PHYSICS OF HYDRODYNAMICS AND CAVITATION IN IMPELLER TYPE OF LEFT VENTRICLE ASSIST DEVICE

[1,2] **Mazurenko Oleksandr**

[1] *Silesian Centrum for Heart Diseases in Zabrze, department of cardiac anesthesiology SUM, Poland*

[2] *National Medical Academy of Postgraduate Education named P.L. Shupyk, AIC Department, Kyiv, Ukraine*

ФИЗИКА ГИДРОДИНАМИКИ И КАВИТАЦИИ В СИСТЕМАХ МЕХАНИЧЕСКОЙ ПОДДЕРЖКИ ЛЕВОГО ЖЕЛУДОЧКА СЕРДЦА ИМПЕЛЛЕРНОГО ТИПА

Мазуренко А.П.

Резюме: Благодаря современные системы механической поддержки кровообращения у многих пациентов, с тежелыми формами сердечной недостаточности разных типов, появилась возможность безопасно и комфортно дождаться возможности пересадки сердца. Оссобенностями данной апаратуры, которая физически является гальваническим магнитно-индуктивным насосом, является внутрення левитирующая роторная составляющая импеллерного типа, которая характеризуется крыльчато-лопастной гидродинамической частью, которая имеет кавитационные характеристики. Анализ кавитационных последствий работы данных типов внутрисердечных помп был проведен на основе существующих практических мировых примеров, изучены теоретически и изложены характеристики сравнения полученных результатов. К вниманию представлены механизмы физическо-математического рассчета кавитационной продуктивности и гидродинамических характеристик данных типов помп на разных режимах работы, что влияет на возможность возникновения клинических осложнений у пациентов при их использовании.

Ключевые слова: импеллерные роторы, кавитационная продуктивность, гидродинамические потоки в системах механической поддержки кровообращения.

PHYSICS OF HYDRODYNAMICS AND CAVITATION IN IMPELLER TYPE OF LEFT VENTRICLE ASSIST DEVICE

Mazurenko O.

Abstract. Thanks to modern systems of mechanical support of blood circulation in many patients with severe forms of heart failure of various types, it became possible to safely and comfortably wait for the possibility of a heart transplant. The features of this equipment, which is physically a galvanic magnetic inductive pump, is the impeller-type internal levitating rotor component, which is characterized by a vane-blade hydrodynamic part, which has cavitation characteristics. An analysis of the cavitation consequences of the operation of these types of intracardiac pumps was carried out on the basis of existing practical world examples, theoretically studied, and the characteristics of comparing the results obtained were described. The attention is given to the mechanisms of physical and mathematical calculation of cavitation productivity and hydrodynamic characteristics of these types of pumps at different operating modes, which affects the possibility of clinical complications in patients using them.

Key word: LVAD, impeller, blade rotor, cavitation productivity, flow hydrodynamic.

Introduction. Annually around the world, millions of patients have a diagnosis of heart failure. The limited number of donor hearts available to these patients leads to a huge need for a system of mechanical blood flow support, either as a total artificial heart (TAH) or as a ventricle assist device (L / R VAD). VADs replace the work of the heart and give it time for regeneration and potential recovery by discharging the ventricle, while maintaining adequate peripheral and coronary blood flow. Often left ventricle of the heart have problem, then right. VAD have either pumping fluctuation systems or centrifugal rotor-dynamic pumped impeller systems of continuous flow.

Continuous-flow VADs are small and can be located in the body with the help of minimally invasive techniques, in addition, they reduce the percentage of clinical and technical complications. Despite the success of impeller types of pump systems, it is necessary to understand the hydrodynamics of the operation of these devices and situations that can lead to unstable operation due to the discrepancy between their modes of use. The figure 1 below depicts the scheme of work and location of the impeller type of LVAD and the motion vectors of the blood moving by it and transverse sections of the device showing the inductive forces holding the proper impeller (the impeller of the motor rotor).

VADs have work parameters that can be used to observe the sequence of stability of its operation. These include the power of the pump indicated by the voltage in watts (Wt), the pulsation index (PI) is the measurement of the pulse of the flow of blood through the pump, the speed of the impeller turnover in thousands of turnovers per minute, the resulting pump flow is expressed in liters per minute, which must correspond to the heart index .

