PARAMETRIC OPTIMIZATION OF CURVILINEAR CONFUSER-TYPE CHANNEL

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Abstract. Parametric optimization of a curved channel was made with changing the geometric shape under pre-set conditions when liquid or gas flows through it. Mathematical modelling of hydrodynamic processes was performed in curved channels of the confuser type. As a result of numerical modelling of the hydrodynamic processes, using the ANSYS Fluent CAD software product, the distributions of velocities and pressures in the confuser channel were obtained. The optimal curved channel profile was selected based on the conditions of minimal pressure losses in the channel. The obtained results may be used in the design of the heat exchange and aerodynamic equipment.

Keywords: parametric optimization, curved channels, confuser, pressure, velocity (speed), laminar flow.

Introduction

When designing devices with hydrodynamic flows, an important feature of the flow channels is the pressure loss in these channels when liquid or gas is flowing. Such channels are found, for example, in the wind generators, turbines, heat exchangers, etc. Therefore, it is necessary to select a channel geometry that will minimize these losses. An optimal geometry of the channel is determined as a result of solving an optimization problem by changing the geometric shape of the channel, with constant parameters of the liquid or gas flowing through it.

Wang et al. [1] presented multi-objective optimization algorithms to optimize the compactness, pressure drop, and thermal performance of AFF PCHE under different inlet velocity conditions. Said et al. [2] optimized C-shaped PCHEs by combining a multi-objective genetic algorithm (MOGA), machine learning, and CFD modelling. Zeng et al. [3] presented an improved PSO-BP neural network, combined with NSGA-II algorithm, to design AFF PCHE. Jiang et al. [4] selected four parameters to optimize AFF PCHE by integrating machine learning, CFD modelling and optimization algorithms.

In recent years, Bezier curves have attracted considerable attention due to their effectiveness as a method for parametrizing shapes in aerodynamic studies [5-7]. However, the studies have not yet been used to optimize the thermal-hydraulic characteristics of AFF PCHE. The Bezier curve is defined by a set of control points P_k with $m + 1$ parameters [8].

As a continuation of the study, the authors [9; 10] conducted an experimental research of a new design of the wind flow concentrator, using an aerodynamic subsonic wind tunnel. As a result, it was found that in the area of the wind generator blades, the speed of the air masses increases 4 times, compared to the speed of air at the entrance to the wind flow concentrator. An assessment was made of the use of a wind flow concentrator to improve the efficiency of the vertical axis wind turbines.

When optimizing a curved channel, the best solution of the problem is to select such parameters of the curved channel that meet the specified requirements for the channel geometry, as well as the conditions and limitations for the hydrodynamic flow in this channel. In a mathematical optimization problem the solution is formulated as a search for the extremum (maximum or minimum) of a given objective function [11]. The objective function is known a priori and is determined by an analytical dependence on one or more independent arguments (parameters).

If a function $F(X)$ is defined on a set X from an n-dimensional Euclidean space R^n that has extreme values, then the optimization problem consists of finding the extrema of this objective function

$$\text{Extr } F(X), \text{ where } X \in R^n. \quad (1)$$

In the future, we will consider only the minimization problem of a function for which we can also reduce the problem of finding the maximum of a function

$$\min F(X), \text{ where } X \in R^n. \quad (2)$$

The solution to the optimization problem consists of finding the global minimum X*, where the objective function has the smallest value over the entire feasible region

$$F(X^*) \leq F(X), \forall X \in R^n. \quad (3)$$

Based on the analysis of literary sources, it can be concluded that the issues of optimization of curvilinear channels, which are used in various power plants, have not been sufficiently studied. Therefore, it is relevant to solve the optimization problems for such channels that make it possible to reduce the aerodynamic flow resistance and improve the characteristics of the energy devices.

Materials and methods

In order to analyse the influence of different geometric dimensions and improve the performance of the curved channel, structural variables, corresponding to diverse geometric dimensions of the channel, were defined and varied within certain limits. In this parametric model of a curvilinear channel a layout scheme has been developed, the analysis of which determines all channel control parameters [12]. These are the main dimensions that control all the other dimensions of the 2D channel model (Fig. 1). The main parameter is the radius of the arc of the channel sidewalls R1. For this parameter the corresponding variables considered are the main variables of the 2D model parameters. The dimensions of radius R2 (inlet to the channel) and R3 (outlet from the channel) remain unchanged. Thus, it is necessary to optimize the size of the radius R1, i.e. the radius of curvature of the channel to its outlet, which has a radius R3.

