CFD study of two-phase flow pressure drop in helical tube steam generator

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1. Introduction

Helical steam generators emerged as a popular choice for many advanced reactors being developed across the globe. One of the main advantages of helical steam generators is their ability to enable in-service inspection through Eddy Current Testing (ECT) among compact heat exchangers. However, helical steam generators are known to primarily produce superheated steam by boiling inside the tube, which can cause two-phase flow instability. In light of this, the U.S. regulatory agency, the NRC, withheld final approval of the safety of helical steam generators, specifically with respect to two-phase flow instability, during their standard design approval process of an advanced reactor [1]. To reduce the instability, installation of an orifice with high resistance value at the tube inlet of helical steam generator is recommended, although this leads to an overall increment in pressure drop, there by decreasing the power plant efficiency. Therefore, it is important to find an optimized resistance value for the orifice during the design process of the steam generator, and for this purpose, it is important to accurately predict the two-phase flow pressure drop in a helical tube.

The flow in a straight tube and the flow in a helical tube significantly differ from each other due to centrifugal and torsion forces acting on the fluid induced by the geometry [2]. When a single-phase flow occurs in a helical tube, a secondary flow in the form of circular trajectory of water or steam can be observed as shown in Fig. 1. Furthermore, if two-phase flow occurs in a helical tube, water and steam are separated by the centrifugal force generated by the helical tube creating interface different from a straight tube case.

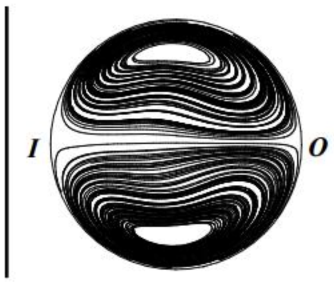

Fig. 1. Streamlines of the secondary flow in a helically-coiled tube [3]

In the past, the two-phase frictional pressure drop in helical tubes were investigated by many researchers. As a result of investigation, the modified Lockhart and Martinelli model was confirmed to have errors within 50% of the measured data [4]. This study employs computational fluid dynamics (CFD) to calculate pressure drops associated with two-phase flows in helical tubes. The analysis confirms the ability to reproduce the Martinelli-Nelson curve with CFD. Streamline post-processing is also conducted for each analysis case to provide insight into the flow patterns within the helical tube.

2. Methods and Results

2.1 Reference steam generator

In this study, a helical steam generator for SMART, developed by KAERI in South Korea, was chosen as the reference system to evaluate the pressure drop in helical tubes. The pitch, diameter, angle, and thermal hydraulic information of the helical steam generator in SMART can be obtained from publicly available references [5,6,7].

Table I: SMART Helical SG Information

Layer number	17
Helical Angle	8.5 – 8.8 °
Helical Diameter	577 – 1297 mm
Helical Pitch	280 – 600 mm
Tube Inner Diameter	12mm
Steam Outlet Temperature	290.5 °C
Steam Outlet Pressure	5.2 MPa
Mass flow rate	20.1 kg/s

2.2 CFD Analysis

For the analysis, the initial layer with a helical diameter of 577 mm and a helical pitch of 280 mm was chosen for CFD calculation. To minimize the boundary effects at the inlet and the outlet, a CFD analysis was carried out on a tube comprising three windings, and the results were used to obtain the pressure drop value for a single turn. Water and steam properties were based on saturation properties at 5.2MPa. The saturation temperature is 266.4 °C. The problem geometry is shown in Figs. 3 and 4.

The Ansys-CFX code is based on two-fluid model and calculates liquid and gas phases separately by using governing equations. The Ansys-CFX code reflects the influence of the interaction occurring at the interface between the two phases. The behavior of each phase can be simulated by solving continuity equation, momentum equation, and energy equation simultaneously [8].

