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Impact of the Closed, Semi-Opened, and Combined Contra-Rotating Stages on Volume Loss Characteristics

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Abstract. The article is devoted to studying the contra-rotating stages with different impellers and blade discs. Determining the reduction of volumetric losses by modeling the contra-rotating stages in the software package ANSYS CFX. The work aimed to create and study the flow and characteristics: semi-open, closed impellers, and blade discs. As a result of the work, the following contra-rotating stages were determined and compared: the semi-opened impeller with the semi-opened blade disc; the closed impeller with the closed blade disc; the semi-opened impeller with the closed blade disc; the closed impeller with the semi-opened blade disc. As a result of research, fluid flows in contra-rotating stages and their characteristics in the form of pressure and efficiency were obtained. According to the obtained data, the expediency of using contra-rotating stages as a working body of the pump is written.

Keywords: pump, energy efficiency, semi-opened impeller, semi-opened blade disc.

1 Introduction

Today, centrifugal cantilever pumps are widely used in various industries. Such pumps are thoroughly researched and have the best values of pressure and efficiency that can only be achieved. A new branch in pump construction is the cantilever contra-rotating centrifugal pump.

The new pump has a modified flow part and a different principle of operation of energy transfer from the working bodies to the liquid. The pump's impeller rotates clockwise, and the blade disc rotates counterclockwise. This creates a contra-rotating effect between the discs (bd), which transmits much more energy to the fluid than conventional centrifugal pumps [1–9].

Due to speed changes, the pump can create a much higher pressure. This, in turn, leads to increased volumetric losses that occur in the area between the cover disc and the pump housing. A leaking seal can only reduce volumetric losses, not eliminate them. However, exploring the contra-rotating stage with different types of impellers is an option to avoid volumetric losses.

The main advantage of semi-opened and opened impellers is the absence of losses caused by friction of the outer surfaces of the discs and fluid in the pump casing.

There is also no volume loss between the pump casing and the cover disc. However, the use of such impellers reduces efficiency. The channels in the impeller are formed by the blades and a case wall (Figure 1).

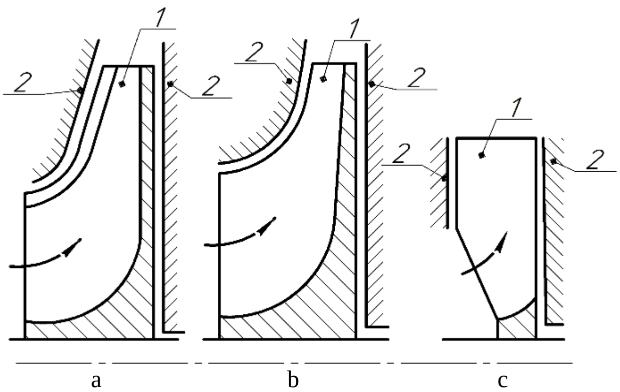


Figure 1 – Schematic representation of the flowing part with impellers of different types: a – closed impeller; b – semi-opened impeller; c – opened impeller; 1 – blade; 2 – housing of the pump

2 Literature Review

Centrifugal pumps mostly use closed impellers. However, nowadays, the impellers are divided into closed according to the design of the discs (Figure 2a), semi-opened (without cover disc, Figure 2b), and opened (without cover disc and part of the main disc (Figure 2c).

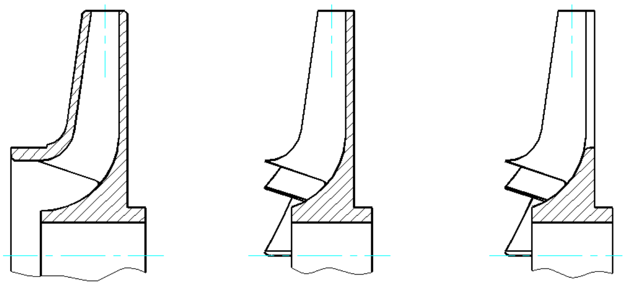

a b c

Figure 2 – Types of impellers depending on the design of the discs: a – opened; b – semi-opened; c – closed

The impeller type choice depends on the pump's purpose and operating parameters. According to the design, the closed impellers (Figure 2a) have front (cover) and rear (main) discs. The semi-opened impellers (Figure 2b) do not have a cover disc, and the blades are attached only to the main disc. The opened (Figure 2c) impellers have attached bushings with blades.

The contra-rotating effect works as follows. For ease of perception, the impeller and blade disc is delivered to a distance "a" (Figure 3).

