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A New Two-Phase Friction Multiplier Approach for Annular Flow in Helically Coiled Tube

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ABSTRACT

This study considers the prediction of the two-phase frictional pressure drop with water–steam flows through helically coiled steam generator, special emphasis is given to the annular flow present in helical systems. An empirical correlation based on the Lockhart-Martinelli parameter is proposed and fitted using an experimental pressure drop database containing 698 points. A new pressure drop correlation for helically tubes is proposed to increase prediction and knowledge in this class of systems, selecting only annular flow data. The new correlation is suitable for the following operation variables, the mass flux in the range of 192 to 810 $\frac{kg}{m^2\,s}$, the quality from 0.13 to 0.89, the pressure from 1.7 to 6.3 MPa and heat flux from 43.68 to 232.87 $\frac{kW}{m^2}$.

Keywords: Lockhart-Martinelli parameter, steam generator, flow pattern, thermo-hydraulic analysis, energy science.

NONMENCLATURE

D	helix diameter	m
d	tube inner diameter	m
f	friction factor (Darcy)	
G	mass flux	kg/m^2s
P	Pressure	Pa
RMSE	Root Mean Squared Error	
x	thermodynamic equilibrium quality	
Symbol		
s ρ^*	photographic density	kg/m^3
ρ	density	kg/m^3
μ	viscosity	$Pa \times s$
ϕ_l^2	Two-phase multiplier (liquid-only)	

1. INTRODUCTION

Helical coil heat exchangers have recently been involved in sustainable projects in different energy conversion systems, for instance geothermal heat exchangers, solar energy concentration, evaporators [1], condensers [2], as well as, as a component of power plant or nuclear reactor applications. Helical coils are compact and promote a favorable heat exchange, however the pressure drop of boiling fluids increases considerably compared to horizontal pipes. In real application, the calculation of the pressure drop of the boiling flow of a helical coils is essential to determine the total head of the feed water pump in a Rankine Cycle.

Several authors have worked on the thermal-hydraulic characterization of the two-phase flow in helical pipes, with special emphasis on frictional pressure drop, below some examples considering water flow boiling.[3] presents an frictional two-phase pressure drops correlation in a helically coiled steam generator, the experimental campaign collected 940 experimental points under several operating conditions range from

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192 to 824 $\frac{kg}{m^2s}$ for the mass flux, from 0 to 1 for the quality, from 1.1 to 6.3 MPa for the pressure, from 50 to 200 $\frac{kW}{m^2}$ for the heat fluxes.[4] carry out a study with special emphasis on low-medium pressure, low mass flux and low heat flux of typical of single-pass steam generators with boiling in the tube, interesting in the article is the consideration of the homogeneous model to present the new methodology.[5] have developed a new correlation that provides higher prediction precision compared to other correlations for nucleate boiling using experimental data, the system pressure was in the range of 1.8 MPa and 7.8 MPa, mass flux ranged between 300 $\frac{kg}{m^2s}$ and 1100 $\frac{kg}{m^2s}$, and heat flux varied from 100 $\frac{kW}{m^2}$ to 450 $\frac{kW}{m^2}$. A correlation to calculate the liquid-only two-phase frictional pressure drop multiplier was presented by [6] for helical pipes of inner diameters of 12.5 mm and 14.5 mm, helical coils of 180, 280 and 380 mm and the system pressure range from 2 to 8 MPa.[7] develop a computational model to predict the thermo-fluid-dynamic behavior of a helically coiled steam generator by proposing a frictional two-phase pressure drops correlation based on Martinelli parameter and experimental information of [3]. The papers previously described study the thermal and hydraulic behavior of the boiling flow in helical pipes, however, the flow pattern present in the two-phase flow have not yet been emphasized. As far as is known, propose correlations based on the knowledge of the flow patterns in two-phase flow increases the precision of the prediction and the future design of this kind of helical coils.

The objective of this study is to present a new correlation to predict a liquid-only two-phase frictional pressure drop multiplier as a function of the Martinelli parameter and exclusive for annular flow. The new equation is based on the experimental helical coil once-through steam generator campaign described in [3] and [7].

2. SYSTEM DESCRIPTION

Figure *1* shows the schematic diagram of the experimental apparatus used in this study. A complete description of the experimental test facility was also described in [3].

