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EXPERIMENTAL TEST OF CRITICAL REYNOLDS NUMBER CORRELATION IN BIFURCATIONS

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Abstract. In this work, it is proposed to experimentally confirm a forecast correlation of critical Reynolds Number, Re_{crit}, in bifurcations with varied asymmetric angles, raised and published in a recent article by the author. It is well known that a disturbance in a straight section of piping, where there is a flow in laminar regime, such as a curve, a valve or a bifurcation, will cause turbulence in the stream. But after the obstacle, it returns to the laminar state. However, there is a Reynolds Number value that indicates that the flow will not return to the initial condition and the correlations that indicate such a quantity are known for a large number of geometries. For experimental verification and validation of the correlation for bifurcations, a hydraulic apparatus was designed, composed of an acrylic container, with support for asymmetric glass forks with a tube diameter equal to 0.016 m (or 5/8") and several angles. A pump with a maximum flow rate of $5.8x10^{-5}$ m^3/s (or 3.5 l/min, according to the manufacturer's original specification), being controlled by a potentiometer and a rotameter that indicates the imposed flow rate, makes the fluid (water) circulate from the filled container into the fork. When making the water pass through this circuit, an injector drives a colored thread, whose behavior is observed along the flow inside the outlets. The apparatus was installed and operated in the university's hydraulics laboratory. Basically, the resource allows the researcher to observe the trajectory of the fillet through the bifurcated channels. When the flow changes from laminar to turbulent regime and does not return to the initial condition, the flow rate is recorded. The velocity value and the consequent Reynolds Number can thus be calculated and compared to that predicted by the proposed correlation. Most of prediction work has been based on computer simulation only and this experimental evidence makes previous conclusions more reliable. Preliminary results indicate very low values of Re_{crit}. New bifurcations are being manufactured to carry out complementary tests, aiming to complete the analysis of the adequacy of the correlations and the maturity of the conclusions.

Keywords: Bifurcations, Critical Reynolds Number, Experimental Validation

1. INTRODUCTION

In recent years, several studies have been published with proposals for correlations that deal with flow and thermal developments at the entrance of bifurcations, with variation in angles, flow rates and channel diameters (Avelino et al 2016, Amado et al, 2018a, b, c, Amado et al, 2019a, and Amado et al, 2020a, b, c). Similarly, correlations for Critical Reynolds Number prediction have been proposed from some decades, by researchers such as Ito, 1959, Kubair and Varrier, 1962, Schmidt, 1967, Srinivasan et al, 1968 and 1970, Mishra and Gupta, 1979 for toroidal and helical geometries. Through these references, it is possible to see that the flow in obstructed and sinuous structures is of great interest to academia and industry.

2. BIBLIOGRAPHIC BASIS

Amado and Corradi, 2020d, proposed a critical Reynolds Number prediction correlation in bifurcations with diameters of 0.02 m, feed tube and outlets of 0.09 m in length and half angles ranging between 5 and 90 degrees, in the shape of Eq. (1), arriving at Eq. (2).

$$Re_{crit} = c_1 \left[1 + \frac{c_2}{(R/a)^{c_3}} \right] \tag{1}$$

$$Re_{crit} = 135 \left[1 + \frac{13.7}{(R/a)^{-0.31}} \right] \tag{2}$$

This reference was based on previous work on the survey of Re_{crit} prediction correlations, according to the authors shown in Table 1, in the geometries indicated in the second column of the table.