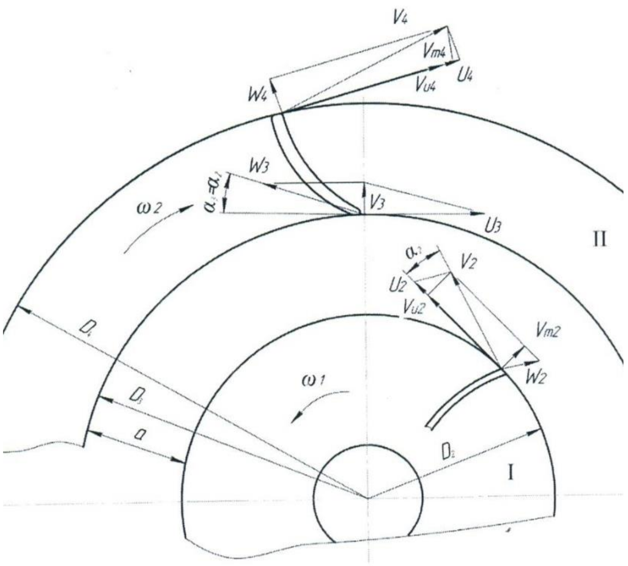
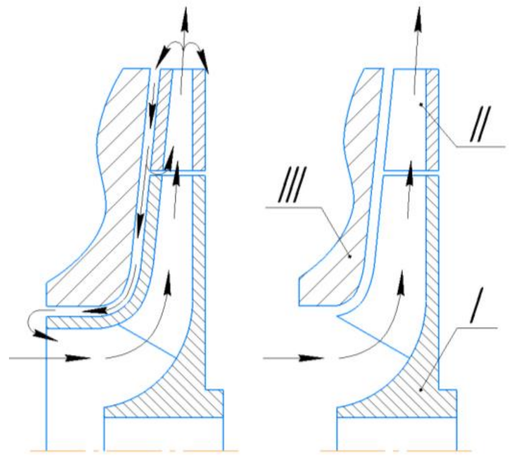


Figure 3 – Flow kinematics in contra-rotating centrifugal systems

Velocity vectors and their components are given for the axisymmetric flow scheme and conditions $\omega_I = -\omega_{II}$ (the gratings rotate in opposite directions with the same angular velocity). In addition, at the entrance to the first grid, selected conditions without circulating leakage. The flow at the entrance to the second grid is coming out of the first. It has a significant moment (twist), created by the first grid ($\upsilon_{u2} \cdot r_2$). Simultaneously, its direction is opposite to the second grid's rotation direction.

It should also be noted that the second grid's blades move towards the current coming from the first grid, changing its momentum in a very short time. And this, according to the moment theorem, causes a sharp increase in the force of interaction between the solid surface of the blade and the current that attacks it. This, obviously, leads to a significant increase in the intensity of the energy transfer process. Considering the working process of the contra-rotating blade system and, first of all, the work of the second grid, an assumption arises that the first grid, created at the entrance to the second flow with significant negative circulation, Γ_2 thus provides an intense contra-rotating for the blades of the second rotor (they actively interact). This flow's kinetic energy quickly passes into the state of pressure energy, which resembles the working process in hydraulic machines of the active principle of the action (for example, in jet bucket turbines). As the pressure increases, the volumetric losses will also increase.

In Figure 4, fluid flow and volumetric losses are shown in two contra-rotating stages. The 1st stage (Figure 4a) has cover discs, on the 2nd (Figure 4b) – they are missing.



a b

Figure 4 – Volumetric losses in contra-rotating stages: a – the closed type, b – the semi-opened type

Thus, the volume loss can be observed only in Figure 4a.

The study's primary purpose is to increase the energy efficiency of the contra-rotating pump by constructing the impeller with the semi-opened and closed working bodies using the method of numerical research. For this purpose, the following methods were used:

– a study of the flow part of the pump using the known design of the semi-opened and the closed impeller;

– design of impellers for contra-rotating pump with the semi-opened and closed impeller and vane disc of different designs;

– conducting a numerical study of the flow part of the pump using the proposed changes;

– evaluation of the obtained results.

3 Research Methodology

The object of the study is the contra-rotating stage with the base impeller of the pump CNS 180-1900. The following contra-rotating stages were created to reduce volumetric losses. The contra-rotating stages (Figure 5) have impeller I and blade disc II.

