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Original Research

Analysis of Hydraulic Parameters of Conical Vortex Regulators

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Abstract

On the basis of current knowledge covering a wide range of vortex devices, the methodology of model tests was developed (in pilot-plant scale) for liquid flow in vortex regulators. Our paper presents selected investigation results related to the influence of such dimensionless geometric parameters as d_{out}/d_{in}, h_c/d_{in}, D/d_{in}, R_o/d_{in}, cos θ, and constant K, as well as spray cone angle (γ) on liquid flow throttling effect for regulators with conical vortex chamber shape. Developed empirical formulae allow for a rational selection of geometrical parameters (or a resistance coefficient) for such regulators for applications in environmental engineering, which was demonstrated in the example.

Keywords: hydraulics, flow throttling, model testing, liquid flow, conical regulator

Introduction

Flow regulators are commonly used in environmental protection engineering for flow rate control. Traditional throttling devices such as orifices, reducers, or gate valves allow for a relatively simple regulation of flow rate at the expense of a pipe cross-section reduction, on which they are mounted. As a result, a regulator active cross-section may cause its clogging, especially in the case of polluted liquids. In addition, moving mechanical parts may lower the operational reliability of such devices. Hydrodynamic regulators with vortex liquid flow are devoid of such defects [1].

The prototype of vortex devices was the so-called throttled check valve patented by Thoma [2] in 1928, also known in literature as a vortex diode. The device construction became the subject of investigations in the Ph.D. theses of Heim [3] and Zobel [4]. Their papers were intended to optimize construction parameters of the device to achieve the highest value of the throttled flow (vortex) to free-flow resistance ratio.

When the device performs only a throttling action, it is called a flow regulator or a vortex valve [5] in literature. The first vortex regulators have cylindrical chambers. Regulators with conical vortex chambers [6] were introduced toward the end of 1970s. Such regulators are characterized by a lower hydraulic resistance (higher flow capacity) at free-flow in comparison to cylindrical regulators. Hydrodynamic regulators of conical vortex chambers are the subject of the paper, because they are the least known and most seldom used [7]. Despite a considerable number of papers [8-11] – mainly in the field of fluidics - literature offers few vortex regulators, including conical ones (investigations used in environmental engineering for throttling liquid flows). Furthermore, the device itself is still treated as the so-called "black box." Thus far, analytical descriptions of vortex regulator operations break down to Torricelli's formula, in which the discharge coefficient is determined empirically and individually for each regulator [6, 12, 13]. There is a lack of overt hydraulic characteristics specifying the quantitative and qualitative relation of geometric and operational parameters with the throttling effect of the device, measured with such parameters as loss coefficient (ζ) or discharge coefficient (μ). This makes it

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impossible to assess the operational reliability of such devices, especially of large dimensions.

The hydraulic performance of conical vortex regulators is marked by a hysteresis occurring in the initial range of their operation (at a low total pressure loss ΔH), where the characteristics for increasing pressure at the outflow does not coincide with the characteristics for decreasing pressure, which influences their scope of application [1].

Objective, Scope and Methodology of Investigations

In a conical vortex chamber (Fig. 1), a liquid flows to the device through an inlet (1), located in a larger base of the cone, and hence, it receives a vortex flow that is maintained throughout the entire chamber length (2), all the way to an outlet (3) in the narrow end of the truncated cone. In the resulting flow, peripheral speed is increased when approaching the cylinder axis. Because of the centrifugal force in the vortex chamber, the pressure decreases toward its axis until it reaches an ambient pressure on the air core surface (4). The air core being generated has a crucial influence on the throttling efficiency of the device. The cone axis is most often tilted from the horizontal by an angle such that one of the cone elements is horizontal to obtain self-drainage of the device. The sprayed liquid in the outflow of the regulator creates a cone with the angle of flare γ.

This paper tackles model testing of conical vortex regulators in a pilot-plant scale aimed at determining the influence of geometric and operational parameters on throttling efficiency. From the investigations, empirical formulae were developed in which the discharge coefficient is dependent on device construction dimensions, as well as spray cone angle (γ), allowing rational designing and application of the devices. Such investigations have been rare in literature.

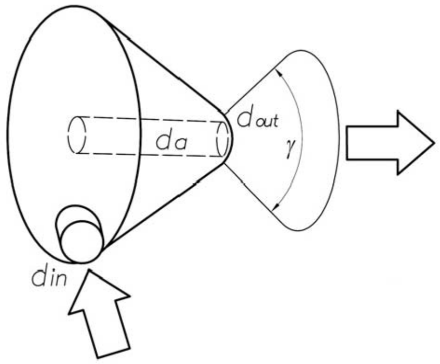

Fig. 1. A conical vortex valve.

