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Comparison of steady-state and transient CFD results for two-phase flow analysis in steam generator helical tube

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1. Introduction

'Small modular reactors (SMRs)' or 'Advanced reactors' emphasize the importance of minimizing on-site construction work by reducing the overall size of the reactor system for transportability. Consequently, competitive SMRs being developed worldwide impose limitations on the size of the reactor vessels as a design condition. The steam generator serves as a key component determining the size of the reactor vessel, responsible for heat exchange between the primary and secondary sides of the reactor. Particularly, in SMRs, a helical steam generator with higher heat exchange surface density is adopted instead of conventional U-tube steam generators used in commercial large light water reactors. Both Korea's i-SMR and the USA's NuScale adopt helical steam generators.

In the case of helical steam generators, maximizing the length of the tubes within height and volume constraints is achieved through a helical shape, enabling a longer tube length compared to straight-tube heat exchangers. When using tubes of the same inner and outer diameters, increasing the length of the tubes allows for higher fluid velocities within the same volume, thus securing a higher Reynolds number on the tube side. Consequently, compared to U-tube heat exchangers or shell and tube heat exchangers using straight tubes, helical steam generators possess higher heat exchange rate per unit volume.

However, helical steam generators exhibit fluid flow characteristics differing from conventional flow within straight tubes due to the centrifugal force acting on the fluid inside the helical tubes. Typically, single-phase flow within helical tubes is known to generate secondary flows due to centrifugal forces, resulting in the fluid flow along semi-circular trajectories. Since boiling occurs within the steam generator tubes, two-phase flow is induced, leading to more complex flow patterns. As helical steam generators are made up of multiple helical tubes of different shapes, if the pressure drop and two-phase flow pattern of the helical tubes are not accurately understood, critical problems such as two-phase flow instability or uneven outlet temperature of helical tubes may occur.

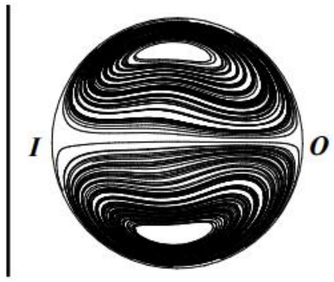

Fig. 1. Streamlines of the secondary flow in a helically-coiled tube [1]

Existing 1D system codes such as MARS-KS or RELAP5 have limitations in capturing phenomena such as centrifugal forces or secondary flows. Therefore, to accurately understand pressure drop and two-phase flow pattern within helical tubes, experiments or three-dimensional flow analysis such as Computational Fluid Dynamics (CFD) is necessary. Hence, this study analyzes two-phase flow using the commercial CFD code CFX to understand two-phase flow and pressure drop in helical tubes. In particular, a comparison between steady-state and transient state analysis was conducted to observe in two-phase flow behavior due to transient terms. Additionally, steady-state and transient state CFD analyses were performed in a straight tube for comparison.

2. Methods and Results

2.1 Steam generator data

In this study, the helical steam generator design data that are publicly available were collected to create CFD analysis input. The helical steam generator data of NuScale and SMART are summarized and shown in Tables 1 and 2 [2,3,4,5,6]. SMART's helical tube data, which is publicly available, was used to determine the angle of the helical tube.

Fig. 2. SMART Helical Steam Generator [5]

Fig. 3. NuScale Helical Steam Generator [7]

Table I: NuScale Helical SG Information

Helical Angle	13.69 °
Tube Inner Diameter	13.34 mm
Steam Outlet Temperature	287.75 °C
Steam Outlet Pressure	6.9 MPa
Mass flow rate per tube	0.0705 kg/s
Helical Tube Length	22.4 – 25.9 m

Table II: 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 CFX

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].

