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Results of Development of the Automated System of Calculation the Coriolis and Boussinesq's Coefficients at the Swirling Flow

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Abstract

The results of the calculation of the Coriolis and the Boussinesq's coefficients for the swirling flow in a parallel flow cyclone which separation camera has a variable cross-section due to the presence of plunger of the central vortex are considered. Calculations are made in the automated system, developed by the authors according to the regression dependencies of the experimental profiles of the full speed vector and angle of its tilt for conical or a profiled inner plunger from the dimensionless radius. Approaches to the description of the motion of a swirling conveying flow based on: the imposition of a flat flow on the potential rotation are considered; the Bernoulli equation and the constant angular momentum along the channel radius; the theory of fluid motion in a centrifugal nozzle; using the equations of continuity, conservation of energy and state with the use of the empirical dependences for viscosity and the differential Navier-Stokes equations for describing the axially symmetric motion of the continuous phase are considered. Their shortcomings are indicated. The Coriolis coefficient takes into account the nonuniformity of the velocity distribution over the cross section of the flow and is equal to the ratio of the actual kinetic energy of the flow passing through the given section of the tester to the kinetic energy calculated from the average speed. The Boussinesq's momentum coefficient is equal to the ratio of the true amount of motion, calculated considering the uneven velocity distribution, to the flow of momentum calculated at the average speed. In the scientific and technical literature, these coefficients are defined only for the translational flows, without imposing rotational, vibrational, vortex and other additional components of motion on them. The results of a numerical calculation of the Coriolis and Boussinesq coefficients for a swirling flow in a direct-flow cyclone, which separation chamber has a variable cross section because of the presence of a central vortex displacer in it, are presented. The calculations were carried out in an automated system developed by the authors in terms of the regression dependences of the experimental profiles of the total velocity vector and its angle of inclination for a conical or profiled internal plunger from a dimensionless radius. It was found that the greater the uneven distribution of the swirling flow velocity is, the more the values of the Coriolis and Boussinesq coefficients will be greater than one. Coriolis and Boussinesq coefficients reach their maximum values in the sections where there is an inverse, counter current flow. For the swirling component of the flow motion with a conical plunger, the Coriolis and Boussinesq coefficients are less than one and do not obey the laws, which are typical for the translational motion. With a profile plunger in the output section of the cyclone, the vortex flow regime is again established and the coefficients are less than unity.

Keywords: automated system, uniflow cyclone, profiled plunger, angle of inclination of the full-velocity vector, field of full, axial and tangential velocity, Coriolis coefficient, Boussinesq coefficient.

INTRODUCTION

Swirling flows are widely used for the intensification of various technological processes (drying, separation, welding and many others). Swirling flows are characterized by large local gradients of both velocities and other parameters, and are accompanied by complex hydrodynamic phenomena that appear, apparently, as a result of the action of various mechanisms. The structures of the flows under consideration are formed mainly by the action of the centrifugal force and the Coriolis effect [1]. However, the study [2] of the influence of the Coriolis force in dust-collecting testers with swirling flows showed that the Coriolis force has no noticeable effect on the velocity of solid particles in the circumferential direction. At the same time, knowledge of some physical processes in turbulent two-phase swirling flows remains still insufficient.

The description of the motion of a swirling conveying flow is based, as a rule, on one of the four different approaches:

1) the flow is represented as a superposition of a flat drain on the potential rotation [3-6]. The calculation method relies on the use of the empirical coefficients and provides the determination of the hydraulic resistance only [3, 7];

2) One can use the Bernoulli equation and the extremal principle for one of the characteristics of the flow, while preserving the angular momentum along the radius of the channel [8, 9], based on the theory of fluid motion in a centrifugal nozzle [8, 9]. The disadvantages of this approach are a rough schematization of the flow and a lack of consideration of the features of motion in the axile zone of the canal [10, 11];

3) One can apply the Bernoulli equation for the motion of liquid in a spiral chamber. This method requires preliminary determination of a number of characteristics that depend on the geometric parameters of the channel, and does not provide for the determination of all velocity components [11]. The drawbacks of these methods considerably narrow the area of their application for the calculation of a swirling flow;

4) The description of the axially symmetric motion of a continuous phase with rotation is based on the use of the differential Navier-Stokes equations, which are simplified depending on the formulation of the problem and the accepted physical flow model, as well as the continuity, energy and state conservation equations using empirical dependences for viscosity [12-29].

