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# Non-uniform wall temperature distribution of nucleate boiling heat transfer in helically coiled tubes

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## ABSTRACT

Numerical simulation is carried out for nucleate boiling heat transfer of a helically coiled tube. The boiling heat transfer characteristics and the non-uniform wall temperature distribution are in basically consistent with existing experimental data. The influences of operating conditions and shapes on wall temperature are discussed in detail. The results show that the liquid gathers at the outside and the bottom of the cross section during nucleate boiling heat transfer, resulting in a lower wall temperature in these locations. However, the movement of the vapor phase to the top and the inside walls results in higher local wall temperatures. The maximum temperature difference throughout the cross section is approximately 10 K. Furthermore, the distribution of vapor volume fraction becomes uniform as the secondary flow enhances. Due to the vapor–liquid phase distribution, the wall temperature of the cross section shows a sharp rise before decreasing. Under different experimental conditions, the position of the maximum wall temperature changes from 90° to 180° and the maximum deviation is more than 60°.

## 1. Introduction

Helically coiled tubes are used as the heat exchange element in integrated reactors and the fourth generation reactors due to their compact structure and ease of manufacture (Lin et al., 2013; Hwang et al., 2014; Majumdar et al., 2008). The cross section thermal characteristics usually exhibit a non-uniform property due to the influences of the secondary flow and the centrifugal force on the fluid flow in the tube, which are more obvious in the boiling heat transfer process (Shi et al., 2017). The additional stress and vibration brought on by this non-uniform distribution of the thermal characteristics can affect the safety and reliability of helically coiled bundles. Thus, numerous scholars have conducted both physical experiments and numerical simulations to study boiling heat transfer in helically coiled tubes.

Jayanti and Berthoud (1990) studied the boiling and dryout in vertical helically coiled tubes, and found that the distribution of the vapor–liquid phase in the tube was associated with the heating area, the heat flux density, and the position in the cross section. The quality in the cross section was generally high at the inside and the top of the tube, and low at the outside and the bottom (shown in Fig. 1(a)). Guo et al. (2002) analyzed the heat transfer characteristics of single-phase and boiling in a helically coiled tube under pressure drop oscillations. They found that whether the heat transfer coefficients at the top and the bottom were symmetric or asymmetric was influenced by single-phase flow and vapor–liquid phase flow. Murai et al. (2005) used backlight-imaging tomography to study the flow of air and water in a vertical helically coiled tube and found that the air mainly distributes at the inside and the top of the cross section. As the flow velocity increased, the space occupied by air moved from the top of the cross section to the inside. Chen et al. (2011) studied boiling and dryout of R134a in a horizontal helically coiled tube, and found that for the four thermocouples arranged in the same cross section, the temperatures of the thermocouples at 0° and 180° were obviously higher than the temperatures at 90° and 270° (shown in Fig. 1(a)). Moreover, the temperatures decreased more slowly when power was removed from the system. They also found this phenomenon occurred when they studied the effect on dryout of the shape characteristics and the inlet and outlet of helically coiled tubes (Chen et al., 2010). Chung et al. (2014) analyzed boiling and dryout under different pressure conditions in vertical helically coiled tubes. Their results showed that the outer wall temperature of the cross section with a quality of 0.03 was 10 °C higher at 180° than that at 0°, while it was 15 °C higher at 180° than that at 0° with a quality of 0.74.

