Forced convection boiling heat transfer inside helically-coiled heat exchanger

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Abstract. For decades, forced convection boiling heat transfer has been considered as one of the most efficient type in the heat transfer mechanism. It has been widely utilized in heat transfer equipment of various industries. Meanwhile, helically-coiled heat exchanger has been commonly utilized in numerous industrial applications. Thus, there is an interest to utilize forced convection boiling heat transfer in helically-coiled heat exchanger. Boiling phenomenon inside helically-coiled tube is more complex as compared to the straight tube due to the secondary flow induced by centrifugal force. This study investigates flow boiling heat transfer performance of water-vapor inside helically-coiled tube by using computational fluid dynamic approach. A Eulerian-Eulerian two-fluid model is used to capture interphase exchange forces and heat transfer between liquid and vapor phase. Wall boiling model is adopted to take into account the boiling condition in the vicinity of the wall. The developed model is then validated against the previously published experimental data. Good agreement for the outlet vapor quality and pressure drop between numerical study and experimental measured value is achieved. The result reveals that the boiling starts at the inner wall of the tube ($\phi=450^\circ$) due to the presence of secondary flow induced by coil curvature. The relationship between HTC and vapor quality along the helically-coiled tube are discussed and evaluated. This study serves as a guideline for future study on forced convection boiling heat transfer in the helically-coiled tube.

1. Introduction
Helically-coiled heat exchanger is one of the heat exchangers that has been used in many engineering industries. The primary advantage of this heat exchanger as compared to other types of heat exchanger is its ability to cater high quantity of heat and mass exchange at small footprint. Furthermore, the existence of secondary flow within the helically-coiled tube that comes from coil curvature become an interesting topic to scrutinize among the global researchers [1]. The first researcher who investigated the flow movement within coiled tube is Dean [2,3]. Subsequently, an enormous amount of research on the experimental case [4] and numerical condition [5] had been studied to investigate the flow behavior inside the tube. Nowadays, most of the research in helical tubes have investigated the single-phase flow condition with only few researchers conduct the research on two-phase flow phenomenon within the coiled tube. Fsadni and Whitty [6] have indicated that there was some lack of information needed in the literature for two-phase flow condition inside coiled tube. Hence, the two-phase flow inside helically-coiled tube has become the major topic among the global researchers.
Boiling heat transfer (HT) is one of the best options in the heat transfer process. It holds an important role in the numerous industries. In boiling condition, helical tube offers more complex phenomenon as compared to the straight tube. It is due to the centrifugal force that could generate secondary flow within the helical tube. Moreover, the boiling results phase separation between the liquid and vapor which have different densities [7]. Santini et al. [8] investigated flow boiling HT in the helically coiled steam generator for nuclear industry. The outcomes displayed that the heat transfer coefficient (HTC) depends on the mass and heat flux in the HT development. The behavior of fluid (water) in the helically coiled tubes used to determine HTC and pressure drop at the local position when the boiling occurred was introduced by Hardik and Prabhu [9]. It was calculated that the boiling HTC inside helical tube is higher than the normal tube for subcooled and low-quality region, nevertheless, the boiling HTC for both tubes is equivalent when the quality is getting higher. The boiling HT peculiarity in the helically coiled tube at high pressure with water as a medium fluid was experimentally investigated by Xiao et al. [10]. The outcome shown that the pressure, heat, and mass flux have significant contribution in all boiling process. Nucleate boiling (subcooled and saturated) HTC will improve by increasing in heat flux and pressure condition. Nonetheless, the saturated convective boiling HTC will increase only by enhancing the mass flux.

Based on the explanation above, most of boiling HT investigation that has been reported in the published journal does not cover all the range of parameters to understand two-phase flow and HT performance inside helically coiled tube. This is due to the difficulty of conducting experimental study. According to the author’s best knowledge, the numerical study on the boiling HT in the helically coiled tube only carried out with several operating condition. Thus, the numerical simulation should be investigated in detail to provide in-depth substantial information about the forced convection boiling HT within helically coiled tube with broader coverage in terms of operating and geometrical conditions compared to the experimental measured value. The objective is to identify the thermal hydraulic performance of flow boiling HT in the helically coiled tube. The relationship between HTC and vapor quality along the helical tube are discussed and evaluated. This study contributes as a practical reference to design helically coiled tube in various industries.