DERIVATION OF EQUATIONS FOR CALCULATING THE CORIOLIS AND BOUSSINESQ COEFFICIENTS

It is known that the basic equation of hydraulics since 1740 is the Bernoulli's equation, which is the law of conservation of energy for the liquid. This equation has been successfully applied in a wide range of hydraulic and aerodynamic applications, and in particular, in determining the hydraulic characteristics of various types of technical devices. Bernoulli's equation for incompressible gas is as follows [30, 31]:

$$\rho_g \frac{\alpha_k W_1^2}{2} + P_1 + \rho_g g z_1 = \rho_g \frac{\alpha_k W_2^2}{2} + P_2 + \Delta P,$$

where subscripts 1 and 2 are the cross sections at the entrance to the cyclone and in the exhaust pipe; z – the distance between the sections; ΔP – hydraulic pressure loss (both local and friction) in the cyclone; $P_1 - P_2$ – static pressure drop measured according to the indication of a U-shaped manometer [*m*] and which is equal $\rho g h$, [*Pa*]; ρ – density of water; *W1, W2* – average flow velocity in the annular space at the inlet of a cyclone and an exhaust passage; *ρg* – air density; *αk* – Coriolis coefficient.

Kinetic Bernoulli's equation member comprises Coriolis coefficient which represents the ratio of the flow kinetic energy $E_{ист}$ passing through a given unit's section, with an area F_k to kinetic energy E_{cp} calculated from the average speed in the same section [30]:

$$\alpha_k = \frac{E_{ucm}}{E_{cp}} = \frac{0{,}5\rho_g \int_{F_k} W^3 dF}{0{,}5 m W_{cp}^2} = \frac{\int_{F_k} \overline{W}^3 dF}{F_k},$$

where $m = \rho_g W_{cp} F_k$ – the mass of the gas flowing through the cross section F_k at a time, $\overline{W} = W / W_{cp}$ – relative rate of flow.

Thus, this correction factor accounts for the uneven velocity distribution in the quick flow section. Coriolis coefficient depends on the way the fluid flows. It is 2 for the laminar regime, and 1.13 ... 1.15 [32] for the turbulent regime.

Similarly to the Coriolis coefficient, another coefficient, b_k, is used in the calculations of pump and compressor equipment, which is the ratio of the true number of brush movement, calculated taking into account the uneven distribution of velocities, to the momentum flow K_{cp}, calculated at an average speed of [30]:

$$b_k = \frac{K_{ucm}}{K_{cp}} = \frac{\rho_g \int_{F_k} W^2 dF}{m W_{cp}} = \frac{\int_{F_k} W^2 dF}{W_{cp}^2 F_k} = \frac{\int_{F_k} \overline{W}^2 dF}{F_k}.$$

This coefficient also takes into account the uneven velocity distribution in the quick flow section. It is called the coefficient of momentum or Boussinesq coefficient. There is a relation for symmetrical velocity profiles between the coefficients α_k and b_k:

$$\alpha_k \approx 3b_k - 2,\ \alpha_k \geq 1, b_k \geq 1 \text{ [30, 33]}.$$

In other cases:

$$\alpha_k > \text{ or } \alpha_k < 3b_k - 2$$

Therefore, in general, you should use a more exact correlation [30]:

$$\alpha_k = 3b_k - 2 + \frac{\int_{F_k} \overline{W}^3 dF}{F_k}$$

It should be noted that in the scientific literature these coefficients are defined for translational movements without imposing on them the rotational, vibrational, and other additional vortex motion components. In some applications, these additional components may exceed the principal translational speed several times. Thus, in a parallel flow cyclone with intermediate dust extraction (Fig. 1) the tangential velocity component may exceed the axial component in 2 – 2.5 times [34]. Neglect of this fact leads to significant errors in the assessment of the hydraulic characteristics of flow with superimposed movements.