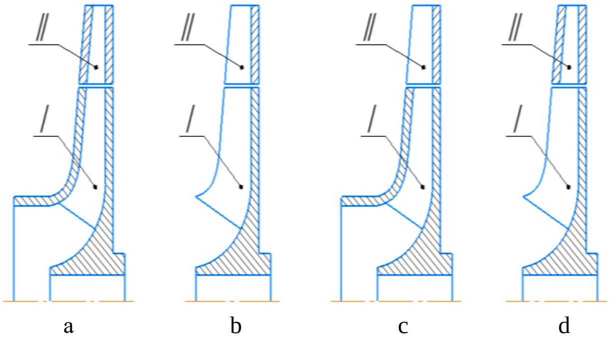


Figure 5 – Contra-rotating stages: a – closed impeller and closed blade disc; b – semi-opened impeller with semi-opened blade disc; c – closed impeller and semi-opened blade disc; d – semi-opened impeller and closed blade disc

The following contra-rotating stages have been created for calculations: the closed impeller with the closed blade disc (Figure 5a); the semi-opened impeller with the semi-opened blade disc (Figure 5b); the closed impeller with the semi-opened blade disc (Figure 5c); the semi-opened impeller with the closed blade disc (Figure 5d). Each stage had an impeller with eight blades. A distinctive feature of such stages was the presence of the cover disc and the number of blades in the blade disc, which in turn were equal to 8, 10, and 12 pcs.

In the beginning, the blades of the contra-rotating stages (Figure 6a) with optimal angles of attack of 9° and output of 12° were calculated. With the help of the Solid Works software product (Figure 6b), 3D models of flowing parts of various blades and impellers were created. With the help of ANSYS CFX, the created models were broken on the surface (Figure 6c) and created a calculation grid (Figure 6d).

