Applied Thermal Engineering 128 (2018) 444–452

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Performance of porous coated 5 × 3 staggered horizontal tube bundle under flow boiling

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HIGHLIGHTS

- Flow boiling on outside porous coated tube bundles is studied.
- A new type of correlation is proposed in terms of Peclet number and Froude Number.
- ANFIS model is also developed and is found to be performing better than empirical model.
- Variation of HTC with mass flux is found to be insignificant up to a certain value and then it decreases.

ARTICLE INFO

Article history:
Received 11 March 2017
Revised 30 August 2017
Accepted 8 September 2017
Available online 8 September 2017

Keywords:
Boiling
Heat transfer coefficient
Tube bundles
Porous coating
Plasma spraying
Flow boiling

ABSTRACT

The present article focuses on the flow boiling heat transfer performance of plasma sprayed copper coated tube bundles. The details of the flow boiling experiments over coated tube bundles is presented in the article. The variations of bundle average heat transfer coefficients are presented and analysed for saturated flow boiling of distilled water with respect to operating parameters such as heat flux, mass flux and pitch to diameter ratio. The range of operating parameters considered for present investigation is as follows: heat flux = 12.25–65.94 kW/m^2, mass flux = 20.25–192.9 kg/m^2 s and pitch to diameter ratio = 1.25, 1.6 and 1.95. The results show that the bundle averaged heat transfer coefficient increases with the increase in heat flux. However, it does not vary significantly with mass flux up to a certain value and decreases thereafter with further increase in mass flux. The tube bundle with lower pitch to diameter ratio is observed to be performing better. Semi-empirical correlation and ANFIS model are developed to predict the flow boiling bundle average heat transfer coefficients.

1. Introduction

The boiling heat transfer finds its extensive application in various kinds of industries such as chemical, food processing, refrigeration, nuclear, paper-pulp and other allied industries [1]. The process of boiling is a complex phenomenon due to involvement of large number of influencing factors such as heater surface characteristics, heater material properties, heater arrangement, size of the heater, operating conditions and thermo-physical properties of the liquid [2]. Moreover, the boiling process becomes further complicated when flow boiling occurs over tube bundles. The reason behind this is the involvement of additional influential parameters such as mass flux, pitch to diameter ratio & bundle configuration [3], and more importantly the enhancement technique applied to the surface of the tubes. The study of flow boiling heat transfer over tube bundle is of great importance from the perspective that most of the industries such as thermal power plants, chemical process plants, nuclear power plant use heat exchangers as a major heat transfer equipment.

Hsieh et al. [4] studied the nucleate pool boiling of R-134A over plasma coated copper tubes with varying heat flux conditions. Their experimental data includes a variety of combinations of heated tubes and instrumented tubes like only lower middle tube, middle column lower three tubes and lower two rows heated conditions. The heat transfer rate at a wall superheat is observed to be magnified for plasma coated tubes than for plain smooth tubes. The inline bundle with the same tube spacing has a higher heat transfer rate than the staggered one. The bundle factor is defined as the ratio of the area averaged bundle HTC to the isolated tube HTC.

Schafer et al. [5] also investigated the performance of plasma coated tube bundle using the R-134a refrigerant. They observed a

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http://dx.doi.org/10.1016/j.applthermaleng.2017.09.038
1359-4311/

Nomenclature

Letters

D	outside diameter of tube (m)
d_p	diameter of copper particles (μm)
G	mass flux (kg/m^{2}s)
g	acceleration due to gravitation (m/s^2)
k	thermal conductivity of tube material (W/m^{2}K)
P	center to center distance between tubes (m)
q	heat Flux applied to tubes (W/m^2)
t_p	thickness of plasma coating (μm)
ε	porosity of Surface
ρ	density of liquid kg/m^3
α	thermal Diffusivity, m^2/s
λ	latent heat of vaporization, J/kg
σ	surface tension, N/m

Acronyms

EF	enhancement factors
HTC	heat transfer coefficient, W/m^2 K
P/D	pitch to diameter ratio of a bundle
PID	proportional, Integral and derivative
FESEM	field emission Scanning electron microscope

Subscripts

l	liquid
v	vapour
o	outer Surface
p	plasma Coated Surface

Dimensionless numbers

Cn	coating parameter $Cn = \varepsilon * d_p/t_p$
Fr	Froude number $Fr = G^2/(\rho_l^2 gD)$
Pe_b	Peclet number $\frac{q}{\alpha\rho_v\lambda}\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}$
Nu_{BA}	Bundle averaged Nusselt number for flow boiling over plain tube bundle
$Nu_{BA\text{-}C}$	Bundle averaged Nusselt number for flow boiling over plain tube bundle

good enhancement over smooth tube bundles. The pool boiling heat transfer coefficients increased with saturation pressure in their observation.

