

Transient VOF Simulation of Air-Water Two-Phase Flow in Helically Coiled Tubes under Various Flow Regimes

Sangoh Shin^a, Janghun Han^a, Yujeong Ko^b, Byeongil You^b, Hyoung Kyu Cho^{b**}, Minseop Song^{a*}

^aDepartment of Nuclear Engineering, Hanyang University, 222, Wangsimni-ro, Seongdong-gu, Seoul 04763

^bDepartment of Nuclear Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826

*Corresponding author: hysms@hanyang.ac.kr

**Corresponding author: chohk@snu.ac.kr

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1. Introduction

Helically coiled tube steam generators have been widely adopted in small modular reactors (SMRs) due to their compact design and superior heat transfer performance. In helical tubes, flow behavior is significantly influenced by centrifugal forces arising from the tube curvature, resulting in flow characteristics distinctly different from those in straight pipes. These centrifugal forces induce secondary flow patterns that redistribute the gas-liquid interface and generate distinct flow regimes including bubbly, plug, slug, and annular flows [1,2].

Void fraction distribution in two-phase flows is a critical parameter for thermal-hydraulic analysis essential to SMR steam generator design and safety evaluation. Void fraction distribution directly affects interfacial area concentration, which governs heat transfer performance, and determines pressure drop characteristics unique to helical geometries [3]. Flow instability in steam generators is closely related to transient variations in void fraction. Therefore, comprehensive understanding of void fraction temporal evolution and cross-sectional distribution patterns across multiple flow regimes is necessary for reliable design and operation of SMR steam generators.

Despite extensive research on helical tube heat transfer and pressure drop, detailed experimental and computational investigation of void fraction distribution in the tube cross-section remains limited. Previous studies using system codes focused on steady-state correlations without addressing transient void fraction evolution and spatial distribution [4]. Additionally, systematic validation of transient CFD predictions against high-resolution experimental measurements across multiple flow regimes is scarce. In helical coils, the curvature induces variations in friction factors compared to straight pipes, necessitating specialized treatment of friction factor characteristics for accurate pressure drop predictions [5]. These friction factor variations fundamentally affect the thermal-hydraulic design and performance assessment of helical coil steam generators.

This study addresses these gaps through comprehensive transient VOF-CFD analysis of air-water two-phase flow in helical coil tubes under adiabatic

conditions. Four representative flow regimes (bubbly, plug, slug, and annular) are investigated with detailed validation against Wire-Mesh Sensor experimental data [6]. The objectives are: (1) to perform mesh and time-step convergent CFD analysis for four flow regimes; (2) to validate void fraction predictions against experimental measurements; (3) to characterize temporal void fraction oscillation patterns for each regime; and (4) to analyze cross-sectional void fraction distributions with emphasis on centrifugal force-induced interface tilting. The results will provide fundamental insights into helical coil two-phase flow physics and establish validation criteria for CFD modeling of helical tube geometries in nuclear applications..

2. Methodology

2.1 Geometry and CFD Setup

The helical coil geometry investigated in this study has an inner diameter of 13 mm, total length of 4 m, coil diameter of 422 mm, helix angle of 6.459°, and pitch of 150 mm as described in Fig. 1. This work presents a transient CFD analysis of adiabatic air-water two-phase flow using the Volume of Fluid (VOF) methodology.

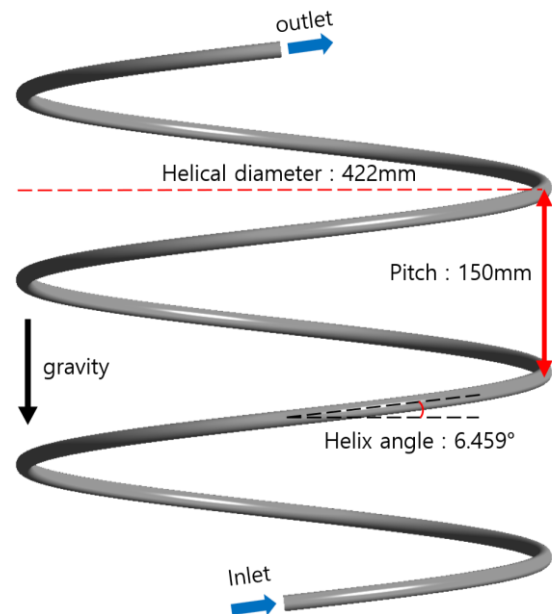


Fig. 1. Schematic diagram of helical coiled tube geometry

In the VOF approach, a single set of momentum equations is solved for the mixture while the volume fraction of the gas phase is tracked. The gas volume fraction α is computed from the transport equation shown in Eq. (1).