- $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0$
- $\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U \otimes U) = -\nabla \mathrm{p} + \nabla \cdot \tau + S_M$
- $\frac{\partial (\rho U h_{tot})}{\partial t} - \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U h_{tot}) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (U \cdot \tau) + U \cdot S_M + S_E$

2.2 CFD geometry & mesh

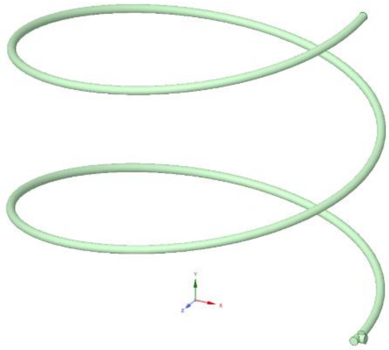

Fig. 4. Helical Tube Geometry

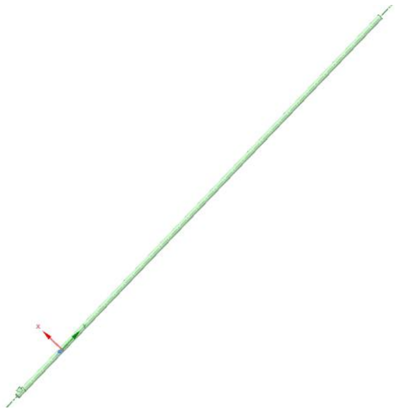

Fig. 5. Straight Tube Geometry

The helical tube geometry was modeled to have a helical diameter of 500mm, a helical angle of 8.5°, and two turns of the helical tube based on SMART's steam generator geometry information. The straight tube is 1.2 meters long, which is a portion of the whole tube. For both shapes, the inlet boundary was made in two to separate the inlet boundary of water and vapor.

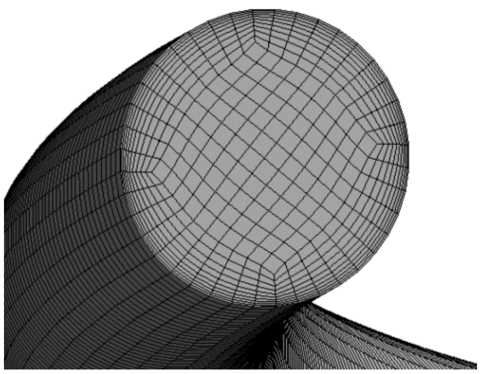

Fig. 6. Helical Tube Mesh for CFD (Outlet Boundary)

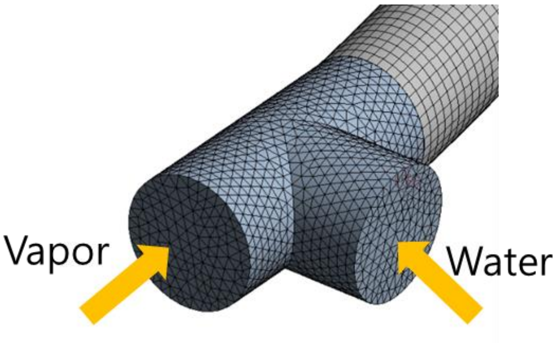

Fig. 7. Helical Tube Mesh for CFD (Inlet Boundaries)

A structured O-grid mesh is selected as the mesh system for simulating two-phase flow in tubes. To create an O-grid like mesh for the helical tube, face meshing option and multizone option were used. In addition, to replicate the flow near the tube wall surface, inflation option was used for meshing.

2.3 CFX Analysis Option

Steady-state and transient analyses were performed for both helical and straight tubes. The transient analyses were performed with timestep, 5e-5 s, and using the steady-state analysis result as the initial condition. Therefore, initially it was expected that the results of transient analyses will converge to the initial condition. Water and vapor properties were based on saturation properties at 5.2MPa. The saturation temperature is 266.4 °C. Other CFX options, including the Turbulence option, are summarized in the table below.

Table III: CFX pre-input Option

Inlet Boundary	Mass flow rate – 0.0633kg/s (Water 20%, Vapor 80%)
Outlet Boundary	Average Pressure – 5.2 MPa
Turbulence Option	Shear Stress Transport Homogenous model (Two-phase)
Buoyancy Model	Buoyant Gravity: -9.806 m/s^2 Reference Density: 26.4271 kg/m^3 (Vapor Density)
Wall Function	Automatic in CFX
Free Surface Model	Standard
Surface Tension Model	Continuum Surface Force
Interphase Transfer	Free Surface

