Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

Simulations of single and two-phase flows through helical tubes with different geometries and mass flow rates

To cite this article: M Giardina and P Buffa 2025 *J. Phys.: Conf. Ser.* **2940** 012026

Simulations of single and two-phase flows through helical tubes with different geometries and mass flow rates

M Giardina, P Buffa

Department of Engineering, University of Palermo, Viale delle Scienze, Ed. 6, Palermo, Italy

Corresponding author: mariarosa.giardina@unipa.it (Mariarosa Giardina)

Abstract. Predictions of pressure drops in helical pipes using the Relap5/mod3.3 code are explored, despite the code's limitations in modeling such geometries. To address this, the code was modified to incorporate helical tube geometries and correlations for frictional pressure drops under both single-phase and two-phase flow conditions. Comparisons with experimental data on pressure drops across test sections with varying curvature ratios, operational pressures, and mass flow rates were made. The study demonstrates that the modified Relap5 code significantly improves the accuracy of frictional pressure drop predictions for the examined experimental data.

Keywords: helical pipe, pressure drops, single flow, two-phase flow, Small Modular Reactor

1 Introduction

Various Generation III+ and Generation IV nuclear reactor projects are expected to use helically coiled pipes in Steam Generators (SG). In this context, some Small Modular Reactor (SMR) designs aim to incorporate once-through helically coiled SGs [1]. This integral layout enhances reactor compactness, improves heat transfer efficiency, and, by design, reduces the risks and consequences of various postulated accidents, such as Large Break LOCA events.

The curvature of helically coiled tubes has been shown to induce secondary flows, which enhance fluid mixing and improve heat transfer characteristics compared to straight tubes. However, this also leads to an increase in pressure drop, making its prediction more complex than for straight tubes.

Several researchers from the Engineering Department at the University of Palermo have conducted numerous studies focused on simulating single-phase and two-phase flows in vertical helical pipes (HPs) using the best-estimate Relap5 nuclear code, which initially lacked the ability to model components with helical geometries and the associated thermal-fluid dynamic phenomena.

The Relap5/mod3.3 release [2] has been modified as described in this paper to include a schematization for coiled tube geometries and integrate correlations for simulating frictional pressure drops under both single-phase and two-phase flow conditions.

The modified code has been validated against experimental data from the literature, as well as experiments conducted at various international and national research laboratories, with varying curvature, operational pressures, and mass flow rate conditions.

The results obtained demonstrate that the modified version of the code accurately predicts frictional pressure drops across a wide range of pressures and mass flow rates.

2 Correlations for predicting pressure drops in HPs

In previous studies, various authors have explored the issue of frictional pressure drops in both single-phase and two-phase flows in helical pipes (HP), using their experimental results to develop corresponding correlations.

Many of these correlations, typically suited for HPs with low pitch-to-diameter ratios and low surface roughness, establish a relationship between the friction factor, Reynolds number (Re), and the curvature of the helix, which is the ratio of pipe diameter to coil diameter, d/D.

Among the various approaches, Ito's correlations [3] for both laminar and turbulent single-phase flows are frequently considered some of the most dependable in the literature [4, 5]. For two-phase flow pressure drops, numerous correlations have been proposed.

Some researchers suggest using correlations originally developed for straight pipes, like the Lockhart-Martinelli (L-M) method, to estimate pressure drops in helical pipes by replacing the single-phase friction factor with adjusted correction factors for helical geometries [5].

Other researchers have developed correlations specifically for HPs, but these are often limited in their validity range and are based on dimensional parameters or models that do not maintain dimensional consistency. Additionally, when used outside their original development conditions, these correlations tend to produce significantly different results, demonstrating a lack of robustness to changes in flow parameters.

In this study, among the available correlations in the literature, the friction factor from Ito for single-phase flow is used, while for two-phase flow, the L-M correlations, as modified in [4], are adopted.

The following sections provide details about the correlations implemented in the Relap code for simulating HP, aiming to extend its applicability to various operating conditions in terms of working pressure and fluid flow rate.

2.1 Correlations for single phase flows

The single-phase experimental database includes approximately 2000 data points, covering Re from 40 to 145,000, with curvature ratios d/D ranging from 0.003 to 0.3.