1.2.1.1. The Continuity Equation

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho \boldsymbol{U})=0$$

1.2.1.2. The Momentum Equations

$$\frac{\partial(\rho \boldsymbol{U})}{\partial t}+\nabla\cdot(\rho \boldsymbol{U}\otimes\boldsymbol{U})=-\nabla p+\nabla\cdot\tau+\boldsymbol{S}_M$$

where the stress tensor, τ, is related to the strain rate by

$$\tau=\mu\left(\nabla\boldsymbol{U}+(\nabla\boldsymbol{U})^T-\frac{2}{3}\delta\nabla\cdot\boldsymbol{U}\right)$$

1.2.1.3. The Total Energy Equation

$$\frac{\partial(\rho h_{tot})}{\partial t}-\frac{\partial p}{\partial t}+\nabla\cdot(\rho \boldsymbol{U} h_{tot})=\nabla\cdot(\lambda\nabla T)+\nabla\cdot(\boldsymbol{U}\cdot\tau)+\boldsymbol{U}\cdot\boldsymbol{S}_M+\boldsymbol{S}_E$$

where h_{tot} is the total enthalpy, related to the static enthalpy $h(T,p)$ by:

$$h_{tot}=h+\frac{1}{2}\boldsymbol{U}^2$$

Fig. 2. Governing equation of CFX

A structured O-grid mesh is recognized as the optimal mesh for simulating two-phase flow in a tube [8]. Thus, to replicate the flow near the tube wall surface, an O-grid mesh with inflation option was generated in this study on the helical tube as shown in Fig. 4. Mesh information as well as selected options are summarized in Table II.

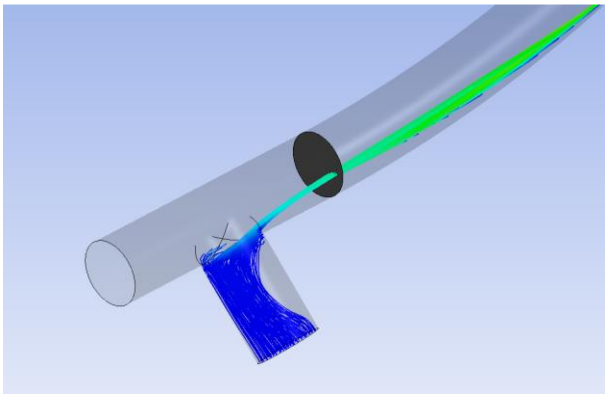

Fig. 3. Streamline of water near the inlet boundary (Mass fraction Steam 80%, Water 20%)