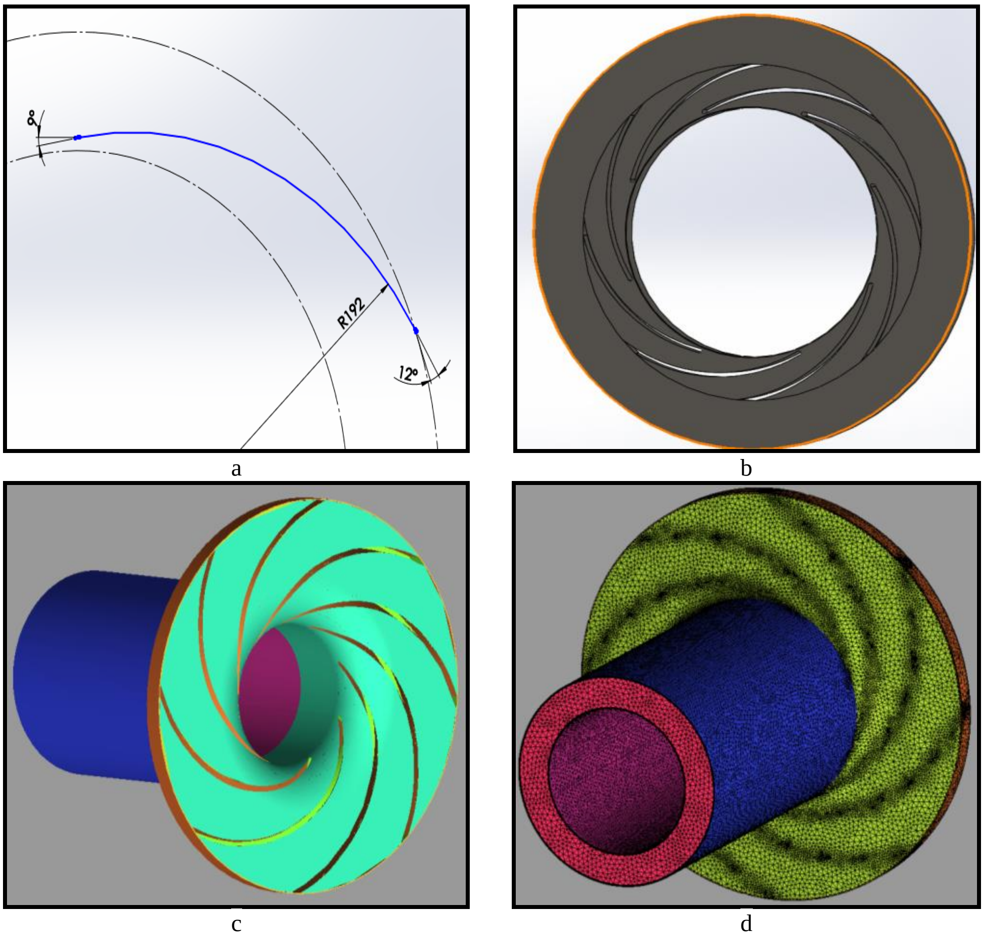
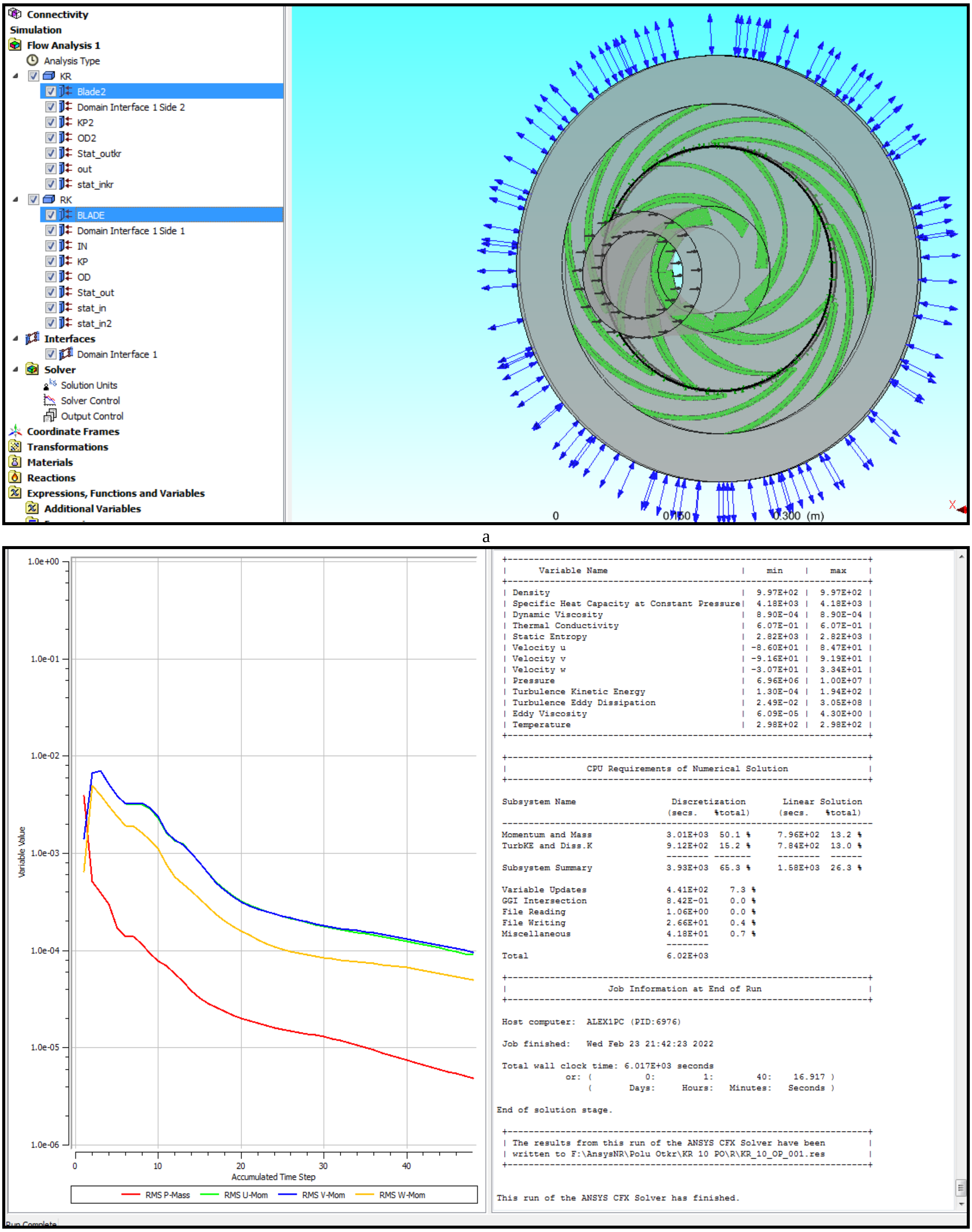


Figure 6 – stages of research: a – calculation of blades; b – the creation of 3D models; c – breaking surfaces; d – creating a grid; e – setting boundary conditions; f – numerical calculation

The next step for each model was to set the conditions for input, output, the configuration of the pumped medium, and set specific boundary conditions (Figure 7a). After that, the numerical calculation of the contra-rotating stages was performed (Figure 7b).

The university version of software product ANSYS CFX was used based on the numerical solution method of the fundamental hydromechanics laws [10, 11]: equations of motion of a viscous fluid together with the equation of inseparability.



a

b

Figure 7 – Boundary conditions (a) and numerical calculations (b)

This is a sufficient condition for the validity of the application of the results of numerical research.

It should be noted that ANSYS CFX was repeatedly tested in solving the problems of pump construction, and the discrepancy between numerical and physical modeling results does not exceed 5 %.

