RELAP5 SIMULATION OF TWO-PHASE FLOW EXPERIMENTS IN VERTICAL HELICAL TUBES

M. Casamirra*, F. Castiglia*, M. Giardina*, G. Morana*, M. De Salve°, M. Orio°, B. Panella°

* Department of Nuclear Engineering of the University of Palermo
Viale delle Scienze-Parco d'Orléans, 90128 Palermo, Italy
° Politecnico di Torino Department of Energetics,
Corso Duca degli Abruzzi, 24, 10129 Torino Italy

ABSTRACT

In the framework of the studies concerning the thermalfluid dynamic phenomena in helicoidal pipes of the innovative nuclear reactor IRIS steam generators, the Department of Nuclear Engineering of the University of Palermo in collaboration with the Politecnico di Torino Department of Energetics has been engaged in a work aimed to adapt, by implementing new suitable models, RELAP5/mod3.2.2β code to simulate the thermalfluid-dynamics and geometries such as the ones involved in helicoidal pipes. In fact this code is based on one-dimensional thermal-hydraulic relationships and presents limitations to model complicated geometry such as helicoidal pipes. Therefore the code was improved with additional correlations that are valid for two-phase flow and allow to overcome the drawbacks. The validation work of the models that were added is based on the experimental data carried out at the Politecnico di Torino Department of Energetics. In this paper it will be shown that the so modified RELAP5 code allows to represent adequately the experimental data.

INTRODUCTION

The widespread use of the helicoidal pipes in heat exchangers for air conditioning and refrigeration systems, chemical reactors, and nuclear power engineering is due to the high efficiency in heat transfer and compactness in volume.

Depending on specific applications of these components, for adequate design purposes, it is important to dispose a thorough knowledge of pressure drop and heat transfer, both in single and in two phase flow conditions. In fact, as it is well known, the secondary flow due to the centrifugal force in the cross section of the helicoidal pipes is a significant factor affecting the entire phenomenology.

Recently, at the Politecnico di Torino Department of Energetics an experimental activity regarding the single and two phase flow phenomena taking place in helicoidal pipes has been carried out. On the other hand, the research group of the Department of Nuclear Engineering of the University of Palermo has been engaged in a validation work of models on these issues [1, 2], implemented in RELAP5/mod3.2.2β code [3]. This has been performed taking into consideration that the code, based on one-dimensional thermalhydraulic relationships, presents limitations for modelling complicated geometry and the thermalfluid dynamic phenomena such as those involved in helicoidal coil tubes. So, at first, the code was improved with additional correlations valid for single-phase flow that could allow to overcome these difficulties. Subsequently, it was modified to allow also the studies of two-phase flow by using Lockhart-Martinelli multipliers, valid for helical pipes, as modified by some authors [4-7].

In the framework of the collaboration undertaken between the above mentioned institutions, we continued the activity and in this paper report the results obtained by using this modified RELAP5 code version for the simulation of two-phase flow experiments in vertical helicoidal pipes.

The validation work has been performed by using experimental data carried out at Torino laboratory to investigate the effect of the centrifugal forces on the flow pattern. Two test sections with different helicoidal coil diameter were tested. The measured experimental data were the pressure drops along the helical pipe and the average void fraction detected by means of the quick closing valve technique.

In this paper it will be show that the so modified RELAP5 code allows to represent fairly well the experimental data taken into consideration.

ANALISYS OF EXPERIMENTAL DATA CARRIED OUT AT THE DEPARTMENT OF ENERGETICS OF POLITECNICO DI TORINO

Plant Description

For more details, we refer to [4, 5]. Here there is only a brief description of the test sections and the associated instrumentation.

The experimental facility consists of an air/water flow loop in which two different helical test sections are inserted. These are made of plexiglass pipes, 12 mm inner diameter, that are wrapped in two different helical coils: the first one with 1 m coil diameter and a helix pitch of 0.79 m; the second one with 0.64 m coil diameter and a helix pitch of 0.485 m.

The geometric characteristics are reported in Table 1.

