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Heat transfer distribution in helical coil flow boiling system

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ABSTRACT

The objective of the present work is to study the heat transfer distribution in the helical coil flow boiling system. Infrared thermal imaging technique is used to measure the local wall temperature. The wall temperature is measured across the circumference and in axial direction along the length of a helical coil. The literature showing circumferential heat transfer distribution in a helical coil during flow boiling process is scarce. The present work compares the wall temperature and heat transfer coefficient distribution on the inner side and the outer side of helical coils at different diameter ratios and density ratios. In the present study, the experimental databank (containing total 400 heat transfer coefficient data points) includes the data not only from the present experimental study but also from the literature. The data bank includes the subcooled and the saturated flow boiling data. The data includes two fluids namely water and R123. Data covers the range of parameters namely a density ratio of 30–1600, a mass flux of 100–1300 kg/m^2 s, a heat flux of 2–640 kW/m^2, an exit quality of −0.5 to 1 and a coil to tube diameter ratio of 14–58. Ten empirical correlations which include well referred correlations of straight tubes and available correlations of helical coils are evaluated with the databank. The study concluded that the circumferential wall temperature variation in helical coils decreases with increase in a diameter ratio and with decrease in a density ratio. The circumferential averaged heat transfer coefficient during a saturated flow boiling in a helical coil is same as a straight tube. A correlation is suggested to measure the circumferential average heat transfer coefficient in helical coils.

1. Introduction

Helical coils are widely used in many industrial applications due to their compact structures and good thermal expansion performances. The nuclear industries use a helical coil as the steam generator for electricity production. Due to compact structure, the helical coil reactor is an attractive option for the marine propulsion. Most helical coil heat exchangers used for industries and commercial application require the local heat transfer and local heat transfer coefficient information for design purposes to improve the effectiveness of heat exchanger. Research to use helical coil tubes for receiver of concentrating type solar collector for power generation system is going on. For this system, highest heat flux is at the concave side of the tube. To investigate this system, knowledge of local heat transfer coefficient on inner side and outer side require. The information should help to design and increase the efficiency of the receiver.

Flow boiling heat transfer represents one of the most efficient type of heat transfer mode. Flow boiling plays an important role in the design and analysis of evaporators and condensers. Flow boiling mechanism inside a helical coil may be different than that in a straight tube due to secondary flows generated inside a helical coil. The boiling results into two-phase flow of liquid and vapour which have different densities. The curvature of a helical coil generates the centrifugal force which may cause phase separation with a low density vapour being on the inner side and a high density liquid on the outer side of a helical coil during flow boiling process. Hence, the density ratio of boiling fluid and its vapour may affect the circumferential HTC distribution. The intensity of secondary flows and centrifugal force depend on coil curvature. Hence, diameter ratio of helical coil may affect the circumferential HTC variation during flow boiling process.

Naphone and Wongwises [21], Vashisth et al. [28], Fsadni and Whitty [7,8] and many others reviewed two-phase flow in helical coils. Reviews concluded that there is scarcity of the literature on helical coils compared to straight tubes and there is a need of research on helical coil to understand the different aspect of heat transfer mechanism. Owhadi et al. [23] carried out pioneering research on heat transfer coefficient in helical coil flow boiling.

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Nomenclature

Symbol	Definition (Unit)
Cp	specific heat at constant pressure (J/kg K)
d	tube diameter (m)
D	helical coil diameter (m)
Deviation	$(C_{cal} - C_{\mathrm{exp}})/C_{exp} \times 100$ (%)
f	friction factor
G	mass flux (kg/m^2 s)
g	gravitational constant (9.81 m/s^2)
h	heat transfer coefficient (W/m^2 K)
I	current (A)
i	enthalpy (J/kg)
k	thermal conductivity (W/m K)
L	length (m)
M	molecular weight (g/mol)
$\dot{m}$	mass flow rate (kg/s)
Mean	$(\lvert C_{cal} - C_{\mathrm{exp}}\rvert)/C_{\mathrm{exp}} \times 100$ (%)
P	pressure (N/m^2)
p	pitch (m)
P_r	reduced pressure ($P_{\mathrm{system}}/P_{\mathrm{critical}}$)
Q	heat supply (W)
q''	heat flux (W/m^2)
T	temperature (°C)
V	voltage (V)
x	quality of steam
X	lockhart Martinelli parameter $X = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1}$

