EXPERIMENTAL RESULTS OF A VISCOUS FLOW AROUND A "T" PROFILE

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Abstract: The purpose of the paper is to visualise the vortex shedding process behind a bluff body. It was considered a plane flow of a viscous fluid (water) around a ″T″ profile having the geometric sizes modified. It was measured the fluid flow speed in the section of the measurements and the frequency of the vortex detachment from the profile. The vortex development phenomenon depends by the profile's geometry and the Reynolds number of the flow. The relation between Reynolds number and Strouhal number was obtained for different sizes ″T″ profiles. The experimental study is necessary to improve the vortex flowmeter performances.

Keywords: vortex shedding, visualization, frequency, flowmeter

1. INTRODUCTION

In the fifteenth century Leonardo da Vinci observed and sketched the vortex shedding behind a stick stuck in the river bed. How the vortex are born, which is the mechanism of vortex detachment from a profile, the stability or instability of the vortex shedding behind a body immersed in a fluid in motion are just some of the issues that concern the scientific community for more than a century. Thus, in 1878 Strouhal founded that the tones generated by a wire in the wind were proportional to wind speed divided by the wire thickness. One year later, Lord Rayleigh found the existence of the lift force, which occurs at low Reynolds numbers, with the emergence of vortex. The lift force is perpendicular to the direction of flow.

Theodore von Karman (1912) discovered that when a non-streamlined object (called *bluff body*) is placed in a fast moving fluid, the fluid is unable to remain attached to the object on its downstream sides and will alternately separate from one side and then the other. The fluid in the boundary layer on the bluff body becomes to detach, a back flow and formation of vortices (or eddies) occur [1]. The vortices appeared as a consequence of fluid viscosity. The fluid layers moving at different speeds on both sides of the body and so the pressure is different.

The fluid on the side of the vortex has less pressure (but greater kinetic energy) than the fluid on the other side with less kinetic energy (but more potential energy).

The vortex street phenomenon is applied in flow measurements as the principle of operation of the vortex flowmeter [2]. The bluff body used as vortices generator should have sharp edges to stabilize the separation point of the boundary layer. The most common bluff body used in the vortex flow meter is the cylinder. The first modern vortex applied to measure the flow rate in closed pipes was designed by Yamasaki in 1967. The first commercial vortex flowmeter was manufactured in 1969 by the Japanese company Yokogama. In Europe, the British company Kent Instruments was the most famed manufacturer of vortex flowmeters [3].

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This paper aims to present to a certain range of Reynolds numbers the flow spectrum around a ″T″ profile placed in a channel with free surface and having a closed circuit. The profile is partially submerged and horizontally placed on the channel axis, with "foot" point upstream. We studied the frequency dependence of the vortex separation profile regarding to Reynolds number for different sizes of ″T″.

2. EXPERIMENTAL SET-UP and MEASUREMENTS

The experiments of flow visualization around the profile "T" used a free surface channel, closed circuit belonging to the Department of Hydraulics, Hydraulic Machinery and Environmental Engineering of the University Politehnica of Bucharest [4].

The scheme stand is shown in Figure 1. The channel is a metal structure that has the following main rates overall: length (maximum) value of 3.00 m, width (average) - 1.1 m, height (maximum) - 0.35 m. The plant provides horizontal movement of the working fluid, water. The water height in the channel is 0.285 m. The channel structure consists of four parts (called areas): the test area (or working area), the downstream side (relative to the test), the crossing area and the upstream side. The channel is sealed and corrosion protected.

