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Evaluation of the Effect of Two-Phase Correction Factors on Pressure Drop Prediction in Helical Coils

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1. Introduction

The recent interest in Small Modular Reactors (SMRs), driven by increased demand for electricity and other non-electrical applications (hydrogen production, district heating, desalination etc.), has led to the rapid development of various SMR designs worldwide. One of the most promising types for early deployment is the integral SMR, based on traditional Light Water Reactor (LWR) technology. [1] In integral SMRs, the primary and secondary systems, including Steam Generators (SGs), are integrated inside the Reactor Pressure Vessel (RPV). Such design eliminates the risk of Loss of Coolant Accident (LOCA) events since there is no Reactor Coolant System (RCS) piping on the primary side. The SGs use helical coil (HC) design, where the primary coolant flows on the outside, and secondary water flows inside of the helical SG tubes, where boiling happens and steam is generated. Due to their helical shape, pressure drop and heat transfer differ significantly from those in straight tubes. Additionally, such helical coils may be prone to flow instabilities, particularly the Density Wave Oscillation (DWO), which can occur under specific operating conditions and varies with the geometry. [2, 3] The flow instability, including DWO, can lead to decreased heat transfer or damage to the structural integrity of the helical tubes. Traditional safety system codes often lack appropriate correlations for helical coils, and when implemented, they are usually available only as a developmental option. Since the occurrence of DWO is strongly dependent on the accurate prediction of pressure drop and heat transfer in the helical coil, there is a critical need for precise methods to evaluate these phenomena using the conventional system codes. This paper is therefore focused on a research study investigating the applicability of two-phase wall friction factors for pressure drop prediction in helical coils using the default models in MARS-KS 2.0, based on the available experimental data.

2. Literature Survey

2.1 Helical Coil Steam Generator

There are various SMR concepts in development that include the Helical Coil Steam Generator (HCSG), such as the NuScale [4], or Korean SMART and i-SMR [5]. Although none of the above have been deployed for commercial operation yet, extensive research and many experiments were conducted on helical coils to study the physical phenomena inside such tubes and also to develop suitable correlations for pressure drop, heat transfer, critical heat flux, and others. Helical coils have higher pressure drop and better heat transfer when compared to straight tubes because of their curved shape and longer path. This increases friction and mixing due to the centrifugal force, and together with secondary flows, these two effects are especially important in two-phase flow conditions, such as boiling.

2.2 MARS-KS and Helical Coil Modelling

The MARS-KS is a best-estimate thermal-hydraulic system code widely used for safety analyses of nuclear power plants, especially the conventional LWR types. However, the base version of the MARS-KS does not include specific correlations for pressure drop in helical coil geometry by default, unless a developmental option is activated. Instead, MARS-KS relies on the default straight-pipe correlations, such as Lockhart-Martinelli for two-phase flow pressure drop [6], which are not suitable for helical coils and result in poor predictive accuracy for these geometries.

Many studies were conducted to evaluate prediction capability of system codes with modified correlations tailored for helical coil geometry. One of the examples is a study by Oh et al. [7] that focuses on the MARS-KS code with two modifications, named MARS-KS-C and MARS-KS-F, which use different correlations for both pressure drop and heat transfer. This paper is mainly focused on the DWO prediction and stability maps for helical coils and clearly shows that implementing new correlations for helical coils can greatly improve the prediction capability of MARS-KS. Another example is the NRELAP5 code, a modified version of RELAP5, used for safety analyses of the NuScale SMR in the design certification process for the US NRC [8].

Additionally, it is important to note that correlations that are suitable for specific helical coil geometries and operating conditions may not work well for others. This happens because the behavior inside the helical coils changes with different designs, such as tube and coil diameters; and operating parameters, such as pressure and mass flux. As a result, it is challenging to find one correlation that would work accurately for a wide range of helical coil designs and operating conditions.

2.3 Experiments with Helical Coil

Various experiments have been conducted on helical coil tubes, and several publications provide detailed design data (coil geometry) as well as the experimental parameters (inlet and outlet conditions). We concluded that for the systems code evaluation, the most useful data come from the following experiments: (a) SIET facility [9-13]; (b) facility at Politecnico di Milano [14]; and (c) SWAMUP-II facility [15-20]. Data from these sources can be used to create models of each test facility, simulate the experimental conditions, and evaluate response of the code by comparing simulation results with the experimental data.

3. Methodology

Several input models were developed for MARS-KS using data from the publications in the previous chapter. Since the main focus is on the helical coil tube, we did not model the entire facility and instead created an independent model of the test section using the design parameters of each HC. That includes the coil length, inner and outer tube diameters, coil diameter and pitch, tube angle, material properties, and the inlet throttling. Additionally, this approach significantly reduces the computation time, which is crucial given the hundreds of experimental datasets. For each experimental case, we specified parameters such as the mass flux, inlet subcooling or quality, and tube outlet pressure (set to atmospheric conditions for open-loop systems). For cases with external heating, we included the heat structure and applied a uniform heat transfer rate based on experimental data. The results of each simulation provided the pressure drop of the test section, which we compared with experimental data. Sample nodalization of the independent HC model is shown in Fig. 1.