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{u}) = 0 \quad (1)$$

Here, α represents the gas volume fraction ($0 \leq \alpha \leq 1$) and $\mathbf{u}$ is the velocity vector. The phase-dependent properties, density ρ and dynamic viscosity μ , are determined as volume-weighted averages shown in Eq. (2) and Eq. (3).

$$\rho = \alpha \rho_g + (1 - \alpha) \rho_l \quad (2)$$

$$\mu = \alpha \mu_g + (1 - \alpha) \mu_l \quad (3)$$

The conservation of momentum for the mixture is expressed in Eq. (4).

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g} + \mathbf{F}_\sigma \quad (4)$$

In this equation p is pressure, $\boldsymbol{\tau}$ is the stress tensor, $\mathbf{g}$ is gravitational acceleration, and $\mathbf{F}_\sigma$ represents the surface tension force computed using the continuum surface force (CSF) model.

All simulations were conducted using ANSYS Fluent 2025 R1. The Realizable k - ϵ turbulence model with enhanced wall treatment was employed for turbulence closure. The convergence criterion for each time step was set with a residual tolerance of 10^{-4} for all equations. CFD simulations were conducted using boundary conditions identical to the experimental setup [6]. As summarized in Table 1, the inlet mass flow rates of water and air for each flow regime were specified using ANSYS Fluent's VOF model to match the experimental conditions. Outlet gauge pressures, as listed in Table 1, were imposed as pressure boundary conditions. The helical tube wall was treated with a no-slip condition. All simulations were performed at atmospheric pressure and 22°C under adiabatic conditions. Initial conditions were set with the domain filled with quiescent liquid (water) at rest.

Table I: CFD boundary conditions and flow conditions

Flow regime	Inlet water mass flow rate [kg/s]	Inlet air mass flow rate [kg/s]	Outlet gauge pressure [Pa]	Water superficial velocity [m/s]	Air superficial velocity [m/s]
Bubbly	2.22×10^{-1}	2.41×10^{-6}	18,675	1.674	0.013
Plug	1.11×10^{-1}	4.42×10^{-5}	10,175	0.837	0.253
Slug	1.66×10^{-1}	5.57×10^{-4}	20,675	1.256	2.915
Annular	5.54×10^{-2}	1.74×10^{-3}	13,675	0.419	9.69

Fluid properties at outlet conditions were used in the simulations, as presented in Table 2. Water density and viscosity remained constant across all flow regimes at 997.8 kg/m³ and 9.55×10^{-4} kg/(m·s), respectively. The air density, however, varied between 1.316 and 1.440 kg/m³ depending on the superficial gas velocity of each flow regime. Surface tension was uniformly set to 0.072 N/m for all cases.

Table II: Fluid properties

Flow regime	water		air		Surface tension [N/m]
	Density [kg/m ³]	Viscosity [kg/m·s]	Density [kg/m ³]	Viscosity [kg/m·s]	
Bubbly	997.8	9.55×10^{-4}	1.417	1.82×10^{-5}	0.072
Plug	997.8	9.55×10^{-4}	1.316	1.82×10^{-5}	0.072
Slug	997.8	9.55×10^{-4}	1.440	1.82×10^{-5}	0.072
Annular	997.8	9.55×10^{-4}	1.367	1.82×10^{-5}	0.072

2.2 Mesh Sensitivity Study

A mesh sensitivity study was conducted to evaluate the dependence of CFD results on grid resolution. Slug flow among the four flow regimes was selected as the basis for grid convergence assessment. Slug flow represents a transitional two-phase flow regime with intermediate to high superficial velocities for both gas and liquid phases, making it an appropriate choice for grid dependency evaluation.

