UDC 663

STUDY OF THE POTENTIAL FOR MODIFYING THE DESIGN OF A TURBINE STIRRER BLADE TO REDUCE THE EFFECT OF SHEAR STRESSES ON MICROORGANISMS IN CULTIVATION PROCESSES

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Abstract. *Stirring in bioreactors is an important element for the efficient cultivation of cell cultures in biotechnological production. But high-speed stirrers can create high level of shear stresses that negatively affect microorganisms. Therefore, it is important to develop the design of new stirring devices to minimize the negative impact of shear stresses on cells during cultivation. The purpose of this study is to analyze the effect of the designs of turbine stirring devices, proposed by authors, on the parameters of the stirring process during the cultivation of cell cultures by methods of computer modeling. The computer modeling was performed in ANSYS for the process of liquid stirring in a bioreactor. Two new designs of turbine stirrers have been proposed. The idea of the new design is to divide the working blade into two, i.e. to create a cutout in the blade. In the first case, the cutout is a rectangle, in the second - a parallelogram. To compare the efficiency of the proposed designs, we also modeled the stirring with a classical turbine 6-blade stirrer. Based on the modeling results, were obtained contours of the velocity distribution, turbulent kinetic energy, shear strain rate, velocity vectors, and ISO-surfaces forming the core of the rotation vortex. It was found that the presence of cutouts in the turbine stirrer does not lead to a decrease in the velocity of the main flows and redistribution of motion vectors, but significantly reduces the value of turbulent kinetic energy from and shear strain rate. The maximum value of turbulent kinetic energy for the classical stirrer is 2.489* m^2/s^2*, while for the*

stirrers with cutouts it barely reaches 1.245 m^2/s^2. The shear stresses decrease by 10 % from $19.63 \cdot 10^{-3}$ Pa for the classical design to $17.67 \cdot 10^{-3}$ Pa for the stirrer with parallelogram-shaped cutouts. The further development of this study will be to analyze the influence of the geometric parameters of the stirrer with parallelogram-shaped cutouts on the qualitative indicators of stirring. The results obtained in this work can be used by engineers and technologists to design bioreactors with reduced values of shear stresses.
Keywords: *bioreactor, stirring, turbine stirrer, shear stress, computer modeling, ANSYS*

Introduction. One of the key aspects of ensuring optimal conditions for the cultivation of cell cultures in biotechnology is stirring. The stirring process solves several important tasks at once (Maiorano et al., 2020; Singh, 1999):

- ensures the distribution of nutrients, which contributes to optimal cell growth and development;

- helps to keep the cells floating;

- intensifies oxygen transfer and metabolite removal;

- equalizes temperature and metabolite concentration gradients.

Thus, stirring in bioreactors is an important element for the efficient cultivation of cell cultures in biotechnology production.

However, high-speed stirrers, such as propeller and turbine stirrers, which are most commonly used in industry, also have a negative impact on microorganisms. Such phenomena include the occurrence of shear stresses due to the displacement of the culture liquid layers relative to each other (Huang et al., 2018). Shear stress can adversely affect microorganisms in various ways:

1. Excessive shear stress can lead to increased cell death, decreased cell growth rate and viability, or even cell lysis.

2. Shear stress affects biofilm formation and structure, which are strongly related to the extracellular electron transfer phenomena and bioelectrical performance of bioanodes (Yang et al., 2019).

3. Shear-reducing viscosity experienced by rotating cilia is the main reason for the increased swimming speed of bacteria in a Newtonian fluid (Qu & Breuer, 2020).

These factors directly affect the efficiency of cultivation processes, and therefore it **is extremely important** to develop new designs of stirrers to minimize the negative impact of shear stress.

Analysis of recent researches and publications. Ways to reduce the level of shear stress can be to reduce the viscosity of the culture medium, reduce the number of air bubbles, reduce the speed of rotation of the agitators, and change the design of the stirrer (BRANDY SARGENT, 2017). It is impossible to change the viscosity of the culture medium and the amount of air injected into the bioreactor due to the need to comply with all technological parameters of cultivation of a particular cell type. Reducing the speed of the stirrer rotation will lead to a decrease in the intensity of mass transfer and heat transfer processes, and therefore to a decrease in the efficiency of the bioreactor in general (Korobiichuk, Shybetskyi, et al., 2022). Therefore, the confirmation of the effectiveness of new stirrer designs that would reduce the level of shear stress is the basis of this work.

The following methods are used to determine the level of exposure of cells to shear stresses: studying the response of cells and tissues to shear stresses (Espina et al., 2023) and biomechanical studies of cells (Silvani et al., 2021).

These methods allow to assess the level of influence of physical quantities on cells, but they are expensive and difficult to perform; before using them, it is necessary to make sure that the proposed changes in the design of the stirrer will be effective. For this purpose, it is worth using various methods of mathematical and computer modeling. CFD modeling in ANSYS is a powerful tool for the analysis of new stirrer designs to reduce the level of shear stress (Korobiichuk et al., 2021).

