



DIMENSIONING, ESSAY AND NUMERICAL SIMULATION OF FLOW IN HYDROCYCLONES

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Abstract. *The process of recycling industrial effluents has been known to be an attractive alternative for complying with environmental standards. However, the complexity of separating heterogeneous mixtures with exceedingly small particles usually requires attention and equipment with time-consuming maintenance. Therefore, the use of the hydrocyclone proves to be effective because it provides flow to the production line, once the operation needs velocity to happen; low operational cost, since there is no internal element; and, consequently, easy maintenance. The basic principle of operation of the equipment consists of the circular movement induced by the tangential entry that results in the centrifugal inertial force, which is effective due to the difference in density between the parts of the mixture. This dynamic displaces the denser phase to the outer region of the equipment cone and eliminates it by the lower outlet (underflow) and keeps the less dense phase close to the axis of rotation and, as a result, eliminate it by the upper outlet (overflow). Although the simplicity of this equipment, the modeling of the physical phenomenon that occurs inside of it is quite complex, which hamper the adjustments in the geometric and operational variables to optimize the performance. For this reason, the main contribution of this work is presenting a sizing methodology based on the main authors, with flow rate and particle density as the most important input data to obtain customized dimensions for the proposed operating conditions; and a numerical computational simulation using ANSYS® CFX, more specific the BSL Reynolds Stress model, which was validated by an experimental assay performed with a manufactured hydrocyclone dimensioned by the methodology proposed previously. Both the experimental and the numerical assays were conducted with a homogeneous mixture for the purpose of understanding the fluid dynamics' main variables, to facilitate the identification of the secondary flows, which are characteristic of this flow, and to verify the operation that the equipment was intended (clarification, thickening or classification), all these decisive factors for the efficiency of the separation were studied and identified during the tests. A reliable reproduction of the internal flow was not the exclusive outcome of the validated simulation presented in this work; it also provided a confirmation of the dimensioning methodology.*

Keywords: *Hydrocyclone, CFD simulation, Separation Process, BSL Reynolds.*

1. INTRODUCTION

As a consequence of the concern about the environment, control bodies required more strict measures regarding the disposal of industrial effluents. In response to this situation, industries have improved their wastewater treatment systems, consequently creating new technologies referring to separation of mixtures, a critical stage of treatment (FREITAS, 2009).

The process of separating mixtures is in constant improvement due to the requirement for maximum purity. This operation is challenging because it is rarely successful, due to the complexity of the chemical nature of the mixtures or lack of technology. From this scenario, the hydrocyclone appears as a highly attractive alternative due to the simplicity of operation. It does not require exchange of filter elements or parts replacement (the geometry is fixed and with few machine elements) and does not require constant supervision which reduces maintenance costs.

The basic principle of this operation is based on the difference in density between the parts of the mixture, which consists of the circular motion that results in the centrifugal inertial force. As a result, the denser phase moves to the external region of the equipment, driven by centrifugal accelerations, and the less dense phase remains close to the axis of rotation (RIETEMA; VERVER, 1961). The equipment is built with a basic geometry composed of a tangential entrance perpendicular to a cylindrical region connected to a cone. In addition, as shown in Figure 1, there are two exits located on opposite sides: at the top of the equipment a portion of the mixture is eliminated by the overflow, which is driven by the internal spiral driver (vortex finder) and at the bottom, another portion of the mixture is eliminated by the underflow, driven by the external spiral.

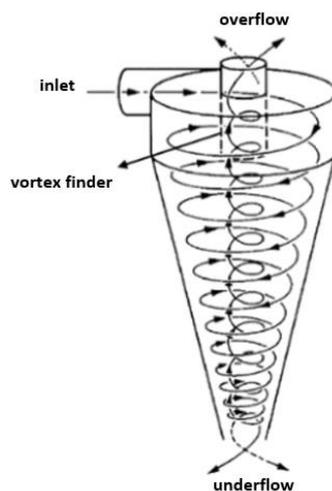


Figure 1. Base geometry and hydrocyclone fluid dynamics Right: adapted from Façanha (2012).

In order to explore the potential for separation or classification of a hydrocyclone, it is important that its variables, geometric and operational, are constantly improved. Through comparative tests, it is possible to identify the points that hinder the success of the separation. Therefore, it is sensible to understand the effects of each variable on the internal flow of the equipment and how the variables influence each other.

