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Experimental investigation of flow boiling in narrow channel

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The flow boiling in narrow channel is investigated experimentally. The aim of the present work is to study the heat transfer phenomena. The working fluid is n-pentane which is chosen for its low boiling point (36 °C at atmospheric pressure). The independent variables are velocity in the range from 0.015 m/s to 0.06 m/s and boiling heat flux with values between 9 and 137 kW/m^2. The wall superheat and exit vapor quality are presented as dependent variables. The flow pattern was predicted based on temperature fluctuations. The experimental results are compared to those available in the literature (Shah, Gungor-Winterton and Jens correlations). A new correlation has been developed for the average heat transfer coefficient during flow boiling in a rectangular channel with validity in boiling heat flux from 9 to 137 kW/m^2 and Reynolds number between 380 and 1522.

1. Introduction

Many industrial processes use plate heat exchangers for applications with phase change. In these processes, the heat transfer coefficient is depending on the boiling regime (nucleate or convective); where the nucleate boiling is a type of boiling that takes place when the surface temperature is hotter than the saturated fluid temperature by a certain amount and the convective boiling refers to the convective process between the heated wall and the liquid-phase. Therefore, it is necessary to identify the basic mechanisms which occur during boiling in heat exchanger channels. There has been considerable effort to understand the boiling mechanisms and to predict the heat transfer coefficient in both tube and rectangular channel. In this paper, we try to understand the heat transfer phenomena in channel of millimetric order heat exchanger. It can be applicable in many areas: oil-cooling, heat exchanger for microcomputers.

For the vertical tube, Chen [1] envisioned the local two-phase flow boiling coefficient to be the sum of the nucleate boiling and the convective boiling contributions. He proposed a correlation based on Forster-Zuber [2] and Dittus-Boelter [3] correlations with some correcting factors. Shah [4], proposed a correlation to implement his chart calculation method which consider the nucleate and convective boiling as principal heat transfer mechanisms. He proposed a method applicable to both vertical and horizontal tubes. Gungor and Winterton [5] proposed a new form of Chen [1] correlation with a large database of 3693 points from the literature for water, refrigerants and ethylene glycol, his correlation can be applicable to both up and down flow.

To increase exchange surface and enhance the heat transfer coefficient, the plate heat exchangers are more and more used. Feldman [6] studied the local nucleate and convective boiling heat transfer in plate fin exchanger and the influence of fin geometry. Unfortunately, he used only two mass fluxes. Which is insufficient to mount the influence of mass flux on the heat transfer coefficient.

Kim and Sohn [7] studied experimentally the flow boiling in a rectangular channel with offset stripe fins for large range of heat flux and Reynolds number. They developed a correlation for local heat transfer coefficient. This latter gives a dispersion equals to 25% compared to the experimental data. To improve the efficiency of systems using ocean thermal energy, Arima et al. [8] studied the local heat transfer coefficient in the plate heat exchangers using Ammonia and ammonia–water as working fluid. Also, in this work a visualization of the flow patterns has been carried. In the same range of heat flux, Taboas et al. [9,10] has carried a same study but with a more important mass flux. Zakarias et al. [11] studied the boiling heat transfer in the plate generator for an absorption machine using ammonia–lithium as working fluid, he notes that the two-component mixture formed by ammonia and lithium nitrate has a lower boiling heat transfer coefficient than that of pure

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Nomenclature

CI	confidence interval (–)
Cp	specific heat (J/kg°C)
D_h	hydraulic diameter (m)
k	thermal conductivity (W/m. K)
L	channel length (m)
m	flow rate (kg/s)
Q	heat flux (W)
Re	Reynolds number (–)
S	heat exchanger surface (m^2)
T	temperature (°C)
V	velocity (m/s)
z	position (m)
x	quality
AMV	arithmetic mean value
Bo	boiling number
F	Shah's constant (–)
E, S	Gungor's constant (–)
N	dimensionless parameter (–)
I	electric current (A)
U	voltage (V)
M	molar mass (kg/mol)
G	mass velocity (kg/m^2s)
P	pressure (Pa)
h_{fg}	latent heat (kJ/kg)

