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Experimental studies on local and average heat transfer characteristics in helical pipes with single phase flow

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ABSTRACT

In order to investigate the effects of centrifugal force and buoyancy on the local and average convective heat transfer characteristics of single phase, experiments were carried out on uniformly heated helical pipes. The local wall temperature is measured along the length of coil as well as in the circumferential direction using eight thermocouples at each cross section, which is made of INCONEL alloy 625 tubes with an inner diameter of 15.26 mm and a thickness of 1.8 mm. The ratio of the pipe diameter to coil diameter is 0.0436 and coil pitch is 194 mm. It is shown that the circumferentially local heat transfer coefficient vary drastically between different regions at cross section in helical coil tubes. A non-dimensional number which represents the ratio of centrifugal force and buoyancy could predict heat transfer characteristic in helical coil tubes well. It is also demonstrated that experimental data of the average Nusselt number agrees well with existing correlations. However, the local circumferential average Nusselt number is not well predicted by existing correlation.

1. Introduction

Major advantage of helical coils is providing more surface areas for a given volume (compactness). Under this circumstance, centrifugal force, that is derived as fluid flows through curved tubes, will induce a secondary flow which is essentially responsible for the increase in the heat transfer. In helical coils, the curvature of the coil governs the centrifugal force while the pitch (or helix angle) influences the torsion to which the fluid is subjected to.

The secondary flows in helical coils create different velocity whose pattern changes with the Dean number of the flow. Although single-phase heat transfer characteristics in the helically coiled tubes have been studied numerically, many researchers identified that the measurement of heat transfer coefficient was complex due to circumferential variation in the wall temperature.

The convective heat transfer in a helical pipe is comprehensively reviewed by Berger et al. (1983), Shah and Joshi (1987) and Naphon and Wongwises (2006). The constant wall temperature boundary condition is an ideal assumption in heat exchangers with phase change such as condensers, while modeling of the constant wall heat flux boundary condition (Shah and Joshi, 1987; Nandakumar and Masliyah, 1982; Prabhanjan et al., 2004) facilitates the study on separate effects of heat transfer phenomena in the tube.

Seban and Mclaughlin (1963) experimentally investigated laminar and turbulent heat transfer in helical coils with constant wall heat flux. The curvature ratios of the helical coils are 0.0096 and 0.0588. The variation of Reynolds number is 6000–65,500 and the Prandtl number ranges from 2.9 to 5.7. Ten thermocouples is placed circumferentially at only one axial location. The correlation error may come from the assumption of constant fluid properties when processing the data.

Similar to Seban and Mclaughlin (1963), variation of physical properties with temperature changes were not taken into account in the work of Mori and Nakayama (1967). They investigated two different helical coils with curvature ratio of 0.0535 and 0.025, and wall heat flux boundary condition is applied for turbulent flow inside the tubes.

Subsequently, constant wall temperature boundary condition for the same helical coils was studied by Mori and Nakayama (1967). They observed that the heat transfer was remarkably affected by a secondary flow. The Nusselt number prediction formula used for wall heat flux boundary condition could also be used for the wall temperature boundary condition.

Dravid et al. (1971) measured the heat transfer in a helical coil with five liquids with the application of wall heat flux boundary

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Nomenclature

C_p	constant pressure specific heat, J/kg·°C
d_i	inner diameter, mm
d_o	outer diameter, mm
D	coil diameter, mm
g	gravitational acceleration, m/s^2
G	mass flux, $kg/m^2 \cdot s$
h	Heat transfer coefficient, $W/(m^2 \cdot °C)$
i_{in}	Enthalpy of inlet, kJ/kg
i_{out}	Enthalpy of outlet, kJ/kg
I	current, A
L	length, mm
Lu	Lu number, dimensionless
p	pitch, mm
P	pressure, MPa
q	power, W
q_e	input power, W
q_i	inner wall heat flux, W/m^2
q_w	outer wall heat flux, W/m^2
T	temperature, °C
T_f	bulk temperature, °C
T_w	circumferentially-averaged inner wall temperature, °C
T_{wi}	local inner wall temperature, °C
T_{wo}	local outer wall temperature, °C
U	voltage, V
V	velocity, m/s
x	quality
Z	axial location, mm

Greek symbols

θ	circumferential angle, °
φ	helix angle, °
β_b	bulk volume expansivity, 1/°C
μ	dynamic viscosity, Pa · s
ρ	density, kg/m^3
η	Efficiency
λ	thermal conductivity, W/(m·°C)

Superscripts

—	average

condition. The experimental results revealed the essential uniform of the peripheral wall temperature.

