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Investigation of helical flow by using tracer technique

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Abstract. The flow through coiled tubes is, in practice, important for pipe systems, heat exchangers, chemical reactors, mixers of different gas components, etc., and is physically interesting because of the peculiar characteristics caused by the centrifugal force. Therefore, it is not so easy to observe flow parameters in the helical pipe experimentally. Tracer techniques are being increasingly used to determine characteristics such as volume flow rate, residence time, dispersion and mixing process in industry. In this study, the flow in the helical pipe was obtained in the laboratory and investigated by using the tracer technique. The experimental system including the helical pipe was set up in the laboratory. In the experiments methylene-blue ($C_{16}H_{17}N_3S$) has been used as the tracer. The experiments were successfully performed with different flow rates and their results were evaluated with the flow parameters.

1. INTRODUCTION

The flow through coiled tubes is, in practice, important for pipe systems, heat exchangers, chemical reactors, mixers of different gas components, etc., and is physically interesting because of the peculiar characteristics caused by the centrifugal force. Flow through curved pipes has attracted much attention because curved pipes are widely used in heat exchangers and chemical reactors. The curved pipe can have more or less pitch, but is usually helically coiled. The flow in a helical pipe is affected by torsion as well and shows more complicated characteristics [1]. There have been many recent studies on the fully developed flow in a helical circular pipe under the influence of both curvature and torsion [2–4].

The motion of fluid flow in non-straight pipes is a fundamental problem [5]. Many of the researches have examined this problem theoretically, numerically and experimentally. However, the majority of those past studies are theoretical due to experimental challenges.

It is not easy to observe flow parameters in the helical pipe experimentally. For experimental studies, visualization techniques are generally preferable methods for the determination of the flow rate, for example by using smoke. Therefore, experimental studies of flow in helically coiled tubes have been observed by a flow visualization technique and by laser Doppler velocimeter [6]. In this study, dye tracer technique was used for the determination of the flow speed.

2. EXPERIMENTAL STUDIES

2.1. Experimental set-up

An experimental system was set up in the laboratory for the visualization of helical pipe flow. Experimental system is shown schematically in Figure 1. Experimental test device include a graduated water storage vessel with an adjustable valve, a helical pipe with an acrylic pipe connection and other related necessary equipment.

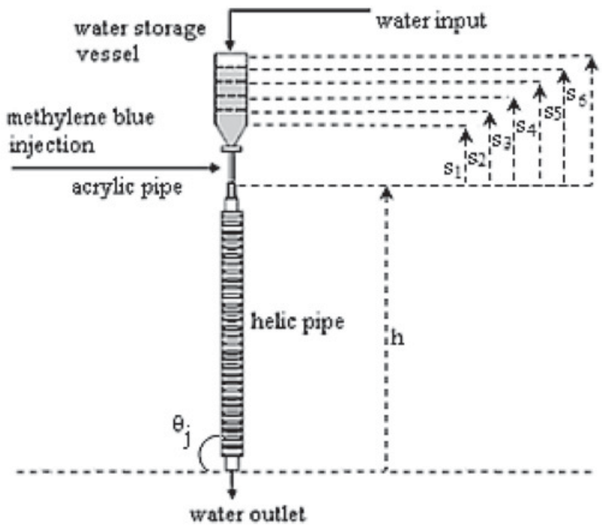

Figure 1. Experimental set-up.

The pressure in a homogeneous, incompressible fluid at rest depends on the depth of the fluid, and is not influenced by the size or shape of the tank or the container in which the fluid is held [7]. Water was supplied from a water storage vessel where water level was kept constant for each experimental condition. The total height of the water column (h_d) was calculated for different water levels (s_i) with following equation:

$$h_d = (h + s_i)\sin\theta_j \quad i = 1-6,\ j = 1-3 \qquad (1)$$

where h is the linear helical pipe length and θ is the sloping angle.