Situations in which the performance of the intracardiac pump changes is the result of changes in the conditions of the hydrodynamics physics, which depend on the clinical variables of the parameters of the patient's health. Such clinical parameters are indicators of the hemostasis system, water, electrolyte, colloidal blood balance and others, the impact of which is studied in the author's dissertation, the result of which
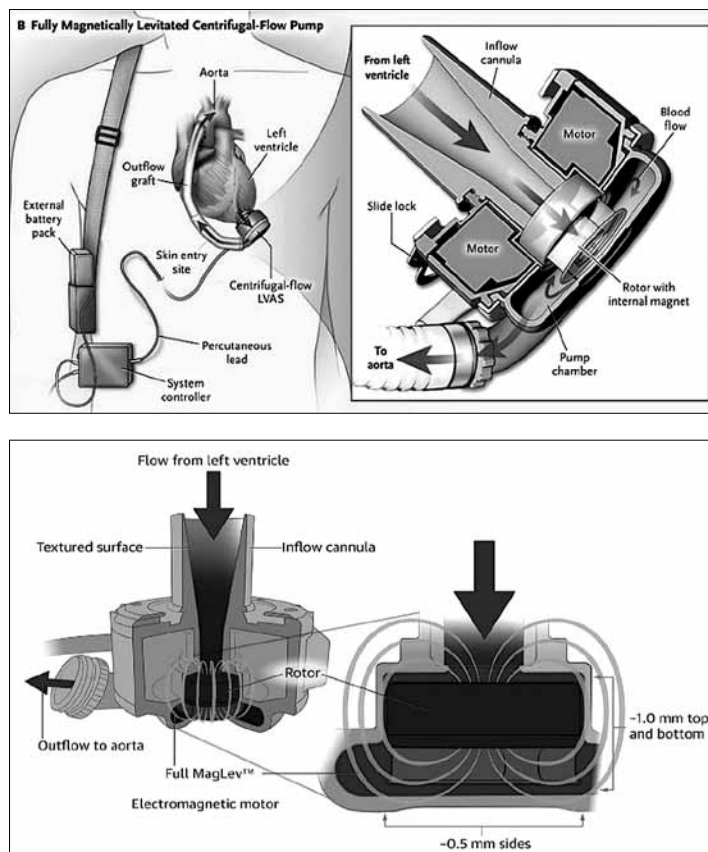
B Fully Magnetically Levitated Centrifugal-Flow Pump

Aorta
Left ventricle
Outflow graft
External battery pack
Skin entry site
Centrifugal-flow LVAS
Percutaneous lead
System controller

From left ventricle
Inflow cannula
Motor
Blood flow
Slide lock
Motor
To aorta
Rotor with internal magnet
Pump chamber

Flow from left ventricle
Textured surface
Inflow cannula
Rotor
Outflow to aorta
Full MagLev™
Electromagnetic motor
~1.0 mm top and bottom
~0.5 mm sides

Fig. 1

is given scientific work. In the analysis of literature data, it turned out that cavitation in miniature pumps was experimentally analyzed and proven by semi-open-centered wing-shaft impeller rotors. Also described were flow analyzes using a numerical model of a three-dimensional turbulent flow in pumps near the peaks of the efficiency point using the VOF turbulence model and cavitation. The prediction of the average cavitation productivity of each impeller with digital modeling was analyzed. The results indicated the similarity of the cavitation characteristics of small intra-heart pumps to industrial-size pumps, with the productivity of the cavitation of the semi-open impeller, reduced by increasing the axial gap of the tips. The literature describes the possibility of improving the hydraulic and cavitational productivity of the semi-open impeller by changing the angle of the working blades, as well as a uniform flow of high pressure before the entrance of the blood to the impeller.

With the impeller, the rotary part of the pump, we can obtain a moment of low pressure at the edges of blades with a pronounced gradient of pressure P1 and P2 on the critical side of the transition to the cavitation and supercavitation mode (Fig. 2), where the vice on the blades is lower than the level of partial pressure of oxygen in blood, which can lead to the formation of a cavitation cavity, which can lead to the destruction of blood cells, as well as significant hemodynamic and embolic complications.
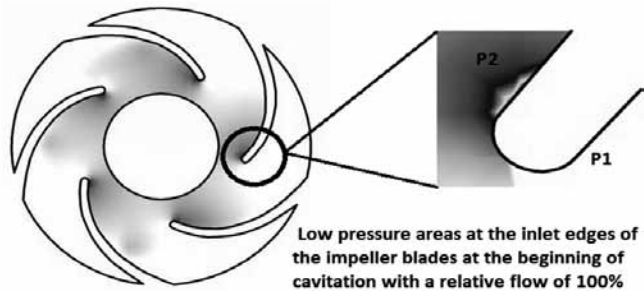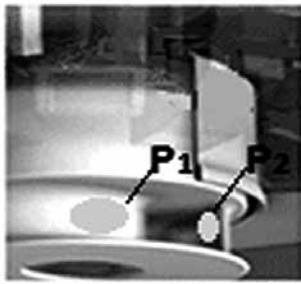
Fig. 2