CFD modeling makes it possible to consider various factors that affect the hydrodynamics and heat transfer in bioreactors, such as stirrer geometry, blade type and speed, fluid properties, chemical reactions, phase change, etc. This helps to obtain more accurate and realistic results than using simplified analytical models. Computer modeling also allows to optimize the design of the stirrer to achieve the desired goals. CFD modeling in ANSYS allows for parametric studies, multiple simulations, comparative analysis, and other methods to determine the optimal stirrers design that maximizes efficiency, uniformity, stability, and minimizes shear stress. This helps to reduce the cost of conducting a physical experiment (Korobiichuk, Mel'nick, et al., 2022).

The **purpose** of this study is to analyze the effect of the new proposed designs of mixing devices on the parameters of the mixing process during the cultivation of cell cultures by computer modeling in the ANSYS.

Methods. Computer modeling was carried out for the process of liquid stirring in a bioreactor. The main purpose of the simulation was to determine the efficiency of new designs of turbine stirrers, to establish the regularities of the distribution of liquid flows caused by their movement, and to compare their performance with the classical design. Two new designs of turbine stirrers were proposed for the study (Fig. 1, a, b). A unique feature of the new designs is the division of the working blade into two; in the first case, the cutout is a rectangle (Fig. 1, a), in the second - a parallelogram (Fig. 1, b). The total area of the blade remained unchanged. To compare the efficiency of the proposed structures, the stirring with a classical turbine 6-blade stirrer was also simulated (Fig. 1, c).

The geometric parameters of the stirring devices were calculated in accordance with generally accepted methods. The diameter of the stirrer in all cases is d_m=800 mm.

ANSYS software, FluidFlow (CFX) module, was chosen for modeling.

To implement the finite element method, the volume of the apparatus, which contains the medium and the stirrer, was divided into a set of mesh elements using the Mesh module. The number of elements is 380280, the number of nodes is 72888.

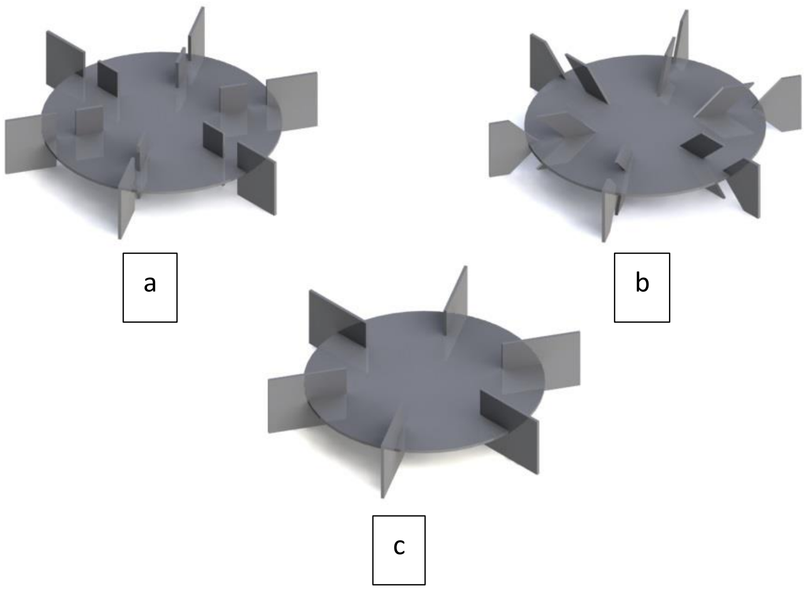

Fig. 1. 3-D models of stirring devices for the modeling process (without considering the hub): a - turbine stirrer with a rectangular cutout; b - turbine stirrer with a parallelogram-shaped cutout; c - classical turbine stirrer.

In the simulation, two computational domains were created (Fig. 2): the volume of the internal cavity of bioreactor 1 and the volume of the stirrer 2. Volume 1 has type "Fluid Domain" and consists of one substance – "Water". The properties of "Water" correspond to the physical properties of water at a temperature of 20 °C. Volume 2 has the type "Immersed body" and rotates around the Y-axis with a frequency of 3.3 s^{-1}.