Two different pumps were used to supply water flows in the ranges from 200 to 400 l/h, and from 400 to 800 l/h, respectively, for each water flow rate the air flow was varied from 0.043 g/s to 0.26 g/s.

The directly measured quantities were the flow rate, pressure drops and mass of water.

The air and water flow were measured by high precision rotameters, whereas, the pressure drops were measured by nine pressure taps disposed along the coiled tube and eight differential pressure transducers which connect the pressure taps.

Table 2 reports the various positions of the instruments to measure the pressure drop between the first tap (named by 1) and the subsequent ones (named by 2 through 9).

All the measured data were acquired by a multi-channel acquisition system which allows 25 readings per second for each channel.

	Description	SI	Helix 1	Helix 2
D	Helix diameter	m	0.64	1
R	Helix radius	m	0.32	0.5
d	Pipe diameter	m	0.012	0.012
p	Pitch	m	0.485	0.79
pr	Reduced pitch	m	0.0772	0.1257
pa	Dimensionless pitch		0.24	0.25
k	Curvature	1/m	2.95	1.88
τ	Torsion	1/m	0.71	0.47
ε	Dimensionless curvature		0.0177	0.0113
n	Coils number		5	3
L	Length	m	10.85	10.3
β	Helix angle	°	13.56	14.12

Table 1 - Test sections geometrical data

Taps Pos.	**Helix D = 0.64 m**		**Helix D = 1 m**	
	Δz [m]	**ΔL [m]**	**Δz [m]**	**ΔL [m]**
1-2	0.98	4.72	0.22	1.183
1-3	1.096	5.2	1.003	4.39
1-4	1.225	5.75	1.192	5.17
1-5	1.342	6.24	1.395	6
1-6	1.462	6.744	1.594	6.82
1-7	1.946	8.78	1.789	7.62
1–8	2.19	9.88	2.185	9.25
1–9	2.44	10.858	2.385	10.07

Table 2 – Level and coil pipe length differences between the first tap position and the subsequent ones

The void fraction was measured by the quick closing valves method which allows to trap the water hold-up in the test section.

Two-phase flow pressure drops

As well known, the total pressure gradient in two-phase flow $(dP/dz)_{TP}$ can be expressed by three terms:

$$\left(\frac{dP}{dz}\right)_{TP} = \left(\frac{dP}{dz}\right)_{TP,f} + \left(\frac{dP}{dz}\right)_{TP,g} + \left(\frac{dP}{dz}\right)_{TP,a} \quad (1)$$

where $(dP/dz)_{TP,f}$ is the friction pressure gradient, $(dP/dz)_{TP,g}$ the gravitational pressure gradient, and $(dP/dz)_{TP,a}$ the acceleration pressure gradient. Owing to no phase change the last term can be ignored.

For two-phase flow in vertical coils, the gravitational pressure gradient is determined from the void fraction data using the following equation:

$$\left(\frac{dP}{dz}\right)_{TP,g} \approx (1-\alpha)\rho_l\, g \sin\beta \quad (2)$$

with α the void fraction, ρ_l liquid density, g the gravitational acceleration and β helix angle.

The friction pressure gradient can be determined from the total pressure gradient, that is measured in the experiment, and the gravitational pressure gradient, that is calculated in accordance with Eq. (2), by using the following expression:

$$\left(\frac{dP}{dz}\right)_{TP,f} = \left(\frac{dP}{dz}\right)_{TP} - \left(\frac{dP}{dz}\right)_{TP,g} \quad (3)$$

It is to be noted that the fluid properties, especially the gas ones, were determined using the average value of inlet and outlet pressures as a reference.