2.1.1. *Helical pipe*

The main element of the experimental set up is a helical tube, which is made of transparent glass pipe with 3.06 mm radius and 155 cm length. Firstly, a radiograph was used

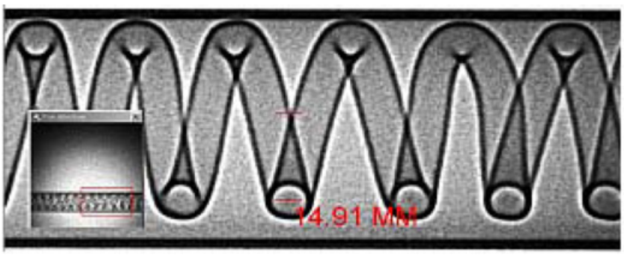

Figure 2. Radiograph of the helical pipe.

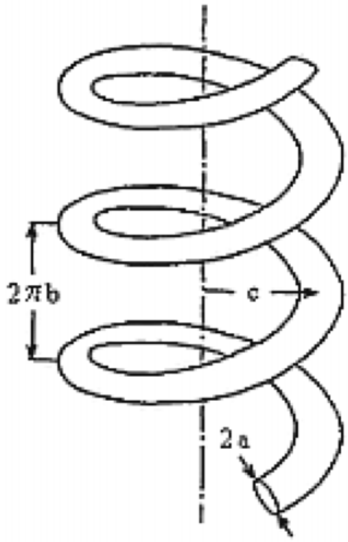

Figure 3. Schematic view of helical pipe.

for helical pipe for determination of the helical parameters of the pipe.

VIDISCO foX-Rayzor X-ray machine, which produces pulsing X-rays, was used for taking a radiograph of the helical pipe [8]. In order to obtain a clear image of the helical pipe, the applied voltage and current to the X-ray tube were selected as 270 kV and 99 mA, respectively. The exposure time to take the radiograph image was 36 milliseconds. A radiograph of the helical pipe is shown in Figure 2.

The schematic illustration of the helical pipe is presented in Figure 3.

The dimensions of the helical pipe that were determined from the radiograph are tabulated in Table 1. These parameters are the diameter 2a and the pitch $2\pi b$ of the helical glass tube, and the distance c between the center line of the outer pipe and the center of the helical glass tube. The length of the helical pipe was calculated as 1550 mm by application of a routine method [9].

For the helical flow, some non-dimensional parameters are important for the determination of the flow. One of them is curvature (δ) defined as [10]:

$$\delta = \frac{ac}{b^2 + c^2}. \tag{2}$$

Table 1. Dimensions of the helical pipe.

Helical Pipe Properties	Dimension (mm)
a	3.06
b	2.49
c	14.91
L	1550
h	302

Table 2. Non-dimensional parameter of the helical pipe.

Helical pipe parameter	Value
Curvature (δ)	0.2
Torsion (τ)	0.033
Torsion parameter (β_0)	0.052

Table 3. Properties of some dye tracers.

Dye	Chemical Compound	Solub. in Water (g/L)	Molar Mass (kg/kmol)
Methylene Blue	$C_{16}H_{18}CIN_3S.2H_2O$	50	319
Methyl Violet	$C_{25}H_{30}CIN_3$	30	408
Methyl Orange	$C_{14}H_{14}N_3NaO_3S$	0.4	327

Other non-dimensional parameters are torsion (τ) defined by

$$\tau = \frac{ab}{b^2 + c^2} \tag{3}$$

and the torsion parameter (β_0) defined by

$$\beta_0 = \frac{\tau}{\sqrt{2\delta}}. \tag{4}$$

The non-dimensional curvature, the non-dimensional torsion, and the torsion parameter were calculated and tabulated in Table 2.

2.2. Dye tracer

Tracers can be used to label substances or objects in order to distinguish them, to follow their movement, changes of concentration, distribution between phases, etc. Such properties as colour, refractive index, conductivity, radioactivity and density of additive substances have been successfully used in tracing experiments [11].

Dye is one of the most universal and practical tracer for flow investigations. Methyl violet is a conventional dye tracer frequently used in tracer experiments. In this work, methylene blue was used as dye tracer. Selection of the dye tracer is an important stage of the experiment. Some dyes and their properties are shown in Table 3 [12].

