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**EXPERIMENTAL INVESTIGATION OF PARAMETERS THAT CHARACTERIZE
OPEN-CHANNEL FLOW**

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Abstract: *Open-channel flows are characterized for having a free surface open to the atmosphere, having a great number of practical applications in engineering. The characterization of the flow in an open-channel depends on a variety of factors, such as: the fluid, flow area, flow rate, flow depth, bed slope and the surface roughness of the channel material. This paper is based on the experimental study of a tests section in a hydraulic open-channel with a rectangular cross-section operated with water as the work fluid. The aforementioned parameters are extensively analyzed via experimental tests. In general, it was observed that the flow was practically turbulent and supercritical during the testing period. The water level was reduced by half as the channel slope was increasing. The average for the Manning and the Chézy coefficients were, respectively, 0.00784 e 59.1.*

Keywords: *Open-channel, experimental study, flow, water.*

1. INTRODUCTION

Water channels are equipment designed to provide a flow with well-known controlled characteristics inside of the tests section. Once built, this kind of apparatus must be judiciously evaluated, through the realization of tests in order to investigate the flow's characteristics (Mega, 2009).

Open-channel flows are characterized for having a free surface open to the atmosphere, having a great number of practical applications in engineering (Fox, McDonald and Pritchard, 2010). Its complexity resides on the vast combination of factors that define the channel, since the free surface can vary on time and space, and, as a result, the flow depth, the flow rate and the bed slope are interdependent physical quantities (Porto, 2006).

This paper is based on the experimental study of a tests section in a hydraulic open-channel with a rectangular cross section operated with water as the work fluid. The flow was analyzed as for its type (subcritical or supercritical), by determining the Froude number (Fr) for several points. Furthermore, the type of flow regime (turbulent or laminar) was analyzed, determining the Reynolds number (Re) for the same points. These results are preliminary data intended to validate the experimental setup.

2. METHODOLOGY

A description of the test bench, the experimental procedures and the mathematical modelling for the evaluation of the main parameters involved in the water flow through the open-channel is presented below.

2.1. Test bench description

The test bench consists of an open-channel model built in acrylic that possesses a mechanism to elevate the channel slope. Figure 1 shows the test bench.



Figure 1. Test bench of open-channel flows.

The flow rate given by the pump set can be fixed and specified by a flowmeter. A graduated support in one of the sustentation extremities of the channel allows the execution of a controlled variation of the channel slope, as shown in Figure 2. For each variation of the slope, it is possible to determine the height of the water level with a graduated ruler.



Figure 2. Mechanism for elevation of the channel slope.

2.2. Experimental procedures and mathematical modelling

The tests consisted in measuring the height of the water level for 10 different slopes, keeping the water flow rate constant. With the data collected it is possible to determine the average velocity V of the water flow, the Reynolds number Re and the Froude number Fr . Re and Fr are generally used as dimensionless parameters of physical problems related to closed and open conduits, respectively (Baptista et al., 2013).

The average velocity of the flow can be determined by Eq. (1), the Reynolds number by Eq. (2) and the Froude number by Eq. (3) (Çengel, 2007). The equations take into account that the cross section of the channel is rectangular and constant.

$$V = \frac{Q}{By} \quad (1)$$

$$Re = \frac{\rho V L_{character}}{\mu} \quad (2)$$

$$Fr = \frac{V}{\sqrt{g \cdot y}} \quad (3)$$

Where ρ is the density of the fluid (997.0 kg/m^3 at $25 \text{ }^\circ\text{C}$), V is given in m/s , $L_{character}$ is the characteristic length of the channel (m), μ is the dynamic viscosity of water ($0.00103 \text{ Pa}\cdot\text{s}$ at $25 \text{ }^\circ\text{C}$), g is the gravitational acceleration (9.81 m/s^2),

B is the channel width (0.135 m), Q is the water flow rate (0.00085 m³/s) and y is the height of the water level. $L_{charact}$ is given by Eq. (4).

$$L_{charact} = 4R_h = 4\left(\frac{By}{2y+B}\right) \quad (4)$$

$L_{charact}$ equals 4 times the hydraulic radius R_h of the channel, which on the other hand is the relation between the cross-section area of the flow over the wetted perimeter. It is possible to write a relation of the height of the critical layer for a channel with defined geometry. That is, the height of the water layer on which the flow regime is critical y_{crit} and is in imminent change ($Fr = 1$). Eq. (5) shows this relation.