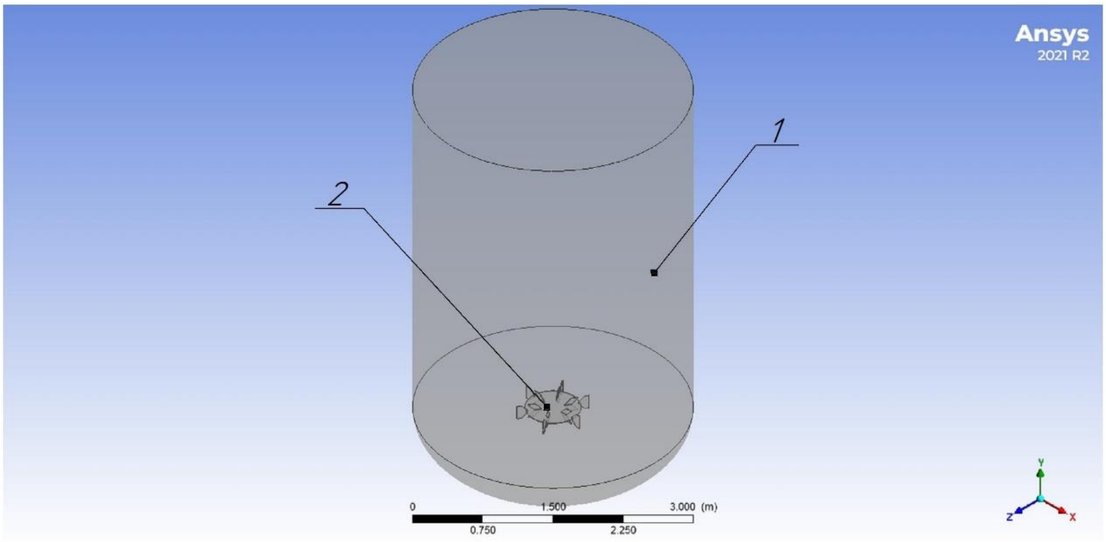

Figure 2. Computational domains: 1 - the volume of the bioreactor internal cavity; 2 - the volume of the stirring device.

Simulation type – "Transient". The total simulation time was 20 s, with time intervals from 0.01 s to 0.5 s to ensure a Courant number of less than 10.

The boundary conditions "Wall" were set on the outer surface of volume 1. The walls of the stirring device were automatically defined as the interface between the two volumes.

At the initial moment of time, the substance in the bioreactor is stationary, so the velocities u, v, ware 0. The pressure in the apparatus at the initial moment of time is 0.1 MPa.

Results. As the results of modeling were obtained the velocity, shear strain rate and turbulent kinetic energy distribution contours, velocity vectors, and ISO surfaces that form the core of the rotation vortex.

Fig. 3 shows the flow velocity contour in the longitudinal section of the bioreactor.

The profile of the velocity distribution in the cross-section of the stirrer is approximately the same; in the classical stirrer, the areas with velocities of 0.75-3.00 m/s are larger in area, although not significantly.

The distribution of velocities along the height of the bioreactor also has similar patterns, the differences are insignificant and can be explained by the non-stationarity of the mixing process.

