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FLOW PATTERN WITHIN HYDROCYCLONE

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The paper deals with the measurement methods of tangential, radial, axial velocities evolving in hydrocyclone and the characteristics of the velocity distributions defined in the course of the experiments. The definition of the cut-size diameter based on the so-called equilibrium model requires a review according to the authors. In the sense of the model there are only twoo forces acting on a unique particle settling: the centrifugal force and the one, opposite of the motion, resistance strength, and it does not take into consideration, that liquid flows in hydrocyclon. In the hydrocyclone the medium flowing inwards from the tapered cloak wall has a transport velocity and so an effect on the settling onto a particle may not be apart from attention to let. In the hydrocyclone the phenomenon of an air core taking shape in his axis line was explained by means of the basis equations of the hydrostatics till now. The authors demonstrated that the development of the air core is justifiable also with the necessities of the rotating bowls on an actual example.

Keywords: hydrocylone, flow, application, working principle

Introduction

Considering the construction of hydrocyclone it is one of the simplest separation machines working continuously in centrifugal field. A liquid rotation around the axis of the apparatus comes into existence as a result of liquid flow introduced tangentially under a pressure.

Based on the phases to be sparated one may distinguish *liquid-solid* hydrocyclons, where the liquid usually is water, as well as hydrocyclons for separation of liquids consisting of two ones not mingling in each other, e.g. when operation aim is separation of oil with water. In the following we deal with the relations of flow of liquid belonging to the first group. As regards the characteristics of the second group refer to the literature [1, 2].

The first patent announcement concerning hydrocyclone has happened more than 100 years ago /Bretney, 1891/, despite this industrial application of hydrocyclones has really begun only after the Second World War. The first publications in Hungary also appeared at this time, in the field of coal and ore preparation [3-5], as well as in the building material industry [6, 7].

The benefits of hydrocyclones – they do not have moving component, simple structural forming, small place for installation etc. – and their disadvantages – do not give sharp separation, danger of erosion in case of hard grains etc. – practically are the same as it is for gas cyclones [8]. The fact that the the density of the liquid cannot be neglected compared to density of solid material means a considerable difference. In the hydrocyclones the driving force of particle settling is only close to half of the driving force in the gas cyclones.

Mode of operation

Fig. 1 shows a typical cylindrical-conical classifier hydrocyclone.

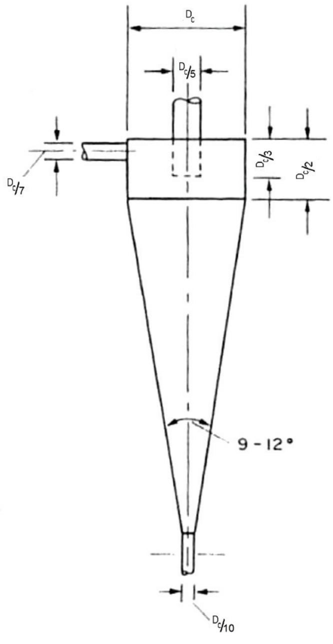

Figure 1: Schematic drawing of a typical cylindrical-conical hydrocyclone

According to the practice for hydrocyclones it is well that other sizes are given with ratio to diameter of the cylindrical shell, D_c. The suspension enters in tangentially on the upper part of the cylindrical cloak and streams curling downwards, overwhelmingly beside the exterior wall of the apparatus. The bigger and/or the heavier particles are concentrated at the wall and then get into the lower outflow in the form of thick slurry. The smaller or easier particles in big dilution are transported upwards by streaming liquid into the upper outflow on the middle of the cyclone through the vortex finder pipe. The flow curling downwards beside the wall changes direction on a certain level of the cone and starts to move upwards with an identical twist. The ratio of the two volume-flows (the leaving one, Q_u, on the bottom, through the so-called apex, and leaving one from above, Q_o) is the Split:

$$S = Q_u / Q_o. \quad (1)$$

If we relate the Q_u to the entry volume-flow, Q_i, we get the ratio of the partial current proportion, R_f, (flow ratio). It is simply justifiable, that

$$R_f = S / (1+S). \quad (2)$$

According to the experience the single part of massflow under the lid of the apparatus on a short road under the vortex finder pipe lower his edge cross – unclassified – leaves through the upper slot. Yeah, the so-called short circuit flow for Q_i value 10–15% may attain it. This loss can be reduced by a constructional road [8], eg. with double introduction, or introductory pipe of evolvens shape. In the same time these solutions reduce the appearance of whirl /Eddy flow/ between the vortex finder and the cylindrical cloak, mainly if the velocity of the entry liquid is equal to the tangential velocity occuring in the cylindrical part, what is the condition of striking-free flow.

Bradley in the monograph about the hydrocyclones [9] suggested the next experimental formula for S value if outflows from the cyclone are free or regulated with choking:

$$S = C(D_u / D_o)^x Q_i^{-y}, \quad (3)$$

where $C \approx 5$, if the measure for Q_i is Imp.gal/min; x is between 1.75 and 4.4, while y changes between 0.75 and 0.44. The smaller exponents are recommended for hydrocyclones with small diameter, while the bigger ones concern evidently the cyclones of bigger diameter.

