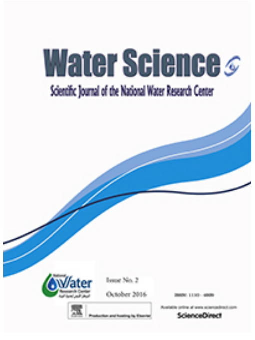


Water Science

ISSN: (Print) 2357-0008 (Online) Journal homepage: https://www.tandfonline.com/loi/twas20

# Free-surface elevation in open vortex flow controls

Szymon Mielczarek & Jerzy M. Sawicki

Water Science
ScienceDirect
Water Science 30 (2016) 76–83
journal homepage: www.elsevier.com/locate/wsj

# Free-surface elevation in open vortex flow controls

Szymon Mielczarek*, Jerzy M. Sawicki

*Faculty of Civil and Environmental Engineering, Gdansk University of Technology, ul. Gabriela Narutowicza 11/12, 80-233 Gdansk, Poland*

Received 26 May 2016; accepted 19 September 2016
Available online 19 November 2016

**Abstract**

Among many practical applications in hydraulic engineering, rotational separators of a suspension and vortex flow controls may serve as especially interesting examples. This form of motion, despite some evident regularity, is a complex phenomenon so to describe it one should make use of CFD tools or pursue an experimental approach to the subject. Both of these possibilities are not very convenient, so any rational method that provides a possibility for calculating the velocity field and pressure distribution is welcome. For the considered class of technical objects, the family of kinematic models is to the purpose. The velocity field is described in this case by some algebraic relations, assumed arbitrarily on the basis of a qualitative evaluation of this field and the model constant is calculated from a delivered and dissipated energy in the energy balance. This method was effectively used in the description of rotational separators and pressure flow controls operation. This paper presents an application of such an approach to open flow regulators.


*Keywords:* Rotational flow; Vortex valve; Flow control

## 1. Introduction

Rotational motion of a fluid has interesting conceptual aspects and, at the same time, is very important from a practical point of view. In the technical objects this kind of flow is often induced by the specific location of the transit conduits. Namely, the inlet is placed tangentially to the chamber wall, whereas the outlet is situated centrally (Fig. 1a).

The swirl of the device content generates some important effects, among which the most important are the following:

- centrifugal force;
- improvement of the velocity field uniformity;
- an increase in pressure from the chamber axis toward the wall.

* Corresponding author.
*E-mail address:* szymon.mielczarek@op.pl (S. Mielczarek).
Peer review under responsibility of National Water Research Center.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.wsj.2016.09.001