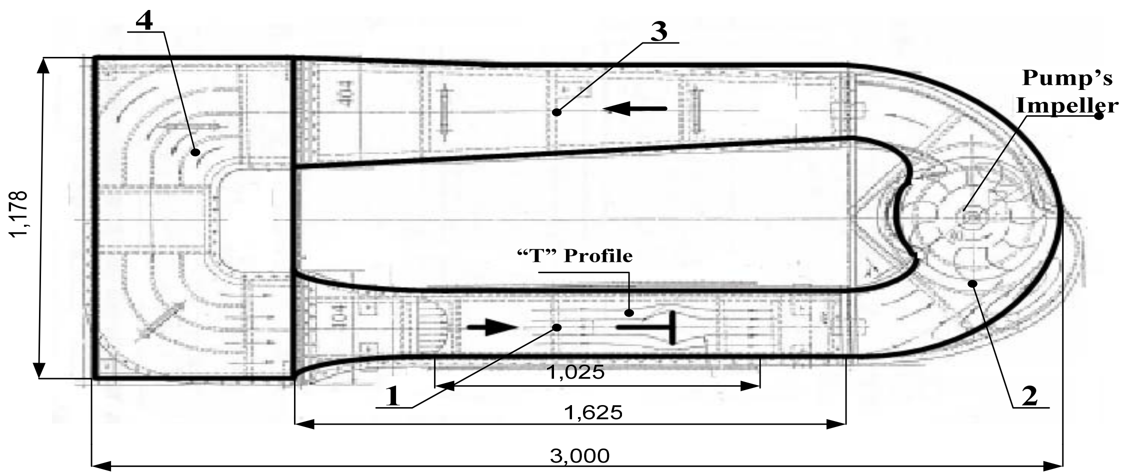


Fig. 1. Scheme of the open channel used to visualize the flow of Newtonian and non-Newtonian fluids:
1 — test area; 2 — downstream side; 3 — crossing area; 4 — upstream area.

The test area (1) has a width of 0.230 m and length 1.00 m. The height is the channel height given previously. The test area is glazed on both sides in order to observe the flow spectrum and to capture it as photos. The flow spectrum could be seen in three dimensions and in plane, too. The test area is provided with fastening systems profiles or geometric configurations, around which or through which the working fluid flows.

In our experiments it was used a ″T″ shape made of two plexyglass plates with small thickness. The ″T″ profile was placed on the channel axis, horizontally and with the ″foot″ point upstream. The profile was fitted to the channel bed and was partially submerged in the water. The remaining portion above the liquid was of 35 mm to view and capture the plane flow spectra.

The downstream side (2) provides the first bend drift of the flow direction with 180 degrees. Here is placed the pump which has a vertical rotor blade to ensure the movement in horizontal planes of the working fluid. The free surface remains in the same horizontal plane and the working fluid is trained on its full height. The flow rate (and hence the velocity of flow) is a uniform function of the pump's speed. The pump pressure drop is small.

The constant pump's speed ensures uniformity of motion. The pump is driven by a DC electric motor (via a speed reducing gear), whose speed can be set from the control panel by means of a multi-stage dimmer.

The crossing area (3) ensures the movement of working fluid to the upstream side (4). Its dimensions have been so designed as to provide a calming and smoothing flow downstream of the pump. The upstream side (relative to the site) provides the second bend drift of the flow with 180 degrees. In the upstream side is placed a device with blades to guide and improve the flow at the entrance in the test area. So the speeds of the water were measured in the centre channel, at the entrance of the test area, where the velocity field is significant smoothing and without eddies.

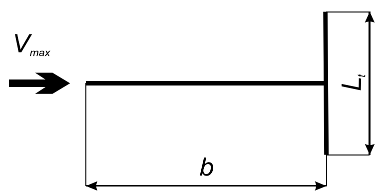
The channel is equipped with an adjustable fixing device for a digital camera or a video camera and also, with an appropriate lighting system, designed to obtain photographs of the hydrodynamic spectra. Command and control console provides the starting of the flow channel and changing the speed of the pump electric motor drive. It can control the lighting installation and connection of electrical measurement, control out of service.

The pump used in installation has a rotor blade with the exterior diameter of 0.46 m and the energy transmitted to the fluid is the same in perpendicular planes to the axis of the rotor. The pump is driven by a DC electric motor with the following parameters: power of 1.5 kW, voltage 40 V, intensity 48.5 A and speed is variable with the values of 435, 600, 735, 835, 900 and 1200 rpm (six steps of speed).

