Journal of Applied Research in Water and Wastewater 1(2014) 35-39

Journal of
Applied Research in Water and Wastewater

Journal homepage: www.arwww.razi.ac.ir

Original paper

Hydraulic influence of geometrical defects in Venturi flumes: shall we destroy and rebuild?

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ARTICLE INFO

Article history:
Received 04 November 2013
Received in revised form 15 January 2014
Accepted 11 March 2014

Keywords:
Discharge
Venturi flume
Defect
Tolerance

ABSTRACT

Venturi flumes are measurement structures commonly used in water systems to measure the flow discharge. Some of them are not well installed or present some geometrical defects. The objective of this study is to investigate the hydraulic influence of a number of typical wrong installations and geometrical defects of long-throated Venturi flumes: significant positive or adverse slopes, humps and hollows on the walls of the throat, hump or hollow on the bed of the throat. The geometric tolerances corresponding to an acceptable tolerance on the discharge of 2% and 5% are calculated for each defect. A number of corrections of the head –discharge relationship are proposed to avoid the destruction of a flume if the geometric tolerance is not respected.

1. Introduction

Venturi flumes are hydraulic devices commonly used in water systems to measure the flow discharge. A Venturi flume consists of an upstream channel, a converging zone, a constricted section called the throat of the flume and then an enlargement (Fig. 1). The local constriction of cross-section in the throat is a favorable condition to critical flow to occur (Hager 1999). One of the characteristics of critical flow is that a bijective relationship Q = f(h) exists between the discharge Q and the water depth h, which makes possible the determination of the discharge with only one water level measurement. Instead of measuring the water level in the throat where the free surface is inclined and generally instable, the measurement is carried out in the approach channel (generally three to four times the maximum depth upstream of the converging zone, as recommended by ISO 4359:2012) where the free surface is nearly horizontal and quite stabilized (Fig. 1).

Our own field experience reveals that a significant number of Venturi flumes are not well installed or present some geometrical defects. Whereas the bed of the flume must be horizontal as required by ISO 4359:2012 (which may be very difficult in practice), some devices presents a positive or an adverse significant slope (Fig. 2). This may raise two problems: is the head – discharge relationship corresponding to a horizontal flume relevant? Where must the datum of the water level measurement be undertaken? Moreover, the walls of the throat are often not completely parallel; the bed, not completely flat. Indeed, they can present some humps or some hollows on their surface (Figure 3 and Figure 4), which may be problematic because the geometry of the throat is the hydraulic control of the head – discharge relationship.

The objectives of this study are the following: investigate the hydraulic influence of a number of typical wrong installations and geometrical defects of Venturi flumes; define the acceptable tolerances corresponding to each geometrical defect; if possible, propose a correction of the head – discharge relationship to take into account the geometrical default of the measurement device.
The investigations are restricted to the Venturi flumes corresponding to the requirements of ISO 4359, namely the long-throated devices.

$$C_V C_D = \frac{Q}{\left(\frac{2}{3}\right)^{3/2}\sqrt{g}\,B_t h^{3/2}} \qquad (1)$$

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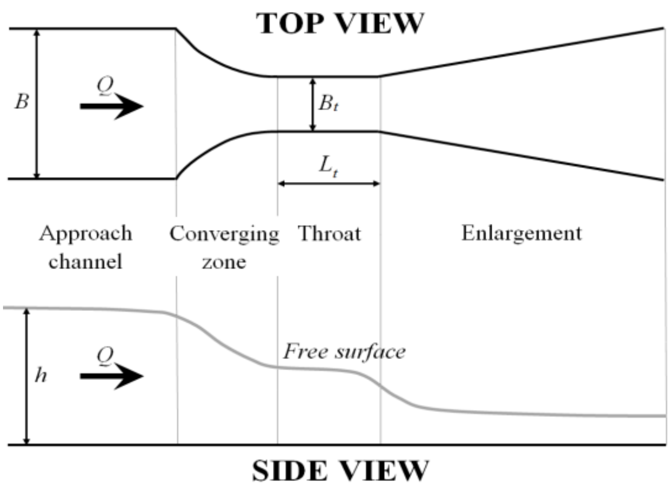

Fig. 1. Top view and side view of a Venturi flume.