Data used in the mesh sensitivity analysis were selected based on the following conditions. After the bubble released at the inlet reached the outlet and sufficient time had elapsed, simulation data over a 5-second interval were extracted. This procedure ensured removal of initial transient effects and provided physically meaningful statistics. Time-averaged void fraction at the 2.5 m cross-sectional plane was used as the convergence criterion to assess grid independence.

The mesh was generated using SALOME 9.11.0. A structured hexahedral mesh with bell-shaped O-grid topology was employed, which accurately represents the circular cross-section geometry and effectively implements fine grid refinement near the wall to capture viscous effects. Seven grid refinement levels were generated by systematically varying both the cross-sectional mesh size and the helical direction grid spacing, with the total number of cells ranging from 5.7×10^4 to 230×10^4 cells. Fig. 2 shows the cross-sectional and axial mesh distribution of the selected final mesh. The grid levels designed for slug flow were uniformly applied to all four flow regimes to ensure consistent analysis. A convergence threshold of 1% relative error was established for grid independence.

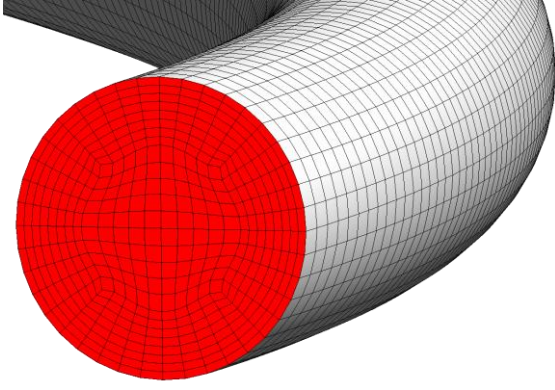


Fig. 2. Configuration of the final mesh (112×10^4 cells)

The convergence analysis results for slug flow are presented in Fig. 3. Fig. 3 shows the variation of time-averaged void fraction with mesh number. The analysis confirmed convergence behavior: the relative error was 0.84% when transitioning from 76×10^4 to 112×10^4 cells, and 0.27% when transitioning from 112×10^4 to 230×10^4 cells (both $< 1\%$). Since the relative error between the 112×10^4 mesh and the adjacent finer mesh (230×10^4) fell below 1%, 112×10^4 cells was selected as the final mesh. This grid resolution provides an optimal balance between computational accuracy and cost efficiency and was uniformly applied to all four flow regimes.

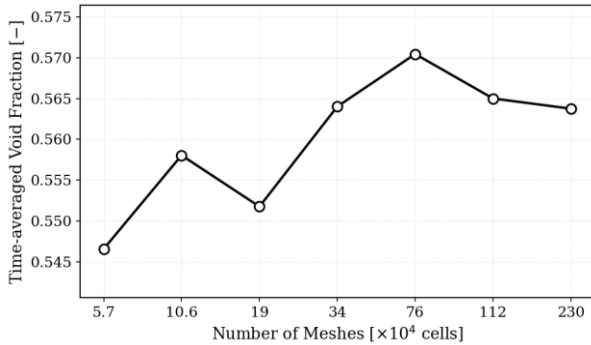


Fig. 3. Effect of mesh number on time-averaged void fraction

2.3 Time Step Sensitivity Study

To evaluate the dependence of numerical results on time step size, a time step sensitivity study was conducted. Using the 112×10^4 cells grid selected in Section 2.2, the convergence of time-averaged void fraction was verified for five different time step magnitudes based on slug flow.

Using the same data selection criteria as Section 2.2, simulation data over a 5-second interval at the 2.5 m cross-section was extracted to assess the convergence of time-averaged void fraction.

Five time step levels (1.0 ms, 0.5 ms, 0.2 ms, 0.1 ms, 0.05 ms) were evaluated for convergence. The time step designed based on slug flow conditions was uniformly applied to all four flow regimes to ensure consistent

calculations. A convergence criterion threshold of 1% relative error was established for time step independence.