The usual parameters for the operation are the following: $D_c = 0.01–2.5$ m, the limit cut-size $d_h = 5–300$ µm, $Q_i = 0.1–340$ m^3/h and the solid material concentration at feeding is $c_i = 10–60\%$. At the top overflow the concentration is 5–30%, while at the bottom outflow it is 50–70%.

Bigger volume flows – similarly to the gas cyclone – could be achieved by several units put together paralelly, called multi-cyclones. Simultaneously only one of the compositions for the top or lower outflow – fitted to the operation purpose with the right value of S – is designable. The prescribed composition for both outlet could only be achieved by units connected in series.

The peculiarity of a function in hydrocyclones – which is not properly cleared up until now – is the phenomenon of the air core taking shape in the axis line of the cyclone. In the hydrocyclone an air core arises, if even the top or the lower outflow is in contact with the atmosphere. Since near the axis the flow velocity of the liquid rotating in the cyclone attains a value to which – in the sense of the hydrostatics equations – belongs a pressure decrease already yielding vacuum. The measure of the vacuum may expand from some kPa to 10–20 kPa, according to literature [10]. However air core may occur in locked systems, joining into tanks, and in this case the air core is filled with steam released from the liquid or gas. We yet return to this debatable question later ones.

The diameter of the air core along the full height of the hydrocyclone, on an irregular manner, is constant, its value is (0.06–0.33) D_c. The bigger value belongs to the bigger rotation velocities. It may occur if the diameter of the air core is big that it covers the lower outflow slot. In this case the lower outflow may cease. This state is actually observable in case of clear water flow, but rarely with suspensions, because the settling particles accumulate on the bottom of the cone and decrease the velocity of the rotating motion. To smaller rotating motion on the other hand belongs an air core with smaller diameter, which does not cover the lower outlet slot.

Examination of flow-pattern

It is clear from the previously ourlined description of the function manner that the flow-pattern of the simple structured classifier hydrocyclone and running simply is complicated.

The hydrodynamic complexity increases, because 3D whirlpool motion evolving in the hydrocyclone /both in the free vortec and the forced one, as well as below cap of the hydrocyclone resultant of the feeding /eddy flow/ is not izotrop, it is not completely axially - symmetric, even though, because of the recessionary motion of the air core forming it changes even in the time. In case of bigger solid concentrations the conditions of free settling are not fulfilled. In such a case the characteristics of the granular bulks, e.g. the free voidage factor must be considered in the calculation. The interactive effect of particles settling down onto the motion of the liquid also put questions to be cleared up.

In the latter years increasingly more scientists undertook [11-15] onto the modeling of the sketched complex current picture and his theoretical treatment, consequently of the development in Computational Fluid Dynamics (CFD). When doing numerical treatment of the turbulent flows, however, the validation of the applied models is always necessary. To this modern measurement technique is need which is used for the systematic and carefully carried out experiments.

Since the starting works of Kelsall [16] and Rietema [17] even recently most of the publications [18-20] deal with the clarification of a complex picture took shape in the hydrocyclone. The lectures of international conferences about hydrocyclone and organised four yearly since 1984 confirm also the previous statement [10, 21]. It could be made clear from the publications until now, that for the measurement of flow situations in the hydrocyclones the application of indirect methods which do not disturb the flow is preferable. Such a technique is for eaxample photography of motion /cinematography/ where the isokineticallly injected coloured liquid or the very fine and light particles moving together with the liquid as trace materials can be detected by a microscope with rotating objective /Kelsall, 1952/ or by cinematography of big velocity /Knowles, 1973/. With the development of the electronics and computer science (for example picture recogniser programs) the laser methods are spreading. Here can be listed LDA /Laser Doppler Anemometer/ [22], LDV /Laser Doppler Velocimeter/ [19] with the two beams or the PDPA /Phase Doppler Particle Analyser/ applied also in the Research Institute of Technical Chemistry (MÜKKI), Veszprém, by which the velocity distribution of a secunder flow was possible to check in a twisted static mixer element [23]. The velocity measurement method based on the demonstration of the flow, PIV (Particle Image Velocimetry) [24] is a quickly developing one. The PIV method applied for velocity distribution in plane beside the research work on the Department of Fluid Mechanics at Technical University of Budapest serves also the practical training of students [25].

The microholographie is also a multy way applicable method. The combination of He–Ne laser beam of continuous radius used in the holographic laboratory of MÜKKI and the Q-switch rubin laser with its holograms of short flash of nanosecond order in magnitude the movement of the traced particles in 3D are measurable. It is promissing although costly the newly developed tomography method: EIT (Electrical Impedance Tomography) as well as ERT (Electrical Resistance Tomography) [26, 27]. Williams [28] examined the dynamics of the motion of the air core with ERT technique.

