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MATHEMATICAL EVALUATION OF HEMOLYSIS IN A CHANNEL CENTRIFUGAL BLOOD PUMP

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The objective of this work is to conduct research on a mathematical model to assess hemolytic characteristics in a channel centrifugal blood pump developed by us with 2000–3400 rpm impeller speed range and 100–250 mmHg pressure drop in different parts of the pump flow path. Hemolysis index was measured at 1 to 10 L/min flow rate. The result was an estimate of the average magnitude of the shear stress (SS), taking into account the distribution in the pump, which ranged from 40 to 60 Pa. The most critical areas of the pump in terms of blood injury were evaluated. The maximum SSs were determined: 456 Pa in the impeller wheel zone and 533.3 Pa in the adjacent area of the body, with an exposure time of 0.0115 s and 0.0821 s respectively. In these zones, maximum hemolysis index values were 0.0420 and 0.0744 respectively. Based on the data obtained, these zones were optimized in terms of minimizing hemolysis.

Keywords: 3D modeling, mechanical circulatory support, channel centrifugal blood pump, shear stress, exposure time, hemolysis index.

INTRODUCTION

In the development of modern pumps for auxiliary circulation, one of the main stages is a preliminary theoretical assessment of the influence of the pump on the hemocompatibility parameters in terms of minimizing conditions leading to blood injury [1, 2]. To solve this problem, modern software systems are used, which in the process of designing pumps will allow determining the directions for optimizing the design of pumps. In this work, a theoretical analysis of the channel centrifugal pump (CCP) developed by us is carried out from the point of view of minimizing blood trauma when using the pump when bypassing the left ventricle of the heart (LV) and extracorporeal membrane oxygenation (ECMO) with the results of calculations of the shear stress (SS) and exposure time (ET), which are the main parameters determining blood trauma. Based on the data obtained, the calculated hemolysis indices (HI) for the main working zones of the pump were estimated.

Fig. 1. Calculation model of the channel centrifugal pump

MATERIALS AND METHODS

The studies were carried out on the CCP model developed by us with a detailed calculation of the pump components – inlet path, impeller (I), spiral casing (SC) and outlet channel, as well as transition zones described in more details in [3]. The general view of the pump is shown in Fig. 1.

The geometrical parameters of the I flow path represent an updated model of a closed-type blade structure. The inner diameter of the entrance cannula is 10 mm. The 46 mm outer diameter I disc has four tubular channels with a constant cross section of 5 mm in diameter. Each channel is formed along a logarithmic spiral and has a circular cross-section, providing conditions for a laminar flow. The main elements of the pump are shown in Fig. 2. I rotation is performed by means of a magnetic coupling, which is a mechanism for contactless transmission of rotational energy from the pump drive to I. The outlet is terminated with a 10 mm fitting (8). The gaps between I and the inner surface were 500 μm. In this work, SS was evaluated for seven main pump zones, critical from the point of view of blood injury and shown in Fig. 2: upper zone UZ (1726.9 mm^2), spiral casing zone SC (1449.2 mm^2), lateral zone LZ (1135.0 mm^2), channel zone CZ (3152.3 mm^2), lower zone LZ (1688.9 mm^2), impeller zone IZ (4435.1 mm^2) and diffuser zone DZ (473.3 mm^2).

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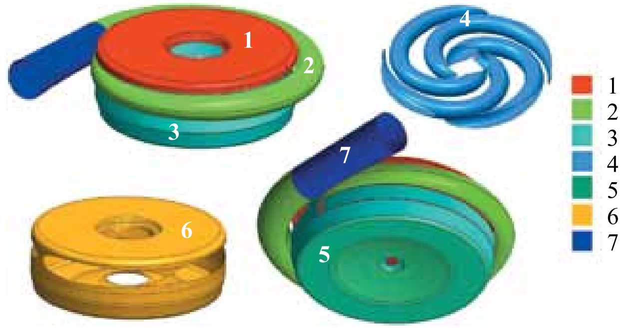

Fig. 2. Pump areas for investigation. 1, upper zone; 2, spiral outlet; 3, lateral zone; 4, channel zone, 5, lower zone, 6, impeller zone; 7, diffuser zone

