INFLUENCE OF TURBINE IMPELLER BLADE GEOMETRY ON HYDRODYNAMICS IN A BIOREACTOR: NUMERICAL SIMULATION IN ANSYS CFX

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Abstract
This study investigates the impact of turbine impeller blade geometry (rectangular, circular, triangular, and star-shaped) with identical cross-sectional area and volume on hydrodynamics in a bioreactor using ANSYS CFX. Flow velocity and shear strain rate distributions were analysed to assess mixing efficiency. The rectangular blade exhibited the highest flow velocity but also elevated shear stress, potentially harmful to sensitive cultures, while the triangular blade showed lower shear stress, suitable for delicate microorganisms. Results highlight the importance of blade geometry optimization for enhancing biotechnological processes.
Keywords: *bioreactor, impeller blade geometry, hydrodynamics, ANSYS CFX, shear strain rate, mixing efficiency, flow velocity*

Introduction. The mixing efficiency in bioreactors is a key factor in creating optimal conditions for the cultivation of microorganisms. It affects mass transfer, nutrient distribution, and cell viability. The geometry of the impeller blades determines the fluid flow characteristics, turbulence level, and shear stresses, which can both contribute to and limit the performance of bioprocesses [1]. Standard rectangular blades, as are widely used in industrial bioreactors, however, alternative forms can improve energy efficiency and reduce damage to sensitive crops.

The paper by Yang et al. investigated the effect of the new impeller configuration on fungal physiology and cephalosporin C production, where it was found that improved mixing and fluid homogeneity contribute to increased performance and reduced energy consumption [2]. Galaction et al.'s study analysed the mixing efficiency of immobilized yeast in a mobile bed bioreactor using six radial impellers, where it was found that the geometry of the impellers, in particular the Smith turbine, significantly affects the mixing time and homogeneity of the slurry [3]. These data emphasize the relevance of optimizing the geometry of agitators to increase the efficiency of bioprocesses.

The aim of the study is to compare the hydrodynamic characteristics of turbine impeller blades with different geometries: standard rectangular blade and modified shapes (round, star-shaped, and triangular) under conditions of the same cross-sectional area and volume using numerical simulations in ANSYS.

Materials and methods. The study was carried out using numerical simulations in the ANSYS 2021R2 software to analyse the hydrodynamic characteristics of a turbine impeller with different blade geometries in the bioreactor [4, 5]. A model of a cylindrical bioreactor with a height and diameter of 240 mm (volume of approximately 10.86 L) was used as a fermenter. The bioreactor was filled with 2/3 of water, which was used as a model medium for simulation of the nutrient medium.

For mixing, a turbine impeller with a diameter of 80 mm was used, located on a shaft at a distance of 50 mm from the bottom of the bioreactor. Four configurations of blade geometry were investigated: rectangular (standard blade with an aspect ratio of

4:3), round, star-shaped, and triangular, with the impeller diameter for round, triangular, and star-shaped blades being able to vary slightly to keep the blade surface area equivalent. The cross-sectional surface area of each blade was 300 mm^2. Schematic sections of the blades are shown in (fig. 1). The rotation speed of the agitator was fixed and was 250 rpm.