The friction pressure drop data can be correlated as the pressure drop multipliers ϕ_L and ϕ_G versus Lockhart-Martinelli parameter χ, which are defined as follows:

$$\phi_L^2 = \frac{\left(\frac{dP}{dz}\right)_{TP,f}}{\left(\frac{dP}{dz}\right)_L}, \quad \phi_G^2 = \frac{\left(\frac{dP}{dz}\right)_{TP,f}}{\left(\frac{dP}{dz}\right)_G} \quad (4)$$

$$\chi^2 = \frac{\phi_G^2}{\phi_L^2} \quad (5)$$

The pressure drop multipliers, in case of straight pipes, are represented in terms of the Lockhart-Martinelli parameters by using the following correlations:

$$\phi_L^2 = 1 + \frac{C}{\chi} + \frac{1}{\chi^2} \quad (6)$$

$$\phi_G^2 = 1 + C\chi + \chi^2 \quad (7)$$

where the constant C changes from 5 to 20, depending on the laminar or turbulent flow that takes place in the pipe.

Concerning the two phase flow in helicoidal pipes, three forces affect the flow pattern and pressure drops: inertial force; liquid gravity; and centrifugal force. Inertial force enhances the mixing of the two phases; whereas liquid gravity and centrifugal forces, if each of them acts alone on the flow, tend to separate the two phases, due to the large density difference between the liquid and gas phases. However, when the flow direction changes, the net effect can be the separation or the mixing of the phases.

The effects of these forces can be represented in terms of Froude number, Fr ($Fr = u^2/gd$, with u the phase velocity, g the gravitational acceleration and d the tube diameter), the ratio of pipe diameter to helical one, d/D, and the helix angle, β.

Various authors [8, 9] indicate that most of the two-phase flow pressure drop data in helical coils can be satisfactorily predicted by the above quoted Lockhart-Martinelli correlations (4), with however the specific definition of the Lockhart-Martinelli parameter (5) based on the single-phase flow friction pressure drop in helicoidal pipes.

Furthermore, Xin et al. [6, 7] obtained extensive data on the pressure drop of two-phase flow in vertical and horizontal helicoidal pipes, respectively, and in ref. [6] correlated the friction pressure drop multipliers as a function of Fr, d/D, β parameters.

In particular, they propose the following relationship to evaluate the pressure drop multipliers ϕ_L, to deal with helicoidal geometry:

$$\phi_L = [1 + K \;\; \chi \;\; Fd^n](1 + \frac{C}{\chi} + \frac{1}{\chi^2})^{1/2} \qquad (8)$$

with C is equal to 20.0 and the parameter F_d defined as:

$$F_d = Fr_L \left(\frac{d}{D}\right)^{1/2} (1 + \tan\beta)^{0.2} \qquad (9)$$

where Fr_L is the liquid phase Froude number.

The values of the other parameters in Eq. (8) are reported in Table 3.

Fd	**≤ 1**	**≥ 1**
K	0.01528	0.0023
n	-0.6	-1.7

Table 3 – Values of the parameter in Eq. (8)

With this, the liquid phase influence is taken into account by the liquid Fr number, whereas the influence of the gas phase is accounted by the Lockhart-Martinelli parameter χ.

The above relationships are valid in the range of D/d = 26 through 50. The maximum deviation between the prediction of Eq. (8) and the experimental data of the pressure drops multiplier ϕ_L was evaluated by Xin about ± 35 %.

On the basis of experimental data performed at Torino Laboratory, the constant C was estimated equal to 36.85 to get good results. Note that these experiments are characterized by ratio D/d of 53 and 83 which are higher than the geometrical conditions used by Xin.

RELAP5 ANALYSIS

Taking into account what has been reported in the previous paragraph, the RELAP5/Mod3.2.2β code was supplemented by FORTRAN subroutines, which can allow to simulate the geometrical data and thermal-hydraulic conditions as suggested by Eq. (8).

To evaluate the two-phase flow pressure drops, Eq.s (4), (5) and (8), (9) were used. Moreover, to calculate the friction factor in single-phase pressure gradients, $(dP/dz)_L$ and $(dP/dz)_G$, in the above mentioned equations, the Ito correlations [10] as described in Table 4 were used.

In this Table Re is the Reynolds number, D is the helix diameter and d the internal duct one.