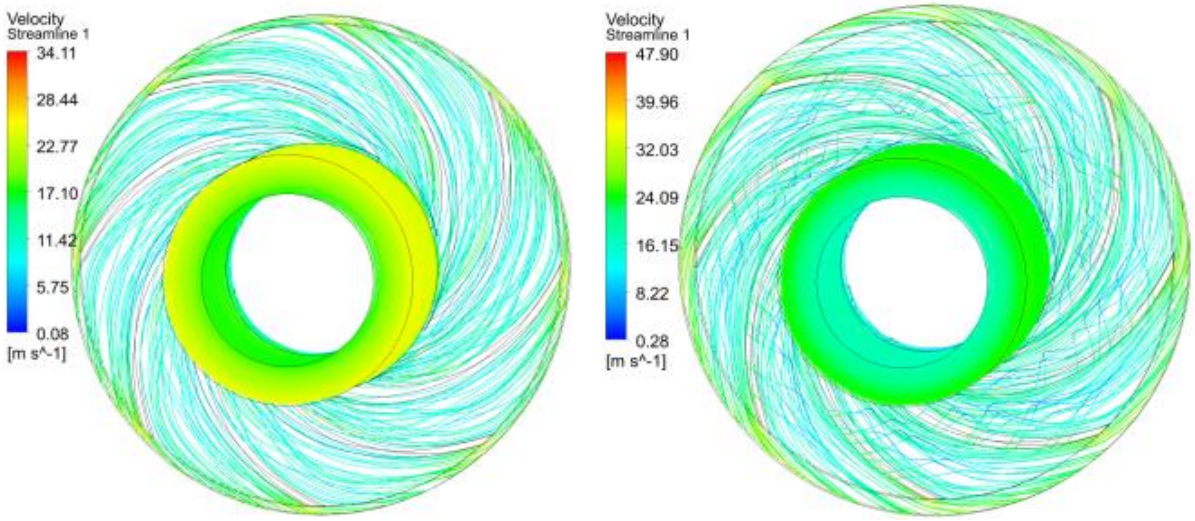
Therefore, this software product is suitable for solving the stated research problem. As a result of research the liquid flows in contra-rotating stages, and their characteristics in the form of pressure and efficiency are received.

4 Results

To begin with, the basic impellers without blade discs were calculated (Figure 8). The characteristics of the closed and the semi-opened impeller were obtained to clarify and compare characteristics with contra-rotating stages.

The closed impeller (Figure 8a) has the following parameters: head – 149 m; energy efficiency – 95 %.

The semi-opened impeller (Figure 8b) has the following parameters: head – 113 m; energy efficiency – 76 %.



a b

Figure 8 – Closed (a) and semi-open (b) impellers

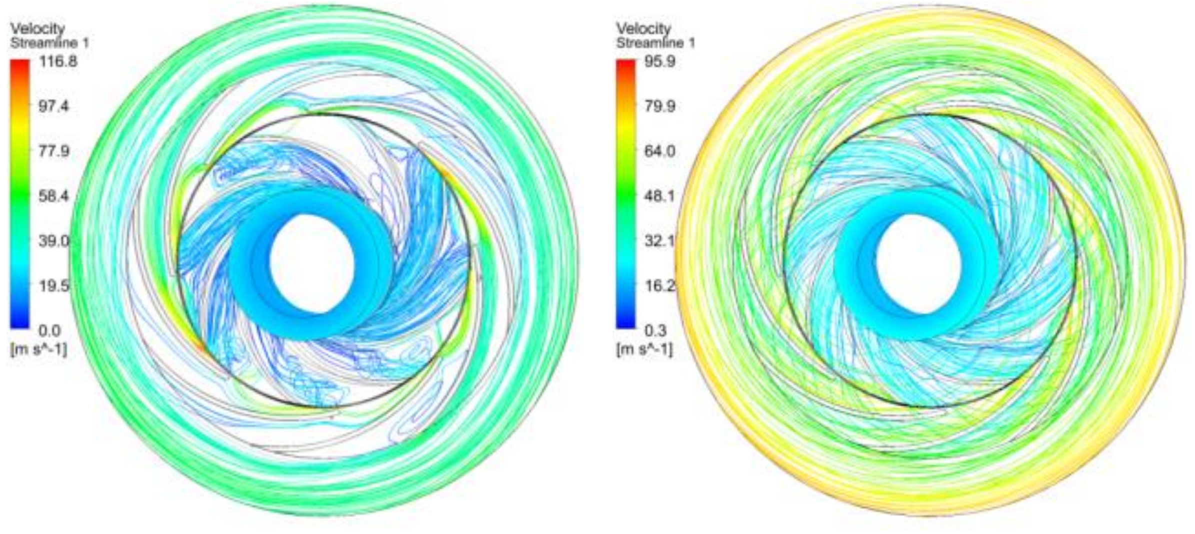
The fluid flow in the closed wheel is stable, without vortices. The maximum flow rate is 19.3 m/s. As for the semi-opened impeller, we can see fluid flow between the blade channels, leading to vortex formation and reduced efficiency. The maximum flow rate is 26.6 m/s. In addition to the flow of fluid between the housing and the blades, the flow is also stable.