The objectives of this work consist of collecting the most accepted methods used until today in the construction of the equipment, understanding the main variables and carrying out a numerical computational simulation to confront, without disrespecting the physical phenomena, the results of the existing models. In addition, to build - from the dimensioning of the main authors - a prototype that validates the numerical models.

It is worth mentioning that although the equipment promotes the separation of heterogeneous mixtures, in this initial numerical modeling the system will be considered monophasic, thus facilitating the visualization of the speed and pressure fields. This identifies the identification of the turbulence phenomenon, as well as the effects of the centrifugal force and the operational variables and geometric.

2. MATERIALS AND METHODS

2.1 CALCULATION METHODOLOGY

The design of the studied hydrocyclones was based on three authors to compare the performance of the construction methods proposed by them. The operating variables and the separation diameter (d_{50}) determined for each scenario are described in Table 1. The separation diameter is the diameter of the particle that has the equilibrium radius coinciding with the location of zero vertical velocity, that is, when this particle reaches this location, it has the same chance of being collected in both overflow and underflow (SVAROVSKY, 1984). From this concept and knowing that particles above d_{50} are directed to the underflow and the smaller particles to the overflow, the separation diameter is determined according to the desired operation. It is worth mentioning that this division is imperfect: eventually smaller particles will be eliminated by the underflow. It is worth noting that the operating flow and the mixture concentration are the same in all designs, $0.001806 \text{ m}^3/\text{s}$ and 100 g/l , respectively. The calculation methodology and geometrical proportions of each author are presented in items 2.1.1, 2.1.2 and 2.1.3.

Table 1 – Operating variables and the separation diameter (d_{50}) for each scenario.

Authors	Operation	Specific mass of wet solid phase, ρ_s (kg/m^3)	Separation diameter, d_{50} (mm)	Characteristic number (Cy_{50})	Fluid Ratio, R_f (%)	p	n	k
Bradley (1965)	Clarification	2000	1.2	–	–	–	–	–
Rietema and Vever (1961)	Clarification	2000	1.05	6.9	–	–	–	–
Massarani and Araujo (1986)	Thickening	1700	0.05	–	30	1.22	2.9	0.056

2.1.1 GEOMETRICAL PROPORTIONS PROPOSED BY BRADLEY (1965)

Bradley (1965) carried out tests and studies in order to unify the main theories of separation: orbital and residence time. According to Bradley, it resulted in the base equation with greater degree of efficiency and certainty, equation (2.1), presented below.

$$d_{50} = 4,1 \cdot \left(\frac{D_c^3 \cdot \mu}{Q \cdot (\rho_s - \rho)} \right)^{\frac{1}{2}} \quad (2.1)$$

d_{50} = particle diameter with 50% efficiency, or separation diameter [m];

D_c = diameter of the cylindrical part [m];

μ = continuous phase dynamic viscosity [Pa · s];

Q = feed flow [m³/s];

ρ_s = specific mass of solid phase [kg/m³];

ρ = specific mass of water [kg/m³].

From this equation and the value of the specific separation diameter (d_{50}), it is possible to obtain the diameter of the cylindrical part (D_c), which is the initial point of the design. The geometrical proportions in Table 2, results in the other dimensions.

Table 2 – Geometrical proportions for hydrocyclones proposed by Bradley (1965)

Author	D_i/D_c	D_o/D_c	l/D_c	L/D_c	h/D_c	$\theta(^{\circ})$
Bradley	0.133	0.2	0.33	6.85	2	9

Right: adapted from Svarovsky (1984).

2.1.2 GEOMETRICAL PROPORTIONS PROPOSED BY RIETEMA AND VERVER (1961)

Rietema and Verver (1961) followed the same line of reasoning presented later by Bradley (1965). In addition, the authors introduced the concept of the hydrocyclone characteristic number, Cy_{50} . This variable represents the minimum value that satisfies the requirements of low separation diameter (d_{50}), low pressure drop and high flow. With this, the authors elaborated equation (2.2), which also, when isolated and manipulated, results in the diameter of the cylindrical part (D_c). The other dimensions are obtained by the geometrical proportions established empirically and shown in Table 3.

$$C_{y50} = \frac{d_{50}^2 \cdot (\rho_s - \rho) \cdot L \cdot \Delta P}{\mu \cdot \rho \cdot Q} \quad (2.2)$$

L = total length of hydrocyclone [m];

ΔP = pressure difference [Pa];

Table 3 – Geometrical proportions for common classifier hydrocyclone proposed by Rietema and Verver (1961)

Author	D_i/D_c	D_o/D_c	l/D_c	L/D_c	h/D_c	$\theta(^{\circ})$
Rietema and Verver	0.133	0.167	0.23	1.17	1.1	160

Right: Rietema and Verver (1961).