$f_c = \frac{16}{Re}$	$Re < 13.5(D/d)^{-0.5}$
$f_c = \frac{344(D/d)^{-0.5}}{\{1.56 + \log_{10}[Re(D/d)^{-0.5}]\}^{5.73}}$	$13.5(D/d)^{0.5}<Re<13.5(D/d)^{-0.5}$
$f_c = 0.076\,Re^{-0.25} + 0.0075 \cdot \left(\frac{D}{d}\right)^{-0.5}$	$Re > 15000$

Table 4- Friction factor losses from Ito correlation

The constant C values of 20 and of 36.85 have been tested for comparison purpose.

To simulate the considered experimental data, Relap5 nodalization, shown in Fig. 1, was used.

The time dependent volume components, numbered 500 and 560, were used to specify the inlet and outlet conditions of the helical coil loop.

Through the time dependent junction, named 505 (TMPJUN505), the air/water mixture is sent to PIPE 506 which schematizes helical coil inlet condition. By using this junction the air/water flow conditions are changed, according to the simulated experiments.

The helical pipe is represented by the volume PIPE 510, divided into 50 sub-volumes, for a better approximation of pressure taps position along the pipe length. In each internal junctions of this pipe, a flag which allows helical tube models application has been used.

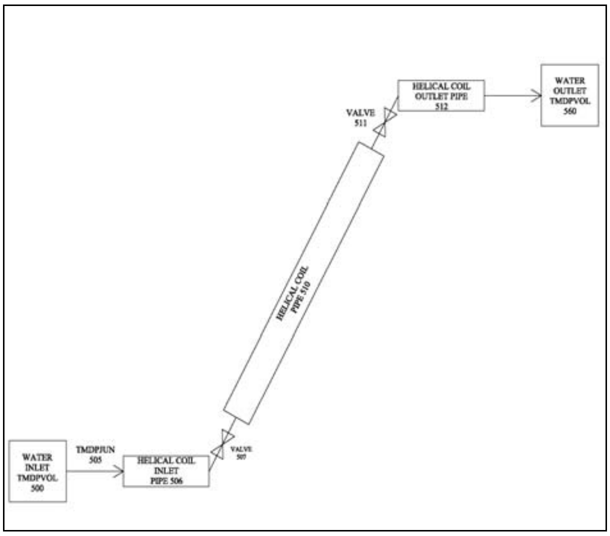

Figure 1 - Relap5 plant nodalization

RESULTS

The experimental data have been simulated by the modified RELAP5/mod3.2.2 β code, for each coil diameter, by setting the water flow, and changing the air flow. This operation is repeated for all water flow values.

The same cases have been simulated by the not modified Relap5 code, which, as expected, heavily underestimates the experimental data, as shown only in some graphs. In table 5 are reported the simulated tests.

For the sake of brevity, only some results are shown in this paper.

Figures 2 through 5, for a helix diameter equal to 0.64 m, show the total pressure drops along the helical coil, with an increasing water flow. Below water flow value of 600 l/h, the best prediction is obtained taking the constant C equal to 36.85, with an error lower than 10%, whereas by using C = 20 the error can reach also 40%. It's evident that for water flow equal to 800 l/h, the code prediction with C = 36.85 worses, while with C = 20 improves. As previously said the not modified code gives bad results.

The same behaviour is obtained for the experiments with helix diameter of 1 m, as it can be seen in Figures 6 through 8.

On the contrary for the maximum water flow value (800 l/h) the situation reverses (Fig. 9) and the modified code prediction with C = 20 gives the best results.

