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Flow states in the classical Venturi channel water gauge

Режимы течения в классическом водомерном канале Вентури

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Ключевые слова: безнапорное течение; измерение расхода воды; лоток Вентури; критическая глубина

Abstract. The paper relates to the field of hydraulics and is devoted to the study of fluid flow states in a non-submerged Venturi channel. The aim is improvement of the method of hydraulic calculation of the classical Venturi channel. Authors applied experimental methods with the use of hi-tech certified measurement equipment allowing for digital technology-based automated collection and processing of empirical information; calculation and analytical methods. Distribution of depths, velocities and Froude numbers in flow direction inside the classical Venturi channel water gauge are obtained. The theoretical method of hydraulic calculation of the full-capacity discharge of the Venturi channel is considered, which does not contain empirical coefficients. It is established that the calculation of the full-capacity discharge of the classical Venturi channel in accordance with the current State Standard of the Russian Federation MI 2406-97 gives underestimated values of the design flow rate with the actual flow rate with a systematic error of more than -2 %, the theoretical method of hydraulic calculation of the full-capacity discharge of the Venturi channel has a relative error of ±1 %.

Аннотация. Работа посвящена исследованию режимов течения жидкости в неподтопленном расходомерном канале Вентури. Целью является совершенствование метода гидравлического расчета классического канала Вентури. Были применены экспериментальные методы с использованием высокотехнологичного сертифицированного измерительного оборудования, позволяющего на основе цифровых технологий производить автоматизированный сбор и обработку эмпирической информации; и расчетно-аналитические. В результате были получены распределения глубин, скоростей и чисел Фруда в потоке по длине проточного тракта классического расходомерного канала Вентури. Рассмотрен теоретический не содержащий эмпирических коэффициентов метод гидравлического расчета пропускной способности канала Вентури. Установлено, что расчет пропускной способности классического канала Вентури по действующему Госстандарту РФ МИ 2406–97 даёт заниженные значения расчетного расхода относительно расхода действительного с систематической погрешностью более -2 %, теоретический метод гидравлического расчета пропускной способности канала Вентури имеет относительную погрешность ±1 %.

1. Introduction

Attitude to water not as the main resource of life support for the population, but as an expendable material that does not have strategic value for the State and human, leads to out-of-order consumption of water, decrease in its quality in water bodies, aggravates the contradiction between water users. The priority of the use of water resources for domestic and drinking water supply purposes, declared in the Water Code of the Russian Federation, is not being fulfilled. Today, monitoring the volume of water consumption from natural sources and the return of treated wastewater to the environment has become the main function of the State hydrometric services, the implementation of which must be ensured by the high accuracy data obtained at gauges. Of importance became the commercial accounting of water consumption [1]. The requirements for its organization are approved by the resolutions of the Government of the Russian Federation of 12.02.1999 No.167 "On Approval of the Rules for the Use of Public Water Supply and Sewage Systems in the Russian Federation", dated 10.04.2007 No. 219 "On Approval of the Regulations on Implementation of State Monitoring of Water Bodies" and dated July 29, 2013 No. 644 "On Approval of the Rules of Cold Water Supply and Sanitation and on Amending Certain Acts of the Government of the Russian Federation", as well as the Order of the Ministry of Natural Resources of Russia of 08.07.2009 No. 205 "On Approval of the Procedure for the Owners of Water Bodies and Water Users to Take into Account the Amount of Water Abstraction (withdrawal) from Water Bodies and the Volume of Discharge of Sewage and (or) Drain Water, their Quality". These documents determine that the gauges of commercial recording the volumes of clean water intake and discharge of effluents must be installed at all enterprises in the Russian Federation, without exception. Measurements of water flow in open canals and channels are governed by several State Standards, the main of which are the two regulatory documents [2, 3]: MI 2220-13 "The Flow Rate and Volume of the Waste Fluid. Gauging Procedure in Non-pressure Water Conduits by the Level of Filling with Preliminary Calibration of the Measuring Section" and MI 2406-97 "Liquid Flow in Open Channels of Water Supply and Sewerage Systems. Gauging Procedure with the Use of Standard weirs and Flumes".

According to regulatory documents, flow gauges are recognized as effective means of determining the discharges of pure and suspended load-bearing open flows in natural watercourses, reclamation canals and in domestic water supply and sewerage systems. The Venturi flume water gauge (Fig. 1) [3–9] is a typical self-cleaning flume, which is an open non-prismatic channel with vertical walls, gradually tapering downstream forming a convergent channel followed by a straightforward gorge portion, then gradually expanding downstream portion (diffuser). The Venturi flume is capable to pass fine and coarse mechanical inclusions: suspended load, sand, branches, logs and other debris. The Venturi flume hydraulics have been studied for over a hundred years [10], but even today it is of interest for the engineering and scientific community. This is reflected in a number of publications devoted to this issue with the research carried out across the entire spectrum of directions of hi-tech science from experimental to numerical and theoretical [3, 11–24]. Undoubtedly, this is due to the necessity to improve the methods for calculation of hydraulic characteristics of the Venturi flume – one of the main water gauge tools for open flows. The classical Venturi flume in the State Standard of the Russian Federation MI 2406-97 and the International Standard ISO 4359:2013 is a horizontal channel of critical depth with a free (not flooded) fluid outflow, at which the downstream water level variation (h_0) has no effect on the flow rate (Q). There are similar Standards in the most developed countries of the world, for example, U.S. ASTM D 5640-95(2014).

Figure 1. Venturi flumes: on the left – prototype (view from downstream pool); on the right – model (view from upstream pool)

Considering the Venturi flume as a channel of critical depth, the Standards declare that within a straight gorge portion there is a stream transition from a calm subcritical to a stormy supercritical flow through the critical depth h_c (Fig. 2). This statement was transferred from the previous domestic and international Standards (RPD 99-77, MI 2122-90, ISO 4359:1983, ISO 4359:1983/Cor.1:1999), based on the results of experimental studies carried out in the 60-70s of the last century on the equipment that is substantially inferior to the modern one. Since then, it has been 50 years, obviously, it's time to refine or supplement the provisions of the current Standards, using modern hi-tech equipment, devices and instruments. Such papers began to appear recently [3, 22, 24–28].