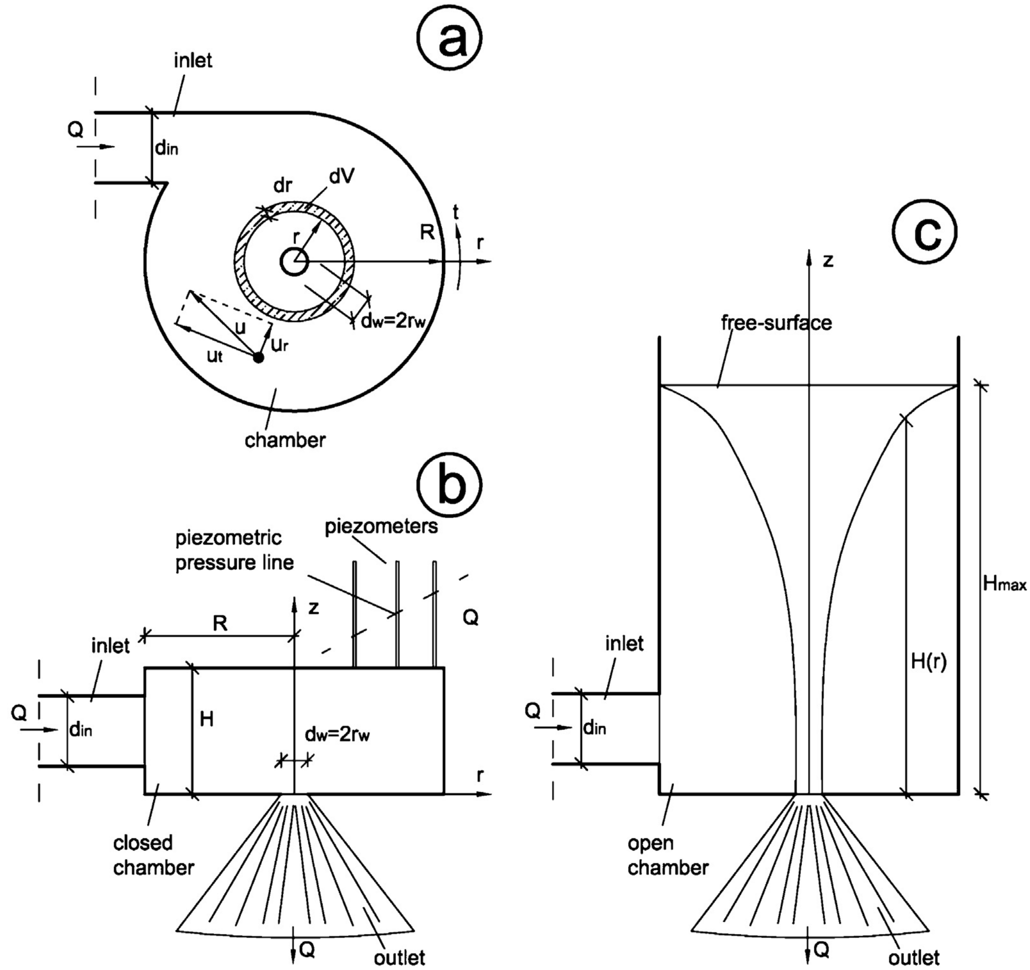


Fig. 1. Hydraulics schemes of vortex flow controls (a – top view, b – vertical section of pressure version; basic case $H$ = const., c – vertical section of open version).

Each effect finds a practical application. The first one advantageously influences the gravitational separation of a suspension, as the centrifugal force drives the particles back to the wall, or (at least) slows down their advective motion, which have been put to good use in centrifuges, cyclones and rotational separators (Gronowska-Szneler and Sawicki, 2014).

As an example of an application for the second effect one can consider the aerated grit chamber (Sawicki, 2004). In this kind of device the transversal circulation superimposes together with the longitudinal flow, which enables proper regulation of object exploitation (i.e. more intensive circulation during low advective portion and vice versa).

The third effect mentioned above constitutes the essence of vortex flow controls, which can function in two general categories for these appliances:

- vortex valves (when the circumferential pressure growth increases the hydraulic resistance in the feeding conduit, which causes a decrease of flow discharge);
- vortex dividers (when this pressure growth is transformed into the water free-surface rise; if the water level exceeds some critical value, determined by the ordinate of the side overflow edge, some part of the main stream is directed into a separated conduit and the system works like a storm weir).

One has to add that the classification presented above has a rather conceptual character. In practice these individual functions can be combined together, as it was done for instance in Storm King (Andoh and Saul, 2003).

Vortex flow controls can be constructed in two main variants–as closed regulators, which work under pressure (Fig. 1b) and as open regulators, operating with a water free-surface (Fig. 1c).

These specific kinds of devices can be used in different hydraulic systems. A full presentation of possible solutions would be very extensive. What is more, many new concepts will surely appear in the future, so only some basic technical schemes are shown in this paper (Fig. 2).

