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Experimental investigation of subcooled flow boiling heat transfer in helical coils

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ABSTRACT

Helical coils have been widely used in a variety of applications, such as heat recovery processes, power plants, cryogenic systems, etc, due to the practical importance of high efficiency heat transfer, compactness in structure, ease of manufacture and arrangement. Experiment investigation of heat transfer characteristics of subcooled flow boiling in helical coils with different inner diameters and coil diameters was performed in the present paper. The rise angles of these helical coils were all 6 degrees. The system pressure was in the range of 1.8 MPa and 7.8 MPa, mass flux ranged between 300 kg/(m^2·s) and 1100 kg/(m^2·s), and heat flux varied from 100 kW/m^2 to 450 kW/m^2. The experimental results showed that the onset of subcooled boiling was significantly influenced by heat flux and system pressure. A new correlation to predict the onset of subcooled boiling was proposed, correlating experimental results within ± 20%. The effects of heat flux, mass flux and system pressure on heat transfer behavior in subcooled boiling region were discussed. A new correlation of subcooled boiling heat transfer coefficient in helical coils was developed, correlating experimental results within ± 20%.

1. Introduction

Helical Coils have received considerable attention in recent researches for their high-efficiency heat transfer and the attractive issues are mainly about secondary flow, heat and mass transfer enhancement and unique pressure drop characteristics due to the curvature of tubes (Naphon and Wongwises, 2006; Fsadni et al. 2016). In the meantime, helically coiled tubes are widely used in many engineering applications. Due to compactness in structure, helical coiled heat exchanger become an admirable option for aircrafts and submarines (Chen et al., 2011). In nuclear industries, helical coils are introduced into Once Through Steam Generators (OTSGs) for electricity production (Carelli et al., 2004; Chung et al., 2013). Moreover, helical coils play a favorable role in air conditioning and refrigeration systems, chemical reactors, membrane separation process and so on (Vashisth et al., 2008).

As a transition from single-phase convection to saturated boiling, subcooled boiling involves both of the forced convection and phase change. What's more, there exists severe natural convection near the position where boiling takes place. Due to these factors, the flow and heat transfer characteristics of subcooled boiling become more sophisticated. In the past years, extensive research work about the characteristic of subcooled boiling in straight circular and straight annular tube has been performed.

Bergles and Rohsenow (1964) undertook experiments in a circular straight tube where system pressure ranged from 0.1 to 13.6 MPa and a correlation to predict the onset of subcooled boiling was proposed. Celata et al. (1997) studied the onset of subcooled boiling in a horizon straight tube and found that the onset was significantly affected by flow flux and barely affected by pressure. Liu et al. (2005) presented the visualization of microchannel flow and results showed that heat flux of the onset has positive correlations with both flow flux and sub-cooling degree. In an annual narrow channel, experiments using water at low pressure and flow flux were carried out by Ahmadi et al. (2009), and they found heat flux was mainly affected by flow flux, sub-cooling degree and system pressure. Boyd and Meng (1992) studied subcooled flow boiling in circular tubes with uniform heat flux. Their results obtained under high flux conditions were in good agreement of the correlation suggested by Petukhov (1970). Sato and Matsumura (1964) made an analytical consideration on predicting the heat flux of subcooled boiling with forced convection and compared results with data of previous investigators. They concluded that the analytical results compared favorably with experimental ones at high pressure, however, there existed a deviation between those two referred above when liquid temperature was close to saturated temperature.

Though numerous researches on subcooled boiling have been done in previous decades, there are few studies on subcooled flow boiling through helical coils. Cioncolini et al. (2008) studied the heat transfer characteristics of both saturated and subcooled boiling in helical tubes.

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Nomenclature

A_s	inner surficial area of test section, m^2
Bo	boiling number, dimensionless, $Bo = q/(G{\cdot}h_{fg})$
c_p	constant pressure specific heat, J/(kg·°C)
d	inner diameter, m
G	mass flux, $kg/(m^2{\cdot}s)$
h'	enthalpy of saturated fluid, J/kg
h_f	enthalpy of local fluid, J/kg
h_{fg}	latent heat, J/kg
h_{in}	enthalpy of inlet fluid, J/kg
I	current, A
Ja	Jacob number, dimensionless, $Ja = (c_p{\cdot}\Delta T_{sub})/h_{fg}$
k	thermal conductivity, W/(m·°C)
L	flow length, m
L_h	length of test section, m
Nu	Nusselt number, dimensionless
P	system pressure, MPa
Pr	Prandtl number, dimensionless, $Pr = \mu{\cdot}c_p/k$
q	heat flux, kW/m^2
Q	total heating power, kW
Q_{loss}	heat loss, kW
Re	Reynolds number, dimensionless
T_{bulk}	bulk temperature, °C
T_{in}	temperature of inlet fluid, °C
T_{out}	temperature of outlet fluid, °C
T_{sat}	saturation temperature, °C
T_w	inner wall temperature, °C
T_{wall_ave}	average inner wall temperature, °C
U	voltage, V
x	quality
Δh	total enthalpy rise of test section, J/kg
ΔT_{sat}	wall superheat, °C
ΔT_{sub}	subcooling, °C