Xin and Ebadian (1997) employed air, water, ethylene glycol, and five helical pipes to investigate the effects of the Prandtl number and geometric parameters on the local and average convective heat transfer characteristics. A new set of empirical expressions for the average Nusselt number has therefore been regressed under wall heat flux boundary condition. No obvious effects of the coil pitch or torsion were observed in the scope of this examination.

Rogers and Mayhew (1964) measured average heat transfer coefficient inside a helical pipe which was heated by steam. Curvature ratios of the coils used in studies were 0.0926, 0.075 and 0.05 in the Reynolds number range of 10,000 to 100,000.

Identifying the local circumferential heat transfer coefficient is relatively difficult that plenty of authors only reported Nusselt number variation on outside and inside of the helical coil tubes. Among these, Xin and Ebadian (1997), Seban and Mclaughlin (1963), and Bofeng et al. (1999) placed more than four thermocouples at only one axial location, which is still not enough. Hardik et al. (2015) measured local wall temperature in the circumferential direction using infrared thermal imaging technique. The test sections were heated electrically by passing DC current through the tube wall maintaining the uniform heat flux condition. In particular, correlations of Nusselt number being calculated at local points for inner side, outer side and the whole surface of a helical coil were suggested, which differed the data reduction method from other researchers.

The objective of the present study is to investigate local heat transfer distribution pattern in a helical coil with wide thermal hydraulic conditions. The circumferential variation in the wall temperature distribution and heat transfer coefficient distribution are studied carefully with eight thermocouples placed at different circumferential locations for a given axial location.

2. Experimental setup

The experimental facility is an open loop flow system with deionized water serving as working fluid, which is heated by preheater before flowing into the test section (shown as Fig. 1). The piston pump with a mass flow rate range from 0 to 10 m^3/h is driven by a D.C. motor. Venturi flowmeter, N-type thermocouples, and pressure gages are used to measure the mass flow rate of water, the inlet and the outlet fluid bulk temperatures and pressure respectively. The helical coil tube is heated electrically by passing DC current through the tube wall so that the boundary condition of a uniform heat flux could reasonably be assumed for the current test.

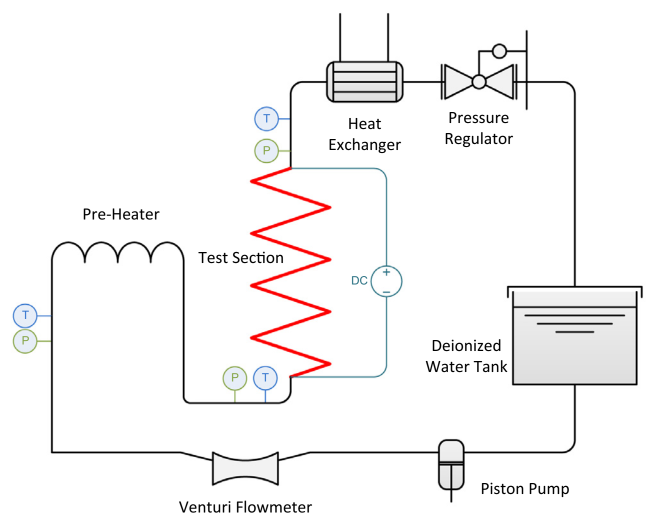

Fig. 1. Schematic diagram of the experimental facility.

During the experiments, eight thermocouples were cemented in each cross section to measure the peripheral temperature distributions. Starting from the entrance of the coil, 15 cross sections along the heated length are equipped with thermocouples circumferentially. 5 differential pressure transducers were employed to measure the pressure drop of test section. All the instruments were monitored with NI PXI Data Acquisition system which is in turn connected to a personal computer.

After the thermocouples were placed, the test section was wrapped and insulated with fiberglass insulation material. Prior to testing, the thermocouples on the insulated test section were calibrated again in situ at three saturated temperatures. This re-calibration was accomplished by passing saturated water which is heated by pre-heater through the test section without electric heating.