The number of blade discs and impellers was created to study the characteristics of the steps. The closed and the semi-opened contra-rotating stages with the same number of blades were compared with each other.

Withing the 1st comparison, parameters of the closed stage are presented in Figure 9a: the number of blades – 8; head – 382 m, energy efficiency – 56 %. Parameters of the semi-opened stage (Figure 9b): the number of blades $z = 8$; head – 228 m; energy efficiency – 31 %.

After the 2nd comparison, parameters of the closed stage are presented in Figure 10a: the number of blades – 10; head – 357 m; energy efficiency – 55 %. Parameters of the semi-opened stage (Figure 10b): the number of blades – 10; head – 231 m; energy efficiency – 31 %.

Within the 3rd comparison, parameters of the closed stage are presented in Figure 11a: the number of blades – 12; head – 364 m; energy efficiency – 55 %. Parameters of the semi-opened stage (Figure 11b): the number of blades – 12; head – 225 m; energy efficiency – 33 %.



a b

Figure 9 – Closed (a) and semi-open (b) impellers ($z = 8$)

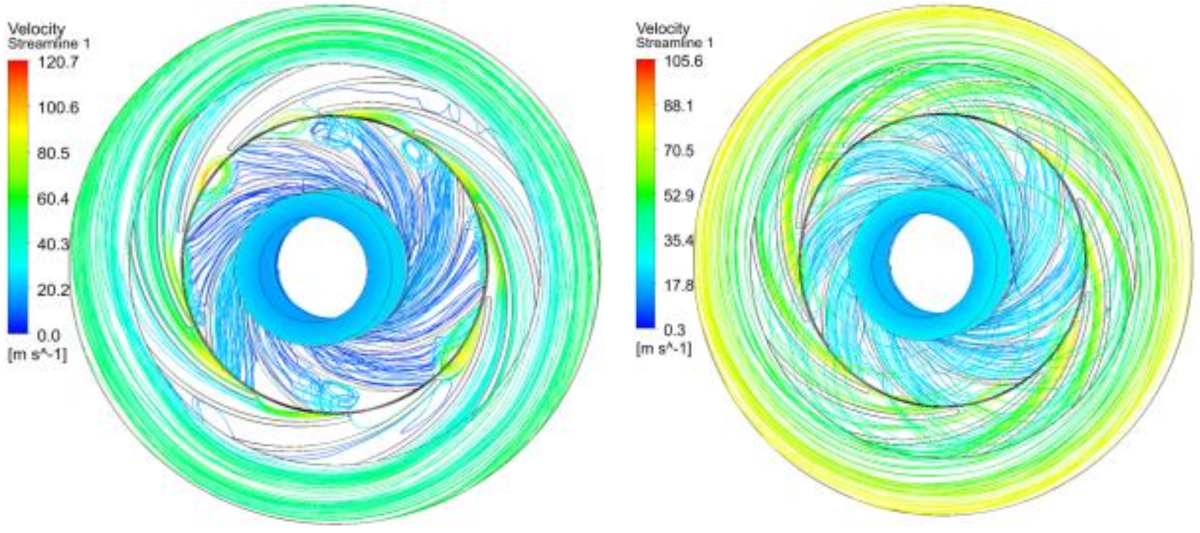


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Figure 10 – Closed (a) and semi-open (b) impellers (z = 10)

