International Journal of Thermal Sciences 132 (2018) 628–644

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Numerical simulation of pool boiling on smooth, vertically aligned tandem tubes

S.M.A. Noori Rahim Abadi[a,*], A. Ahmadpour[b], J.P. Meyer[a]

[a] Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria, South Africa
[b] Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Keywords:
Pool boiling
Eulerian-eulerian
RPI model
Inclination angle

ABSTRACT

In the present study, a numerical simulation of atmospheric pool boiling on tandem, inclined, electrically heated circular tubes is performed. An Eulerian-Eulerian description of the two-phase flow formulations is adopted together with a Rensselaer Polytechnic Institute (RPI) nucleate boiling model to account for the heat and mass transfer in the boiling phenomenon. The pool boiling is studied in the range of 0–100 kW/m^2 for the heat flux and for inclination angles of 0–90°. The effect of the boiling liquid characteristics on the key features of the pool boiling phenomenon is studied, as well as using water, ethanol and FC-72 as the working fluid. The numerical results are validated against available experimental measurements, and the effects of the inclination angle, working fluid and magnitude of the heat flux are explored thoroughly.

1. Introduction

Boiling heat transfer from tubes and tube bundles is an important research area in the multiphase flow and heat transfer fields [1]. Investigations are prompted by the need to understand the boiling mechanism, a key factor in the design of various industrial heat exchangers widely used in power generation and petrochemical plants. In the absence of forced fluid motion, in which the heat transfer coefficient is related to the temperature difference between the inlet and outlet flows and surface heat flux, pool boiling occurs on a heated surface and has its own applications in passive heat exchangers for nuclear reactors, flooded type evaporators and thermosyphon reboilers [2,3].

Pool boiling on a tube or a tube bundle is a complex physical phenomenon that is affected by the thermophysical properties of the working fluid, the quality of the pipe surface, and the tube bundle arrangement, i.e., the tube's pitch and inclination or elevation angle [2]. Experimental measurements have been the primary tool for studying this phase-change phenomenon. A comprehensive experimental database containing pool boiling data from single electrically heated circular tube (submerged in a pool of boiling fluid) with various boiling fluids and tube surface qualities is provided by Stephan and Abdelsalam [4], Gorenflo [5]. Proper correlations for pool boiling on a heated tube bundle were introduced to represent the experimental data by Aprin et al. [6]. They considered different pure hydrocarbons such as n-pentane, propane and iso-butane under several operating conditions (pressure, heat flux and mass flow rate). Two different flow regimes, bubbly and dispersed flow patterns, were distinguished within the experimentations. They showed that in the bubbly flow regime the heat transfer coefficient depended only on heat flux and reduced pressure, but in the dispersed flow regime its hydrodynamic parameters such as vapour velocity and the Reynolds number based on vapour properties played the dominant role. Finally, proper correlations were proposed for each considered two phase flow regime.

Gorgy and Eckels [7] experimentally determined the local heat transfer coefficient for R-134a pool boiling on smooth and enhanced tubes. The heat flux needed to induce pool boiling was provided by warm water flowing inside the tubes. For the enhanced tube, two distinctive regions were detected in the pool boiling curve. Across the first region, the heat transfer coefficient rises sharply with heat flux. In the second region, the heat transfer coefficient is (approximately) independent of the heat flux; as a result, both regions of the pool boiling curve could be accurately modelled using a proper power law model.

In another works, Chien and Webb [8,9] investigated the effect of geometrical parameters on the boiling heat transfer coefficient in "tunnelled" enhanced boiling surfaces. Tests were performed on a 19.1-mm diameter horizontal tube and pore diameters of 0.12, 0.18, 0.23, and 0.28 mm and the pore pitches of 0.75, 1.5, and 3.0 mm, using different refrigerants such as R11 and R123 at 26.7 °C for heat fluxes from 2 to 70 kW/m^2. The results showed that the boiling heat transfer coefficient increased with increasing tunnel height and decreasing of the tunnel pitch. Moreover they found that sharp tunnel corners provided greater enhancement for heat transfer rates.

* Corresponding author.
E-mail address: ali.abadi@up.ac.za (S.M.A. Noori Rahim Abadi).

https://doi.org/10.1016/j.ijthermalsci.2018.07.005
Received 17 November 2017; Received in revised form 16 March 2018; Accepted 3 July 2018
1290-0729/