Convergence analysis results for slug flow are presented in Fig. 4. Fig. 4 shows the variation of time-averaged void fraction with time step. The analysis confirmed convergence behavior: the relative error for time-averaged void fraction between 0.1 ms and 0.05 ms was 0.45% ($< 1\%$). Since the relative error at the 0.1 ms time step compared to the adjacent time step (0.05 ms) was below 1%, 0.1 ms was selected as the final time step. This time step provides an optimal balance between computational accuracy and cost efficiency and was uniformly applied to all four flow regimes.

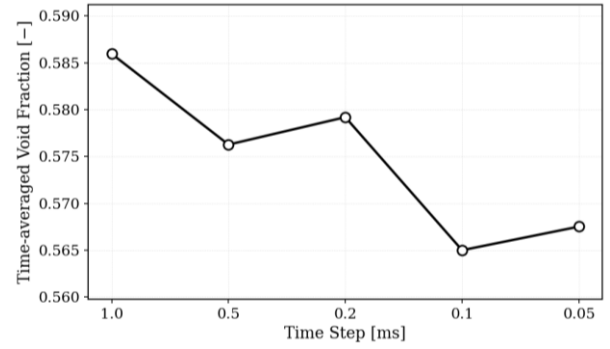


Fig. 4. Effect of time step on time-averaged void fraction

2.4 Flow Development Analysis

Using the optimized grid (112×10^4 cells) and time step (0.1 ms) selected from Sections 2.2 and 2.3, flow development characteristics were analyzed for all four flow regimes: Bubbly, Plug, Slug, and Annular. The axial variation of time-averaged void fraction was examined to identify cross-sections where fully developed flow conditions are satisfied.

For Bubbly flow, the time-averaged void fraction remains low and stable throughout the domain, indicating that the flow reaches a nearly fully developed state from the inlet. For Plug flow, the time-averaged void fraction exhibits uniform distribution across the entire domain, demonstrating that periodic plug patterns are established immediately after the inlet. Slug flow exhibits the longest development length among the four regimes, showing oscillatory behavior in time-averaged void fraction during the initial section and approaching convergence beyond approximately 2 m. Annular flow displays pronounced development in the inlet region, with fully developed conditions approached beyond 2 m. The axial development of time-averaged void fraction for all four regimes is presented in Fig. 5.

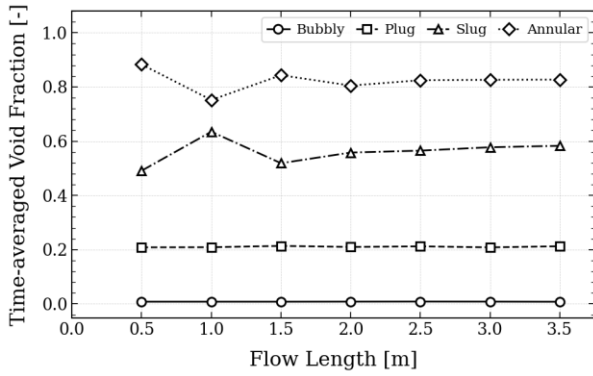


Fig. 5. Axial development of time-averaged void fraction for all four flow regimes

Analysis revealed that all flow regimes satisfy fully developed flow conditions beyond approximately 2 m axial distance, where time-averaged void fraction achieves stable values. Bubbly, Plug, and Annular flows reach stable conditions more rapidly (beyond approximately 1–1.5 m), while Slug flow exhibits the longest development length and approaches convergence beyond 2 m. Therefore, the 2.5 m cross-section is identified as a representative analysis plane where all flow regimes have reached fully developed conditions, while maintaining sufficient distance from the outlet boundary condition to minimize its influence on the subsequent analyses.

By combining the grid convergence analysis and time step convergence analysis, the optimal computational grid (112×10^4 cells) and time step (0.1 ms) were determined based on convergence criteria with relative errors below 1% for time-averaged void fraction. Confirmation that all flow regimes achieve fully developed flow at the 2.5 m cross-section validates the robustness of the selected numerical parameters and justifies the use of time-averaged data from the fully developed 2.5 m axial plane as the foundation for all subsequent flow characteristic analyses presented in this study.

