Hydraulics of the subcritical Venturi channels

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Abstract. The purpose of the research is to develop and verify the method of hydraulic calculation of the Venturi channel in the flooded outflow mode. The criterion that separates the flooded and free flow regimes is the ratio of the flow depth in the throat of the Venturi channel \( h_m \) to the critical depth \( h_c \) exceeding one \( (h_m/h_c > 1) \). The article theoretically and experimentally substantiates a method for determining the flow rate in a flooded Venturi canal using two control cross-sections, one of which is in the upper basin of the canal, the other in its throat. The differential equation for an uneven flow in a non-prismatic channel was obtained in the form (13). The analysis showed that in a flooded Venturi channel with a subcritical flow at Froude numbers less than one \( (Fr < 1) \), the denominator of equation (13) is always greater than zero; therefore, at the entrance to the channel in the region of constriction, when \( dh/dl < 0 \), the depth is downstream decreases \( (dh/dl < 0) \), and in the lower diffuser, where \( dh/dl > 0 \), the flow depth increases \( (dh/dl > 0) \). Thus, the curve of the flow surface has a dip in the throat of the flooded Venturi channel. Integration of differential equation (13) made it possible to obtain the function of changing the Froude numbers in the flow along the length of the flooded Venturi channel (16), and then, using relations (17), to determine the depths and flow velocities. The verification showed that the calculated data are in good agreement with the experimental ones. The deviations between calculation and experiment do not exceed ±3%. This makes it possible to recommend the outlined methods for application in engineering practice.

1. Introduction

Let us consider the method of hydraulic calculation of the Venturi flowmeter channel in a submerged water outflow (Figure 1), when the depth of the flow in the throat of the channel \( h_m \) is greater than the critical \( h_c \). According to the current State Standard of the Russian Federation МИ 2406–97, subcritical flow regimes in water measuring channels are unacceptable. However, in practice, every year the conditions of free non-flooded outflow are violated more and more often [1]. This is directly related to global climate changes in the world with a tendency for the volume and intensity of floods and storm runoffs to increase, raising the level in front of water retention dams and in overflowing water bodies and rivers receiving extreme runoff.

The relevance of the issue is determined by the fact that if the free flow regimes in the Venturi flowmeter channel of critical depth are regulated by the State Standard of the Russian Federation МИ 2406-97, and the methods for calculating the flow in this case are well developed and have been tested by many years of practice [2 – 10], then the flooded outflow regimes are not only not regulated by the
State Standard, but practically not investigated and methods of their calculation are absent [1 and 11]. The incorrectness of the operational accounting of extreme flows at water measuring posts is often revealed with a significant delay, when, at best, the measurement results begin to raise doubts among the service personnel, at worst, when the water retaining structures lost their stability and begin to erode with all the ensuing, including catastrophic, consequences.

The purposes of the research are to determine the criterion separating the free and flooded outflow regimes in the Venturi water-measuring channel of critical depth, to develop and verify the method of hydraulic calculation of the flow in the Venturi channel in the mode of submerged outflow.

2. Results and Discussion

2.1. Flow rate in the subcritical Venturi channel

We will assume that, due to the smooth configuration of the vertical walls in the Venturi channel, there are no vortex zones and, as a result, there are no local hydraulic losses, and, given the small length of the working section from upper pool (cross-section 0 in Figure 1) to the throat, where the flow depth \( h_m \) is minimal (section 1), we assume that the hydraulic losses along the length are also practically negligible here. Overall, this makes it possible to consider the flow-measuring Venturi flume as an ideal channel not having hydraulic losses, and to write the Bernoulli equation for cross-sections 0 and 1 in the form.

\[
H + \frac{\alpha V^2}{2g} = h_m + \frac{\alpha V_m^2}{2g},
\]

where \( V \) and \( H \) are the mean flow velocity and depth in the upper pool at cross-section 0; \( V_m \) and \( h_m \) is the velocity and depth of the flow in the throat in cross-section 1, with \( h_m \) greater than the critical
depth \( h \) (cf. Figure 1); \( \alpha \) is the Coriolis (Saint – Venant) coefficient; and \( g \) is the acceleration due to gravity, \( g = 9.81 \text{ m/sec}^2 \).