Ito’s correlations, applicable to both the laminar and turbulent regimes, provide the best fit to the experimental data, with errors of about 2% and 4% for the turbulent and laminar regimes, respectively.

Ito summarized the entire status of the fluid Fanning friction factor (f_f) for HPs as follows for laminar and turbulent flows, respectively:

$$f_f=\frac{344(d/D)^{0.5}}{\left\{1.56+\log_{10}\left[Re\left(\frac{d}{D}\right)^{0.5}\right]\right\}^{5.73}} \quad 13.5\left(\frac{d}{D}\right)^{0.5} < Re < 2000\left[1+13.2\left(\frac{d}{D}\right)^{0.6}\right] \tag{1}$$

$$f_f=0.076Re^{-0.25}+0.0075\left(\frac{d}{D}\right)^{0.5} \quad Re > 15000 \tag{2}$$

For Re number $13.5(d/D)^{0.5}$, friction factor for laminar flow in straight tubes can be considered valid:

$$f_f=16/Re \tag{3}$$

2.2 Correlations for two-phase flows

Early researchers primarily used the L-M method [6] to predict the frictional pressure drop in two-phase flow conditions.

Given that the L-M correlations were initially created for two-phase pressure drop in horizontal straight tubes, adjustments are necessary to align the results with experimental data for helical geometries [4, 7, 8].

In [4], by using the L-M method, a correlation factor derived from experimental data fitting for helically coiled tubes is proposed.

As is well known, the frictional pressure drop data can be correlated by the pressure drop multipliers ϕ_l and ϕ_g as a function of the L-M parameter χ, defined as follows:

$$\emptyset_l^2 = \frac{\left(\frac{dP}{dx}\right)_{TP,f}}{\left(\frac{dP}{dx}\right)_l} \qquad \emptyset_g^2 = \frac{\left(\frac{dP}{dx}\right)_{TP,f}}{\left(\frac{dP}{dx}\right)_g} \tag{4}$$

$$\chi^2 = \frac{\emptyset_g^2}{\emptyset_l^2} = \frac{\left(\frac{dP}{dx}\right)_l}{\left(\frac{dP}{dx}\right)_g} \tag{5}$$

$\emptyset_l$ and $\emptyset_g$ represent the two-phase friction multipliers for liquid-only and vapor-only flows, respectively. $(dP/dx)_{TP,f}$ denotes the frictional pressure gradient in two-phase flow, while $(dP/dx)_l$ and $(dP/dx)_g$ correspond to the pressure drops when only the liquid phase or gas phase flows through the channel, respectively.

It is important to specify that the pressure gradients (dP/dx)l and (dP/dx)g are evaluated assuming that each phase flows alone with its respective partial flow rate, i.e., G(1−x) for the liquid phase and Gx for the gas phase, with G being the total flow rate and x the quality. This approach differs from another common method in the literature, where the liquid and gas pressure gradients are calculated assuming that each phase flows alone but with the total flow rate G.

For straight pipes, the liquid and gas pressure drop multipliers are determined using the following correlations:

$$\emptyset_l^2 = 1 + \frac{c}{\chi} + \frac{c}{\chi^2} \tag{6}$$

$$\emptyset_g^2 = 1 + c\chi + c\chi^2 \tag{7}$$

The constant c in Eqs. (6) and (7) depends on the flow regimes of the liquid and vapor. To more accurately account for the effect of system pressure, as observed in the results reported in [4], the ratio (ρ_{mix}/ρ_l) is introduced as a correction factor in Eq. (6), consistent with approaches used in other studies [5].

The proposed correlation is as follows:

$$\emptyset_{l*}^2 = 0.032\ \emptyset_l^2\ De_l^{0.305} \left(\frac{\rho_{mix}}{\rho_l}\right)^{-0.51} \tag{8}$$

where $De_l = Re_l(d/D)^{0.5}$ is the Dean number of the liquid phase as it flows alone in the channel, used to account for the effect of the centrifugal force. The parameter $\emptyset_l^2$ is evaluated by Eq. (6) and the mixture density is determined by the relationship:

$$\rho_{mix} = \left[\frac{x}{\rho_g} + \frac{(1-x)}{\rho_l}\right]^{-1} \tag{9}$$

2.3 RELAP modification

Additional fortran subroutines were incorporated into Relap5/mod3.3 to facilitate the modeling of helical geometries for both single-phase and two-phase flow conditions. For single-phase flow, the subroutine responsible for calculating f_f was modified by integrating Eqs. (1) through (3).