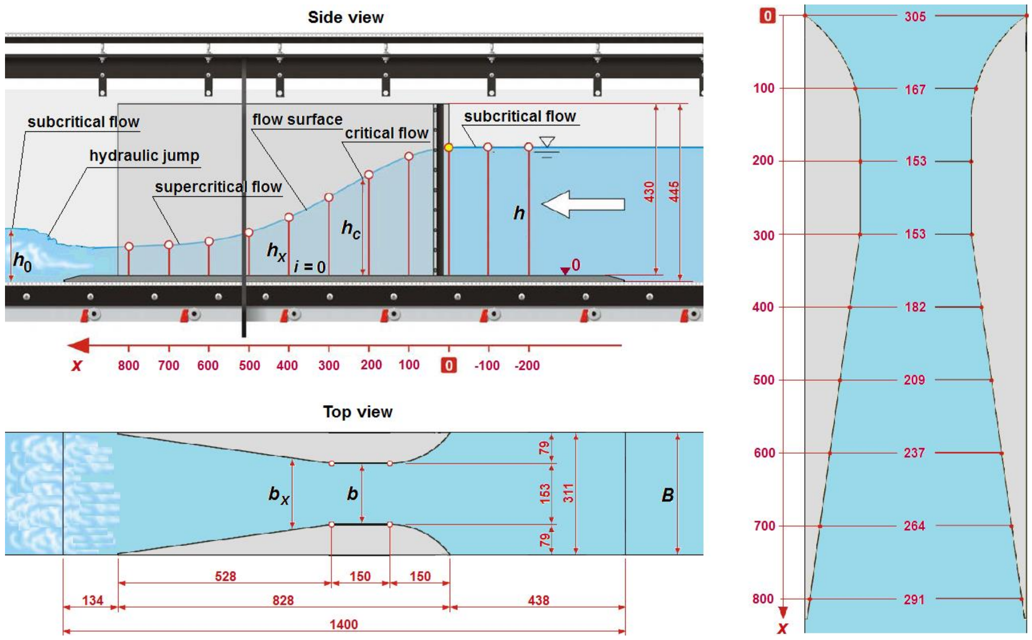

Figure 2. The laboratory model of Venturi flume (measurements in millimeters)

Objectives of the Experiments: determination of flow states within the flow path of the classical Venturi channel; determination of the position of the section in which the flow passes through a critical depth; determination of the hydraulic characteristics of the Venturi flume on the basis of experimental studies performed on hi-tech certified measurement equipment, allowing on the basis of digital technologies for automated collection and processing of empirical information; checking the provisions of the State Standard of Russia MI 2406-97; improvement of the method of hydraulic calculation of the Venturi channel.

2. Methods

2.1. Equipment, Devices and Instruments

Experimental studies of the model Venturi flume water gauge have been made in the National Research Moscow State University of Civil Engineering (NUR MGSU). The following equipment, devices and instruments have been used in the studies [24, 27 and 28]:

- HM 162 scientific research hydraulic calibrating flume [29] (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 made of hardened glass and its floor (stainless steel) produced according to the Manning design [10] 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 10 D 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 [29] (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. Fig. 2) [30] (manufacturer: G.U.N.T. Gerätebau GmbH, Germany) with height 430 mm, width and length of the gorge portion b = 153 mm and l = 150 mm, made of plexiglass and attached on a polyvinyl chloride plate,15 mm thick; the model is a prototype of Venturi channel water gauge, which practically corresponds to the typical design 902-9-44.87 [31] with the design maximum flow rate Q_{max} = 250 m^3/h;
- 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.

2.2. Methods of the Experimental Research

1. Before performing the study the hydraulic flume HM 162 was set in horizontal position (i = 0) and the model of Venturi channel HM 162.51 placed in the middle part of the flume (cf. Fig. 2). 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 (manufacturer: G.U.N.T. Gerätebau GmbH, Germany) 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.

2. The forward flow rate (or discharge) Q was specified on the panel used to control the operating regime of the laboratory flume HM 162 or from the computer and the flume pump SHS4 80-200/40/P then turned on.

3. Following stabilization of the discharge with the pump turned on or with a variable operation regime of the pump (stabilization time 10 min), the value of the discharge was written to the hard disk of the control computer into a newly created data file by the HM 162.12 program. The total time needed for the measurement was 200 sec with interval between measurements 1 sec; during this period the computer system automatically executed 200 measurements. The obtained data were translated into an Excel file in the course of laboratory processing of the measurement results in which the average value of the full-capacity discharge in the course of a measurement session

$$Q = \frac{1}{k}\sum_{j=1}^{k} Q_j$$

and the normed standard deviation

$$\sigma = \frac{1}{Q}\sqrt{\frac{1}{k}\sum_{j=1}^{k}(Q_j - Q)^2}$$

were calculated, in which k is the size of the sample, k = 200; Q_j is the jth element of the sample. The values of Q and σ are written in Table 1.

4. The same Table 1 shows measured digital level gauge HM 162.91 values of flow depths (or water levels) h_x at 11 points x along the length of the model of Venturi flume HM 162.51 (cf. Fig. 2). 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_x at points x. The values of x and the corresponding values of b_x are written in the title lines of Table 1.

5. Next, the discharge transmitted through the flume was changed with preliminarily selected step ΔQ and the operations from Step 3 to Step 5 repeated. The total being investigated 11 regimes of transmission discharge Q from 10.06 to 110.37 m^3/h with step $\Delta Q \approx 10$ m^3/h. All measured values were written in units of dimensions of the measuring instruments.

Table 1. Experimental Data

Q, m^3/h	σ	x, mm	-200	-100	0	100	200	300	400	500	600	700	800
		b_x, mm	311	311	305	167	153	153	182	209	237	264	291
110.37	0.00245	h_x, mm	227.98	226.84	224.75	211.70	178.34	139.34	109.11	89.64	75.02	64.72	55.97
99.95	0.00273	h_x, mm	213.32	213.32	210.78	198.58	166.12	129.93	102.05	83.64	70.39	59.94	52.09
90.14	0.00262	h_x, mm	200.12	199.43	196.97	184.63	154.47	119.74	94.38	77.66	65.07	55.13	47.87
80.15	0.00201	h_x, mm	185.58	184.68	181.87	170.19	141.28	108.83	87.04	71.76	59.82	50.43	43.14
69.92	0.00226	h_x, mm	169.29	168.73	166.69	154.92	127.35	98.57	78.95	65.49	54.48	45.00	39.64
60.08	0.00235	h_x, mm	153.08	153.08	150.23	138.79	113.28	87.68	71.26	59.30	48.18	39.66	35.87
49.89	0.00251	h_x, mm	135.77	135.77	133.18	122.05	99.20	76.78	63.81	52.38	41.11	34.18	32.85
39.96	0.00224	h_x, mm	117.27	116.38	114.23	105.02	83.90	65.55	55.00	44.76	33.81	29.89	29.48
29.83	0.00427	h_x, mm	96.31	95.69	93.60	85.49	67.89	54.31	46.11	35.14	26.93	25.58	25.50
19.94	0.00394	h_x, mm	73.26	72.78	70.97	64.79	50.56	41.93	35.84	24.91	21.11	21.11	19.85
10.06	0.00689	h_x, mm	46.10	46.10	44.83	39.99	31.54	28.19	20.77	15.98	15.15	13.74	11.91