2. Methods description of the approach

Since it would have been difficult to build Venturi flumes with calibrated defects, it has been decided to follow a Computational Fluid Dynamics (CFD) approach. This tool has shown its capability to simulate the flow in Venturi flumes (Dufresne and Vazquez 2013). After validation of the numerical model against experimental data from literature (Yeung 2007), the methodology consists in generating a numerical databank of simulations of flow in Venturi flumes with perfect and distorted geometries.

2.1. Numerical databank

The simulations were performed with two geometries of rectangular Venturi flume. The first one is a small-size device corresponding to the one investigated by Yeung (2007): the breadth of its throat is equal to 101 mm, which corresponds to the lower limit of the domain of validity of ISO 4359:2012. The small flume was used to

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study the influence of the defects for a large range of distortions. The second flume is a larger device (the breadth of the throat is equal to 480 mm) used to investigate scale effects for a limited number of defects. The whole characteristics of the two flumes are given in Table 1. The defects investigated are listed in Table 2. A total number of 158 simulations have been carried out for this study. The deformation of the walls is characterized by 2Δ/Bt since Δ is the deformation on one side (the breadth is therefore modified by 2Δ).

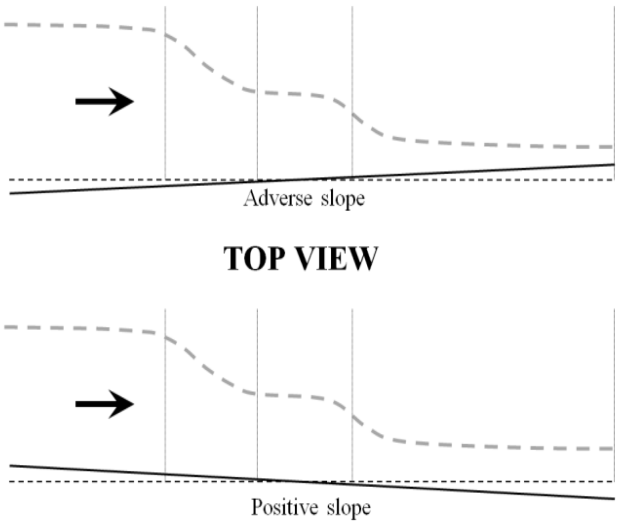

Fig. 2. Venturi flume installed with a longitudinal slope different from horizontal.

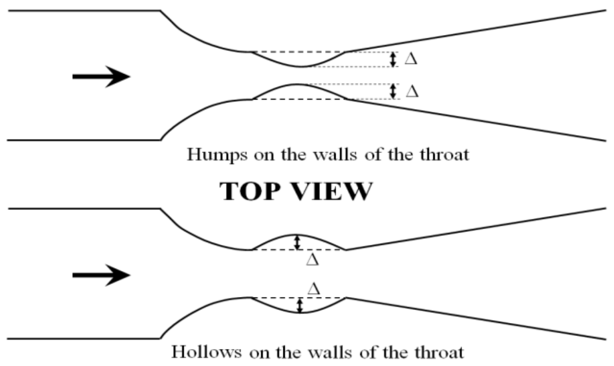

Fig. 3. Venturi flume presenting a distortion on the walls of the throat (humps or hollows) – the amplitude Δ is exaggerated in the Fig.

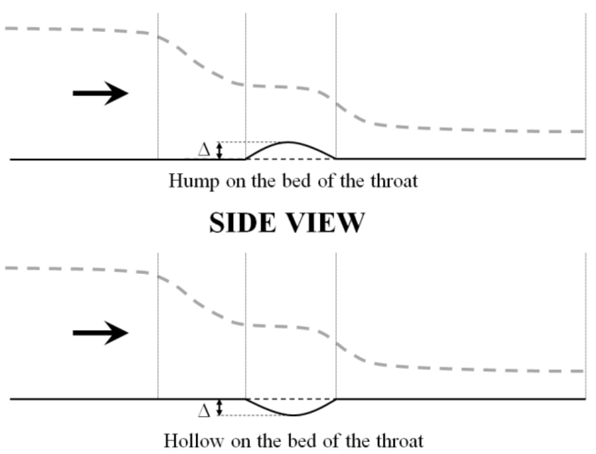

Fig. 4. Venturi flume presenting a distortion on the bed of the throat (hump or hollow) – the amplitude Δ is exaggerated in the figure.