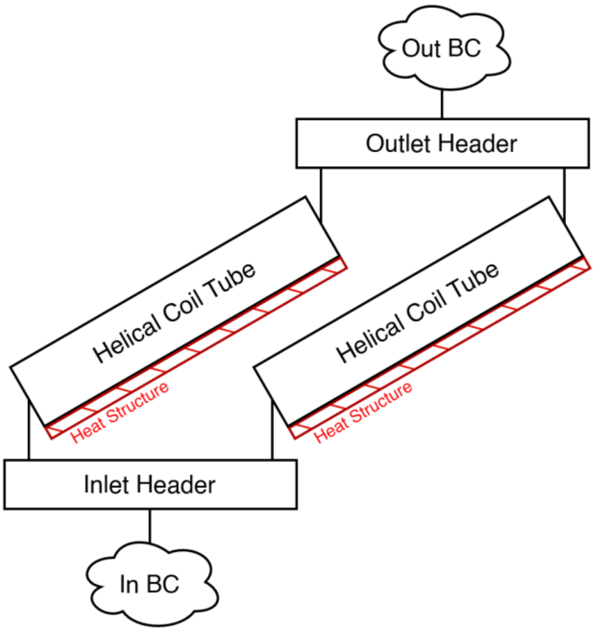

Fig. 1. Sample Nodalization of Independent HC Model

The pressure drop results from sample simulations of the SIET facility are shown in Fig. 2 for the adiabatic case (with no external heating) and in Fig. 3 for the diabatic case (uniform heating). Both cases use the default (straight pipe) pressure drop model and the correction factors are not applied. For the adiabatic case in Fig. 2, the code strongly underpredicts the pressure drops, as most data points lie well below the diagonal line. Unlike for the pressure drop, the helical coil heat transfer model was activated in the heat structure for diabatic case. However, the diabatic case in Fig. 3 result in more scattered data, showing a weaker relationship between the experimental and predicted values, despite the helical coil heat transfer model. This confirms that the default model of MARS-KS struggles to accurately predict pressure drop due to the complex heat transfer phenomena and two-phase flow in the helical coils.

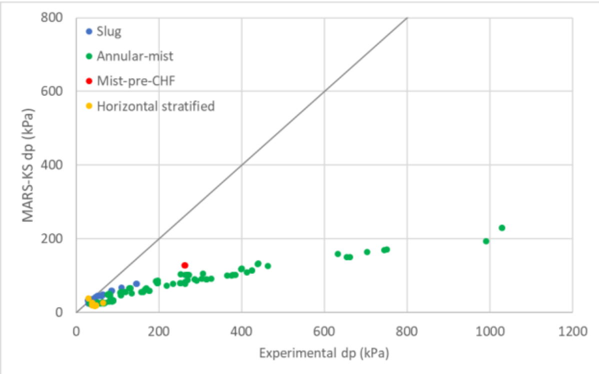

Fig. 2. Result for Adiabatic Conditions (SIET facility)

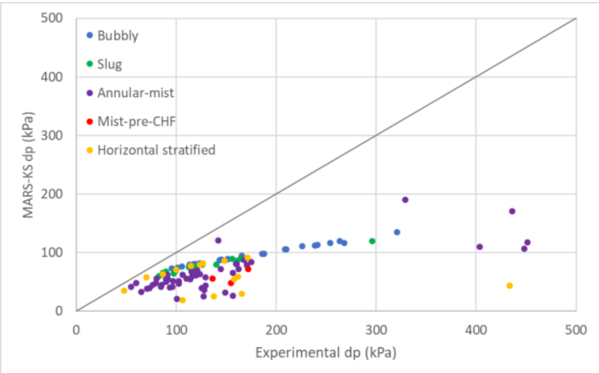

Fig. 3. Result for Diabatic Conditions (SIET facility)

It is widely recognized that the straight pipe pressure drop model is not suitable for helical coils and leads to inaccurate predictions, as can be seen in the results. Although these results strongly suggest the need for improved correlations in the MARS-KS code to better capture the pressure drop in helical coils with various geometries and under different experimental conditions, our objective is to find a different way how to improve the code prediction capability for HCs without utilizing new correlations. Therefore, we investigated an option within MARS-KS to adjust the two-phase wall friction multipliers. By modifying these ‘Correction Factors’ (CFs), we intended to better capture the two-phase flow behavior in helical coils and assess their impact on the accuracy of the results. Since the complex behavior in HCs cannot be addressed by simply finding one CF value that would suit all cases, we considered the possibility of applying several correction factors for each group of the dataset. This approach involves categorizing the pressure drop data from simulations based on criteria such as the pressure, exit quality, flow regime, or mass flux. Then, a single CF value can be applied to a specific range of parameters, if a consistent pattern is identified. Similarly, heat structure correction factors will be adjusted to improve diabatic predictions. We anticipate that these modifications will improve the code ability to predict the DWO occurrence. The final results of this study will be presented at the conference.

4. Conclusions

In this study, we investigated an approach to refine pressure drop predictions for helical coil geometries using the MARS-KS code with its default straight pipe models, which are not optimized for helical geometries. Based on the published experiments, we created independent models of several helical coil test sections. We then simulated these models using experimental conditions and aimed to improve the pressure drop predictions by adjusting the two-phase wall friction correction factors. Accurate pressure drop and heat transfer predictions allow for improved identification of the DWO regions, and this work aims to enhance the prediction capabilities without utilizing specialized correlations for helical coils. As this research progresses, future work will refine these simulations and evaluate their effectiveness in improving DWO prediction.

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