Table 1. Correlations that define Re_{crit} according to literature

Author	Geometry	Restriction	Correlation	
Ito, 1959	Toroidal	15<R/a<860	$Re_{crit} = 2000 \left[1 + \frac{13.2}{(R/a)^{0.6}} \right]$	(3)
Kubair and Varrier, 1962	Helicoidal	10<R/a<2000	$Re_{crit} = \frac{12730}{(R/a)^{0.32}}$	(4)
Schimidt, 1967	Helicoidal	R/a<200	$Re_{crit} = 2300 \left[1 + \frac{210}{(R/a)^{1.12}} \right]$	(5)
Srinivasan et al, 1968, 1970	Helicoidal	R/a<200	$Re_{crit} = 2300 \left[1 + \frac{210}{(R/a)^{1.12}} \right]$	(6)
Mishra and Gupta, 1979	Toroidal and helicoidal		$Re_{crit} = 20000 \left\{ \frac{1}{\frac{R}{a}\left[1 + \left(\frac{b}{2\pi D_H} \right)^2 \right]} \right\}^{0.32}$	(7)
Cioncolini and Santini, 2006a, b	Helicoidal	R/a>150	$Re_{crit} = \frac{20000}{(R/a)^{0.32}}$	(8)
		R/a<24	$Re_{crit} = \frac{30000}{(R/a)^{0.47}}$	(9)
		30<R/a<110	$Re_{crit} = \frac{12500}{(R/a)^{0.31}}$	(10)
		30<R/a<110	$Re_{crit} = \frac{120000}{(R/a)^{0.57}}$	(11)
		R/a>150	$Re_{crit} = 2300 \left[1 + \frac{210}{(R/a)^{1.12}} \right]$	(12)

The fluid dynamics and thermal understanding in bifurcations has been of interest to researchers because problems with flow in these structures are commonplace in the life of industry and in the medical field. Almeida et al, 1999, investigated the behavior of the flow of generic fluid through branched structures with applicability in porous media, pulmonary respiration and blood circulation. The reference makes a detailed analysis that correlates high and low Reynolds Number values to various flow characteristics along successive bifurcations. In Brazil, the distribution of subsea pipelines that carry oil and gas constitutes a complex tangle of tubes that rest on the seabed, with many bifurcations, junctions, by-passes, ascents, descents, etc. Although the flowing fluid be multiphase, the study of single-phase flow in these structures helps to understand how problems occur and also in finding solutions to them.

2.1 Research goals

Given the above and in addition to the existence of correlations that propose to describe this behavior only based on numerical simulations, the purposes of the present work are stablished: the observation of the real phenomenon in experimental apparatus, as well as the execution of measurements that will serve to test the effectiveness of the formulations that were presented, which are supported only in CFD analysis.

3. MATERIALS AND METHODS

The experimental apparatus set up to test the proposed correlations can be seen in a freehand sketch in Figure 1. The scheme shown does not follow symbology rules. It is just an outline for the reader to understand better. Figure 2a and b show the actual infrastructure.
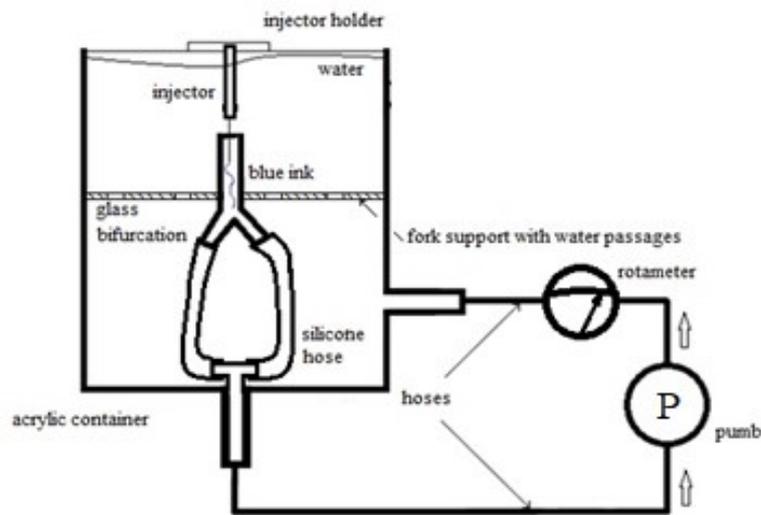

Figure 1. Scheme showing the functioning of the experimental apparatus
set up to analyze the behavior of a thread through a bifurcation (out of
standardized symbology)