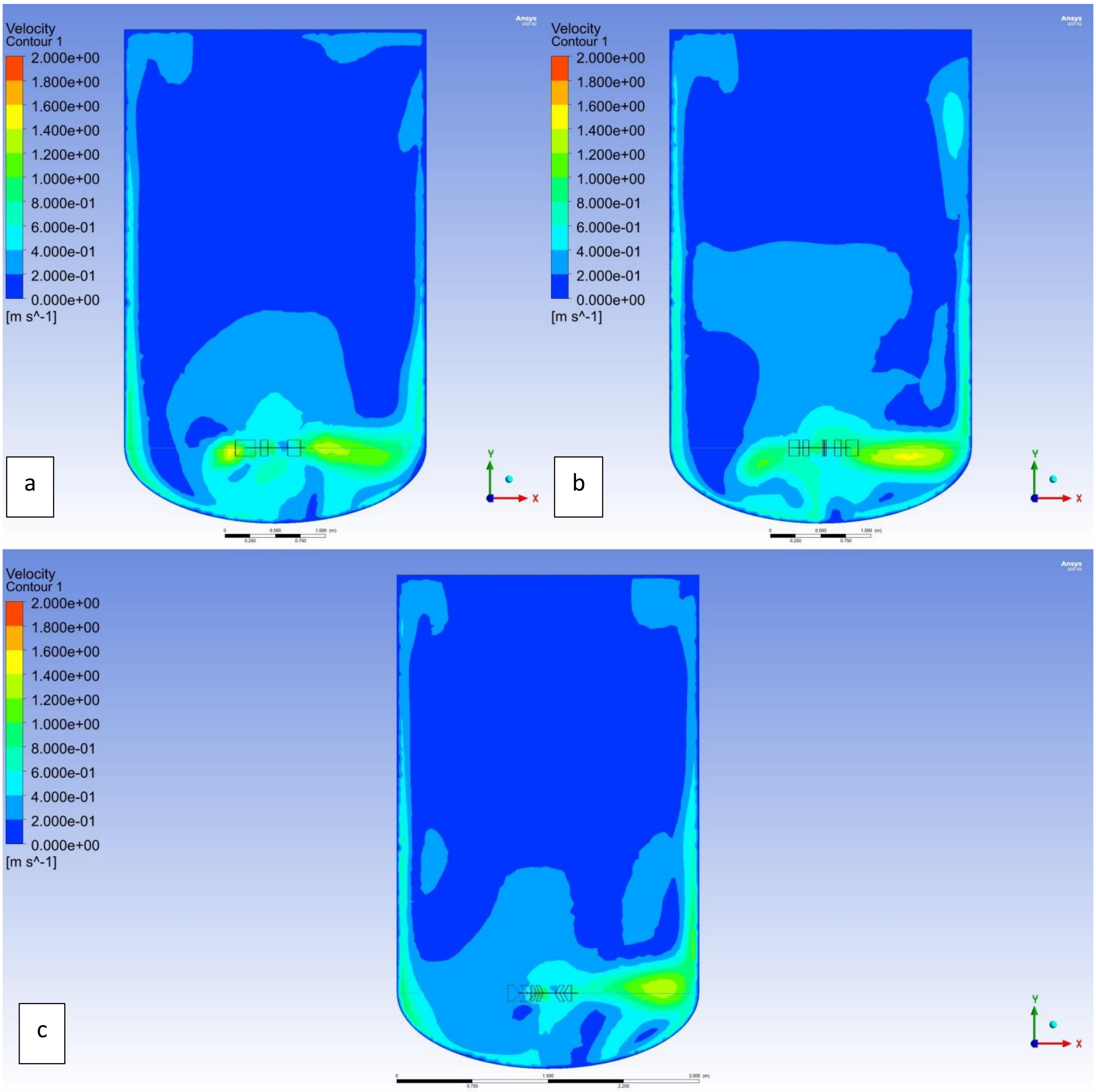

Fig. 3. Velocity contours: a - classical turbine stirrer; b - turbine stirrer with a rectangular cutout; c - turbine stirrer with a parallelogram-shaped cutout.

Figs. 4-5 show the distribution of fluid velocity vectors. Similarly to the velocity distribution contours velocity vectors in the plane of the stirrer shows the same pattern of vector distribution with the same vortex patterns and main flows generated by the stirrer blades (Fig. 4).

