International Journal of Heat and Mass Transfer 95 (2016) 551–565

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Review

A review on the two-phase heat transfer characteristics in helically coiled tube heat exchangers

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ARTICLE INFO

Article history:
Received 29 July 2015
Received in revised form 14 December 2015
Accepted 16 December 2015
Available online 4 January 2016

Keywords:
Two-phase flow
Curved tubes
Heat transfer
Boiling
Nanofluids

ABSTRACT

Helically coiled tube heat exchangers are the most widely used from the family of coiled heat exchangers. This is due to their compact design, ease of manufacture and enhanced heat transfer efficiency. The purpose of this review is to summarise and critically review the published studies on the heat transfer characteristics of two-phase flow in helically coiled tubes. The first section presents the experimental and theoretical results for the boiling heat transfer characteristics reported by several authors whilst the second section focuses on the results for the heat transfer characteristics with nanofluids. Therefore, this review provides researchers in academia and industry with a practical summary of the relevant correlations for the calculation of the two-phase heat transfer coefficient. A significant scope for further research was also identified in the field of two-phase flow at non-boiling conditions and in the application nanofluids.

Contents

1. Introduction

Due to their compact design, ease of manufacture and heat transfer efficiency, helically coiled tube heat exchangers are the most common type of curved tube heat exchangers. Their use has long been established in a number of industries and processes such as in the food, nuclear and power generation industries and in heat recovery, refrigeration, space heating and air-conditioning processes. Helically coiled heat exchangers are known to yield enhanced heat transfer characteristics when compared to straight tube heat exchangers due to the secondary flow, perpendicular to the axial fluid direction, which results in an improved fluid mixing, thus reducing the thickness of the thermal boundary layer. Goering et al. [1] estimated the secondary flow to account for 16–20% of the mean fluid flow velocity. This phenomenon finds its origins in the centrifugal force due to the curvature of the coil structure and is more evident with laminar flow due to the limited fluid mixing in straight tube laminar flow [2,3]. In applications with particles suspended in the fluid, such as is the case with nanofluids, Brownian motion is also known to enhance the heat transfer

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.12.034
0017-9310/

Nomenclature

A	cross-sectional area of tube (m^2)
Bo	Boiling number (–)
c_p	specific heat (J/kg K)
$C_{1\&2}$	empirical constants (–)
CHF	critical heat flux (kW/m^2)
d	tube diameter (m)
D	helix diameter (m)
De	Dean number (–)
Di	diameter of nanoparticle (m)
E	corrugation height (m)
f	pulsation frequency (s^{-1})
F	correction factor (–)
FB	body forces (N)
FR	filling ratio (–)
F_e	enhancement factor (–)
G	mass flux (kg/m^2 s)
He	helical coil number (–)
h^*	mean heat transfer coefficient after applying enhancement techniques (Nanoparticles and helical coils) (W/m^2 K)
h_{st}	mean heat transfer coefficient inside a straight tube with base fluid only
h_{tp}	two-phase heat transfer coefficient (W/m^2 K)
i_{lg}	latent heat evaporation (J/kg)
ID	inner tube diameter (m)
k	thermal conductivity (W/m K)
K	relative heat conductivity (–)
L	heated length (m)
m	mass flux (kg/m^2)
$\dot{m}$	mass flow rate (kg/s)
M	molecular weight (mol/g)
N	Avogadro number (mol^{-1})
N_{cb}	convective boiling number (–)
Nu	Nusselt number (–)
OD	outside tube diameter (m)
p	corrugation pitch (m)
p_r	pitch ratio (–)
P	system pressure (–)
PI	performance index (–)
Pr	Prandtl number (–)
P_r	reduced pressure ($P/P_{critical}$)
$\bar{P}$	mean pressure (Pa)
ΔP^*	mean pressure drop after applying enhancement techniques (nanoparticles and helical coils) (Pa)
ΔP_{st}	mean pressure drop inside a straight tube with base fluid only (Pa)
q	heat flux (kW/m^2)
Q	heating power (kW)
r	tube radius (m)
rd	radius of nanoparticle (m)
R	helix coil radius (m)
Re	Reynolds number (–)
Re^*	modified Reynolds number (–)
S	boiling suppression factor (–)
T	temperature (°C)
VC	volume concentration as fraction (–)
VF	volumetric void fraction (–)
WC	mass concentration as fraction (–)
Wo	*Wo* number (–)
x	steam quality (–)
y	latent heat of vaporisation (J/kg)

Greek symbols

δ	curvature ratio: Internal tube radius d_i/mean coil radius D (–)
κ	Boltzmann constant (J/K)
μ	dynamic viscosity (Pa/s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ	sheer stress (N/m^2)
η	performance index (–)
φ	volume concentration (%)
ϕ	dissipation term (m^2/s^3)
χ_{tt}	Martinelli parameter for the case where the liquid and vapour phases are turbulent (–)

Subscripts

b	bulk
bf	base fluid
cb	convective boiling
eff	effective
eq	equivalent
g	gas properties
it	inner tube
l	liquid properties
lf	liquid film
m	mixture
n	*n*th
nb	nucleate boiling
nf	nanofluid
np	nanoparticle
of	outer fluid
osc	oscillatory
ot	outer tube
sat	saturation conditions
slo	superficial for total liquid flow
st	single-phase conditions
TP	two-phase conditions
tt	turbulent liquid and vapour flow
v	vapour
w	wall

characteristics [4]. A number of active and passive methods have also been applied to helically coiled tube heat exchangers to further enhance their performance. Typical passive methods are fluid additives, the variation of the coil and tube design, [5], the use of propellers, [6], fins [7] and internal springs [8]. Active methods include the application of induced pulsation [9] and pipe rotation [10]. The performance of helical coils is also a function of the geometry and design parameters such as the tube diameter and the pitch (Fig. 1). Most of these methods were designed to enhance the fluid mixing, thus improving the convective coefficient of heat transfer at the wall.

Therefore, the open literature, presents a considerable amount of studies on the single-phase flow and heat transfer characteristics in helically coiled tube heat exchangers. A lesser number of studies have investigated the two-phase flow and heat transfer characteristics in helically coiled tubes. When compared to single-phase flow, two-phase heat transfer characteristics are significantly more complex whilst being more relevant to real-life engineering systems. A number of studies investigated the flow and boiling heat transfer characteristics [11,12] whilst more recently a number of authors investigated the application of nanofluids [13,14] in helical coils. Intriguingly, there are no studies that investigated the heat transfer