As can be seen, the infrastructure is composed of an acrylic container, which supports a perforated plate, which in turn holds a glass fork. 9 bifurcations were manufactured, with combinations of half angles of 30°x30°, 45°x0°, 45°x20°, 45°x25°, 45°x45°; 45°x60°, 45°x75°, 45°x90°, 45°x105°, 0.09 m long feed tube, 0.075 m long outlets, as well as 5/8" (15.88 mm) outside and 13 mm inside diameters. The outlets of the assembled bifurcations are connected to the suction of a pump with a maximum flow rate of 3 l/min (5×10^{-5} m³/s), which is modulated by a potentiometer and monitored by a rotameter or flowmeter. This pump causes a fluid (in this case, water) to circulate between the exit, located at the base of the container, and the entrance located on the side of the container. It so happens that the only path that water can take to be drawn by the pump is the inlet of the feeder tube of the fork. An injector mounted on the top of the infrastructure injects a blue fillet. With the water circulation, the behavior of the blue thread can be observed, as well as measurements of the flow developing region can be made and noted when the fluid changes from laminar to turbulent regime. The rotameter with a capacity of 3.5 l/min (5.8×10^{-5} m³/s) can be seen in the Figures 2a and b, near the base of the container and in Figure 3 below.
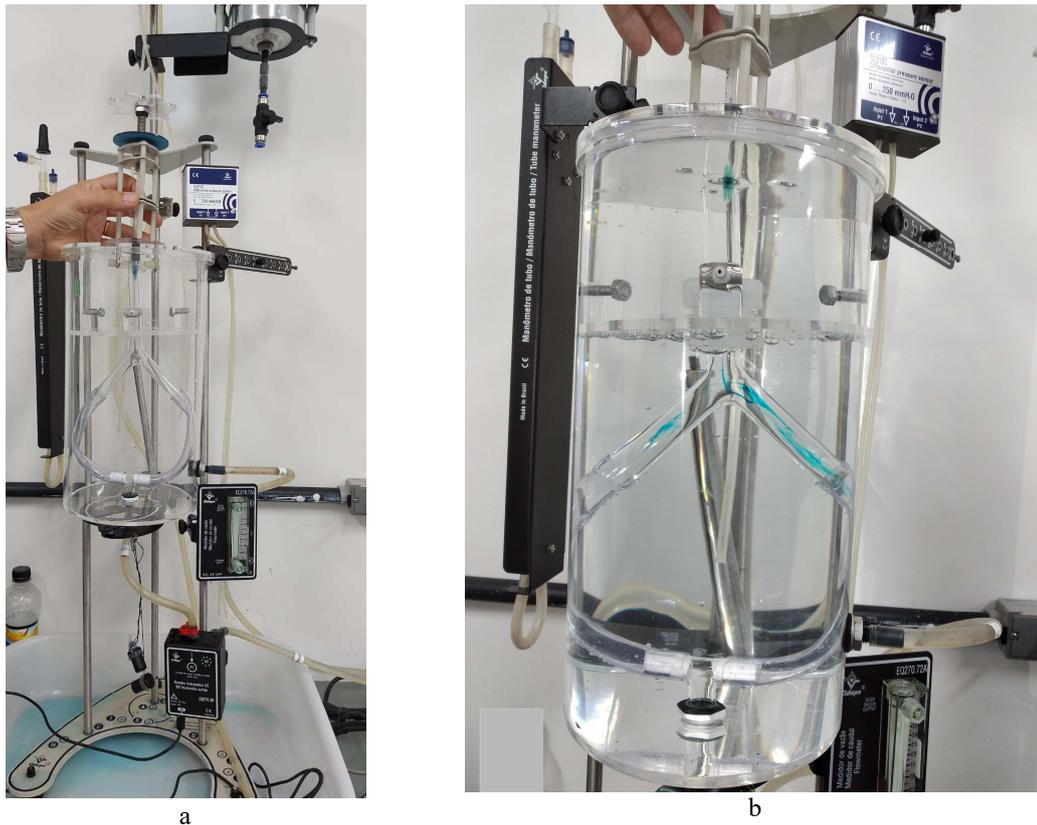
<center>a</center>
<center>b</center>

Figure 2. Real experimental apparatus, set up to observe the behavior of a blue ink fillet through the exits of a bifurcation

Figure 3. Flowmeter (or rotameter) for measuring
the flow rate in the feeder tube of the branch under
test

During rehearsals, the fillet usually chose one side to flow. It turns out that any restriction imposed by a bending of the silicone tube reduced the flow rate on one side and the other imposed itself on the thread as the preferred path.

