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Single and two-phase flow fluid dynamics in parallel helical coils

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Abstract. The design of helical coiled steam generators requires the knowledge of the single and two-phase fluid dynamics. The present work reports the results of an experimental campaign on single-phase and two phase pressure drops and void fraction in three parallel helicoidal pipes, in which the total water flow rate is splitted by means of a branch. With this test configuration the distribution of the water flow rate in the helicoidal pipes and the phenomena of the instability of the two-phase flow have been experimentally investigated.

1. Introduction

The helicoidal pipes have been used extensively in chemical engineering and nuclear power, like heat exchangers and steam generators. They are adopted in the nuclear field for their compactness and the heat transfer high efficiency; in order to perform a good design it is important the knowledge of pressure drops and heat transfer, both in single and in two phase flow conditions. A review on flow and heat transfer on curved tubes is due to Naphon and Wongwises [1]; in the framework of integral Small-medium Modular Reactors (SMRs) steam generators, Santini et al [2,3], Papini et al. [4], Bertani et al. [5] have studied several aspects of pressure drops and two-phase flow in helical pipes. Some preliminary results have been presented at XXX UIT Heat Transfer Conference [6]. The approach by means of the CFD codes has been used by Jayakumar et al. [7] to compare the CFD results with experimental friction factors.

The present work reports the results of an experimental campaign on single-phase and two phase pressure drops and void fraction in three parallel helical pipes, in which the total water flow rate is splitted by means of an inlet branch; with this test configuration the main objective is to experimentally investigate the distribution of the water flow rates in helical pipes and the phenomenon of the instability of the two-phase flow.

2. Experimental facility

The experimental facility at the Energy Department of the Polytechnic of Turin, consists of three helicoidal test sections, the water and air lines, an inlet branch and an outlet branch, the instrumentation for measuring the flow rates and the differential and absolute pressures, and the acquisition data system. The figure 1 shows the experimental facility schematic and a picture of it.

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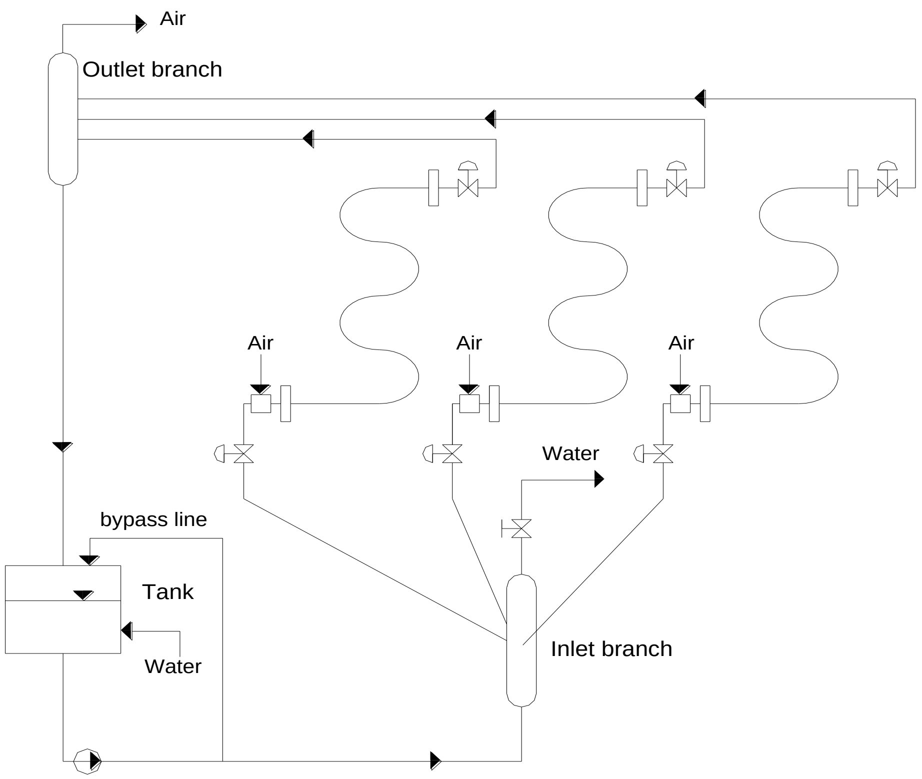

(a)

(b)

Figure 1. Experimental facility: schematic **(a)** and picture **(b)**

The three test sections have the helix diameter of 0.64 m, 1 m and 1.39 m and pitches of 0.485 m, 0.79 m 0.954 m respectively; they are made with tubes of polymethylmethacrylate whose inner diameter is equal to 12 mm; the geometry characteristics of the helical coils are shown in table 1.