At the given experiments in hydrocyclones water, or transparent liquid streamed. The suspensions optically are not transparent, so there is not yet a measurement technique uniformly accepted for examination of the flow velocity distribution of suspensions containing particles. Only qualitative statement can be made about the fact that the presence of the particles decreases the velocities in clean water.

Velocity distribution in hydrocyclone

Gusztáv Tarján in a coursebook [5] written together with Gábor Fejes summarized his own results and the ones of researchers known until that time. He presented the velocity of medium introduced tangentially into the hydrocyclone by three components shown on *Fig. 2*.

The figure on the left shows the change of tangential velocity through the longitudinal section of the hydrocyclone, the middle one concerns the axial velocity and the figure on the right is for the change of the radial velocity. It is clear from the length segments that the places of isotangential velocities are coaxial cylinder surfaces, the place of isoaxial velocities are close to coaxial conical surfaces with an identical apex, while the places of isoradial velocities in the conical space part are roughly conical surfaces with a common vortex angle. In both latter cases the velocity distributions of the cylindrical space parts were influenced by whirling (eddy flow) caused by the feeding on a manner shown on the figure.

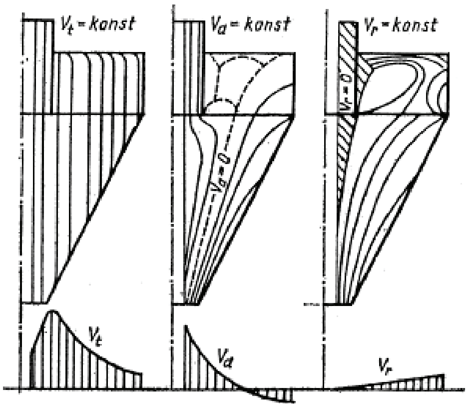

Figure 2: Velocity distributions in hydrocyclone

On the middle figure the dashed line marks the $v_a = 0$ dots (loci of zero vertical velocity). On the right from this line the direction of the axial velocity is downwards while on the section close to the axis it is directed upwards.

On the dashed line the forces acting on the settling particles are in a dynamic equilibrium. More authors, e.g. Kelsall [16], Bradley [9] or Tarján [5] based on this phenomenon the so-called equilibrium model which makes possible to define the cut size diameter. We shall return yet onto the assessment of this model.

None of the distribution curves along the radius starts from $r = 0$ which can be seen below on Fig. 2 because of the air core. The velocities along the radius was first determined by Kelsall [16] (see *Fig. 3*).

On the figure we have shown distributions of the velocities (tangential v_t; axial v_a and radial v_r) converted them into metric measurement system. We note that the author was able to measure only the v_t and v_a velocities with the help of a microscope supplied with rotating objectives, the v_r values were defined by calculation with respect of the continuity equation. The diameter of the experimental hydrocyclone was 75 mm and its cone angle was 20°. The vortex finder with length of 100 mm /on the figure indicated with hatching/ reached the conic part of the cyclone. The author wished to insure with this non usual solution the stability of the flow and its symmetry around the axis. For the greatness of the single velocities the scales give guidance. It is seen that v_r is much smaller than v_t or v_a.

According to Fig. 3 the tangential velocity increased from the wall of the cone towards the axis, then reaching the maximum, it steeply decreased. The maximum values with a good approach fall on a line of $r = 5$ mm = constant. We note that the diameter of vortex finder, D_o was 12.7 mm, while the diameter of the air core was 5 mm.

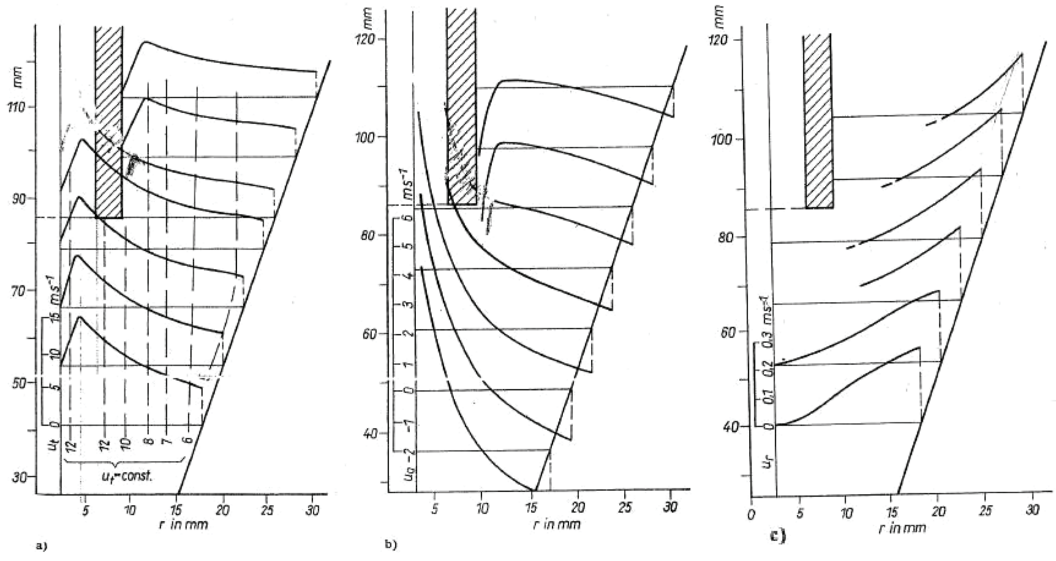

Figure 3: Velocity distributions according to Kelsall
a) v_t – tangential, b) v_a – axial, c) v_r – radial velocity distributions