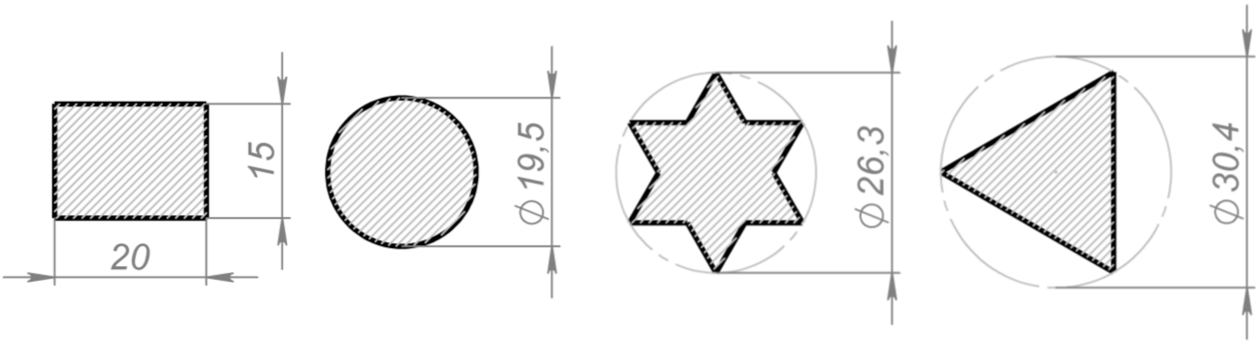

Fig. 1. Schematic sections of blades with the same area of 300 mm^2, and their dimensions, where: a - rectangular blade, b - round blade, c - star-shaped blade, d - triangular blade.

Numerical simulations were performed in ANSYS CFX using the SST (Shear Stress Transport) turbulence model and a multiphase model that took into account 2/3 of the filling of the bioreactor with water. The calculated grid consisted of approximately 1.6 million elements, and to ensure the convergence of the model, about 50 thousand iterations were carried out. Simulation conditions included a temperature of 20°C and atmospheric pressure.

Hydrodynamic characteristics, including flow rate distribution, turbulence intensity, and shear stress, were evaluated to determine the mixing efficiency of each impeller configuration. The simulation results were processed in the ANSYS CFX Function Calculation, where an analysis of the velocity, turbulence, and local shear stress distributions was performed to compare the performance of different impeller blade geometries.

Results and discussion. Numerical simulations of the hydrodynamic characteristics of a turbine impeller with different blade geometries (rectangular, round, star-shaped, and triangular) were performed in ANSYS CFX to evaluate mixing efficiency in the bioreactor. Flow rate distribution, turbulence, and shear strain rate were analysed using the ANSYS CFX Function Calculation.

Plots of the flow rate distribution in the horizontal plane of the bioreactor (fig. 2) show that the rectangular blade creates the largest zone of high flow rate, while the triangular blade forms less intense turbulence, which can affect mixing uniformity.