The facility is made by a supply section and test section. The flow rate is controlled with a throttling valve positioned downwards the feedwater pump, and with a by-pass line; the throttling valve introduces a strong localized pressure drop in order to avoid any eventual dynamic instability. An electrically heated helically coiled pre-heater is located before the test section and allows creating the desire temperature at test section inlet. The test section is electrically heated via Joule effect by DC current. Two distinct independently controllable and contiguous section are provided: the first one (24 m long) simulates the subcooled zone and the two-phase zone of the steam generator.

The test section consists of a stainless-steel tube, curved in helical shape, and connected to a lower and an upper header. The geometric data of the steam generator tube are show in Table *1*.

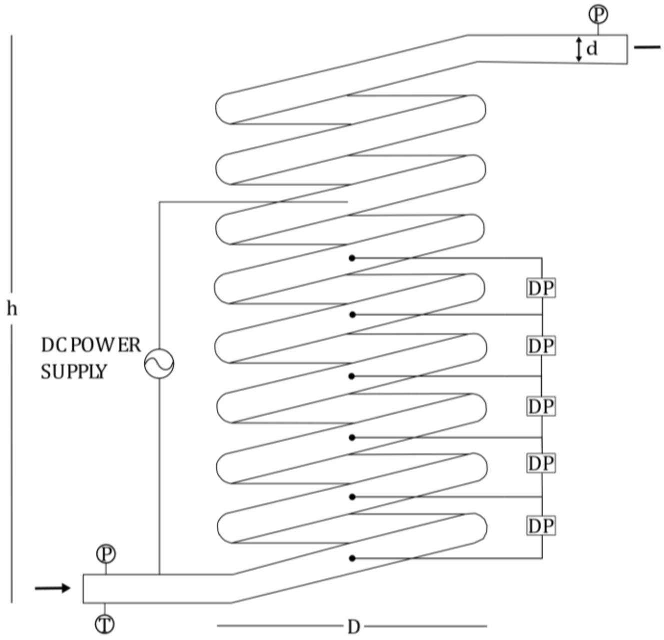


Figure 1 Schematic Diagram of the steam generator

An accurate measurement of the flow rate is obtained by a Coriolis flowmeter, having a maximum error of about 1% in the range of the explored flow rates. Fluid bulk temperature is measured at inlet with K-type thermocouples. Pressures is measured in the at inlet by absolute pressure transducers. Nine pressure tabs are disposed nearly every 4 m along the coiled tube and eight differentials connected the pressure taps for differential pressure measurements. The main data of the operation conditions and transport characteristic are listening in Table *2*. The steam generator tube is carefully insulated, and the small thermal losses were previously determined.

Table 1 Test section geometry

Parameters	Value
Tuber material	SS AISI 316
Inner diameter, d (mm)	12.53
Outer diameter (mm)	17.24
Coil diameter, D (mm)	1000
Coil pitch (mm)	800
Tube length (m)	32
Steam generator height, h (m)	8
Number of pressure taps	9

2.1 Possible flow patterns involve in the helical coil.

The present work considers the use of flow pattern models and visual tools available for identification also called flow pattern map. When a liquid is vaporized in a heated channel the liquid and the vapor generated take a variety of configurations known as flow patterns.

Table 2 operation conditions and transport characteristic

Parameters	Value
Fluid	water-steam
Pressure (MPa)	$1.1 - 6.3$
Mass flux, G $(kg/m^2 s)$	$192 - 811$
Thermal flux (kW/m^2)	$50 - 200$
Reynolds number for liquid Re_l	$1.79e^{03} - 9.19e^{04}$
Reynolds number for vapor Re_v	$2.10e^{04} - 5.12e^{05}$
Dean number De	$2.15e^{03} - 1.19e^{04}$
Quality, x	$0 - 1$

These structures of the flow depend on the conditions of pressure, flow, heat flux and channel geometry. According to the analysis, we give special emphasis and define the following structures [8]. The first is the *annular flow*, it occurs at high surface velocities of steam flowing in the core of the cross-sectional area in the pipe. The liquid phase flows as liquid films that wet the walls and as small drops entrained in the core of the vapor phase. The gas and liquid droplets that flow in the nucleus can assume a homogeneous mixture. The second is the *churn flow* (also called semi-annular or slug-annular flow), it's a two-phase gas-liquid flow regime characterized by a highly agitated flow where the bubble gas are sufficient in numbers to both interact with each other. The vapor flows in a chaotic manner through the liquid which is mainly displaced to the channel wall.