D_{helix} = 0,64 m						
W_{water} [l/h]	W_{air} [l/h]					
300	50	100	150	200	250	300
400	50	100	150	200	250	300
600	50	100	150	200	250	300
800	50	100	150	200	250	300
D_{helix} = 1 m						
W_{water} [l/h]	W_{air} [l/h]					
200	50	100	150	200	250	300
300	50	100	150	200	250	300
350	50	100	150	200	250	300
400	50	100	150	200	250	300
600	50	100	150	200	250	300
800	50	100	150	200	250	300

Table 5 – Experimental tests conditions

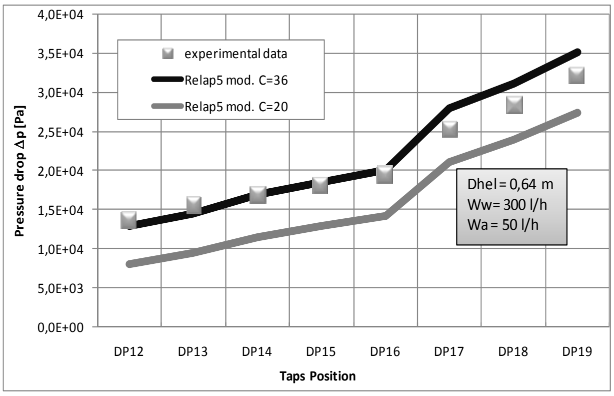

Figure 2 - Pressure drops between the first tap (1) and the subsequent ones (2-9), at W_{water} = 300 l/h and W_{air} = 50 l/h.

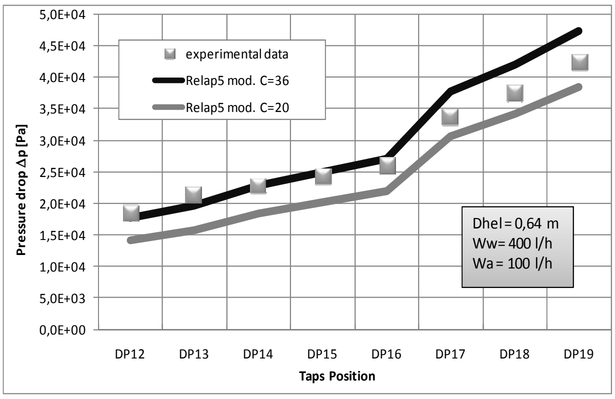

Figure 3 - Pressure drops between the first tap (1) and the subsequent ones (2-9), at W_{water} = 400 l/h and W_{air} = 100 l/h.

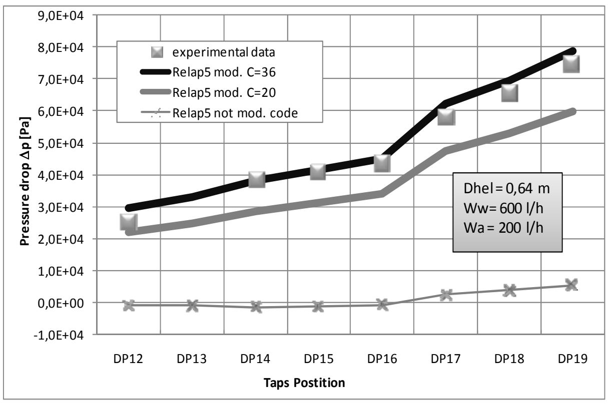

Figure 4- Pressure drops between the first tap (1) and the subsequent ones (2-9), at W_{water} = 600 l/h and W_{air} = 200 l/h.

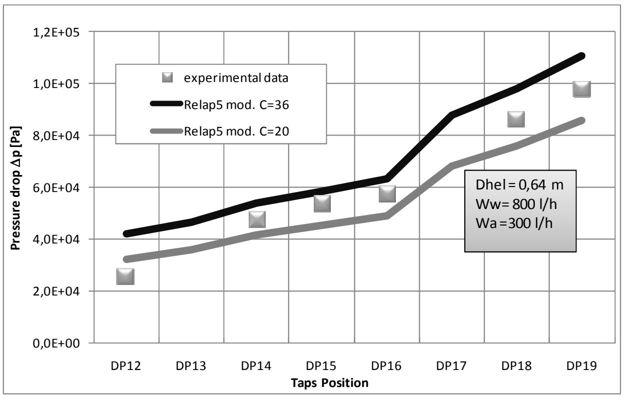

Figure 5 - Pressure drops between the first tap (1) and the subsequent ones (2-9), at W_{water} = 800 l/h and W_{air} = 300 l/h.