Based on preliminary computer studies, a 3D CCP model was built with the Solid Works Corporation (Concord, MA) software, which served as the basis for building the CCP structure. The resources of the Fluent v16.0 software package (ANSYS inc., Canonsburg, Pennsylvania) were used to simulate the CCP computational grid. The software package uses the SST turbulent flow model adapted for calculations near the wall. The working fluid was assumed to be incompressible and Newtonian with a viscosity of 4.0 SP, a density of 1.050 kg/m^3, which reflects the picture of an expected hematocrit of 35%. In this case, the concentration and size of the particles were selected in accordance with the physiology of the blood cells. The choice of boundary conditions reflected the parameters for applying CCP in LV and ECMO procedures. The rotational speed range of the CCP I is from 2000 to 3400 rpm in 200 increments. Five test points for analysis were selected to cover the clinically relevant working area: 1.0 L/min (low flow), 2.5; five; 7.5 l/min (nominal flow) and 10.0 l/min (high flow). The roughness of the surface was chosen as 10 microns.

Calculation of shear stress and hemolysis index

Pa cause platelet activation, and uncontrolled hemolysis occurs at values above 150 Pa [4], which we have taken as a threshold value. The investigated SS τ at a steady speed of fluid movement υ changes according to a linear law depending on the distance from the wall y, regardless of the nature of the movement [5]:

$$\tau = \mu \frac{d\upsilon}{dy}, \qquad (1)$$

where μ – dynamic viscosity coefficient.

Exposure time (ET) is an important factor. In this study, t was calculated from the mean travel time of a particle obtained in a software calculation. ET is calculated as the time average of 10 particle tracks. In this case, ET is calculated as the distance between the start and end points along the area of interest, divided by the average speed for the segment.

One important aspect of flow-induced blood damage is hemolysis, defined as the release of hemoglobin into plasma due to damage to the erythrocyte membrane. Pump-induced NNC and Bt are the main factors causing hemolysis. It is still considered useful for engineering problems a power-law equation for estimating the amount of increase in released hemoglobin ΔHb, expressed in concentration units, relative to the baseline ΔHb value [4, 6]:

$$\frac{\Delta Hb}{Hb} = A \times t^{\alpha}\tau^{\beta}, \qquad (2)$$

where τ – shear stress acting on blood, *t* – ET in the shear stress area. Goubergrits and Affeld model, which uses Euler's numerical model for hemolysis, is calculated using the coefficients of the equation $A = 3.62 \times 10^{-7}$, $\alpha = 0.785$, $\beta = 2.416$. The constants are successfully used, despite the fact that their validity has been questioned by many researchers for the fact that they overestimate hemolysis to a large extent [7–9].

CALCULATION RESULTS

The calculations were performed on particles comparable in size to the size of an erythrocyte. ET averaged 0.6 to 0.08 seconds over the entire input range with increasing pump flow. In Fig. 3 shows the change in SS in the channels, on the impeller and on the inner surface of the pump. The maximum values of SS for each area are highlighted, shown in Fig. 4 for each zone, which are an evaluation criterion for hemolysis. For these purposes, the regions above the threshold voltages were considered. The critical SS was based on the value of 150 Pa.

The calculations showed a stable increase in the maximum value of SS with an increase in the rotation speed from 2000 to 3400 and the transition from the LVC mode to ECMO. The average SS value did not exceed the critical threshold. The highest values were obtained in the IZ and LZ. There is also a tendency for the SS values to increase with increasing flow rates, which stress the volute and diffuser. Based on the data obtained and calculations of *t*, the dependences of the average hemolysis index (HI) were derived (Fig. 5).

HI increases with increasing flow rate and with increasing rotation speed I, however, it is within the permissible norm. Since the estimate of the average HI reflects only the general trend of changes in the parameters of the effect of the pump cavity on the blood, the most reliable sign of hemolysis is a zone of high SS above 150 Pa. In