The total head loss ΔH in a conical flow regulator (Fig. 2) depends on the following dimensional variables: liquid density (ρ), dynamic viscosity of water (μ_w), gravitational acceleration (g), and volume flow rate (q_V). The geometrical parameters were: vortex chamber radius at the cone base ($R=D/2$), swirl radius at the inlet ($R_o=R-r_{in}$), inlet radius (r_{in}) located at the angle (θ) in relation to the cone base plane, outlet radius (r_{out}), vortex chamber height (h_c), outlet hole edge thickness (s), and regulator wall roughness (k). From the dimensional analysis, the head loss formula was determined to be in the form of:

$$\Delta H = \zeta \frac{q_V^2}{2gA_{in}^2} \tag{1}$$

...where: ζ – minor loss coefficient (hydraulic resistance) of the device, being a function of the following dimensionless similarity numbers and parameters:

$$\zeta = \zeta\left(Re, Fr, \frac{R}{r_{in}}, \frac{R_o}{r_{in}} \frac{r_{out}}{r_{in}}, \frac{h_c}{r_{in}}, \frac{s}{r_{in}}, \frac{k}{r_{in}}\right) \tag{2}$$

Re – Reynolds number: $Re = 2\rho q_V/\pi\mu_w r_{in}$
Fr – Froude number: $Fr = q_V^2/2g\pi^2 r_{in}^5$

Hence in relation to $1/\sqrt{\zeta} = \mu$:

$$q_V = \mu A_{in}\sqrt{2g\Delta H} \tag{3}$$

Notation (3) is defined in literature as Torricelli's formula, in which μ is the flow coefficient – a function similar to form (2). Such an approach to the problem is commonly used for a quantitative description of vortex regulator operation. Coefficient value μ, computed from formula (3), is mainly used for comparing flow-throttling effects with classic throttling devices [6].

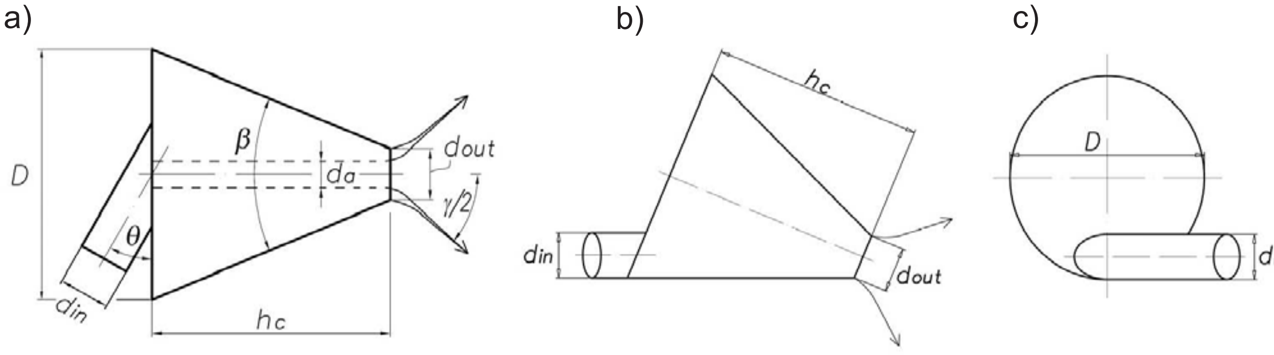

Fig. 2. Conical vortex valve: a) top view b) end view c) front view.

A discrete change of an inlet entry angle to a regulator in the range of $\theta = 30^{\circ}$; 45º, and 60º results in the reduction of angular momentum at the regulator inlet by the value of function cosθ. In addition, accounting for the fact that momentum at swirl radius R_o on the regulator inlet produces a vortex flow in which a dominant peripheral speed depends on an inlet area (r_{in}^2) while a centrifugal force in an outlet cross-section is inversely proportional to the third power of outlet radius (r_{out}^3), the following combination of power products of linear dimensions was introduced to the function (2):

$$K = \frac{R_o \cos\theta \, r_{in}^2}{r_{out}^3} = \frac{2R_o \cos\theta \, d_{in}^2}{d_{out}^3} \tag{4}$$

...where: K – geometric constant of investigated vortex regulators.

In addition to geometric constant K, a trigonometric function cosθ for inlet entry angle was introduced to the notation (2). Thus, the coefficient μ function (similarly to ζ) assumes a final form of:

$$\mu = \mu\left(Re, Fr, K, \frac{R}{d_{in}}, \frac{R_o}{d_{in}}, \frac{r_{out}}{d_{in}}, \frac{h_c}{d_{in}}, \frac{s}{d_{in}}, \frac{k}{d_{in}}, \cos\theta \right) \tag{5}$$

The importance of influence of particular dimensionless parameters and similar numbers on coefficient μ was investigated empirically.