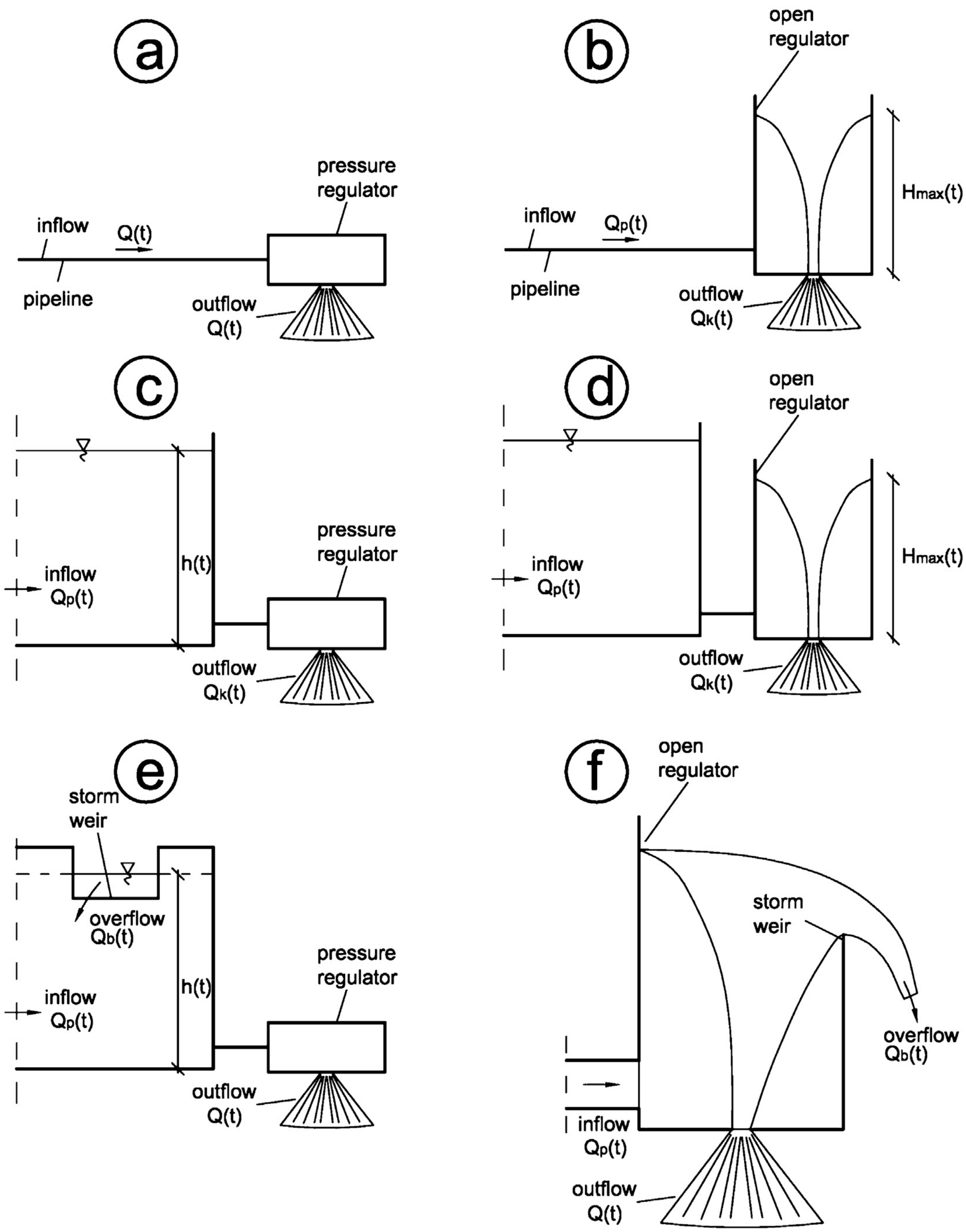


Fig. 2. Basic hydraulic systems with vortex flow regulators: pipeline with pressure regulator (a) or with open regulator (b), storage reservoir or open channel with pressure regulator (c) or with open regulator (d), storage reservoir or open channel with storm weir and pressure regulator (e), open regulator with storm weir (f).

The general idea of the swirl devices operation sounds simple however from the physical, and especially the hydraulic, points of view, it is quite complex. As a matter of fact, only centrifuges are described by the formally simple relations, which give acceptable conformity between theoretical predictions and technological observations. As a consequence the literature on the problem presents two main kinds of approach toward the description of the operation of vortex separators and regulators. Namely, on the one hand specialists apply methods of computational fluid dynamics (CFD), which are practically reduced to the commercial software, e.g. (Dyakowski et al., 1999; Martignoni et al., 2007), and on the second hand an empirical approach, e.g. (Kotowski and Wojtowicz, 2010). One way or the other, specialists feel the lack of some mediate methods, which would be mathematically simple and have proper physical and technical precision, which would enable execution of rough calculations (e.g. before the full application of the developed CFD methods), and could also serve as a convenient tool in the everyday technical activity.

A proposal for such a rational method for the description of open vortex flow controls is presented in this paper.