The value of Re_{crit} was taken as the one in which the thread passes through the flow developing region of an outlet, gains turbulence and no longer returns to the laminar regime. For the proper calculation, the adopted viscosity value was 0.0008903 Ns/m² and density was 1000 kg/m³, both typical properties of water under NTP conditions.

4. RESULTS AND DISCUSSION

Figure 4 below shows a sketch of the path taken by the blue thread through a bifurcation outlet past the flow developing region, in laminar condition on the left and turbulent on the right.
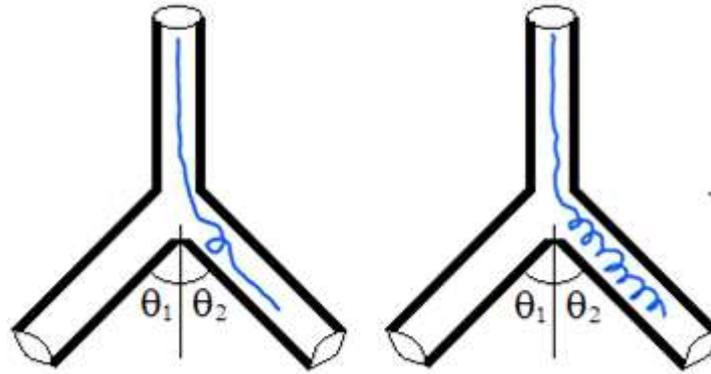
Figure 4. Sketch of the path taken by a fillet in laminar flow on the left and turbulent flow on the right, through one of the outlets of a bifurcation of half angles θ_1 and θ_2

In Figure 5, which shows a bifurcation of half-angles equal to 45°x30°, the real behavior of a thread flowing in a laminar regime through the feeder tube can be seen. It finds the flow developing region, takes the spiral shape and returns to the laminar regime, regressing to a straight line. In Figure 6, which shows the flow through a bifurcation of half-angles equal to 30°x30°, the thread remains in a turbulent condition after the entrance region in the outlet on the right. The turbulent regime can be seen by the existence of continuous spirals along the entire path.

In Amado et al, 2020d, Re_{crit} values were collected as shown in Table 2, however based solely on computer simulation, as stated initially. The simulated bifurcations were of half-angles paired with 45 degrees, as per the first column. The diameter of the tube used was 0.02 m. The experimental values could thus be compared to the values of this reference.

Table 2. Values of half-angles, flow rates and respective Re_{crit}, shown in Amado et al, 2020d

Half-angle (degrees)	Flow rate (m³/s)	Re_{crit}
0	0,00003	2533,88
5	0,00007	2208,71
10	0,00007	2183,47
15	0,00007	2141,60
20	0,00007	2083,44
25	0,00007	2009,42
30	0,00008	2194,41
35	0,00008	2075,66
40	0,00009	2183,70
45	0,00009	2015,69
50	0,00010	2035,94
55	0,00012	2180,31
60	0,00013	2058,78
65	0,00015	2007,47
70	0,00019	2057,12
75	0,00025	2049,43
80	0,00038	2035,02
82,5	0,00050	2025,77

The experimental flow rate values that imply the non-return of the fillet to the laminar condition were noted for each of the bifurcations at different angles. These values are shown in Table 3. The respective critical Re_{crit} value was calculated and appears in the penultimate column of the same table. As can be seen, the values are quite different from those raised in Amado and Corradi, 2020d, shown in the last column of Table 2. Therefore, the experiments do not corroborate Eq. (2) proposed in the reference.