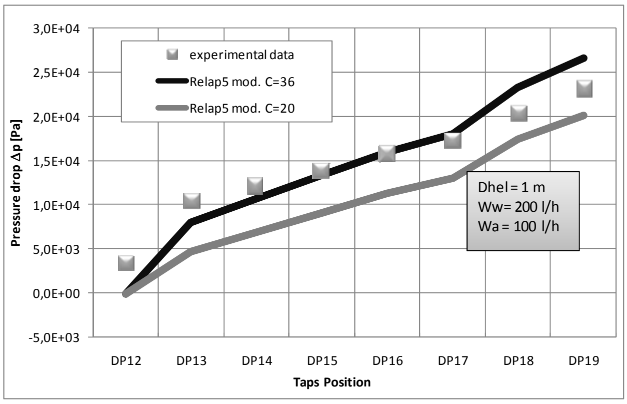

Figure 6 - Pressure drops between the first tap (1) and the subsequent ones (2-9), at W_{water} = 200 l/h and W_{air} =100 l/h.

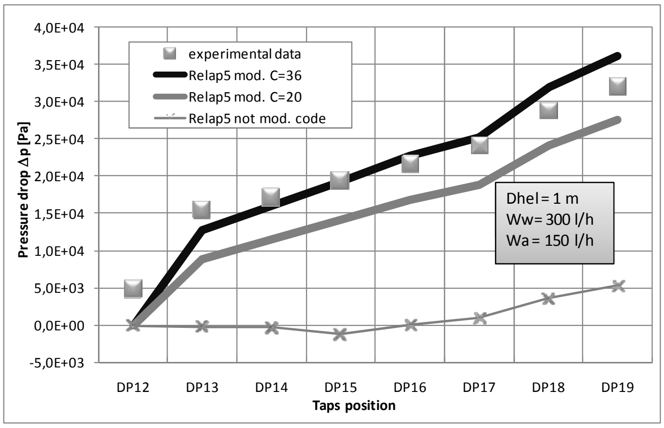

Figure 7- Pressure drops between the first tap (1) and the subsequent ones (2-9), at W_{water} = 300 l/h and W_{air} = 150 l/h.

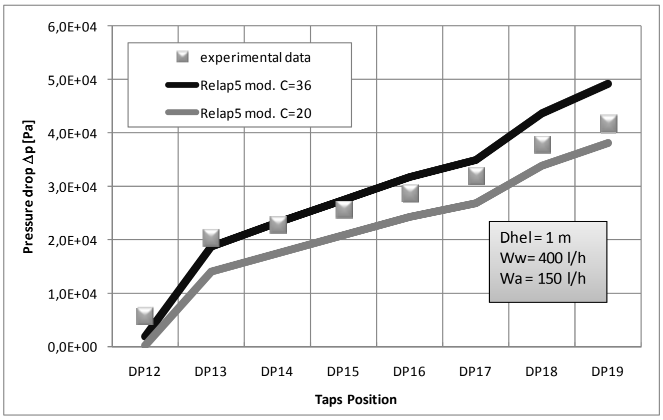

Figure 8- Pressure drops between the first tap (1) and the subsequent ones (2-9), at W_{water} = 400 l/h and W_{air} = 150 l/h.

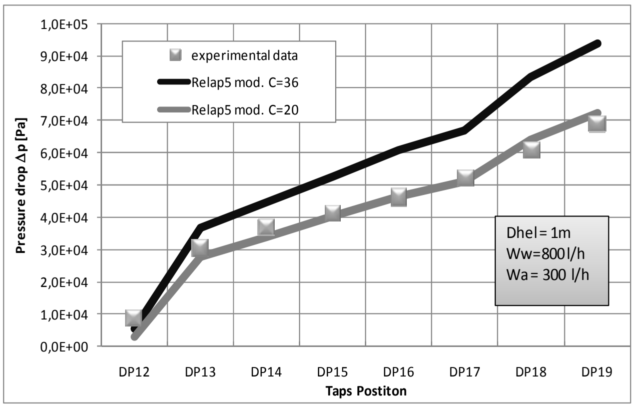

Figure 9- Pressure drops between the first tap (1) and the subsequent ones (2-9), at W_{water} = 800 l/h and W_{air} = 300 l/h.