## 2. Material and methods

### 2.1. General approach to the methodology

Among simplified methods for describing fluid-flow systems a very important role is played by a family of kinematic models (Sawicki, 1989). These models comprise relations describing the velocity field in each individual case, which are matched on the basis of qualitative estimation of the flow character (e.g. with measurements or an intuitively sketched course of streamlines).

When the flow field is determined with acceptable accuracy (and fulfills the equation of continuity), the pressure distribution can be calculated from the equation of momentum conservation (or from the Bernoulli theorem in some cases). As a classic example of this group of models one can consider the plane potential flow (Landau and Lifshitz, 1987) or the screw fluid motion (Sawicki, 2004).

Within the category of flows considered in this paper, such a kinematic model was successfully developed for the rotational separators (Gronowska-Szneler and Sawicki, 2014) and for the pressure vortex flow controls (Mielczarek and Sawicki, 2015). The following mathematical expressions, describing the velocity vector components ($u_r$ – in radial direction, $u_t$ – in tangential direction, $u_z$ – in vertical direction) can be accepted in this case (Rhodes, 2008; Stairmand, 1951):

$$u_r(r) = \frac{Q}{2\pi r H},\ u_t(r) = B\,r^{-0.5},\ u_z(r) = 0 \tag{1}$$

where $r$ is the radius, $Q$ is the discharge of fluid, and $H$ is the local depth of fluid. The model constant $B$ was determined from the physically and technically obvious statement, that the rotational motion is maintained owing to the tangential position to the wall of the inlet stream. Hence the power of the supplying stream $P_{in}$ is equal to the power of dissipation during the rotational motion $P_{dis}$:

$$P_{in} = P_{dis} \tag{2}$$

The first value can be calculated from the simple relation:

$$P_{in} = \frac{8\varrho Q^3}{\pi^2 d_{in}^4} \tag{3}$$

where $\varrho$ is the fluid density and $d_{in}$ is the inlet diameter, whereas the power of dissipation can be expressed by the following integral:

$$P_{dis} = \int \mu_T \omega^2 \, dV \tag{4}$$

where $\mu_T$ is the dynamic coefficient of turbulent viscosity, $\omega$ is the rotation of flow and $V$ is the volume of a chamber. Velocity rotation, according to the mathematical definition (Serrin, 1959) takes a very simple form in this case:

$$\omega = \frac{\partial u_t}{\partial r} + \frac{u_t}{r} = \frac{B}{2r^{1.5}} \tag{5}$$

The momentum conservation equation, which describes the pressure distribution, also has a simple shape (Slattery, 1999):

$$\frac{\partial p}{\partial r} = \frac{\varrho u_t^2}{2} \tag{6}$$

so can be easily integrated analytically, yielding (with the obvious boundary condition, expressing free outflow of fluid through the bottom orifice: $p = p_{atm}$ for $r = r_w$ – Fig. 1):

$$p(r) = p_{atm} + \varrho B^2 (r_w^{-1} - r^{-1}) \tag{7}$$

During the free-surface flow, when the moving fluid volume maintains a cylindrical shape, the two-dimensional model of flow is acceptable (Fig. 1) and one can assume a hydrostatic distribution of pressure along the vertical direction $0z$. As a consequence, the free-surface shape in the chamber can be described by the following function:

$$H(r) = \frac{p(r) - p_{atm}}{\varrho g} = \frac{B^2 (r_w^{-1} - r^{-1})}{g} \tag{8}$$

The above expressions have been well confirmed empirically for the rotational separators and pressure flow controls, which made it possible to derive some simple and convenient relations that describe the operation of these devices (Gronowska-Szneler and Sawicki, 2014; Mielczarek and Sawicki, 2015).

### 2.2. *The case of open vortex flow control*

The character of motion in two objects, referred in Section 2.1 allows for acceptance of the plane model of flow (Eq. (1)) and in consequence – acceptance of Eqs. (6)–(8). Relatively cylindrical shapes of rotating liquid volumes are formed in these cases by the existence of the central outlet pipe (rotational separator) or owing to the upper cover closing the chamber (the pressure vortex flow regulator).

Another situation arises for the vortex regulator (Fig. 1c). The chamber is opened from above, which enables the water free-surface to rise. This rise increases together with the discharge of the feeding stream. As an effect, the shape of the whirling liquid deviates from the idealized form, which was an acceptable condition in the previous case.