$$y_{crit} = \left(\frac{Q}{\sqrt{g}B}\right)^{2/3} \quad (5)$$

By analyzing the acting forces over a control volume of water flowing through the channel, it is noticed that there is an equilibrium between the surface force (drag), opposing the movement of the fluid flow and the gravitational force, acting in the same direction of the flow. Thus, it is possible to reach Eq. (6) and Eq. (7) that represents, respectively, the Chézy coefficient C and the Manning coefficient n , which are dimensionless numbers related to the friction effect that exists between the fluid and the channel walls.

$$C = \frac{V}{R_h^{1/2} I^{1/2}} \quad (6)$$

$$n = \frac{R_h^{2/3}}{C} \quad (7)$$

Where I is the channel slope (m/m) for small angles, given by Eq. (8). The flow velocity can be written according to Eq. (9).

$$I = \frac{\Delta z}{L} \quad (8)$$

$$V = \frac{1}{n} R_h^{2/3} I^{1/2} \quad (9)$$

Where Δz (m) is the manually imposed slope via the mechanism for elevation of the channel slope and L is the total length of the channel (2.22 m).

The specific energy of the flow E is determined as a function of the piezometric energy y (m), named E_1 and of the kinetic energy ($V^2/2g$), named E_2 according to Eq. (10).

$$E = E_1 + E_2 = y + \frac{V^2}{2g} \quad (10)$$

3. RESULTS

Table 1 gathers the experimental data collected and the parameters calculated for the analysis of the type of flow regime. Figure 3 shows the relation between both dimensionless numbers related to the characterization of the flow.

Table 1. Data collected and parameters calculated for the flow analysis.

Δz (m)	y (m)	Velocity (m/s)	Re	Regime	Fr	Regime
0	0.017	0.370	19998	Turbulent	0.907	Subcritical
0.005	0.015	0.420	20483	Turbulent	1.094	Supercritical
0.01	0.012	0.525	21256	Turbulent	1.529	Supercritical
0.02	0.0115	0.548	21390	Turbulent	1.630	Supercritical
0.03	0.01	0.630	21804	Turbulent	2.010	Supercritical
0.04	0.0095	0.663	21946	Turbulent	2.171	Supercritical
0.05	0.009	0.700	22089	Turbulent	2.354	Supercritical
0.065	0.0085	0.741	22235	Turbulent	2.565	Supercritical
0.08	0.008	0.787	22382	Turbulent	2.809	Supercritical
0.1	0.007	0.899	22682	Turbulent	3.432	Supercritical

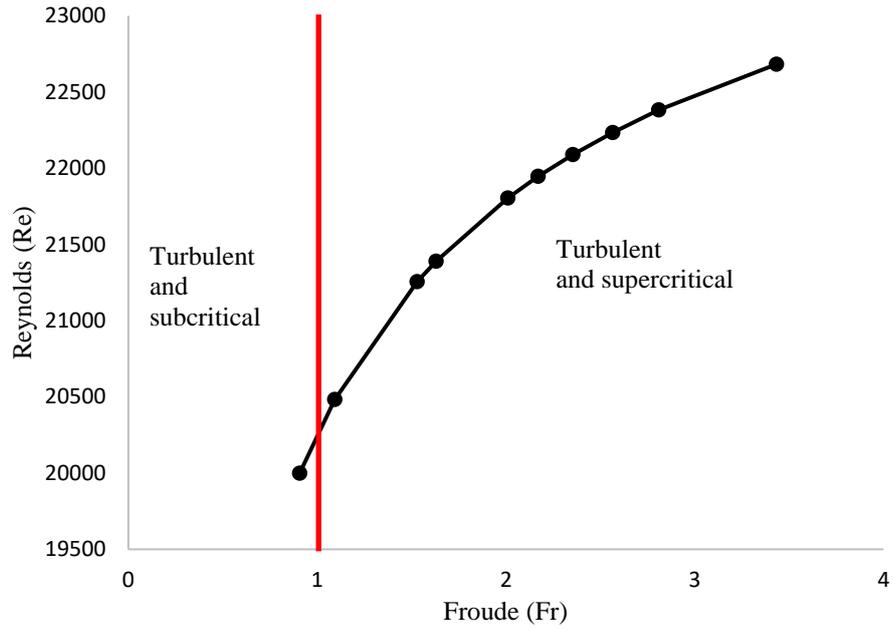


Figure 3. Reynolds x Froude

It is possible to observe that as the slope is increasing, there is a reduction of the height of the fluid layer, as a result of the increase of velocity, since the flow rate remains constant. For analysis in open-channel flows, the dimensionless number Fr is more significant, therefore, it is noted that for the selected flow rate and for the difference in heights over 0.017m the regime tends to be supercritical, characterized by Fr being greater than 1. For values of Fr lower than 1, the flow is subcritical. In general, the flow is supercritical for almost all observed points.