Mechanical transmission is ensured by a worm gear reducer with the overall advantage of a small size, high efficiency and a constant gear ratio, which is maintained even at very low speeds. To change the flow velocity in the test area (1) when the speed of the pump is constant (at 435 rpm), it was changed the flow section of the downstream side (2) by using a flat gate valve. For a given size of the ″T″ profile were obtained four or five different Reynolds numbers.

Profile around which was studied the flow is composed of two flat plates of plexyglass having a thickness of 3 mm and arranged in the shape of letter "T". Placing the profile of the water stream is shown in Figure 1. There were used different sizes of "T" profile. Geometric shape of the profile, encoding profiles and their sizes are in Table 1.

Table 1. Profile dimensions ″T″

Profile code		
	b	***L_t***
T300110	300	110
T30088	300	88
T30066	300	66
T30022	300	22

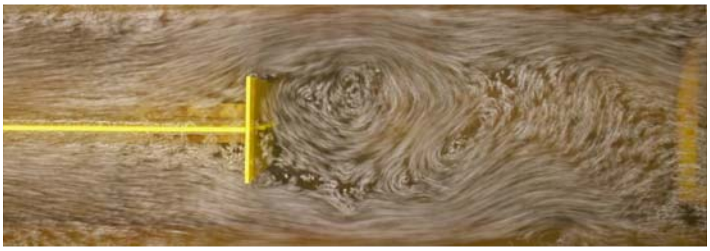
According to the "T" profiles specified in Table 1 were made pictures of the flow around the profiles for different Reynolds numbers in the range of 10^4 and $2{\cdot}10^5$. The flow streamlines were achieved by using plexyglass float freely sprinkled on the surface of the water because their good property of flotation. Was used a white plexyglass which allowed the viewer to obtain a strong contrast between the float and the black colour of the channel walls. Distribution of free float on the surface of the water channel was uniform to ensure continuity of streamlines. In areas with vortices were sprinkled extra float.

Pictures were taken in steady-state flow. Exposure times were correlated with the flow rates, the length of the viewing area and the average vortices speeds around the profiles picture.

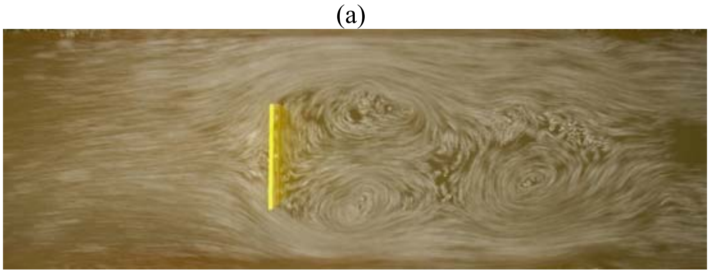
The pictures were made with a digital camera Konica - Minolta Z3. The device had the ability to set shutter speed and sensitivity with which it captures the image (ISO). The time exposure was made by repeated tests until it was obtained a good quality of pictures in the terms of clarity and continuity of the stream lines of the hydrodynamic flow for each speed of the water in the channel. The sensitivity with which photos were made was ISO 100.

3. RESULTS

In order to see a larger downstream area where the vortices are developed behind the bluff body (profile "T") it was reduced the area of the flow upstream of the profile. Figure 2 compares the pictures of the flow streamlines for the flow around "T" profile and a vertical flat plate. It was used the T30088 profile and the vertical flat plate had the size of 88 mm, the same as the L_t size of the "T" profile (see Table 1). Pictures were made for comparable Reynolds numbers: Re = 10,315 for ″T″ profile, Re = 10,216 for vertical flat plate. It can be seen that the upstream flow profiles is important and different: the horizontal plate from the ″T″ profile will equalize the flow upstream compared with the upstream flow of the vertical flat plate.