3. Results and Discussions

3.1 Void Fraction Time Series and Experimental Validation

To characterize the temporal behavior of void fraction in helical coil two-phase flow, CFD data extracted at the 2.5 m axial cross-section were compared with Wire-Mesh Sensor experimental measurements. Time series data spanning 5 seconds post-stabilization were extracted for each flow regime and presented in Table III, revealing distinct temporal characteristics and oscillation patterns unique to each regime. Time-averaged void fractions were subsequently extracted and compared to quantify the prediction accuracy of the CFD model.

For Bubbly flow, dispersed small bubbles are distributed randomly in the liquid phase. The time series in Table III exhibit extremely low void fractions with

stable temporal behavior. Although the relative error of 20.5% appears significant, the absolute difference of 0.002 indicates satisfactory prediction accuracy, with the large relative error attributable to the inherently low absolute void fraction characteristic of dispersed bubble flow. This behavior demonstrates that CFD predictions are reliable for bubbly flow even when relative errors appear large in absolute terms.

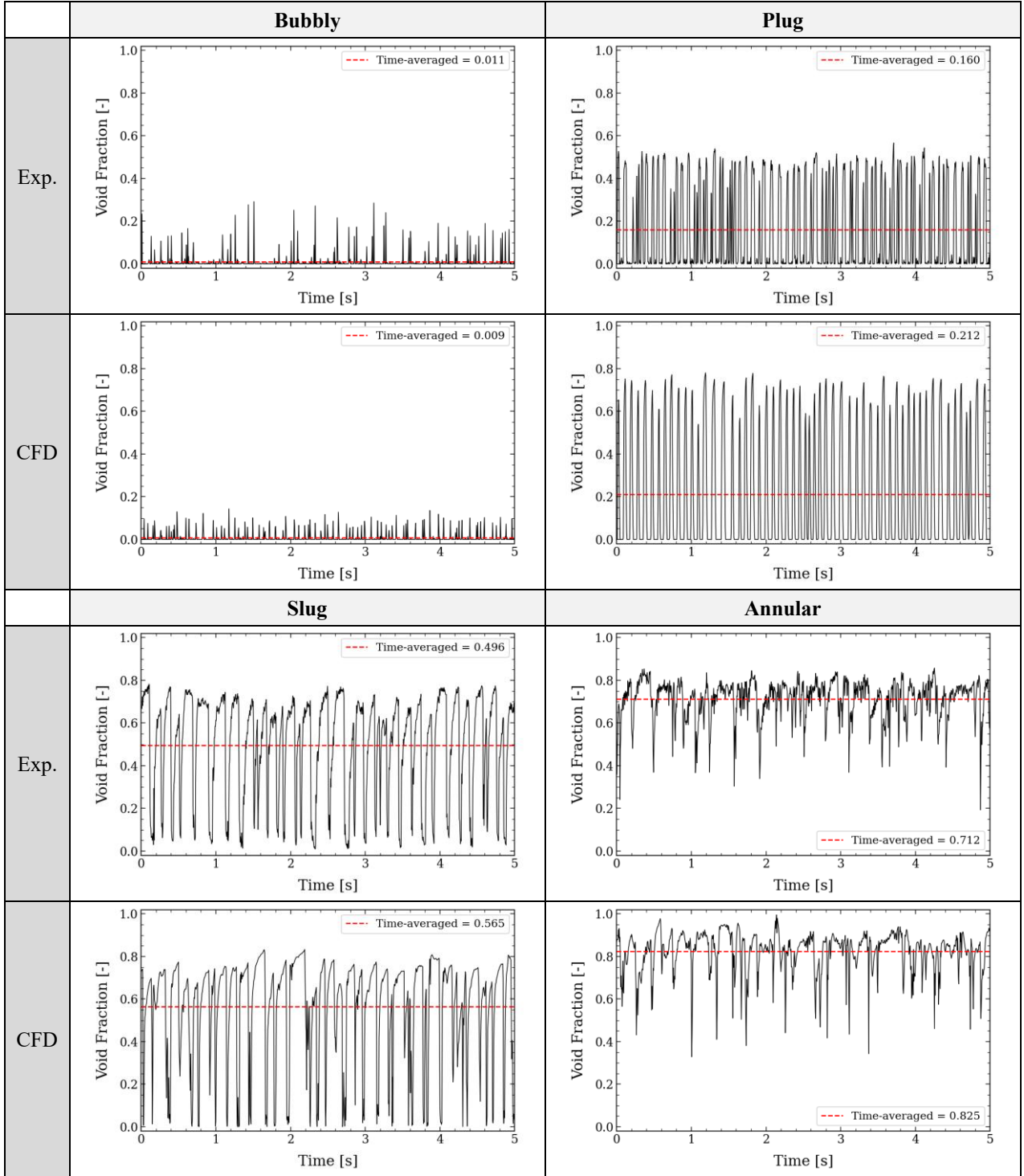
For Plug flow, large elongated bubbles alternate with liquid slugs in a periodic pattern, as reflected in the time series presented in Table III. The CFD prediction of 0.212 exceeds the experimental value of 0.160, yielding a relative error of 32.5%—the largest discrepancy among the four regimes. This significant overprediction suggests that the CFD model tends to overpredict plug bubble size or residence time, likely due to limitations in interfacial force modeling within the VOF framework. The Plug flow regime represents a transitional state between Bubbly and Slug flows, and modeling this transitional behavior accurately remains challenging.