The left part of *Fig. 4* shows the change of the tangential velocity on a log-log diagram

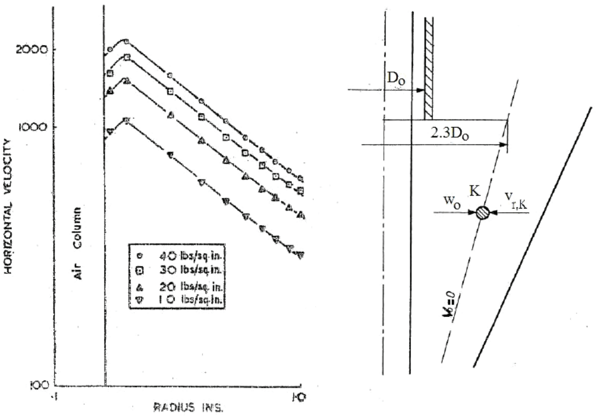

Figure 4: The diagram of the tangential velocity (log-log plot) and schematic drawing explaining the equilibrium

The changing parameter was the pressure of the feeding. The breakpoint of the lines corresponds to the maximum value of the v_t. On the left from the breakpoint in the expression $v_t r^n$ = constant which desribes the line for the exponent $n = -1$ is good approximation, that is $v_t = r\omega$, where ω is the steady rotational angular velocity. This expression is equal to the equation characterise the rotation of the rigid bodies with a constant revolution. Kelsall called this section forced vortex.

For the exponent of $v_t r^n$ = constant valid for the longer line being on the right from the breakpoint on the basis of measurements offered $n = 0.77$, that is $v_t r^{0.77}$ = constant. In the sense of Fig. 2 the tangential velocity, v_t is only function of the radius, the liquid parts may only rotate around an axis perpendicular onto the plane, in our case around the axis of hydrocyclone.

The velocity of a potential whirl can be described by the equation of $v = K / r$ [25], that is, the velocity distribution of $v_t r^{0.77}$ = constant forming in the hydrocyclone, can be well approached by one of the potential whirl, similarly to dust-precipitator gas cyclones. By that way the free vortex term suggested by Kelsall for this current flow pattern in hydrocyclone indicates a potential whirl as regards the flow dynamics.

Based on relevant publications of hydrocyclones it can be said about the change of exponent n the following: n increases when D_c, D_o, or D_i, as well as the cone angle, θ of the hydrocyclone increases. The interval of the change is from 0.4 to 0.9 otherwise. The value of n was $n \approx +1$ only when the hydrocyclone was without cone, it consisted of only cylindric part [9].

The knowledge of the tangential velocity is important for designing of hydrocyclone including the definition of the cut-size, d_p as well as the size taken as separation average size.

Kelsall, according to the right sketch of Fig. 4, indicated the intersection of the line described by relation $v_a = 0$ and the plane belonging to the the lower edge of of the vortex finder at $2.3D_o$. The radial velocity at point K on the surface of the cone defined by the basic plane with diameter of $2.3D_o$ and the $v_{ax} = 0$ dots and generatrix L is given by

$$v_{rK} = \frac{Q_o}{2.3\,D_o L\pi/2}. \tag{4}$$

Taking into consideration the value of S according to expression $Q_o = Q_i / (S+1)$ instead of Q_o in Eq.4. Q_i can be written.

The researchers using the equilibrium model assume that in the point K one can write the following:

$$v_{rK} = w_o. \tag{5}$$

If the Stokes-law for settling is valid, the settling velocity of the particle is

$$w_o = \frac{d_p^2\,(\rho_S - \rho_L)}{18\mu}\,\frac{v_{tK}^2}{r_K}, \tag{6}$$

where v_{tK} is the tangential velocity belonging to point K.

If $v_{rK} = w_o$, then the particle of size d_p is orbitting on a circles of radius r_K. If $v_{rK} > w_o$, then the circling particle moves away into the direction of the axis, while if $v_{rK} < w_o$, then the particle moves towards the wall of the cone. The validity of Stokes law exists when $Re \leq 1$. In clear water ($\nu = 0.01$ cm^2/s) and in case of $Re = 1$ to radial velocities of 5, 10 and 20 cm/s, the d_p values belong of 20, 10 and 5 μm. The d_h, the value of a separation average size is understood as the average of d_p values got by different K points on $v_a = 0$ line.