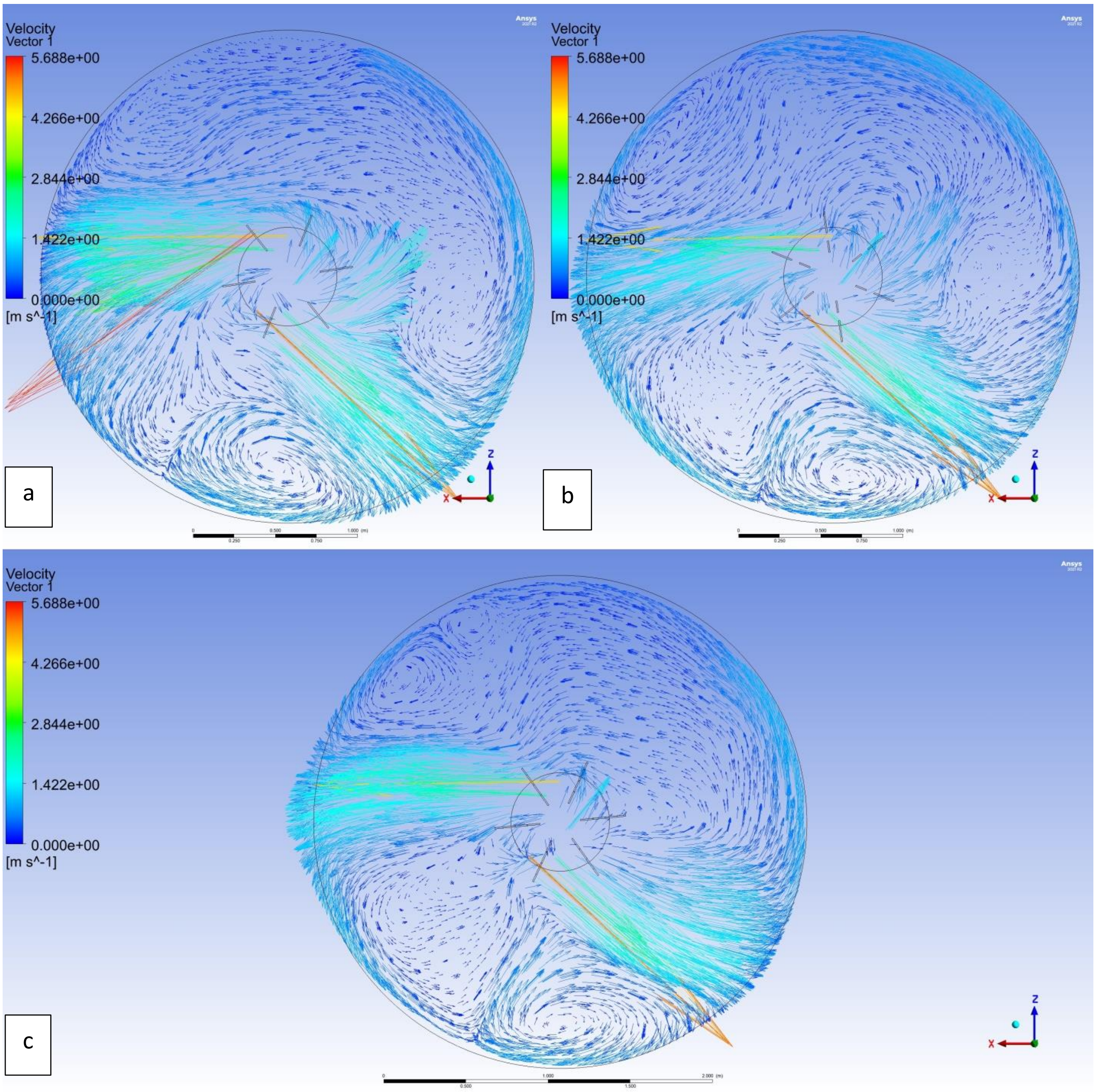

Fig. 4. Velocity vectors (stirrer plan): a - classical turbine stirrer; b - turbine stirrer with a rectangular cutout; c - turbine stirrer with a parallelogram-shaped cutout.

The longitudinal plan shows that for a stirrer with a rectangular cutout (Fig. 5, b), the area of liquid moving at a higher velocity than the overall liquid flow is more widely represented.

In Figs. 4-5, the maximum velocity limit is used to better understand the overall distribution of the fields. The maximum velocities of the fluid particles reach 7.5 m/s.

