INVESTIGATION OF THE INFLUENCE OF SPIRAL BAFFLES ON THE HYDRODYNAMICS IN BIOREACTOR JACKETS

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Abstract
The study investigates the hydrodynamics of fluid flow in a bioreactor equipped with a conventional jacket featuring spiral baffles. Emphasis is placed on analysing the influence of spiral geometry on flow behaviour and pressure drop, with the goal of optimizing flow conditions to enhance heat transfer efficiency.

Keywords: *bioreactor, conventional jacket with spiral baffles, hydrodynamics, flow optimization*

Introduction. Fermenters are key equipment in the food, biotechnology, and pharmaceutical industries, enabling the cultivation of microorganisms, biomass accumulation, and the synthesis of target products. The main components of a fermenter include the conventional jacket, agitators, spargers, sterilizing filters, baffles, and parameter control systems. The technical specifications and operational efficiency of the equipment are largely determined by its design features, which significantly affect heat transfer, mass transfer, and hydrodynamic processes within the reaction zone [1].

The heat exchange jacket is a critical element of the fermenter, providing effective heat exchange and maintaining the required temperature regime. Several structural types of heating and cooling jackets exist, including conventional jackets, conventional jackets with guiding baffles, half-pipe jackets, conventional jackets with nozzles for flow tubulisation, and dimpled jackets. In some cases, internal spiral coils are also employed. The choice of heat exchange jacket type and the necessity for zonal temperature regulation depend on the thermodynamics of the process, sanitary and hygienic requirements, the presence of exothermic reactions, and the demands for heat transfer intensity [2].

The aim of this study is to analyse the influence of the spiral baffle geometry on the conventional jacket channel, to determine the flow parameters, and to assess their impact on heat transfer efficiency, with subsequent optimization of the spiral pitch to enhance heat transfer performance.

Materials and Methods. The study focuses on the analysis of the hydrodynamic characteristics of a conventional jacket equipped with a spiral baffle compared to a typical heat exchange jacket without additional elements. Particular attention is paid to the impact of spiral geometry on the flow structure of the heat carrier, specifically on flow velocity, flow regime (laminar, transitional, or turbulent), and heat transfer efficiency. Three configurations are considered: a typical heat exchange jacket, a conventional jacket with a spiral baffle height of 18 mm, and a conventional jacket with a spiral baffle height of 180 mm.

Analytical calculations were performed according to the classical methodology outlined in [3], utilizing the energy equation, as well as Reynolds (Re), Nusselt (Nu), and Prandtl (Pr) numbers to evaluate the thermal regime.

The heat transfer coefficients were calculated using the following correlations:

For the typical heat exchange jacket:

$$Nu = C \cdot (Gr_{\text{в}} \cdot Pr_{\text{в}})^{a}, \tag{1}$$

where C = 0,76, $Gr_{\text{в}}$ – is the Grashof number for water, $Pr_{\text{в}}$ – is the Prandtl number for water, and a = 0,25 for $10^3 \leq Gr_{в} \cdot Pr_{в} \leq 10^9$.

For conventional jackets with a spiral baffle:

$$Nu = 0{,}17 \cdot Re^{0{,}33} \cdot Pr_{B}^{0{,}43} \cdot Gr_{\text{в}}^{0{,}1} \left(\frac{Pr_{\text{в}}}{Pr_{\text{ст}}}\right)^{0{,}25}, \tag{2}$$

where $Pr_{\text{ст}}$ – is the Prandtl number at the wall surface.

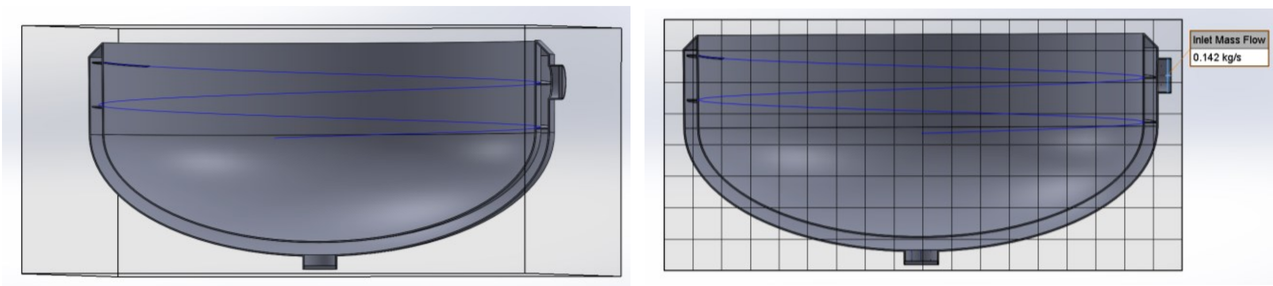
The heat transfer coefficient was determined using the following formula:

$$\alpha = \frac{Nu \cdot \lambda_B}{d_{\text{екв}}}, \tag{3}$$

where λ_B – is the thermal conductivity of water and $d_{\text{екв}}$ – is the equivalent diameter.