Investigated regulator models were assembled from components to obtain a wide range of geometric parameter variations. Particular elements were made from stainless steel. They were connected by means of flange joints sealed with o-rings. The following geometric parameters (Fig. 2) were varied: inlet diameter (d_{in}), outlet diameter (d_{out}), and chamber height (h_c), as well as inlet entry angle (θ) in relation to cone horizontal element. The larger cone diameter of vortex chamber amounted to D=290 mm, while the outlet edge thickness (in the smaller cone base – d_{out}) was s=2 mm. Device models were investigated in the total of 81 measurement runs. The following dimensions and parameters were assumed: vortex chamber height h_c=140, 280, and 420 mm, inlet diameters d_{in}=30, 50, and 80 mm, and angles θ =30, 45, and 60º. At the same time, for each inlet diameter, din outlet diameter was d_{out} = 30, 50, and 80 mm.

The test stand consisted of two basic systems: testing and feeding (Fig. 3). The testing system was made up of: an inflow chamber (1), outflow chamber (2), and a measuring weir (3). The feeding system consisted of: a lower tank (4), circulating pump (5), and upper tank (6) with a surge weir (7). The water inflow to the testing system was controlled by a ball valve (8) located in front of a feeding chamber (9), which was connected to an inflow chamber (1). A telescopic weir (10) with an anti-surge baffle (11) allowed for regulator testing (12) in a dry and wet setup. The stand is shown schematically in Fig. 3.

The triangular measuring weir was calibrated by a volumetric method, while the digital gauge pressure transmitters (14) were calibrated by means of piezometers (13). The spray cone angle (γ) was measured by a photographic method using a digital camera and Autocad 2004 software.

Relative uncertainty of discharge coefficient μ for conical flow regulators are between 0.52% and 7.90%.

Interpretation of Results

The Influence of Reynolds and Froude Numbers on Coefficient μ

Two types of flows can be distinguished in vortex regulators: free-flow (including non-vortex motion as well as pressure flow) and vortex flow. With the increase in Reynolds number, discharge coefficient μ increases to its maximum value when free-flow changes into vortex flow. Because of the discontinuity of regulator hydraulic characteristics, the hysteresis area is limited by two values of Reynolds number – the upper (Re_1) describing a free-to-vortex flow transition for increasing q_V and ΔH, and the

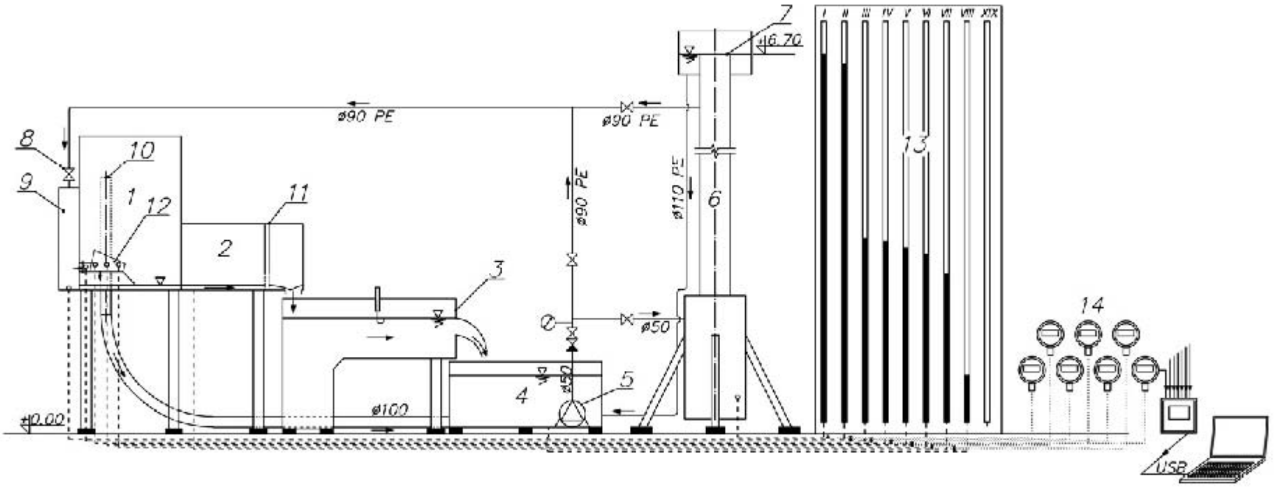

Fig. 3. Scheme of experimental set up (description in text).