One method of representing the various transitions is in form of a flow pattern map like shows in Figure *2*. The respective patterns maybe represented as areas on a graph, the co-ordinates of which are generalized parameters that contain the actual superficial phase velocities.

3. DATA REDUCTION

The methods used to study a two-phase flow are extensions of the use in single-phase flows. the procedure begins by describing the mass, momentum, and energy governing equations. The following hypotheses are considered, i) two-phase flow has a same velocity distribution, ii) the flow is assumed steady and characteristic mean values of phases densities and velocities are assumed, iii) one-dimensional separated phases model in which each phase is assumed occupying a definite portion of tube cross-sectional area.

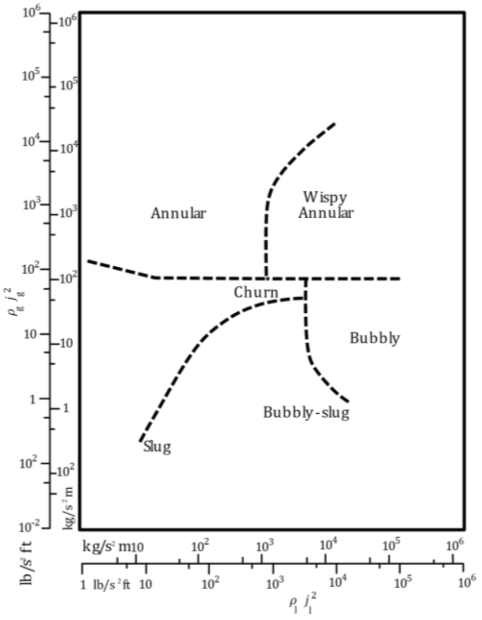


Figure 2 Flow pattern map for vertical flow [9]

The pressure drop can be expressed both by momentum balance as following:

$$dP_M = G^2 d\left[\frac{x^2}{\alpha\rho_g} + \frac{(1-x)^2}{(1-\alpha)\rho_l}\right] + \tau_w \frac{s}{A} ds + \rho^* g dz \qquad 1$$

The energy balance can be formulated as following:

$$dP_E = \frac{1}{2}\rho_m G^2 d\left[\frac{x^3}{\alpha^2\rho_g^2} + \frac{(1-x)^3}{(1-\alpha)^2\rho_l^2}\right] + \ldots \qquad 2$$

$$\ldots + \rho_{mdR_m} + \rho_m g \cdot dz$$

where R_m is the energy dissipated per unit mass in the fluid flow due to reversibility, x is the equilibrium thermodynamic quality, α is the volumetric gas fraction, G is the mass flux, $\tau_w$is the tangential stress in the wall, s is tube perimeter, A is the inner cross-sectional area of the tube, p_l and p_g are the density of the liquid and vapor phases respectively, ρ^* is the real density (photographic density) given by:

$$\rho^* = \alpha\rho_g + (1-\alpha)\rho_l \tag{3}$$

and ρ_m is the flow rate mixture density (identical to the homogeneous value):

$$\rho_m = \frac{1}{v_m} = \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right)^{-1} \tag{4}$$

The total pressure losses obtained by applying equations *1* and *2* are obviously the same $(dP_M = dP_E)$, but different are the relative weight and the physical meanings of the three terms involved. Friction, gravity, and acceleration terms coincide in the momentum and energy balance approaches for the total pressure drops.