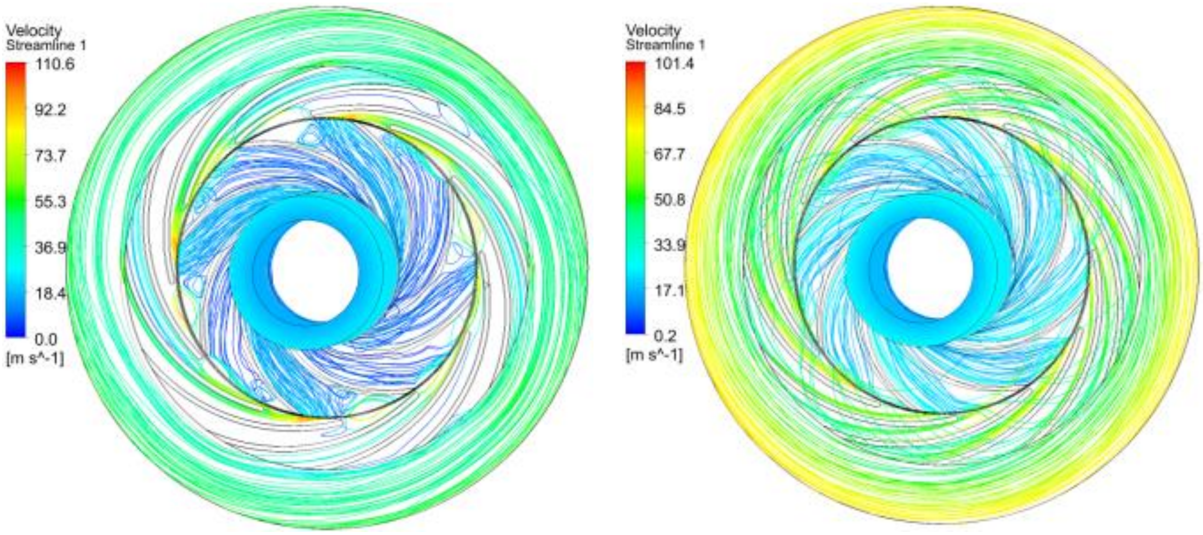

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Figure 11 – Closed (a) and semi-open (b) impellers (z = 12)

After the obtained results, a solution was proposed to combine impellers and blade discs of different designs (Figures 12, 13). After considering their pressure and energy efficiency, the interaction of different stage elements becomes essential. For this study, two contra-rotating stages were taken with the number of blades 10 and 12, respectively.

The 1st study with combined elements presents parameters of the closed contra-rotating stage with 10 blades (Figure 12a). The impeller is closed, and the blade disc is semi-opened: head – 286 m., energy efficiency – 36 %. Parameters of the semi-opened contra-rotating stage with 10 blades are presented in Figure 12b). The impeller is semi-opened, and the blade disc is closed: head – 319 m; energy efficiency – 45 %.

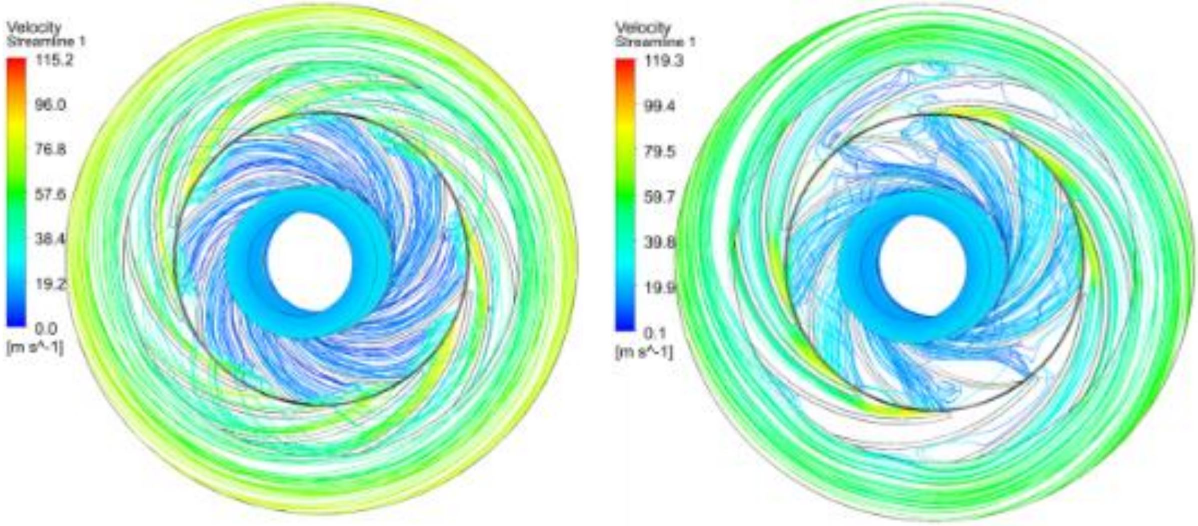
The 2nd study with combined elements presents parameters of the closed contra-rotating stage with 12 blades (Figure 13a). The impeller is closed, and the blade disc is semi-opened: head – 256 m; energy efficiency – 37 %.

Parameters of the semi-opened contra-rotating stage with 12 blades (Figure 13b). The impeller is semi-opened, and the blade disc is closed: head – 328 m; energy efficiency – 47 %.

Characteristics of the contra-rotating stage of different designs are summarized in Table 1.

