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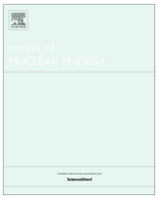

Experimental investigation of boiling heat transfer in helically coiled tubes at high pressure

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ABSTRACT

Helically coiled once-through steam generators have been used widely during the past several decades for small nuclear power reactors. The boiling heat transfer characteristics of helically coiled tubes are important to optimal design of helically coiled steam generators. In the present work, various experiments with helically coiled tubes are performed to investigate the boiling heat transfer characteristics at high pressure with water as the working medium. Six test sections are made of thin walled stainless steel tubes having inner diameters of 12.5 mm and 14.5 mm. The system pressure is varying from 2 to 8 MP. The effects of heat flux, mass flux and system pressure on boiling heat transfer behavior are discussed in detail. Increase in heat flux increases the subcooled boiling and saturated nucleate boiling heat transfer coefficient. However, heat flux has no influence on saturated convective boiling heat transfer coefficient. Mass flux increases the saturated convective boiling heat transfer coefficient. Increase in system pressure increases the subcooled boiling and saturated nucleate boiling heat transfer coefficient but decreases the saturated convective boiling heat transfer coefficient. For the investigated experimental conditions, the results show that the Baburajan's correlation gives the best prediction in subcooled boiling region and the Gungor and Winterton's correlation predicts well with the experimental data in saturated boiling region. For the investigated experimental conditions, the results also indicate that the helically coiled tubes have similar performance of heat transfer in boiling regions compared with straight tubes.

1. Introduction

A wide variety of industries use coiled tube heat exchangers for the heating and cooling of liquids and gases. In particular, helically coiled once-through steam generators have been used widely during the past several decades in nuclear Industry, especially in small modular-type nuclear reactors (Chung et al., 2012; Hwang et al., 2014). The main advantages of a helically coiled heat exchangers as compared to straight tube heat exchangers are an inherently high efficiency heat transfer, a more compact heat exchanger, and freedom from thermal deformation (Aria et al., 2012; Chen et al., 2011; Kumar et al., 2006; Santini et al., 2008; Styrikovich et al., 1984; Zhao et al., 2003). The formation of a secondary flow is one of the most important differences in the flow in a coiled tube compared to that in a straight tube. Due to the centrifugal force, which occurs because of the coil geometry, exerted upon the fluid, vortices arise in helically coiled tubes. These vortices format a secondary flow, which has been found to exist in both single and two-phase flows. These phenomena enhance the flow heat transfer in helical coils. Enhancement ratio as high as 1.37 and 2.15 has been reported for flow boiling in helical coils by Wongwises and Polsongkram (2006) and Akhavan-Behabadi et al. (2009), Aria et al. (2012) for vertical and horizontal helical coils respectively. The boiling heat transfer characteristics are important to the optimal design of helically coiled steam generators, and many studies have been conducted to investigate the heat transfer characteristics.

Owhadi et al. (1968) were the first to investigate the flow boiling heat transfer characteristics in helically coiled tubes via experiment. Investigation on forced boiling heat transfer at atmospheric pressure for a tube diameter of 12.5 mm, and ratio of tube to coil of 0.05 and 0.024 was performed. Their results showed that the correlation presented by Chen (1966), which is widely used to predict the flow boiling characteristics in straight tubes, could be used to predict the heat transfer characteristics in helically coiled tubes with sufficient accuracy.

Nariai et al. (1982) conducted an experimental study on thermal-hydraulic characteristics inside the coiled tubes in a once-through steam generator, where the helically coiled tube was heated with liquid water. The system pressure of the

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Nomenclature

C_p	specific heat at constant pressure (J/kg K)
d	diameter of tube (m)
D_h	helical diameter (m)
g	gravitational acceleration (m/s^2), gas
G	Mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K), enthalpy (kJ/kg)
k	thermal conductivity (W/m K)
L	length m
P	pressure (Pa)
q	heat flux (kW/m^2)
T	temperature (°C)
x	quality of steam
X_{tt}	Lockhart Martinelli parameter

Greek symbols

ρ	density (kg/m^3)
μ	viscosity (Pa s)
σ	surface tension (N/m)
θ	helical angle (°)