(a)



(b)

Fig. 2. Streamlines upstream of the ″T″ profile (a) and vertical flat plate (b).

For every picture was measured the length of the trace (x_m) which was left by the float on the picture and the exposure of the picture, t_{exp}, adjusted with the flow speed (t_{exp} is between 0.5 and 0.2 s). Were calculated the maximum speed (V_{max}) measured in middle of the channel, the Reynolds number (*Re*) in the upstream area and Strouhal number (*Sh*):

$$V_{max} = \frac{x_m}{t_{exp}},\ Re = \frac{V_{max} \cdot l_C}{\nu},\ Sh = \frac{f \cdot L_t}{V_{\max}} \tag{1}$$

where: l_C= 230 mm is the width of the channel in the test area, ν = 10^{-6} m^2/s is the kinematic viscosity of water at operating temperature (20^0 C), f is frequency-vortex formation, L_t - ″T″ profile width, transversely to the direction of liquid flow. The results are presented in Table 2. The vortex frequency detachment could be calculated with:

$$f = \frac{Sh \cdot \mathrm{Re}}{l_c \cdot L_t} \cdot \nu\ . \tag{2}$$

Table 2. Measured an calculated values

Profile	L_t mm	x_m mm	t_{exp} s	V_{max}(average) mm/s	*Re*	*f* 1/s	*Sh*
T300110	110	20.85	0.5	41.69	9589	0.665	1.755
	110	26.14	0.5	52.28	12025	0.720	1.515
	110	28.72	0.5	57.43	13209	0.766	1.467
	110	35.80	0.5	71.60	16468	1.167	1.793
T30088	**88**	**22.42**	**0.5**	**44.85**	**10315**	**0.500**	**0.981**

	88	**29.07**	**0.5**	**58.14**	**13373**	**0.650**	**0.984**
	88	**35.68**	**0.5**	**71.36**	**16413**	**0.796**	**0.982**
	88	**41.76**	**0.5**	**83.53**	**19211**	**0.932**	**0.982**
T30066	66	23.35	0.5	46.70	10742	0.416	0.588
	66	25.40	0.5	50.80	11683	0.500	0.650
	66	31.42	0.5	62.84	14453	0.532	0.559
	66	33.95	0.5	67.91	15619	0.527	0.512
T30022	22	19.39	0.5	38.77	8918	0.500	0.284
	22	23.37	0.5	46.74	10751	0.750	0.353
	22	28.87	0.5	57.73	13278	0.875	0.333
	22	33.68	0.5	67.37	15494	1.000	0.327

The pictures presented below (Figure 3, Figure. 4, Figure 5, Figure 6 and Figure 7) are made for the profiles given in Table 1 and having the parameters calculated in Table 2.