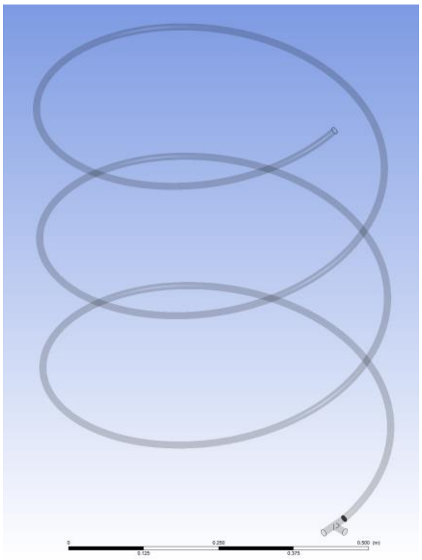

Fig. 4. 1st layer Helical tube shape for CFD analysis

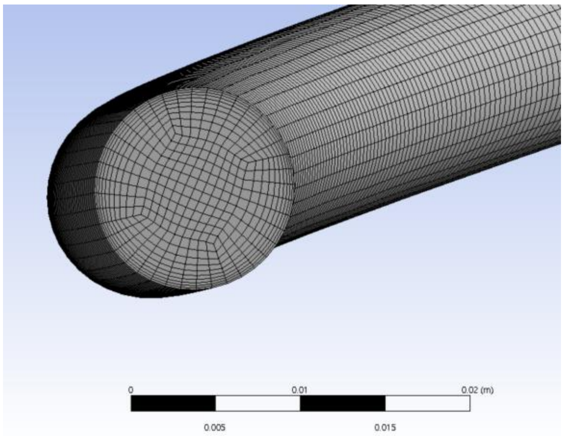

Fig. 5. Helical tube mesh for CFD analysis

Table II: Mesh information and CFD-pre Input

Mesh information	
Element Size	1e-3 m
Number of Nodes	2,898,128
Number of Elements	2,816,295
CFD-pre Input	
Analysis Type	Steady State
Inlet Boundary	Mass flow rate – 0.633 kg/s
Outlet Boundary	Average Pressure – 5.2 MPa
Turbulence Option	Shear Stress Transport
Wall function	Automatics in CFX
Heat Transfer	Isothermal
Turbulence Numerics	High Resolution

It is a well-known fact that the pressure drop in two-phase flow in a straight pipe is generally larger than that of single-phase liquid flow. In this study, it was confirmed that the pressure drop of two-phase flow in a spiral tube is higher than that of single-phase flow, which is consistent with that of a straight tube case. Moreover, it is shown that the trend observed by Martinelli-Nelson correlation can be reproduced in the CFD analysis results as shown in Fig. 6.

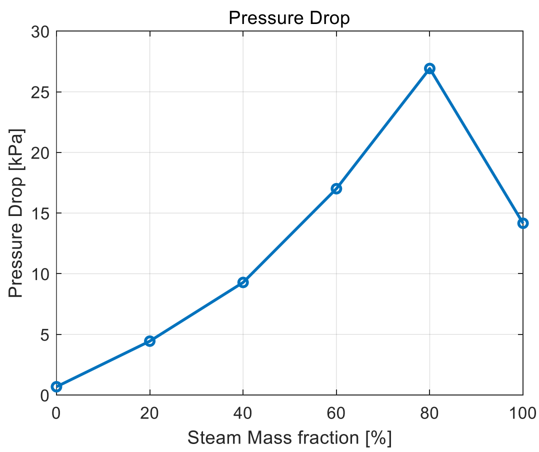

Fig. 6. Helical tube Pressure Drop by CFD calculation

Figs. 7-10 present cross-sectional views of two-phase flow CFD simulation results in a helical tube with varying steam mass fractions. These figures reveal that the shape of the spiral tube induces a centrifugal force, causing the water phase to flow downward towards the outer right side of the tube creating different interfacial shape from the straight tube case.

Figs. 11-15 show the results of streamline post-processing results as the steam fraction increases. The Streamline post-processing analysis confirms that the secondary flow appears symmetrical when steam is 100%, which is consistent with other studies. However, when water is mixed the secondary flow becomes asymmetrical.

Additionally, it was observed that the small flow actually flows in an elliptical trajectory, which was not evident in the streamline post-processing due to its relatively low volume as shown in Figure 13. When the mass fraction of vapor was increased to 80%, water and steam were found to be mixed in the outer part, resulting in a relatively high pressure drop due to the increased effect of two-phase flow.

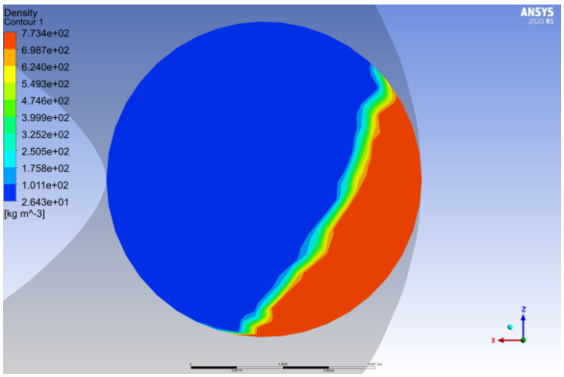

Fig. 7. Density Contour for a cross-section of a helical pipe (Mass fraction Steam 20%, Water 80%)