Table 1. Geometry parameters

Test section pipe number	1	2	3
Helix diameter D [m]	0.64	1	1.39
Helix pitch p [m]	0.485	0.79	0.954
Inner diameter tube d [mm]	12	12	12
Helix length L [m]	10.85	10	13.9
Turns	5	3	3
Branch length [m]	1.2	1.2	1.2
Outlet straight pipe length [m]	2.82	0.71	5.52

A centrifugal pump sucks water from a tank, where the water flow in turn returns by means of an outlet branch. A bypass system that is placed after the pump provides for the regulation of the water flow rate. Downstream of the pump there is the inlet branch, from which the branches of pipes which feed the three test sections depart.

The feed branches of the three helical coils are placed symmetrically at 120 ° from each other and are located at half the height of the inlet branch. In each horizontal branch that is connected to each test section there is a flow meter of water. Upstream and downstream of each test section, there are two pneumatic quick closing valves for the rapid and simultaneous interception of the mixture inside the sections for measuring the volumetric void fraction. To get the two-phase flow conditions air is injected directly into the pipe. At the end of the three helicoidal test sections and downstream of the pneumatic valves, the mixture of water and air flows to an outlet manifold where the phases are separated.

The liquid flow rate ranging up to 800 kg /h is measured by means of three orifices with a 1% f.s.v accuracy value. The air flow rate ranging up to 500 Nl/h is measured by means of a rotameter with a 5% f.s.v. accuracy value. The Statham type pressure drops transducers accuracy is 0.1 % f.s.v.. The void fraction is measured by means of the quick closing valves technique with a 5 % accuracy.

The single phase tests were carried out by using only water and the total flow rate, sum of the three water flow rates in each test section, ranges between 70 g/s and 600 g/s. The pressure drops across each helicoidal test section are presented in figure 2.

The experimental results (figure 2) show the effects of the helix lengths. The effect of the pitch and the coils diameter on pressure drops is small. The Fanning friction factor f can be derived from the measured pressure drops by the equation:

$$f = \frac{\Delta p \cdot d}{2 \cdot \rho \cdot u^2 \cdot L} \tag{1}$$

The friction factor is shown in figure 3 versus the Reynolds number; it is also compared with the Ito correlation prediction [6], that is valid for curved tubes, and with the formulations for straight pipes for laminar and turbulent flow: the experimental results are well approximated by the correlation for straight pipes in turbulent flow.