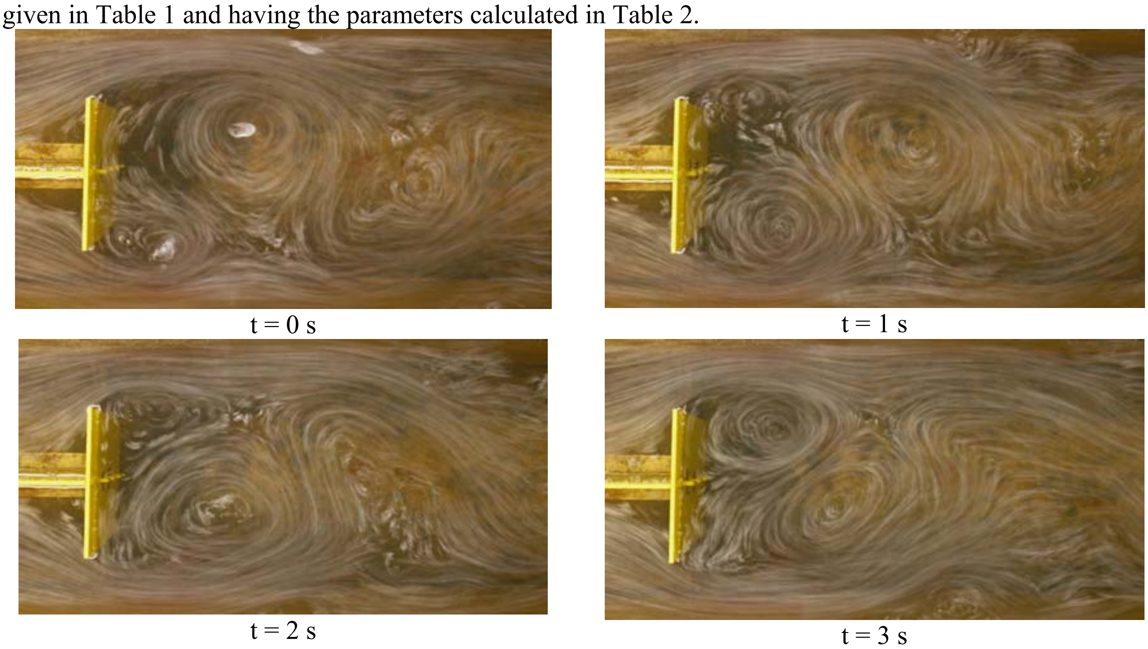


Fig. 3. Alternating vortices behind T300110 profile for *Re* = 13,200 (frame interval 1 s).

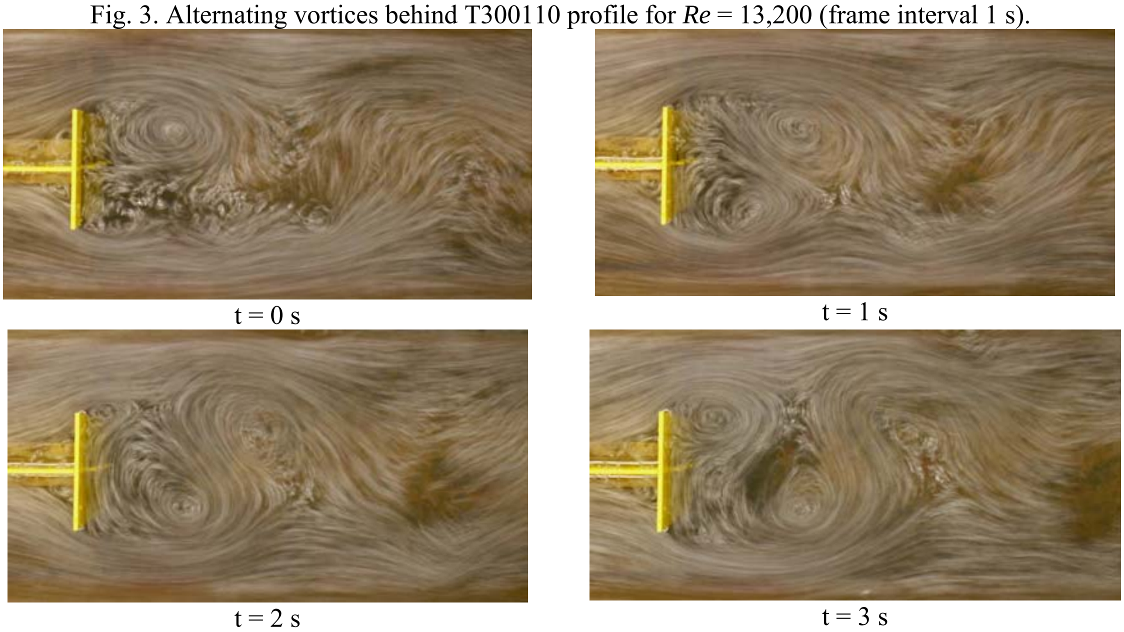


Fig. 4. Alternating vortices behind T30088 profile for *Re* = 13,400 (frame interval 1 s).

