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REVISTA INGENIO

Determination of experimental flow curves for a 6” Parshall flume based on the variation in the channel bottom slope.

Determinación de curvas de aforo experimentales para una canaleta Parshall de 6” a partir de la variación de la pendiente de fondo del canal

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PALABRAS CLAVE
Estructuras hidráulicas, ingeniería hidráulica, medición hidrológica, métodos de medición, aforador Parshall, medición del caudal de descarga de agua.

RESUMEN
En este artículo se reportan los resultados de la investigación basada en pruebas experimentales en laboratorio de un aforador Parshall de 6 pulgadas de ancho de garganta, diseñado y construido según la norma ASTM D1941-21, constituido en polimetilmetacrilato (acrílico), instalado en el interior del canal hidrodinámico del Centro de Investigaciones y Estudios de Ingeniería de los Recursos Hídricos de la Escuela Politécnica Nacional (CIERHI – EPN); las pruebas determinan la variación de los caudales aforados en función de la variación de las pendientes del fondo del canal hidrodinámico s (5 pendientes) en condiciones de descarga libre; se comparan entre las curvas de aforo experimentales resultantes y la curva teórica - empírica normada, se obtienen los errores y diferencias relativas y se establecen zonas gráficas del ábaco correspondiente, donde el máximo error relativo tolerable para los caudales aforados con la curva teórica es Er=10%.

KEY WORDS
Hydraulic structures, hydraulic engineering, hydrological measurement, measuring methods, Parshall Flume, water discharge flow measurement.

ABSTRACT
This article reports the results of research based on experimental laboratory tests of a Parshall flume with a 6-inch throat width, designed and constructed in accordance with ASTM D1941-21 standard, made of polymethyl methacrylate (acrylic), installed inside the hydrodynamic channel of the Center for Research and Studies in Water Resources Engineering at the National Polytechnic School (CIERHI – EPN); the tests determine the variation in measured flow rates based on the variation in the slopes of the bottom of the hydrodynamic channel s (5 slopes) under free discharge conditions. The resulting experimental flow curves are compared with the standardized theoretical-empirical curve, the relative errors and differences are obtained, and graphic zones are established on the corresponding chart, where the maximum tolerable relative error for the flow rates measured with the theoretical curve is Er=10%

1. INTRODUCCION

In hydraulic engineering, it is vitally important to measure flow rates for the various uses and needs of humans in their activities. Parshall flumes, developed by Ralph L. Parshall in 1920, are used to accurately measure flow rates in open channels and canals with free surface flow, such as: water distribution channels, municipal sewers, ditches, drinking water and wastewater treatment plants, irrigation channels, dam discharges, industrial effluents, and leachate discharges [1] and as a device for the rapid mixing and dispersion of coagulants in water treatment systems.

The Parshall flume must be designed to connect to an approach section with subcritical flow (low velocities) by means of a section with an ascending bottom ramp and circular flaring on its walls, followed by a converging section with a level bottom, a throat section with a descending inclined bottom, and a diverging section with an ascending

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inclined bottom [2], all with vertical walls [3]; this design forces the flow to accelerate [4] and transform it inside to supercritical, with velocities greater than in the approach section [5]; when forcing a change in regime, critical flow is imminent in a specific section within the flume, hence the name critical depth meters for gauging structures that contemplate bottom elevations and/or transverse contractions, with Parshall flumes being the most widely used in this category [5]. Critical flow has a unique surface profile for each flow rate, therefore, there is a direct relationship between the depth near the critical depth zone and the circulating flow rate, expressed through an empirical equation that allows the estimation of flow rates by entering the depth values in a defined section; This equation is independent of channel roughness and other uncontrollable factors [5], is specific to the geometry of each Parshall flume, and has the following form [6]:

$$Q = C.{H_a}^n \tag{1}$$

Where $\boldsymbol{Q}$ is the measured flow rate; $\boldsymbol{C}$ is a dimensional factor that depends on the throat width; $\boldsymbol{H_a}$ is the critical flow depth within the converging section, measured at a distance of 2/3 of ***Lc*** (convergence length) from the start of the throat; $\boldsymbol{n}$ is a dimensionless exponent that depends on the throat width [2].

For each Parshall flume with a standard throat width $\boldsymbol{W_t}$, operating in free flow, there are theoretical values of $\boldsymbol{C}$ and $\boldsymbol{n}$, whose values vary depending on the units for length and volume used. For example, for the throat width chosen for this research, $\boldsymbol{W_t}$ **= 6" = 0.152** ***m***, for flow rates in l/s and depths in cm, $\boldsymbol{C}$ **= 0.264** and $\boldsymbol{n}$ **= 1.58** [6], while for flow rates in m^3/s and depths in m, $\boldsymbol{C}$ **= 0.3812** and $\boldsymbol{n}$ **= 1.58** [2]; the latter were used for this research, resulting in equation (2).

$$Q = 0.3812.{H_a}^{1.58} \tag{2}$$

Where $\boldsymbol{Q}$ is the measured flow rate; $\boldsymbol{H_a}$ is the critical flow depth within the converging section, measured at a distance of 2/3 of ***Lc*** (convergence length) from the start of the throat.