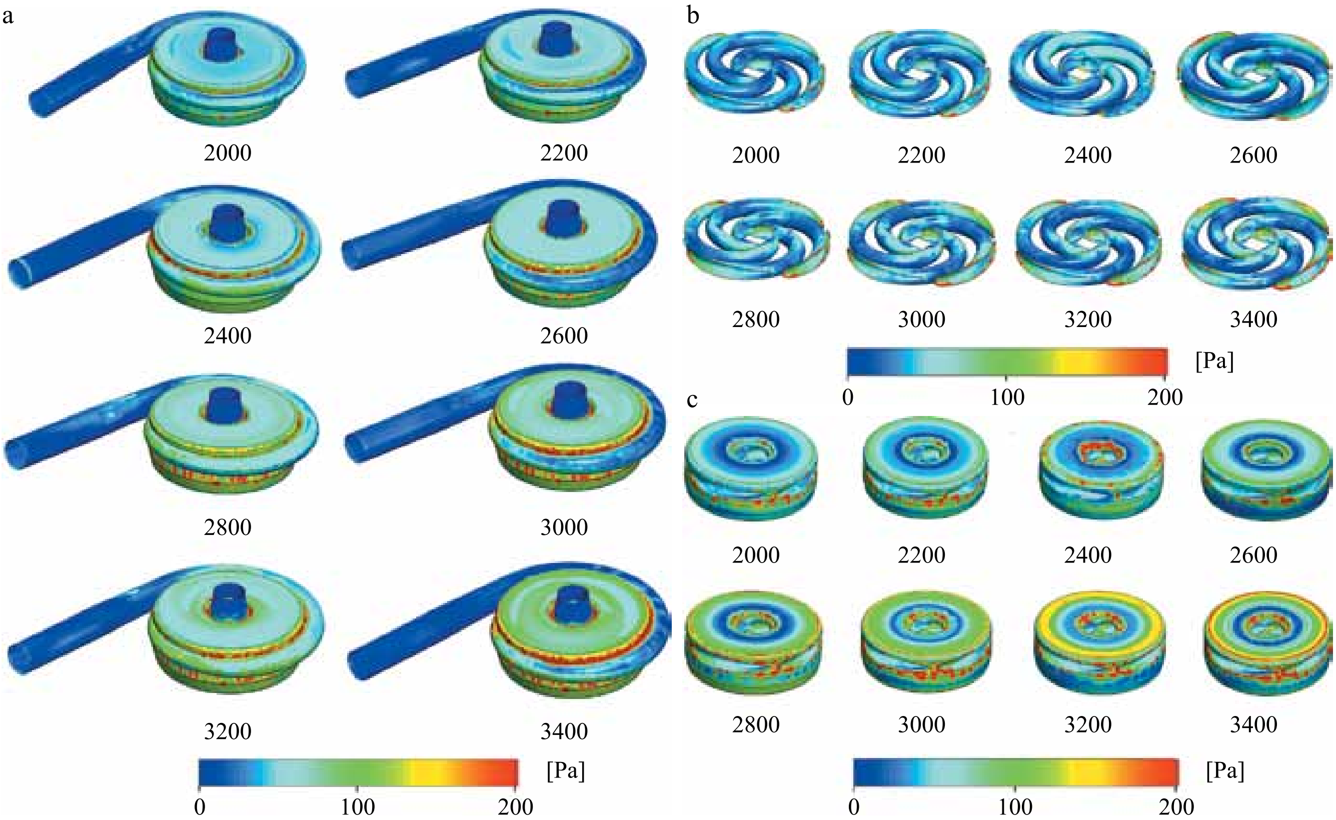

Fig. 3. Change of shear stress in the pump cavity (a), in the channels (b) and on the surface of the impeller (c) with an increase of the impeller's speed and a fixed flow rate of 5 l/min

this case, the maximum SS values in each considered pump zone were analyzed. It should be borne in mind that the SS values exceeding the critical threshold have a high scatter of values, from 150 to 500 Pa. In view of this, an estimate of HI for each value above 150 Pa is impractical. Therefore, an assumption was made, as a result of which the calculation of HI was made based on the maximum values of SS and *t* observed in a separate study area. As a result, it can be assumed that the calculation of the maximum HI will be somewhat overestimated, but nevertheless it reflects the main values of hemolysis. In addition to SS, to assess the effects of the pump on the blood, a numerical assessment of the surface area causing hemolysis of erythrocytes was carried out for each zone. In this case, the area is the sum of areas of high SS over 150 Pa. Fig. 6 shows the average and maximum values of the hemolysis index in each zone. These calculations objectively show the importance of optimizing IZ and LZ. The rest of the areas do not require significant improvement.

