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Research Paper

Experimental study of two-phase frictional pressure drop of steam-water in helically coiled tubes with small coil diameters at high pressure

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HIGHLIGHTS

- Frictional pressure drops in helical coils with small coil diameters are investigated.
- The frictional pressure drop multiplier is insensitive to the curvature ratio.
- Impact of heat flux on the flow boiling frictional pressure drop is not significant.
- Correlations for single and two-phase frictional pressure drops in helical coils are proposed.

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ABSTRACT

The pressure drop characteristics of helical coils are important to the design optimization of helically coiled steam generators. Single-phase and two-phase flow pressure drop characteristics have been experimentally investigated in coiled tubes of inner diameters of 12.5 mm and 14.5 mm. The helical diameters of the helical coils are 180, 280 and 380 mm and the system pressure range from 2 to 8 MPa. The effects of flow and geometry parameters on two-phase frictional pressure drop multiplier are discussed. For flow parameters, the two-phase frictional pressure drop multiplier decreases with higher system pressure and is insensitive to mass flux and heat flux. For geometric parameters, the two-phase frictional pressure drop multiplier is insensitive to the curvature ratio under the investigated conditions. Comparison with correlations reported in the literature is performed. A single-phase friction factor correlation and a two-phase frictional pressure drop multiplier correlation for helical coils with small coil diameters at high pressure are proposed and give good agreements with the experimental data.

1. Introduction

Coiled tube heat exchangers were used in a wide variety of industries. In particular, helically coiled once-through steam generators have been used widely during the past several decades in the nuclear industry, especially in small modular reactors. The main advantages of helically coiled heat exchangers as compared with straight tube heat exchangers are heat transfer efficiency [1–7], compact design [8–10], and ease of manufacture [7,11]. In helical coils, the geometry induced centrifugal force exerts upon the fluid, and vortices arise. The vortices format a secondary flow, which is one of the most important differences between the flow in coiled tubes and that in straight tubes. The secondary flow has been found to exist in both single and two-phase flows, which enhances the heat transfer in helical coils. Enhancement ratio as high as 1.37 has been reported for flow boiling in helical coils by Wongwises and Polsongkram [12] for vertical helical coils.

The pressure drop characteristics of helical coils are important to the design optimization of helically coiled steam generators. Many researchers have conducted experimental studies for a wide range of system parameters and a number of correlations for the frictional pressure drop in helical coils are reported in the literature [11,13]. Fsadni et al. conducted a review of the two-phase pressure drop characteristics and correlations. He concluded that the curvature ratio does not appear to have a significant influence on the two-phase frictional pressure drop multiplier whilst there is some controversy surrounding the influence of the coil orientation and heat flux [11].

For the range of experimental parameters of the correlations for two-phase frictional pressure drop of steam-water in helically coiled tubes, most correlations, such as Owhadi et al. [14], Kozeki et al. [15], Nariai et al. [16], Guo et al. [17] and Hardik et al. [18], are developed for low system pressure ($P < 3.5$ MPa). For the

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Nomenclature

c_p	specific heat at constant pressure (J/kg K)
D	diameter of tube (m)
D_c	Dean number (m)
f	friction factor
f'	fanning friction factor
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 (MPa)
q	heat flux (kW/m^2)
T	temperature (°C)
v	specific volume (m^3/kg)
x	equilibrium quality of fluid

Greek symbols

α	void fraction
δ	curvature ratio $\delta = D/D_e$
ρ	density (kg/m^3)
μ	viscosity (Pa s)
σ	surface tension (N/m)
θ	helix angle (○)
ψ	equation coefficient
Φ^2	two-phase frictional pressure drop multiplier

Abbreviation

Avg	average
HTC	heat transfer coefficient
RMS	Root Mean Square

Dimensionless number

D_e	Dean number $De = Re(D/D_c)^{0.5}$
Nu	Nusselt number $Nu = h{\cdot}D/k$
Pr	Prandtl number $Pr = \mu c_p/k$
Re	Reynolds number $Re = G{\cdot}D/\mu$
X_{tt}	Lockhart Martinelli parameter

Subscripts

cal	calculation
cr	critical
e	equilibrium state
exp	experiment
g	gas
l	liquid
lo	liquid-only
m	mixture
tp	two-phase
′	saturated liquid
″	saturated vapor

correlations developed for high system pressures (P > 3.5 MPa), such as Ruffell [19], Unal et al. [20], Chen and Zhou [21], Santini et al. [22], Ju et al. [23] and Colombo et al. [24], most coil diameters of their helical coils are greater than 400 mm.

As mentioned above, only few experiments have been performed to investigate the two-phase frictional pressure drop in helical coils with small coil diameters less than 400 mm at system pressure in excess of 3.5 MPa. In this study, various experiments are performed to investigate two-phase flow frictional pressure drop characteristics in helically coiled tubes with small coil diameters at high pressure. The helical diameters of the helical coils, having inner diameters of 12.5 mm and 14.5 mm, are 180, 280 and 380 mm and the system pressure range from 2 to 8 MPa. The effects of flow and geometry parameters on two-phase frictional pressure drop multiplier are discussed in detail. A single-phase friction factor correlation and a two-phase frictional pressure drop multiplier correlation for helical coils with small coil diameters at high pressure are proposed and give good agreements with the experimental data.

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 carefully insulated with rock wool, and the small thermal losses were determined by dedicated calibration experiments. The inlet enthalpy of pre-heater 2 is keeping subcooled in the tests. Thus, the inlet enthalpy of test section can be obtained accurately even under two-phase condition. 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. The 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 transducer. The pressure drop over the test section is obtained using a capacitance-type differential pressure transducer. Fluid temperatures at the inlet and the outlet of the test section are measured by two ungrounded N-type thermocouples with a sheath outer diameter of 0.5 mm. All data are collected and recorded using a National Instrument data acquisition system.

As shown in Fig. 2, the helically coiled tubes were made of stainless steel pipes having heated lengths about 8000 mm. The coil diameters of the six test sections were 180, 280 and 380 mm, and the inner diameters were 12.5 and 14.5 mm. The helically coiled tubes were vertical in the tests. Table 1 shows the dimensions of the test sections in detail. The design pressure and temperature of the test sections were 10 MPa and its saturation temperature, respectively. The outer wall of the test section was carefully insulated with rock wool, and the small thermal losses were determined by dedicated calibration experiments.

A group of differential pressure transducers was employed to measure the pressure drop of the test sections. To determine pressure drops at different qualities, the inlet quality was increased at a