The length L, with a good approach is $L = D_c / (2tg\Theta)$. After replacing and arrangement we get

$$d_h = \left[\frac{tg\Theta}{D_c \pi / 2} \frac{\mu\beta Q_i}{\rho_S - \rho_L} \right]^{1/2} \frac{6}{v_t^*}. \qquad (7)$$

In the previous expression v_t^* means the average of tangential velocities belonging to the line of v_a=0.

Romankov and Kurocskina in their book [30] published other nine equations for the definition of the d_p cut size particle. All of the authors of the equations started from the equilibrium model outlined previously. The diversity of the equations reflects that a uniform computational method for the definition of dp and d_h did not developed yet. The reason of this is on one hand that the authors deducing the equations started out from different hypotheses.

E.g. the validity of the Stokes law for suspensions was presupposed which is valid only till 2.5 volume percentage of particles. Apart from this at bigger solid concentrations the particles settling to the the wall displace the liquid being there, which is obliged to flow towards the inside of the hydrocyclone. Forming so drag, the free settling velocity, w_0 decreases. Because of this the validity of the Stokes law is debatable. An additional difference follows if the sizes or structural arrangemnet of hydrocyclone are different from Kelsall's one. In that case the so-called diameter of a basis circle may be different from the Kelsall's one, which was 2.3 D_0 for him. The average residential time in hydrocyclones is short, for example the average residential time in a hydrocyclone of diameter of 100 mm with a performance of 8 m^3/h is altogether 0.55 s. For this reason it is uncertain whether the velocity of a given particle in the suspension with size d_p might be able to reache its quilibrium on the line $v_a = 0$ suiting to it. At the same time this is a prerequisite for adaptability of the equilibrium model.

The authors of the present paper on the other hand take the force-balance for settling particle misguided.

According to the authors of the equilibrium model in a coordinate system co-rotating with the liquid there acts only two forces on a particle settling down: the centrifugal force and the drag force, that are in balance at the places of $v_a = 0$, that is they are equal. The authors of the present paper consider this notion a wrong one. This equality is only true for settling happening in a medium of rest. In a streaming medium, so in a hydrocyclone, too, it is necessary to take into consideration transport velocity, $\underline{u}$ of the liquid that, according to Bloor-Ingham [18] actually is commensurable with the movement or drift velocity of the particle. So, fluid-mechanically correctly, beside the centrifugal force and the one of flow resistance it is necessary to take into consideration an other force, namely the force which can be defined by the product of mass of the particle and the acceleration, $d\underline{u}/dt$.

Implicitly so the vectorial equation is:

$$\frac{d_p^3}{6} \rho_S \frac{d\underline{u}}{dt} = \frac{d_p^3}{6} (\rho_S - \rho_L) \frac{v_t^2}{r\underline{r}^0} + 3\mu d_p \underline{w}. \qquad (8)$$

In Eq. (8) $\underline{w} = \underline{v}_r - \underline{u}$ is the relative velocity related to the particle, where $\underline{v}_r$ is the radial velocity of the liquid, $\underline{r}^o$ the radial unit vector. Writing this equation we presupposed that the velocity of the moving particle became steady-state. For hydrocyclones this is generally allowed, because a particle of 100 μm size and of density $\rho_S = 2700$ kg/m^3 in 0.006 s attains the the acceleration-free, steady-stae velocity, the so-called terminal velocity.

In case of known velocity $\underline{v}_t$ and $\underline{v}_r$ the balance equation modified by us is numerically solvable.

We previously showed (see Fig. 4) that the decrease of the tangential velocity in the hydrocyclone near to its axis can be given by expression of $v_t r^{-1}$ = constant. We also referred to that this expression – according to the researchers' uniform opinion – is analogous with $v_t = r\omega$, peripheral speed of rigid bodies circulating with constant angular velocity, ω. Until now, according to the knowledge of the authors of the present paper, nobody in the literature has examined the possibility, that the flow pattern in the hydrocyclone in the environment of its axis, with the air core in it could not be characterised with the flow properties of the rotating bowls?

It is known [25] that in rotating vessels, e.g. in a centrifugal clarifying drum, the surface of the liquid is equipotential surface which is described by a rotatory paraboloid of second degree. As a result of the rotation in the bowl the middle of the originally horizontal surface is sinking down, and at the same time it rises up beside the wall of the vessel. It can be justified on the basis of fluid mechanics, that the largest sinking in the axis line of the paraboloid and the largest rise at the wall of the vessel is equal:

$$\Delta h = R^2\omega^2/4g. \qquad (9)$$

Taking the measurement data of Kelsall as a basis the radius of the rotating vessel is founded bought R=5 mm, what is the radius of hydrocyclone giving the maximum tangential velocities. The maximum tangential velocity is 15 m/s, the angular velocity belonging to this is 3000 s^{-1}. With these data it comes out that $\Delta h = 1.15$ m. The whole height of the experimental hydrocyclone is smaller than 0.3 m, so the peak of the rotatory paraboloid gets under the outlet slot /apex/ of the hydrocyclone. If at the time of starting the water in standstill fills the hydrocyclone, that is in our case the height of the water column is $h \approx 0{,}3$ m, then it can be seen that $h < \Delta h$, but on the other hand, in this case, according to the necessity of the rotating vessels, the liquid layer in the drum of the centrifuges is nearly parallel to the vessels wall. The liquid flowing out from the drum of the centrifugal clarifyer is prevented with flange (rim) arranged above. In the hydrocyclone because of the continuous operation, ring road of thickness Δr is forming and the water circulates in it. Its volume flow is equal to the outflow from the hydrocyclone on the top, Q_o. Inside the ring there is air with an atmospheric pressure. Taking Kelsall measurements as a starting point the thickness of the ring $\Delta r = 3.85$ mm and the diameter of the air column is around 5 mm.

Based on the previous lines we consider possible that in the hydrocyclone for the development of the air core, not exactly cleared up completely, not only the vacuum is responsible, the reason should also be the centrifugation of the fluid as a layer next to the inside wall of the bowl, typically characteristic for rotating vessels! Our opinion is supported by experiments of Smyth and Thew [10], too.

The researchers of Southampton University have tested in a Vortoil-F type hydrocyclone with diameter of 70 mm that what kind of measure expands the carbon dioxide from the liquid saturated with the CO_2 due to the vacuum reigning in the air core, As a surprise it was experienced that negligibly few gas bubbles freed from the saturated liquid, far not so much, than for as much would have been needed due to the pressure decrease to expand. The English researchers tried to explain this unexpected phenomenon by the rotating flow caused over-saturation. In our opinion this explanation is a forced one because of the flow mechanical doctrines concerning equipotential surfaces. Since it is known that in force fields the equipotential surfaces coincide with the surfaces with a constant pressure. It follows from this, that the force fields do not cause pressure increase on their own equipotential surface. If there is no pressure increase, then over-saturation neither may occur.

With the data of the previous example the centrifugal acceleration of rotating liquid mass as rigid body, surrounded the air core, is 4587 times bigger than the gravitational acceleration field, g, belonging to of the Earth, for this reason pressure increase of the inertial force increasing proportionally by the water depth is negligible.

The above described usage of data from Kelsall of 1952 brings up the question how sound they are in the mirror of the newer experiments. Based the velocity distributions measured by modern measurement-techniques and presented on the following figures (see *Figs. 5-8*) it can be stated that in the conical part the distributions of the tangential and axial velocity are of identical character, which means that the use of these data of Kelsall based on the newer experiments can be said legitimate. But, opposite this, the radial velocity distribution defined with calculation of Kelsall is debatable. Only in the lane beside the conical wall can be considered valid the

$$v_r = v_a \,\mathrm{tg}(\Theta/2) \qquad (10)$$

expression.

On Fig. 5, from left to right, data of a tangential velocity distribution are seen from Knowles et al. (1973), Kelsall (1952) and Ohasi and Maeda (1958).

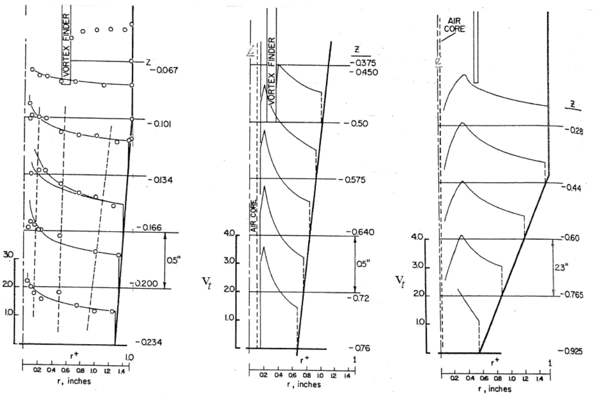

Figure 5: Tangential velocity distributions

In all the three cases the diameters of the hydrocyclones, the quantity of input liquid flow, its velocity and pressure were near identical. There was a slight difference in cone angle, in the manner shown on the figure (11.3°, 20° and 15.2°). Knowles and his colleagues [29] worked with a hydrocyclone of the optimal geometry size assessed by Rietema [17]. In their experiments they injected coloured liquid of density of 0.99327 kg/litres into the water, and they checked the velocity distribution by cinematography with high speed (20000 frame-quarters in a second). Because of their shorter vortex finder they waited for bigger velocity fluctuation as compared to Kelsall's measurements and despite of this the velocity distributions were commensurable.

Compairing the three hydrocyclones the most significant difference appeared in the air core. Ohasi and Maeda were choking the lower outflow beside the free upper outflow, because of this they have got other air-core diameter than Kelsall. Knowles and his colleagues hintered the development of the air core, but despite of this the character of the distributions is similar.