2.1.3 METHODOLOGY PROPOSED BY MASSARANI AND ARAUJO (1986)

Massarani and Araujo (1986) developed a calculation methodology for the diameter of the cylindrical part (D_c) of the hydrocyclone based on the particle size of the solid part, the inlet volumetric flow and the desired total efficiency. This resulted in the following equation (2.3): the other dimensions are obtained by the geometrical proportions established empirically and shown in Table 4.

$$D_c = \left(\frac{d_{50} \cdot Q^{0.5} \cdot (\rho_s - \rho)^{0.5}}{k \cdot \mu^{0.5} \cdot (1 - R_f)^{0.5} \cdot p} \right)^{\frac{2}{3}} \quad (2.3)$$

k = configuration dependent constant [dimensionless];

R_f = fluid ratio [dimensionless];

p = correction factor for the concentration of solids in the feed [dimensionless].

Table 4 – Geometrical proportions for hydrocyclones proposed by Massarani and Araujo (1986)

Author	D_i/D_c	D_o/D_c	l/D_c	L/D_c	h/D_c	$\theta(^{\circ})$
Rietema and Verver	0.133	0.167	0.23	1.17	1.1	160

Right: adapted from Svarovsky (1984).

2.2 EXPERIMENTAL TEST

As mentioned before, the mixture tested is homogeneous (water only) for the purpose of analyzing the equipment's characteristic flows without the interference of particles. The tested geometry was Bradley's (1965) clarifier, but with changes in the inlet piping to meet the installation requirements. Rotameters were installed at the entrance and overflow of the equipment in order to collect data for later comparison with the computational simulation.

2.3 SIMULATION OF SINGLE-PHASE FLOW

In this section, the influence of geometric and operational variables on the internal flow of the hydrocyclone will be analyzed with ANSYS® CFXTM 2020 R2 software. It is important to mention that at first this comparative study will be carried out only on the geometry used in the experimental test, and later the established setup will be reproduced in the three models mentioned in items 2.1.1, 2.1.2 and 2.1.3.

The mesh of this study was generated with 3,186,655 nodes and 1,752,465 elements of approximately 1mm each, using the inflation refinement method. In addition, the main parameters configured in this set-up were: continuous fluid domain, activated convective gravitational effect and BSL Reynolds Stress turbulence model with 5% intensity.

The boundary conditions, mass flow at the inlet and opening pressure at the outlet, were chosen with the intention of submitting the simulation to a more flexible condition. This is selected in cases where the software predicts the flow behavior from the propagation of the boundary conditions, matching the scenario of this experiment where the exact condition of the variables in the outputs is not known.

The recommended residual value for this type of flow is $1 \cdot 10^{-6}$. However, due to the complexity of the flow in this study, this value was extrapolated to a maximum number of convergence of 5000 iterations with a residual value of $1 \cdot 10^{-9}$ of Maximum residual type (MAX) ensure that the model was developed fully.

3. RESULTS

In order to establish a reliable setup and eliminate the need for prototypes, it is reasonable to carry out a comparative analysis between the computer simulation and the experimental test, the data obtained is shown in Table 5. As previously mentioned, both tests were conducted with the same geometry to guarantee the flow reproduction.

Table 5 – Comparison between flow rates (kg /s) of computational and experimental tests

Opening	Simulation	Experimental	Error [%]
Feed	1.67	1.67	-
Overflow	0.653	0.637	2.51
Underflow	1.020	1.03	0.971

The analysis of the table 5 demonstrates that the simulated flow proved to be compatible with reality since the error presented is less than 10%, a crucial factor in the validation of the chosen setup. In addition, a mesh convergence study, based on the Grid Convergence Index method (CELIK et al., 2008), demonstrated that the mesh proves that the results obtained are independent of the refining process.

Once the setup is established, the behavior of the internal flow in the hydrocyclone was analyzed in three distinct geometries: the clarifier of Bradley (1965), classifier of Rietema and Verver (1961) and thickener of Massarani and Araujo (1986). The operation that each geometry was designed to do has been achieved owing to the presence of higher mass flow at the underflow for the clarifier (1.34 kg /s) and classifier (1.57 kg /s) and also of higher mass flow at the overflow for the thickener (1.01 kg /s).