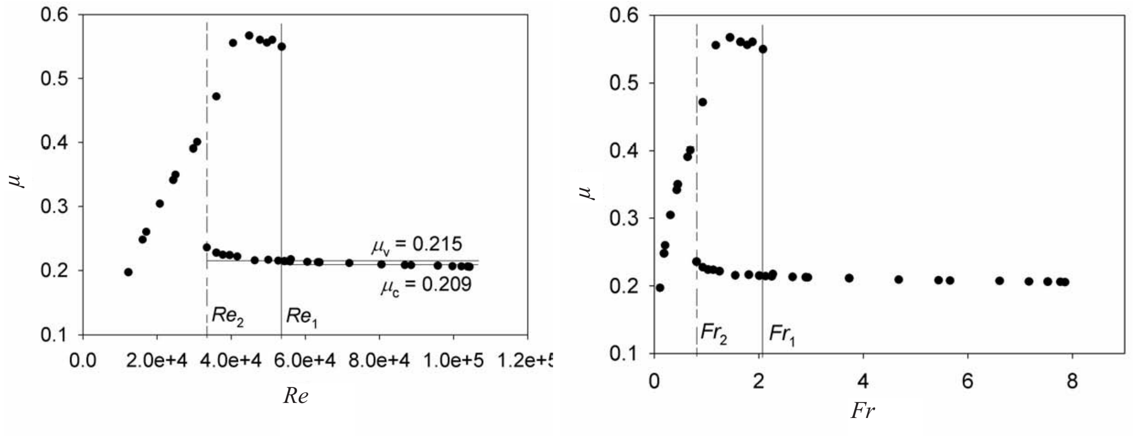

Fig. 4. The dependency of coefficient μ on numbers *Re* and *Fr* for $d_{\text{in}}=d_{\text{out}}=50$ mm, $h_c=280$ mm, and $\theta=30^{\circ}$.

lower (Re_2) separating free and vortex flow zones for decreasing q_V and ΔH. In the area, the single value of Reynolds number (q_V) corresponds to two values of ΔH and μ (in free and vortex flows). A free-flow area was considered irrelevant and thus omitted since the hydrodynamic regulators function with maximum flow throttling efficiency.

The dependency of coefficient μ on numbers *Re* and *Fr* was shown in diagrams (Fig. 4), from which it follows that its value is practically independent of *Re* and *Fr* in a vortex flow for values of $Re > 50{,}000$ and for $Fr > 2$.

In particular, from the dependency analysis of the discharge coefficient on Reynolds number, it appears that its value depends on *Re* to a small extent in the lower range of vortex flow and hysteresis area ($Re_1 \div Re_2$). Because the tests were performed on scaled-down models of real objects, measurement results obtained for high values of $Re > Re_2$, where μ is practically constant, have practical significance for assessing μ value. The mean value of the discharge coefficient computed from the entire vortex flow range (μ_v), that is above the boundary value of number Re_2, was compared to the mean value (μ_c) computed from the range above the boundary value of number Re_1. The mean values differ on average by 1.4%. This allows for μ_c to be accepted for interpretation of the results [14].

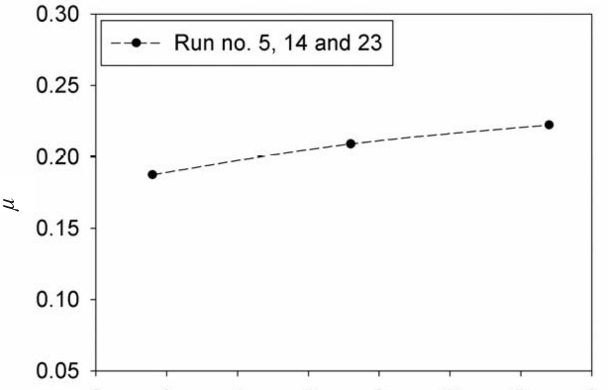

Fig. 5. Dependency of coefficient μ on the relation h_c/d_{in} for $D/d_{\text{in}}=5.8$ at $d_{\text{out}}/d_{\text{in}}=1$ and $\theta=30^{\circ}$.

Influence of Geometric Parameters on Discharge Coefficient

Dimensionless relations ($d_{\text{out}}/d_{\text{in}}$, h_c/d_{in}, D/d_{in}, R_o/d_{in}, K, and $\cos\theta$), were subjected to analysis, eliminating a priori k/d_{in} and s/d_{in} from function (5). In papers of Zobel [4] and Elalfy [15], it was shown that the roughness (k) of vortex regulator walls has an influence on the discharge coefficient. An increase in roughness reduces flow resistance. This is contradictory to the goals put forward for the devices, that is flow resistance maximization. Thus, regulator models were produced in a pilot-plant scale from smooth stainless steel – as in reality. The thickness (s) of the discharge hole edge in the lower base of the truncated cone of all investigated regulator models was 2 mm, which is close to a metal plate thickness in reality. Selected dependencies of function (5) are described and shown below.