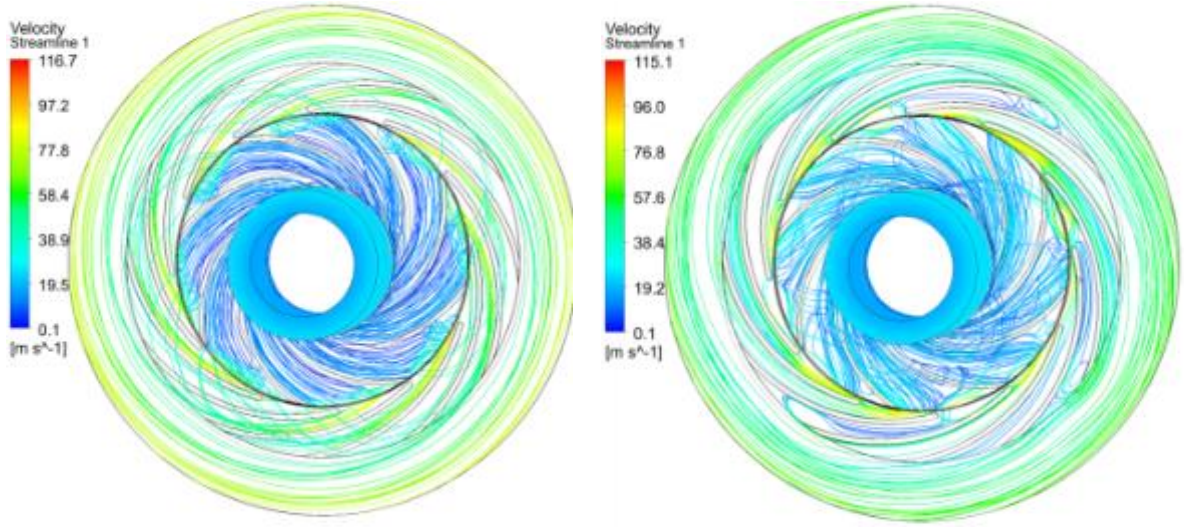
Table 1 – Characteristics of contra-rotating stage of different design

Number of blades	Head, m / Energy efficiency, %			
	Semi-opened blade disc / semi-opened impeller	Closed blade disc / Closed impeller	Semi-opened blade disc / semi-opened impeller	Closed blade disc / Closed impeller
8	228 / 31	382 / 56	N/A	N/A
10	231 / 31	366 / 55	319 / 45	259 / 36
12	225 / 33	364 / 55	328 / 47	256 / 37



a b

Figure 12 – Impellers with z = 10: a – closed impeller and semi-opened blade disc; b – semi-opened impeller and closed blade disc



a b

Figure 13 – Impellers with z = 12: a – closed impeller and semi-opened blade disc; b – semi-opened impeller and closed blade disc

5 Discussion

As we can see from the results, fluid flow in closed stages has vortex formation (Figures 9a, 10a, and 11a). This all leads to lower efficiency. In semi-opened stages, everything is much better (Figures 9b, 10b, and 11b). The flow of fluid is constant, but there is a flow of fluid from one between the blade channels to another.

Having obtained the characteristics of contra-rotating stages, we can say that they have higher pressure characteristics than the basic impellers, although inferior to them in efficiency. Compared with the semi-opened and closed stage, without considering the number of blades, the semi-opened contra-rotating stage has worse characteristics than the closed. In comparison with separately the closed and the semi-opened contra-rotating stage, we can see that the pressure and efficiency of this blade shape do not change.

Although the most significant pressure in the closed contra-rotating stage is achieved due to the stage, which has eight blades.

For combined impellers with blade disc, in the case of the semi-opened impeller and the closed blade disc system (Figures 12b, 13b), we got much better performance than the closed impeller and the semi-opened blade disc (Figures 12a, 13a).

Comparing a completely closed contra-rotating stage with a stage where the impeller is opened and the blade disc is closed, we can say that the pressure and efficiency have decreased, but thanks to this, we have removed the volumetric losses. Such good pressure characteristics can be explained by the fact that the closed blade disc is at the same time a guide device for the fluid after the semi-opened impeller. The fluid in the disc does not flow between the blade channels, and there is a formation of flow at the outlet.

6 Conclusions

As a result of research, it was found that it is better to use closed steps to get the highest pressure. Fully the semi-opened steps have the worst characteristics. Typically, such impellers are used for liquids with solid impurities, but how this will affect the operation of the contra-rotating stage is unknown. Such contra-rotating stages are best used for pure liquid without impurities. Using the combined contra-rotating stage to prevent massive losses did not live up to expectations. Volumetric losses are much less than losses on efficiency and pressure; therefore, they can be neglected.

Many unexplored factors in this area affect the nature of the flow and the pressure and energy characteristics of the contra-rotating stages. The research in this area is just beginning, and there will be further calculations of the contra-rotating stage.

7 Acknowledgment

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