Greek symbols

μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

e	experimental
f	liquid
g	gas
in	inlet
tp	two-phase

Acronyms

HTC	heat transfer coefficient, $W/(m^2{\cdot}°C)$
ONB	onset of nucleate boiling
OTSGs	once through steam generators

System pressure ranged from 120 to 660 kPa, flow flux varied from 290 to 690 $kg/m^{-2}s^{-1}$, heat fluxes were in the range of 50–440 kW/m^2. They found former correlations didn't fit well with current experimental results of subcooled boiling, due to the excess of range of validity for those correlations. Kong et al. (2017) carried out experiments in vertical helical coils using R134a to study the phenomenon of subcooled boiling. They indicated that the heat transfer coefficients increased with the increase of pressure and decreased when reducing incipient sub-cooling degree. Moreover, they correlated the database and proposed an empirical correlation for subcooled boiling in helical coils.

An overview of the previous study indicates that existing works mainly focus on heat transfer characteristics of subcooled boiling in straight circular or annular channels. Due to the centrifugal force, heat transfer of subcooled boiling in helical coils is more complicated, however, less investigations have been conducted over the years, compared to straight tubes. Hence, there is a need to furtherly study the subcooled boiling in helical coils, which is beneficial for the heat transfer enhancement in heat exchangers. Especially in the nuclear engineering field, the understanding of subcooled boiling heat transfer behavior in helically coiled tubes is quite essential for the performance improvement of OTSGs.

The purpose of this paper is to know about the phenomenon of subcooled boiling in helical coils and predict the onset of subcooled boiling. The effects of heat flux, mass flux and system pressure on onset of subcooled boiling and heat transfer behavior in subcooled boiling region were discussed. This work provides certain references to design of OSTGs.

2. Experimental apparatus and test section

Fig. 1 shows the facility SWAMUP-II located at Shanghai Jiao Tong University, which is designed to conduct heat transfer tests with a supercritical water or steam-water two phase flow. Distilled and deionized water from the water tank is driven through a filter by two high pressure plunger-type pumps with an operating pressure up to 35 MPa. The main flow goes through the re-heater to absorb the heat of the hot fluid coming from the test section, then it is heated up to the target temperature by the pre-heater and enters into the test section. It exits the test section with a high temperature up to 550 °C. The pre-heater is directly heated by AC power with a maximum heating capability of 600 kW while the test section is heated by DC power with a maximum heating capacity of 900 kW. Another flow goes through the bypass branch to the mixing chamber. Water exiting the test section is cooled down by the re-heater and mixes with water from the bypass branch before entering into the heat exchanger. After receiving sufficient cooling in the heat exchanger, water returns back to the storage tank. Two Venturi flow meters with different ranges are installed in parallel in the main flow loop for mass flow rate measurement of water flowing into the test section. Inlet pressure of the test section is controlled by adjusting the pressure regulator valve at the exit of the main loop. Fluid temperatures at the inlet and outlet of the test section are measured by two ungrounded N-type thermocouples with sheath outer diameter of 0.5 mm. All data are collected and recorded by a National Instrument data acquisition system. All of the tests are undertaken under conditions shown in Table 1.

The test section is shown in Fig. 2. Due to high temperature tolerance, good corrosion resistance and excellent processing properties, 0Cr18Ni9 stainless steel is selected as the material of helical coils used in tests. Fsadni et al. (2016) and Gou et al. (2017) provided a review of flow heat transfer in helical coils. In view of the ranges of geometry parameters adopted in past researches, different ones are applied to the helical coils in this study. Specific geometry parameters are tabulated in Table 2. The resistance of tube wall is uniformly distributed to heat the working fluid with a maximum power of 900 kW .The outer wall of the test section was thermally insulated and a slight heat loss were considered into data reduction. Thermocouples are arranged uniformly along the tube to measure the outer wall temperature and the distance between adjacent temperature measurement sections of all three helical coils is 300 mm. Four N-type thermocouples are installed evenly around the circumference, at 0°, 90°, 180°, 270°, on each temperature measurement section. The arrangement and installation positions are shown