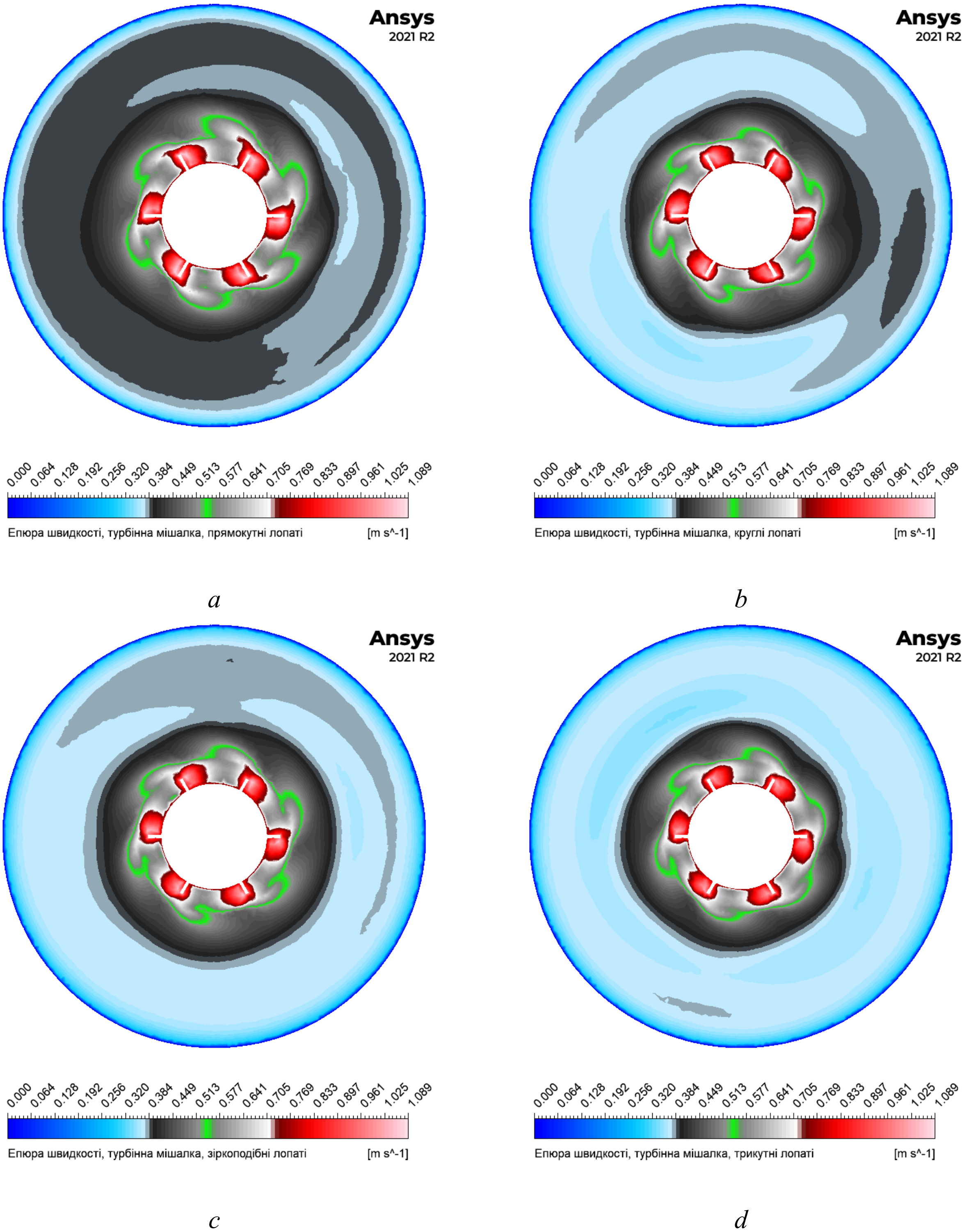

Fig. 2. Plots of the distribution of flow velocity in the horizontal plane m/s, where: a - rectangular blade, b - round blade, c - star-shaped blade, d - triangular blade.

The simulation results (Table 1) show that the rectangular blade has the highest average flow rate (0.335 m/s) and maximum velocity (0.920 m/s), but also the highest shear stress (106.8 s^{-1}), which can damage sensitive crops. The triangular blade showed the lowest velocity values (0.321 m/s and 0.761 m/s) and shear stress (88.9 s^{-1}), making it preferable for delicate microorganisms.

Table 1. Results of modelling hydrodynamic characteristics for different blade geometries derived from the ANSYS CFX Function Calculation.

Blade geometry	Average speed, m/s	Maximum speed, m/s	Maximum Shear stress, s^{-1}
Rectangular	0.335	0.920	106.8
Round	0.327	0.850	93.2
Star-shaped	0.324	0.826	95.2
Triangular	0.321	0.761	88.9

The results are consistent with the literature: Yang et al. [2] confirm that optimized geometry drives blending, and Galaction et al. [3] emphasize the effect of geometry on blending time. A rectangular blade is effective for rapid mass transfer, but a triangular blade is preferable for sensitive crops due to its lower shear stress. The limitation is the use of water as a medium, which requires further modelling with real media.

Conclusions. Numerical simulations of the hydrodynamic characteristics of the turbine impeller in the ANSYS CFX revealed a significant effect of blade geometry on mixing efficiency in the bioreactor. The standard rectangular blade provides the highest average (0.335 m/s) and maximum (0.920 m/s) flow rates, as well as intense turbulence, which contributes to rapid mass transfer but is accompanied by high shear stress (106.8 s^{-1}), which can be harmful to sensitive microorganisms. The triangular blade, on the other hand, exhibits the lowest values of velocity (0.321 m/s and 0.761 m/s) and shear stress (88.9 s^{-1}), making it a better choice for bioprocesses with delicate crops, although it can prolong mixing times. The round and star-shaped blades showed intermediate characteristics (velocities 0.327 – 0.324 m/s, shear stress 93.2 – 95.2 s^{-1}), which ensures their versatility for a wide range of biotechnological applications. The results obtained highlight the need to choose the geometry of the impeller depending on the specifics of the bioprocess and the sensitivity of crops, as well as the need for further studies with real culture media to take into account their viscosity.

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