2.4 CFX Result

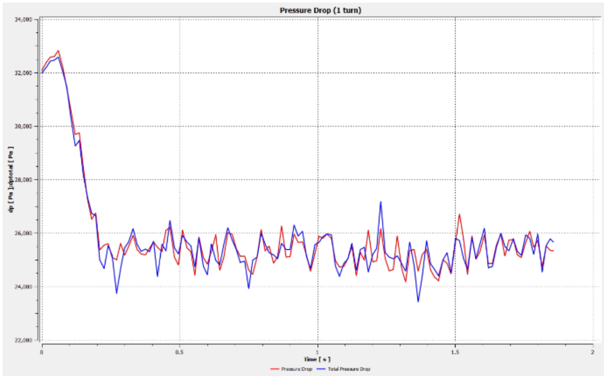

Fig. 8. CFX Transient Analysis result (Helical Tube)
- Pressure Drop for 1 turn

The transient analysis pressure drop results, which used the steady-state results as initial conditions, are shown in Figure 8. The red line shows the pressure drop for one turn of helical tube, and the blue line shows the total pressure drop for one turn of helical tube. From the analysis, it can be seen that the transient pressure drop values decrease rapidly from the steady state value. In the steady state analysis, the pressure drop value for one turn was 32,087 Pa, while the average pressure drop value was 25,334 Pa in the transient state. Compared to the steady-state results, the transient state pressure drop value is about 21% lower.

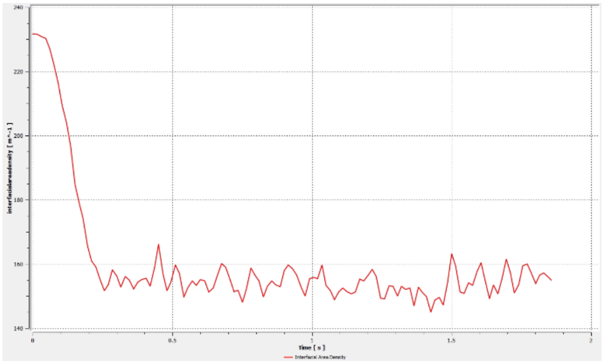

Fig. 9. CFX Transient Analysis result (Helical Tube)
- Interfacial Area Density (Volume average)

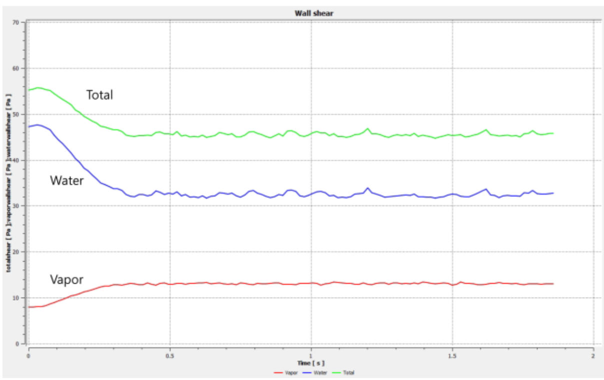

Fig. 10. CFX Transient Analysis result (Helical Tube)
- Wall Shear (Tube Surface Average) (Vapor, Water, Total)

To analyze the reason why the pressure drop converges to lower value in the transient analysis compared to the steady state result, the interfacial area density and total wall shear values were investigated. The results are shown in Figure 9 and Figure 10. The results show that both the interfacial area density and total wall shear decrease from the steady state to the transient state, which affects the two-phase flow pressure drop in the tube.

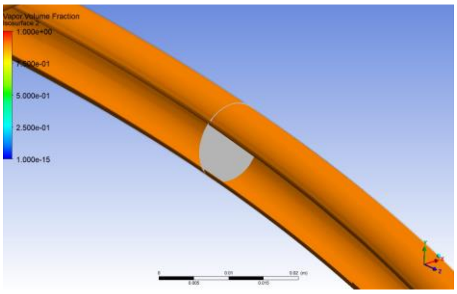

Fig. 11. CFX Steady-State Analysis result (Helical Tube) (Iso-surface: Vapor Volume Fraction 0.9)

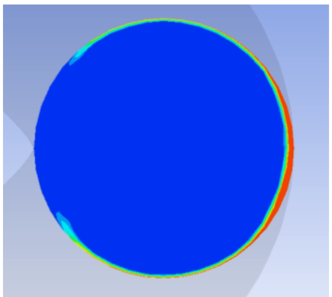

Fig. 12. CFX Steady-State Analysis result (Helical Tube) (Contour: Water Volume Fraction)