Table.1. Characteristics of the two Venturi flumes investigated (see Fig. 1).

Characteristics	Small flume	Large flume
Breadth of the throat Bt (mm)	101	480
Breadth of the approach channel B (mm)	203	800
Length of the throat Lt (mm)	300	900

For each simulation, the global discharge coefficient CVCD is evaluated using Eq. 1, where Q is the discharge; g, the gravity acceleration; Bt, the breadth of the throat and h, the water depth in the measurement section. The discharge coefficient CVCD is the product of the velocity coefficient CV (taking into account the relationship between the water depth and the energy head) and the 'true' discharge coefficient CD (taking into account the influence of the approximations of ISO 4359:2012).

Table 2. Characteristics of the defects studied (Bt is the breadth of the throat and Δ is the amplitude of the deformation, see Figs. 3 and 4).

Defects	Values
Slope	-2.0% (adverse slope), -1.6%, -1.2%, -0.8%, -0.4%, -0.2%, -0.1%, 0%, +0.1% (positive slope), +0.2%, +0.4%, +0.8%, +1.2%, +1.6%, +2.0%
Deformation of the walls of the throat 2Δ/Bt	-20% (humps), -10%, -4%, -2%, 0%, +2% (hollows), +4%, +10%, +20%
Deformation of the bed of the throat Δ/Bt	-10% (hollow), -5%, -2%, -1%, 0%, +1% (hump), +2%, +5%, +10%

For each simulation corresponding to a Venturi flume with a defect, the error EP that is done if the flume is considered to be geometrically perfect is evaluated using Eq. 2. Here, (CVCD) perfect is the discharge coefficient of the Venturi flume with no defect; (CVCD) actual is the actual discharge coefficient of the Venturi flume with the defect.

$$E_P = \frac{(C_V C_D)_{\text{perfect}} - (C_V C_D)_{\text{actual}}}{(C_V C_D)_{\text{actual}}} \quad (2)$$

Corrections of the head – discharge are tested using the error EC that is done when the corrected discharge coefficient (CVCD)corrected is used, as written in Eq. 3.

$$E_C = \frac{(C_V C_D)_{\text{corrected}} - (C_V C_D)_{\text{actual}}}{(C_V C_D)_{\text{actual}}} \quad (3)$$

2.2. Settings of the numerical model

Numerical simulations were performed with the computational fluid dynamics code Open FOAM (Open FOAM 2013). The Reynolds-averaged Navier-Stokes (RANS) equations were used. In order to reproduce the non-uniformity of the water level distribution, the two-phase Volume of Fluid (VOF) model was chosen. Since the aim of the numerical investigations was to simulate the water level (and not the velocity field neither other variables maybe linked to the anisotropy of the turbulence), the k-ω SST turbulence model was chosen. The near-wall region is bridged using standard wall functions (ERCOFTAC 2000).

The main difficulty of the use of computational fluid dynamics in hydraulic applications is neither the choice of the turbulence model nor the choice of numerical schemes but the definition of the computational domain and the boundary conditions. Since the regime is subcritical in the upstream zone of the flume, the water depth in the approach channel is controlled by the critical section in the throat. Therefore, the upstream face of the computational domain was defined as a velocity inlet whose height was roughly chosen based on the value of the discharge. The approach channel was defined sufficiently long to ensure a stabilization of the water level upstream of the inlet convergence. Since the flow downstream of the throat is supercritical, the outlet boundary condition was simply defined as a pressure outlet. In order to reproduce atmospheric pressure, the top face of the domain was defined as a pressure outlet too. Free surface was defined in post-processing as the zone where the water volume fraction was equal to 50%.