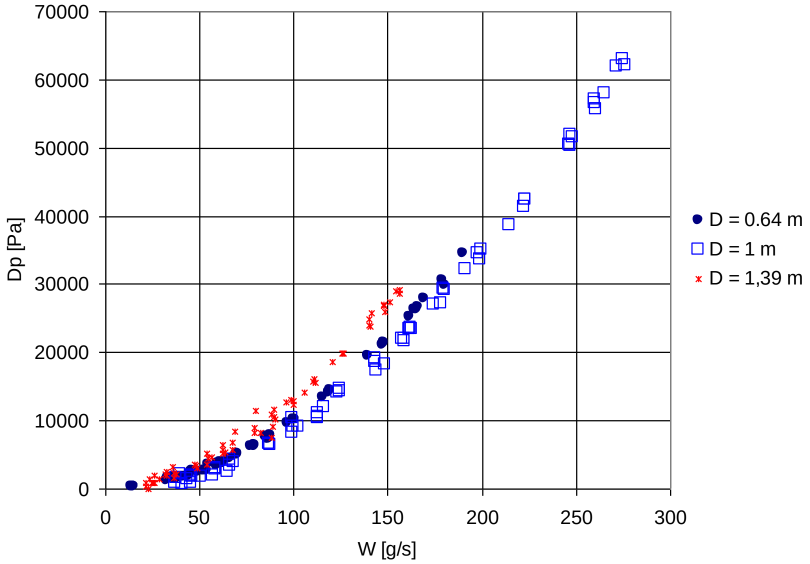

Figure 2. Measured pressure drop in single phase flow

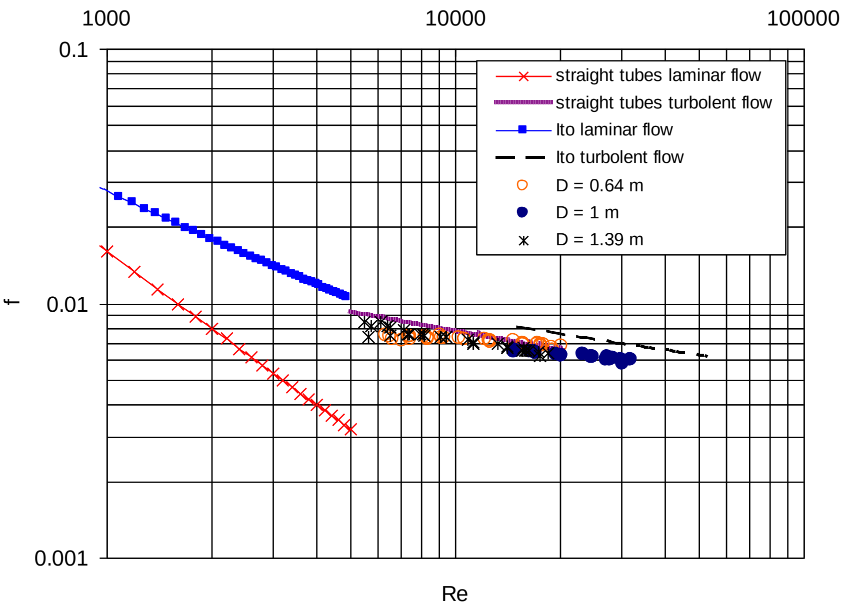

Figure 3. Friction factor versus Reynolds number

In the transition region the friction factor value is lower than that one estimated by the straight tubes turbulent flow correlations.

3. Experimental results for two phase flow

Two different experimental procedures have been adopted for two-phase flow conditions:

- two-phase flow in one section a time;
- two-phase flow in the three test sections.

In both cases the inlet water flow rate is measured for the three helical coils, while the air flow rate is measured in the two-phase test sections; the pressure drops across the test sections, as well as the volumetric void fraction and the average pressure are measured too.

The first set of runs was carried out by imposing the two-phase flow in a single helicoidal pipe and the single phase flow in the remaining two test sections; the water flow rate to the branch ranges from 290 g/s to 580 g/s, and for each water flow rate the air flow rate range is from 0.25 g/s to 0.85 g/s (table 2).

The second set of runs was carried out by imposing the two-phase flow in all three tubes simultaneously.

Table 2. Experimental matrix

	Water flow rate [g/s]	Air flow rate [g/s]
Two phase flow one section a time(test A)	290 – 530 – 560 – 580	0 – 0.25 – 0.58 – 0.85
Three test sections in two-phase flow (test B)	290 – 530 – 560 – 580	0 – 0.25 – 0.58 – 0.85
Three test sections in two-phase flow (test C)	112 – 240	1.45 – 1.65 – 1.9

The water flow rate to the branch and the air flow rate within the test sections, for the test B1, are the same as the first set of measurements, but two lower water flow rates and three higher air flow rates (test B2), have been tested too (see table 2). The total water flow rate is divided into the three test sections in a different way due to the different lengths of the three helical coils and of the outlet pipes. The figure 4 shows an example of the redistribution of the total flow rate (W_{tot} = 290 g/s) for different air flow rates in the three test sections for the test A.