For example, the most critical pump operation mode in ECMO systems is considered, at an impeller speed of 3400 rpm. The average and maximum values of HI in the zones under consideration, the area of impact on erythrocytes and *t* for each zone were registered. The values have been recorded in the Table for a flow rate of 5 l/min.

DISCUSSION

The results of CFD modeling and mathematical calculation made it possible to analyze the design of the CCP with the assessment of SS and hemolysis under

Table

Distribution of parameters in the pump areas at the flow rate of 5 L/min and 3400 rpm

Zone	UZ	LZ	LZ	CZ	WWZ	SC	DZ
Mean SS, Pa	87.0	170.1	60.1	42.5	140.7	50.2	14.3
Max SS, Pa	189.2	533.3	189.2	185.3	359.0	157.1	100.7
Index by max SS	0.0083	0.042	0.0091	0.0037	0.0744	0.0105	0.0022
Zone area, mm^2	1726	1135	1688	3152	4435	1449	473
Zone area of high SS >150 Pa, mm^2 (% of zone)	100 (5.8%)	566 (49.8%)	302 (17.9%)	60 (1.9%)	788 (17.8%)	103 (7.1%)	0 (0%)
ET, s	0.0321	0.0115	0.0411	0.0352	0.0821	0.0832	0.0240

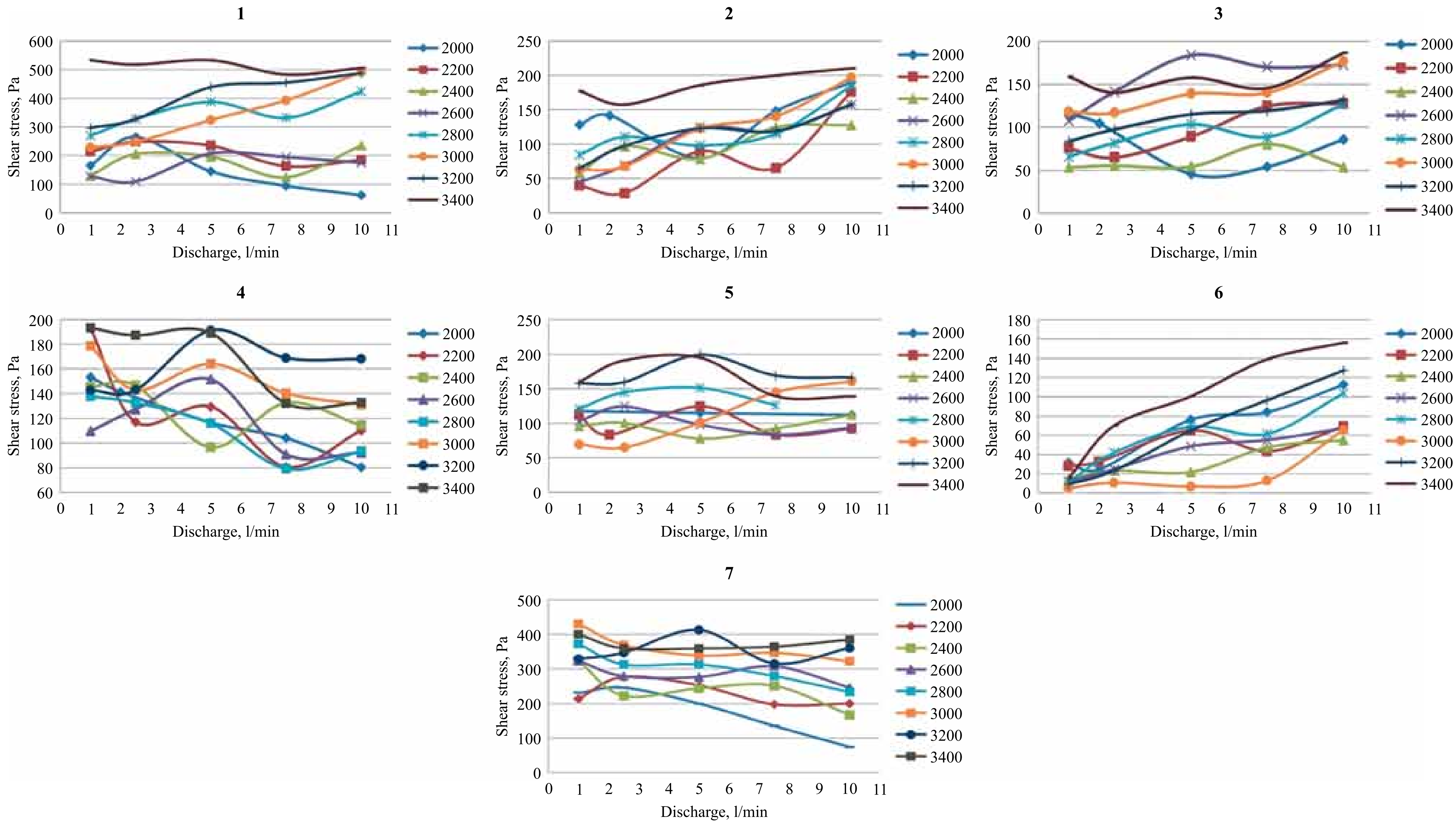

Fig. 4. Maximum shear stress in the studied zones: lateral (1), channel (2), SS (3), lower (4), upper (5), diffuser (6), and impeller (7)

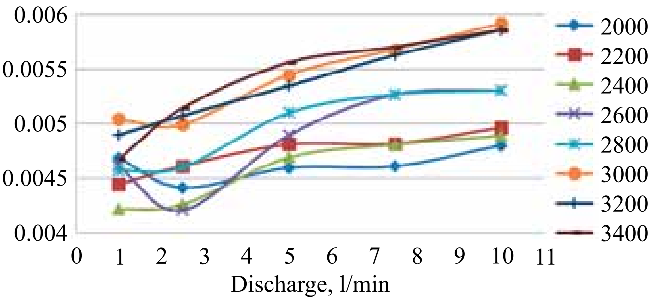

Fig. 5. Change in the calculated average hemolysis index of the channel centrifugal pump

conditions of its operation in LVC and ECMO systems in a wide range of blood flow rates. One of the main results of the calculation performed is the assessment of ET in various areas of the pump, which determines the duration of exposure to blood cells. The zones are characterized by a decrease in HI with increasing flow, which can be explained by a decrease in ET. It was shown that the calculated exposure time of blood for the zones does not exceed 0.09 s, which, together with SS in the range of 150–200 Pa, determines a low level of hemolysis for such zones as UZ, LZ, CZ and DZ. The SC zone has one of the highest ET, but low SS, which also provides a low I.I. In critical regions, such as LZ and I, the maximum ID values are 0.0420 and 0.0744. This is due to the high SS – 533.3 Pa on the inner side surface and 456 Pa on the side surface I, with a corresponding t of 0.0115 and 0.0821.