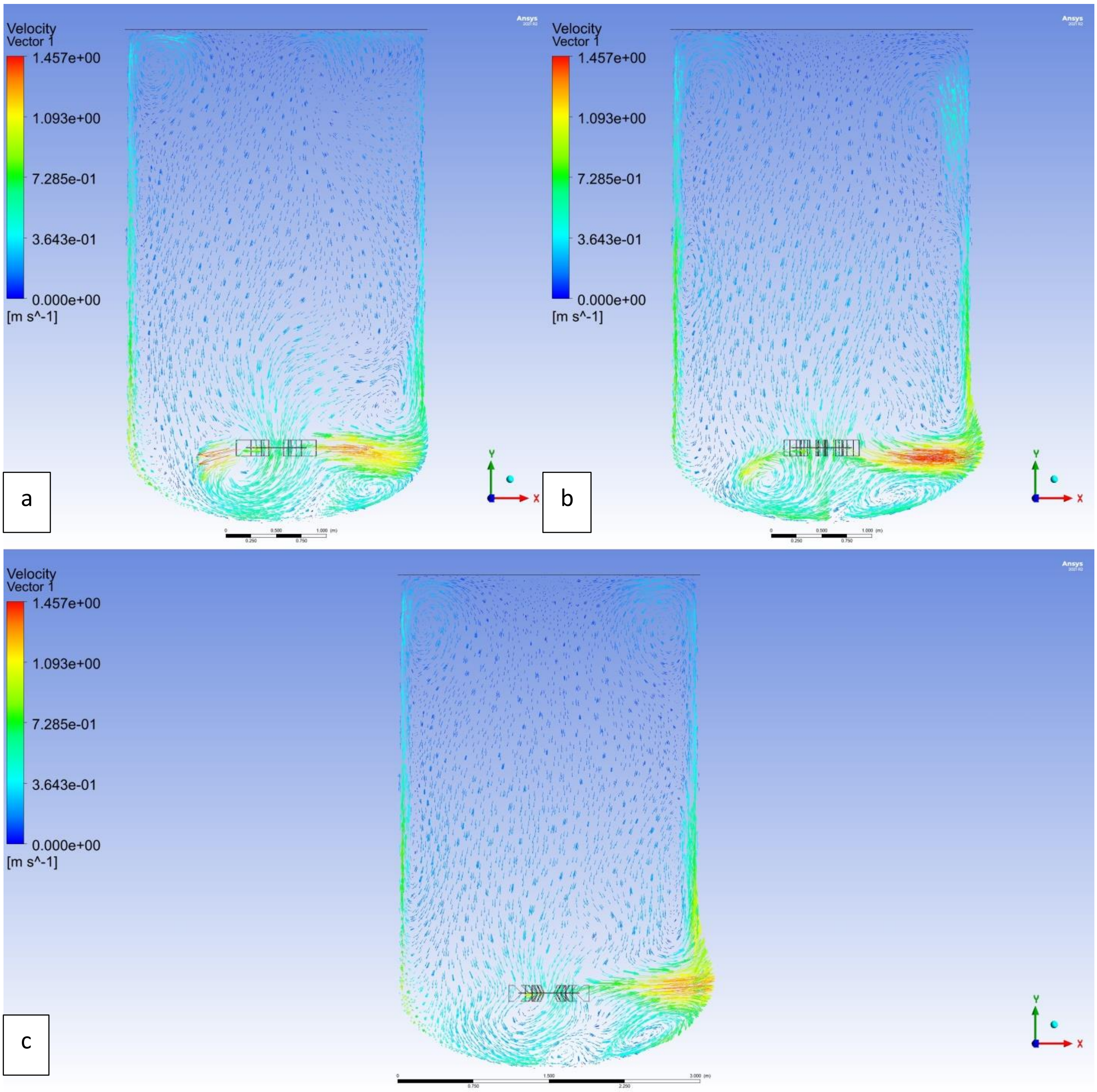

Fig. 5. Velocity vectors (longitudinal plan): a - classical turbine stirrer; b - turbine stirrer with a rectangular cutout; c - turbine stirrer with a parallelogram-shaped cutout.

To evaluate the degree of influence of stirring devices on microorganisms during the cultivation process, it is necessary to estimate the values of shear strain rate arising from stirring (Fig. 6). According to Newton's law of viscosity, the shear stress is directly proportional to the shear strain rate.

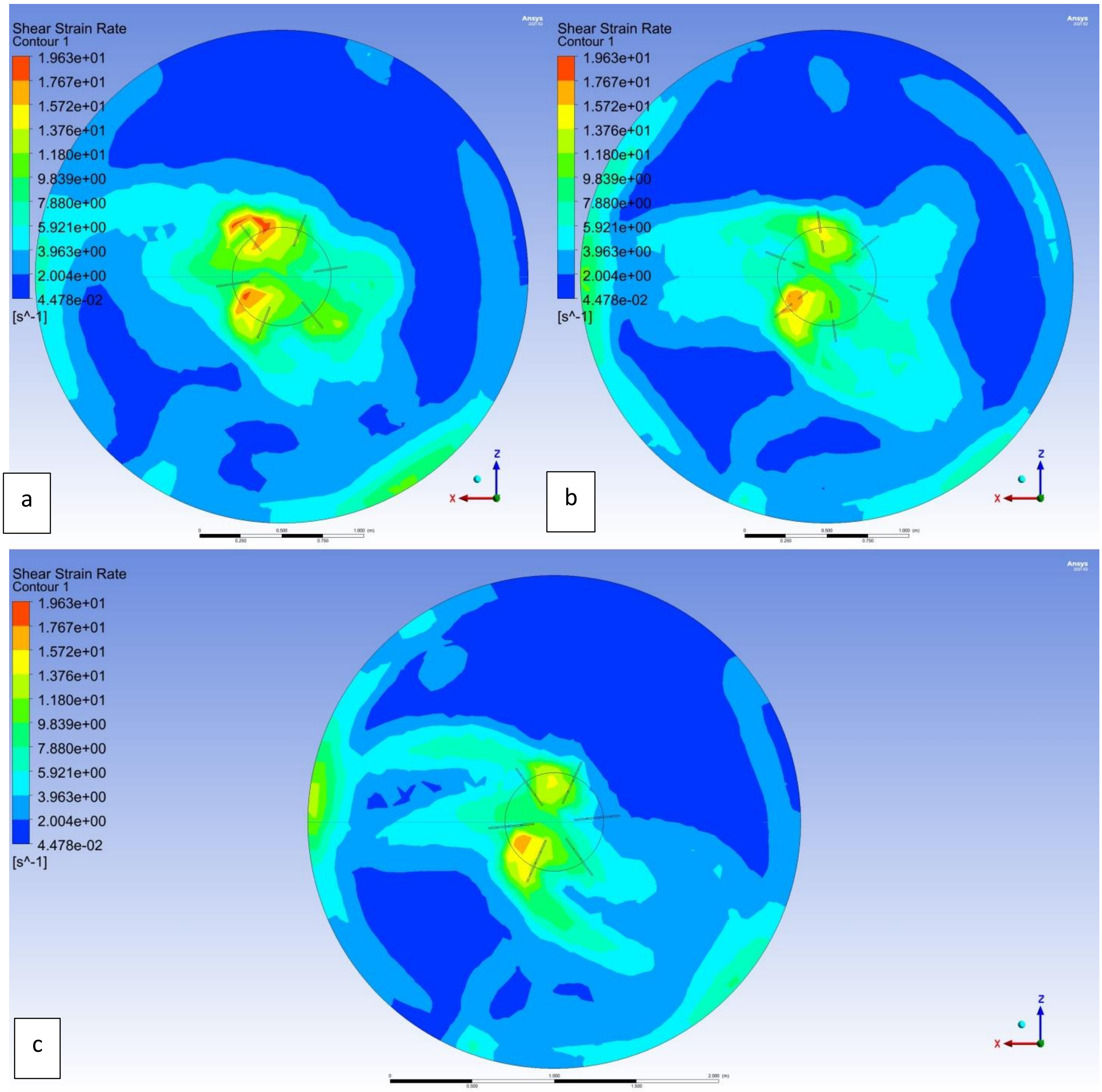

Fig. 6. Shear strain rate contours: a - classical turbine stirrer; b - turbine stirrer with a rectangular cutout; c - turbine stirrer with a parallelogram-shaped cutout.