Abbreviation

Avg	average
HTC	heat transfer coefficient
RMS	root mean square

Dimensionless number

Bo	boiling number q/Gh_{fg}
Ja	Jakob number $Ja = c_p \cdot \Delta T_{sc}/h_{fg}$
Nu	Nusselt number $Nu = h \cdot D/k$
Pr	Prandtl number $Pr = \mu c_p/k$
Re	Reynolds number $Re = G \cdot D/\mu$

Subscripts

cal	calculation
cr	critical
DB	Dittus-Boelter
Do	dryout
exp	experiment
l	liquid
lo	liquid only
pool	pool boiling
sat	saturated
sc	subcooled
v	gas
tp	two phase

secondary side was 2, 3, or 5 MPa. Their results showed that the effect of D_h on the average h was small, and the Schrock–Grossman correlation, which is for straight tubes, could also be applied to the coiled tube at $P < 3.5$ MPa.

Zhao et al. (2003) conducted an experimental study on flow boiling in water inside a horizontal coiled tube and proposed a new Martinelli type convective boiling heat transfer correlation, which includes a term of boiling number to account the effect of saturated nucleate boiling mechanism. The system pressure was 0.5–3.5 MPa. Flow boiling heat transfer was affected by G and q.

Hwang et al. (2014) and Chung et al. (2014) conducted an experimental study on flow boiling in water inside vertical coiled tubes at system pressure of 1–6 MP and with regions of steam quality lower than 0.1. Their investigations are the few studies at a system pressure in excess of 3.5 MPa. Their results showed that the pressure effect was important for the boiling heat transfer, and the helical angle or coil diameter effect was relatively small. They reported a good agreement of their experimental results with the Steiner and Taborek correlation (Steiner and Taborek, 1992) for the whole test range.

The purpose of the present investigations is to understand flow boiling phenomena in helically-coiled tubes and to predict the heat transfer coefficient over range of system pressure at which flow boiling experiments have not been studied in detail previously. Pressure significantly affects the latent heat of vaporization of water and the density of vapor, which can influence flow boiling. Few studies have investigated the flow boiling heat transfer in helically coiled tubes using water and steam at a system pressure in excess of 3.5 MPa. In the present work, various experiments with the helically coiled tubes are performed to investigate the boiling heat transfer characteristics at system pressure of 2–8 MP. The effects of heat flux, mass flux and system pressure on subcooled and saturated boiling heat transfer behavior are discussed in detail. Comparison of local heat transfer coefficients with the existing correlations is carried out to identify an appropriate correlation which performs well in subcooled boiling regions and saturated regions for water in helically coiled tubes at high system pressure.

2. Experimental apparatus and test section

Fig. 1 shows a schematic diagram of the test facility SWAMUP-II at Shanghai Jiao Tong University, which is designed to perform heat transfer tests with a supercritical water or steam-water two phase flow. The design pressure of the SWAMUP-II is 35 MPa. Distilled and deionized water from the water tank is driven through a filter by two high pressure plunger-type pumps. The main flow goes through the re-heater to absorb the heat of the hot fluid coming from the test section. It passes the pre-heater where it is heated up to a pre-defined temperature and enters into the test section. It exits the test section with a high temperature up to 550 °C. The pre-heater 1 is directly heated by AC power with a maximum heating capability of 600 kW. The pre-heater 2, which power is accurately measured, is directly heated by AC power with a maximum heating capability of 200 kW. The outer wall of the pre-heater 2 is well insulated thermally from the atmosphere, and the heat loss to the environment was accurately calibrated. Thus, as long as the inlet of the pre-heat 2 is subcooled, the inlet enthalpy of test section can be obtained accurately even under boiling condition. The test section is heated by DC power with a maximum heating capacity of 900 kW. Another flow is led through the bypass line to the mixing chamber. The water temperature is reduced after relieving heat in the reheater and mixing with the low temperature fluid from the bypass line before it enters into the heat exchanger. Water exiting the heat exchanger goes back to the water tank. Two Venturi flow meters with different ranges are installed in parallel in the main flow loop to measure the mass flow rate of water entering the test section. The pressure at the inlet of the test section is controlled by adjusting the pressure regulator valve at the exit of the main loop. The pressure at the inlet of the test section is measured by a capacitance-type pressure trans-