3. Results and Discussion

Laboratory processing of the measurement results was implemented in Microsoft Office Excel 2007 and the results of computations are written in Tables 2 – 4. The following quantities were calculated:

- critical depths [10, 24, 27, 28, 30] (Table 2)

$$h_c = \sqrt[3]{\frac{Q^2}{gb_x^2}},$$

where g is the gravitational acceleration, g = 9.81 m/sec;

Table 2. Critical Depths

Q, m^3/h	x, mm	-200	-100	0	100	200	300	400	500	600	700	800
	b_x, mm	311	311	305	167	153	153	182	209	237	264	291
110.37	h_c, mm	99.69	99.69	100.99	150.89	159.96	159.96	142.48	129.93	119.48	111.19	104.20
99.95	h_c, mm	93.31	93.31	94.53	141.24	149.73	149.73	133.37	121.62	111.84	104.08	97.54
90.14	h_c, mm	87.10	87.10	88.23	131.83	139.76	139.76	124.49	113.52	104.39	97.15	91.04
80.15	h_c, mm	80.54	80.54	81.59	121.91	129.24	129.24	115.12	104.98	96.54	89.84	84.19
69.92	h_c, mm	73.53	73.53	74.49	111.30	117.99	117.99	105.10	95.84	88.13	82.02	76.86
60.08	h_c, mm	66.46	66.46	67.33	100.60	106.65	106.65	94.99	86.63	79.66	74.13	69.47
49.89	h_c, mm	58.72	58.72	59.48	88.88	94.22	94.22	83.92	76.53	70.38	65.49	61.38
39.96	h_c, mm	50.64	50.64	51.30	76.65	81.26	81.26	72.38	66.00	60.70	56.48	52.93
29.83	h_c, mm	41.67	41.67	42.21	63.07	66.87	66.87	59.56	54.31	49.95	46.48	43.56
19.94	h_c, mm	31.86	31.86	32.27	48.22	51.12	51.12	45.53	41.52	38.18	35.53	33.30
10.06	h_c, mm	20.20	20.20	20.46	30.57	32.41	32.41	28.87	26.32	24.21	22.53	21.11

- Flow velocities (Table 3)

$$V = \frac{Q}{b_x h_x}; \quad (1)$$

Table 3. Flow Velocities

Q, m^3/h	x, mm	-200	-100	0	100	200	300	400	500	600	700	800
	b_x, mm	311	311	305	167	153	153	182	209	237	264	291
110.37	V, m/sec	0.4324	0.4346	0.4472	0.8672	1.1236	1.4381	1.5439	1.6364	1.7243	1.7943	1.8823
99.95	V, m/sec	0.4185	0.4185	0.4319	0.8372	1.0924	1.3966	1.4949	1.5883	1.6643	1.7545	1.8316
90.14	V, m/sec	0.4023	0.4037	0.4168	0.8120	1.0594	1.3667	1.4576	1.5426	1.6235	1.7203	1.7974
80.15	V, m/sec	0.3858	0.3877	0.4014	0.7834	1.0300	1.3372	1.4055	1.4846	1.5705	1.6724	1.7736
69.92	V, m/sec	0.3689	0.3701	0.3820	0.7507	0.9968	1.2878	1.3517	1.4190	1.5042	1.6349	1.6837
60.08	V, m/sec	0.3506	0.3506	0.3642	0.7201	0.9629	1.2441	1.2869	1.3466	1.4616	1.5940	1.5989
49.89	V, m/sec	0.3282	0.3282	0.3412	0.6799	0.9131	1.1798	1.1934	1.2660	1.4224	1.5359	1.4498
39.96	V, m/sec	0.3044	0.3067	0.3186	0.6329	0.8647	1.1068	1.1089	1.1865	1.3852	1.4067	1.2939
29.83	V, m/sec	0.2766	0.2784	0.2902	0.5804	0.7977	0.9972	0.9873	1.1282	1.2982	1.2270	1.1166
19.94	V, m/sec	0.2431	0.2447	0.2559	0.5119	0.7160	0.8634	0.8491	1.0639	1.1071	0.9938	0.9589
10.06	V, m/sec	0.1950	0.1950	0.2045	0.4186	0.5793	0.6482	0.7396	0.8371	0.7786	0.7707	0.8066

- Froude numbers (Table 4) [10, 31, 32]

$$\mathrm{Fr} = \frac{V}{\sqrt{gh_x}}. \quad (2)$$

Table 4. Froude Numbers

Q, m³/h	x, mm	-200	-100	0	100	200	300	400	500	600	700	800
	b_x, mm	311	311	305	167	153	153	182	209	237	264	291
110.37	Fr	0.2891	0.2913	0.3012	0.6017	0.8495	1.2300	1.4922	1.7450	2.0100	2.2519	2.5403
99.95	Fr	0.2893	0.2893	0.3003	0.5998	0.8557	1.2371	1.4940	1.7534	2.0028	2.2881	2.5623
90.14	Fr	0.2871	0.2886	0.2998	0.6034	0.8606	1.2610	1.5148	1.7673	2.0321	2.3392	2.6228
80.15	Fr	0.2859	0.2880	0.3005	0.6063	0.8749	1.2941	1.5211	1.7694	2.0501	2.3777	2.7263
69.92	Fr	0.2863	0.2877	0.2987	0.6090	0.8918	1.3096	1.5359	1.7703	2.0576	2.4606	2.7000
60.08	Fr	0.2861	0.2861	0.3000	0.6171	0.9135	1.3414	1.5391	1.7656	2.1260	2.5555	2.6954
49.89	Fr	0.2844	0.2844	0.2985	0.6214	0.9256	1.3594	1.5083	1.7660	2.2399	2.6524	2.5539
39.96	Fr	0.2838	0.2870	0.3010	0.6235	0.9531	1.3802	1.5096	1.7906	2.4053	2.5977	2.4060
29.83	Fr	0.2846	0.2874	0.3029	0.6337	0.9775	1.3661	1.4680	1.9215	2.5258	2.4493	2.2325
19.94	Fr	0.2868	0.2896	0.3067	0.6421	1.0166	1.3461	1.4320	2.1521	2.4327	2.1839	2.1729
10.06	Fr	0.2900	0.2900	0.3083	0.6684	1.0415	1.2326	1.6384	2.1142	2.0197	2.0993	2.3599

By results of measurement and processing of the experimental data the hydraulic characteristics of flows inside Venturi flume have been constructed. They are presented in Figures 3–5.