Regarding the Reynolds number, literature (Potter, 2004) describes that, for values greater than 4000, the flow can be considered turbulent. Below 2300 the flow is laminar and between these values, there is the transition regime. All recorded values are over 20000, so the flow is turbulent for all analyzed points.

Table 2 gathers the other calculated parameters. Figure 4 displays the behavior of the energies involved in the flow (piezometric and kinetic).

Table 2. Parameters measured and calculated.

Δz (m)	y (m)	Velocity (m/s)	Re	Fr	E_1 (mm)	E_2 (mm)	E (mm)	n	C
0	0.017	0.370	19998	0.907	17.0	7.0	24.0	-	-
0.005	0.015	0.420	20483	1.094	15.0	9.0	24.0	0.00602	79.8
0.01	0.012	0.525	21256	1.529	12.0	14.0	26.0	0.00601	77.5
0.02	0.0115	0.548	21390	1.630	11.5	15.3	26.8	0.00795	58.2
0.03	0.01	0.630	21804	2.010	10.0	20.2	30.2	0.00782	58.0
0.04	0.0095	0.663	21946	2.171	9.5	22.4	31.9	0.00832	54.1
0.05	0.009	0.700	22089	2.354	9.0	24.9	33.9	0.00854	52.3
0.065	0.0085	0.741	22235	2.565	8.5	28.0	36.5	0.00889	49.8
0.08	0.008	0.787	22382	2.809	8.0	31.6	39.6	0.00895	49.0
0.1	0.007	0.899	22682	3.432	7.0	41.2	48.2	0.00808	53.2

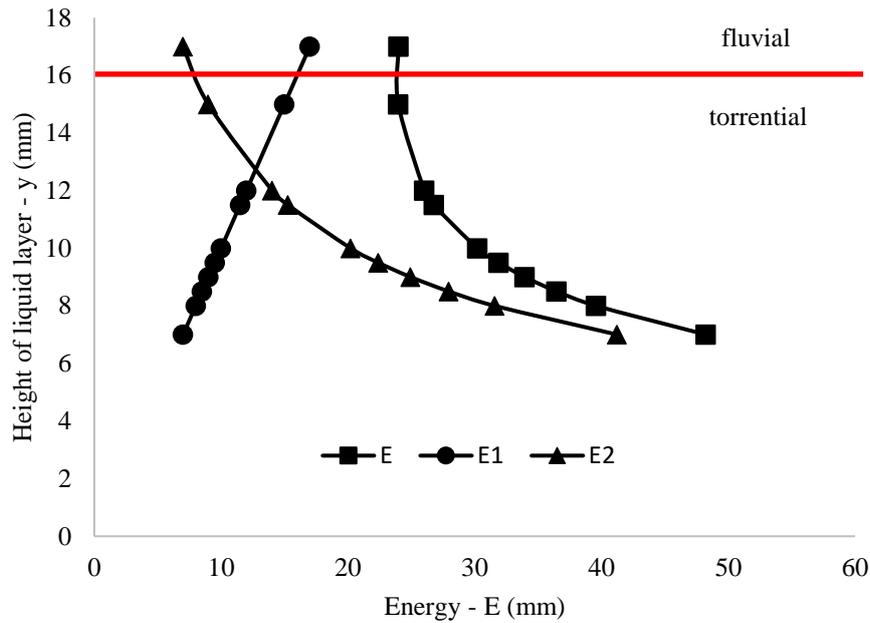


Figure 4. Energies involved in the flow.

The curves on Figure 4 represent the height of the liquid layer as a function of the total, piezometric, and velocity heads. It is noted that the point on which occurs a change on the curvature of the total energy function (E) is denominated critical point and represents the operational situation on which the coefficient Fr equals 1, delimiting the transition from the subcritical regime to the supercritical regime. Using Eq. (5), the same value corresponding to Figure 4 is reached, that is, 1.6 cm. Also, it is observed that as the fluid layer reduces, the piezometric energy decreases and the kinetic energy increases, due to the gain of flow velocity. In general, the situation with less specific energy happens on the point of curvature change.