Materials and methods: the hydraulic parameters of different types of semi-open impeller pumps were studied, which showed the efficiency of the tilted blades of the semi-open rotor in terms of hydraulic performance in contrast to the closed rotor [2]. Described are cavitation studies of hydraulic productivity of semi-open centripetal impellers, conducted by calculations and experimental tests of intracardiac miniature pumps at speeds from two to twelve thousand turnovers per minute. Shovels and geometry of the location were presented in the previous figure. The flow temperature, according to the needs of the experimental part, was a constant and controlled monitoring and cooling system. The experiment was based on the gradual reduction of absolute pressure in the total intake chamber of injection to the appearance of modes of cavitation and supercavitations, which were observed more than 11700 rev / min. The peak performance of hydraulic performance and cavitation manifestations indicated the ratio of the lumen of the axial impeller tip to the width of the blades.

Theoretical part: Typically, the parameters of the input geometry of the impeller are decisive for the performance of the cavitation pump. The blade blocking factor, ie B, is especially important among these parameters, which is defined as follows:

$$B = \frac{2\pi r_1}{2\pi r_1 - z\delta u}$$

The flow from the axial to the radial direction D_{1c}/D_r has cavitation characteristics, calculated as follows:

$$D_{1c}/D_r \approx 1{,}05\sqrt{\left(1 + \overline{d_1^2}\right)/2}, \text{ when } D_{1c}/D_r > 0.8$$

On the private cavitation characteristics can be noted several critical modes of cavitation. Cavitation cavities on the blades appear at a cavitation reserve Δh_i. This is the mode of occurrence of cavitation. The presence of caverns is not affects the pressure and power. The first (I) critical mode corresponds to the beginning of a change in head or power, the second (II) – to the beginning of a sharp change in head and power. When a vane pump operates on a single component fluid, such as blood, not containing impurities of undissolved gas, caverns are observed in dense blades in this mode, which are closed on the blades to form vortices. Vortex wakes behind cavities are washed out by the main flow before leaving the wheel, and therefore do not affect the kinematics
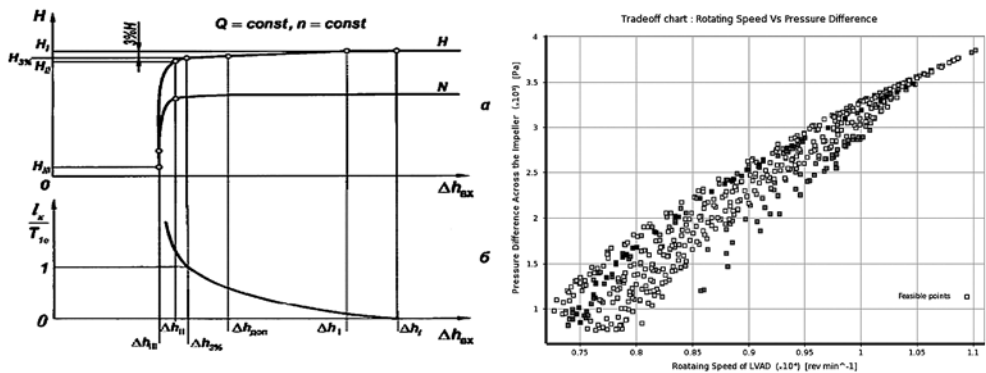
Figure 3: Private cavitation characteristics of the pump (a) and the length of the cavity (b)

of the flow at the exit from it. Therefore, the pressure and power in the second critical mode vary slightly compared with those in cavitation free regimes. With the subsequent small decrease in the cavitation reserve, the cavities reach the exit from the wheel, and then extend beyond its limits, which is accompanied by a sharp drop in pressure and power. The fully developed cavitation flow mode with long cavities closing up behind the rotating rotor is the limiting third (III) critical mode, supercavitation mode, or the cavitation breakdown mode of the impeller pump. Head, power and cavitational reserve in this mode reach their minimum values.