Each of the 22 standardized Parshall flumes is mainly characterized and named by its throat width W_t, with standardized geometries, dimensions, and flow ranges, which must be kept accurate (tolerable error 2%) since they are not scale hydraulic models of each other, they are completely different, given that the length and slope of the throat bottom remain constant for several of them, while other dimensions vary [2]. Their inner surface should be at least as smooth as the surface of good quality concrete [6]. For this reason, and in order to visualize and measure the flows, the experimental setup for this research was constructed in acrylic.

A Parshall flume with a throat width W_t = 6" = 0.152 m, under free discharge conditions, has the capacity to measure flows from 1.42 L/s to 110.4 L/s (0.00142 m^3/s - 0.11040 m^3/s) [2], with depths H_a from 0.029 m to 0.456 m, respectively; the inlet section has a ramp with a slope of 1:4 to the start of the convergent section and, as it is a W_t < 1*ft*, a flare with circular walls of radius R = 0.41 m; at the outlet of the divergent section there may be a step to the bottom of the channel [3] (see Fig. 1).

In a Parshall flume, the ratio between the representative depths of the flow H_b and H_a is called the percentage of submergence or, for practical purposes, simply submergence S, defined by equation (3):

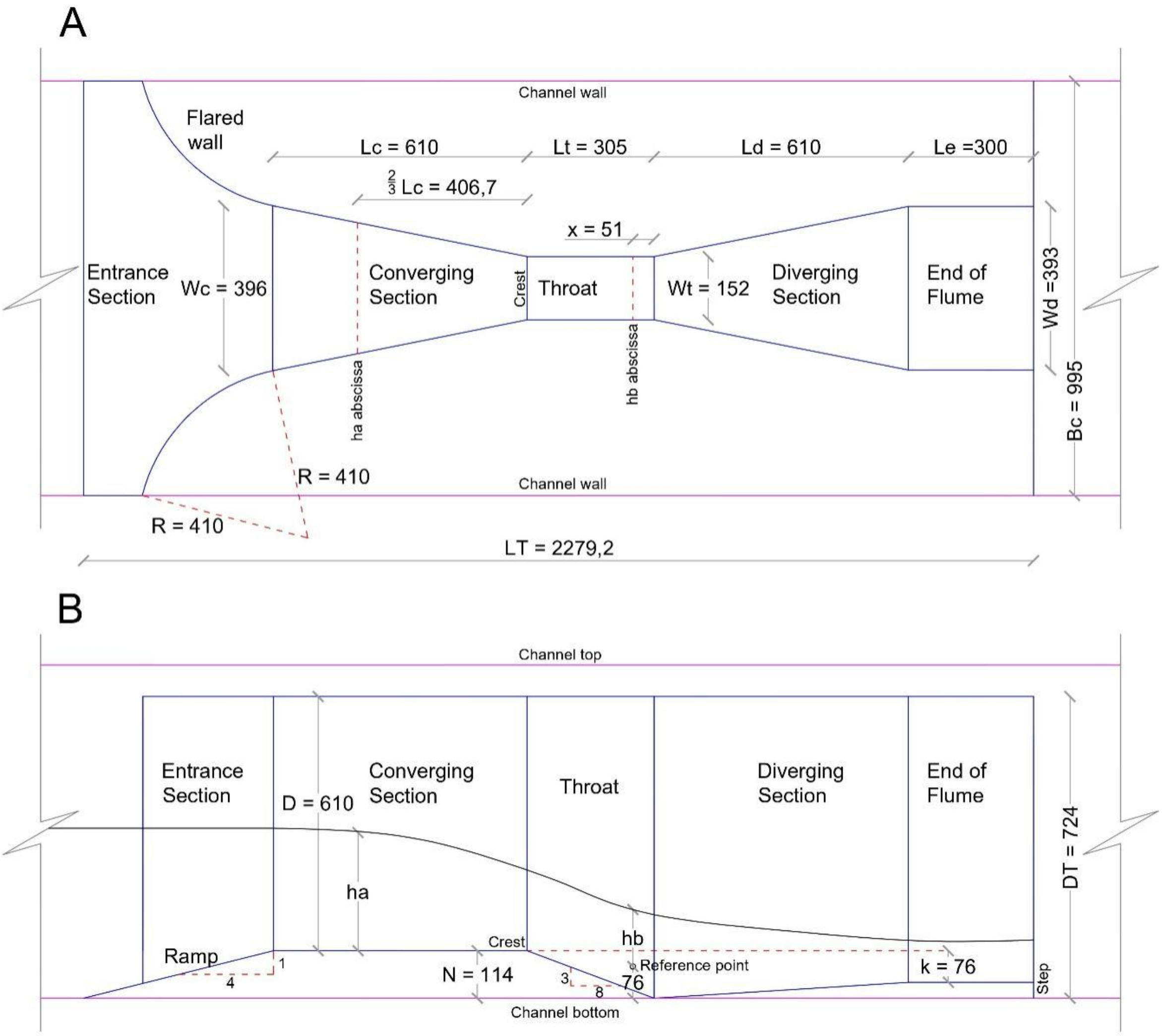
$$S = H_b/H_a \tag{3}$$

Where S(%) is the submergence, H_b is the depth near the end of the throat, and H_a is the critical flow depth measured in the converging section, measured at a distance of 2/3 of *Lc* from the start of the throat (see Fig. 1.). Both depths must have the same units of length.

Depending on the submergence, there are two possible flow conditions inside a Parshall flume:

- Free flow: occurs when, downstream of the flume, the water surface is not high enough to reduce the flow through it; in this case, provided that the bottom of the channel remains horizontal, only a single reading at the main measurement point (H_a) is needed to calculate the measured flow using the general theoretical equation (1). The limit of S is established for each Parshall flume, for example, for W_t = 6" = 0.152 m, S_{Limit}=60%, if S<S_{Limit} then the flow is free [6].
- Submerged flow: drowning occurs due to hydraulic conditions downstream of the gauge, existing obstacles, lack of slope, and/or forced levels in subsequent sections [3], causing the water surface elevation to be high enough to reduce the flow velocity, increase upstream depths, and thus create a backwater effect and greater resistance, decreasing the flow through the gauge. This additionally requires the reading of a depth H_b near the final section of the throat [1] to apply negative or reduction corrections to the Q result calculated with (1), using diagrams or abacuses as a function of S for different flow