The frictional pressure drops are directly correlated to the system parameter, such as flow rate, quality, and pressure. In the present work, we only considered an only-liquid two-phase friction multiplier ϕ_l^2, that is defined as the ratio between two-phase pressure drops and the the pressure drops obtained when the liquid phase is assumed to flow alone in the channel at its actual flow rate.

$$\phi_l^2 = \frac{\left(\frac{dp}{dz}\right)_{fric}^{TP}}{\left(\frac{dp}{dz}\right)_{fric}^{l}} \tag{5}$$

For the term in the numerator, we can obtain from the data where the gravitation and the acceleration terms are calculated and subtracted to the total pressure losses that are include in in the data, as shown by the following equation:

$$dP_f = dP_{measured} - G^{2d}v_m - \rho_m \cdot gdz \tag{6}$$

The denominator of (*5*) can be calculated using the correlation for pressure drops due the friction in single phase

$$dP_f = f\frac{G_l^2}{2\rho_l d}ds \tag{7}$$

where f is the Darcy friction factor, which is evaluated from the equation (8), it was proposed by White for considering $Re > 2300$ and suggested for this kind of system in the work of [7].

$$f = 0.32Re^{-\frac{1}{4}} + 0.0480\left(\frac{d}{D}\right)^{\frac{1}{2}} \tag{8}$$

where d is the tube inner diameter and D is the helix diameter. Several authors and formulations have concluded that the friction factor multiplier can be predicted only knowing the pressure drop in a single-phase and the Lockhart-Martinelli correlation. Equation 9 shows the approximation of Lockhart-Martinelli.

$$X_{tt}^2 = \left(\frac{\mu_f}{\mu_g}\right)^{0.25}\left(\frac{1-x}{x}\right)^{1.75}\left(\frac{\rho_g}{\rho_f}\right) \tag{9}$$

where X_{tt} is the Lockhart-Martinelli parameter, μ_f and μ_g are the dynamic viscosity of the liquid and vapor flow, respectively. The traditional approach to approximate the two-phase friction multiplier factor for turbulent flow is as follows:

$$\phi_l^2 = 1 + \frac{20}{X_{tt}} + \frac{1}{X_{tt}^2} \tag{10}$$

where the coefficients, 1, 20 and 1 can be adjusted to available experimental data. As can be seen in [7]. The Lockhart-Martinelli approach can be used to estimate the two-phase flow, however, there is no clear difference between the flow structures that could manifest in the helical system.

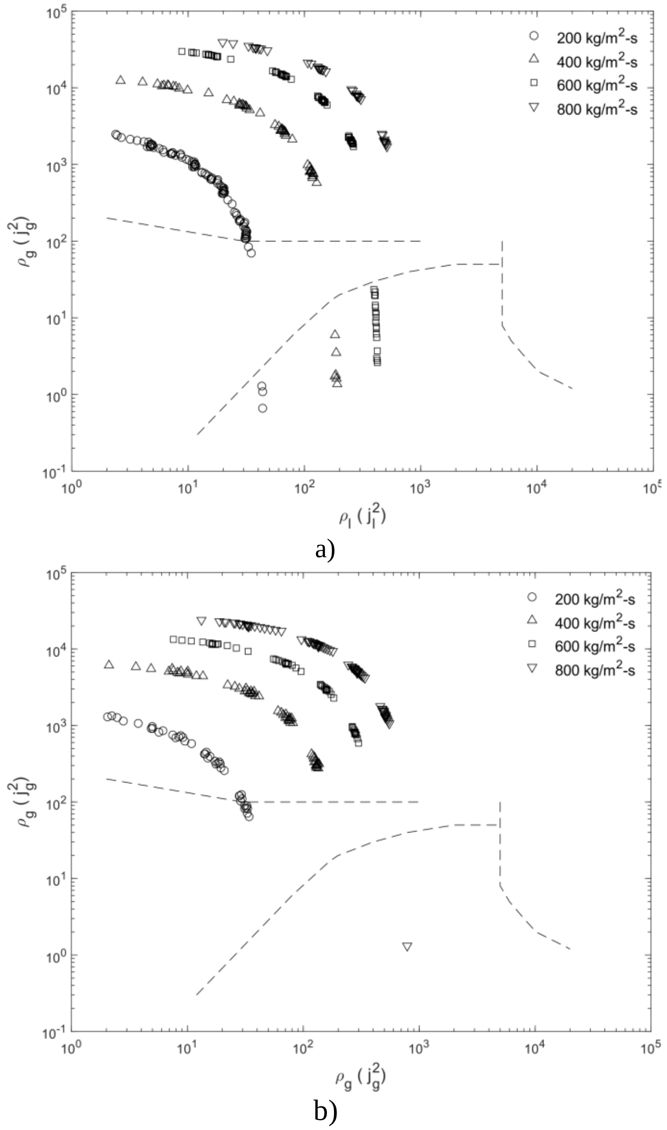
As far as the authors are aware, it is necessary to use an appropriate flow structure map, however, as a first step we use the map shown in Figure *2* for vertical flow and obtained from [9]. This map is in term of the superficial momentum of the liquid and vapor phases defined in equations (11) and (12)