Fig. 5 shows the dependency of coefficient μ on the relative vortex chamber height h_c/d_{in} for conical regulators of $h_c=140$, 280, and 420 mm at $d_{\text{in}}=d_{\text{out}}=50$ mm and $\theta=30^{\circ}$ (investigated in runs 5, 14, and 23).

It follows from the diagram that a threefold increase of relative chamber height (h_c/d_{in} from 2.8 to 8.4) produces a percentage increase ranging only from 10% to 20% in the coefficient μ value (from 0.188 to 0.222) with remaining geometric parameters being constant. This means that for increasing vortex chamber height, device hydraulic resistance (ζ) decreases. According to Ebert [16], the influence of the boundary layer on velocity and pressure distribution is significant for small-height vortex chambers when $h_c/R \ll 1$. Due to the throttling effect, it is therefore rational to use the smallest possible conical vortex chamber heights (h_c/d_{in}).

Fig. 6 presents the dependency of the discharge coefficient on the relative swirl radius (R_o/d_{in}). The value of discharge coefficient is reduced with the increase of the R_o/d_{in} value, thus, the hydraulic resistance of the device is also reduced. In the investigated interval of variability R_o/d_{in} included in the range from 1.31 to 4.33, coefficient μ reaches an approximately constant value for $R_o/d_{\text{in}} > 2.5$. It should be concluded that as a result of the R_o increase, and thus diameter D of a vortex chamber (in relation to the inlet diameter d_{in}), the contact surface between swirling liquid and walls is increased and so are flow resistances. Because the momentum increase is compensated for by frictional forces, it is therefore irrational to design such regulators for the relation $R_o/d_{\mathrm{in}} > 2.5$ with $d_{\mathrm{out}}/d_{\mathrm{in}}=1$, thus, respectively, for $D/d_{\mathrm{in}} > 6.0$.

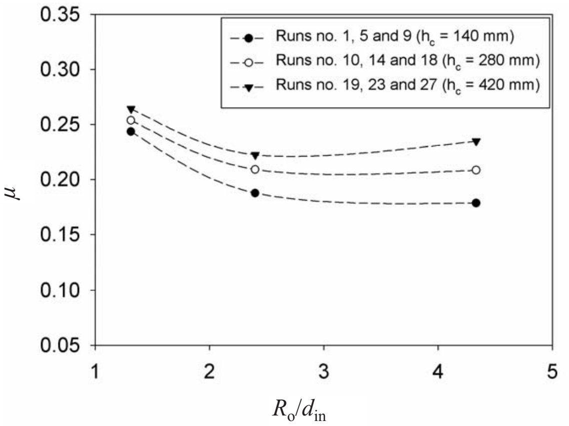

Fig. 6. Dependency of coefficient μ on the relation R_o/d_{in} at variations of h_c for $d_{\mathrm{out}}/d_{\mathrm{in}}=1$ and $\theta=30°$.

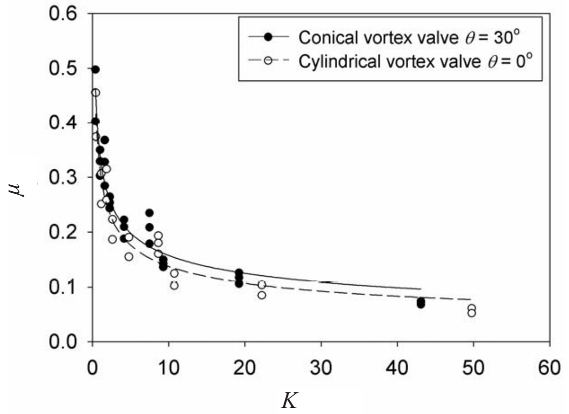

Fig. 7. Dependency of coefficient μ on the constant K for conical regulators ($\theta=30°$) and cylindrical of ($\theta=0°$).

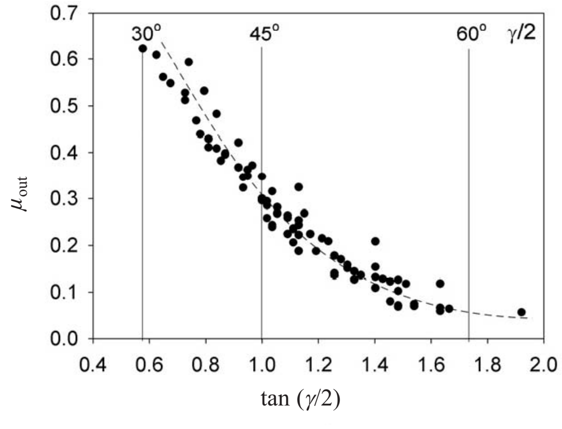

Fig. 8. Dependency of coefficient $\mu_{\mathrm{out}} = \mu\ (d_{\mathrm{in}}/d_{\mathrm{out}})^2$ on tan $\gamma/2$.