Nomenclature

A_b	Part of the wall surface covered by nucleate bubbles [m^2]
$A_{interfacial}$	Interfacial area [m^2]
C_D	Drag coefficient [−]
C_L	Lift coefficient [−]
C_p	Specific heat [J/kgK]
d	Bubble diameter [m]
D_w	Bubble departure diameter [m]
Eo	Eotvos number [−]
F	Force [N]
g	Gravitational acceleration [m/s^2]
h	Fluid specific enthalpy [J/kg]
h_b	Boiling heat transfer coefficient [W/m^{2}K]
h_{lv}	Latent heat of evaporation [J/kg]
h_c	Single-phase heat transfer coefficient [W/m^{2}K]
k	Thermal conductivity [W/mK]
Mo	Morton number [−]
n	Number of phases [−]
Nu	Nusselt number [−]
N_w	Nucleate site density [−]
P	Pressure [Pa]
Pr	Prandtl number [−]
q''	Heat flux [W/m^2]
$\dot{q}_C$	Convective heat flux [W/m^2]
$\dot{q}_Q$	Quenching heat flux [W/m^2]
$\dot{q}_E$	Evaporative heat flux [W/m^2]
Q	Intensity of heat exchange between the different phases [W/m^2]
r	Radius [m]
Re	Reynolds number [−]
$\vec{u}$	Velocity [m/s]
$\dot{\Gamma}$	Mass transfer source term [kg/m^{3}s]
Sc	Schmidt number [−]
S_u	Momentum source term [N/m^{3}s]
S_h	Energy source term [J/m^{3}s]
t	Time [s]
T	Temperature [K]

Greek symbols

τ	Shear stress [N/m^2]
α	Volume fraction [−]
ρ	Density [kg/m^3]
μ	Dynamic viscosity [Pa.s]
k	Turbulent kinetic energy [m^2/s^2]
ε	Turbulent energy dissipation rate [m^2/s^3]
Ω	Mean rate of rotation tensor [1/s]
σ	Surface tension [N/m]
δt	Time scale in boiling model [s]
θ	Tube inclination angle [deg]

Subscripts

b	Bubble
p	Phase index
k	Phase index
l	Liquid
lv	Liquid-vapour
L	*Laminar*
M	*Mixture*
Sat	*Saturation*
T	*Turbulent*
V	*Vapour*
v,m	*Virtual mass*
w	*Wall*

Gupta et al. [10] experimentally determined the local pool boiling heat transfer coefficient for a staggered bundle of vertical tubes. The local heat transfer coefficient increases along the direction of the nucleated bubbles' flow. Similar measurements in a vertical array of horizontal pipes under flooded condition were determined by Ribatski et al. [11]. Regardless of the tube bundle arrangement, a local maximum emerges in the profile of the local heat transfer coefficient, along a vertical direction; the heat transfer rate tends to an asymptotic value beyond this local extrema.

Nucleate pool boiling from a small staggered tube bundle flooded in water, methanol and refrigerant R141b was evaluated via an experiment by Krasowski and Cieslinski [12]. The highest overall heat transfer coefficient was determined for the case of a tube bundle flooded in water and operating under atmospheric conditions. Moreover, these researchers determined that as the pitch-to-diameter ratio of the tube bundle increases, the heat transfer coefficient increases as well.

Kang [13] investigated the pool boiling phenomenon on the outside and inside surfaces of a 51 mm horizontal tube. He found that the maximum and the minimum values of the heat transfer coefficients on the outside surface occurred at $\theta = 45^\circ$ and 180°, respectively. However the minimum value on the inside surface occurred at $\theta = 0^\circ$. To justify this peculiar behaviour, Kang argued that for the boiling occurred on the outer surface of the circular tube, the liquid agitation and bubble coalescence were the main mechanisms of the pool boiling; in contrast, on the inner surface of the tube, the phase change phenomenon was dominated by micro layer evaporation and liquid agitation.

The effect of the tube bundle pitch on pool boiling was studied by Kang [14] on a pair of stainless steel tubes positioned vertically above each other. In the later work, water was chosen as the working fluid. The study determined that raising the total heat transfer rate weakens the tube bundle effect as the tube pitch increases. Kang extended this work by considering several staggered arrangements for heated tubes [15]; the elevation angle was chosen as the primary variable, and its effect was studied on pool boiling heat transfer. Kang determined that the convection heat transfer for the upper tube increases with elevation angle [15].

Kang [16] conducted a comprehensive experimental investigation on pool boiling from an inclined circular tube bundle placed in an atmospheric water tank. The setup consists of two smooth, vertically aligned stainless steel tubes with a diameter of 19 mm and a length of 400 mm. These tubes submerged in a bath with the height, length and width of 1400 mm, 1300 mm, 900 mm, respectively [16]. The inclination angle of the tubes (θ) could be adjusted between 0° and 90° in respect to the horizontal direction; both tubes were electrically heated by an adjustable flux of q''_L for the lower tube and q''_T for the upper tube. The surface temperature of the upper tube was denoted by T_w and was an important variable. The enhancement of heat transfer from the upper tubes (due to the departure of vapour bubbles from the lower tubes which agitates the flow field around the upper tube) is significantly affected by the inclination angle of the tube bundle and the magnitude of the heat flux. The reported elevation in the convective heat transfer coefficient is more pronounced for smaller inclination angles and heat fluxes.

In another work, Ustinov et al. [17] studied the pool boiling heat transfer from tandem tubes with different novel microstructures. The microstructures consisted of copper micro pins upon the tube with the diameter between 0.1 μm and 25 μm, and maximum height of 100 μm and maximum density of 10^9 pins/cm^2. They used two refrigerants