For the experiments, methylene blue was selected as the tracer due to appropriation to the water [13, 14]. Water-methylene blue mixture was prepared by using 60 mM methylene blue solution for 25 mL.

For the dye tracer application methylene blue was preferred as dye due to its strong color and easily solubility in the water.

Table 4. Experimental Parameters.

Angle	Symbol of Height	Height (cm)	Pressure (Pa)	Reynolds Number
90°	S_1	4.2	3375	2332
	S_2	5.9	3541	2460
	S_3	8.7	3816	2742
	S_4	11.4	4081	2883
	S_5	14.2	4356	2993
	S_6	16.9	4621	3091
75°	S_1	4.1	3260	2240
	S_2	5.7	3421	2258
	S_3	8.4	3686	2387
	S_4	11.0	3942	2479
	S_5	13.7	4207	2681
	S_6	16.3	4463	2717
60°	S_1	3.6	2923	1897
	S_2	5.1	3067	2020
	S_3	7.5	3305	2069
	S_4	9.9	3534	2136
	S_5	12.3	3772	2234
	S_6	14.6	4001	2277

2.3. Experimental procedure

The experiments were carried out using the experimental system shown in Figure 1. After creating a fully developed flow, 5 mL methylene-blue solution was injected for each application. Injection was performed instantaneously through the acrylic pipe manually. It is assumed that the effect of injection amount is negligible. Flow time (Δt) where the dye tracer pass through helical pipe was measured by using a chronometer that measures the transport time between start and stop of the peaks of the tracer pulses. Time measurements were based on visual inspection. Chronometer was started when the tracer passed a specific point at the inlet of the helical pipe.

Flow speed (v) was calculated by using helical pipe length (L) and measuring time;

$$\mathrm{v} = \mathrm{L}/\Delta \mathrm{t}. \tag{5}$$

Volumetric flow rate were calculated by using the experimentally determined speed;

$$\mathrm{Q} = \mathrm{v}(\pi \mathrm{d}^2/4) \tag{6}$$

where Q is volumetric flow rate, d = 2a the pipe diameter.

The experiment were performed with three different angles of the pipe (60°, 75° and 90°), and six different pressures for each of the angles. The different pressures were adjusted by the level of the water in the storage vessel. Working pressure levels were between 2923 and 4621 Pa.

The Reynolds numbers were calculated by using the following equation [1]:

$$R = \frac{d\,w}{\upsilon} \tag{7}$$

where υ is the kinematic viscosity and w is the average axial velocity through the pipe. The height of water columns in storage vessel, related hydrostatic pressures and Reynolds numbers for different angled positions are given in Table 4.

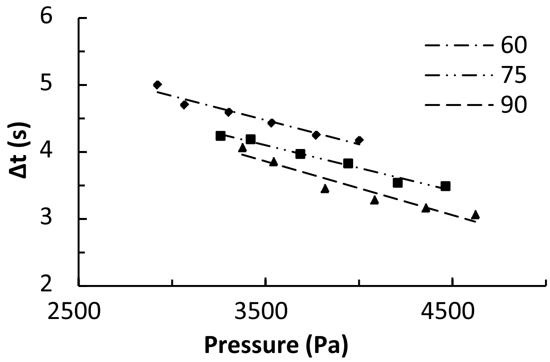

Figure 4. Transport time as a function of pressure for different angles.

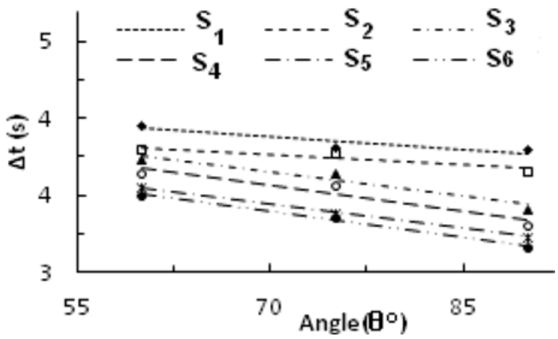

Figure 5. Transport time as a function of angle for different pressures.