Figure 5 displays the curve for the channel slope I as a function of the water layer y , as well as Fr as a function of y .

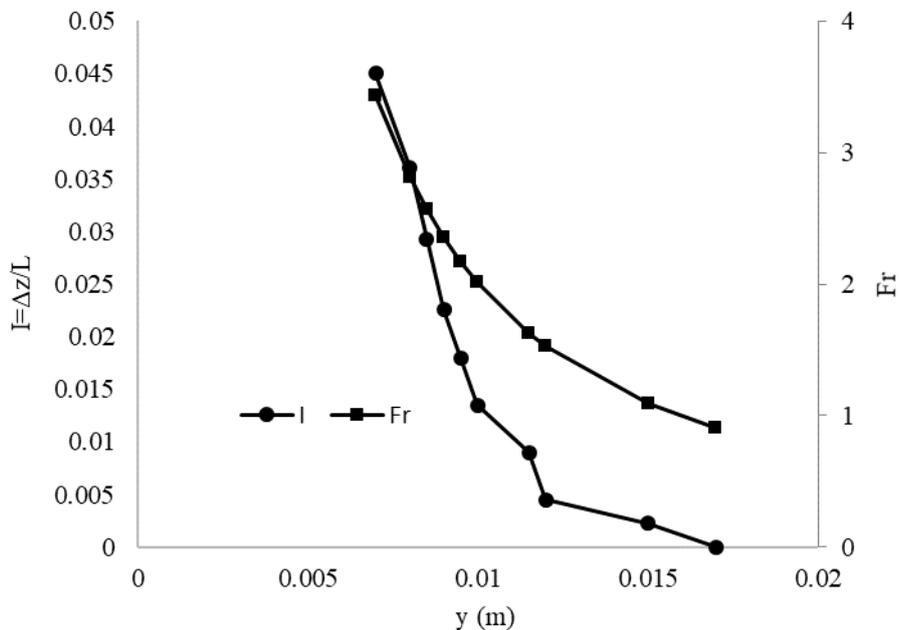


Figure 5. I and Fr as a function of y .

By the tendency curves showed on Figure 5, it is noticed the tendency of very high values for Fr and I as the water layer decreases. Due to this behavior, it is inferred that there is a critical slope on which, for higher values than it, the water layer practically doesn't change. Concomitantly, Fr assumes high values, characterizing the flow as torrential

Figure 6 displays the Chézy and Manning coefficients for the analyzed channel. Since the test consisted in analyzing variables for a single flow rate, these coefficients oscillations are on the vertical of the graph. The values obtained show a significant variation in relation to the others, which can be justified by parallax errors (water movement in relation with the ruler at the time of measure) and by the imprecision of the position of the ruler that measured the depth of the fluid

layer. The average for the Manning coefficient experimentally obtained for the acrylic channel equals to 0.00784 and for the Chézy coefficient equals to 59.1.

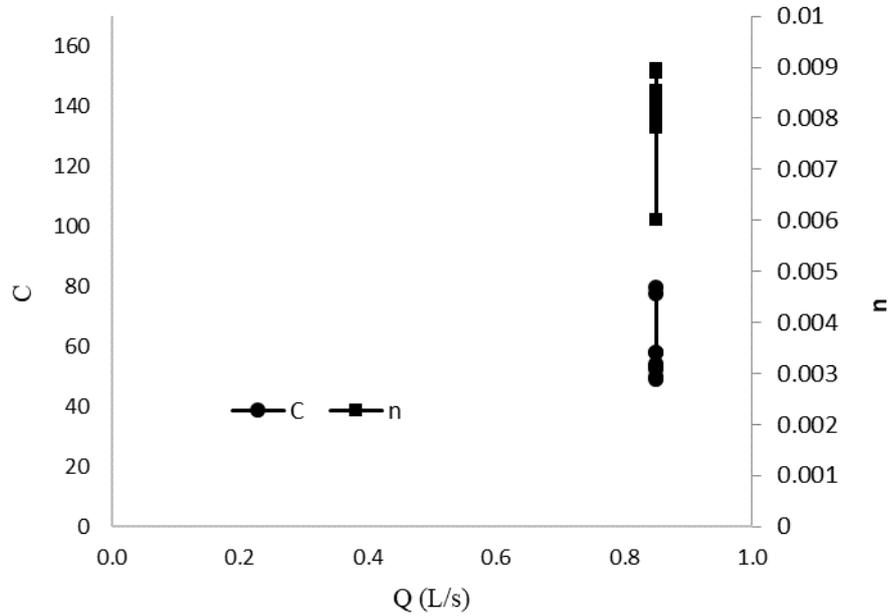


Figure 6. Coefficients related to the roughness of the channel wall.