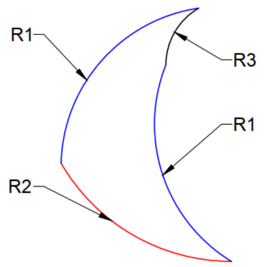

Fig. 1. **External appearance of a curved channel**

To solve the problem of parametric optimization of a curved channel, using static and dynamic parameters, the radius of the arc of the side wall of the channel was used as a variable main parameter. It varied over a wide range (from 110 mm to 250 mm) with a step of 20 mm. The area was monitored with the highest values of velocity and pressure at the channel outlet (with radius R3).

During the optimization process, based on the main geometric dimensions of the channel, the values of the optimization parameters were selected in such a way that, when changing the channel dimensions, they would allow for minimal hydraulic losses for maximum flow velocity at the exit from the channel.

For the investigation there was used commercial software ANSYS Fluent to solve the equations of the flow in the channel. Mathematical modelling of the processes of the air mass transfer in a curved confuser-type channel is done, applying the Navier-Stokes equation in a two-dimensional formulation in the laminar flow mode, which is typical for the movement of the air flows in channels of this type [13]:

$$\left.\begin{aligned} \rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)&=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right),\\ \rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)&=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right),\end{aligned}\right\} \quad (4)$$
$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0.$$

The following boundary conditions are set for the walls of the channel and at its inlet and outlet:

$$u(t=0)=v(t=0)=0\,;$$

$$\text{at } x=x_{i,wall}\,,\ y=y_{i,wall}\,;\ i=1,2\,;\ u=v=0\,;\ \frac{\partial u_{i,wall}}{\partial \bar{n}}=\frac{dv_{i,wall}}{\partial \bar{n}}=0\,;$$

$$\text{at } x=x_{in}\,;\ y=y_{in}\,;\ u_{in}=v_{in}=W_0\,; \tag{5}$$

$$\text{at } x=x_{out}\,;\ y=y_{out}\,;\ \frac{\partial u_{out}}{\partial x}=\frac{\partial v_{out}}{\partial y}=0\,.$$

The following notations are adopted for this model: x, y – Cartesian coordinates; t – time; u, v – velocity components; ρ – density of the liquid or gas; $\bar{n}$– normal vector on the channel wall; indices $i = 1, 2$ and *wall* denote the walls of the channel; *in, out* – inlet and outlet of the channel; W_0 – air velocity at the inlet of the channel.

Numerical modelling of the hydrodynamic processes in a curved confuser-type channel was performed using the ANSYS Fluent software product. A computational grid has been constructed in the channel, which has refinement near the walls. An element of such a grid, which was calculated using this computer program, is shown in Fig. 2. It should be noted that the finite element method is used in numerical modelling of hydrodynamics and the heat and mass transfer problems. The mesh was constructed using the ANSYS Meshing generator, based on the Workbench platform. When constructing the mesh for the tube bundle of all models, there was used the local mesh control. A triangular mesh was constructed (as shown in Fig. 2), using the Total Thickness boundary layer method, with the first layer thickness being 0.1 mm and the number of layers 15. The Orthogonal Quality indicator of the mesh is 0.206. The minimum size of the element is 0.1 mm. The maximum size of the edge is 0.4 mm.

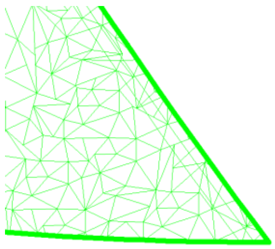

Fig. 2. **Element of the computational grid in the channel**

As a carrier flowing in the channel there is selected air with a velocity of $W_0 = 1\ \text{m}\cdot\text{s}^{-1}$ at the entrance to the channel.

Results and discussion

There was performed a numerical calculation of the dynamic characteristics of the flow in the channel to be investigated. Characteristic distributions of pressures and fields of velocities are shown in Fig. 3. As a result of numerous calculations, the pressure distribution in the channel was obtained, as shown in Fig. 3 a. As it is evident from the figure, there is a pressure drop at the outlet of the channel. In quantitative terms, however, the magnitude of this drop is insignificant, which is due to the curvature of the surface for the air flow in the channel.

Fig. 3 b shows the distribution of the velocity fields in the channel. As we can see from the obtained distributions, the maximum values of speed are observed at the end of the channel. At the surface of one of the walls of the channel there is a stagnant zone in which the air moves at a low speed, changing the direction of its movement from the inlet to the outlet.