Figure 3 also shows the allowable cavitation stock Δh. Allowed cavitation reserve is the minimum cavitation reserve in which the pump operates without cavitation or with cavitation safe for it. In the latter case, the pressure, power, vibration, intensity of cavitation erosion and other indicators of work may change due to cavitation within the permissible limits. Also has pictured, the dependence of the sharp gradients of velocities on the impeller with the increase of its turnovers leading to cavitation events is shown.

In addition, according to cavitation characteristics, cavitation reserves were recorded, corresponding to the first I Δh and third III Δh critical cavitation modes. In modes without reverse currents at the entrance to the wheel a cavity appears on the section of the entrance edge of the blade adjacent to the covering disk. In the case of a non-impact flow of the relative flow, when the blade attack angle $δ = β_{1L} – β_1$ is zero, the discharge peak on the blade is minimal. Accordingly, the cavitation reserve of the beginning of cavitation is minimal. With normal incoming blood flow, when the angles of attack are negative, the cavity is observed on the front side (pressure side) of the blade, and for small flows – on the back side of the blade (discharge side).

As the supply decreases (the angle of attack increases), the cavitation margin for the onset of cavitation i Δh decreases, reaches a minimum, and then increases. With a further decrease in feed at the entrance to the wheel, reverse currents arise, the flow is rebuilt, the boundary of the vortex zone shifts to the axis of rotation, which reduces the angle of attack of the blade in the active flow. Cavitation reserve decreases again.

Cavitation stall. From the equations of flow, energy and quantities of motion for the super cavitation flow around a straight grid of plates of finite thickness, the expression for the cavitation coefficient was obtained in:

$$\lambda_{III} = \left\{ \left[\sin\beta_1 + \sqrt{\sin^2(\beta_{1\pi} - \beta_1) + a\sin(2\beta_1 - \beta_{1\pi})} \right] / [\sin\beta_{1\pi} - a] \right\}^2 - 1$$

Dependence $\lambda_{III} = f(\varphi_1, \beta_{1\pi}, a)$, is presented in fig. In this formula, β_1 – angle, relative flow before the entrance edge of the blade, β_{1l} – angle of the blade installation at the wheel entrance, a =K σ_1/T_1.

As a result of the statistical processing of cavitation characteristics of more than 100 models of centrifugal impeller pumps, a critical cavitation coefficient λ_{II} was obtained. It is expressed by the following Shemelya-Shapiro formula:

$$\lambda_{II} = 1{,}2\varphi_1\left(0{,}7\,\mathrm{e}^{6{,}8\overline{\sigma}1} - 8{,}8\varphi_1\overline{\sigma}_1\right)$$

The Thomas cavitation coefficient, which is defined as follows: σ = NPSH \ H, where NPSH is the flow rate at the input to the pump and H is the output speed. Cavitation productivity is calculated by the following formula: $= \dfrac{n\sqrt{Q}}{NPSH\frac{0{,}75}{c}}$, were Q – volume

flow of impeller productivity in meters cubic per minute, n – frequency of rotation of a rotor in thousands per minute.

Also, calculate the total pressure Cpt based on the following equation [1,2]:

$$C_{pt} = \frac{p_s + \rho v^2/2 - p_{t0}}{\rho u^2/2},$$

where Ps-static pressure in Pa, ρ is the liquid density in kg/m^{-3}, v is the absolute velocity in m\s^{-1}, u is the peripheral velocity m\s^{-1}.

Discussion and results: Proceeding from the above methods of calculating the results of the hydrodynamic and cavitation productivity of impeller pumps, it can be argued that

1. Calculation of the cavitation reserve for the turbulence of internally cardiac miniature pumps showed an average drop in hydrodynamic performance, which is a satisfactory result for this type of pump.
2. Imperators of intra-heart pumps with a positive central inclination of blades have better hydrodynamic performance and higher cavitation stock.
3. The impellers of the internal heart pomp have an increasing critical cavitation factor when increasing the flow velocity to peak at increasing speed.
4. The value of reducing the diameter of the input neck in increasing the input pressure before the impeller is intended to increase the cavitation stock and the critical cavitation coefficient.
5. Generally, the hydrodynamic and cavitation characteristics of miniature impelerated intra-heart pumps are similar to large industrial ones of the same type.
6. Increasing the axial gap of the tip induces cavitation and lower productivity for the intra-heart pump. [1,2]