Figure 3 shows a grid consisting of two families of intersecting curves: the first family shown by black dots and lines reflects the experimental data of flow depth measurements lengthwise the flow path of the examined Venturi flume $h_x = f(x)$ (cf. Table 1). The second family (blue lines) shows the calculated values of the critical depths $h_c = f(x)$ (cf. Table 2). To the right of the graph opposite the experimental curves, the values of the corresponding flow rates Q are indicated in black. The flow rates corresponding to the blue lines of critical depths are indicated in blue for maximum and minimum values in the chart field. The points of intersection of curves $h_x = f(x)$ and $h_c = f(x)$ are shown in red. These points show the positions of the critical depths on the free surface lines of the stream at various flow rates through the Venturi flume. The red envelope curve is drawn along these points. To the right of this curve there are calm subcritical flow states, below there are stormy supercritical ones, and the red envelope curve corresponds to the critical flows.

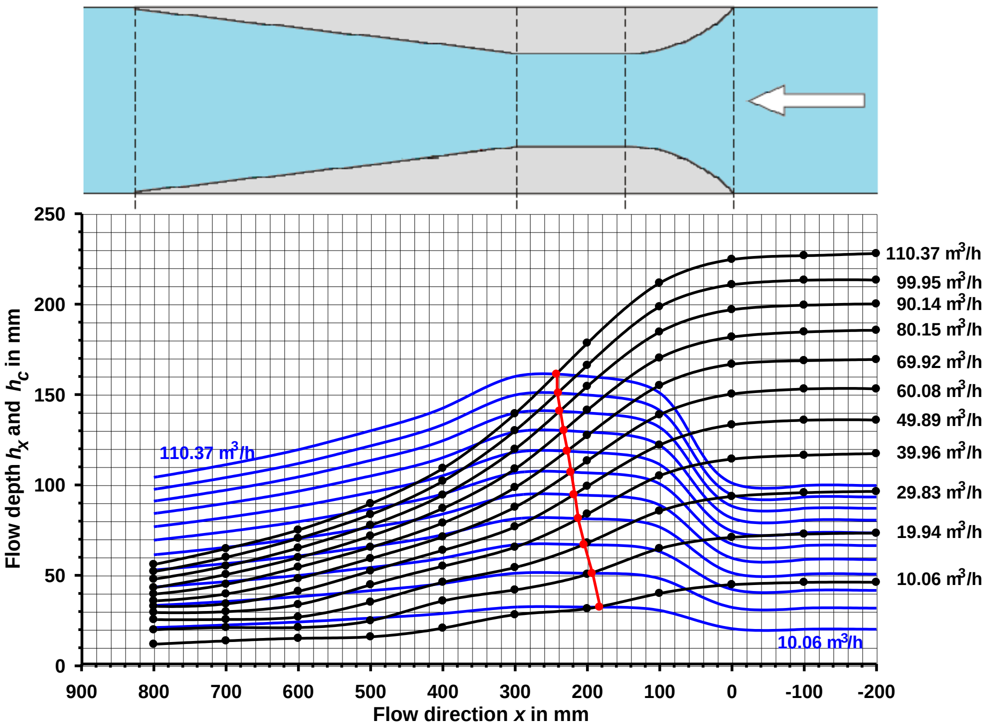

Figure 3. Water levels in the flow direction (profiles) for different flow rates

According to the data obtained (cf. Fig. 3), it can be asserted that in the classical Venturi flume with free (not flooded) fluid outflow, regardless of the flow rate, the flow passes a critical depth always within the gorge portion with parallel vertical walls. And the position of the critical section corresponds to the middle of the gorge. Just a minor displacement of the critical depth range in one direction or another from the middle of the gorge depends on the flow parameters (on the flow rate passed), in particular, with an increase in the flow rate, the critical depth shifts slightly toward the diffuser. These studies, as well as studies carried out earlier [24], have shown that the flow inevitably passes the critical section within the gorge length of a multiple (3 to 5 times) less than in accordance with the regulations of the State Standard of Russia MI 2406-97. Thus, the length of the rectilinear gorge portion, recommended in MI 2406-97, is unreasonably overestimated that accordingly leads to unreasonable hydraulic losses in the entrance section of the Venturi flume. This distorts the hydraulics of the classic flume, according to which the hydraulic losses in its inlet section should be reduced to the utmost, and ideally reduced to zero. This is exactly what is observed in the studied channel [24], in which the hydraulic losses at the inlet section to the critical cross-section are negligible and lie in the range of accuracy of hydraulic studies. The authors believe that the Venturi open channel can be performed as a pressure flow gauge nozzle of the same name where the smooth confusor terminates with a gorge section, immediately followed by a smooth diffuser. In this case, the gorge will be the dividing cross-section, and hydraulic losses at the inlet to be virtually eliminated. The fact of formation of a flow with critical depth in a dividing cross-section is well known from hydraulics of structures [10, 27, 28]. However, this assumption requires experimental verification.

Since the flow with critical depth is physically unstable [10], the flow passes the critical section in a rapid fall with a sharp change of depth in the form of a waterfall. The fall of the depth below the critical one with formation of supercritical flow in the horizontal channel should cause subsequent flow braking, which is what happens. However, this is imperceptible for flows with a large discharge and, therefore, with a high inertia, but is very noticeable in the flows of low inertia with low flow rate. Explicit the flow braking we can be observed in the diffuser of the flume. Change in the flow velocities along the flow channel of the Venturi flume is shown in the graphs of Fig. 4 ($V = f(x)$) – Table 3).