The calculation sequence included: for conventional jackets with spiral baffles, the Reynolds number was determined first, followed by the Nusselt number and the heat transfer coefficient; for the typical heat exchange jacket, the Nusselt number was directly determined via the Prandtl number, followed by the heat transfer coefficient calculation. The average flow velocities, hydrodynamic regime, as well as the heat transfer coefficients and overall heat transfer performance, were determined.

To verify the results, computer simulations were performed using SolidWorks Flow Simulation, as described in more detail in [4]. Three-dimensional models of the conventional jackets with specified geometric parameters were constructed (Fig. 1a), followed by setting up the computational mesh and boundary conditions (Fig. 1b) to ensure the accuracy of the analysis.



A **b**

Fig. 1. (a) Three-dimensional model; (b) Computational mesh and boundary conditions for the conventional jacket with a spiral baffle, h=180 mm.

Results and Discussion. For the typical heat exchange jacket, the water flow velocity was determined to be 0.0024 m/s, indicating a laminar flow regime (Re = 228). This low flow velocity does not provide sufficient conditions for active fluid mixing, thereby limiting the heat transfer process. The fluid moves in uniform layers, preventing effective heat exchange through the jacket walls.

Simulation results (Fig. 2) obtained using SolidWorks Flow Simulation confirmed that in the typical heat exchange jacket, the flow remains laminar with low flow velocities. The hydrodynamic conditions do not promote the development of turbulent eddies, thus restricting heat transfer efficiency.

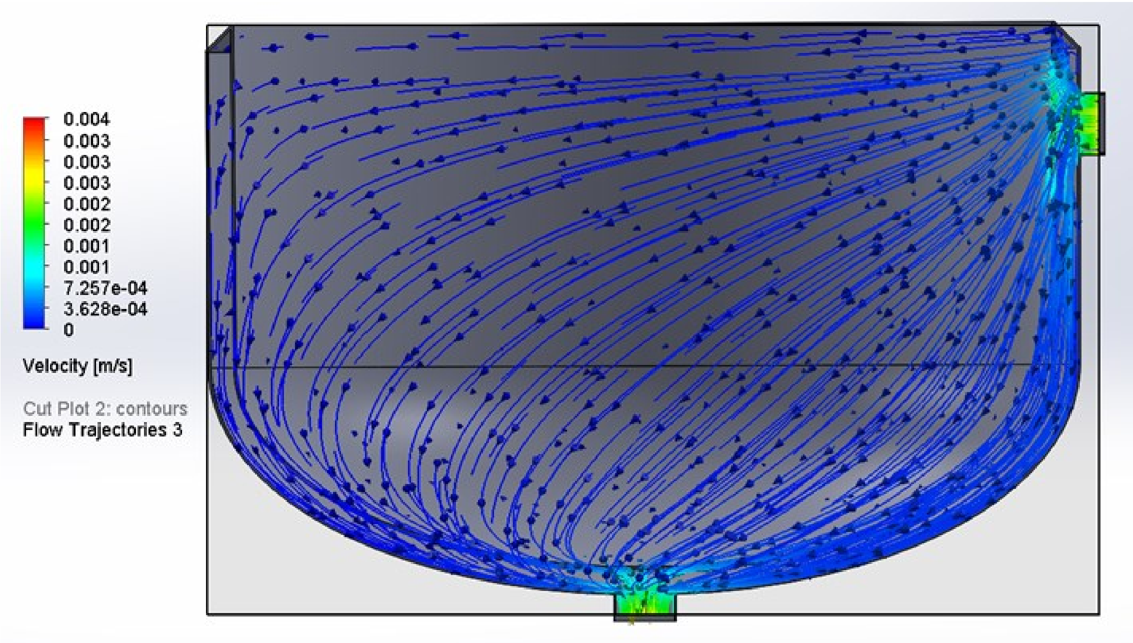


Fig. 2. Velocity distribution map of the heat carrier in the typical heat exchange jacket.

The results showed that the conventional jacket with a channel height of 180 mm exhibited a water flow velocity of 0.016 m/s, corresponding to a laminar flow regime (Re = 1236). Laminar flow indicates that the fluid moves uniformly without chaotic eddies, resulting in weak fluid mixing within the channel and limiting the heat exchange process between the jacket wall and the heat carrier.

Simulation results (Fig. 3) confirmed that the flow velocity remained almost unchanged, further verifying the laminar nature of the flow. Under such conditions, hydrodynamic inertia is insufficient to promote effective movement of the heat carrier, leading to low heat transfer coefficients and limited heat transfer intensity.