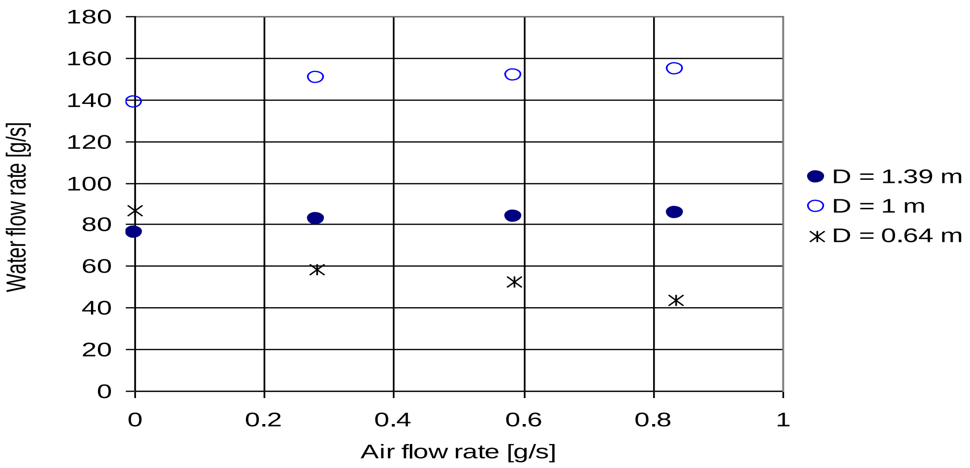

Figure 4. Example of total water flow rate distribution (Test A)

For the case of injection of the air flow in a single coil, at the same pump power, a reduction of total liquid flow rate occurs but the liquid flow rate in the small and medium coils increases while the liquid flow rate in the large coil decreases when air is injected in the coil number 1 that is characterised by the lowest helix diameter: the flow rate distribution in the coils is affected by the outlet straight pipe length that is lower for the coil number 2 and higher for the coil number 3 (see table 1).

The void fraction is measured by means of the quick closing valves technique and is presented in figure 5 as a function of the flow quality, for the test A; the flow quality is lower than 0.02.

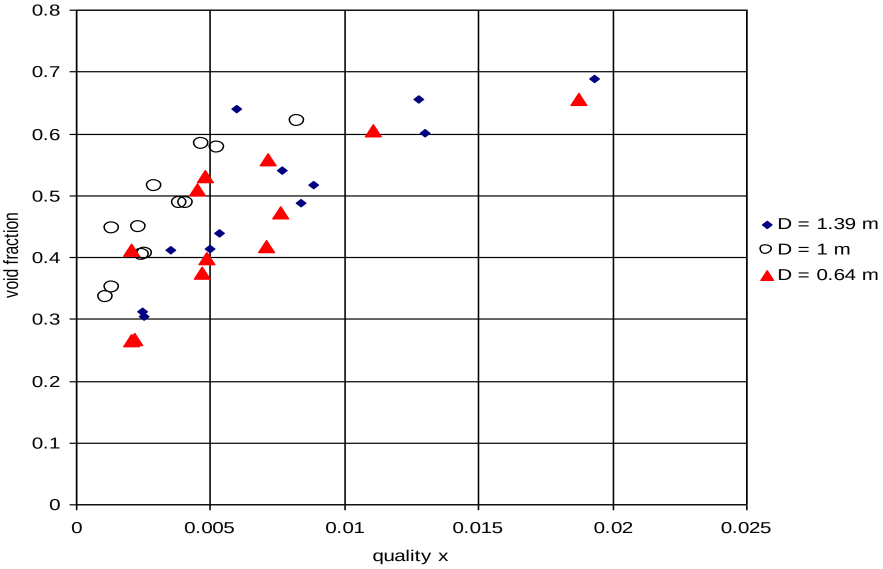

Figure 5. Void fraction versus flow quality (Test A)