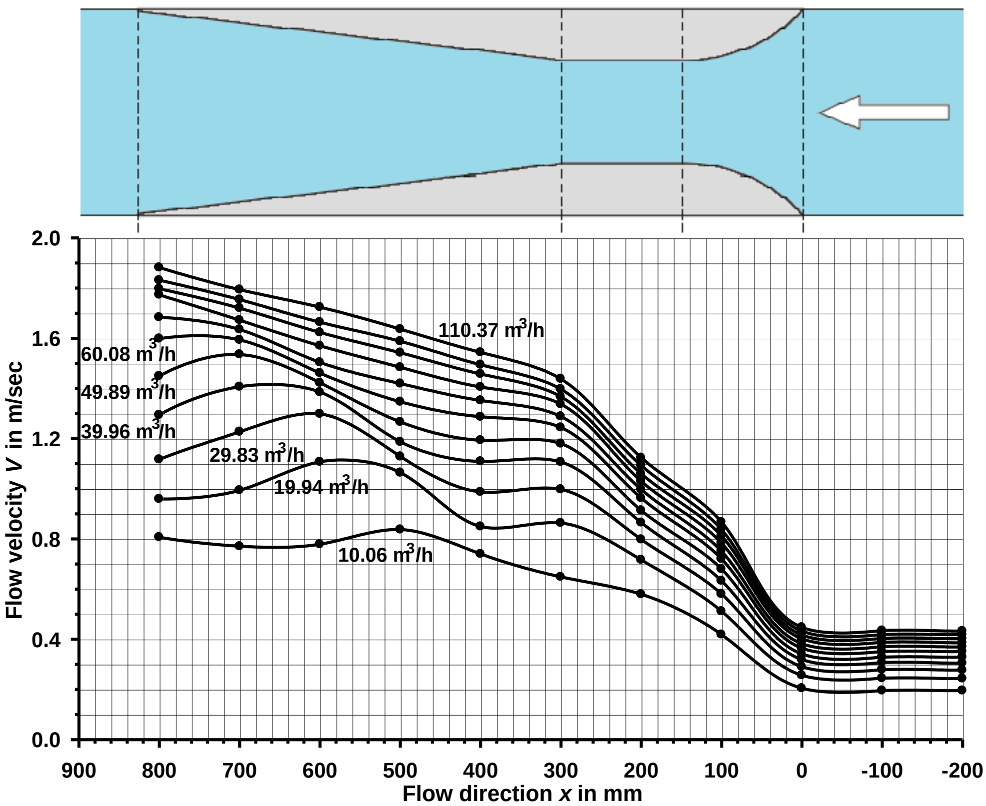

Figure 4. Flow velocities in the flow direction for different flow rates

In Figure 4 one can see significant fluctuations in the flow rates within the diffuser. This phenomenon is typical for the flows with low rates and is manifested in the wavy nature of the free surface. Such a surface can be seen in the photo on the left in Figure 1, made from the downstream side, where the entire section of the diffuser with surface waves are clearly visible. The phenomenon is associated with many factors, including flooding in the downstream h_0 and the possible formation of a hydraulic jump (cf. Fig. 2). However, this does not affect to the flow within the gorge section and, hence, does not affect to the main hydraulic characteristic of the Venturi flume: its discharge-head characteristic

Q – *h*. Thus, the Venturi flume remains a channel of critical depth regardless the flow nature within the diffuser.

Figure 5 shows the change in the Froude numbers in the direction of flow for all flow states being investigated (Fr = *f*(*x*) – Table 4). As is well known [10] the Froude number shows the flow state: accordingly with Fr < 1, the flow is calm subcritical, with Fr = 1 – transient critical flow and with Fr > 1 – stormy supercritical flow. Therefore, in the figure, the red horizontal line shows the value Fr = 1, which, being a boundary state, separates the subcritical flow states from the supercritical ones. What lies beneath this red boundary line, refers to subcritical states, what is above – to supercritical states. Also red lines are allocated zone of critical depths in the gorge of the Venturi flume. Thus, the graphs in Figure 5 show the change of flow states lengthwise the classical (not flooded) Venturi flume: in the upstream portion of the flume and in its confusor (converging portion) the flow is calm subcritical, in the middle section of the flume gorge, regardless of the flow rate passed, the flow features the critical flow state and supercritical flow in the diffuser.

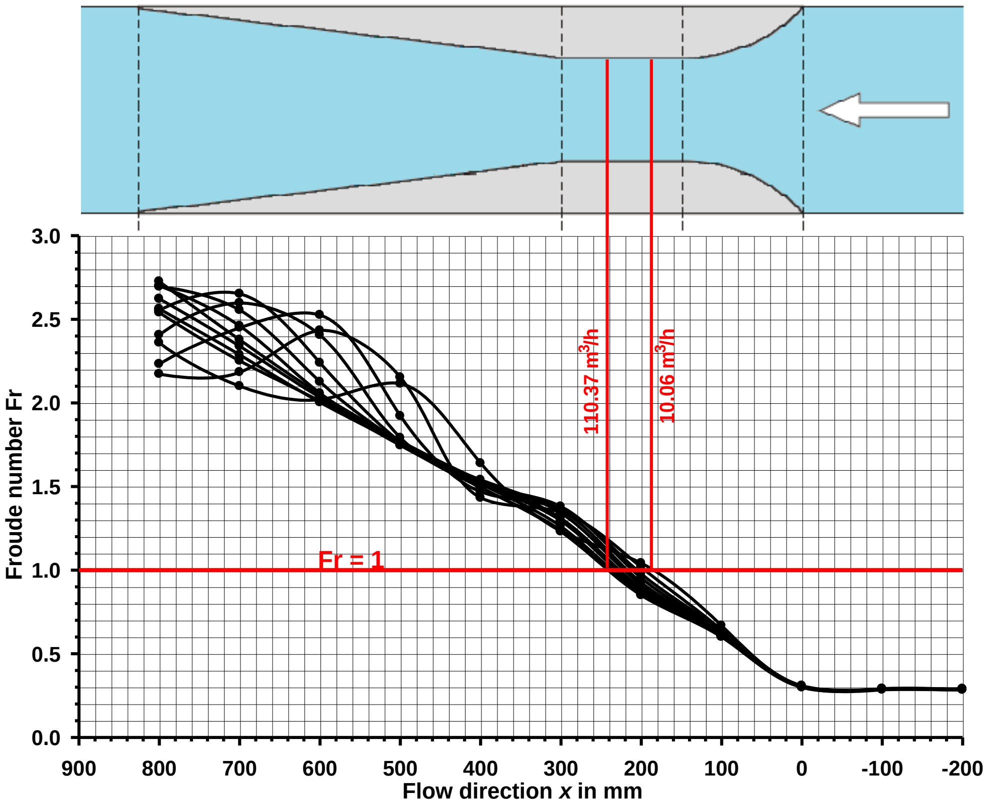

Figure 5. Froude numbers in the flow direction for different flow rates

According to the graphs in Figure 5 we also note important noteworthy features. Upstream of the inlet to the Venturi flume, the Froude numbers are always less than unity and have the same value (Fr = *C* = const) for all the flow rates passed through the flume. Hence, according to Eq. (2) the flow velocity in the upstream pool can be written as

$$V = C\sqrt{gh},$$

where *h* is upstream water level.