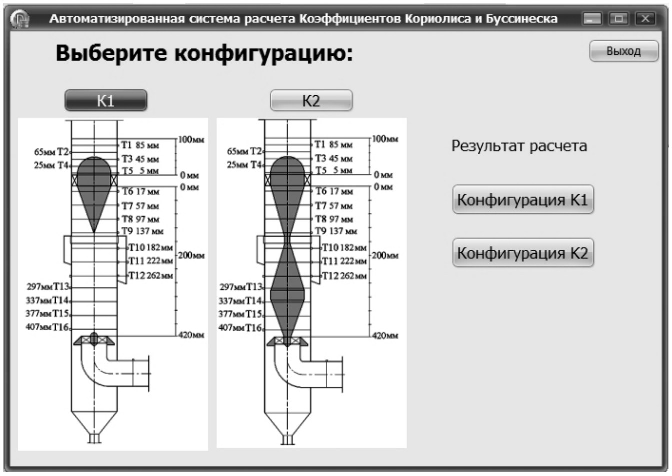

Figure 1. Main screen of the automated system for calculating the Coriolis and Boussinesq's coefficients and measuring points T1-T16 of full speed

We had a problem in determining the correction coeficcients (Coriolis and Boussinesq) attempting to take into account the second component of the velocity when applying rotary motion to linear motion. The logical way out of this situation was the proposal for the three values of each correction coefficient: 1 – the coefficient values for the unevenness of the translational velocity component; 2 – the non-uniformity of the tangential component of the velocity; 3 – unevenness of the full speed (i.e. the vector sum of translational and tangential velocity). As for the forward movement, we can find some ways to average the speed by the quick flow cross section in the scientific literature, in particular, calculating the mean integral value by the cross section value. But averaging the tangential and full speeds was debatable.

During the discussion of the secondary rotation phenomenon an average linear velocity of the rotary motion was proposed, but then has been rejected due to the unphysical description of the tangential velocity in the radial direction. As a parameter of an averaged rotational movement an average angular rotation rate at the solid-state of the conventional averaged flow. Thus, we had to give up on the average speed in the linear dimension in the rotational motion averaging model and proceed to the average speed in the angular dimension. Then, an average speed W_{cp} – a member of the correction coefficients – in case of the rotational movement is no longer a constant but is a function of radius: $W_{\tau cp} = r\omega_{cp} = R\bar{r}\omega_{cp}$, where $\bar{r} = r/R$ – dimensionless radius; – cyclone radius. In this case, the Coriolis and Boussinesq's coefficients are:

$$\alpha_k = \frac{\int\limits_{F_k} \rho_g W^3 dF}{\int\limits_{F_k} \rho_g W_{\tau cp}^3 dF}; \; b_k = \frac{\int\limits_{F_k} \rho_g W^2 dF}{\int\limits_{F_k} \rho_g W_{\tau cp}^2 dF}$$

A prerequisite for the further discussion was a heterogeneity flow pattern during its rotation, since in this case the quasi-solid and quasi-potentional areas of the flow are detected [6, 7]. These flows have qualitatively different tangential velocity gradients which are balanced by the maximum value of the tangential velocity at the boundary of the quasi-solid flow core. An estimation of the average integral over the cross section is debatable for the average tangential velocity. Opposing assessments were:

– average integral radial angular velocity:

$$\omega_{cp} = \frac{\int \omega(r) dr}{\int dr} = \frac{\int \frac{W_\tau(r)}{R\bar{r}} dr}{\int d(R\bar{r})} = \frac{\int \frac{W_\tau(\bar{r})}{\bar{r}} d\bar{r}}{R\int d\bar{r}}$$

– average integral cross-section angular velocity:

$$\omega_{cp} = \frac{\int \omega(r) 2\pi r dr}{\int 2\pi r dr} = \frac{\int \frac{W_\tau(r)}{R\bar{r}} R\bar{r} \cdot d(R\bar{r})}{\int R\bar{r} \cdot d(R\bar{r})} = \frac{\int W_\tau(\bar{r}) d\bar{r}}{R\int \bar{r} d\bar{r}}$$