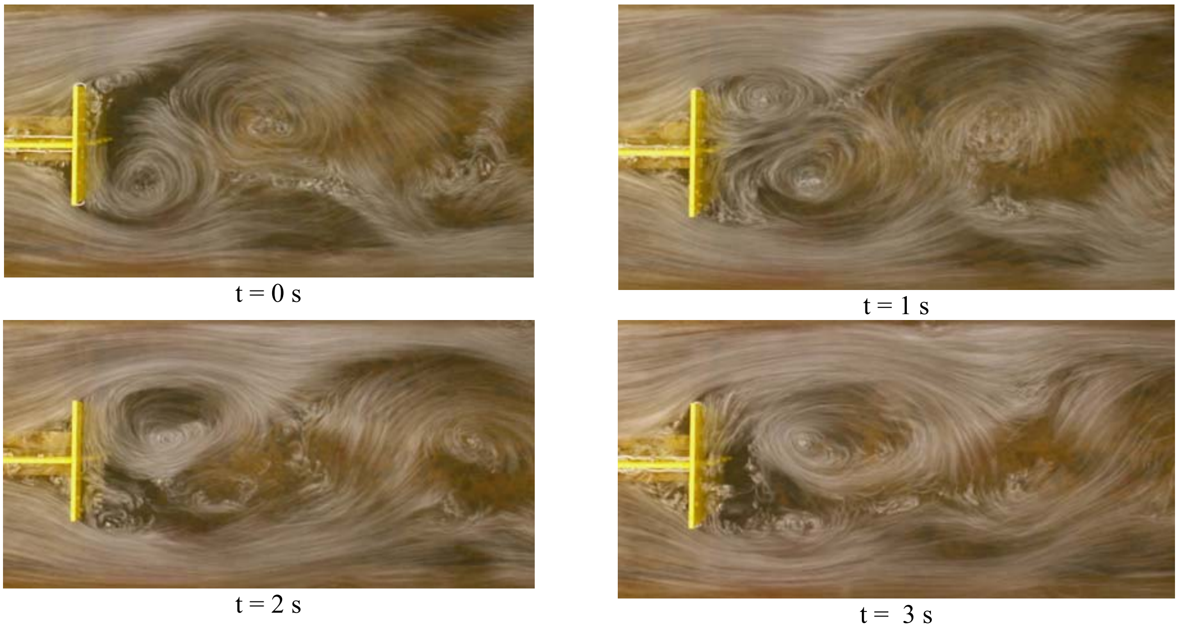


Fig. 5. Alternating vortices behind T30088 profile for *Re* = 19,200 (frame interval 1 s).