meter sizes. For W_t = 6" = 0.152 m, if S>60% then the flow is submerged [6]; S must be kept below the practical limit of 95%, because the measurement will not be reliable if the submergence is greater [5]. W_t = 6" corresponds to a small flow meter, therefore, the position of the reference point for measuring the depths H_b is 51 mm upstream and 76 mm above the lowest point at the end of the throat (see Fig. 1). The most desirable condition in practice is free flow [6], because it will be restricted to a single load measurement [3], and a double measurement results in a significant loss of accuracy [4].

Figure 1. *Diagram of the parts and measurements of the experimental Parshall flume setup located inside the CIERHI hydrodynamic channel; A) Plan view; B) Longitudinal section.*



Likewise, expression (1) does not take into account possible settlements of the Parshall flume, therefore, various authors propose correction coefficients for C and n in view of possible inclinations or slopes of the convergent section of the flume s; this research focuses on the experimental determination of precise values for C and n for five different slopes, within a moderate range in which the flume adequately fulfills its function. The Parshall flume should be constructed and installed in such a way that the bottom of the convergent zone (floor or ground) is level within a slope that does not exceed 3 mm in any dimension [6].

The main advantages of Parshall flumes are:

- The head loss in Parshall flumes is low, less than approximately one quarter of that required to operate a thin-walled, sharp-crested weir (with the same control width) [4].
- They are self-cleaning in the case of flows containing moderate amounts of solids, unlike weirs, where sediments or suspended particles will settle in the upstream reservoir, gradually changing its discharge coefficient [5];
- They can withstand relatively high degrees of submergence and still be accurate [1];
- Their construction, installation, and operation inside open channels represent low costs and technical advantages;
- They can be constructed from various materials: concrete, masonry, wood, metal, brass, etc.;
- They do not require the bottom to be raised, i.e., the channel does not need to be modified in terms of its dimensions for the setup of a Parshall flume;
- If the flow is free, it is sufficient to measure the depth in a single section to determine the flow rate accurately [3];
- Their designs are available for W_t from 2.54 cm to 15.2 m, covering flow measurements from 0.0057 to 85 m^3/s [6].

The main disadvantages of Parshall flumes are:

- They can be more expensive than a sharp-edged weir or submerged orifices in unlined channels [4];
- They cannot be used directly or in combination with an upstream gate [5];
- They are only applicable to open channels and are inoperative under pressurized flow or full pipe conditions [6].