2. Mathematical formulation

For developing the CFD model, Cioncolini’s study [11] is selected to be the design of the helically coiled tube. Figure 1 and Table 1 are the physical arrangement and geometrical and operating conditions of the developed model in this study that needs to be scrutinized.

![Figure 1](image_url)

**Figure 1.** The schematic representation of helical coiled tube: a) side view, b) cross-section of the mesh

2.1. Governing equations

In the Eulerian scheme theory, the conservation equations of mass, momentum, and energy for both phases are governed separately. Interaction between liquid and vapor phase were connected using interphase exchange models.
\[ \frac{\partial}{\partial t} \left( \alpha_q \rho_q \mathbf{v}_q \right) + \nabla \cdot (\alpha_q \rho_q \mathbf{v}_q \mathbf{v}_q) = \sum_{p=1}^{n} (\dot{m}_{pq} - \dot{m}_{qp}) + S_q \]  

Conservation Equations for Momentum

\[ \frac{\partial}{\partial t} \left( \alpha_q \rho_q h_q \right) + \nabla \cdot (\alpha_q \rho_q \mathbf{u}_q h_q) = \alpha_q \frac{\partial p_q}{\partial t} + \overline{\tau}_q \nabla \mathbf{u}_q - \nabla \cdot \mathbf{\dot{q}}_q + S_q + \sum_{p=1}^{n} (Q_{pq} + \dot{m}_{pq} H_{pq} - \dot{m}_{qp} H_{qp}) \]  

Conservation Equations for Energy

2.2 RPI model

Based on the RPI model [12], there are three main factors to determine the heat flux at the heated wall. The factors are the single-phase convection heat flux \( q_c \), the wall quenching heat flux \( q_Q \), and evaporation heat flux \( q_E \). The interphase HT is illustrated by the HT process in the adjacent wall from liquid to gas phase and in the main flow from bubbles to liquid phase. The mechanism is described with liquid evaporation and vapor condensation. The interfacial mass transfer is based on the calculation of the interfacial HT.

The interfacial momentum transfer between both phases are executed by the interphase forces. The forces is including drag, lift, wall lubrication, and turbulent dispersion forces [13–16]. The virtual mass force is not being center of attention in the present study due to the velocity of secondary phase is set at zero condition.

The study applied turbulent model which is usually common with a single-phase condition approach, nonetheless there is additional source terms that should be calculated in the secondary phase when dealing with multiphase flow. k-ε Standard model is suitable for this particular case [17] although there is some correlations that should be added for turbulence model in the secondary phase. Non-equilibrium wall-function is used in the study for estimating the boiling condition at the wall.

2.3 Constitutive relations

The equilibrium quality corresponds to the vapor flow fraction only if there is a thermodynamic equilibrium between the phases. Since the equilibrium quality is prescribed in terms of the enthalpy of the fluid, the value may be greater than one and less than zero. Under these conditions the equilibrium quality may be considered as a measure of the degree of the fluid’s subcooling or superheat but cannot be used to determine the fluid state.

2.4 Boundary conditions

The following boundary conditions (B.C.) have been proposed to solve the investigation of forced convection boiling HT in the helically coiled tube: constant velocity and temperature is prescribed at the inlet. For the outlet, we put the zero-gauge pressure and zero streamwise temperature gradient. For the heated wall, we specified the no slip condition and constant wall heat flux.
3. Numerical methodology
The series of mass, momentum, and energy equations and RPI model with the interphase exchange forces for both phases are conducted by utilizing finite volume method (ANSYS Fluent) solver. Properties of the water-liquid and water-vapor were recorded from the NIST database [18] and presented as the piecewise-linear function in the solver. Coupled algorithm has been incorporated in the model to figure out the pressure-velocity coupling. For the discretization methods, all the options except gradient is selected on First Order Upwind. Then, for gradient selection, the least squares cell based is taken from the options. The model is considered to be converged when the residuals below $10^{-4}$ and the mass flow rate imbalance reached below 1% while the outlet vapor fraction is constant in the numerical simulation.