With the development of computational fluid models and their

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**Nomenclature**

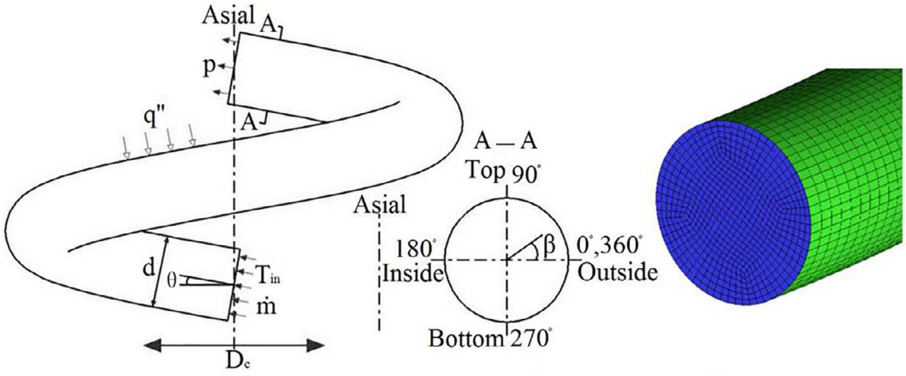
| | |
|---|---|
| $A$ | surface, [m$^2$] |
| $a$ | diffusivity, [m$^2$·s$^{-1}$] |
| $d$ | diameter of coiled tube, [m] |
| $D_c$ | circle diameter of coil, [m] |
| $D_w$ | bubble departure diameter, [m] |
| $D_b$ | bubble diameter, [m] |
| $F$ | interfacial force, [N] |
| $f$ | frequency, [s$^{-1}$] |
| $g$ | gravity acceleration, [m·s$^{-2}$] |
| $h$ | heat-transfer coefficient, [kW·m$^{-2}$·K$^{-1}$] |
| $i$ | enthalpy, [kJ·kg$^{-1}$] |
| $L$ | length of coiled tube, [m] |
| $\dot{m}$ | mass flow rate, [kg·s$^{-1}$] |
| $Nu$ | Nusselt number |
| $p$ | pressure, [Pa] |
| $Pr$ | Prandtl number |
| $\dot{q}$ | heat flux, [kW·m$^{-2}$] |
| $Q$ | heat transfer per unit volume, [W·m$^{-3}$] |
| $r$ | latent heat, [kJ·kg$^{-1}$] |
| $Re$ | Reynolds number |
| $T$ | temperature, [K] |
| $U$ | velocity, [ m·s$^{-1}$] |
| $V$ | volume, [m$^3$] |
| $x$ | quality |

*Greek symbols*

| | |
|---|---|
| $\theta$ | helical angle, [°] |
| $\beta$ | degree, [°] |
| $\alpha$ | volume void fraction |
| $\rho$ | density, [kg·m$^{-3}$] |
| $\tau$ | time, [s] |
| $\mu$ | viscosity, [Pa·s] |
| $\lambda$ | thermal conductivity, [W·m$^{-1}$·K$^{-1}$] |
| $\delta$ | curvature, $d/D_c$ |
| $\Delta T$ | temperature difference, [K] |

*Subscripts*

| | |
|---|---|
| $l$ | liquid |
| $lv$ | from phase l to phase v |
| $sat$ | saturation |
| $v$ | vapor |
| $vl$ | from phase v to phase l |
| $w$ | wall |



(a) Schematic of a helically coiled tube                (b) gird model

**Fig. 1.** Schematic representation and grid model of a helically coiled tube with its main geometric parameters.

corresponding accuracy, more and more researchers are studying fluid flow and heat transfer in helically coiled tubes with the help of computational fluid dynamics (CFD). Jo and Jhung (2008) took the integrated pressurized water reactor of a SMART steam generator as a prototype and used the solver CFX to study the vibration induced by the flow and boiling in the steam generator. Piazza and Ciofalo (2010) applied CFX to research the turbulent flow and heat transfer in curved tubes, and found that the simulated results of the pressure drop and the heat transfer coefficient for the SST-ω and the RSM-ω models were in agreement with experimental data. Ferng et al. (2011) simulated the effects of Dean Number and pitch size on the heat transfer characteristics of single-phase flow in a helically coiled tube heat transfer. Vashisth and Nigam (2009) conducted a simulation study of the distribution and pressure drop of water and air in a helically coiled tube. The results showed that the secondary flow and phase separation existed, and the friction factor of the outside of the cross section was double more than that of the friction factor of the inside. Yang et al. (2008) used a volume of fluid (VOF) model to investigate the distribution of the vapor–liquid phase on two-phase flow during boiling heat transfer in a horizontal coiled tube. They found that the high wall temperature region corresponded to the vapor region, and that the distributions of wall temperature and phases were in good agreement. Finally, Ciofalo et al. (2015) conducted an investigation simulating the laminar flow and heat transfer in a helically coiled tube using Fluent. The results showed that the secondary flow in a helically coiled tube could weaken the boundary layer.

The mist flow regime in the straight pipe was simulated by a discrete phase model based on the Eulerian-Lagrangian method. And the wall temperature and the heat transfer coefficient under both thermal equilibrium and non-thermal equilibrium conditions were predicted (Torfeh and Kouhikamali, 2015). Annular flow with evaporating liquid film was simulated by the Eulerian-Lagrangian method. The mass, momentum and energy transfers between the liquid film, gas, and entrained droplets have been taken into account in this method. And the dryout occurrence was predicted by the critical thickness or critical velocity of the liquid film (Li and Anglart, 2015). The pressure drop and convective heat transfer behavior of water and water–silver nano-fluid in the helically coiled tubes were simulated based on the Eulerian-Lagrangian method in connection with an RNG k–ε turbulence model (Bahremand et al., 2015). At present, the whole information of the particles is obtained by the Eulerian–Eulerian method which is used for the wide range of volume fraction. And the computational resources are