This statement essentially complicates the feasibility of a description of the work of the open vortex regulator by means of the model, which was put to a good use for both of the remaining devices belonging to the same category. However, in an intuitive handling of a subject, it seems, that one can accept that the position of water free-surface in the open regulator (Fig. 1c), by some degree, is equivalent to the course of the piezometric pressure line in the closed unit (Fig. 1b). Hence, there arises a conclusion that it is purposeful to make use of Eq. (8) also in the considered case. This hypothesis will be verified on the basis of measurements of the water elevation, described in Section 3. Certainly, one can turn down this possibility at the very beginning of the discussion. However it would mean the rejection of what is quite an interesting concept, viz. a derivation of a mathematically simple relation, which can at least serve as a method of estimation for characteristics of the considered device.

### 2.3. *Determination of the free-surface shape*

In order to apply the procedure presented in Section 2.1, the coefficient of turbulent viscosity has to be determined. For the considered case, to obtain an analytical solution of the problem, it is very convenient (and physically justified) to choose an algebraic relation (Launder and Spalding, 1972), in which the characteristic velocity $v_c$ is equal to the shear velocity and the characteristic scale of turbulence, $L_c$, is expressed by some fraction of the distance from the outer wall, $(R - r)$. The final relation has the following form in this case (where $\lambda$ is the Nikuradse coefficient of flow resistance):

$$\mu_T = 0.0168\, \varrho v_c\, L_c = 0.0168\, \varrho \left(\frac{\lambda}{8}\right)^{0.5} u_t (R - r) \tag{9}$$

Elementary volume $dV$ in Eq. (4) equals (Fig. 1a):

$$dV = 2\pi r\, H(r)\, dr \tag{10}$$

Substituting these relations and Eq. (5) into Eq. (4), and after some formal calculations (that take into account the evident proportion $r_w \ll R$) one obtains:

$$P_{\text{dis}} = \frac{0.0081\,\pi\,\varrho\,\lambda^{0.5}RB^5}{g\,r_w^{2.5}} \tag{11}$$

which according to Eqs. (2) and (3) yields:

$$B = \frac{3.17g^{0.2}r_w^{0.5}Q^{0.6}}{d_{\text{in}}^{0.8}\lambda^{0.1}R^{0.2}} \tag{12}$$

Making use of Eq. (8) we obtain the following expression, which describes the shape of water free-surface in open vortex flow control:

$$H(r) = \frac{10.05\,Q^{1.2}(1 - r_w/r)}{g^{0.6}\,d_{\text{in}}^{1.6}\lambda^{0.2}R^{0.4}} \tag{13}$$

### 2.4. Laboratory verification of Eq. (13)

To verify the hypothesis presented in Section 2.2, according to which the elevation of the water free-surface in the open flow regulator can be described using the same approach as used for the closed unit (Mielczarek and Sawicki, 2015), some measurements in a hydraulic laboratory were carried out.

The investigated regulators were made of polyvinyl chloride (PVC), according to the sketch shown in Fig. 1a and c. The total number of the tested units was equal to 16, which was the number of combinations of their basic dimensions (for $R = 116$ mm), according to the following juxtaposition:

$r_w$: 15.5 mm – 30.0 mm – 45.5 mm – 60.5 mm
$d_{in}$: 25.0 mm – 40.0 mm – 50.0 mm – 60.0 mm

During these measurements regulators were supplied by running water from the hydraulic laboratory closed circuit. Each cycle of investigations consisted of two basic steps, namely:

- fixing and measurement (by means of a water meter) of water discharge $Q$;
- a measurement of the maximal distance of stabilized water free-surface from the chamber bottom ($H_{max}$), by means of the standard needle level gauge.

Each unit was investigated for seven different intensities of water flow (in the scope $Q = 0.4$–$1.2$ dm$^3$/s for smaller units and for $Q = 1.0$–$5.0$ dm$^3$/s for bigger ones) – see Figs. 3–5.