Grid independent study was arranged to cater grid independent result by systematically enhanced the grid elements as displayed in Table 2. It is found that no substantial difference for vapor quality and pressure drop when the grid is 1234k elements and higher. Therefore, the grid will be used in the rest of the study.

Table 2. Grid independent study for present model

| Case | Outlet Pressure Drop (kPa) | Outlet Quality ($x$) | Percentage Difference (%) |
|------|---------------------------|----------------------|---------------------------|
| Experimental | 34.39 | 0.0483 | -                     |
| Simulation (450k mesh) | 34.424 | 0.0459 | 5.027%                 |
| Simulation (776k mesh) | 34.425 | 0.0459 | 5.028%                 |
| Simulation (1234k mesh) | 34.35 | 0.0458 | 5.294%                 |
| Simulation (1843k mesh) | 34.307 | 0.0457 | 5.564%                 |
| Simulation (2624k mesh) | 34.257 | 0.0456 | 5.869%                 |

4. Results and discussion

4.1 Model validation
The developed model is validated against the previously published experimental data [11]. Good agreement is accomplished between numerical simulations and experimental investigation of the outlet pressure drop with regards to the outlet vapor quality. It was found that the relative error for the outlet pressure drop and outlet vapor quality is around 5-12%. For the case 1, we found that the outlet vapor quality and outlet pressure drop are quite similar for both studies. The error value for vapor quality and pressure drop are 5.177% and 0.117% respectively on both configurations. While on the case 2, 3, and 4, the outlet vapor quality and outlet pressure drop between both studies are increasing. It is due to the numerical prediction prone to provide more extensive information as compared to the experimental study. The difference between both investigations for the outlet vapor quality and outlet pressure drop are 1.124% and 10.24% for case 2, 1.217% and 7.825% for case 3, 0.956% and 4.54% for case 4.

4.2 The variations of vapor volume fraction along the coiled tube
The outcome from the selected operating condition is conducted with a computational investigation. The contours of vapor volume fraction at specific locations along the coiled tube are shown in Figure 2. It is displayed that the beginning of the boiling is started in the inner position of the helical coiled tube ($\phi=450^\circ$). It is as a result of the development of centrifugal force caused by secondary flow and gravity [19]. The outcome is more visible at $\phi=540^\circ$ as shown in this figure.
4.3 **HTC vs vapor quality along the coiled tube**

The relationship between HTC and vapor quality along the coiled tube is displayed in Figure 3. The graph presents that the HTC is increasing at the vapor quality around -0.057-0.046. There is a significant increment of HTC when the vapor quality above zero. It is due to active nucleate spots in the wall begins to evolve which corresponds to the bubble nucleation at the tube. Hence, bubble nucleation is the predominant HT process in this region [10].

![Figure 2. Vapor volume fraction contours at different angles in the helically coiled tube](image)

![Figure 3. HTC vs vapor quality along the helically coiled tube](image)

5. **Conclusion**

Numerical simulation of boiling HT inside helically coiled tube has been conducted. A 3D CFD model has been developed for this study. The variations of vapor volume fraction along the coiled tube at different helical angle and HTC along the coiled tube have been discussed and evaluated. It was found that the boiling generated at the inner region as a result of the centrifugal force and gravity. HTC keeps improving with the vapor quality varied in a range of -0.057-0.046. This phenomenon is caused by the nucleate bubble development in the tube. Bubble nucleation is the primary HT process for this particular case. Hence, this study can provide as a guideline for future study on forced convection boiling HT in helically-coiled heat exchanger.

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