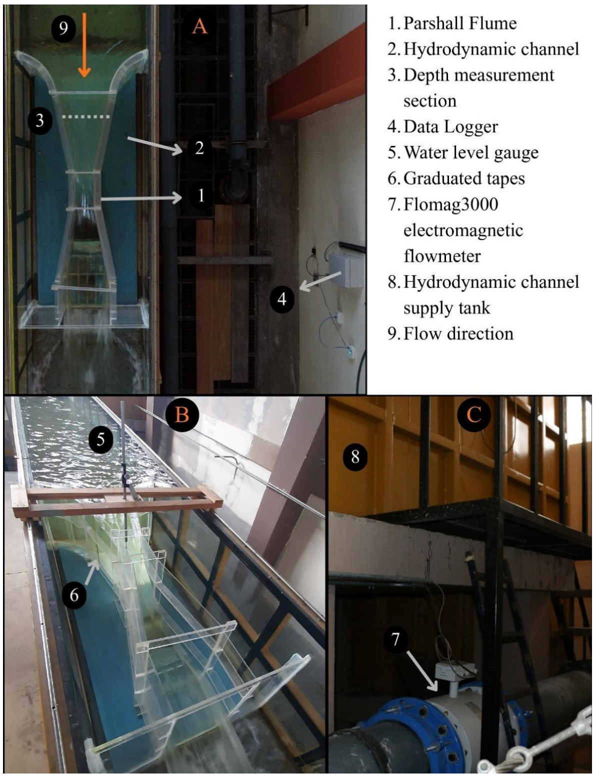
2. Methodology

The experimental setup consists mainly of a hydrodynamic channel, which is a steel structure, 1 meter wide and 25 meters long, and a SCADA control system for adjusting its slope between 0.10% and 3.76%. Inside, the primary flow measurement instrument is installed, namely the Parshall flume (see Fig. 2. A), whose secondary instruments for measuring water depth are a needle limnimeter (water level gauge) with a 0.0001 m resolution and graduated tapes (as staff gages) with 0.001 m resolution (see Fig. 2. B); the precise and accurate reference flow measurement instrument is the Flomag3000 electromagnetic flowmeter, which measures and records flow rates (see Fig. 2. C).

Parshall flume was constructed entirely of acrylic, with a wooden base to ensure its coupling and structural stability within the hydrodynamic channel. It is located at +4.70 meters, which complies with the recommendation for the length of the inlet flow approximation of the hydraulic structure, which should be at least 10 to 20 times the throat width, i.e., greater than 3.04 m. [6].

2.1 Experimental setup calibration

Figure 2. *Experimental setup: A) Parshall flume general layout inside the hydrodynamic channel; B) Water level gauge and graduated tapes used to water depth measures; C) Flomag3000 electromagnetic flowmeter.*



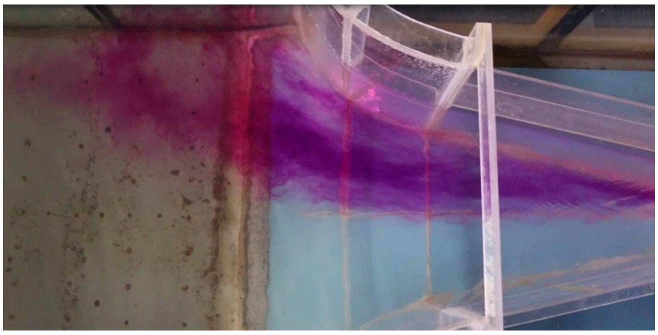
The experimental setup first undergoes a hydraulic leak test to determine the existence of and correct any possible water leaks, completely flooding the interior of the Parshall flume. All the construction dimensions obtained for the Parshall flume are within the permissible error limit of 2% compared to the standardized dimensional values for the structure selected for a throat width W_t=6"=0.152 *m* (see Table 1).

Table 1. *Construction dimensions and errors obtained in the Parshall flume.*

	Parshall Flume design dimensions $W_t = 6" = 0.152\ m$ [6]			Actual dimensions built	Error	
	Symbol	*ft*	*mm*	*mm*	*mm*	%
Throat width	Wt	0.50	152.4	152.0	-0.4	0.26%
Convergence width	Wc	1.30	396.2	396.0	-0.2	0.06%
Divergence width	Wd	1.29	393.2	393.0	-0.2	0.05%
Convergence length	Lc	2.00	609.6	610.0	0.4	0.07%
Throat length	Lt	1.00	304.8	305.0	0.2	0.07%
Divergence length	Ld	2.00	609.6	610.0	0.4	0.07%
Walls height	D	2.00	609.6	610.0	0.4	0.07%
Vertical distance from the crest to the bottom throat	N	0.38	114.3	114.0	-0.3	0.26%
Vertical distance from the crest to the lower end of the flume	K	0.25	76.2	76.0	-0.2	0.26%
Inlet curvature radius	R		410.0	410.0	0.0	0.00%

In addition, its optimal hydrodynamic performance and uniform distribution of streamlines at the inlet of the flare (see Fig. 3) were verified with the circulation of various flow rates, thus confirming the perfect conditioning of joints and edges. The hydrodynamic behavior of the structure was tested under critical operating conditions to ensure that water level readings can be taken without any interference that could generate anomalous data.