The effect of the centrifugal force on the flow provided by the geometry was reproduced in the three simulations, as demonstrated in Figure 2. The tangential entry resulting from the positioning of the supply pipe was evidenced, as well as the formation of the external spiral, which when meeting the cylindrical body wall is directed towards the apex. The transfer of the amount of movement of the tangential component of velocity at the end of the conical body was also identified since there is formation of the internal spiral and the transfer of mass to the overflow.

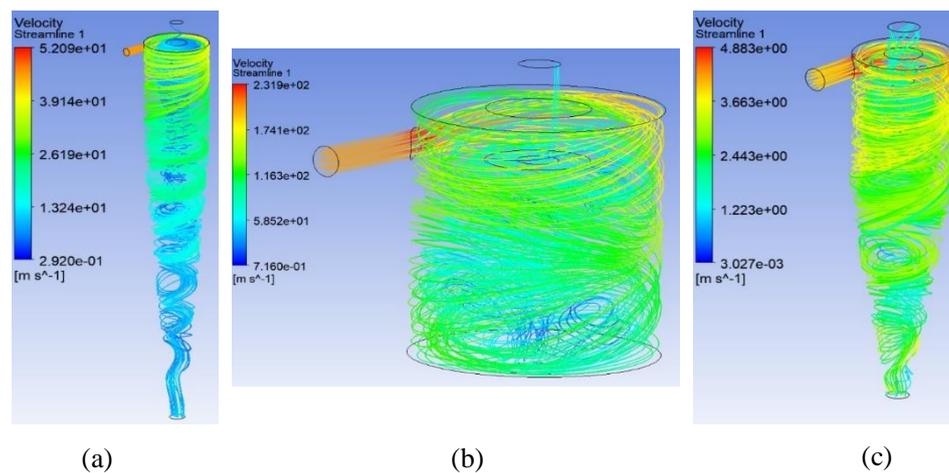


Figure 2. Hydrocyclone internal flow streamlines

(a) clarifier of Bradley (1965); (b) classifier of Rietema and Verver (1961); (c) thickener of Massarani and Araujo (1986).

Besides the general behavior of the internal flow, other expected characteristic flows were also identified in all simulated geometries, such as the short-circuit flow, recirculation zones and zero vertical velocity location (Figure 3).

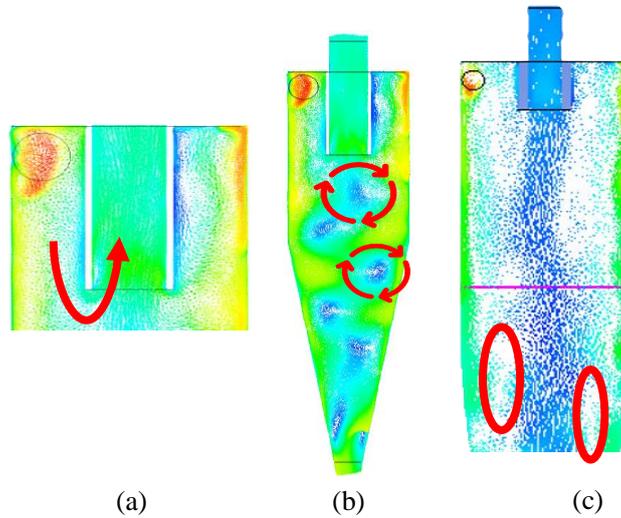


Figure 3. Characteristic flows

(a) short-circuit flow; (b) recirculation zones; (c) zero vertical velocity location.

Table 6 indicates the expected locations for the zero speed locations for each author, according to Bradley (1965) that should occur approximately in a diameter of $0.43 \cdot D_c$, as well as the location obtained from the simulations.

Table 6 – Zero speed locations. Dimensions in millimeters

	D_c	Expected location ($0,43 \cdot D_c$)	Real location
Bradley (1965)	53,7	23,1	42,0
Rietema e Verver (1961)	25,5	11,0	6,00
Massarani e Araujo (1986)	99,0	42,6	34,0

The geometry dimensioned by Massarani and Araujo (1986) was the only one that came closest to the indicated location, $0.34 \cdot D_c$ (see Figure 4b), on the models, Bradley (1965) and Rietema and Verver (1961), the phenomenon occurred at $0.78 \cdot D_c$ and $0.23 \cdot D_c$, respectively (see Figure 4a and Figure 5).