In the case of using stirrer with a parallelogram-shaped cutout, a decrease in the shear strain rate is observed compared to a classical stirrer by up to 10 %. The value for the classical turbine stirrer reaches 19.63 s^{-1}, for the stirrer with a parallelogram cutout 17.67 s^{-1}. This is equivalent to shear stress values of $19.63 \cdot 10^{-3}$ Pa and $17.67 \cdot 10^{-3}$ Pa in the case of a medium viscosity close to that of water at a temperature of 20˚C.

When examining the contour of the change in shear strain rate along the height of the bioreactor, the smallest values and narrowest regions with increased values of shear strain rate are observed for the stirrer with parallelogram-shaped cutouts.

The formation of a vortex can also be used to assess the efficiency of the stirring device and determine the features of the combined action of axial and radial flows (Fig. 7).

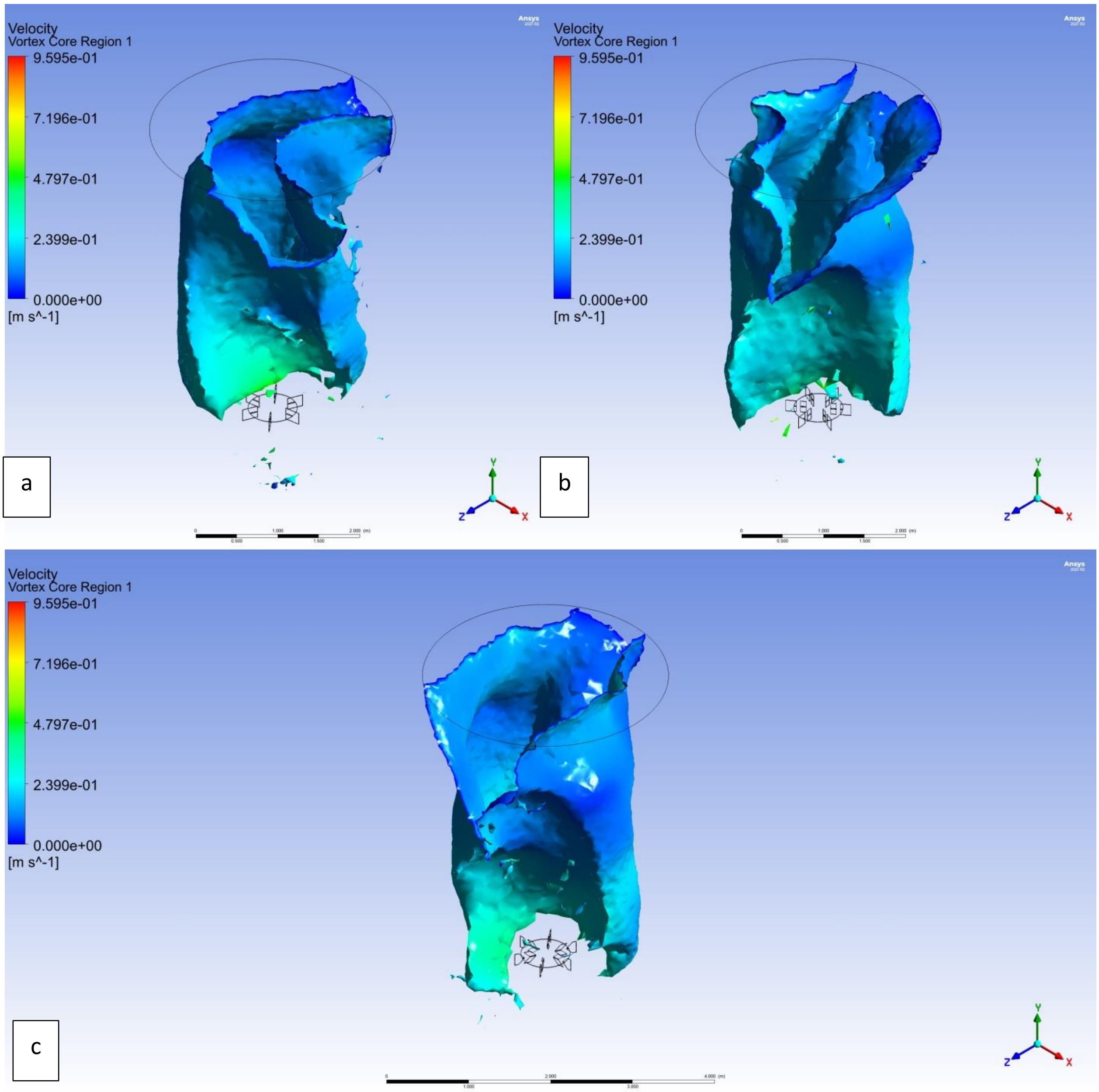

Рис. 7. Vortex core surfaces: a - classical turbine stirrer; b - turbine stirrer with a rectangular cutout; c - turbine stirrer with a parallelogram-shaped cutout.

The core of the vortex formed by all three agitators has the same structure, slightly deformed due to the non-stationarity of the flow.

Discussion. The conducted studies allow us to draw the following conclusions:

1. The presence of cutouts in the turbine stirrer does not lead to a decrease in the velocity of the main flows and redistribution of motion vectors, creating the same pattern of velocity distribution and an identical core of the vortex.

2. For a classical turbine stirrer, the value of turbulent kinetic energy increases significantly, with a maximum value of 2.489 m^2/s^2. Whereas for the stirrers with cutouts it barely reaches 1.245 m^2/s^2. The regions themselves are also wider, indicating significant turbulence near the stirrer.

3. To reduce negative impact on the microorganisms used in the cultivation process, it is advisable to use a stirrer with a parallelogram-shaped cutout. The maximum value of the shear stress for such a design is up to 10% lower than for a classical turbine stirrer. The shear stresses are $19.63 \cdot 10^{-3}$ Pa for a classical stirrer and $17.67 \cdot 10^{-3}$ Pa for a stirrer with a parallelogram-shaped cutout for medium with a viscosity of water at a temperature of 20˚C.

The results obtained in this work can be used by engineers and technologists to design bioreactors with reduced values of shear stresses.