For Slug flow, the time series in Table III reveal irregular high-amplitude oscillations for both CFD and experimental data. The CFD prediction of 0.565 exceeds the experimental value of 0.496 with a relative error of 13.9%. Despite this quantitative difference, the overall oscillation patterns and amplitude ranges remain comparable between CFD and experiment, indicating reasonable capture of slug flow dynamics by the CFD model. The agreement in oscillation characteristics is particularly significant for understanding the transient behavior of two-phase flow in helical coils.

For Annular flow, the continuous gas phase occupies the majority of the tube interior with a thin liquid film confined to the wall. The time series in Table III maintain high void fractions exceeding 0.71 with relatively stable temporal variation. The CFD prediction of 0.825 exceeds the experimental value of 0.712, with a relative error of 15.8%, suggesting a slight underprediction of liquid film thickness. The stable behavior of annular flow in both CFD and experiments indicates well-established flow structure in this regime.

Overall, CFD exhibits a consistent tendency to overpredict void fraction in three regimes (Plug, Slug, Annular), with relative errors ranging from 13.9% to 32.5%. The large error in Plug flow (32.5%) is particularly noteworthy, suggesting limitations in bubble dynamics modeling for this transitional regime. These quantitative discrepancies reflect the inherent challenges of modeling helical coil two-phase flow using VOF methodology, including the effects of centrifugal force, secondary flow structures, and complex interfacial interactions. Notably, Slug and Annular flows show acceptable agreement with experimental measurements, indicating that CFD predictions are most reliable for these dominant flow regimes in practical applications. These levels of quantitative deviation are consistent with prior CFD validation studies of helical coil two-phase flow reported in previous studies.

Table III: Time series of void fraction for four flow regimes: CFD predictions versus experimental measurements



3.2 Spectral Analysis of Void Fraction

To characterize the frequency domain behavior of void fraction in helical coil two-phase flow, Power Spectral Density (PSD) analysis was performed on the time series data using the Welch method. The analysis focused on the physically meaningful frequency range of 0–50 Hz. Dominant frequency and cosine similarity were used as quantitative indicators to evaluate the oscillation characteristics of each flow regime.

Bubbly flow exhibits a broadband PSD distribution across the entire frequency range, as indicated in Table IV. No distinct dominant frequency peak is identified, reflecting the random nature of bubble dispersion without inherent periodicity. The cosine similarity of 0.901 confirms that both CFD and experiment capture this broadband characteristic with excellent agreement, correctly representing the physical nature of dispersed bubble flow.

Table IV: Frequency domain analysis results

Flow Regime	Dominant Frequency [Hz]		Cosine Similarity
	CFD	Experiment	
Bubbly	-	-	0.901
Plug	11.0	9.1	0.750
Slug	4.9	4.9	0.935
Annular	2.2	2.5	0.967

Plug flow demonstrates periodic oscillations with distinct frequency peaks. The CFD dominant frequency is 11.0 Hz, while the experimental value is 9.1 Hz, yielding a discrepancy of 1.9 Hz as summarized in Table IV. The cosine similarity of 0.750 is the lowest among the four regimes, indicating substantial differences in spectral distribution between CFD and experiment. This frequency mismatch suggests that CFD overpredicts the bubble passage frequency, consistent with the large quantitative void fraction error observed in Section 3.1 and confirming the limited reliability of CFD predictions for Plug flow.

