by both the pulsation-enhanced heat transfer and the so-called ”pushing effect” that elevated the compressor suction and discharge pressures immediately after each pulse.

Recently, the effect of flow pulsations was studied in an air-to-refrigerant finned-tube evaporator experimentally by Wang et al. [10] using R134a as the refrigerant. The evaporator consisted of 24 staggered tubes, 385 mm long including U-bends, 6.2 mm inner diameter, 8.0 mm outer diameter, 596 fins per meter, and a single refrigerant pass. The pulsations were generated by a solenoid valve, operated at 50% opening degree and cycle times from 2 s to 20 s. The results showed that the overall and refrigerant-side heat transfer coefficients improved up to 27% and 123%, respectively, with the highest enhancement at lowest cycle time.

The main objective of the current paper is to demonstrate the *possible* heat transfer enhancement with flow pulsations by comparing the pulsating flow boiling heat transfer results with that of continuous flow boiling, including the points not addressed in the earlier paper [1] (whole quality range, larger subcooling, four wall temperature measurements, independent heat flux and vapor quality), in order to provide a better foundation for the comparison and analysis, and to consolidate the earlier results. The oscillating dry-out location, superheat and associated system effects are not considered herein. The hypothesis is that the pulsations will increase the flow boiling heat transfer by means of better bulk fluid mixing, increased wall wetting and flow-regime destabilization.

The paper includes a description of the updated experimental apparatus, including the data reduction method and uncertainty analysis, as well as a single-phase heat transfer comparison, and a comparison of the continuous flow boiling results with correlations in the literature. Then the comparison between continuous and pulsating flow boiling is presented in three subsections: a non-normalized presentation of some raw data, a regression-normalized comparison, and some correlation-normalized