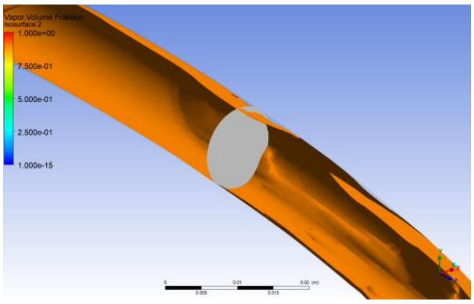

Fig. 13. CFX Transient Analysis result (Helical Tube) (Iso-surface: Vapor Volume Fraction 0.9)

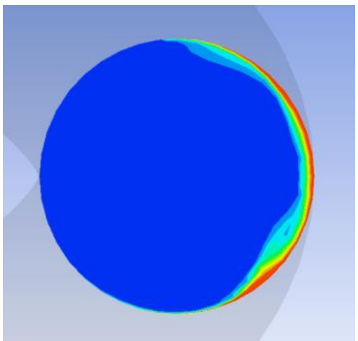

Fig. 14. CFX Transient Analysis result (Helical Tube) (Contour: Water Volume Fraction)

The results of the location of the two-phase interface in the tube and the vapor distribution across the tube cross-section during steady-state and transient state are shown in Figures 11-14. It is observed that the vapor film, which is wide in the tube during the steady state calculation, clusters outward from the center of the helical due to centrifugal force in the transient analysis.

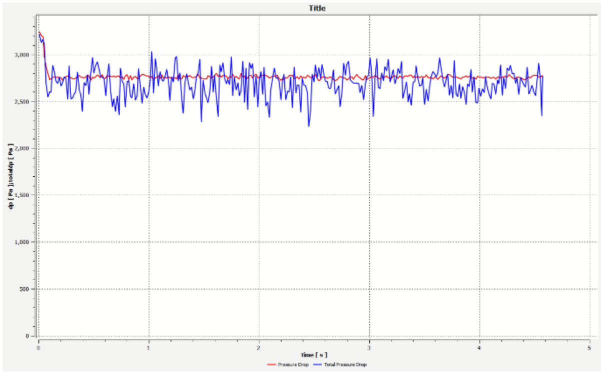

Fig. 9. CFX Transient Analysis result (Straight Tube) - Pressure Drop

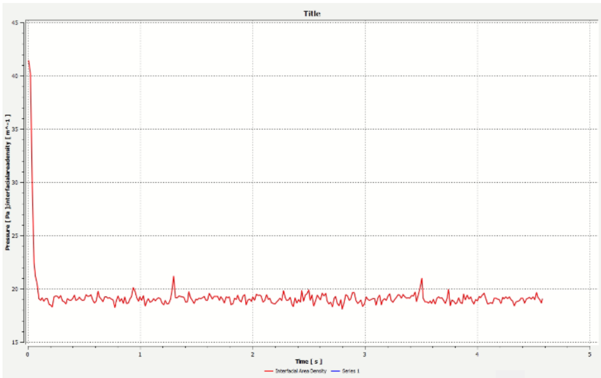

Fig. 10. CFX Transient Analysis result (Straight Tube) - Interfacial Area Density (Volume average)

In order to understand this difference and investigate if the centrifugal force is the reason, a straight tube case is further analyzed. Surprisingly, the CFX analysis showed that the pressure drop value for the straight tube case also converges to lower value compared to the steady state result. The interfacial area density seems to be the main reason and it also decreases as the calculation mode changes from steady state to transient. Similar to the helical tube, the transient pressure drop value was calculated to be about 17% lower than the steady-state pressure drop value. This implies that the lower pressure drop in transient analysis compared to the steady state result is not mainly dependent on the centrifugal force.

3. Summary and Future Works

In this study, CFX, a commercial CFD code, was utilized to analyze the two-phase flow pattern of helical and straight tubes. The steady-state analysis was performed for both straight and helical tubes, and then the transient analysis was performed with the steady-state analysis results set as the initial state. The results showed that the pressure drop values decreased from steady state when the calculation mode is changed to transient for both helical and straight tubes. This result seems to be due to the fact that the vapor is more agglomerated by the transient term than as it is in the steady state. As the vapor agglomerates, the interfacial area density, which affects the interfacial friction, decreases and thus the pressure drop also decreases. In addition, the overall wall shear was also reduced because the slower flowing water was in relatively more contact with the wall instead of vapor, and the overall wall shear was also reduced.

This effect will be further analyzed in the future to understand the importance, and ultimately which calculation mode is more appropriate for the two-phase flow simulation will be determined from the understanding.

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