Figure 7 shows the velocity as a function of the hydraulic Reynolds and the channel slope. It can be observed that the velocity increases as the Reynolds and the slope also increases.

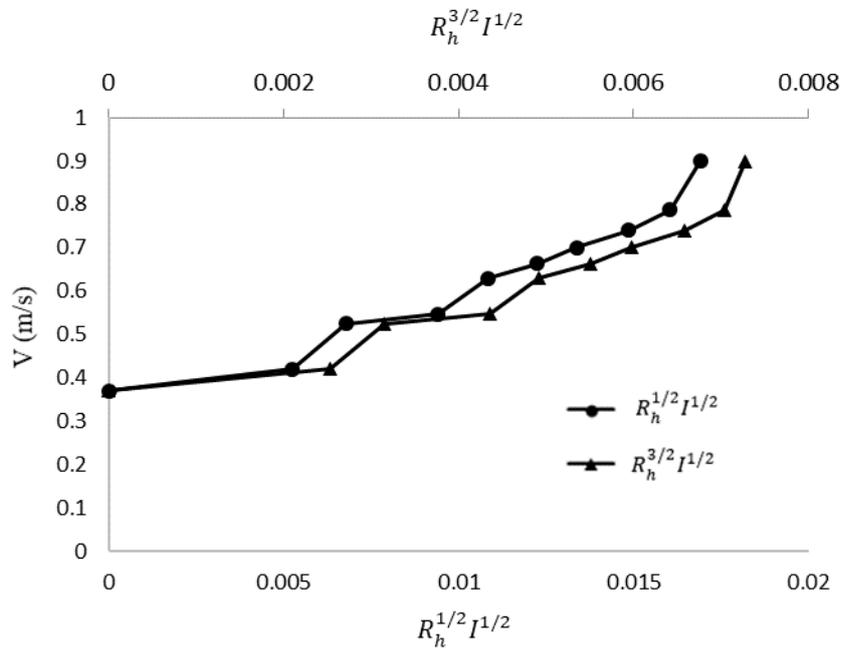


Figure 7. Velocity as a function of the hydraulic Reynolds and the channel slope.

4. CONCLUSIONS

The observation of the flow regime of an open-channel is essential to predict and understand the behavior of the analyzed system, ensuring, for instance, safety for population and facilities located near these systems, by projecting energy dissipation elements when supercritical flow is noticed.

The analysis of the dimensionless Froude number is a parameter that helps the determination of the flow regime, and can be easily achieved in an execution of models to scale. During the elaboration of the models, the effect due to the surface roughness of the model and prototype must be correlated, therefore, the analysis of the Manning coefficient is indispensable.

In general, it was observed that the flow was practically turbulent and supercritical throughout the entire period of tests for the fixed flow rate. The water layer decreased as the channel slope increased. The average Manning and Chézy coefficients were, respectively, 0.00784 and 59.1.

5. REFERENCES

- Çengel, Y.A., 2007. *Mecânica dos Fluidos, Fundamentos e Aplicações*, 1^o edição, McGrawHill, São Paulo.
- Baptista, M.B.; Coelho, M.M.L.P.; Cirilo, J.A.; Marcarenhas, F.C.B., 2003. *Hidráulica aplicada*, 2^o edição, ABRH, Porto Alegre.
- Fox, R.W.; McDonald, A.T.; and Pritchard, P.J.. *Introduction to fluid mechanics*, 5th edition, John Wiley & Sons, New York, 2010.
- Mega, E.A.F., 2009. *Estudo experimental do escoamento em cavidades abertas utilizando um canal de superfície livre*. Master's thesis, Post-Graduate Program in Mechanical Engineering, Universidade Estadual Paulista Júlio de Mesquita Filho, Ilha Solteira.
- Porto, R.M., 2006. *Hidráulica Básica*. 4^o ed. São Carlos: EESC/USP.
- Potter, M.C.; Wiggert, D.C.; Hondzo, M.; Shih, T.I.P., 2004. *Mecânica dos Fluidos*, Pioneira Thomsom Learning, São Paulo.