Greek symbols

Δ	differential
σ	standard deviation
υ	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

f	fluid
w	wall
elec	electrical
ther	thermal
Sat	saturation
L	liquid
cb	convective boiling
in	inlet
out	outlet
a	average
b	boiling
TP	two-phase
s	suppression
nb	nucleate boiling

ammonia. Lee et al. [12] have experimentally studied the flow boiling heat transfer in a plate heat exchanger at low mass flux condition, his study shows that the influence of the convective boiling heat transfer is suppressed under the test conditions, and the effect of boiling heat transfer was dominant. This is stating obvious from the insignificant effect of vapor quality on flow boiling heat transfer coefficient at low mass flux. Koyama et al. [13] studied the flow boiling for plate heat exchanger, heated from one side, they found that the heat transfer coefficient is governed by the nucleation and the bubble behavior driven by buoyancy rather than forced convection. Wang et al. [14] studied the boiling incipient in vertical narrow rectangular channel, he make a parametric study to evaluate the effect of pressure, inlet sub-cooling, heat flux and mass flux. His entire experimental data obtained through different determination methods indicate that inception wall superheat is dependent on the inlet sub-cooling, heat flux and mass flux, but the variation of pressure does not lead to a significant change in boiling incipience.

As one can see the available studies in the literature (Table 1) focus on local heat transfer phenomena, while, for the industrials, the most important parameter in the heat exchangers is the mean heat transfer coefficient, because this is the only parameter which can give us a relevant idea about heat exchanger efficiency.

The present work deals with an up-ward flow boiling in narrow rectangular heat exchanger, the effect of heat flux, velocity, wall superheated and exit vapor quality on heat transfer phenomena are experimentally investigated. These results are compared with a number of correlations available in the literature.

2. Experimental facilities

A complete experimental analysis of flow boiling requires the knowledge of pressures, temperatures, and velocities in the device.

The experimental test section built in-situ (Fig. 1), creates the needed conditions to conduct various tests and their reproducibility. It is equipped with pressure sensors, thermocouples and flow meters. The accuracy of the measurement is related to the acquisition chain used in the present set-up. Note that the acquired measurements allow determining the spatial-temporal evolution of the transport phenomena.

The Hydraulic loop (Fig. 2) is composed of several devices. A tank is designed to store up to 30*l* of working fluid (pentane). To set the fluid temperature at the channel inlet, this tank is equipped with an electrical resistance controlled by a thermostat. A gear pump with stainless steel volute ensures a continual feeding of the test section. The fluid velocity varies between 0.015 and 0.06 m/s. The liquid pumped from the tank is evaporated in the test channel and separated in the separator; the flow rate of the separated liquid is measured using balance at the outlet of the channel. However the condensed steam returns in the tank.

The test section built in-situ (Fig. 3) is composed of two heated plates made from bronze (Fig. 3). These plates are wrapped in PTFE (PolyTetraFluorEthylene) sheets, thus ensuring both the mechanical retention and the thermal insulation of the channel. The test channel has following dimensions: 0.05 m (length) × 0.005 m (width) × 0.025 m (depth) [m^3]. The D_h is equal to 0.0083 mm.

K-type thermocouples have been used to measure the local temperature. Their diameter is equal to 0.5 mm for not disturb the flow. Locations of thermocouples are given in Fig. 3 (a). They are implanted in both wall and inside the channel along two vertical axes. Note that the fluid measurements are taken in the center of the channel.

The working fluid is n-pentane which is chosen for its low boiling point (36 °C at atmospheric pressure) and its small latent heat (382.450 kJ/kg) compared to water. It circulates in the upward vertical direction, between the heated plates. Four heater cartridges located vertically in the heated plates are used to heat the assembly. The heating power varies between 3.04 and 6.88 W/cm^2.The channel sealing is ensured by plate gaskets made from Vitton.

3. Experimental results

Fig. 4 displays fluid and wall temperature (°C) versus time (s) given by the thermocouples at z = 0.035 m for Q = 3.04 W/cm^2,