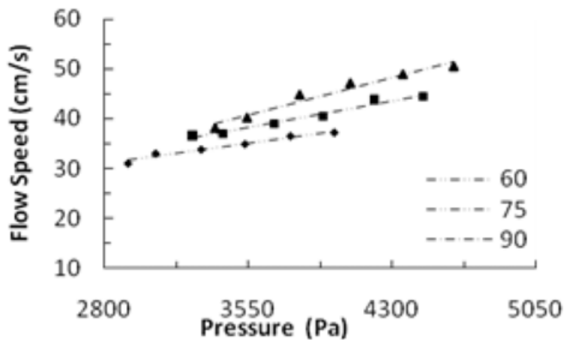

Figure 6. The change in flow speed via pressure for different angle positions.

3. RESULTS AND DISCUSSION

Experimental results for the helical pipe are tabulated in Table 5. The graphs are drawn with using the experimental data. The fitted graph is given in figure 4 for three different angles and the fitted graph for the six different pressures is given in Figure 5.

The flow speed as a function of pressure and angle are shown in Figure 6 and Figure 7, respectively. The experimental data have been fitted by least squares method.

As indicated in Figure 6, the flow speeds correlate well with the pressures where flow speed increases with increasing pressure. The empirical equations (8–10) were

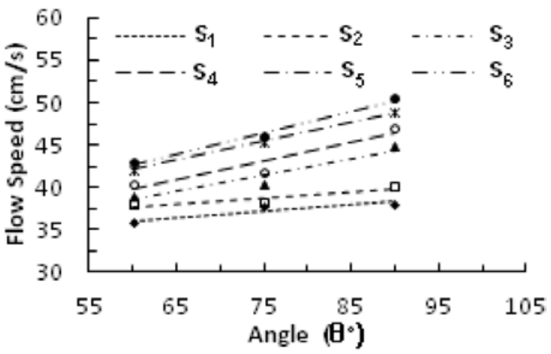

Figure 7. The change in flow speed via angle for different pressures.

Table 5. Experimental results for the helical pipe.

Angle	Time (s)	Speed (cm/s)	Volumetric Flow Rate (cm^3/s)
90°	4.07	38.1	11.2
	3.86	40.2	11.8
	3.46	44.8	13.2
	3.29	47.1	13.8
	3.17	48.9	14.4
	3.07	50.5	14.8
75°	4.24	36.6	10.8
	4.19	36.9	10.9
	3.97	39.0	11.5
	3.83	40.5	11.9
	3.54	43.8	12.9
	3.49	44.4	13.1
60°	5	31.0	9.1
	4.7	33.0	9.7
	4.59	33.8	9.9
	4.43	34.9	10.3
	4.25	36.5	10.7
	4.17	37.2	10.9

obtained for the flow speeds (Y) related to pressure (X) for three different angles.

For angled position of 60°;

$$Y_1 = 0.0054X + 15.704 \tag{8}$$

For angled position of 75°;

$$Y_2 = 0.0071X + 12.878 \tag{9}$$

For angled position of 90°;

$$Y_3 = 0.01X + 5.1113. \tag{10}$$

The correlation coefficients for equations obtained for 60°, 75° and 90° were determined as 0.966, 0.972 and 0.959, respectively.

4. CONCLUSIONS

The dye tracer technique was applied to the nearly homogenous, isotropic fully developed flow in helical pipe. Methylene blue was used as the dye tracer and injected from upper side of the helical pipe. The following results were obtained in this study.

1. Velocities of the helical pipe flows can be determined experimentally.
2. Three different flow angles were examined.
3. Effects of changes in pressure were observed successfully.
4. Volumetric flow rates were determined for all cases.
5. Related flow parameters could be also assigned effectively.
6. The correlation coefficients obtained for three different angled positions are in close proximity to one.
7. Comparison of the results showed that all of them consisted with each other.

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