In single-phase flow through straight pipes, a discontinuity in the friction factor is a well-documented physical phenomenon associated with the transition between laminar and turbulent flow at $Re \approx 2100$. In helical coils, however, this transition is typically smoother due to the effects of curvature and secondary flows, which tend to mitigate abrupt changes in the flow regime.

To address the discontinuity in the friction factor observed in Ito's correlations during the transition from laminar to turbulent flow, a new approach has been implemented, aiming to provide a more accurate representation of the gradual regime change in helical geometries.

This approach involves using a linear interpolation technique for f_f as a function of Re, applied between Re=2000[1+13.2(d/D)0.6] (Ito's upper limit for laminar flow) and Re=15,000 (Ito's lower threshold for turbulent flow).

For two-phase flow in straight pipes, the Relap5 friction model utilizes a two-phase multiplier approach. The multiplier is determined using the Heat Transfer and Fluid Flow Service (HTFS) correlation [9], which aligns with empirical data across a wide range of flow rates and flow regimes.

The HTFS correlation for the two-phase friction multiplier is defined by Eqs. (6) and (7), representing the liquid-alone and vapor-alone multipliers, respectively.

The constant c is evaluated as follows:

$$c = -2 + (28 - 0.3\, g^{1/2}) \exp\left(-\frac{(\log_{10} k + 2.5)^2}{2.4 - g\, 10^{-4}} \right) \tag{10}$$

where g is the total mass flow rate. The parameter κ is the Baroczy dimensionless index defined as:

$$k = \frac{\rho_g}{\rho_l} \left(\frac{\mu_l}{\mu_g} \right)^{0.2} \tag{11}$$

It is worth noting that the definition of the Baroczy dimensionless index in Eq. (10) closely resembles the square of the Lockhart-Martinelli parameter for turbulent-turbulent flow.

In the modified code, by combining Eqs. (4) through (8), the frictional pressure for two-phase flow configuration is computed by the following equation:

$$\left(\frac{dP}{dx}\right)_{TP,f} = \left[0.032\ De_l^{0.305} \left(\rho_{mix}/\rho_l\right)^{-0.51}\right] \left\{ \left(\frac{dP}{dx}\right)_l + c \left[\left(\frac{dP}{dx}\right)_l \left(\frac{dP}{dx}\right)_g \right]^{0.5} + \left(\frac{dP}{dx}\right)_g \right\} \tag{12}$$

To calculate $(dP/dx)_l$ and $(dP/dx)_g$ of Eq. (12), Ito correlations for the friction factors, as previously described, were used. The constant c is evaluated by using Eq. (10).

In the following sections, the modified and unmodified versions of the Relap5 code will be referred to as *modified-R5* and *unmodified-R5*, respectively.

3 Results of validation for single phase flows

3.1 Experiments by Ali (2001)

The experiments presented in [10] were conducted using HPs with varying geometric dimensions, constructed from thick-walled polyethylene tubing. The test sections dimensions result in a d/D ranging from 0.0268 to 0.0519.

Ambient temperature water was used as the test fluid.

The nodalization for the Relap5 system code is based on an inclined pipe divided into subvolumes, which represents the HP test section. The length, tube diameter, and coil diameter are identical to those used in the experiments. A new flag in the Relap5 input file allows these geometric parameters to be specified for the coil pipe component.

As the experiments are carried out under steady-state conditions with a constant water mass flow rate, no pumps are included in the nodalization. The required experimental mass flow rates are maintained through a time-dependent junction that ensures the proper flow rate to the test section for each of the tests conducted.

Fig. 1 shows log-log plots of Euler number, $Eu = \Delta P/(2\rho v^2)$, against Re, based on experiments conducted with coil no. 1, along with results from both modified-R5 and unmodified R5. Fig. 2

illustrates the experimental Eu data versus Re for coils no. 5, 6, and 8, compared with predictions obtained using only modified-R5.