The optimization parameter is selected as the objective function, which is the ratio $K = P\cdot V^{-1}$, characterizing the change in the loss of pressure with a change in the flow velocity, where P and V are the average values of pressure and velocity at the outlet of the channel. The value of the radius of the curved wall R1 changed at constant values of other geometric characteristics of the channel.

We performed calculations on PC for this parametric optimization of the channel, which was conveniently presented in the form of longitudinal profiles, in which the optimized parameter K changes, i.e. depending on the values of the pressure drops *P* at the inlet and outlet of a curved channel of the confuser type, as well as various values of the flow velocity drops *V* at the inlet and outlet of the channel. The images of these profiles can be presented in the form of generated tables, in which various profiles are depicted, for which various constant values of radii R1 are specified at a certain step. We have chosen the following values of radius R1 of the curved wall of the channel: the minimum value of the radius R1 of the curved wall is 110 mm, and the maximum is 279 mm. There will be 9 images of such channel profile.

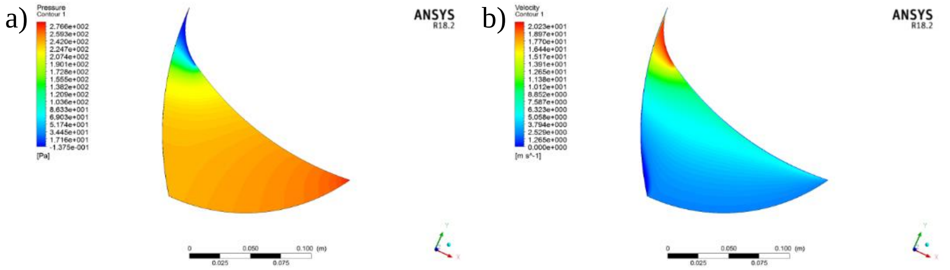

Fig. 3. **Field of pressure distribution (a) and velocity (b) in a curved channel**

In Fig. 4 there are shown images of the longitudinal profiles of channels for the determination of the optimal values of pressure drops at the inlet and outlet from the channels. In addition, the values of the pressure drops at the inlet and outlet from the curved channel, as well as the geometric dimensions, are specified in the form of scales (colors and scale) that accompany each depicted view.

Fig. 5 provides images of longitudinal profiles of channels for the determination of the optimal values of flow velocity differences at the inlet and outlet from the channels. Here for each profile there are also given the values of the velocity differences at the input and output, as well as the geometric dimensions, which are presented in the form of corresponding similar scales.