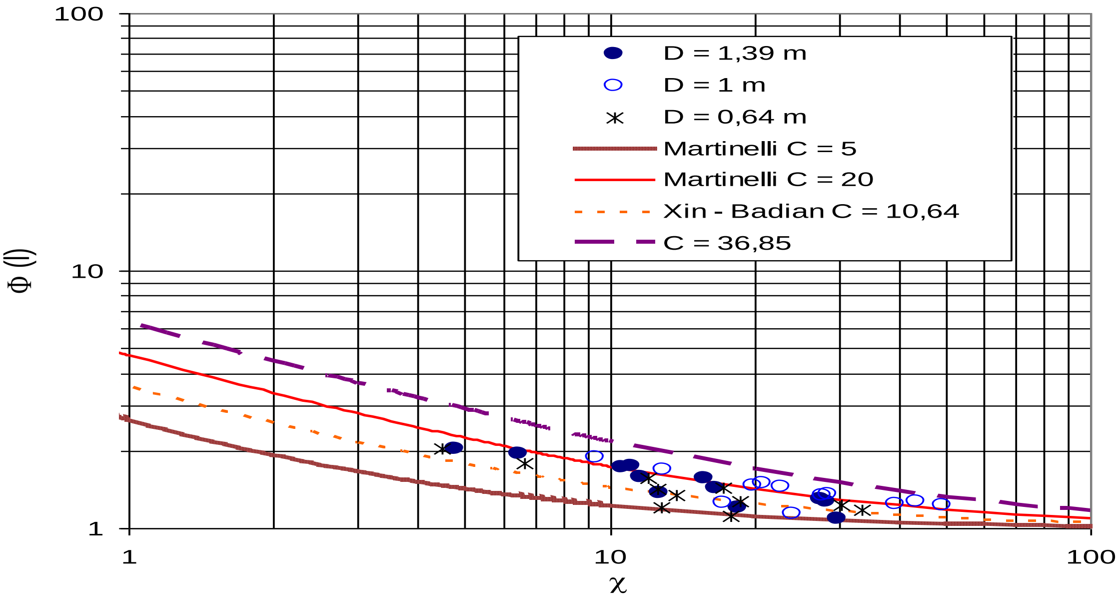

Figure 6. Experimental liquid two-phase multiplier and Lockhart-Martinelli prediction

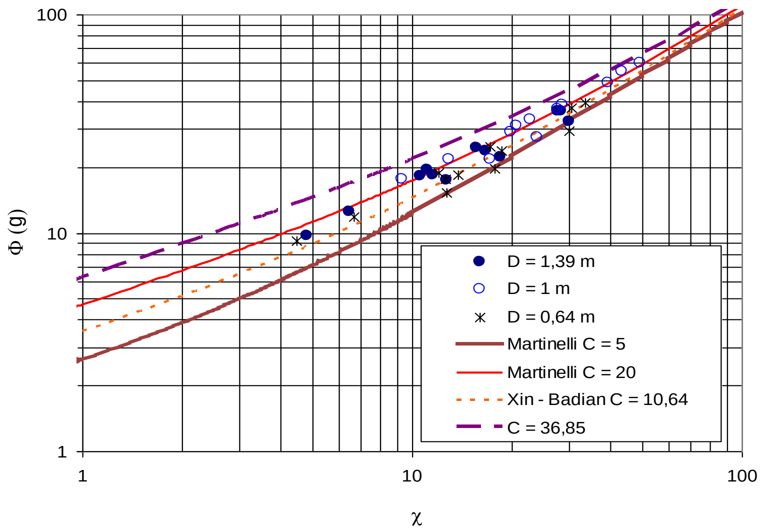

Figure 7. Experimental gas two-phase multiplier and Lockhart-Martinelli prediction

The experimental two-phase multiplier and void fraction have been compared with the Lockhart-Martinelli prediction only for the test A (figures 6 and 7).
The Martinelli parameter χ^2 and friction multipliers for two phase flow Φ_l and Φ_g, for the liquid and gas phases, are defined in eqs. (2), (3) and (4):

$$\chi^2 = \frac{\left(\frac{dp}{dz}\right)_{friction\_monophase\_water}}{\left(\frac{dp}{dz}\right)_{friction\_monophase\_air}} \quad (2)$$

$$\Phi_l^{\,2} = 1 + \frac{C}{\chi} + \frac{1}{\chi^2} \quad (3)$$

$$\Phi_g^{\,2} = 1 + C\chi + \chi^2 . \quad (4)$$

The parameter C, for straight tubes, according to the model of Lockhart-Martinelli, has a value between 5 and 20, depending on the laminar or turbulent flow for the liquid and gas phases. Xin et al. [9,10] have found a value of the coefficient C of 10.64, by applying the model of Lockhart-Martinelli to helicoidal pipes with an annular flow pattern. In the test campaigns, that was performed previously with the present test sections [5], the value of 36.85 was estimated for the parameter C. However for the tests that have been performed in the present experimental campaign a value of C that is adequate to estimate the friction two-phase multipliers was not found for each test condition, but the a value between 20 and 10 for C seems in agreement with the test data (figures 6 and 7). The experimental void fraction has been compared with the values predicted by the model of Lockhart: the prediction underestimates the measured values.