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ДОСЛІДЖЕННЯ ПОТЕНЦІАЛУ ЗМІНИ КОНСТРУКЦІЇ ЛОПАТКИ ТУРБІННОЇ МІШАЛКИ ДЛЯ ЗМЕНШЕННЯ ВПЛИВУ НАПРУЖЕНЬ ЗСУВУ НА МІКРООРГАНІЗМИ В ПРОЦЕСАХ КУЛЬТИВУВАННЯ

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Анотація. *Перемішування в біореакторах є важливим елементом для ефективного культивування клітинних культур у біотехнологічних виробництвах, однак швидкохідні мішалки можуть викликати високі значення напруженнь зсуву, які негативно впливають мікроорганізми. Тому актуально розробляти конструкції нових перемішуючих пристроїв для мінімізації негативного впливу напружень зсуву на клітини під час культивування. Метою даного дослідження є аналіз впливу нових конструкцій турбінних перемішуючих пристроїв, запропонованих авторами, на параметри процесу перемішування при культивуванні клітинних культур методами комп'ютерного моделювання. Комп'ютерне моделювання проводилось в середовищі ANSYS для процесу перемішування рідини в біореакторі. Було запропоновано дві нові конструкції турбінних мішалок. Ідея нової конструкції полягає в розділенні робочої лопатки на дві, тобто створення отвору в лопатці. У першому випадку виріз є прямокутником, в другому – паралелограмом. Для порівняння ефективності роботи запропонованих конструкцій також проводилося моделювання перемішування класичною турбінною 6-ти лопатевою мішалкою. За результатами моделювання було отримано епюри розподілення швидкостей, турбулентної кінетичної енергії, напружень зсуву потоку, вектори розподілення швидкостей та ISO-поверхні, що утворюють ядро воронки обертання. Було встановлено, що наявність вирізів у турбінній мішалці не призводить до зменшення швидкості основних потоків і перерозподілу векторів руху, але суттєво знижує значення турбулентної кінетичної енергії та напруження зсуву потоку. Максимальне значення турбулентної енергії для класичної мішалки складає 2,489 $м^2/с^2$, тоді як для мішалок із вирізами ледь доходить до 1,245 $м^2/с^2$. Напруження зсуву зменшуються на 10 % з $19{,}63 \cdot 10^{-3}$ Па для класичної конструкції до $17{,}67 \cdot 10^{-3}$ Па у випадку мішалки із вирізами у формі паралелограмів. Подальшим напрямком розвитку даного дослідження буде аналіз впливу геометричних параметрів мішалки із вирізами у формі паралелограма на якісні показники перемішування. Результати отримані в роботі можуть бути використані інженерами і технологами для проектування біореакторів зі зниженими значеннями напружень зсуву.*

Ключові слова: *біореактор, перемішування, турбінна мішалка, напруження зсуву, комп'ютерне моделювання, ANSYS*