– average momentum cross-section angular velocity:

$$\omega_{cp} = \frac{\int \omega(r) \cdot m\omega(r) \cdot r dr}{\int m\omega(r) \cdot r dr} = \frac{\int m\omega^2(r) \cdot r dr}{\int m\omega(r) \cdot r dr} =$$

$$\frac{\int m\left[\frac{W_\tau(r)}{R\bar{r}}\right]^2 \cdot R\bar{r} \cdot d(R\bar{r})}{\int m\frac{W_\tau(r)}{R\bar{r}} \cdot R\bar{r} \cdot d(R\bar{r})} = \frac{\int m\frac{W_\tau^2(\bar{r})}{\bar{r}} d\bar{r}}{R\int m W_\tau(\bar{r}) d\bar{r}}$$

– average energetic cross-section angular velocity (on the kinetic energy of the flow):

$$\omega_{cp} = \frac{\int \omega(r) \cdot m\omega^2(r) \cdot 2\pi r dr}{\int m\omega^2(r) \cdot 2\pi r dr} = \frac{\int m\omega^3(r) \cdot r dr}{\int m\omega^2(r) \cdot r dr} =$$

$$\frac{\int m\left[\frac{W_\tau(r)}{R\bar{r}}\right]^3 \cdot R\bar{r} \cdot d(R\bar{r})}{\int m\left[\frac{W_\tau(r)}{R\bar{r}}\right]^2 \cdot R\bar{r} \cdot d(R\bar{r})} = \frac{\int m\frac{W_\tau^3(\bar{r})}{\bar{r}^2} d\bar{r}}{R\int m\frac{W_\tau^2(\bar{r})}{\bar{r}} d\bar{r}}$$

Furthermore, there are essential uneven pressure distribution of the gas flow in rotation, and, consequently, unevenness of density distribution, and eventually, the uneven distribution of mass during the rotation of gaseous bodies. Since the mass-density-pressure of an ideal gas, respectively, are in direct proportion, then $m \sim P(r)$. Then average momentum cross section angular velocity would be equal to:

$$\omega_{cp} = \frac{\int P(\bar{r}) \frac{W_\tau^2(\bar{r})}{\bar{r}} d\bar{r}}{R \int P(\bar{r}) W_\tau(\bar{r}) d\bar{r}}$$, and average energetic:

$$\omega_{cp} = \frac{\int P(\bar{r}) \frac{W_\tau^3(\bar{r})}{\bar{r}^2} d\bar{r}}{R \int P(\bar{r}) \frac{W_\tau^2(\bar{r})}{\bar{r}} d\bar{r}}$$

Average energetic evaluation was dismissed because of the substantial non-potentiality rotational motion. By virtue of the law of conservation of momentum motion while rotating priority is left to the average momentum evaluation.

The structure of the automated system for calculating the Coriolis and Boussinesq coefficients.

The hydrodynamic study of the strait flow cyclone with intermediate dust extraction (Fig. 1) [5-7] have led to the need of determining the Coriolis and Boussinesq's coefficients in a swirling flow in the annular channel of variable section, because according to the available information in the literature there are data about this coefficients only in terms of translational motion [1, 4]. For this purpose we have been previously measured field velocities.

The results obtained in [36] full speed approximations, regression dependence of the angle of inclination γ of the velocity vector of the relative radius published in the work [34], allow us to calculate the Coriolis and Boussinesq's coefficients for swirling flows in the annular channel of variable section. At the same time the axial velocity is defined by $W_z = W \sin\gamma$, and tangential – $W_\tau = W \cos\gamma$, where W – full speed.

The integrals for the true values of kinetic energy and quantity of motion and the average angular velocity, were calculated by approximations [7] by the trapeze. The calculation was carried out for 10 measuring points (T7-T16) along the length of the cyclone separately to full speed, as well as the axial (translational motion) and tangential (rotational movement) components using an automated system, developed by the authors (Fig. 1, [8]) . The structure of the automated system is shown in Fig. 2.