Figure 3. *Uniform streamlines distribution verification at Parshall flume inlet.*



2.2 Electromagnetic flowmeter as reference measuring instrument.

There are two basic types of flowmeters: long-throat and short-throat; within the latter group are Parshall flumes, since they control the flow in a region where curvilinear flow occurs; the calibration process for these structures is determined empirically by comparison with other more precise and accurate reference measurement systems [4], such as electromagnetic flow meters. This research, all flows are measured using the Flomag3000 electromagnetic sensor flow meter as a reference system for testing the Parshall flume, which is installed in the hydrodynamic channel inlet pipe. This equipment, with a nominal diameter of 300 mm and connected to a real-time transmission system, stores the records every 30 seconds in a YDOC ML-x17 data logger, and allows for a complete record of the series flow rates for each tests planned.

2.3 Testing plan.

Following the recommendations and methodology of the applicable regulations [6], for each of the five slopes tested for the hydrodynamic channel, experimental tests were carried out with 12 flow rates Q (within the corresponding range 0.00142 m^3/s - 0.11040 m^3/s), measuring 5 times each water depth H_a on the corresponding abscissa 2A/3 in the convergent zone; a total of sixty tests were performed, generating a 300 water depth measurements data set (see Table 2).

Table 2. *Flow rates corresponding to the 60 tests planned to be carried out at the experimental setup.*

		Hydrodynamic Channel Slope - s (%)				
		0,10	1,00	2,00	3,00	3,76
Target flow rates (m^3/s)	Q (m^3/s)	Q (m^3/s)	Q (m^3/s)	Q (m^3/s)	Q (m^3/s)	Q (m^3/s)
	0,005	Q_1	Q_{13}	Q_{25}	Q_{37}	Q_{49}
	0,015	Q_2	Q_{14}	Q_{26}	Q_{38}	Q_{50}
	0,025	Q_3	Q_{15}	Q_{27}	Q_{39}	Q_{51}
	0,035	Q_4	Q_{16}	Q_{28}	Q_{40}	Q_{52}
	0,045	Q_5	Q_{17}	Q_{29}	Q_{41}	Q_{53}
	0,055	Q_6	Q_{18}	Q_{30}	Q_{42}	Q_{54}
	0,065	Q_7	Q_{19}	Q_{31}	Q_{43}	Q_{55}
	0,075	Q_8	Q_{20}	Q_{32}	Q_{44}	Q_{56}
	0,084	Q_9	Q_{21}	Q_{33}	Q_{45}	Q_{57}
	0,090	Q_{10}	Q_{22}	Q_{34}	Q_{46}	Q_{58}
	0,100	Q_{11}	Q_{23}	Q_{35}	Q_{47}	Q_{59}
	0,103	Q_{12}	Q_{24}	Q_{36}	Q_{48}	Q_{60}

(The columns for the five slopes are labelled "Experimental flow rates (m^3/s)".)

2.4 Error sources

The hydrodynamic channel allows the converging section of the Parshall flume to be leveled, both laterally and longitudinally, to obtain accurate readings. Flows with depth values H_a<30 mm was avoided to comply with the criteria and recommendations of tests carried out in similar experimental setups; in addition, the recommendation to keep the approach section free of moss or other debris accumulation during the tests was strictly followed [6]. Regarding reference instrument errors, the accuracy of the Flomag3000 flow meter is guaranteed with an error within the range of 0.5% - 2.2%, according to the manufacturer [7].

3. Results and Discussion

Table 3 shows the average results of the 5 H_a measurements taken in each of the 60 tests in the experimental setup test plan, corresponding to the 12 flow rates Q for each of the 5 slopes investigated.

Table 3. *Results of the average depths and flow rates corresponding to the 60 tests in the experimental setup test plan.*