At maximum I speed, the area of influence on the blood corpuscles with SS above 150 Pa increases. On the example of the pump operating mode in the ECMO systems UZ, CZ, SC and LZ practically do not affect the blood. In LZ, there is a moderate spread of high SS. A significant predominance of high SS areas is seen in LZ and I.

It is also worth noting an increase in voltage in the spiral bend, especially in the area of transition to the diffuser at low and high liquid flows. This can be explained by the high pressure in this area and the high speed. High-velocity zones are associated with an increase in hydraulic resistance during the development of turbulent flow and an increase in fluid viscosity. This fact causes a sharp increase in the shear stress in the region of the transition of the helix to the diffuser for each I rotation speed.

The results obtained provide grounds for optimization of SC, LZ and WWZ, critical in terms of the impact on the blood of the pump zones. The most important decision seems to be to expand the SC area by increasing its throughput. Since the channels of constant cross-section provide optimal SS parameters, expanding the channel diameter by 5–7 percent will maintain flow at lower RPM I. This will reduce the radial flow velocity when leaving the channel, which in accordance with equation (1) will provide a decrease in SS. Increasing the lateral clearances between I and LZ will also decrease SS.

CONCLUSION

Computer-aided analysis of CFD in CAD systems is becoming the main tool for researching a variety of medical device designs for IPC. However, this tool has its limitations. The calculated SS ranges in the pumps are necessary to preliminary assess the hemocompatibility of the pumps in terms of the likelihood of blood injury and will serve as a basis for pump optimization.