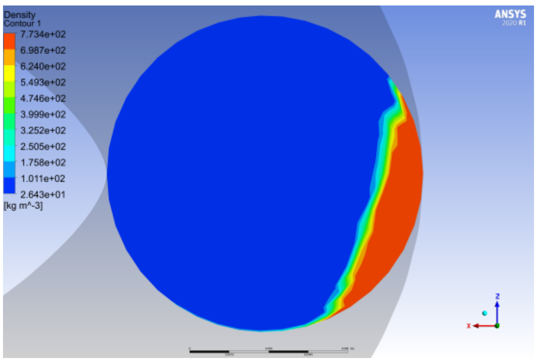

Fig. 8. Density Contour for a cross-section of a helical pipe (Mass fraction Steam 40%, Water 60%)

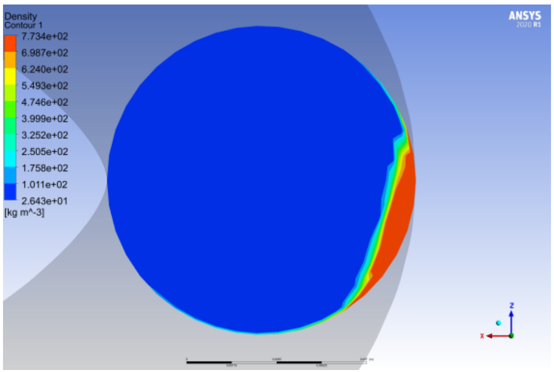

Fig. 9. Density Contour for a cross-section of a helical pipe (Mass fraction Steam 60%, Water 40%)

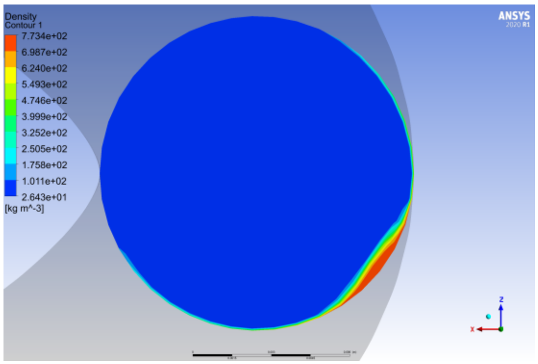

Fig. 10. Density Contour for a cross-section of a helical pipe (Mass fraction Steam 80%, Water 20%)

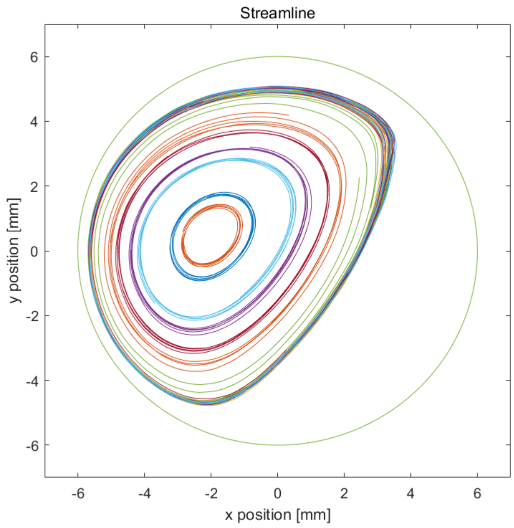

Fig. 11. Streamline (Mass fraction Steam 20%)

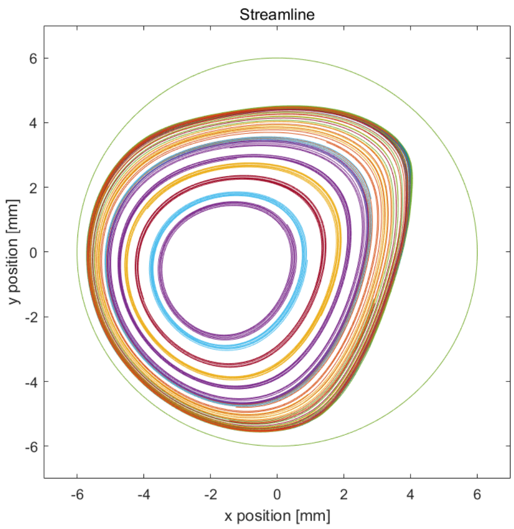

Fig. 12. Streamline (Mass fraction Steam 40%)