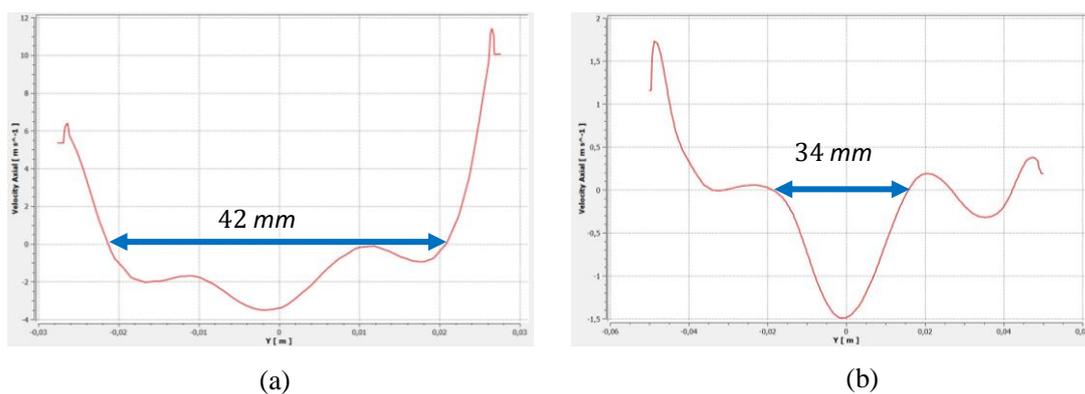


Figure 4. Zero vertical velocity graphs

(a) zero vertical speed for Bradley (1965); (b) zero vertical speed for Massarani and Araujo (1986).

It is worth pointing out that due to the disordered flow of Rietema and Verver (1961), the zero-speed location is not centralized (Figure 5).

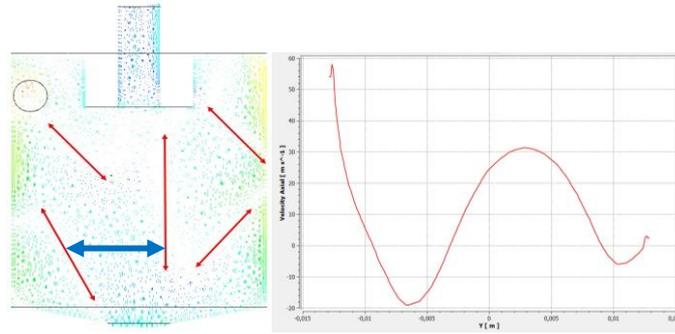


Figure 5. Zero vertical speed location for Rietema and Verver (1961)

Although the flow behaved as expected, reproducing the internal and external spiral and all characteristic flows, the components of the velocities have not. The components had the same performance in the three geometries studied, the points of highs and lows are located in opposite regions.

In order to identify the origin of the excessive amount of secondary flows, recirculation zone and short circuit, and to approximate the speed profiles to those presented in the literature, the operation of the equipment was simulated with some altered geometric and operational variables. The changes refer to increasing the inlet flow in the original geometry, in order to reduce the recirculation zone, and extended vortex finder so that it goes beyond the junction point between the cylindrical and conical sections, to reduce the short-circuit flow.

Table 7 – Comparison between proposed changes in single-phase operation

		Feed	Overflow	Underflow	Reference
		<i>kg/s</i>	<i>kg/s</i>	<i>kg/s</i>	
Clarifier	Original	1,80	0,46	1,34	Bradley (1965)
	High inlet flow	4,00	1,28	2,72	
Thickener	Original	1,80	0,69	1,10	Rietema e Verver (1961)
	High inlet flow	4,00	1,68	2,33	
Classifier	Original	1,80	1,01	0,79	Massarani e Araujo (1986)
	High inlet flow	4,00	2,30	1,70	

When evaluating the changes in the feed flow, it was observed a reduction in the recirculation zones and short-circuit flow only for the geometry of Massarani and Araujo (1986) (see Figure 6). However, for the other geometries, there was no change in the behavior of the original flow.