On the other side consistent with Eq. (1) we have

$$Q = VBh = CB\sqrt{g}h^{1.5},$$

where *B* is the width of the upstream channel.

Thus, the Froude number in the upstream pool, equal to Fr = *C* = const, can be considered as a flow coefficient of the classical Venturi channel. And this coefficient remains constant over the entire range of flow rates, which is an important property of the flow gauge.

A linear increase the Froude numbers along the length of the flow path is observed on the section from the entrance facet of the Venturi flume confusor to the exit from its rectilinear gorge. Here the flow undergoes a drastic change from calm subcritical with Froude numbers less than unity (Fr < 1) to stormy supercritical with Fr > 1, bypassing critical state at Fr = 1 in the middle of the gorge. In the area of smooth linear growth of Froude numbers the hydraulic losses are negligible. The picture changes in the diffuser of the flume where the flow state stormy supercritical (Fr > 1), but the nature of changing the Froude numbers at low flow rates (for the investigated flume its less than 60 m^3/h – cf. Fig. 4) does not follow linear law. Here the flow has a wavy free surface and is accompanied by significant hydraulic losses. The Venturi flume remains a classical channel of critical depth while the supercritical flow state in the diffuser is maintained or within its limits the supercritical flow by hydraulic jump passes into the subcritical one. But, if there is the subcritical flow in the gorge, then the Venturi flume loses the properties of a channel of critical depth and in flume is establishes the flooded mode of fluid outflow [3]. The methods of hydraulic calculation of the Venturi channel with a flooded outflow state are fundamentally different from those described in the State Standard of the Russian Federation MI 2406-97.

The Russian State Standard presents semi-empirical formula for use in hydraulic calculation of the full-capacity discharge of the classical Venturi flume

$$Q = \frac{2}{3}\sqrt{\frac{2}{3}} C_D C_V \sqrt{g} b h^{1.5}, \tag{3}$$

where C_D and C_V are empirical coefficients; b is width of gorge portion; h is upstream water level.

Empirical coefficient C_D takes into account the hydraulic losses on the section between the upstream pool and the gorge. In the document the coefficient is approximated by empirical dependence

$$C_D = \left(1 - 0.006\frac{l}{b}\right) \cdot \left(1 - 0.003\frac{l}{h}\right)^{1.5}, \tag{4}$$

where l is the length of the gorge portion of the Venturi flume.

In article [3], one of the authors of which was a developer of the State Standard of Russia MI 2406-97, this coefficient is determined by equality

$$C_D = \frac{1}{\sqrt{\alpha}}\left(1 - \frac{h_w}{E}\right)^{1.5}, \tag{5}$$

where α is the Coriolis (Saint–Venant) coefficient; h_w is hydraulic losses on the section between the upstream pool and gorge portion; E is unit energy of flow in the head race of the Venturi flume

$$E = h + \frac{\alpha V^2}{2g}.$$

According to empirical dependence (4), the coefficient C_D is less, and the hydraulic losses h_w are the greater, the longer is the gorge. It was noted above that the length of the gorge according to the regulations of the State Standard of Russia MI 2406-97 is unreasonably overestimated in the authors' opinion, at such a length, significant hydraulic losses are quite possible. But on the inlet section of the Venturi flume under study the hydraulic losses are negligible in comparison with the accuracy of hydraulic studies and engineering calculations, so they can be neglected by putting $h_w = 0$ in Eq. (5). In addition, in the incidence sections and all-round compression of the flow in the conditions of increasing velocities of turbulent flow, the boundary layer near the walls breaks down. As a result, the velocities are aligned over the flow cross-section, and the Coriolis coefficient α approaches the unity [10, 24, 27, 28, 30]. All of the above, according to Eq. (5), allows us to put $C_D = 1$.

Empirical coefficient C_V takes into account the relationship between the unit energy of flow and water level in upstream pool. The values of C_V coefficient are presented in Table 4 in the Appendix of the State Standard MI 2406-97 depending on $C_D \cdot b/B$ parameter. In article [3] the coefficient is written in explicit form

$$C_V = \left(\frac{E}{h}\right)^{1.5}$$

and the equation for its calculation is given

$$C_V^{2/3} = 1 + \frac{1}{2}\left(\frac{2}{3}\right)^3 C_V^2 \left(\frac{b}{B}\right)^2. \tag{6}$$

Further in article [3] it is stated that it is rather difficult to find the solution of equation (6) in general form relative to C_V, that is why the authors solve it obviously graphically or by iteration method. Having no objections against using any methods, including graphical and iteration ones, we nevertheless should like to note that this equation has rigorous analytical solution. Let us rewrite it in the form

$$C_V^2 - 2\left(\frac{3}{2}\right)^3\left(\frac{B}{b}\right)^2 C_V^{2/3} + 2\left(\frac{3}{2}\right)^3\left(\frac{B}{b}\right)^2 = 0. \tag{7}$$

Equating now $C_V^{2/3} = y$, we reduce Eq. (7) to classical cubic Cardano equation of $y^3 + py + q = 0$ form [32], in which

$$p = -2\left(\frac{3}{2}\right)^3\left(\frac{B}{b}\right)^2 < 0 \quad \text{and} \quad q = 2\left(\frac{3}{2}\right)^3\left(\frac{B}{b}\right)^2.$$

But if $p < 0$ and the sum

$$\left(\frac{p}{3}\right)^3 + \left(\frac{q}{2}\right)^2 = \left(-\left(\frac{3}{2}\right)^2\left(\frac{B}{b}\right)^2\right)^3 + \left(\left(\frac{3}{2}\right)^3\left(\frac{B}{b}\right)^2\right)^2 = \left(\frac{3}{2}\right)^6 \frac{B^4}{b^4}\left(1 - \frac{B^2}{b^2}\right)$$

is also less than zero, as $B > b$, the cubic Eq. (7) has a trigonometric solution with three real roots

$$\left(C_V^{2/3}\right)_{1,2,3} = 2\sqrt{-\frac{p}{3}}\cos\left(\frac{\beta + 2n\pi}{3}\right) = 3\frac{B}{b}\cos\left(\frac{\beta + 2n\pi}{3}\right), \quad (n = 0, 1, 2),$$

where

$$\cos(\beta) = -\frac{q}{2}\sqrt{-\left(\frac{3}{p}\right)^3} = -\frac{b}{B}.$$

The sought solution must satisfy the condition $1 \le C_V^{2/3} \le 1.5$, as $C_V^{2/3} = E/h = 1 + 0.5\alpha(\mathrm{Fr})^2$, where the Froude number in the upstream pool for a calm subcritical flow is always less than unit (Fr < 1). The analysis showed that the solution of the cubic Eq. (7) is its third root corresponding to $n = 2$

$$C_V^{2/3} = 3\frac{B}{b}\cos\left\{\frac{1}{3}\left[\arccos\left(-\frac{b}{B}\right) + 4\pi\right]\right\} = 3\frac{B}{b}\sin\left[\frac{1}{3}\arcsin\left(\frac{b}{B}\right)\right]$$

or

$$C_V = 3\frac{B}{b}\sqrt{3\frac{B}{b}}\sin^{1.5}\left[\frac{1}{3}\arcsin\left(\frac{b}{B}\right)\right]. \tag{8}$$