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2.3. Numerical uncertainty

A grid sensitivity analysis was performed with the small flume in order to evaluate the numerical uncertainty (Roache 1994). To do so, a fine mesh and a coarse mesh were built. They are respectively composed of 900,000 and 3,078,000 cells; the refinement ratio between the two grids is equal to 1.5. The Grid Convergence Index (GCI) of the discharge coefficient defined in Equation 1 (Bos 1977) for the fine mesh was then evaluated using Eq. 4 (Roache 1994).

$$\mathrm{GCI} = \frac{3}{r^p - 1}\left|\frac{(C_V C_D)_{\text{fine}} - (C_V C_D)_{\text{coarse}}}{(C_V C_D)_{\text{fine}}}\right| \tag{4}$$

Here, r is the grid refinement ratio; p, the order of the method (2 since second-order schemes were used); (CVCD)fine, the discharge coefficient obtained with the fine mesh; and (CVCD)coarse, the discharge coefficient obtained with the coarse mesh.
Results show a GCI on the discharge coefficient for the fine mesh of about 0.6%, which can be considered as an acceptable numerical uncertainty for the purpose of this study.

2.4. Validation of the numerical model

The comparison between the numerical simulations performed for the perfect geometry of the small flume and the experimental data of Yeung (2007) is illustrated in Figure 5. Rather than using the discharge for the abscissa of the graphics, the dimensionless parameter H/Lt is used (H is the upstream energy head; Lt, the length of the throat); H/Lt is representative of the discharge. With the exception of the two points located near a value of the discharge coefficient of 0.95 that probably correspond to errors in the experimental measurements, it can be concluded that the CFD model accurately simulates the discharge coefficient of the Venturi flume.

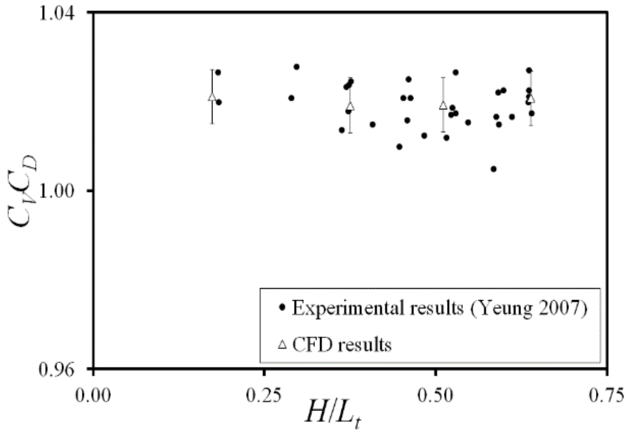

Fig. 5. Validation of the CFD model against experimental results of Yeung (2007) – H is the upstream energy head; Lt, the length of the throat.

3. Results and discussion
3.1. Influence of the slope

The relative error EP for a Venturi flume presenting a slope different from horizontal is given as a function of the H/Lt in Tables 3 and 5, for the small flume and the large flume respectively.

The comparison between the results obtained for the small flume and those obtained for the large flume (also given in Fig. 6 for a limited number of slopes for clarity reasons) shows that the order of magnitude of the error is the same, which proves that the scale effects are negligible. The conclusions drawn below for the small flume can therefore be generalized to flumes of any size.

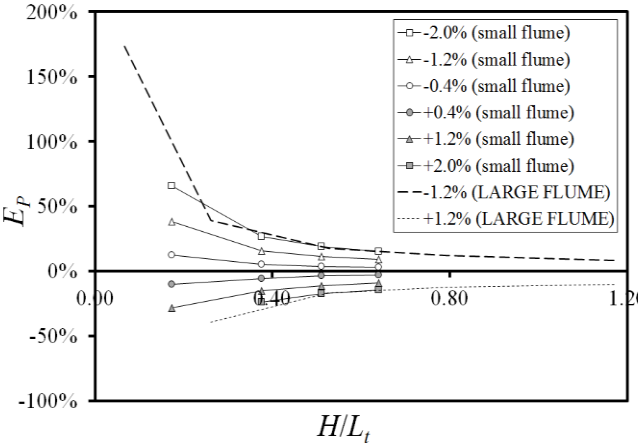

Fig. 6. Error on the discharge in small and large flumes for different slopes as a function of H/Lt.