But the flow velocities at cross-sections 0 and 1 are determined through the flow rate \( Q \) by the equalities

\[ V = \frac{Q}{BH} \quad \text{and} \quad V_m = \frac{Q}{b_m h_m}, \]

(2)

here \( B \) and \( b_m \) are the widths, respectively, of the upper pool and the throat of the Venturi channel.

Then Bernoulli’s equation (1), taking into account equalities (2), should be rewritten as

\[ H - h_m = \frac{\alpha Q^2}{2 b_m^2 h^2} \left( 1 - \frac{b_m^2 h_m^2}{B^2 H^2} \right). \]

Further denoting

\[ h_m = \phi H \quad \text{and} \quad b_m = \phi B, \]

(3)

as a result we get

\[ Q = \phi \sqrt{1 - \frac{\phi}{\alpha (1 - \phi^2)}} B \sqrt{2 g H^{3/2}}. \]

(4)

Formula (4) determines the flow rate of the flow following through the Venturi channel in both free and flooded outflows. To determine the flow rate through the channel, it is required to know the geometric dimensions of the channel \( (B \) and \( b_m) \) and depths in the upper pool \( H \) and in the throat of the channel \( h_m \).

Formula (4) can be written in general form

\[ Q = m B \sqrt{2 g H^{3/2}}, \]

(5)

where

\[ m = \phi \sqrt{1 - \frac{\phi}{\alpha (1 - \phi^2)}} \]

(6)

is a variable flow rate coefficient depending on the relations (3).

The criterion for evaluating the separation of the free and flooded outflow modes in the Venturi water measuring channel is the ratio of the depth in the throat of the channel \( h_m \) to the critical depth

\[ \frac{h_m}{h_c} = \frac{\alpha Q^2}{g b_m^2}. \]

(7)

With a flooded outflow, this ratio should be greater than one

\[ \frac{h_m}{h_c} > 1, \]

(8)

with free outflow, the ratio (8) is equal to one

\[ \frac{h_m}{h_c} = 1. \]

In the latter case, formulas (4), (5) and (6) are reduced to formulas for calculating the flow rates of the Venturi channels of the critical depth: (15) from paper [9] or (9) and (10) from paper [10].

2.2. Flow motion in the subcritical Venturi channel

The differential equation of steady-state smoothly varying fluid motion in a non-prismatic Venturi channel with a horizontal bottom, vertical walls and negligible hydraulic losses has the form

\[ \frac{dh}{dl} = \frac{\alpha Q^2}{g \omega^3} \frac{\partial \omega}{\partial l} \left( 1 - \frac{\alpha Q^2 b}{g \omega^3} \right). \]

(9)
here $h$, $b$ and $\omega = bh$ are the depth, width and flow cross-sectional area variable along the channel length $l$.

Since the depth-independent partial derivative of the function of changing the cross-sectional area of the flow for a channel of variable width $b$ and with vertical walls is equal to

$$\frac{\partial \omega}{\partial l} = h \frac{db}{dl},$$

then equation (9) can be rewritten in the form

$$\frac{d\omega}{dl} = \frac{\alpha Q^2 h}{b} \frac{db}{dl},$$

(10)

Let us now turn to an analysis of formula (10), which reflects the hydraulics of flows in non-prismatic channels with vertical walls and a horizontal bottom, to which the Venturi channels belong.

If the Froude number is written as

$$Fr = \frac{V^2}{gh},$$

(11)

then

$$\frac{\alpha Q^2 b}{g \omega^3} = \frac{\alpha V^2}{gh} = \alpha Fr.$$

(12)

Let us bring equation (10) to the form

$$\frac{dh}{dl} = \frac{\alpha Fr}{1 - \alpha Fr} \cdot \frac{h}{b} \cdot \frac{db}{dl}.$$

(13)