Analyzing all the results from the conducted studies, which are omitted here for brevity, it is evident that the modified-R5 accurately predicts the experimental data trends and values with an error margin not exceeding 10%.

In contrast, the unmodified-r5 produces results that significantly underestimate the experimental data.

3.2 Experiments by Coronel and Sandeep (2003)

The experiments were performed using a heat exchanger consisting of two concentric coils and covering a range of single-phase flow rates from 9.46×10^{-5} to 6.31×10^{-4} m^3/h [11]. Tap water at an initial temperature of 20°C was used as the working fluid and heated to specific endpoint temperatures within the heat exchanger's two coils. The endpoint temperatures were set to 20°C, 93.3°C, 121°C, and 149°C.

The coils geometries are reported in Table 1.

The Relap5 nodalization consists of two inclined pipes, each divided into 50 sub-volumes, connected to heat structure components that supply heat to the water flow. The water is pumped through the two coiled pipes, raising the fluid to the final temperature required for the experiment. The mass flow rates are controlled by a time-dependent junction that ensures the appropriate flow rate to the test section for each analyzed run.

Fig.s 3 and 4 present results showing the pressure drop per unit length as a function of flow rate, with varying endpoint temperatures in both the outer and inner coils.

Also in this case, upon examining the set of results, it can be highlighted that the modified-R5 allows for very accurate predictions of the experimental data, with an error that does not exceed 5%.

Table 1. Coil geometries in the heat exchanger [11].

Coil geometry	Outer Coil [m]	Inner Coil [m]
Outside diameter of tube	0.0127	0.0127
Inside diameter of tube	0.0102	0.0102
Length of coil	39.63	27.44
Diameter of coil	0.162	0.111

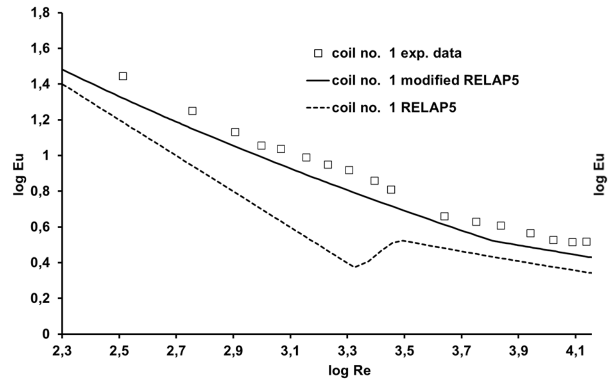

Figure 1. Experimental data for the log Euler numbers of coil no. 1 [11] compared with results from the modified-R5 and unmodified-R5.

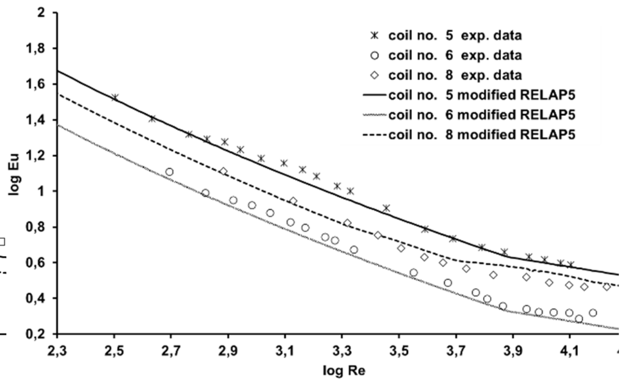

Figure 2. Experimental data for the log Euler numbers of coil no. 5, 6 and 8 [11] compared with results from the modified-R5.

4 Results of validation for two phase flows

4.1 HP with 1 m coil diameter under different test pressures

The experimental data examined in this section were conducted at SIET (Società Informazioni Esperienze Termoidrauliche) research laboratories at Piacenza [12].

The test section comprises a HP with 0.01253 m inner diameter, 1 m coil diameter, and 32 m length. Positioned before the test section is a pre-heater, which is an electrically heated coiled tube section designed to achieve the inlet target temperature. Along the coiled tube, nine pressure taps are distributed approximately every four meters, with eight differential pressure transducers connecting these taps.