The regulator constant K groups geometric parameters of conical vortex regulators such as d_{in}, d_{out}, R_o and θ – formula (5). The dependency of coefficient μ on K is shown in Fig. 7.

It follows from the dependency graph that with increasing K value, μ decreases. Thus, the hydraulic resistance (ζ) generated by the regulator is increased (the highest hydraulic resistance occurs for the lowest value of angle $\theta=30°$). For a specific value of K, three values of μ correspond to cone chamber height variations $h_c=140$, 280, and 420 mm with $\theta=30°$. In other words, with the increase of h_c, the value of μ is increased for a given value of K. The diagram also contains authors' investigation results [7] of cylindrical vortex regulators for $\theta=0°$. Then $\cos\theta=1$ in formula (4) – which emphasizes the universal form of the regulator constant K.

Dependency of Coefficient μ on Spray Cone Angle

It should be noted that in a vortex flow, liquid leaves a device through a discharge ring with an effective jet area A_e, smaller than an outlet hole area A_{out} (of the diameter d_{out}) due to an air core of diameter d_a (Figs. 1 and 2). Furthermore, jets are deflected from the cone axis by the spray cone angle $\gamma/2$, which has not been accounted for in descriptions of vortex regulator operation so far. Therefore, it appears purposeful to account for angle γ in the analysis of its influence on μ (for technical reasons, the air core diameter (d_a) could not have been measured in models produced entirely from steel).

The function of the spray cone angle was defined by the formula: $\tan \gamma/2 = z/(x - r_{\mathrm{out}})$, where z and x are jet coordinates (Fig. 2). The influence of the spray angle ($\gamma/2$) on the discharge coefficient – related to the outlet diameter for all 81 conical regulator models in question: $\mu_{\mathrm{out}}=\mu(d_{\mathrm{in}}/d_{\mathrm{out}})^2$ – is shown in Fig. 8.

From investigations into regulators of a cylindrical shape of a vortex chamber [14], it follows that with an increase in both the relation d_a/d_{out}, and function $\tan \gamma/2$, the coefficient value $\mu_{\mathrm{out}}=\mu(d_{\mathrm{in}}/d_{\mathrm{out}})^2$ is reduced. The increase of relative air core diameter (d_a/d_{out}) is accompanied by a decrease of δ outlet hole liquid filling and an increase of spray angle value ($\gamma/2$). This results in an increase in regulator flow capacity as measured by coefficient $\mu(d_{\mathrm{in}})$. An increase in regulator flow capacity leads to a decrease in device hydraulic resistance (ζ). This can be explained by the fact that liquid momentum (in the outlet hole plane) on the increasing arm (thus, angular momentum) with d_a/d_{out} forces a larger liquid discharge from the hole, and the centrifugal force increases the spray cone angle γ value.

Empirical Equation

It follows from the analysis of graphically presented dependencies of coefficient μ on particular dimensionless parameters *(*$d_{\mathrm{out}}/d_{\mathrm{in}}$, h_c/d_{in}, D/d_{in}, R_o/d_{in}, angle θ*,* and constant K) that the parameters can be approximated by means of a power function ($y=a_0x^{a1}$) or a linear function ($y=a+bx$). To generalize investigation results, a complex model was assumed to describe the dependency of the discharge coefficient on dimensionless similarity numbers. The highest consistency of measurement results and calculations was obtained for a combination of linear dependency of μ on parameters d_{out}/d_{in} and h_c/d_{in} and, alternatively, D/d_{in} and R_o/d_{in}, and a power dependency on the constant K and function $\cos\theta$. Vortex regulator constant K increases quantitative accuracy of the phenomenon description.

For practical purposes, the formula describing operations of 27 regulator models – for angle θ=30°, that is, at which the highest hydraulic resistance is obtained, was determined as a result of a multiple regression by least squares method:

$$\mu = 0.0052\frac{d_{out}}{d_{in}} + 0.0032\frac{h_c}{d_{in}} + 0.0067\frac{d}{d_{in}} + \\ +0.410K^{-0.25} - 0.0021\tan\left(\frac{\gamma}{2}\right)^{3.75} - 0.141 \tag{6}$$

...at $R^2 = 0.998$ and RMSPE = 3.98%. The spray cone angle for formula (6) is derived from the following empirical formula:

$$\tan\frac{\gamma}{2} = 2.41K^{1.72}\left(\cos\theta\right)^{-2.40}\left(\frac{d_{out}}{d_{in}}\right)^{5.50}\left(\frac{h_c}{d_{in}}\right)^{-0.106}\left(\frac{D}{d_{in}}\right)^{-1.88} \tag{7}$$

...at $R^2 = 0.947$ and RMSPE= 5.23%.