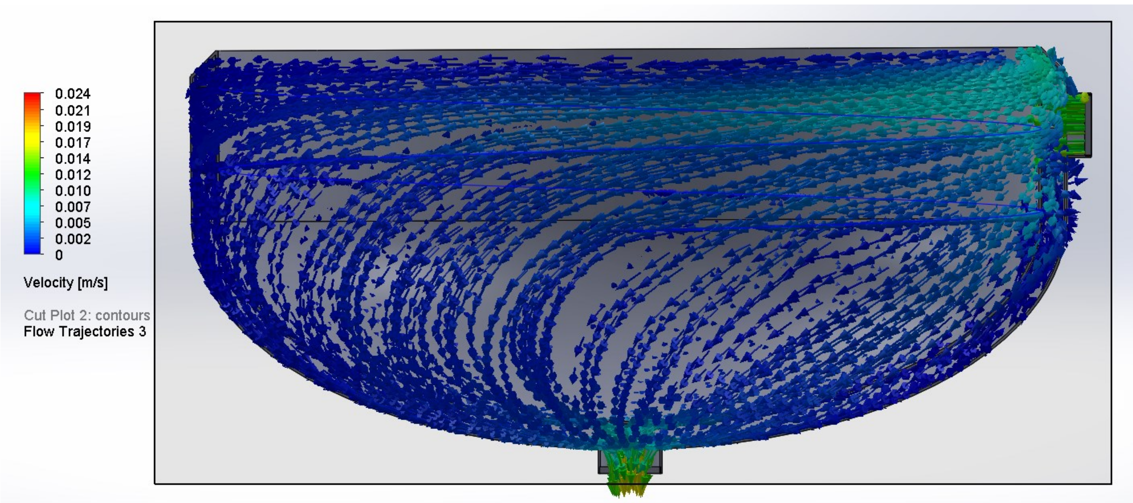


Fig. 3. Velocity distribution map of the heat carrier in the conventional jacket channel with a spiral baffle, h=180 mm.

In the case of the conventional jacket with a channel height of 18 mm, the water flow velocity was significantly higher, reaching 0.158 m/s, corresponding to a transitional flow regime (Re = 4067). The increased flow velocity promotes greater turbulence, which enhances fluid mixing and improves heat transfer efficiency. In this regime, the heat carrier undergoes active mixing, significantly increasing the heat transfer coefficient.

Simulation results (Fig. 4) showed that at higher flow velocities, vortices were formed, indicating a transition toward a turbulent flow regime. This transition enhances heat exchange by increasing the effective surface area for heat transfer. However, reducing the channel size to 18 mm also leads to a rise in hydraulic resistance, negatively affecting flow uniformity and increasing energy consumption due to higher friction between the fluid and the channel walls.

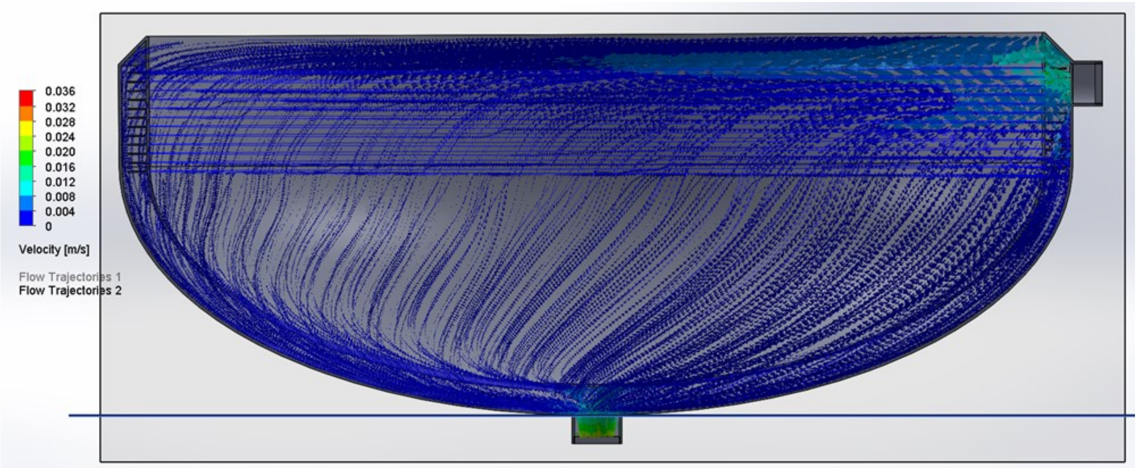


Fig. 4. Velocity distribution map of the heat carrier in the conventional jacket channel with a spiral baffle, h=18 mm.

Conclusions. A comprehensive study was conducted to investigate the influence of spiral baffle geometry on hydrodynamics and heat transfer in fermenter heat exchange jackets. Analytical calculations for channels with heights of 180 mm, 18 mm, and a conventional design allowed the determination of flow velocity, Reynolds number, and heat transfer coefficients.

Simulation results in SolidWorks Flow Simulation confirmed that the use of a spiral baffle improves hydrodynamic conditions and heat exchange efficiency. The channel geometry significantly affects turbulence intensity and heat transfer, making spiral designs superior to conventional ones.

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