Hydrodynamic Channel Slope - s (%)									
0,10		1,00		2,00		3,00		3,76	
H_a (m)	Q (m^3/s)	H_a (m)	Q (m^3/s)	H_a (m)	Q (m^3/s)	H_a (m)	Q (m^3/s)	H_a (m)	Q (m^3/s)
0,0678	0,00570	0,0681	0,00618	0,0625	0,00602	0,0562	0,00592	0,0495	0,00564
0,1307	0,01550	0,1242	0,01520	0,1209	0,01524	0,1149	0,01494	0,1134	0,01520
0,1791	0,02525	0,1744	0,02500	0,1689	0,02488	0,1641	0,02497	0,1585	0,02505
0,2241	0,03540	0,2155	0,03473	0,2114	0,03482	0,2075	0,03513	0,2026	0,03518
0,2638	0,04525	0,2555	0,04502	0,2498	0,04470	0,2448	0,04523	0,2412	0,04506
0,2996	0,05510	0,2912	0,05506	0,2856	0,05473	0,2818	0,05521	0,2761	0,05537
0,3372	0,06550	0,3283	0,06560	0,3227	0,06511	0,3170	0,06527	0,3130	0,06517
0,3709	0,07565	0,3619	0,07520	0,3572	0,07566	0,3516	0,07525	0,3443	0,07517
0,3958	0,08355	0,3871	0,08345	0,3795	0,08267	0,3769	0,08318	0,3725	0,08409
0,4178	0,09035	0,4083	0,09036	0,4044	0,09080	0,3977	0,09053	0,3921	0,09029
0,4466	0,09995	0,4365	0,10000	0,4324	0,10038	0,4286	0,10043	0,4206	0,10031
0,4564	0,10310	0,4466	0,10277	0,4389	0,10292	0,4333	0,10224	0,4314	0,10313

(Rows labelled "Experimental flow rates (m^3/s)".)

Based on the values in Table 3 and the theoretical equation (2), the trend curves in Figure 4 are plotted and the respective experimental flow equations are obtained. The experimental flows in Table 3 are, in each case, the average flow of the flow meter, i.e., the average value of the instantaneous flows measured by the Flomag3000 flow meter during the test and reported by the Data Logger controller and its YDOC – Insights software. The coefficients of determination R2 corresponding to the trend lines used to obtain the experimental flow equations and curves for the Parshall flume (see Fig. 4) have values very close to or equal to 1 (between 0.9984 and 1.0000) for the five slopes tested. Therefore, it is concluded that there is an adequate fit between the values obtained from these equations/curves and the values recorded experimentally for all the slopes analyzed. As can be seen in the respective experimental curves (see Fig. 4), the experimental equations obtained for the five slopes tested are, respectively:

Experimental equation for $s = 0.1\%$: $Q = 0.3413.H_a^{1.5184}$ (4)

Experimental equation for $s = 1.0\%$: $Q = 0.3464.H_a^{1.4987}$ (5)

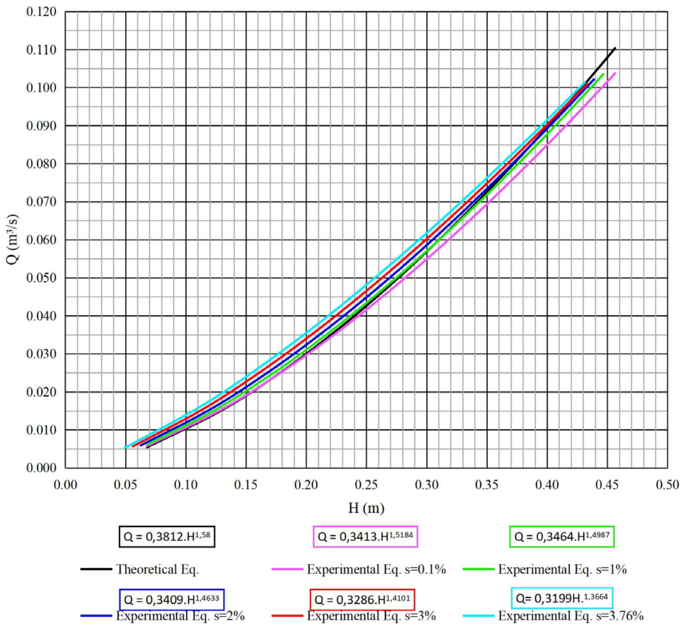
Experimental equation for $s = 2.0\%$: $Q = 0.3409.H_a^{1.4633}$ (6)

Experimental equation for $s = 3.0\%$: $Q = 0.3286.H_a^{1.4101}$ (7)

Experimental equation for $s = 3.76\%$: $Q = 0.3199.H_a^{1.3664}$ (8)

Where s is the slope of the channel bottom or the bottom of the convergent zone; Q is the measured flow rate; H_a is the critical flow depth within the convergent section, measured at a distance of 2/3 of *Lc* (convergence length) from the start of the throat.

Figure 4. *Experimental curves and equations for the five slopes of the Parshall flume tested, compared with the theoretical curve and expression (2).*



When comparing the different experimental flow curves for the Parshall flume tested, there is a clear trend of variation depending on the slopes to which they were subjected (see Fig. 4.); on the one hand, there is parallelism between all the curves for the different slopes, i.e., they do not intersect each other at any point; in contrast, the curve of the theoretical flow measurement equation intersects with all the experimental curves at a different point with each of them. This parallelism is indicative of the direct relationship between the increase in the slope of the Parshall flume and the increase in the measured flow, for the same depth H_a.