Substituting the values of the coefficients C_D and C_V in Eq. (3) we find

$$Q = 2\sqrt{\frac{B}{b}}\sin^{1.5}\left[\frac{1}{3}\arcsin\left(\frac{b}{B}\right)\right]\sqrt{2g}Bh^{1.5}.$$

This theoretical formula not containing empirical coefficients was obtained by us earlier in [24] and underwent experimental verification, which showed that the calculation errors were ±1 %. The formula can be rewritten in the traditional form for weirs

$$Q = mB\sqrt{2g}h^{1.5}, \tag{9}$$

where m is a theoretical flow coefficient of the classical Venturi flume water gauge

$$m = 2\sqrt{\frac{B}{b}}\sin^{1.5}\left[\frac{1}{3}\arcsin\left(\frac{b}{B}\right)\right]. \qquad (10)$$

It can be seen that for b/B = 1 we have $m = 0.5^{0.5}$, and for $b/B \to 0$, respectively $m \to 0$. We note that the flow coefficient is proportional to the Froude number of upstream flow $m = 0.5^{0.5}$ Fr.

The traditional form of the flow formula (9), in which the depth (h) and the width along the flow front (B) are measured in the same section, is more logical than the form of equation (3) from the State Standard of Russia MI 2406-97, in which the depth of the flow (h) is measured in the upstream pool, but its width (b) is measured in the gorge of the flume. Eq. (10) allows us to compare the full-capacity discharge of the Venturi channel with the capacity of other water gauges and select the best variant of water meter or the optimal ratio b/B.

The comparison of the experimental data with the results of calculations using the semi-empirical methodology of the State Standard of Russia MI 2406-97 and theoretical Eqs. (8), (9) and (10) are summarized in Table 5 and presented graphically in Figure 6. The first two columns of Table 5 show the experimental values (cf. Table 1) of the upstream water levels and the flow rates passed through the flume. The values of the upstream water levels (or flow depths) h are measured in the cross-section of the hydraulic flume HM 162 at a distance x = –200 mm before the entrance edge of the confusor of the Venturi channel. The experimental values of flow rates in Table 5, in Figure 6 and further in the text are denoted as Q_0, in contrast to the calculated values of Q. The next four columns of Table 5 show the calculated values: of coefficients C_D (Eq. (4)), obtained as per the regulations of the State Standard of Russia MI 2406-97, of parameters $C_D \cdot b/B$, of coefficients C_V, which are presented in Table 4 in the Appendix of Russian State Standard MI 2406-97, and of flow rates Q. The following column shows the deviations of the calculated values of flow rates Q from their actual values Q_0

$$\Delta = \frac{Q - Q_o}{Q_o} = \frac{Q}{Q_o} - 1; \qquad (11)$$

underneath Table 5 shows the value of the root-mean-square error of the calculation method as a whole

$$\sigma = \sqrt{\frac{1}{k}\sum_{j=1}^{k}\Delta^2}\ , \qquad (12)$$

where k is the size of the sample, k = 11.

The last four columns of Table 5 give the calculated theoretical values: of coefficients C_V (Eq. (8)), of coefficients m (Eq. (10)), of full-capacity discharges of the Venturi channel Q (Eq. (9)) and of deviations Δ (Eq. (11)) of flow rates Q from their actual values Q_0. Underneath Table 5 shows the value of the root-mean-square error of the theoretical calculation method σ (Eq. (12)).

The following dimensions of the Venturi flume under study have been used in the calculations (cf. text above and Fig. 2): width and length of the gorge portion, respectively b = 153 mm and l = 150 mm, width of the cross-section upstream channel B = 311 mm.

Table 5. Full-Capacity Discharge of the Venturi Flume

Initial data		Russian State Standard MI 2406-97					Theoretical Eqs. (8), (9) and (10)			
h, mm	Q_0, m³/h	C_D	$C_D \cdot b/B$	C_V	Q, m³/h	Δ	C_V	m	Q, m³/h	Δ
227.98	110.37	0.9912	0.4876	1.0600	107.40	-0.02688	1.0612	0.20094	108.47	-0.01717
213.32	99.95	0.9910	0.4875	1.0600	97.19	-0.02765	1.0612	0.20094	98.18	-0.01772
200.12	90.14	0.9908	0.4874	1.0600	88.29	-0.02051	1.0612	0.20094	89.21	-0.01027
185.58	80.15	0.9905	0.4873	1.0599	78.82	-0.01667	1.0612	0.20094	79.67	-0.00610
169.29	69.92	0.9902	0.4871	1.0599	68.64	-0.01823	1.0612	0.20094	69.41	-0.00728
153.08	60.08	0.9897	0.4869	1.0598	59.00	-0.01807	1.0612	0.20094	59.68	-0.00664
135.77	49.89	0.9892	0.4866	1.0598	49.25	-0.01293	1.0612	0.20094	49.85	-0.00081
117.27	39.96	0.9884	0.4863	1.0597	39.50	-0.01157	1.0612	0.20094	40.02	0.00146
96.31	29.83	0.9872	0.4856	1.0595	29.35	-0.01589	1.0612	0.20094	29.78	-0.00150
73.26	19.94	0.9850	0.4846	1.0592	19.43	-0.02573	1.0612	0.20094	19.76	-0.00901
46.10	10.06	0.9796	0.4819	1.0585	9.64	-0.04242	1.0612	0.20094	9.86	-0.01997
					σ = 0.02308				σ = 0.01101	