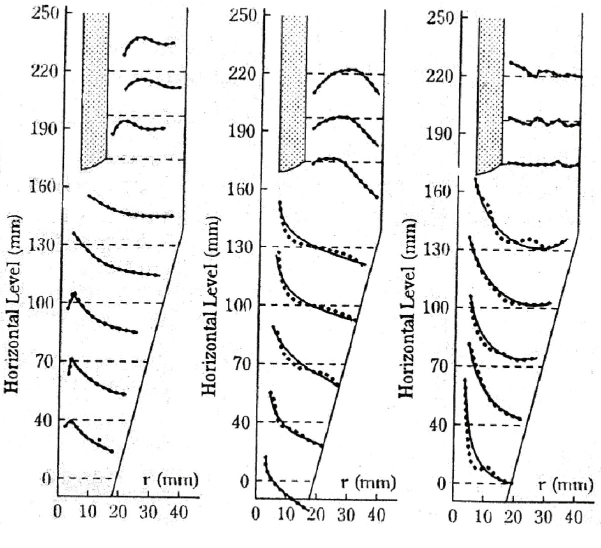

Figure 6: Velocity distributions measured with LDV method

Fig. 6 shows experimental data of Quian et al. from year 1989 [19]. In their experiments the authors used LDV measurement technique. On the figure from left to right we can see velocity distributions for tangential, axial and radial velocities. In the cylindrical section the tangential and radial velocities are small, the axial ones here are around 0.5 m/s. The distributions of the tangential and axial velocity in the cylindrical space part are different of character as compared to distributions in the conical space part because of the effect of the feeding. The tangential velocity in the conical section was describable with expression of $v_t r^n$ = constant, discussed already at Kelsall, although here the v_{tmax} = 4 m/s was smaller in this case. The change in the radial velocity compared to the calculated one of Kelsall shows different character. The velocity of -4 m/s close to the air core seemed particularly big. But on the other hand it counts nearly as a novelty that the authors were able to measure the rotation of the air core with a diameter of 8 mm and it was found 10300 rotations per minute.

Finally, it is worthy to analyse the experiments of Hsieh and Rajamani [11] which used LDV technique, too, from the year of 1991 (see Figs 7 and 8).

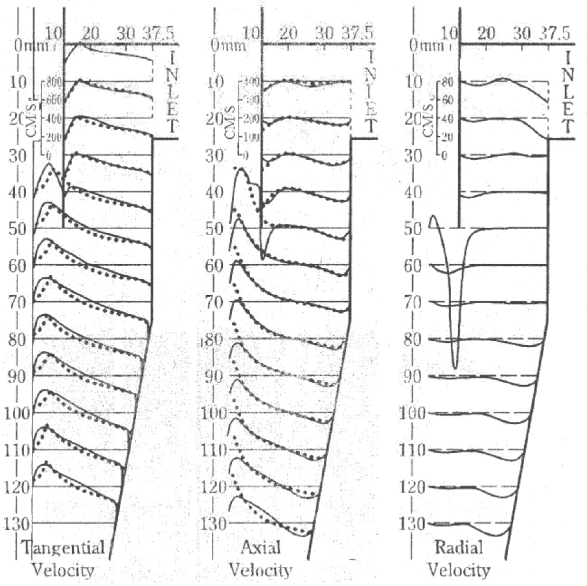

Figure 7: Velocity distributions measured by Hsieh and Rajamani

The authors used silicone carbide particles of 1.5 μm as marked substance. The diameter of the hydrocyclone in this case was 75 mm, the full length was 244 mm and the cone angle 20°. The tangential velocity was 200–800 cm/s, the one of axial 0–400 cm/s, while the radial one changed between values of 0 and 80 cm/s. Because of the fluctuation of the air core the scattering of the tangential velocity was 20–50 cm/s. For this reason the reliability of the measurement of radial velocity values which are similar order in magnitude is questionable. On the figures one can see that the asymmetry appearing in the cylindrical section of the hydrocyclone practically disappeared in the conical section. The distribution of the tangential velocity as regards it tendency is in good agreement of one discussed at Kelsall’ result. The axial velocity changes its direction twice in the cylindrical section, but in the conical part the already discussed traditional distribution is characterictic with thel inear line of $v_a = 0$ dots. The big jump sign in the radial velocity distribution under the vortex finder is unusual.

On Fig. 8 distributions of the tangential velocity can be seen, but the viscosity of the streaming medium was changing on the figure. In case of [a] the steaming medium was clear water, while in case of the [b] it was mixture of water and glycerine, of which the viscosity was 1.4 Pa s. The distribution curves in the two Figure parts are practically identical, so an increase in viscosity indicated above had no effect onto the tangential velocity.