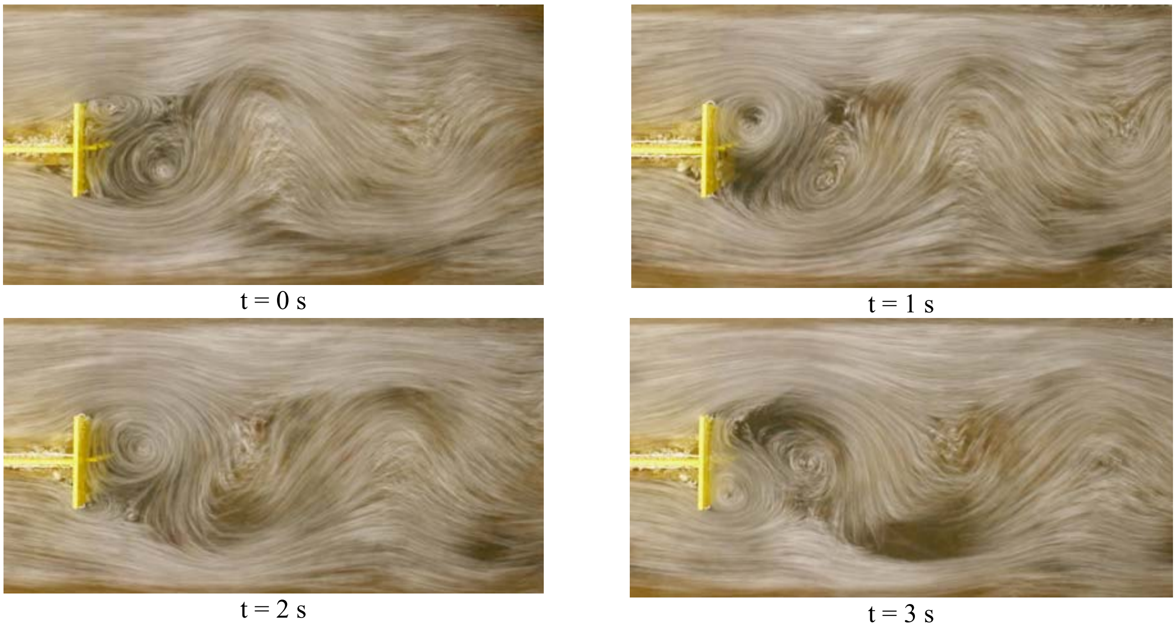


Fig. 6. Alternating vortices behind T30066 profile for *Re* = 15,700 (frame interval 1 s).

Vortex occurrence is essentially a two-dimensional phenomenon even if the flow in a pipe has three dimensions [5]. The processes which appear in flow as turbulence, rotation and gradient velocity affect negatively the eddies occurrence rate. As a consequence of this the Strouhal number versus Reynolds number has a nonlinear variation. Excepted T30088 profile where the dependency between Strouhal and Reynolds is linear and all other profiles have a nonlinear or a weak linear dependency $Sh = Sh(Re)$ (Figure 8).

Vortices formation or their occurrence is a consequence of fluid viscosity [6]. Because of the viscosity boundary layer grows along the body surface and it separated on both sides of the body. Vortices are generated alternately on each side of the body profile as cylindrical vortices which are developed in water depth, perpendicular to the flow. Shaped body should have sharp edges to stabilize the layer separation point limit [3].