The analysis shows: at the inlet portion of the Venturi channel, where there is a calm subcritical flow with Froude numbers less than unity ($Fr < 1$) the denominator of Eq. (13) is greater than zero, therefore, in this area the narrowing of the channel when $\frac{db}{dl} < 0$, causes a decrease in the depth of the stream ($\frac{dh}{dl} < 0$), an expansion of the channel ($\frac{db}{dl} > 0$) causes an increase in the depth ($\frac{dh}{dl} > 0$); in the lower diffuser of the channel, where a calm subcritical flow with Froude numbers less than one ($Fr < 1$) is also observed, the denominator of the Eq. (13) is also greater than zero, the depth of such a flow increases ($\frac{dh}{dl} < 0$) with expansion of the channel ($\frac{db}{dl} > 0$), and a decrease in depth ($\frac{dh}{dl} > 0$) occurs with its narrowing ($\frac{db}{dl} < 0$). Thus, the curve of the free surface of the flow has a dip in the throat of the flooded Venturi channel. In this case, in the section of the maximum dip of the free surface of the flow, its depth $h_m$ does not fall below the critical one $h_c$ according to (7) and (8).

Let's express the derivative $\frac{dh}{dl}$ in terms of the Froude number. According to equalities (11) and $\omega = bh$ we find

$$\frac{dFr}{dl} = -\frac{3Q^2}{gb^2h^4} \frac{dh}{dl} - \frac{2Q}{gh^3b^3} \frac{db}{dl} = -\frac{3Fr}{h} \frac{dh}{dl} - \frac{2Fr}{b} \frac{db}{dl},$$

whence

$$\frac{dh}{dl} = \frac{h}{2Fr} \frac{dFr}{dl} - \frac{2h}{3Fr} \frac{db}{dl}. $$

Substituting the obtained value of the $\frac{dh}{dl}$ derivative into expression (13), we come to equation

$$\frac{\alpha Fr - 1}{\alpha Fr(\alpha Fr + 2)} \cdot \frac{d(\alpha Fr)}{b} = \frac{db}{dl}.$$

(14)

Integrating (14), we find

$$\sqrt{\frac{\alpha Fr + 2}{\alpha Fr}} = Cb.$$
The constant of integration $C$ is found from the following condition. Since within the throat the flow passes through the cross-section with minimum depth $h_m$ (cf. Figure 1), width $b_m$, and area $\omega = b_m h_m$, where, following (12), it’s possible write

$$\frac{\alpha Q^2}{gb_m^2 h_m^3} = \alpha Fr_m,$$

then taking these conditions as the boundary ones, as a result, we find

$$C = \frac{1}{b_m} \sqrt{\frac{(\alpha Fr_m + 2)^3}{\alpha Fr_m}},$$

and finally we get

$$\frac{(\alpha Fr + 2)^3}{\alpha Fr} = \frac{b}{b_m} \sqrt{\frac{(\alpha Fr_m + 2)^3}{\alpha Fr_m}},$$

(15)

where the width $b$ along the length of the Venturi channel varies from $b_m$ to $B$.

With respect to the sought value $\alpha Fr$, equality (15) is reduced to the cubic Cardano equation [12], which has a trigonometric solution satisfying the condition $0 < \alpha Fr < 1$

$$\alpha Fr = 8 \frac{b}{b_m} \sqrt{\frac{(\alpha Fr_m + 2)^3}{27 \alpha Fr_m}} \sin^3 \left[ \frac{1}{3} \arcsin \left( \frac{b_m}{b} \sqrt{\frac{27 \alpha Fr_m}{(\alpha Fr_m + 2)^3}} \right) \right].$$

(16)

Having determined the Froude numbers depending on the variable width $b$ of the Venturi channel, the depths $h$ and the flow velocity $V$ are then calculated

$$h = 3 \sqrt{\frac{\alpha Q^2}{gb^2 \alpha Fr}} \quad \text{and} \quad V = \sqrt{\frac{\alpha Frgh}{\alpha}}.$$

(17)

Let us verification how adequately the computed formulas obtained correspond to actually observed flows. To do this, let’s compare the computed values with the analogous measured characteristics of the model of Venturi channel shown in Figure 1.