Greek	Definition
μ	dynamic viscosity (N·s/m^2)
ρ	density (kg/m^3)

Subscript	Definition
b	bulk
f	fluid
fg	fluid to gas
g	gas
h	heated
i	inlet
l	liquid
lo	liquid only
sat	saturated
SC	subcooled
sys	system
TP	two phase
tt	turbulent liquid and turbulent vapour
w	wall

Abbreviation	Definition
HP	high pressure
HTC	heat transfer coefficient
LP	low pressure
R123	2,2-Dichloro-1,1,1-trifluoroethane

Dimensionless number	
Bo	Boiling number $Bo = q''/Gi_{fg}$
Nu	Nusselt number $Nu = h \cdot d/K$
Pr	Prandtl Number $Pr = \mu \cdot Cp/K$
Re	Reynolds number $Re = 4\dot{m}/\pi d\mu$

The work presented the circumferential variation in heat transfer coefficient in a helical coil during the flow boiling process. Most of the previous studies show overall averaged or circumferential averaged heat transfer coefficient in helical coils. Recently, Santini et al. [24] presented circumferentially averaged and axially local heat transfer coefficient (HTC) in a helical coil. The HTC is shown at twenty different axial locations of a helical coil. To the author's knowledge, literature showing the variation in the heat transfer coefficient across the circumference of a helical coil in the flow boiling process is not described well. There is no work reported to compare the heat transfer on inner side and outer side of a helical coil with the straight tube for high density ratio fluids. Many investigations are carried out on experimental local heat transfer coefficient in single phase flows in helical coils.

Hardik et al. [10] conducted the review on available correlations for single phase heat transfer coefficient. The study derived the local correlations to calculate circumferential averaged heat transfer coefficient on inner side, outer side and total circumference of helical coil. The study on single phase local HTC can be taken as the basis for investigation on flow boiling HTC in helical coils. Hardik and Prabhu [11] conducted the study on local heat transfer coefficient in helical coils with water. They compared local heat transfer coefficient along the axial length of a helical coil with different correlations. They concluded that the heat transfer coefficient in a saturated flow boiling process is same as that in a straight tube. Kandlikar [15] correlations for saturated flow boiling heat transfer coefficient are working reasonably for helical coils. Heat transfer coefficient in a subcooled boiling process is higher than the straight tube.

The effect of the coil curvature on HTC in helical coils discussed in the literature is presented in Table 1 for saturated flow boiling process. Literature suggested three different effects of coil curvature on HTC. (1) HTC in helical coils is higher than straight tubes and curvature effect in boiling process is different than the single phase flows. Some literature concluded HTC in a helical coil is constant along the length of coil and hence with increase of quality (2) Boiling HTC in a helical coil is predicted using a straight tube flow boiling correlation with single phase HTC correlation of helical coils. Hence, the effect of the helical coil is completely included in the single phase HTC correlation. (3) HTC in the helical coil is measured well with the straight tube correlations. Hence, it is same as straight tube.

The objective of the present work is to study the boiling heat transfer distribution in the helical coil with two different fluids namely water and R123. The wall temperature is measured across the circumference of a helical coil and in the axial direction along the length of helical coil. Infrared thermal imaging technique is used to measure the local wall temperature. The wall temperature and heat transfer coefficient distribution is compared on the inner and outer sides of the helical coil for different diameter ratios and density ratios. Experimental databank is collected containing total 400 heat transfer coefficient data points which include the data from the present study and from the literature. The data bank includes the data of subcooled and saturated flow boiling. Data covers the parameter range of a density ratio 30–1600, a mass flux 100–1300 kg/m^2 s, a heat flux 2–640 kW/m^2, an exit quality −0.5 to 1 and a coil to tube diameter ratio 14–58. Ten empirical correlations which include well referred correlations of straight tube and available correlations of helical coil are evaluated with the databank. The details of the available heat transfer coefficient correlations for the helical coils and for the straight tubes are given in Appendix A and B, respectively. The effect of fluid density ratio and helical coil diameter ratio is analysed.