The thermal-hydraulic conditions studied for the adiabatic two-phase flow pressure drops (without power supplied to the test section) include the following parameters: mass flux ranging from 192 to 772 [kg/m²s], pressures of 3, 4, and 6 MPa, and qualities from 0.17 to 0.84.

The Relap5 nodalization incorporates time-dependent volume components and junctions to define the inlet and outlet conditions of the helical coil tube loop. A proportional-integral-derivative (PID) controller is implemented through control variable cards to regulate the inlet pressure at the test section.

For brevity, only a subset of results is presented in Fig.s 5 and 6. These figures compare predictions from the modified-R5 and unmodified-R5 with experimental data of pressures measured along the coil at a channel inlet pressure of 3 MPa and various inlet two-phase mass flow rates. As depicted in Fig. 5, the data points closely align with the 45-degree line, demonstrating good agreement between the experimental measurements and the predictions obtained using the modified-R5.

Table 2 summarizes the root mean square error (RMSE) of pressure predictions along the test section obtained by using modified-R5 and unmodified-R5, for the examined experimental inlet channel pressures.

The modified-R5 improves predictions of experimental data, with an RMSE that is smaller than that obtained by the unmodified-R5.

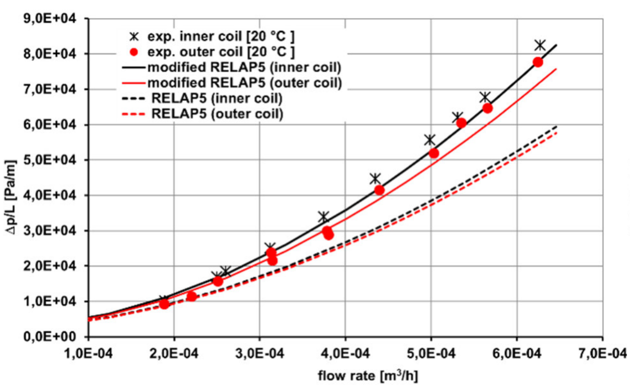

Figure 3. Experimental pressure drops in the outer and inner coils as a function of flow rate, at 20 °C endpoint temperature [12], and results by modified-R5 and unmodified-R5.

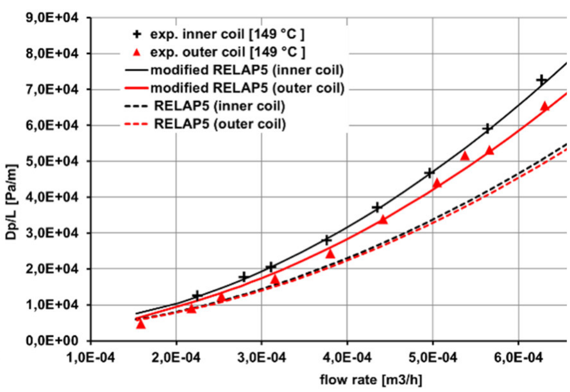

Figure 4. Experimental pressure drops in the outer and inner coils as a function of flow rate, at 149 °C endpoint temperature [12], and results by modified-R5 and unmodified-R5.

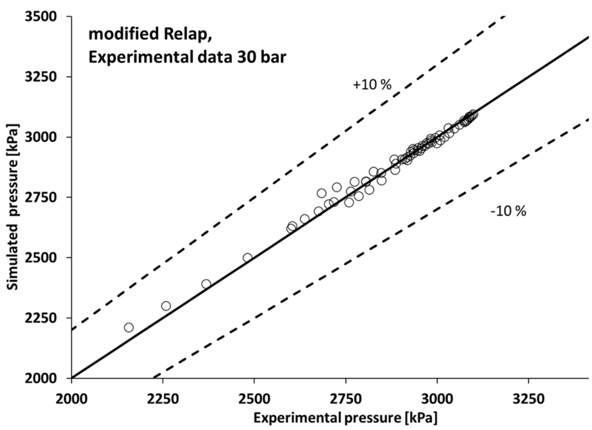

Figure 5. Pressures along the coil pipe predicted by the modified-R5 compared to experimental data [12].