Slug flow exhibits strong periodicity with a clear dominant frequency peak, as illustrated in Fig. 6. Notably, the CFD dominant frequency of 4.9 Hz matches the experimental value of 4.9 Hz exactly—a remarkable agreement rarely observed in helical coil two-phase flow analysis. The cosine similarity of 0.935 is the second highest among all regimes, as listed in Table IV, indicating excellent spectral correspondence. This precise agreement in dominant frequency demonstrates that the CFD model accurately captures the passage frequency of slug bubbles and liquid slugs, validating the qualitative behavior observed in Section 3.1 and confirming high predictive reliability for Slug flow.

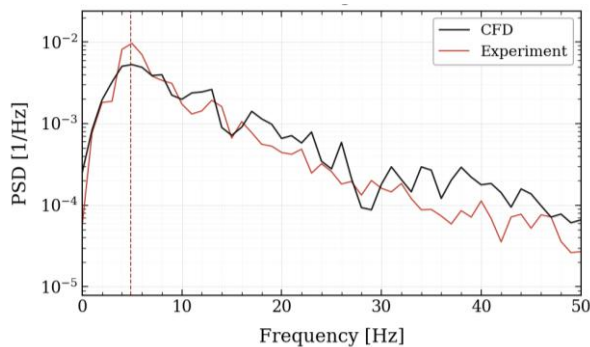


Fig. 6. Power spectral density of void fraction for Slug flow

Annular flow exhibits a broadband PSD distribution without a statistically significant dominant frequency peak, as indicated in Table IV. Although energy

concentrations appear in the low-frequency region (approximately 2–2.5 Hz), these do not represent flow periodicity but rather reflect background spectral characteristics. The cosine similarity of 0.967 is the highest among all regimes, indicating excellent agreement between CFD and experimental spectral shapes, with both correctly capturing the non-periodic nature of continuous gas core flow with thin liquid film.

In summary, the spectral analysis reveals a clear distinction in flow characteristics: Bubbly and Annular flows are fundamentally non-periodic, while Plug and Slug flows exhibit strong periodicity. The most significant finding is the exact coincidence of dominant frequencies for Slug flow, which is a noteworthy validation result demonstrating the accuracy of the CFD model for this regime. In contrast, Plug flow shows a frequency discrepancy of 1.9 Hz, consistent with its large void fraction overprediction documented in Section 3.1. These spectral characteristics, combined with the time series observations from Section 3.1, provide strong evidence that CFD predictions are highly reliable for Slug and Annular flows but show limitations for Plug flow. The excellent cosine similarity values for Slug and Annular flows reinforce this assessment and support the validity of the CFD model for these dominant flow regimes in practical applications.

3.3 Cross-Sectional Void Fraction Distribution and Centrifugal Force Effects

To characterize the gas-liquid phase distribution in helical coil flow, the time-averaged void fraction distribution at the 2.5 m axial cross-section was analyzed using CFD predictions. The cross-sectional void fraction contours reveal the distinctive effects of centrifugal force arising from the helical coil curvature.

Very low void fractions ($\alpha \approx 0.05$ – 0.15) characterize Bubbly flow, distributed nearly uniformly across the entire cross-section as shown in Fig. 7(a). Bubbles do not concentrate at any particular location, and no distinct gas-liquid interface is formed, reflecting the dispersed nature of bubble flow.

Intermediate void fractions ($\alpha \approx 0.2$ – 0.4) are observed in Plug flow, depicted in Fig. 7(b), with bubbles concentrated in the upper region of the tube, skewed toward the inner wall similar to Slug and Annular flows. However, due to the lower void fraction in Plug flow, the VF = 0.5 interface line remains indistinct upon time-averaging.

In contrast to the uniform distributions observed in Bubbly and Plug flows, Slug flow exhibits asymmetric void fraction distribution as illustrated in Fig. 7(c). Most notably, the VF = 0.5 interface line is tilted rather than horizontal. This tilting results from centrifugal force generated by the helical coil curvature, which displaces the gas phase toward the inner wall of the coil.