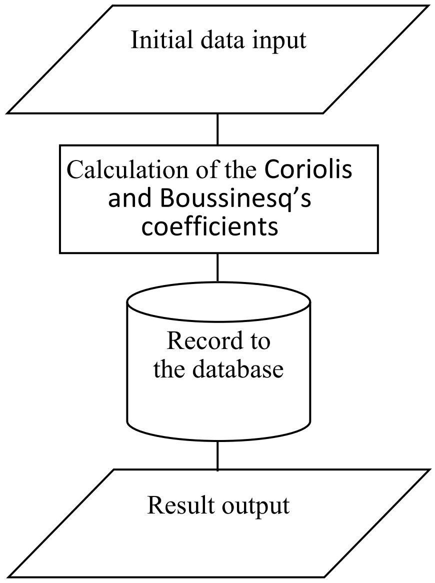

Figure 2. The structure of the automated system

One should fill in the initial data for the calculation of the Coriolis and Boussinesq's coefficients for the K1 configuration using the input form (Fig. 3), available on the button "K1" of the main screen of the automated system. There are the same input of the initial data for the configuration of the cyclone K2.

Results of the numerical investigation for plunger configurations K1 (conical) and K2 (profiled) are presented in Tables 1 and 2, respectively, and Fig. 4. The tables are darkened for clarity of perception of cells in which the Coriolis Boussinesq's coefficients are less than unity.

DISCUSSION OF THE CALCULATION RESULTS FOR THE CORIOLIS AND BOUSSINESQ COEFFICIENTS

Analysis of the data table. 1 and 2 showed that:

1. For the translational component of the swirling flow the same pattern observed for linear flows are performed. The more uneven the distribution rate is, the more value of the Coriolis and Boussinesq's coefficients becomes greater than one, which conforms with the results of I. E. Idelchik and I. R. Shchekin's studies [1, 4]. A maximum value of 3.6 (for K1 see. Table. 1) and 4.4 (for K2, see. Table. 2) for the Coriolis coefficient, and 1.7 (for K1) and 2.1 (for K2) for Boussinesq coefficient is achieved in sections where there is the opposite counter-current flow.

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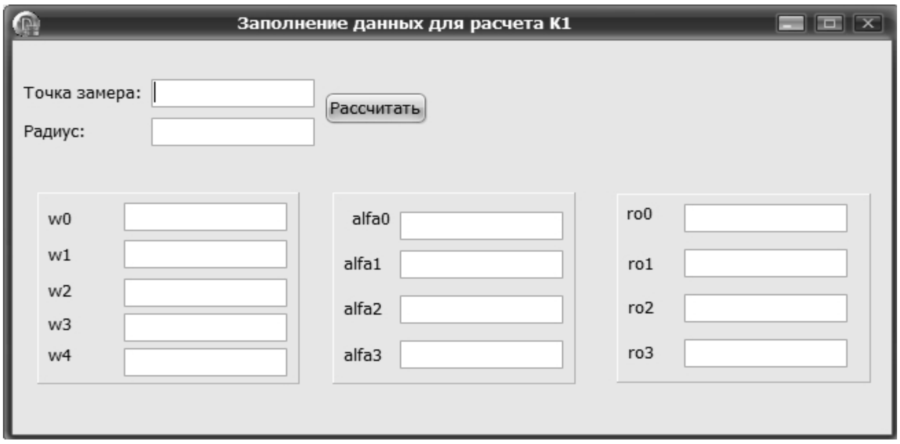
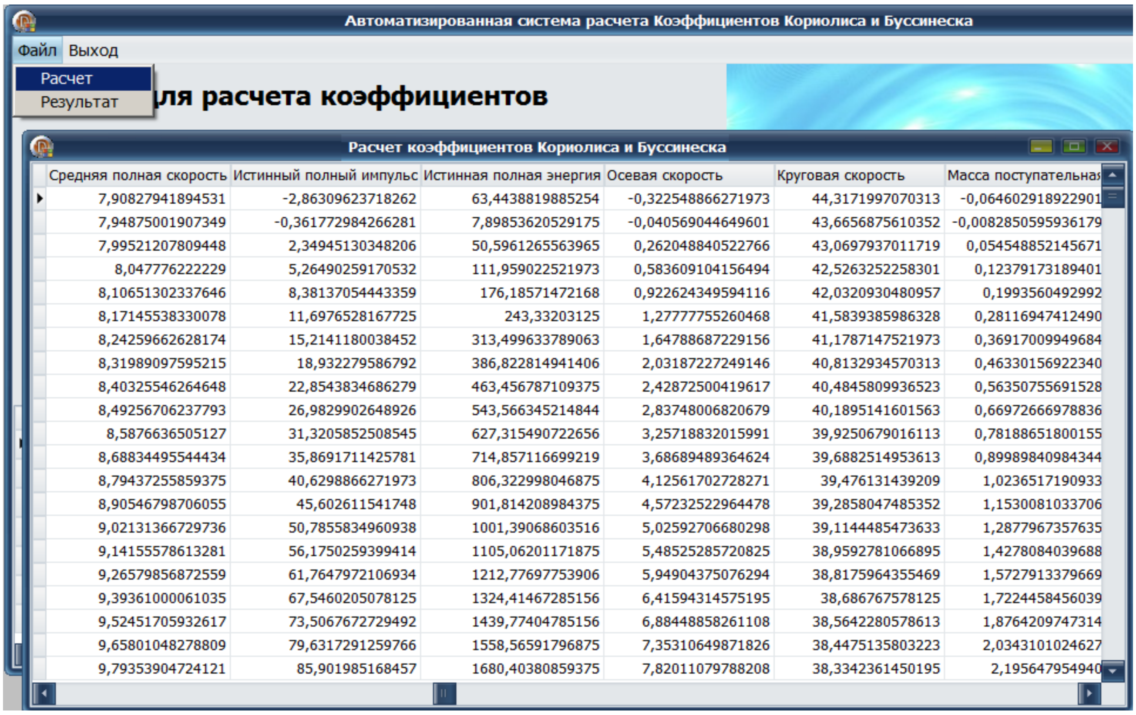