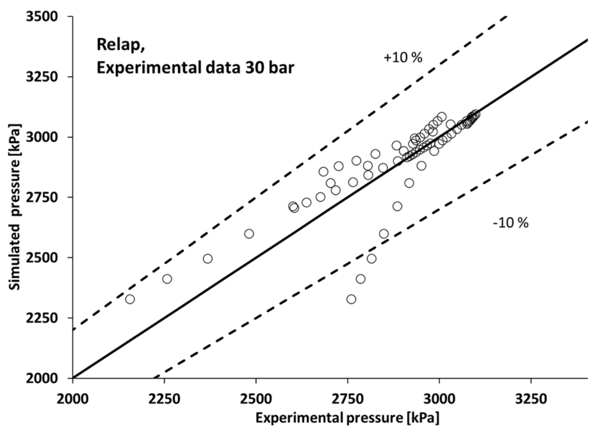

Figure 6. Pressures along the coil pipe predicted by the unmodified-R5 compared to experimental data [12].

Table 2. RMSE of pressure drops calculated by modified-R5 and unmodified-R5.

Test Pressure [MPa]	RMSE, modified Relap P [kPa]	RMSE, unmodified Relap P [kPa]
3	22.52	112.73
4	28.66	102.83
6	17.8	69.38

4.2 HPs with 0.64 m and 1 m coil diameters under atmospheric pressure

The experimental facility at the Department of Energetics of Polytechnic of Torino consists of an air/water flow loop, to which various helical test sections were connected [13].

The helical test sections, constructed from plexiglass to allow observation of flow patterns, consist of two pipes with inner and outer diameters of 0.012 m and 0.018 m, respectively. The first pipe, referred to as "coil 1," has 10.25 m length, 0.64 m diameter, and 0.485 m pitch. The second pipe, "coil 2," features 10.07 m length, 1 m coil diameter, and 0.79 m pitch. The curvature ratios, d/D, for the two coils are 0.01875 and 0.012, respectively. Water was circulated at flow rates ranging from 200 to 800 l/h, while the air flow rate varied from a minimum of 0.043 g/s to a maximum of 0.26 g/s. Pressure drops were recorded using eight pressure transducers positioned along the length of the coiled tubes. The test data for each coil diameter were simulated by setting the water flow rate and adjusting the air flow rate. This process was repeated for all the different water flow rates tested.

Fig.s 7 and 8 present comparisons between experimental pressure drop data along the test section and predicted values for various two-phase mass flow rates. Notably, discrepancies are observed in the predictions from both the modified-R5 and unmodified-R5 codes when compared to many of the experimental measurements. These differences are evident for both coil diameters.

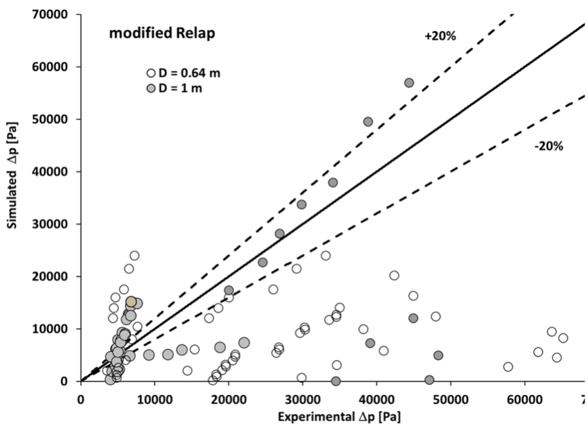

Figure 7. Predicted pressures along the coiled pipe using the modified-R5 compared to experimental data at atmospheric pressure [13].

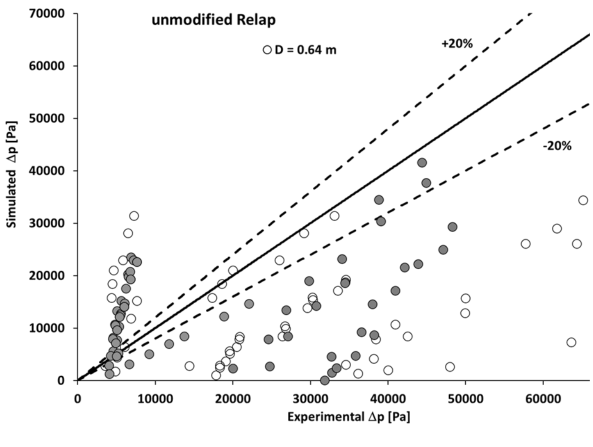

Figure 8. Predicted pressures along the coiled pipe using the unmodified-R5 compared to experimental data at atmospheric pressure [13].