Lakhera et al. [6] investigated the flow boiling performance of distilled water on a single SS 316 flame sprayed coated tube at atmospheric pressure exploring the effect of surface roughness (0.3296 to 4.7321 μm), the mass flow rate and heat flux. The flow boiling experimental data best fitted to the Kutateladze [7] asymptotic relation for cross flow boiling over tube bundle. The HTC value increases with the surface roughness and heat flux for all mass flow rates. The pool boiling experimental data is also validated with the correlation proposed by Gorenflo [8]. The similar kind of observation as observed in literature is seen here in which the HTC increase with heat flux. With the increase in mass flow the nucleation on the tube surface is suppressed except in the wake region of the flow i.e. above the tube. However, the contribution by the single phase convection heat transfer increases with mass flux. It is also observed that the HTC increases with the surface roughness for coated tubes similar to plain tubes.

Lakhera et al. [9] studied the boiling performance of plain stainless steel (Ra = 0.3296 μm) and SS316 coated (Ra = 8.279 μm, porosity < 2%) 8 × 3 tube bundle which is electrically heated. The central column tubes are taken as instrumented tubes. The different pitches to diameter ratios studied in this investigation are 1.4, 1.7 and 2.0. The heat transfer coefficients for the tube bundle with a pitch to diameter ratio 1.4 is found to be performing better than the other two pitch to diameter ratios. The enhancement factor is observed to gradually decrease at higher heat flux values. Recently Zhang et al. [10] studied the flow boiling performance of vertical rod bundle with different inlet qualities under mass flux conditions from 80 to 350 kg/m^{2}s. They observed an increase of heat transfer coefficient with increase in mass flux which is mainly due to single phase convection as nucleate boiling is suppressed.

The above studies are mainly focused on the pool boiling heat transfer over porous coated tube bundles. Only one investigation is focused on flow boiling of distilled water over a single coated tube and no studies are present concerned to evaluation of performance of porous coated tube bundles under flow boiling conditions. Thus, the present investigation is taken up to study saturated flow boiling of distilled water over porous coated tube bundles.

2. Experimentation

The details of the experimental setup used for present investigation are already described in Swain and Das [11]. A line diagram is presented here in Fig. 1 for ready reference. The setup has provision for changing the pitch to diameter ratio of the tube bundle by attaching heating tubes to different PTFE sheets with threaded holes at different pitch distances.

The tube bundle used for the present investigation is a 5 ×3 tube bundle. Therefore, it is necessary to analyze the effect of side walls on it. It is to be noted that all the tubes in the tube bundle are heated with electrical cartridge heater. However, only the heating tubes at the middle column of tube bundle are instrumented with thermocouples to evaluate the flow boiling heat transfer coefficient (HTC) of tube bundle. This is done to study the effect of side columns of tube bundle on the heating tubes of middle column and to eliminate the effect of side walls of vessels on the middle column. To make the flow uniform through the bundle, a perforated plate is placed in between the diverging channel and the test vessel. Even after this, the lower most tube of the middle column is not included in the determination of heat transfer coefficients to eliminate the entry effect. Therefore, only the upper five tubes of the middle column are considered for the determination of bundle average HTC. The top most tube is taken into consideration for determination of HTC as it is affected by the two phase flow coming from bottom tubes. However, the distance between the top tube of middle column and exit point of liquid from the vessel is 110 mm. Thus, due to this sufficient distance, the exit effect may be considered to be negligible on the top tube of middle column of the tube bundle.

The Fig. 2 shows the photographic image of both plain and plasma coated heating tubes. The copper coating is produced over the plain stainless steel tubes by the atmospheric plasma spraying process. Just before carrying out the coating the surface of tube is shot blasted to make it rough for better adhesion. In this plasma spraying process, the fine spherical copper powders are sprayed onto the shot blasted substrate surface through the plasma by the carrier gas. The threaded ends are covered with masking tape for preventing coating on it. Before carrying out the final coatings onto the heating tubes, several trial coatings are carried out on dummy tubes of similar diameter to get the desired coating