The flow rate oscillations in the helicoidal test sections have been analyzed too. Figures 8, 9 and 10 show some examples of the flow rate oscillations in the three helicoidal test sections for the test A.

The analysis of the results for total water flow rates lower than 250 g/s and for an air flow rate higher than 1.4 g/s shows that the oscillations were so large that was not straightforward to estimate an average water flow rate in the test sections.

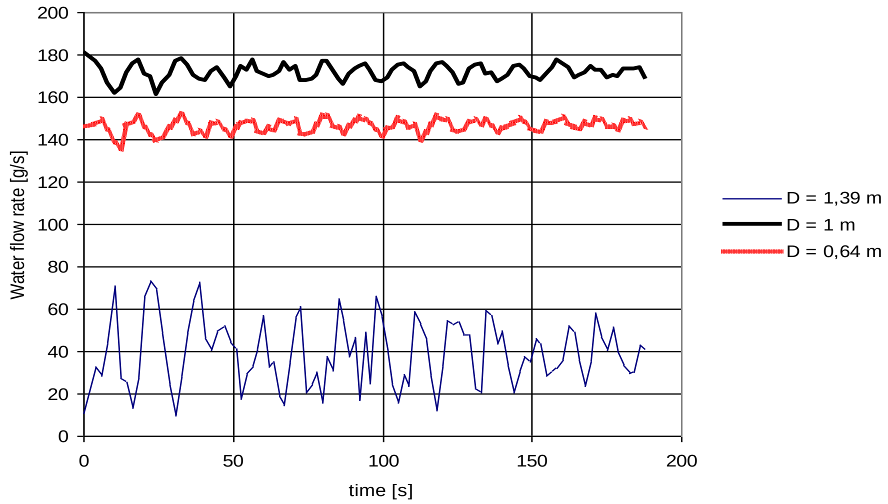

Figure 8. Flow rate oscillations in the helicoidal test sections for test A.

W_{tot} = 290 g/s, W_{air} in the three helical coils = 300 l/h

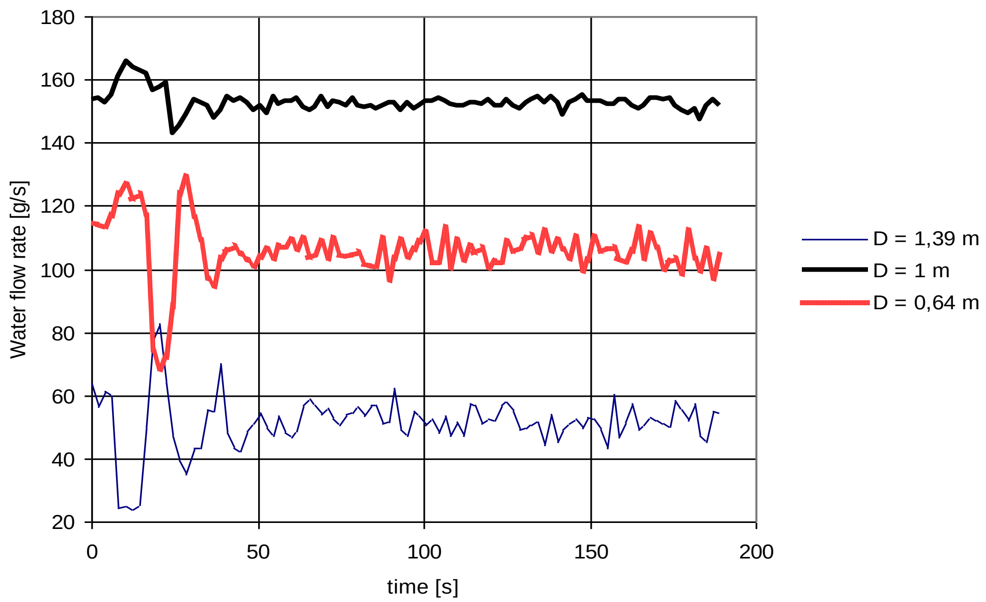

Figure 9. Flow rate oscillations in the helicoidal test sections for test A.