Table 3. Values of bifurcation half-angles, flow rates and respective Re_{crit} measured herein

Bifurcation	Critical flow rate indicated on the rotameter (m³/s)	Outlet flow rate (m³/s)	outlet velocity (m/s)	Re_{crit}	Remark
30º x 30º	0.000002917	0.000001458	0.010987028	160.430596	
45º x 0º	0.000002917	0.000001458	0.010987028	160.430596	Flowed at 45º
45º x 20º	0.000005833	0.000002917	0.021974055	320.861191	Flowed at 20º
45º x 25º	0.000005000	0.000002500	0.018834905	275.023878	Flowed at 45º
45º x 45º	0.000005333	0.000002667	0.020090565	293.358803	
45º x 60º	0.000003167	0.000001583	0.011928773	174.181789	Flowed intermittently
45º x 75º	-	-	-	-	Failed
45º x 90º	-	-	-	-	Failed
45º x 105º	-	-	-	-	Failed

Figure 5. Flow of a thread through a bifurcation of half angles equal to 45º x 30º in which the spiral trajectory in the entrance can be seen and the recovery to the laminar regime after this region

Just as the case happened with the values found in Amado and Corradi, 2020d, Ghobadi and Muzychka, 2016, inform in their work that most of the authors investigated presented Re_{crit} in curved sections greater than those normally found for straight sections. In contrast, in Vasconcelos, 1993, Re values of the order of just a few tens are found for the study of turbulent flow in bifurcations.

Given this behavior and considering that the sampling of results is small, the authors decided not to propose a correlation that encompasses the Re_{crit} values presented in table 3. This survey will be carried out in future research, based on the execution of new experiments, with new bifurcations that present other diameters, as well as a greater variety of half-angles.
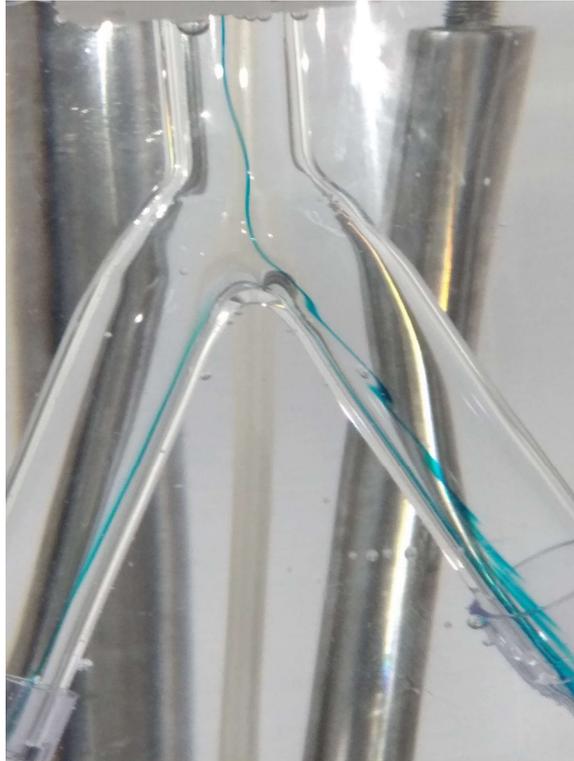
Figure 6. Flow of a thread through the outlets of a bifurcation of half angles equal to 30º x 30º, in
which the spiral trajectory can be seen along the entire path of the outlet on the right, without
returning to the laminar regime

Likewise, in future work, the authors will measure the length of the flow developing region to validate previously proposed correlations for such prediction, which were based solely on computer simulation.

5. CONCLUSION

An experimental apparatus was conceived, manufactured and assembled with the objective of carrying out experiments that aim to corroborate previously proposed correlations, which were exclusively based on numerical simulation. These correlations are intended to predict the lengths of the thermal and flow developing regions, as well as the critical Reynolds Number Re_{crit} values in bifurcations.

A qualitative analysis was carried out, showing that a fillet in laminar flow, upon finding the entrance region of the bifurcation, makes a spiral and returns to the laminar condition at the end of it. In a turbulent condition, the fillet revolves in spirals throughout the bifurcated path, not returning to form a straight line.

Re_{crit} values were experimentally raised. They were quite low compared to those predicted by a correlation proposed in the literature, based only on numerical simulation. It is possible to find in the literature works that indicate that Re_{crit} values are normally higher than those found for straight stretches, as well as works that indicate Re values of the order of only a few tens for turbulent flow in bifurcations.

New experiments must be performed to mature the discussion carried out in this work, as well as to raise a correlation that intends to predict Re_{crit} based on laboratory results.

6. ACKNOWLEDGEMENTS

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