If a tolerance of 2% is accepted for the error on the discharge, even a slope of +/-0.1% is too large and cannot be accepted (Table 3). If 5 % is acceptable, a slope lower than +/-0.2% can be accepted. It must be noticed that such slopes may be difficult to reach in practice.

A simple correction would be to choose the datum of the water level measurement not below the water level measurement in the approach channel but in the throat where the critical flow occurs, more precisely in the downstream section of the throat where the critical flow approximately occurs (ISO 4359:2012). Even if the critical flow does not always occur at the downstream section of the throat (Dabrowski and Polak 2012), the results obtained with this correction are very good, especially for adverse slopes (see Table 4). For a tolerance of 2% (respectively 5%) on the discharge coefficient, a slope of -1.2% is acceptable (respectively around -2.0 %) when the correction is applied. For positive slopes, +0.4% (respectively +0.8%) is an acceptable slope for a tolerance of 2% (respectively 5%).

3.2. Influence of the deformations of the walls of the throat

As for the results obtained for the slope, the orders of magnitude of the error due to the deformation of the walls of the throat are the same for the small and the large flumes (compare Table 7 and Table 8). Table 7 can therefore be seen as general conclusions about the influence of defects on the walls of the throat.

First, the results show that a constriction (humps on the walls) has a much greater impact than an enlargement (hollows on the walls). Indeed, the error is up to six times higher for 2Δ/Bt = -20% than for +20%. This can be hydraulically explained by the fact that a constriction probably moves the location of the critical flow in the section where the breadth is minimum (Hager 1999) whereas a local enlargement probably only creates a dead zone. If a tolerance of 2% (respectively 5%) is acceptable for the error on the discharge, a constriction of -2% (respectively -4%) and an enlargement of 4% (respectively 10%) can be accepted.

Table 3. Relative error EP on the discharge as a function of H/Lt for a small Venturi flume installed with a longitudinal slope S different from horizontal without any correction of the discharge formula – in grey errors > 2%, in dark grey errors > 5% (* presence of a hydraulic jump).

H/Lt	S (m/m)														
	-2.0%	-1.6%	-1.2%	-0.8%	-0.4%	-0.2%	-0.1%	0%	+0.1%	+0.2%	+0.4%	+0.8%	+1.2%	+1.6%	+2.0%
0.17	+66%	+53%	+38%	+26%	+13%	+6%	+4%	0%	-3%	-5%	-11%	-19%	-28%	-40%	*
0.38	+27%	+21%	+16%	+11%	+5%	+2%	+1%	0%	-1%	-3%	-6%	-10%	-15%	-19%	-24%
0.51	+19%	+15%	+11%	+7%	+4%	+1%	+1%	0%	-1%	-2%	-4%	-7%	-11%	-14%	-18%
0.64	+15%	+12%	+9%	+6%	+3%	+1%	+1%	0%	-1%	-1%	-3%	-6%	-9%	-12%	-15%

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Table 4. Relative error EC on the discharge as a function of H/Lt for a small Venturi flume installed with a longitudinal slope S different from horizontal with correction of the discharge formula – in grey errors > 2%, in dark grey errors > 5% (* presence of a hydraulic jump).

H/Lt	S (m/m)														
	-2.0%	-1.6%	-1.2%	-0.8%	-0.4%	-0.2%	-0.1%	0%	+0.1%	+0.2%	+0.4%	+0.8%	+1.2%	+1.6%	+2.0%
0.17	0%	0%	0%	+1%	0%	0%	+1%	0%	0%	+1%	+1%	+4%	+6%	+4%	*
0.38	-4%	-3%	-2%	-1%	-1%	-1%	-1%	0%	0%	0%	0%	+1%	+2%	+3%	+4%
0.51	-2%	-2%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	+1%	+1%	+2%	+3%
0.64	-2%	-1%	-1%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	+1%	+1%	+1%