The authors declare no conflict of interest.

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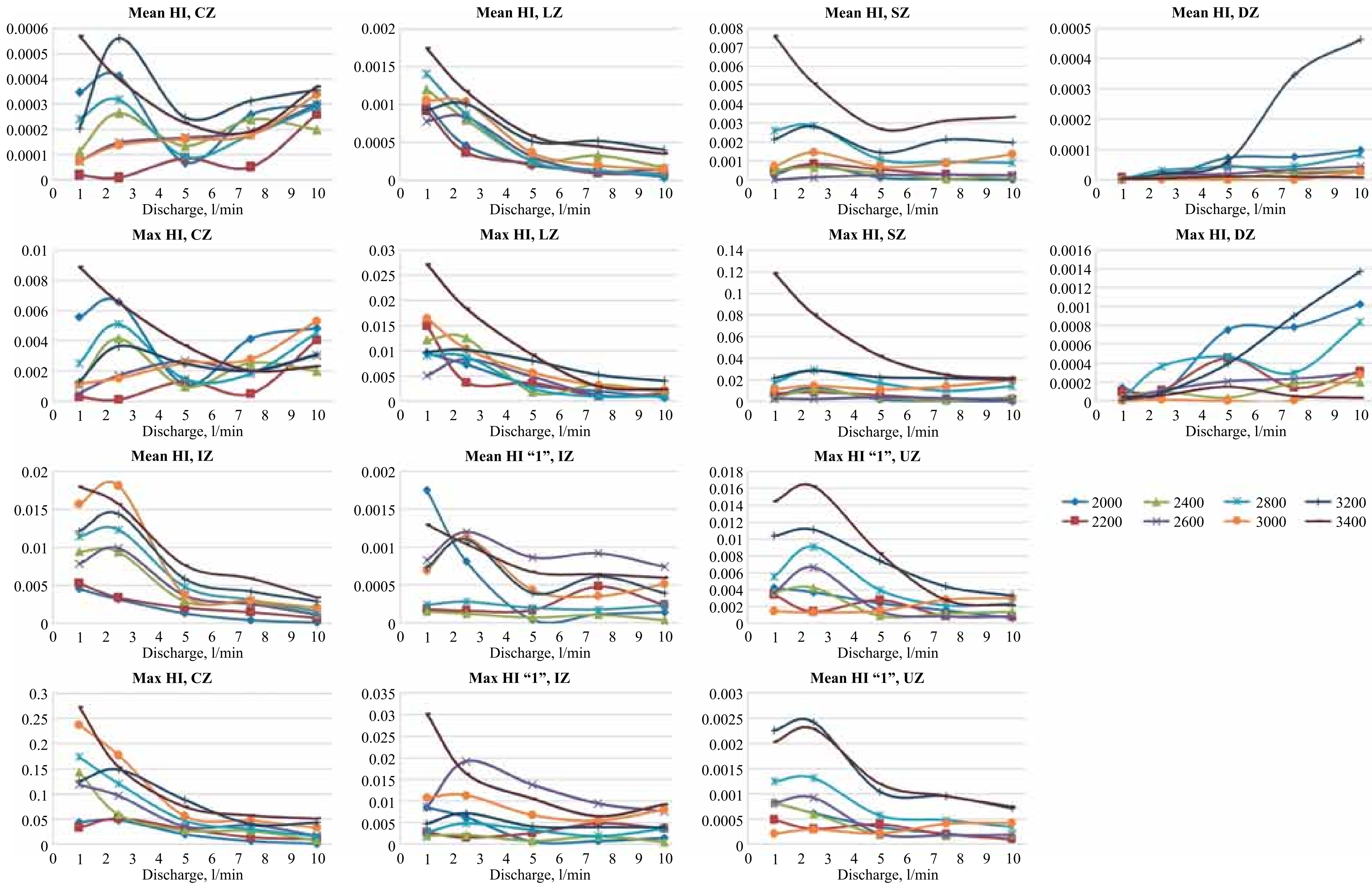

Fig. 6. Dependences of the mean and maximum hemolysis index (HI) in the studied zones of channel centrifugal pump