This figure 4 shows the result of a cavitation test on the axial gaps of impellers identical to the rotors of the internal heart pomp, where one can notice the level λ2 = 0,182, which is a critical coefficient of cavitation, as well as vectors of motion on the shovels. According to experimental data, a decrease in the hydraulic performance of the pump [2] with a tendency to increase λ2 is proved. An increase of λ2 will result in an increase
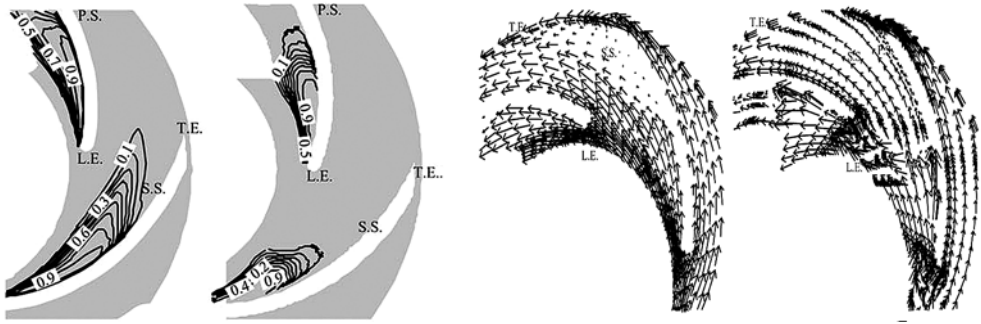
Fig. 4

in NPSHc, and a decrease in cavitation productivity. Thus, it can be seen that increasing the axial gap of the blade tip causes cavitation and lower productivity for a miniature pump. To observe the internal flow of cavitation in the work areas of the impeller blades, the figure shows the distribution of the volumetric velocity of the cavity in the middle section of the surface near the blade edge of the blade of variant 1 and 2 under operating conditions $\lambda 2 = 0.045$, $\varphi = 0.089$, $n = 11700$ min-1, NPSH = 2.7 m. The designated number represents the volumetric frequency of the cavity (the volume of the bubble is a gas phase, while 0 is a liquid phase).

Of great importance for indicators of internal hydrodynamics of intra-heart pumps is the position of the incoming mouth during the surgical implantation of this device in the ventricles. The inclination of the LVAD inlet inappropriately leads to changes in the flow of the exhaust from the pump into the pump and the pressure changes to the downward direction, which results in NPSH <2.4 m, and at n not ≤ 5500 rev / min, as shown in this figure 5.

As you can see in Fig. 5. a), the temperature of the designation of the velocity of the vectors at the inlet at the normal position of the inlet of the pump contributes to the high rate of the input stream, which at constant turns and the performance of the impeller will give high pressure at the entrance to it and will not increase the productivity of cavitation. In Fig. 5b), due to the inclination to the interventricular membrane, we see an increase in the turbulence of the blood flow in the left ventricle, which leads to a de-
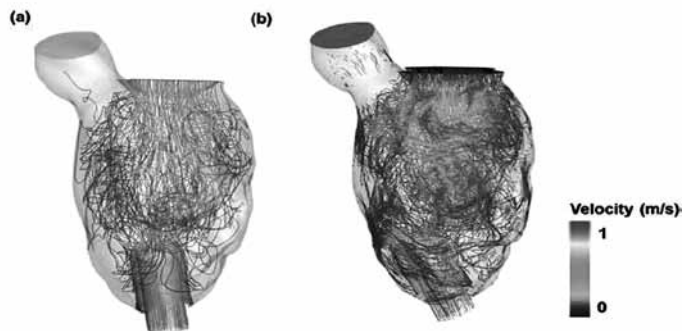

Fig. 5. Vector paths of the flow velocities that intersect in the left ventricle to the entrance to the LVAD inlet, at a) to the corner of 00 (correct) and b) -140 (not true, oriented to the interventricular membrane).
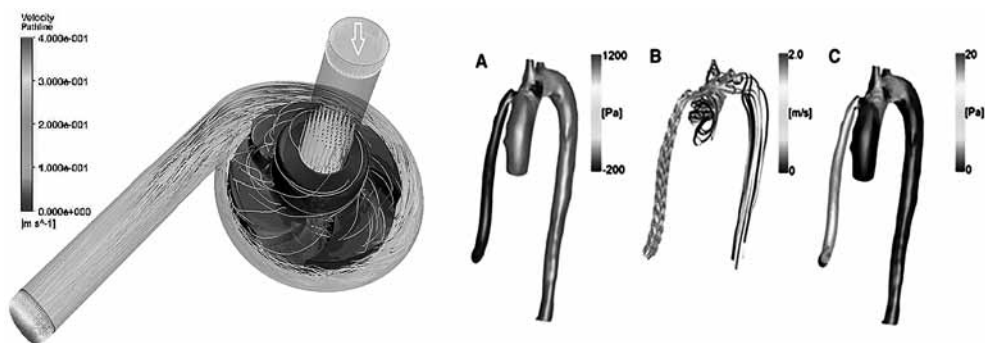
Fig. 6

crease in the pressure at the entrance to the pump and as a result of this dissociation of the curvature of the cavitation to increase its productivity and reduce the hydrodynamic performance of the pump in general, that leads to an increase in the pulse index and the required voltage of the motor [5,6].