A "natural" correction would be to use the breadth of the throat at the location of the deformation (Bt + 2Δ for an enlargement and Bt - 2Δ for a constriction). Since the discharge is proportional to the breadth of the throat (see Eq. 1), this correction leads to directly change the discharge by using the percentage of the defect 2Δ/Bt. A look at Table 9 reveals that this correction is not relevant for enlargement (2Δ/Bt> 0); results are indeed even worse with correction than without correction, especially for large values of 2Δ/Bt! This correction is much more relevant for constrictions and can be used to accept walls with humps up to 2Δ/Bt = -4% (respectively more than -10%) for an acceptable tolerance of 2% (respectively 5%).

Table 5. Relative error EP on the discharge as a function of H/Lt for a large Venturi flume installed with a longitudinal slope S different from horizontal without any correction of the discharge formula – in grey errors > 2%, in dark grey errors > 5% (*presence of a hydraulic jump).

H/Lt	S (m/m)		
	-1.2%	0%	+1.2%
0.07	+173%	0%	*
0.26	+39%	0%	-40%
0.53	+17%	0%	-17%
0.79	+12%	0%	-13%
1.17	+8%	0%	-10%

Table 6. Relative error EC on the discharge as a function of H/Lt for a large Venturi flume installed with a longitudinal slope S different from horizontal with correction of the discharge formula – in grey errors > 2%, in dark grey errors > 5% (* presence of a hydraulic jump).

H/Lt	S (m/m)		
	-1.2%	0%	+1.2%
0.07	0%	0%	*
0.26	0%	0%	-7%
0.53	-1%	0%	-1%
0.79	0%	0%	+1%
1.17	0%	0%	-2%

Table 7. Relative error EP on the discharge as a function of H/Lt for a small Venturi flume presenting a deformation of the walls of the throat without any correction of the discharge formula – in grey errors > 2%, in dark grey errors > 5%.

H/Lt	2Δ/Bt								
	-20%	-10%	-4%	-2%	0%	+2%	+4%	+10%	+20%
0.17	+25%	+11%	+4%	+2%	0%	-1%	-1%	-3%	-4%
0.38	+20%	+8%	+3%	+1%	0%	-1%	-2%	-5%	-7%
0.51	+17%	+7%	+3%	+1%	0%	-1%	-2%	-5%	-7%
0.64	+15%	+6%	+2%	+1%	0%	-1%	-2%	-5%	-8%

Table 8. Relative error EP on the discharge as a function of H/Lt for a large Venturi flume presenting a deformation of the walls of the throat without any correction of the discharge formula – in grey errors > 2%, in dark grey errors > 5%.

H/Lt	2Δ/Bt		
	-2%	0%	+2%
0.07	+2%	0%	-1%
0.26	+3%	0%	-2%
0.53	+2%	0%	-2%
0.79	+3%	0%	-2%
1.17	+2%	0%	-2%

3.3. Influence of the deformations of the bed of the throat

As for the results obtained for the slope and the ones obtained for the deformation of the walls, the orders of magnitude of the error due to the deformation of the bed of the throat are the same for the small and the large flumes (compare Table 10 and Table 11). Table 10 can therefore be seen as general conclusions about the influence of defects on the walls of the throat.

Whereas a hollow has a small impact on the discharge coefficient (the region in the hollow is probably a dead zone), a hump on the bed may have a huge impact, especially for low discharges. For example, the error is up to seven times higher for a hump than for a hollow for a deformation Δ/Bt of 10 %. This behavior can be explained by the fact that a hump acts as a weir for small discharges, which probably moves the critical flow above the hump. If a tolerance of 2% (respectively 5%) is acceptable for the error on the discharge, a hollow of -2% of the breadth (respectively -5%) can be accepted. No hump at all can be accepted for a tolerance of 2% on the error and a hump of 1% of the breadth can be accepted for a tolerance of 5%.

Table 9. Relative error EC on the discharge as a function of H/Lt for a small Venturi flume presenting a deformation of the walls of the throat with correction of the discharge formula – in grey errors > 2%, in dark grey errors > 5%.