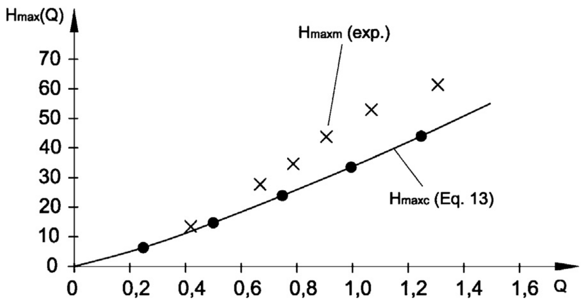


Fig. 3. Comparison of measurements and calculations ($R = 116$ mm, $d_{in} = 50$ mm, $r_w = 15.5$ mm).

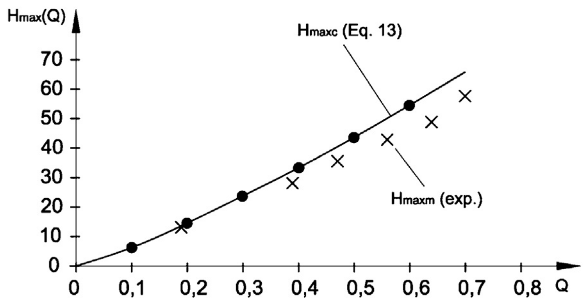


Fig. 4. Comparison of measurements and calculations ($R = 116$ mm, $d_{in} = 25$ mm, $r_w = 15.5$ mm).

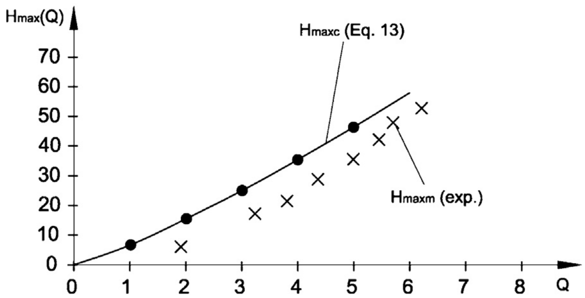


Fig. 5. Comparison of measurements and calculations ($R = 116$ mm, $d_{in} = 60$ mm, $r_w = 60.5$ mm).

## 3. Results and discussion

From the qualitative side, the findings of these investigations have fully confirmed the expected course of the considered process. The volume of water filling the chamber, which was cylindrical at standstill, was dynamically displaced toward the outer wall in each case (and received the shape shown schematically in Fig. 1c). The higher the water discharge $Q$, the more intensive the displacement was. In the central zone of the chamber one could observe a vertical free-surface vortex, reaching to the bottom orifice. Swirling outflowing stream had a very specific shape of an expanded cone, apparently divided (or "sprinkled") into a high number of small individual streamlets. The dynamics of water circulation was so high, that it was practically impossible to carry out measurements with proper precision of the water free-surface in the central region of the chamber. In consequence only one value ($H_{maxm}$) was determined for each variant of investigations.

From the quantitative side, in turn, the conformity of measured values, $H_{maxm}$, with theoretical values of the maximal water depth, $H_{maxc} = H(r = R)$, calculated from Eq. (13), strongly depend on the proportions of the unit's main dimensions: $d_{in}$, $r_w$ and $R$. When the diameters of the inlet and outlet were apparently smaller than the chamber radius, $R$, the conformity was acceptable. Two exemplary diagrams of the function $H_{maxc}(Q)$, according to Eq. (13), in juxtaposition with the set of experimental points of $H_{maxm}$ are shown in Figs. 3 and 4. The value of the Nikuradse coefficient, $\lambda$, was calculated by means of the classical Blasius formula, as the roughness of the investigated material (PVC) was decisively low. The calculations yielded: $\lambda = 0.021$.

Together with an increase of $d_{in}$ and $r_w$ conformity between measurements and calculations definitely worsens. The calculated values of the maximal water depth, $H_{maxc}$, become several times higher than those measured for $H_{maxm}$ (Fig. 5). This effect is logical and consistent with the observed course of the investigated phenomenon. In this case i.e. when the sum: $(r_w + d_{in})$ is closer to the value $R$, the axes of both streams become closer. As a consequence, the distance between the inlet and the outlet is less and the motion shows a tendency to pass from the rotational one to the translator. In the other words, the chamber of the regulator starts working like a deformed elbow connection.