On Fig.6. it is possible to observe a study on impeller models of the values of blood flow velocity in LVAD devices and the values of pressure at the outlet of the blood from the outlet of the pump through the graft to the ascending aorta, as demonstrated by the temperature value.

The analysis of studies of specialists in the hydrodynamics of miniature heart pumps points to the focus of attention of practitioners – physicians on changes in the pressure in the left and right ventricles of the heart, leading to sharp gradients of pressure before and in the impeller and can lead to clinical complications in the form of damage to blood cells , the walls of the aorta against the place of implantation of the graft of the outflow of the pump and the thrombotic-embolus complications that can be observed on the thermovector graph of the engine Fig. 6, where the largest traction velocity vectors Chains on the outer wall of the shoe of the engine in front of the impeller before going to the grate. Also, on the thermography of the discrepancies in speed and pressure of grate and its connection to the aorta a) we see a sharp gradient of pressure on the opposite wall at the time of release, which tells us about constant damage with high pressure [6,7,8]. In the graph b) we observe measured vectors of blood flow from graft to the root of the aorta and on the descending part of it and on the shoulder vessels, c) the period of the protodiastolic.

When working with systems of intra-cardiac pumps, it is important to synchronize the work of the engine with the blood-cycle, the operation of the Ao-valve and the reductions of both the ventricles and the atrium, which will affect the output hydrodynamic performance of the VAD engines. This synchronization is depicted in the scheme proposed by Guyton and Hall in 2006.

Conclusions: The study of the physical conditions of the work of VAD devices is impossible on a theoretical scale; the experimental part should be a compulsory component in the studied features of their hydrodynamics. In the world more than a large number of devices of this type are used to save people with signs of severe heart failure, which leads to the need for further serious study of the hydrodynamic subtleties of their work to facilitate the possibility of their clinical application. From the analytical review
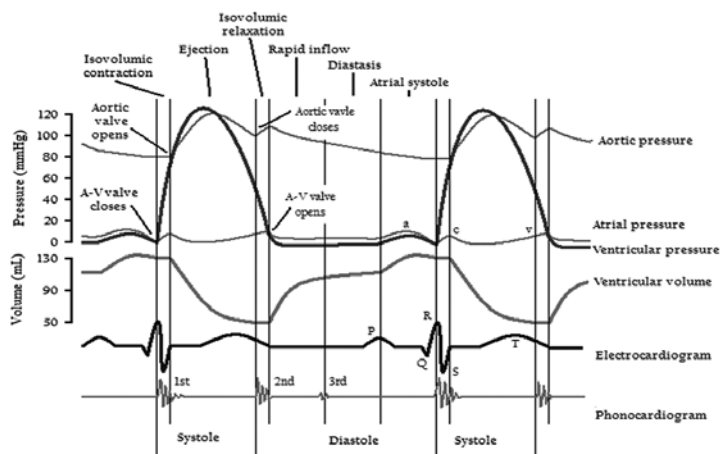
Fig. 7. Cycles of work and VAD events at the heart with marking of volume and pressure values in accordance with the cycles of reduction (Guyton and Hall, 2006).

of the literary material, a number of the following conclusions can be drawn from the physical bases of hydrodynamics and cavitation moments of these devices.

1. The tested miniature pump has a similar cavitation and performance with centrifugal pumps of the same impeller type of normal industrial size.
2. Relative velocity vectors on the middle surface of the impeller blades have the ability to drastically change to the cavitation cavern formation site.
3. Both the hydraulic characteristics and cavitation and the performance of the miniature pumps can be improved when the impellers with inclined blades are used for semi-open working wheels.
4. As the axial gap increases, cavitation increases, and the productivity of miniature pumps decreases.
5. An even flow of high pressure above the entrance to the impeller impeller can be provided by the correct position of the incoming neck with a narrowing diameter, increasing the pressure at the inlet to the rotor, which reduces the probability of oscillations and decreases the pressure and productivity of the cavitation.

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