2.3. Equipment, devices and instruments

Experimental studies of the model Venturi channel water gauge have been made in the Moscow State University of Civil Engineering. The following equipment, devices and instruments have been used in the studies [9 and 10]:

- **HM 162 scientific research hydraulic calibrating flume** [13] (manufacturer: G.U.N.T. Gerätebau GmbH, Germany) with width of cross-section $B = 311$ mm, height 450 mm and length 15.5 m with relative roughness of the walls of the flume (hardened glass) and its bottom (stainless steel) $n = 0.009$;

- Built-in instruments in the HM 162 flume: SHS4 80-200/40/P pump (manufacturer: Lowara S.R.L. Uniperso-nale, Italy) with maximal head 10 m, maximal delivery 150 m$^3$/h, power 5.5 kW; Promag 10D electromagnetic flowmeter (manufacturer: Endress+Hauser Flowtec AG, France) with 0 – 150 m$^3$/h range of measurement, accuracy class 0.3; GSZ-100 lifting jack system for controlling the slope of the flume (manufacturer: ZIMM Maschinenelemente GmbH & Co KG, Austria) with range of variation of slope $i$ from -0.5% to +1.75%;

- **HM 162.91 digital level gauge** [13] (manufacturer: G.U.N.T. Gerätebau GmbH, Germany) with range of measurement from 0 to 455 mm correct to within 0.01 mm;

- **HM 162.51 model of Venturi flume** (cf. Figure 1) [14] (manufacturer: G.U.N.T. Gerätebau GmbH, Germany) with height 430 mm, width and length of the gorge portion $b_m = 153$ mm and $l = 150$ mm, made of plexiglass and attached on a polyvinyl chloride plate,15 mm thick;

- **DLE 40 Professional digital laser rangefinder** (manufacturer: Robert Bosch GmbH, Germany) with range of measurement from 0.05 to 40 m with accuracy within 0.5 mm.

All the equipment is certified consistent with the Russian Laws.
2.4. Methods and results of the experimental research

Before performing experimental studies the hydraulic flume HM 162 was set in horizontal position with a bottom slope \( i = 0 \) and the model of Venturi channel HM 162.51 placed in the middle part of the flume (cf. Figure 1). The digital level gauge HM 162.91 was mounted on instrument carriage and its zero adjusted relative to the floor of the model HM 162.51. The HM 162.12 specialized software package was loaded into the control computer in order to record the discharge, which was measured in course of the study by an electromagnetic flowmeter Promag 10 D.

On the control panel of the laboratory flume HM 162 operation mode or on the control computer, the flow rate was specified and the working pump SHS4 80-200/40/P of the flume was turned on.

Following stabilization of the operating mode of the flume (stabilization time 5 minutes), the flow rate values measured by the Promag 10D electromagnetic flow meter using the HM 162.12 software were written to the disk of the control computer into the generated data file; the flow measurement time was set 200 seconds with an interval between measurements of 1 second; in the process of processing, the obtained data were transferred to an Excel file, in which the average value of the flow rate (mathematical expectation) was calculated

\[
Q_0 = \frac{1}{k} \sum_{j=1}^{k} Q_j
\]

and the normed standard deviation

\[
\sigma = \frac{1}{Q_0} \sqrt{\frac{1}{k} \sum_{j=1}^{k} (Q_j - Q_0)^2},
\]

where \( k \) is the sample size, \( k = 200 \); \( Q_j \) is \( j \)-th element of the sample. The values of \( Q_0, \sigma \) and flow depth in the upstream pool \( H \) (cf. Figure 1) are written in the title lines of Table 1.

The same Table 1 shows measured digital level gauge HM 162.91 values of flow depths (or water levels) \( h \) at 11 points along the length of the model of Venturi channel HM 162.51. The distances \( x \) were determined from the input edge of the model HM 162.51 using the digital laser rangefinder DLE 40 Professional, the same meter determined the values of the width of the Venturi flume \( b \) at points \( x \). The \( x \)-values and the corresponding \( b \)-values are recorded in the left-hand columns of Table 1.