Annular flow, shown in Fig. 7(d), displays a continuous gas core occupying the majority of the tube interior with a thin liquid film distributed along the wall. Similar to Slug flow, the VF = 0.5 interface line is tilted,

indicating that centrifugal force displaces the liquid phase toward the outer wall of the coil. Consequently, the liquid film thickness is distributed asymmetrically, and the center of the gas core is offset from the tube center toward the inner side of the coil.

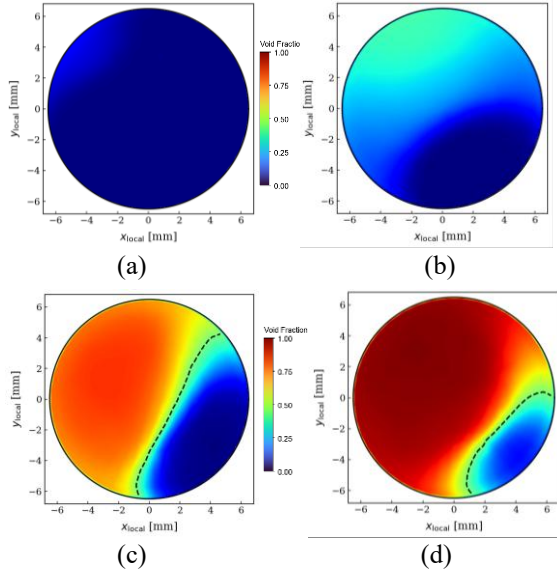


Fig. 7. Time-averaged void fraction distribution: (a) Bubbly, (b) Plug, (c) Slug, (d) Annular

The asymmetric void fraction distributions observed in Slug and Annular flows, characterized by tilted VF = 0.5 interface lines, directly demonstrate the dominant role of centrifugal force in controlling gas-liquid separation within helical coil geometries. These tilted interfaces provide clear evidence that centrifugal force effects govern the distinctive phase distribution patterns unique to helical geometries, providing essential physical insights into two-phase flow behavior.

4. Conclusions

This study presents a comprehensive transient VOF-CFD investigation of air-water two-phase flow in helical coil tubes across four flow regimes. Numerical convergence was established at 112×10^4 cells and 0.1 ms time step, with the 2.5 m cross-section confirmed as fully developed for all regimes. Experimental validation yielded void fraction relative errors of 20.5% in bubbly, 32.5% in plug, 13.9% in slug, and 15.8% in annular flows. Spectral analysis revealed excellent agreement for slug flow with dominant frequency matching experiments exactly at 4.9 Hz (cosine similarity 0.935) and highest cosine similarity for annular flow (0.967), confirming high CFD reliability for slug and annular regimes while identifying limitations in plug flow prediction.

Cross-sectional void fraction distributions demonstrated pronounced centrifugal force effects, with asymmetric distributions and tilted interfaces characterizing Slug and Annular flows. This directly demonstrates centrifugal force dominance in controlling gas-liquid separation in helical geometries, advancing

fundamental understanding of phase distribution mechanisms unique to helical configurations.

CFD predictions demonstrate high reliability for slug and annular flows, though the VOF approach exhibits limitations in modeling interfacial interactions, particularly in plug flow. The Realizable k-epsilon turbulence model and RANS methodology fundamentally limit resolution of fluctuations and secondary flow structures. These combined limitations contribute to quantitative discrepancies, particularly in plug flow.

The quantified centrifugal force effects and characterized phase distribution patterns provide essential insights for helical coil steam generator design in small modular reactors, directly affecting interfacial area concentration and heat transfer performance. The validated CFD methodology establishes a robust basis for thermal-hydraulic calculations in SMR applications.

Future research should include: transient CFD analysis with heat transfer and phase change effects, Large Eddy Simulation or hybrid RANS-LES approaches for improved secondary flow capture, validation across diverse helical geometries and operating conditions, and concurrent measurement of pressure drop and interfacial area concentration. This study successfully characterizes two-phase flow behavior in helical coils, advancing understanding of centrifugal force effects and providing essential validation data for CFD modeling in complex nuclear thermal-hydraulic systems.

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