This effect is especially visible for small values of water discharge, $Q$, and although the intensity of the central vortex increases together with $Q$ for this group of units, the swirling volume of water for larger diameters of the bottom orifices takes the shape of a rotating layer. This shape definitely differs from the cylindrical one, so some three-dimensional model of the velocity field would be necessary to describe the flow.

Energy dissipation sources are more complex in this case. The component resulting from the vertical part of motion becomes more important, so only a fraction of the total energy inflow (Eq. (3)) can be used for the maintenance of rotation (Eq. (4)). As a consequence the observed value of $H_{maxm}$ becomes smaller than the theoretical depth (Eq. (13)).

Making use of the theory presented above, it is impossible to define the terminal value of the proportion $(r_w + d_{in})/R$, separating the range of the regulator dimensions which are subject to the proposed model (to some accepted degree, at least), from this range, where the model cannot be accepted. So for analyzing the results of measurements an approximate evaluation was proposed:

$$r_w + d_{in} < 0.5\,R \tag{14}$$

When this condition is fulfilled, the model expressed by Eq. (13) can be applied.

## 4. Summary

When the swirling volume of water keeps a cylindrical shape, at least approximately, a two-dimensional kinematic model of flow can be used to describe the main variables of the operation of vortex devices, like separators and pressure flow controls.

The situation becomes more complex in the case of open flow controls. An intensive free-surface vortex that appears in such an appliance arouses some doubts concerning the feasibility of making use of this simple model.

Nonetheless, a trial of application of such an approach was undertaken and presented in this paper. The final result of this work can be reduced to Eq. (13), which describes the shape of a water free-surface in open vortex flow controls.

Empirical verification of this relation showed that it can be accepted in some range of the main dimensions, according to Eq. (14). Each specialist applying this relation should be aware, that precision is worse than in the case of the pressure flow regulator. However the authors represent an opinion that it is always better to dispose of a simplified tool for a technical application, than to reject simplified relations.

## Conflict of interest statement

The authors declare that there are no conflicts of interest.

## References

Andoh, R.Y., Saul, A.J., 2003. The use of hydrodynamic vortex separators and screening systems to improve water quality. Water Sci. Technol. 47 (4), 175–183.

Dyakowski, T., Nowakowski, A.F., Kraipech, W., Williams, R.A., 1999. A three dimensional simulation of hydrocyclone behaviour. In: Second International Conference on CFD in the Minerals and Process Industries, CSIRO, Melbourne, Australia, pp. 205–210.

Gronowska-Szneler, M.A., Sawicki, J.M., 2014. Simple design criteria and efficiency of hydrodynamic vortex separators. Water Sci. Technol. 70 (3), 457–463.

Kotowski, A., Wojtowicz, P., 2010. Analysis of hydraulic parameters of conical vortex regulators. Pol. J. Environ. Stud. 19 (4), 749–756.

Landau, L.D., Lifshitz, E.M., 1987. Fluid Mechanics. Pergamon, Elmsford.

Launder, B.E., Spalding, D.B., 1972. Lectures in Mathematical Models of Turbulence. Academic Press, London.

Martignoni, W.P., Bernardo, S., Quintani, C.L., 2007. Evaluation of cyclone geometry and its influence on performance parameters by computational fluid dynamics (CFD). Braz. J. Chem. Eng. 24 (1), 83–94.

Mielczarek, S., Sawicki, J.M., 2015. Model of Pressure Distribution in Vortex Flow Controls. Arch. Hydro-Eng. Environ. Mech. 62 (1–2), 41–52.

Rhodes, M.J., 2008. Introduction to Particle Technology. John Wiley and Sons, London.

Sawicki, J.M., 1989. Kinematic models of plane flow. In: Proc. Int. Symp. "Research on Hydraulic Engineering", Zagreb, Croatia, pp. 323–334.

Sawicki, J.M., 2004. Aerated grit chambers hydraulic design equation. J. Environ. Eng. 130 (9), 1050–1058.

Serrin, J.,1959. Mathematical principles of classical fluid mechanics. In: Fluid Dynamics I/Strömungsmechanik I. Springer, Berlin Heidelberg, pp. 125–263.

Slattery, J.C., 1999. Advanced Transport Phenomena. University Press, Cambridge.

Stairmand, C.J., 1951. The design and performance of cyclone separators. Trans. Inst. Chem. Eng. 29, 356–373.