Next, the discharge transmitted through the flume was changed with preliminarily selected step \( \Delta Q \). The total being investigated 9 regimes of transmission discharge \( Q_0 \) from 110.37 to 69.92 \( m^3/h \). All measured values were written in units of dimensions of the measuring instruments.

| \( Q_0 \), \( m^3/h \) | \( \sigma \) | \( H \), mm | \( x \), mm | \( b \), mm | \( h \), mm |
|---|---|---|---|---|---|
| 110.37 | 0.00245 | 240.03 | 311 | 233.39 | 248.10 | 246.64 | 248.39 | 252.63 | 227.48 | 211.53 | 190.57 | 176.54 |
| 110.37 | 0.00235 | 243.54 | 305 | 233.68 | 244.67 | 250.60 | 255.07 | 261.97 | 224.62 | 212.05 | 189.20 | 176.72 |
| 110.37 | 0.00251 | 249.85 | 167 | 198.28 | 211.10 | 225.78 | 221.98 | 234.67 | 187.50 | 179.84 | 164.42 | 152.15 |
| 110.37 | 0.00243 | 252.78 | 153 | 177.36 | 191.86 | 209.11 | 205.03 | 219.06 | 168.55 | 159.95 | 146.21 | 131.56 |
| 110.37 | 0.00224 | 258.37 | 157 | 186.02 | 198.17 | 211.97 | 213.57 | 219.08 | 177.79 | 165.19 | 153.89 | 137.56 |
| 99.95 | 0.00223 | 224.85 | 186 | 214.16 | 217.47 | 221.54 | 233.52 | 242.63 | 198.02 | 186.26 | 174.63 | 154.94 |
| 90.14 | 0.00273 | 224.85 | 215 | 211.90 | 226.50 | 229.07 | 230.17 | 241.67 | 207.62 | 192.68 | 173.59 | 158.65 |
| 80.15 | 0.00262 | 224.85 | 274 | 222.93 | 229.00 | 231.60 | 243.03 | 249.32 | 204.19 | 196.42 | 182.65 | 163.63 |
| 69.92 | 0.00226 | 224.85 | 303 | 213.49 | 222.77 | 234.05 | 242.10 | 245.60 | 207.03 | 187.94 | 175.24 | 166.04 |
| 69.92 | 0.00201 | 224.85 | 311 | 222.86 | 227.12 | 229.59 | 245.71 | 248.33 | 203.70 | 194.60 | 181.98 | 159.04 |
| 69.92 | 0.00226 | 224.85 | 311 | 224.57 | 227.65 | 241.47 | 236.62 | 250.89 | 203.15 | 192.34 | 179.65 | 159.75 |
The results of comparing the computational methods described in subsections 2.1 and 2.2 are summarized in Table 2 and presented graphically in Figures 2 and 3.

| Experimental data | Calculated values at $\phi = h_B/B = 153/311 = 0.49196$ |
|-------------------|----------------------------------------------------------|
| $Q_0$, m$^3$/h   | $H$, m | $h$, m | $\phi = h_B/H$ | $m$ (Eq. (6)) | $Q$ (Eq. (5)) | $\Delta$ |
| 110.37           | 0.24003 | 0.17736 | 0.16512 | 0.73891 | 110.87 | –0.00452 |
| 110.37           | 0.24354 | 0.19186 | 0.16512 | 0.78780 | 110.06 | 0.00279 |
| 110.37           | 0.24985 | 0.20911 | 0.16512 | 0.83694 | 107.74 | 0.02384 |
| 110.37           | 0.25278 | 0.20503 | 0.16512 | 0.81110 | 113.66 | –0.02982 |
| 110.37           | 0.25837 | 0.21906 | 0.16512 | 0.84785 | 111.16 | –0.00720 |
| 99.95            | 0.22485 | 0.16855 | 0.15456 | 0.74961 | 100.09 | –0.00136 |
| 90.14            | 0.21006 | 0.15995 | 0.14427 | 0.76145 | 89.83 | 0.00343 |
| 80.15            | 0.19436 | 0.14621 | 0.13341 | 0.75226 | 80.34 | –0.00231 |
| 69.92            | 0.17722 | 0.13156 | 0.12180 | 0.74235 | 70.25 | –0.00467 |

According to the data in Table 2, it can be seen that the discrepancies ($\Delta$) between the calculated ($Q$) and measured ($Q_0$) in the process of hydraulic studies, the values of flow rates were within the limit of ±3%, and the normed standard deviation is $\sigma = 0.01324$.