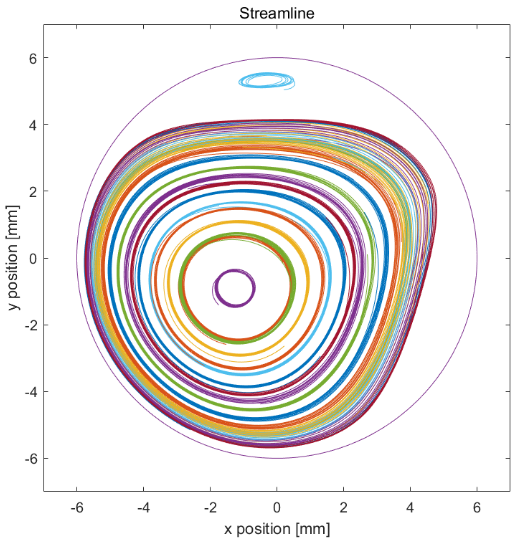

Fig. 13. Streamline (Mass fraction Steam 60%)

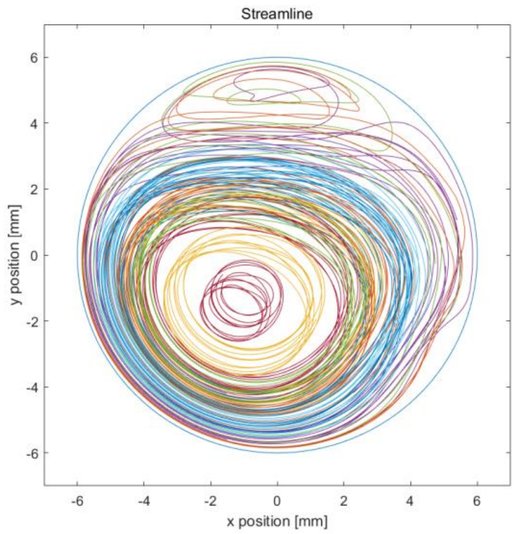

Fig. 14. Streamline (Mass fraction Steam 80%)

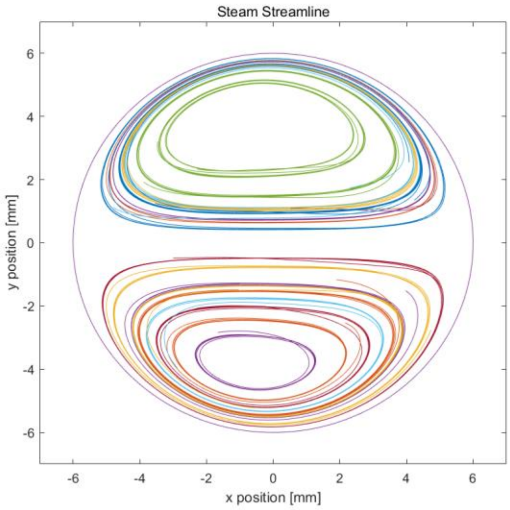

Fig. 15. Streamline (Mass fraction Steam 100%)

3. Summary and Conclusions

In summary, this study analyzed the pressure drop and flow pattern of two-phase flow in a helical tube using CFD. The results revealed that the trend of pressure drop with respect to the mass fraction of steam is similar to that of a straight pipe. By analyzing the density of the cross-section in the CFD results, the location of water and steam on each side was determined with steam and water being separated due to the centrifugal force. Post-processing of the steam streamline showed that the shape of the secondary flow was significantly distorted in two-phase flow. These results suggest that perhaps the mechanism of frictional pressure drop and wall heat transfer in the two-phase flow in a helical tube will differ from those of a straight tube due to the separation of water and steam induced by centrifugal force. Overall, these findings provide valuable insights into the behavior of two-phase flow in helical tubes, with potential implications for steam generator two-phase instabilities.

ACKNOWLEDGEMENT

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