Discharge coefficient μ values obtained for investigated vortex regulators ranged from 0.068 to 0.497. This corresponds to loss coefficient (ζ) values from 216 to 4, respectively. The derived relations are valid for the following dimensionless ranges of similar numbers related to the experiment in question: $0.375 \le d_{out}/d_{in} \le 2.67$; $1.75 \le h_c/d_{in} \le 14.0$; $3.63 \le D/d_{in} \le 9.67$; $0.229 \le K \le 43.1$; $1.31 \le R_o/d_{in} \le 4.33$; $0.50 \le \cos\theta \le 0.87$ ($30^\circ \le \theta \le 60^\circ$); and $0.58 \le \tan\gamma/2 \le 1.92$, while maintaining the Froude similarity criteria: $2 \le Fr \le 97.36$.

An Example of Formulae Applications

A regulator is designed for throttling sewage discharge from a storage reservoir; design geometric dimensions of cylindrical vortex regulators for volume flow rate q_V=0.07 m³/s at the total pressure loss ΔH=2.5 mH$_2$O. The inlet diameter (d_{in}) should be determined from Froude criteria – maintaining a fully developed vortex flow in the regulator: $Fr \ge 2$ (at which a constant value of the coefficient μ occurs) that is, from the relation:

$$d_{in} \le \sqrt[5]{8q_V^2 / \pi^2 g}$$

Thus, for volume flow rate q_V=0.07 m³/s, the following is yielded:

$$d_{in} \le \left[8\cdot 0.070^2 / \left(3.14^2\cdot 9.81\right)\right]^{0.2} = 0.210\ \mathrm{m}$$

Inlet diameter d_{in}=0.20 m (Fr = 2.53) is assumed.

Formulae (6) and (7) were used in computations of discharge coefficient (μ). The required value of the discharge coefficient was computed for the assumed parameters q_V and ΔH, and inlet diameter d_{in}, (after transformation (3) in relation to μ):

$$\mu = \frac{4\cdot 0.07}{\pi\cdot 0.20^2\sqrt{2\cdot 9.81\cdot 2.5}} = 0.318$$

It was assumed from the investigations that, due to throttling, the construction of cylindrical regulators should contain minimum values of the relation: h_c/d_{in}=1.8 and D/d_{in}=6 for angle θ=30°, satisfying the condition of free ball passage in relation to diameters $d_{out}/d_{in} \in$ <1; 2>. The design parameter computations were carried by an iteration method discretely changing its geometrical parameters (d_{out}/d_{in}), until the required value of consistency μ with the computed one $\mu_{(i)}$, was yielded with sufficient accuracy: $(\mu-\mu_{(i)})/\mu = \pm 1\%$.

In the first iteration, $d_{out}=d_{in}$=0.20 m was pre-assumed and an operational parameter $\tan\gamma/2$ was calculated from formula (7) for h_c=1.8·0.2=0.36 m and D=6·0.2 =1.2 m with R_o=0.5 m and K=4.33:

$$\tan\frac{\gamma}{2} = 2.41\cdot 4.33^{1.72}0.866^{-2.40}\left(\frac{0.200}{0.200}\right)^{5.50}\left(\frac{0.360}{0.200}\right)^{-0.106}\left(\frac{1.20}{0.200}\right)^{-1.88} = 1.370$$

Subsequently, the discharge coefficient was computed from formula (6):

$$\mu_{(I)} = 0.0052\frac{0.200}{0.200} + 0.0032\frac{0.360}{0.200} + 0.0067\frac{1.20}{0.200} + \\ + 0.410\cdot 4.33^{-0.25} - 0.0021\cdot 1.370^{3.75} - 0.141 = 0.173$$

Because value $\mu_{(I)}$ from the first iteration is significantly different from the required (μ=0.318), a higher value of d_{out}=0.360 m was assumed in the second iteration. Also, new values of $\tan\gamma/2$=1.673 and $\mu_{(II)}$=0.296 were computed for new K=0.743. The relative deviation of computed coefficient value $\mu_{(II)}$=0.296 from the required μ=0.318 in the iteration amounted to δ=7.1% >1%. In the third iteration, the outflow hole diameter was increased to d_{out}=0.395 m (d_{out}/d_{in}=1.975) and operational parameters $\tan\gamma/2$=1.727 and $\mu_{(III)}$=0.318 were computed (hence the computed relative error μ already amounts to -0.1% < 1%). The real flow capacity of the regulator for total pressure loss ΔH=2.5 mH$_2$O will amount to q_V=0.0703 m³/s.