W_{tot} = 290 g/s, W_{air} in the three helical coils = 200 l/h

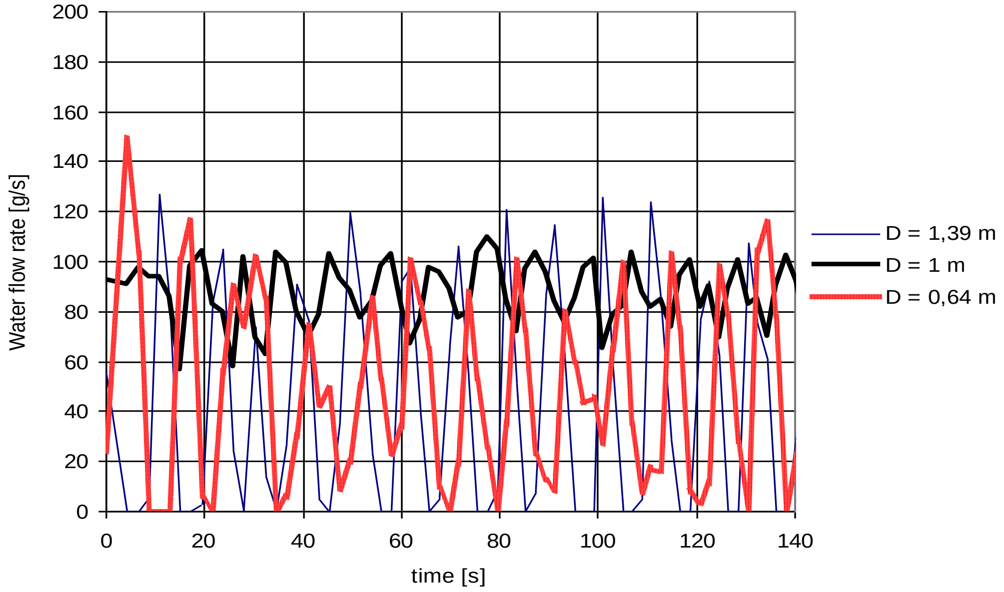

Figure 10. Flow rate oscillations in the helicoidal test sections for test B2.
W_{tot} = 240 g/s, W_{air} in the three helical coils = 500 l/h

4. Conclusions

The experimental results of single phase and two phase pressure drops and void fraction for three parallel helicoidal pipes have been presented.

In single phase flow the three helical coils have about the same pressure drop and it is possible to approximate the friction factor, derived from the experimental results, with the friction factor that is predicted by the correlation for straight pipes in turbulent flow.

In two-phase flow two different experimental procedures have been adopted: two-phase flow in one test section a time or two-phase flow in all the test sections. The model of Lockhart-Martinelli is not adequate to estimate the friction two-phase multipliers for each test condition and also the prediction of the experimental void fraction by means of the model of Lockhart is rather poor.

The flow rate oscillations in the helicoidal test sections are higher for total water flow rates lower than 250 g/s and for air flow rates higher than 1.4 g/s, and for these cases it is not straightforward to estimate an average water flow rate in the test sections, due to oscillatory behaviour.

In the next future CFD codes will be used to evaluate the main flow parameters and the prediction will be compared with the test data.

Acknowledgements

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Nomenclature

A	tube cross section	m^2
d	inner diameter tube	mm
D	coil diameter	m
f	friction factor	
L	coil length	m
p	pressure	Pa
p_i	helical pitch	m
u	velocity	m/s
Re	Reynolds number	
W_i	channel flow rate	kg/s
W_{tot}	total flow rate	kg/s
x	flow quality	
α	void fraction	
Φ	two-phase multiplier	
χ^2	Martinelli parameter	

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