Figure 3. The form of the initial data input for the calculation of the coefficients for the configuration K1



Средняя полная скорость	Истинный полный импульс	Истинная полная энергия	Осевая скорость	Круговая скорость	Масса поступательная
7,90827941894531	-2,86309623718262	63,4438819885254	-0,322548866271973	44,3171997070313	-0,064602918922901
7,94875001907349	-0,361772984266281	7,89853620529175	-0,040569044649601	43,6656875610352	-0,0082850595936179
7,99521207809448	2,34945130348206	50,5961265563965	0,262048840522766	43,0697937011719	0,054548852145671
8,047776222229	5,26490259170532	111,959022521973	0,583609104156494	42,5263252258301	0,12379173189401
8,10651302337646	8,38137054443359	176,18571472168	0,922624349594116	42,0320930480957	0,1993560492992
8,17145538330078	11,6976528167725	243,33203125	1,27777755260468	41,5839385986328	0,28116947412490
8,24259662628174	15,2141180038452	313,499633789063	1,64788687229156	41,1787147521973	0,36917009949684
8,31989097595215	18,932279586792	386,822814941406	2,03187227249146	40,8132934570313	0,46330156922340
8,40325546264648	22,8543834686279	463,456787109375	2,42872500419617	40,4845809936523	0,56350755691528
8,49256706237793	26,9829902648926	543,566345214844	2,83748006820679	40,1895141601563	0,66972666978836
8,5876636505127	31,3205852508545	627,315490722656	3,25718832015991	39,9250679016113	0,78188651800155
8,68834495544434	35,8691711425781	714,857116699219	3,68689489364624	39,6882514953613	0,89989840984344
8,79437255859375	40,6298866271973	806,322998046875	4,12561702728271	39,476131439209	1,0236517190933
8,90546798706055	45,602611541748	901,814208984375	4,57232522964478	39,2858047485352	1,1530081033706
9,02131366729736	50,7855834960938	1001,39068603516	5,02592706680298	39,1144485473633	1,2877967357635
9,14155578613281	56,1750259399414	1105,06201171875	5,48525285720825	38,9592781066895	1,4278084039688
9,26579856872559	61,7647972106934	1212,77697753906	5,94904375076294	38,8175964355469	1,5727913379669
9,39361000061035	67,5460205078125	1324,41467285156	6,41594314575195	38,686767578125	1,7224458456039
9,52451705932617	73,5067672729492	1439,77404785156	6,88448858261108	38,5642280578613	1,8764209747314
9,65801048278809	79,6317291259766	1558,56591796875	7,35310649871826	38,4475135803223	2,0343101024627
9,79353904724121	85,901985168457	1680,40380859375	7,82011079788208	38,3342361450195	2,195647954940