5 Conclusions

The Relap5/Mod3.3 code was used to predict pressure drops in vertical HPs for both single-phase and two-phase flows. This code was enhanced with specific correlations designed to capture key aspects of the complex fluid behavior in these systems.

For single-phase flow, the friction factor correlations from Ito were applied, while for two-phase flow, a modified version of the L-M method, as presented in [5], was used. Experimental data from various international and national research laboratories were employed to validate the model.

The updated Relap5 code enhances the accuracy of pressure drop predictions in HPs for different single-phase flow configurations.

In the case of two-phase flows, good results are obtained for operating conditions characterized by high pressures, while the results are insufficient for conditions at atmospheric pressure. However, the latter result was to be expected because the model reported in [5] was obtained using experimental data characterized by operating pressures higher than 2 MPa.

This aspect will be the subject of further investigations aimed at understanding the applicability of the modified Relap5 code even at lower pressures.

References

[1] International Atomic Energy Agency, 2005, Innovative small and medium sized reactors: design features, safety approaches and R&D trends, IAEA-TECDOC-1451.

[2] Fletcher CD et al., RELAP5/MOD3 Code manual, NUREG/CR–5535, INEL–95/174, Idaho National Engineering Laboratory.

[3] Ito H, 1959, Friction factors for turbulent flow in curved pipes, ASME J. Basic Eng. Trans., 81.

[4] Colombo et al., 2015, A scheme of correlation for frictional pressure drop in steam–water two-phase flow in helicoidal tubes, Chem. Eng. Sci., 123, 460-473.

[5] Ferraris DL, Marcel CP, 2020, Two-phase flow frictional pressure drop prediction in helical coiled tubes. Int. J. of Heat and Mass Transfer, 162, 120372.

[6] Lockhart RW, Martinelli RC, 1949, Proposed correlation of data for isothermal two-phase two-component flow in pipes Chem. Eng. Prog., 45, 39-48.

[7] Guo L, Feng Z, Chen X, 2001, An experimental investigation of the frictional pressure drop of steam-water two-phase flow in helical coils, Int. J. Heat Mass Transfer, 44 (2001), 2601-2610.

[8] Castiglia F, Giardina M, Morana G, De Salve M, Panella B, 2012, Analyses of single- and two-phase flow pressure drops in helical pipes using a modified RELAP5 code, Nuclear Engineering and Design, 250, September 2012, pp 585-591

[9] Chaxton KT, Collier JG, Ward JA, 1972, H.T.F.S. Correlation for Two-Phase Pressure Drop and Void Fraction in Tubes, AERE-R7162, 1972.

[10] Ali S, 2001, Pressure drop correlations for flow through regular helical coil tubes, Fluid Dyn. Res. 28, 295-310.

[11] Coronel P, Sandeep KP, 2003, Pressure drop and friction factor in helical heat exchangers under nonisothermal and turbulent flow conditions, J. of Food Process Engineering, 26(3), 285-302.

[12] Santini L, 2008, Thermalhydraulic issues of IRIS nuclear reactor helically coiled Steam Generator and Emergency Heat Removal System, PhD Thesis, Dipartimento di Ingegneria Nucleare, Politecnico di Milano.

[13] Bertani C, De Salve M, Malandrone M, Orio M, Panella B, 2007, Studio sperimentale del deflusso bifase aria-acqua in un tubo elicoidale, XXV Congresso Nazionale UIT sulla Trasmissione del Calore, Trieste, 18-20 June 2007.

Acknowledgments

The authors wish to acknowledge Dipartimento Energia, Politecnico di Torino, and Dipartimento Energia, Politecnico di Milano, for providing the experimental data used in this article.

These data have significantly enriched the quality and robustness of our analyses, thereby contributing to the validity of the presented results.