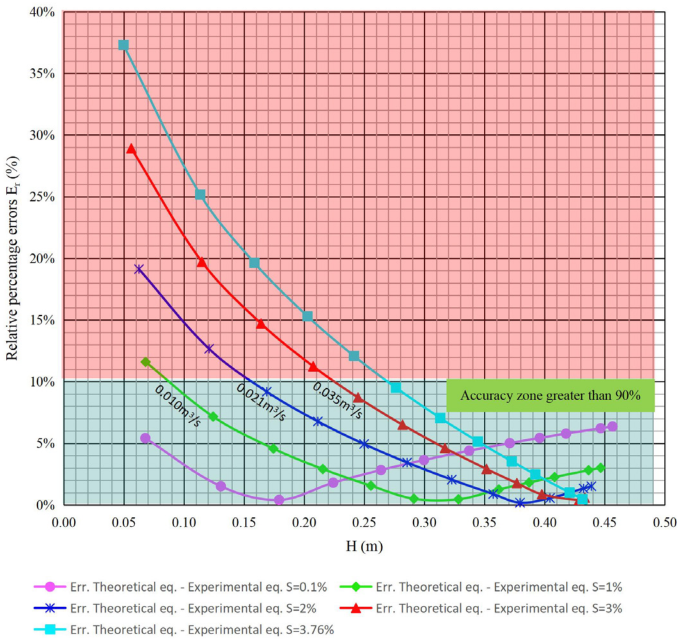
There is a clear trend in the experimental curves (see Fig. 4.): with the same depth H_a, higher flows are measured as the slope of the channel bottom increases; this trend is maintained for the entire range of flows tested with the different slopes. For example, with a depth H_a = 0.35m for a channel slope s = 0.1%, a flow rate Q = 0.069m^3/s is measured; with the same depth for a slope of s = 3.76%, a flow rate of Q = 0.076m3s is measured, while the corresponding theoretical flow rate is Q = 0.073m^3/s. In this example, the difference in measured flow rates between the minimum and maximum slopes is 9.95%, while the difference with respect to the theoretical equation is 4.64%.

Another example that confirms the trend: with a depth H_a = 0.44m for a channel slope s = 0.1%, a flow rate Q = 0.098m^3/s is measured; with the same depth for a slope of s = 3.76%, a flow rate of Q = 0.104m^3/s is measured, while the corresponding theoretical flow rate is Q = 0.104m^3/s. In this example, the difference in measured flow rates between the minimum and maximum slopes is 6.19%, while the difference with respect to the theoretical equation is 6.12%.

When comparing each experimental flow curve individually with the theoretical curve (see Fig. 4), it is evident that there are areas where the theoretical equation overestimates the experimental flow (when the theoretical curve is above the experimental curve) and others where it underestimates the experimental flows (when the theoretical curve is below the experimental curve). For example, for the minimum slope tested, s = 0.1%, the theoretical equation overestimates the flow rates in most of the corresponding depth range; conversely, for the maximum slope tested, s = 3.76%, the theoretical equation underestimates the flow rates in practically the entire depth range.

The relative percentage errors determined by comparing the different theoretical and experimental values were calculated and plotted in order to determine their trends and obtain the maximum values for each of the slopes tested (see Fig. 5), as well as to provide a visual guide for identifying the areas in which the theoretical equation is most accurate and therefore most valid. For example, starting from a maximum tolerable error empirically established at E_r=10% (minimum required accuracy of 90%), the green background area was defined in the graph where the accuracy of the flows measured with the theoretical equation is greater than 90% in relation to the experimental flows. while in the complementary red background area, the accuracy is less than 90%, therefore the flows measured with the theoretical equation would be inaccurate for the ranges defined in this area. Therefore, the theoretical equation is relatively accurate and valid across the entire flow range only for slopes $s \leq 0.1\%$, while it is accurate for certain specific flow ranges, those greater than 0.010 m^3/s , 0.021 m^3/s , 0.035 m^3/s and 0.047 m^3/s for slopes s=1%, s = 2%, s = 3% and s=3.76%, respectively; these flow rates are shown in Figure 5 as the limits from which it is recommended to use the theoretical equation, with an accuracy of at least 90% ($E_r \leq 10\%$).

Figure 5: *Relative percentage errors* $\mathbf{E_r}$ *of Q values obtained with the theoretical equation vs.* **Q** *obtained with the experimental equation of the Parshall flume with throat width* $\mathbf{W_t}$ *= 6” = 0.152 m, with channel slopes* **s** *=0.1%,* **s** *=1%,* **s** *=2%,* **s** *=3% and* **s** *=3.76.*



The graph in Figure 5 shows that the first trend observed is: the greater the slope of the bottom, the greater the relative percentage errors; therefore, the greatest relative errors correspond to the slope s =3.76%. The second trend shown is that the lower the measured flow rates, the greater the percentage errors in the flow rates calculated using the theoretical equation. These trends are partially fulfilled for the curves corresponding to slopes s = 0.1% and s = 1%.