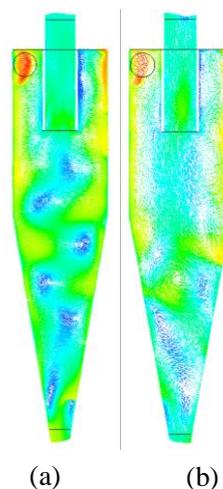


Figure 6. Comparison of the fluid dynamics of Massarani and Araujo (1986)

(a) feed flow 1,8 *kg/s*; (b) feed flow 4,0 *kg/s*;

In addition, the extension of the vortex finder also had an effect on the flow behavior, so that the geometries of Rietema and Verver (1961) and Massarani and Araujo (1986) presented a more ordered flow which, consequently, eliminated the secondary flows, (see Figure 7 and Figure 8) and promoted the approximation of the location of zero vertical velocity to the region indicated in the literature (Table 6).

However, from the proposed change, it was observed that the orderly flow in the operation of this hydrocyclone compromised the separation operation for which it was intended, as shown in Table 7.

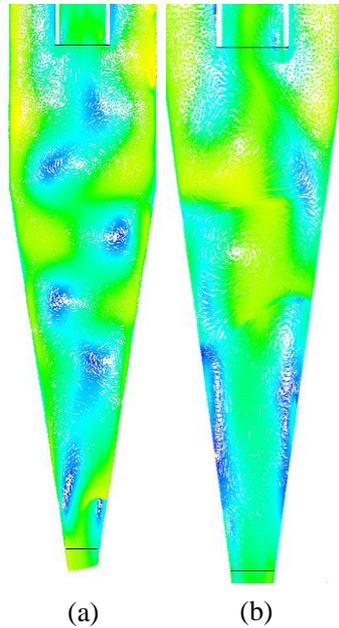


Figure 7. Massarani and Araujo's (1986) vortex finder modified

(a) original geometry; (b) modified geometry;

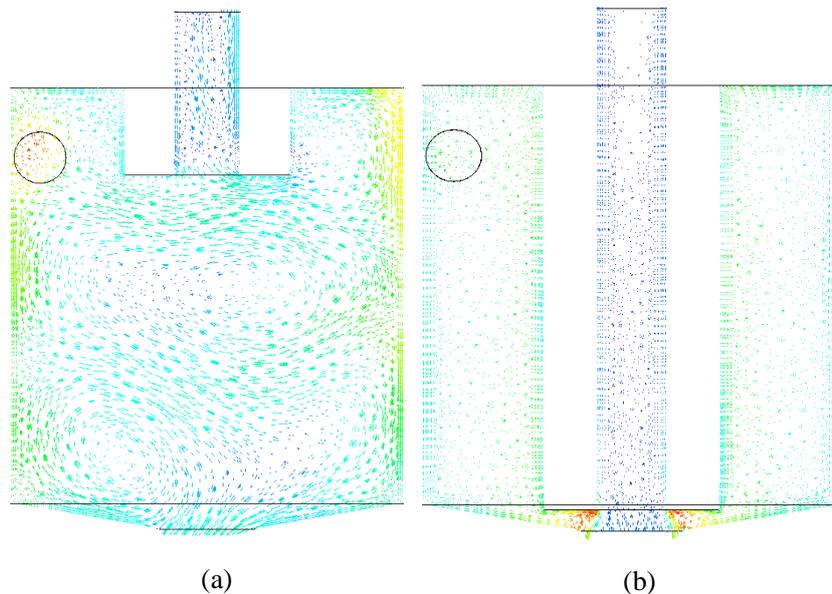


Figure 8. Rietema e Verver's (1961) vortex finder modified

(a) original geometry; (b) modified geometry;

4. CONCLUSION

From the new simulations, it is clear that the suggested changes should consider the geometry as a whole, in order to obtain the balance point between geometric and operational variables. This is because, according to Table 7, it was observed that the same changes in the proposed geometries did not result in the desired effect. That is, there were no significant changes with the increase of the vortex finder for the geometry of Bradley (1965), but for Rietema and Verver (1961) and Massarani and Araujo (1986) the operation was impaired. The high inlet flow, in turn, did not change the separation operation for which the equipment was intended.

However, confirmation of the observations mentioned above requires further study or further changes or even a combination of them. Although comparing authors' geometries for a single operation is another relevant practice for more concrete conclusions, for the current scenario the analysis of different authors and different operations proved to be more attractive.

The implementation of the GCI method provided a balance between the computational cost and the precision of the representation of the studied phenomena. The BSL Reynolds Stress model proved to be adequate for the study of the characteristic axisymmetric flow of the equipment since the computational results are very close to the experimental ones.

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