H/Lt	2Δ/Bt								
	-20%	-10%	-4%	-2%	0%	+2%	+4%	+10%	+20%
0.17	0%	0%	0%	0%	0%	+1%	+2%	+7%	+16%
0.38	-4%	-3%	-2%	-1%	0%	+1%	+2%	+4%	+11%
0.51	-6%	-4%	-2%	-1%	0%	+1%	+2%	+5%	+10%
0.64	-8%	-4%	-2%	-1%	0%	+1%	+2%	+4%	+10%

A'"natural" correction would be to define the datum of the water level measurement at the altitude of the deformation (the top of the hump or the bottom of the hollow). The results applying this correction are given in Table 12. Since a hollow is mainly a dead zone, this correction is irrelevant for such a deformation. Nevertheless, this correction is relevant for humps and may lead to accept flumes with deformations Δ/Bt up to +2% (respectively +10%) if the acceptable tolerance is 2% (respectively 5%).

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Table 10. Relative error EP on the discharge as a function of H/Lt for a small Venturi flume presenting a deformation of the bed of the throat without any correction of the discharge formula – in grey errors > 2%, in dark grey errors > 5%.

H/Lt	Δ/Bt								
	-10%	-5%	-2%	-1%	0%	+1%	+2%	+5%	+10%
0.17	-4%	-4%	-2%	-1%	0%	+3%	+6%	+15%	+30%
0.38	-7%	-4%	-2%	-1%	0%	+1%	+1%	+4%	+9%
0.51	-5%	-3%	-1%	0%	0%	+1%	+1%	+3%	+6%
0.64	-5%	-2%	-1%	0%	0%	0%	+1%	+2%	+5%

Table 11. Relative error EP on the discharge as a function of H/Lt for a large Venturi flume presenting a deformation of the bed of the throat without any correction of the discharge formula – in grey errors > 2%, in dark grey errors > 5%.

H/Lt	Δ/Bt		
	-2%	0%	+2%
0.07	-3%	0%	+23%
0.26	-4%	0%	+5%
0.53	-2%	0%	+2%
0.79	-1%	0%	+2%
1.17	-1%	0%	+1%

Table 12. Relative error EC on the discharge as a function of H/Lt for a small Venturi flume presenting a deformation of the bed of the throat with correction of the discharge formula – in grey errors > 2%, in dark grey errors > 5%.

H/Lt	Δ/Bt								
	-10%	-5%	-2%	-1%	0%	+1%	+2%	+5%	+10%
0.17	+27%	+11%	+4%	+2%	0%	0%	0%	-1%	-2%
0.38	+7%	+3%	+1%	+1%	0%	-1%	-2%	-3%	-5%
0.51	+5%	+3%	+1%	+1%	0%	0%	-1%	-2%	-4%
0.64	+4%	+2%	+1%	0%	0%	0%	-1%	-2%	-3%

4. Conclusions

The objective of this study was to investigate the hydraulic influence of a number of typical wrong installations and geometrical defects of long-throated Venturi flumes: significant positive or adverse slopes, humps and hollows on the walls and the bed of the throat.

The geometric tolerances corresponding to an acceptable tolerance on the discharge of 5% and 2% have been calculated for each defect. A number of corrections have been proposed to avoid the destruction of a flume if the geometric tolerance is not respected:

ΛChange the datum of the water level measurement for a slope significantly different from zero or a hump on the bed of the throat, ΛUse the deformed breadth of the throat for humps on the walls of the throat. Results are summarized in Table 13.

Table 13. Geometric tolerances as a function of the defect and the acceptable tolerance on the discharge – in brackets: geometric tolerances when the proposed corrections are applied (Ø means that no defect is acceptable).

Acceptable tolerance on the discharge	2%	5%
Positive slope	Ø (+0.4%)	+0.2% (+0.8%)
Adverse slope	Ø (-1.2%)	-0.2% (-2.0%)
Humps on the walls on the throat	-2% (-4%)	-4% (-10%)
Hollows on the walls on the throat	+4%	+10%
Hollow on the bed on the throat	-2%	-5%
Hump on the bed on the throat	Ø (+2%)	+1% (+10%)

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