Fig. 9 presents hydraulic characteristics of an example series of type of conical vortex valve sizes with the specification of range of their application – for established design parameters h_c/d_{in}=1.8 and D/d_{in}=6 at θ=30° – helpful in the selection of inlet connector and discharge hole diameters (d_{in}/d_{out}=0.75÷2).

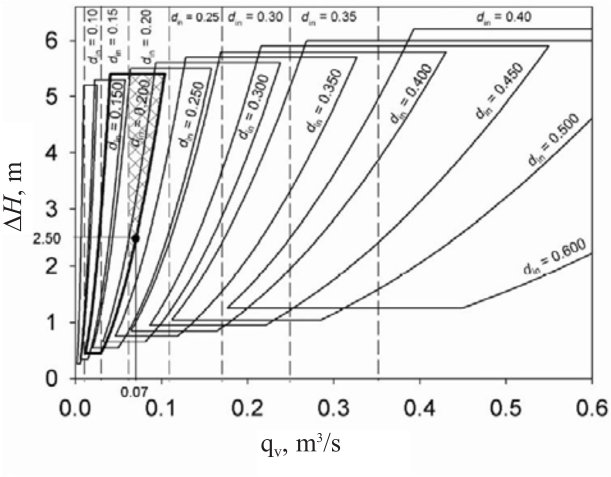

Fig. 9. The nomogram of hydraulic characteristics of the conical vortex regulators for the selection of diameter relation d_{in}/d_{out} with $h_c/d_{in} = 1.8$, $D/d_{in} = 6$ and $\theta = 30^o$.

Conclusions

This paper presents methodology and selected laboratory model results of the influence of geometric parameters (d_{out}/d_{in}, h_c/d_{in}, D/d_{in}, $R_o/d_{in}\cos\theta$, and constant K) as well as the spray cone angle (γ) of regulators of conical vortex chamber on liquid throttling effects. The following conclusions were drawn from the investigation:

1. Two types of flows can be distinguished in conical vortex regulators: vortex and free-flow. On the boundary of the two flows (in the hysteresis area), discharge coefficient (μ) assumes two values: maximum in free-flow and minimum in vortex flow. The vortex flow has a practical significance for the description of a device-throttling operation. In a vortex flow, coefficient μ reaches a constant value approximately above the boundary value of Froude and Reynolds number beyond the hysteresis area of regulator hydraulic performance.
2. In vortex flow, the discharge coefficient is increased when relative inlet diameter (d_{out}/d_{in}), relative vortex chamber height (h_c/d_{in}), and inlet entry angle (θ) are all increased. On the other hand, the increase in the relative vortex chamber diameter (D/d_{in}) and relative swirl radius (R_o/d_{in}) result in the reduction of value μ. The discharge coefficient value for $R_o/d_{in}>2.5$ (then $D/d_{in}>6.0$) is approximately constant. The regulator constant (K) describes the total influence of dimensionless parameters (d_{out}/d_{in}, R_o/d_{in} and $\cos\theta$) on coefficient μ, increasing the accuracy of the quantitative description of device operation. With an increase in K value, coefficient μ decreases.
3. Due to the maximization of the liquid flow throttling effect ($Fr \geq 2$), a small conical vortex chamber height is preferable ($h_c/d_{in} < 3$), for relation $D/d_{in} < 6$ and angle $\theta \leq 30^o$. This is necessitated by the condition of "a free ball passage" and diameter relations $d_{out} \geq d_{in}$.

Empirical formulae established in this paper permit us to assess the influence of construction parameters of conical hydrodynamic regulators on the flow coefficient, and therefore allow for their optimal selection in specific practical applications – especially in environmental engineering.

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Units and Nomenclature

A_{in}	inlet area, m²
A_{out}	outlet area, m²
D	diameter of larger cone base of vortex chamber, m
d_{in}	inlet diameter, m
d_{out}	outlet diameter equal to smaller truncated cone base, m
Fr	Froude number
g	gravitational acceleration , m/s²
ΔH	total head loss, m
h_c	height (axial length) of vortex chamber, m
K	vortex regulator geometrical constant
q_V	volume flow rate, m³/s
Re	Reynolds number
R_o	swirl radius, m
γ	spray cone angle, o
ζ	loss coefficient
θ	inlet entry angle in relation to a horizontal element of a cone, o
μ	discharge coefficient

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