3. Calculation of the Coriolis and Boussinesq's coefficients

Table 1. Calculation for parallel flow cyclone with intermediate dust extraction with a conical plunger (K1)

Measuring point	Boussinesq coefficient			Coriolis coefficient		
	full	translatory	rotation	full	translatory	rotation
T7	0,97558	1,212267	1,480844	0,95799	1,55528	1,482955
T8	1,0 0079	1,379519	1,0712	1,00314	2,09357	1,004195
T9	0,96499	1,778988	0,745901	0,93349	3,61949	0,649328
T10	0,88946	1,578998	0,659006	0,81755	2,74953	0,621976
T11	0,89401	1,62432	0,743153	0,81558	2,95023	0,411256
T12	0,96387	1,516443	0,756398	0,93735	2,74172	0,449779
T13	0,91241	1,385296	0,735584	0,84761	2,09664	0,434254
T14	0,85938	2,055838	0,73659	0,75865	4,86029	0,363123
T15	1,11494	1,37734	0,588892	1,30126	2,37897	0,65607
T16	1,08392	1,240096	0,627826	1,21758	1,68107	0,657976

2. For the swirling component of the flow the Coriolis and Boussinesq's coefficients do not obey the laws, specific to forward motion. The average angular speed was calculated in different ways: by averaging of the tangential velocity, averaging of the angular velocity, calculation of the average speed at the average angular momentum. The averaging was radial, and cross-sectional area as well. Table. 1 and 2 show the results of calculating average integral value at the cross-section angular velocity.

If we take a conical plunger K1 (see. Table. 1), when most of the separation zone is free from the plunger, a swirling flow gets set in the axial zone, making the Coriolis and Boussinesq's coefficients take values less than one, which is impossible according to the forward motion theory. If we take a shaped plunger K2 (see. Table. 2) we can see that the coefficients in most sections of the cyclone ratios are greater than one, except for the outlet section, wherein the vortex flow is established again and the coefficients are less than one.

Table 2. Calculation for parallel flow cyclone with intermediate dust extraction with a shaped plunger (K2)

Measuring point	Boussinesq coefficient			Coriolis coefficient		
	full	translatory	full	translatory	full	translatory
T7	1,03903	1,277608	1,720662	1,09239	1,79275	1,590799
T8	1,07365	1,315606	1,360699	1,16255	1,90733	1,213611
T9	1,33502	2,05359	1,604971	1,81963	4,12783	1,725324
T10	1,24216	2,12293	1,525919	1,55227	4,42683	1,420086
T11	1,14700	1,871349	1,623996	1,33232	3,6788	1,458417
T12	1,08700	1,440415	1,948732	1,18536	2,29285	1,832187
T13	1,00948	1,030506	2,997612	1,02199	1,08595	2,941431
T14	1,00566	1,023146	2,998736	1,01306	1,06626	2,936117
T15	1,00350	1,028535	1,509153	1,01107	1,08734	1,472376
T16	1,04027	1,068038	0,850079	1,16103	1,21614	0,899464

3. Average full speed was also determined in different ways: by averaging the full speed (given in Tables 1 and 2.) and by calculating of average axial and tangential velocity components. The alteration of the Coriolis and Boussinesq's coefficients, in general, remains the same as for the angular velocity component.

As a result, the study of swirling flow hydrodynamics showed that the obtained values for the Coriolis and Boussinesq's coefficients were less than one, which in theory should not be. As a result, the study of swirling flow hydrodynamics showed that the obtained values for the Coriolis and Boussinesq's coefficients were less than one, which in theory should not be. Minimum value of one can only be in uniform motion. In all the other cases, the coefficients are greater than one. Since the results did not obtain any theoretical confirmation for the rotational motion, one should carry out theoretical modeling of some specific tasks for their further interpretation, including rotational motion of the gas in the annular channel of variable cross section.

The research is carried out in terms of the state task to higher educational institutions on research work 7.3385.2011 "Investigation of two-phase swirling flows in a circular channel of variable cross-section", 2012-2014, state registration number No. 01201257743.

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