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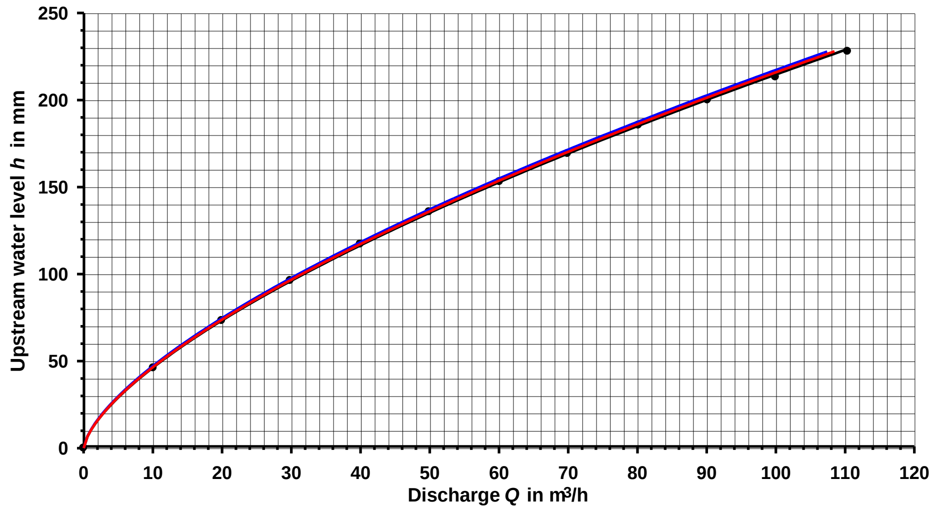

Figure 6. Discharge-head characteristics of the Venturi channel: the black points and line Q_0 – *h* are drawn from the experimental data, the blue line *Q* – *h* is calculated by the method of Russian State Standard MI 2406-97 and the red line *Q* – *h* is calculated from Eqs. (9) and (10)

The obtained results show that the semi-empirical method for calculating the full-capacity discharge of the Venturi channel water gauge by formula (3) from the State Standard of Russia MI 2406-97 has a relative error exceeding 2 % (σ = 0.02308 – see Table 5). Moreover, according to the received data, this error is systematic, by which the calculated values of flow rates *Q* are always less than their actual values Q_0. The same was noted in a previously published paper [24]. Underestimation of the volumes of water resources consumed and wastewater discharge is undoubtedly beneficial directly to water users, but it is not beneficial to the State and population of the country as a whole. Therefore, the situation when the State Standard has a systematic error cannot be considered admissible. The analysis allows us to conclude that this systematic error is associated with overstating the hydraulic losses in the confusor and gorge area of the Venturi channel to the critical cross-section. It is established that the theoretical solution (Eqs. (9) and (10)) obtained that does not have empirical coefficients provides a higher accuracy of the received hydrometric information in relation to the State Standard, and it has a relative error of about ±1% (σ = 0.01101 – cf. Table 5 and [24]). This error is not systematic. Eqs. (9) and (10) work equally well at high and low flow rates, therefore the limitation in the State Standard of Russia MI 2406-97, which regulates the minimum water level in the upstream pool h_{min} = 0.1 m, can be removed. On the whole, the studies performed make it possible to conclude that the theoretical method of hydraulic calculation of the classical Venturi channel water gauge, which meets the modern requirements of engineering practice, can be recommended for inclusion in the new edition of the State Standard of the Russian Federation MI 2406-97.

4. Conclusions

1. The use of hi-tech certified measurement equipments on the basis of digital technologies allows us to obtain empirical information of high accuracy, the analysis of which allows us to clarify, supplement or review the recommendations of existing normative documents, to prepare them in a new edition, partially or completely excluding empirical coefficients. This is especially true for the State hydrometric services, which take into account and control the use of water resources and discharge of waste water into the environment.

2. In the classical Venturi channel with free fluid outflow, regardless of the flow rate, the flow passes the cross-section with critical depth always within a short gorge with parallel vertical walls. It is established that the length of the gorge can be prescribed 3 to 5 times less than specified in the State Standard MI 2406-97.

3. In the upstream pool of the Venturi channel and in its confusor part the flow is calm subcritical with Froude numbers Fr < 1, in the middle section of the gorge the flow is critical (Fr = 1), in the diffusor the flow is stormy supercritical (Fr > 1). The Froude number in the upstream pool of the classical Venturi channel is directly proportional to its flow coefficient $m = 0.5^{0.5}$ Fr and remains constant over the entire range of flow rates, which is an important property of the flow gauge. The flow with critical depth is physically unstable, so the flow passes the critical section in a rapid fall with a sharp change of depth in the form of a waterfall. As long as in the diffuser the flow state is supercritical or within it the flow is transiting from supercritical to subcritical in the hydraulic jump form, the Venturi flume remains a classical

channel of the critical depth. If the subcritical flow is set along the entire length of the gorge, then the Venturi flume loses the properties of a channel of critical depth and the flooded mode of fluid outflow establishes therein.

4. On the section from the entrance facet of the confusor of the classical Venturi channel to the exit from its rectilinear gorge a linear increase in the Froude numbers is observed in the flow direction. In this area of smooth linear growth of the Froude numbers the hydraulic losses are negligible and lie in the range of accuracy of the hydraulic studies. Therefore, coefficient C_D, taking into account the hydraulic losses in the area between the upstream pool and the critical cross-section of the gorge of the Venturi channel, is equal to unity.

5. Coefficient C_V, which takes into account the ratio of the specific energy of the flow in the upstream pool to the water level in it E/h, depends only on the ratio of the width of the gorge of the Venturi flume to the width of the upstream channel b/B and is determined by Eq. (8), but does not depend on parameter $C_D{\cdot}b/B$, as stated in Standard MI 2406-97. The coefficient varies from $C_V \to 1$ at $b/B \to 0$ to $C_V = 1.5^{1.5}$ at $b/B = 1$.

6. It was established that, using the Russian State Standard MI 2406-97, the calculation of the full-capacity discharge of the classical Venturi channel water gauge always give the understated values of the design discharge relative to the values of the discharge which in fact passed through the channel. The systematic error of calculations in accordance with State Standard MI 2406-97 is more than –2 %.

7. As a result of the research, the method of hydraulic calculation of the classical Venturi channel was obtained that meets the to-date requirements of engineering practice. This method is based on theoretical formula (10) for calculating flow coefficient m. Formula (10) is free from empirical coefficients. It is established that the flow coefficient of the classical Venturi channel varies from $m \to 0$ at $b/B \to 0$ to $m = 0.5^{0.5}$ at $b/B = 1$.

8. When specifying and revising the State Standard MI 2406-97, it is recommended to include in the new edition the theoretical method of hydraulic calculation of the flow rate of the classical Venturi channel water gauge based on Eqs. (9) and (10), taking the relative error of the theoretical method equal to ±1 %.

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