$$\rho_l(j_l)^2 = \frac{G^2(1-x)^2}{\rho_l} \tag{11}$$

$$\rho_v (j_v)^2 = \frac{G^2 x^2}{\rho_v} \qquad 12$$

4. RESULTS AND DISCUSSION

The superficial momentum of vapor and liquid was calculated and plotted in the map, and four flow patterns were identified as show in Figure 3 for 20 and 40 bar of pressure operation



a)

b)

Figure 3 Flow pattern for the data, at a) 20 bar, b) 40 bar

During the analysis and construction of figure 3 some of the points collected from the experimental campaign are out of the limits, and it's not possible to identify a pattern in this case. These points are related with very lows or high qualities, this is possible assume that these points don't have a pattern because the poor presence of a second phase in the flow.

One frictional pressure drop correlation considering the annular flow regime was proposed as following:

$$\left(\phi_l^2\right)_{annular} = 1 + \frac{3.113}{X_{tt}} + \frac{2.997}{X_{tt}^{1.946}} \qquad 13$$

This correlation is valid in the experimental campaign conditions (both geometrical parameters and range of operating variables) containing 698 points of the 940 points available.

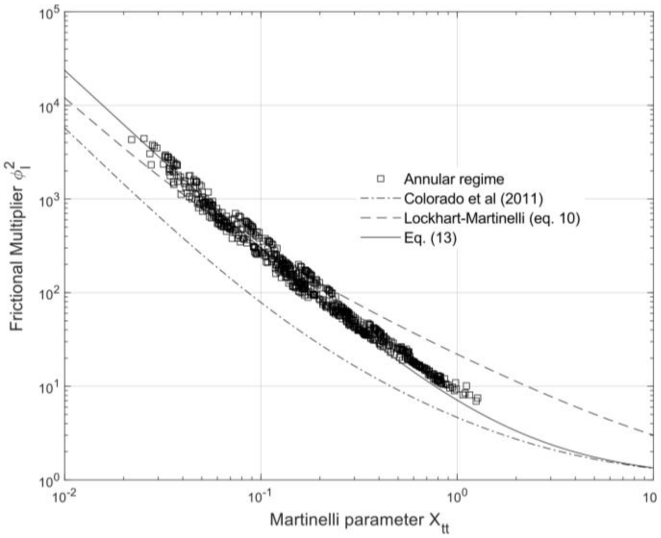


Figure 4 Pressure drop multiplier versus Lockhart-Martinelli parameter for experimental data, the equation proposed in this work and correlations by other authors for helically coiled tube with special emphasis in annular flow.

The only-liquid two-phase friction factor multiplier was fitted as a function of the Lockhart-Martinelli parameter, the adjusted is shown in Figure *4*.

4.1 Statistic analysis.

To ensure the goodness of fit, the RMSE was calculated using the equation (14)

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n-1}} \qquad 14$$

Where $\hat{y}_i$ are predicted values, y_i are observed values and n the number of observations (680 points). Table 3 shows a comparison using RMSE of the model developed in this work (eq 13) and the comparison with adjustments previously reported by other authors.

Table 3. Comparison between the adjustment proposed in this work and previous author.

Correlation	RMSE
Lockhart-Martinelli (eq. 10)	847.4645
Colorado et el [6]	734.2354
This work	129.7921

The model shown in Eq. 13 presents the lowest RMSE value compared to previous adjustments, therefore the best representation of experimental data.

5. CONCLUSIONS

The present work has focused on developing a new friction multiplier approach capable of describing the pressure drop assuming annular flow in once-through steam generator. A data reduction has been carried out using a flow pattern map available and collected the experimental information for annular flow. The main contribution of work is the equation (13), it's not complex because the fitting is achieved via a statistical adjustment and the knowledge of the Lockhart-Martinelli parameter. Equation (13) can be useful to increase the quality of hydraulic calculations of helical systems in full-scale.

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