Figure 2 shows the graphs of changes in Froude numbers ($\alpha_{Fr}$), as well as relative depths ($h/H_0$) and velocities ($V/\sqrt{2gh_0}$) in the flow along the length of the model Venturi channel at the rate $Q_0 = 110.37$ m$^3$/h. The regime with a flow rate $Q_0 = 110.37$ m$^3$/h at a tailwater level $h_0 = 218.26$ mm is considered. Hydrodynamic head here was calculated as the sum

$$H_0 = H + \frac{\alpha}{2g} \left( \frac{Q_0}{BH} \right)^2.$$

When calculating the Froude numbers in the diffuser, hydraulic losses were taken into account.

Figure 2. Functions of variation of depth $h/H_0$, velocity $V/\sqrt{2gh_0}$ and Froude number $\alpha_{Fr}$ in the flow along the length of the model subcritical Venturi channel at $Q_0 = 110.37$ m$^3$/h.
In Figures 2 and 3, the values measured during the experiments are shown by dots, solid lines are obtained by calculation according to the methods described above.

Figure 3. Functions of variation of the flow depth $h$ along the length of the model Venturi channel:
a – depending on the flooding in the downstream ($Q_0 = 110.37 \text{ m}^3/\text{h}$): 1 – $h_0 = 0.24561 \text{ m}$, 2 – $h_0 = 0.23850 \text{ m}$, 3 – $h_0 = 0.23465 \text{ m}$, 4 – $h_0 = 0.22466 \text{ m}$, 5 – $h_0 = 0.21826 \text{ m}$; b – at a variable flow rate ($h_0/H_0 = 0.83 \div 0.87$): 1 – $Q_0 = 110.37 \text{ m}^3/\text{h}$, 2 – $Q_0 = 99.95 \text{ m}^3/\text{h}$, 3 – $Q_0 = 90.14 \text{ m}^3/\text{h}$, 4 – $Q_0 = 80.15 \text{ m}^3/\text{h}$, 5 – $Q_0 = 69.92 \text{ m}^3/\text{h}$.

In general, it can be seen that the functions of changes in Froude numbers (16), depths and flow velocities (17) along the length of the flooded Venturi channel are in good agreement with experimental data. This makes it possible to recommend the methods outlined in subsections 2.1 and
2.2 for use in practical calculations, including in the operational accounting of extreme flows at water measuring posts.

3. Conclusion
According to the State Standard of the Russian Federation МИ 2406–97, flooded modes in water measuring channels are unacceptable. In practice, the conditions of free flow are often violated due to the increase in the intensity of effluents in the context of global climate change. The incorrectness of the operational accounting of extreme flows at water measuring posts is revealed with a significant delay. The purpose of the research is to determine the criterion separating the free and flooded outflow modes in the Venturi channel, and to develop and verify the method for its hydraulic calculation in case of flooded outflows.

The criterion for separating the free and flooded outflow modes in the Venturi water-measuring channel is the ratio of the flow depth in the channel throat $h_m$ to the critical depth $h_c$. With flooded outflow, this ratio should be greater than one ($h_m/h_c > 1$).

The method for determining the flow rate in the flooded Venturi canal using two control cross-sections, one of which is located in the upper pool of the channel, the other in its throat, has been theoretically and experimentally substantiated.

A differential equation for an uneven flow in a non-prismatic channel is obtained in the form (13). An analysis of this equation showed that in a flooded Venturi channel with a subcritical flow at Froude numbers less than one ($Fr < 1$), the denominator of equation (13) is always greater than zero; therefore, at the channel inlet in the narrowing region, when $dh/dl < 0$, the flow depth is down decreases downstream ($dh/dl < 0$), and in the downstream diffuser, where the channel expands ($dh/dl > 0$), the flow depth increases ($dh/dl > 0$). Thus, the curve of the flow surface has a dip in the throat of the flooded Venturi channel. In this case, in the section of the maximum dip of the free surface, the flow depth $h_m$ does not fall below the critical value $h_c$.

The integration of the differential equation (13) was carried out, which made it possible to obtain the function of changing the Froude numbers in the flow along the length of the flooded Venturi channel (16), and then, using (17), to determine the depths and flow velocities. When calculating the flow characteristics in the diffuser of channel, hydraulic losses must be taken into account.

The verification of the developed calculation methods showed that the data obtained by the calculation are in good agreement with the experimental ones. The deviations between calculation and experiment are less than 3%. This makes it possible to recommend the outlined methods for application in engineering practice.

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