When comparing each experimental curve with the theoretical curve (see Fig. 4), only the points of intersection between curves have the same ordered pair of theoretical and experimental values (depth and flow rate), therefore, these points correspond to relative percentage errors E_r = 0% (see Fig. 5).

The inaccuracy in flow measurement using the theoretical equation in cases where the channel bottom has a slope s > 0.1% (slope of the bottom in the convergent zone) can be attributed to the fact that, in determining the general theoretical equation (2), the effects of variations in certain hydraulic factors, such as the effect of slope variation on flow rates, were not taken into account or considered, i.e., the relative accuracy of the general theoretical equation (2) applies only to horizontal bottoms and slopes $s \leq 0.1\%$.

4. Conclusions

Throughout this research, the importance and necessity of having experimental curves and equations suitable for hydraulic conditions not covered in the determination of theoretical expressions has been demonstrated, as in this case, where the theoretical equation for measuring flows with the Parshall flume should only be used for free flow conditions and for a horizontal channel bottom (as well as for a horizontal bottom in the convergent zone), with a maximum slope of $s = 0.1\%$, so that the flows measured across the entire possible range maintain a minimum established accuracy of 90%, i.e., with relative errors $E_r \leq 10\%$.

Given the need and in order to ensure practicality for all types of users, it is understandable that various bibliographic sources provide an intentional simplification by reducing the relationship between depths and flows (independent of the slope) to a single mathematical expression or measurement equation for each of the 22 existing Parshall flumes, as in this case using equation (2) for those with $W_t =$ 0.152 *m*; however, it is necessary for these sources to emphasize and warn of the urgent need to comply with the horizontal condition and minimum slope ($s \leq 0.1\%$) of the bottom of the channel where the flume is installed and/or the bottom of its convergent zone.

In the case of Parshall flumes with channel bottom slopes and/or convergent zone slopes $s > 0.1\%$, the equations and experimental curves obtained based on laboratory tests offer a better and more accurate mathematical representation that relates flow rates *Q* as a function of depths h_a for each slope tested. This is because a single universal theoretical equation (2) is indicated for horizontal or low-slope bottoms ($s \leq$ 0.1%). This emphasizes the need to experimentally test the hydraulic measuring structures that will operate under specific conditions in order to find the equations and curves that take them into account, given that general theoretical expressions do not.

For Parshall flumes with a throat width $W_t = 6" = 0.152$ *m*, it is recommended to use the theoretical equation (2) only for the ordered pairs H_a–E_r located within the green background area of the graph in Figure 5, for which a relative error $E_r < 10\%$ corresponds; the flow rates shown at the intersection of each experimental curve with the tolerable relative error limit line $E_r = 10\%$, correspond to the flow rate limit value above which the theoretical equation is valid.

In short, for practical purposes in multiple industrial and field gauging applications, it is recommended to use equations (4), (5), (6), (7), and (8) for slopes $s = 0.1\%$, $s = 1\%$, $s = 2\%$, $s = 3\%$ and $s = 3.76\%$, respectively. In cases where the bottom of the Parshall flume's converging zone has an intermediate slope within the tested range (0.1%–3.76%), it is recommended to interpolate the lower and upper flow values obtained using the graph in Figure 4 and/or the corresponding flow equations. For example, for a slope $s = 2.6\%$ and depth $H_a = 0.25m$, the lower and upper flows obtained with equations (6) and (7) are $Q = 0.045$m3s and $Q = 0.047 m^3/s$, for slopes $s = 2\%$ y $s = 3\%$, respectively; therefore, when interpolating the values for the intermediate slope in the example, $Q = 0.046 m^3/s$ is obtained.

The theoretical and experimental curves and equations resulting from this research should only be used for Parshall flumes with a throat width $W_t = 6" = 0.152$ *m*, whose geometry and dimensions are standardized; each of the 22 existing Parshall flumes are different, they do not have geometric similarity, they are not scale hydraulic models of each other. Likewise, they should only be used within the flow range of each flume, in this case for flows *Q* between 1.42 L/s and 110.4 L/s ($0.00142\ m^3/s$ - $0.11040\ m^3/s$), with depths H_a between 0.029 *m* and 0.456 *m*, respectively.

The accuracy of the experimental curves and equations will directly determine the accuracy of the flow measurement process using Parshall flumes. Therefore, in systems with particularities in their design, construction, and/or operation, it will be imperative to conduct a specific study that provides the expressions best suited to the variations present in the hydraulic parameters of each system.

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