CONCLUSION

Recently, at the Department of Nuclear Engineering of the University of Palermo, our research group has been engaged in a validation work of models implemented in RELAP5/mod3.2.2β code to simulate the geometries and thermalfluid-dynamic phenomenologies involved in helical pipes. This has been performed taking into consideration that the code, based on one-dimensional thermalhydraulic relationships, presents limitations for modelling the complicated geometry and the thermalfluid-dynamic phenomena such as those involved in helical coil tubes. So the code was modified by using Lockhart-Martinelli multipliers as reported in [5].

The validation work concerned the simulation of some experimental data regarding two helical test sections and different operating conditions, performed at Politecnico di Torino Department of Energetics.

The obtained results (Fig.s 2 through 4 and 6 through 8) show that by using for the constant C in Eq. (8) the value of 36.85, as suggested in [5], there is a good agreement between code predictions and experimental data up to a water flow rate of 600 l/h.

The results also seem to suggest that probably, for higher water and air flows, the value of constant C decreases tending to 20, as reported in literature for straight tubes (see Fig.s 5 and 9). This condition is more evident for the higher helix diameter value (D = 1 m).

It is to be observed that here the influence of the gas Froude number hasn't been considered in its completeness and this can play a role in the simulated phenomenology.

Further investigations both of theoretical and experimental nature are necessary to precise the above quoted aspects.

REFERENCES

[1] M. Casamirra, F. Castiglia, M. Giardina, P. Meloni, RELAP5 Modification for CHEOPE Simulations, International Conference Nuclear Energy for New Europe, Bled, Slovenia, September 5-8, 2005.

[2] M. Casamirra, F. Castiglia, M. Giardina, C. Lombardo, Studio con il codice RELAP5 delle perdite di carico e dello scambio termico in tubi elicoidali interessati da deflussi monofase, XXVII Congresso Nazionale UIT sulla Trasmissione del Calore, Reggio Emilia, 22-24 Giugno 2009, ISBN: 978-88-7488-312-7.

[3] C.D. Fletcher, R.R. Scuhltz, RELAP5/MOD3 Code manual, NUREG/CR–5535, INEL–95/174, Idaho National Engineering Laboratory, June 1995.

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

[5] C. Bertani, M. De Salve, M. Malandrone, M. Orio, B. Panella, Cadute di pressione e grado di vuoto in condotti elicoidali: confronto tra risultati sperimentali e modelli semiempirici, XXVI Congresso Nazionale UIT sulla Trasmissione del Calore, Palermo, 23-25 Giugno 2008.

[6] R.C. Xin, A. Awwad, Z. Dong, M.A. Ebadian, H.M. Soliman, An Investigation and Comparative Study of the Pressure Drop in Air-Water Two-Phase Flow in Vertical Helicoidal pipes, Int. J. Heat and Mass Transf., vol. 39, pp.735-743, 1996.

[7] R.C. Xin, A. Awwad, Z. Dong, M.A. Ebadian, An experimental study of single-phase and two-phase flow pressure drop in anular helicoidal pipes, Int. J. Heat and Fluid Flow, 18, pp. 482-488, 1997.

[8] G. R Rippel, C. R. Eidt, and H. B. Jornan, 1966, Two-phase flow in a coiled tube. Ind. Eng. Chem., 5, 32-39.

[9] S. Banerjee, E. Rhodes, and D. S. Scott, 1969, Studies on concurrent gas-liquid flow in helically coiled tubes. I-Flow patterns, pressure drop, and holdup, Can. J. Chem. Eng., 47, 445-453

[10] H. Ito, 1959, Friction factors for turbulent flow in curved pipes, Trans Series D, J. Basic Engng 81, 123–134