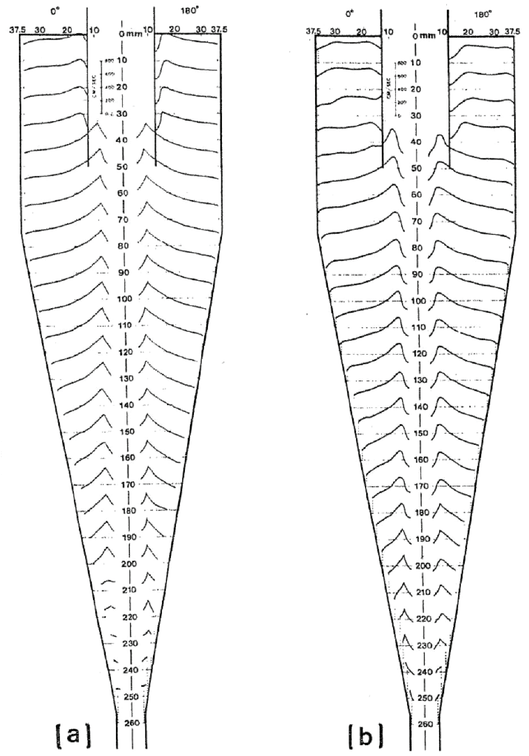

Figure 8: Tangential velocity distribution in case of a fluid with different viscosity

Theoretically it was only to be expected, because neither in the whirl rotating as a rigid body neither in the potential whirl the viscosity does not play a role.

The authors wrote down the balance of forces acting on moving particle in the classifier hydrocyclones, in radial and axial direction. In both cases two forces were taken into consideration, in radial direction the centrifugal force and the drag force being effective against it, while in axial direction the gravity and the resistance force against it.

The balance of radial forces was expressed by the following equation

$$(\rho_S - \rho_m)\frac{v_t^2}{r}\frac{\pi \mathrm{d}_\mathrm{p}^3}{6} = \frac{1}{2}\rho_L v_r^2 \frac{\pi \mathrm{d}_\mathrm{p}^2}{4}\mathrm{C}_\mathrm{D}, \qquad (11)$$

from which the radial velocity of the particle is

$$v_r = \left[\frac{4}{3}\frac{(\rho_S - \rho_m)}{\rho_L}\frac{v_t^2}{r}\frac{\mathrm{d_p}}{\mathrm{C_D}}\right]^{1/2}. \qquad (12)$$

The authors gave the force-balances in axial direction by similar way:

$$(\rho_S - \rho_m) g \frac{\pi \mathrm{d_p^3}}{6} = \frac{1}{2}\rho_L v_a^2 \frac{\pi \mathrm{d_p^2}}{4}\mathrm{C_D}, \qquad (13)$$

from which the axial velocity of the particle is

$$v_a = \left[\frac{4}{3}\frac{(\rho_S - \rho_m)}{\rho_L} g \frac{\mathrm{d_p}}{\mathrm{C_D}}\right]^{1/2}. \qquad (14)$$

In the equations ρ_m is the density of the suspension and $C_D = f(Re)$, the drag coefficient.

Hsieh and Rajamani, similarly to Kelsall – according to our opinion – do unduly not take into consideration the radial as well as axial components of the absolute transport velocity of spirally streaming water in the hydrocyclone

About the velocity distributions given previously the following can be said as a summary:

The distribution of the tangential velocity along radius is of the same character at most of the authors. Near the axis the velocity distribution of the forced vortex can be written as it is for the velocity of the rigid bodies running with constant angular velocity. The maximum tangential velocities can be find in parallel with the axis on the line of r = constant. From this value towards the wall of the hydrocyclone the tangential velocity decreases and as a free vortex with $v_t r^n$ = constant can be well approached by flow pattern of the potential whirl.

The distribution of axial velocities presented here shows already more differences, mainly in the cylindrical space part of the hydrocyclone. In the distributions it is common, that the v_a in the conic part of the hydrocyclone next to the wall points down, though near the axis line points upwards. In the so-called equilibrium models using $v_a = 0$ dots user, in our opinion, when writing up the force balance the transport velocity of the streaming medium was neglected.

The measurement of the radial velocity is the largest difficulty currently. In the direct measurements until now the difference of the values of the v_r is considerable. The validation of numerical flow dynamics /CFD/ calculations being based on different models by measurements can be said uncertain.

We justified with an actual example, that the development of the air core could be explained not only with the arising of vacuum, but also by relationships describing fluid flow in rotating vessels.

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SYMBOLS

c_i	initial particle concentration
d_p	grain size, cut size
d_h	average cut size diameter
g	gravitational acceleration
Δh	change of liquid surface
r	radius of hydrocyclone
$\underline{u}$	velocity of transportation
v_t, v_a, v_r	tangential, axial and radial liquid velocity
w	relative velocity
w_o	settling velocity
C_D	drag coefficient
D_c	the diameter of the hydrocyclone cylindrical part
D_i, D_o, D_u	diameter of input, the upper and lower leading out pipes
L	the length of the surface cone
Q_i, Q_o, Q_u	the volume flow-rate of feeding, upper and lower downstream
R	radius
R_f	flow ratio
Re	Reynolds number
S	volume split
ρ_S, ρ_L, ρ_m	density of particlee, liquid and suspension
μ	dynamic viscosity factor
ν	kinematical viscosity factor
θ	cone angle of the hydrocyclone
ω	angular velocity

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