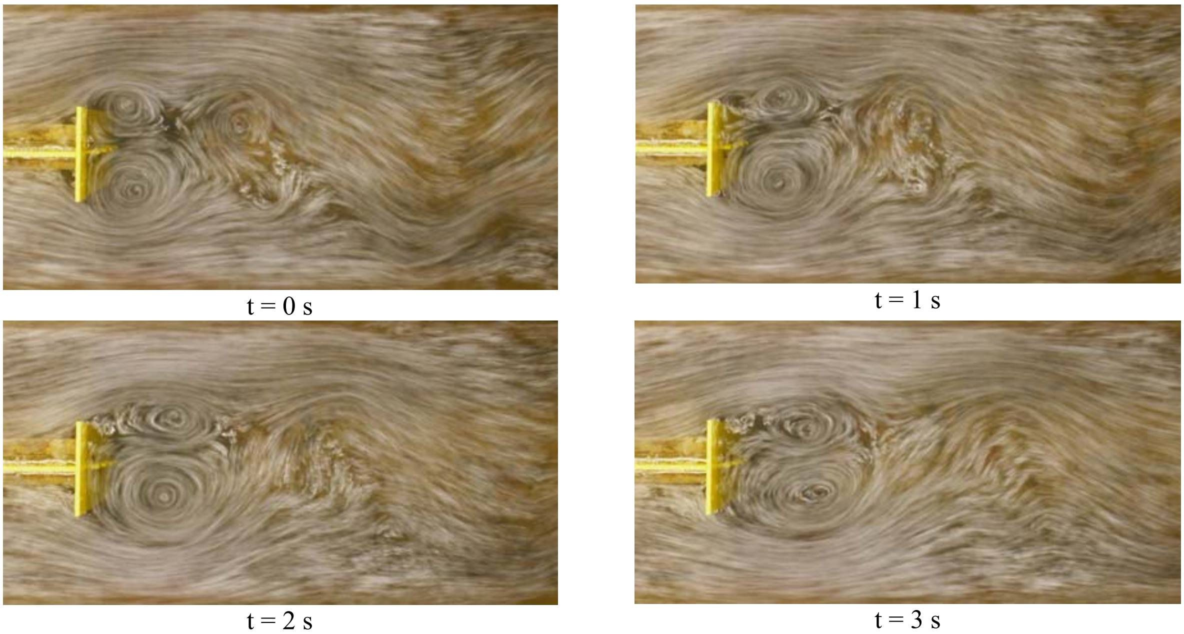


Fig. 7. Symmetric vortices behind T30066 profile for *Re* = 10,700 (frame interval 1 s).

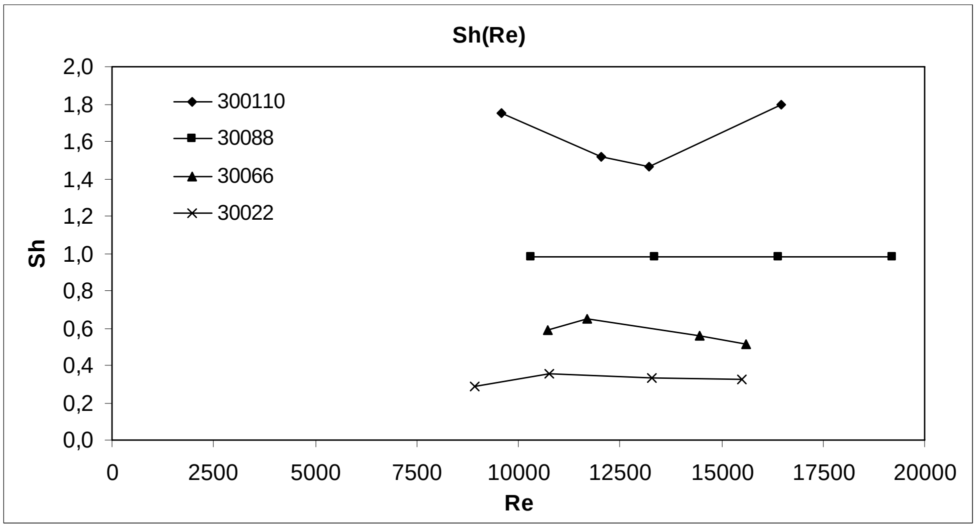


Fig. 8. Strouhal vs Reynold for all the ″T″ profiles discussed.

4. CONCLUSIONS

The behaviour of the flow around a bluff body, ″T″ profile, was investigated by a classical technique of visualisation using the Photo Tracer Method [1, 4], without making use of expansive equipment. The experiments were made for Reynolds numbers between 10^4 and $2 \cdot 10^5$. The ″T″ profile has four sizes, Table 1. Streamlines pictures of the flow around the profile were obtained and the frequency of vortex separation profile was calculated, Table 2. The variation of number Strouhal versus Reynolds was plotted (Figure 8) for all ″T″ profiles studied. Cylindrical vortices which are alternately detached on both sides of the profile have been drawn out, Figures 3 to 6, and cylindrical vortices symmetrically detached as in Figure 7.

It could be seen in Figure 8 that the profile T30088 has Strouhal number equal with 1 for any Reynolds number. The other profiles studied have a nonlinear behaviour of *Sh* according to *Re*.

Recordings made showed that the horizontal plate of T profile is to obtain a uniform flow upstream of the vertical plate of T profile. Recordings were made compared to the flow around a vertical flat plate.

Reynolds and Strouhal numbers defined in relation (1) could be coupled and could be obtained the vortex frequency detachment which does not depend on the size *b* of the horizontal plate from the ″T″ profile, Table 1.

Relationship of all sizes has been defined previously in the paper.

This study entitles us to see the ″T″ profile as a possible vortices generator of vortex flowmeters. Further research will show which is the optimal ratio between the ″T″ geometric dimensions (b/L_t), to obtain high precision and sensitivity for this type of swirling flow generator.

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