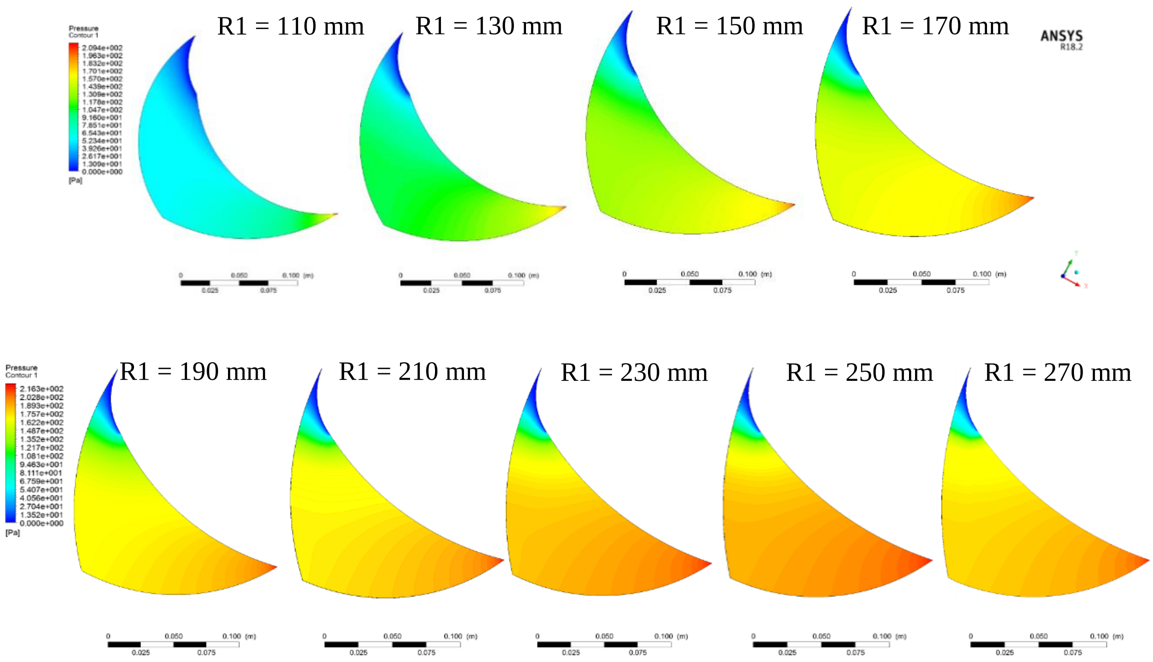

Fig. 4. **Determination of optimal values of the pressure drops at the inlet and outlet of the channel**

As a result of modeling on PC, using the values of the longitudinal profile data, presented in Fig. 4 and 5, there were obtained averaged digital values of velocities *V* at the outlet from the channel, and pressure *P* at the outlet from the channel, and the corresponding values of the optimization parameter *K*.

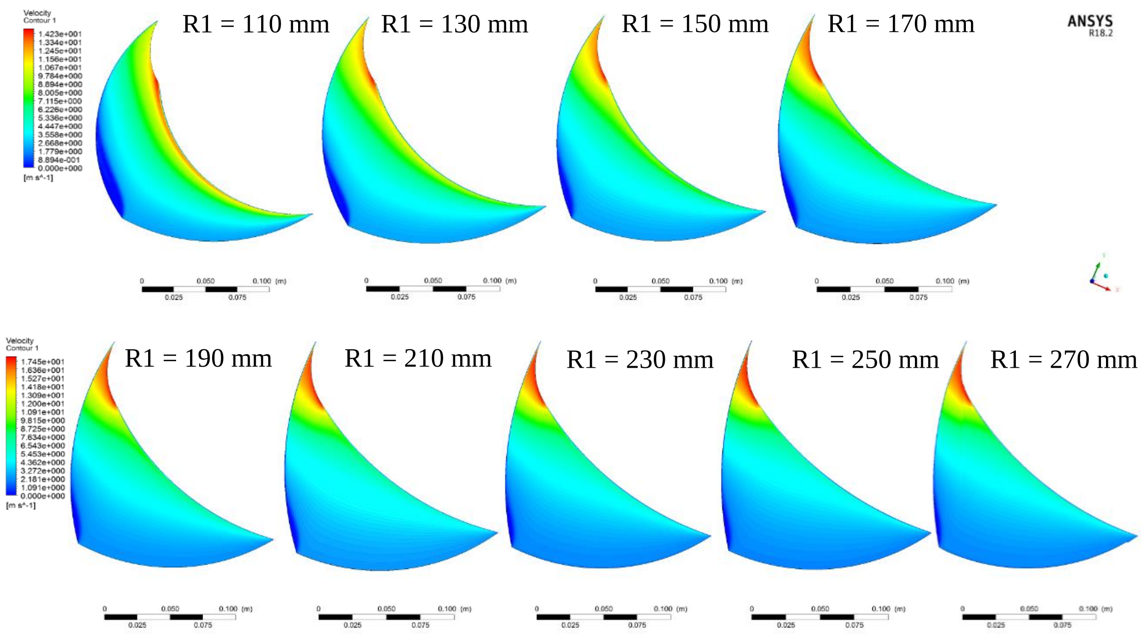

Fig. 5. **Determination of the optimal values of the flow velocity at the outlet from the channel**

The obtained data of numerical calculations are given in Table 1 and presented in a graphic form in Fig. 6.

Table 1

Results of numerical calculations

No	Radius of channel R1, mm	Velocity *V* at the outlet of the channel, $m \cdot s^{-1}$	Pressure *P* at the outlet of the channel, Pa	Optimization parameter, *K*
1	110	1.42	1.30	0.91
2	130	1.45	1.12	0.77
3	150	1.55	1.16	0.75
4	170	1.63	1.24	0.77
5	190	1.75	1.50	0.86
6	210	1.85	1.47	0.79
7	230	1.94	1.60	0.82
8	250	2.02	1.70	0.84
9	270	1.93	1.67	0.86

As it is evident from the graph, presented in Fig. 4, the curve is of a complex nature, which, however, makes it possible to determine that the most optimal values of radius R1 will be the values that correspond to the minimum value of parameter *K*.

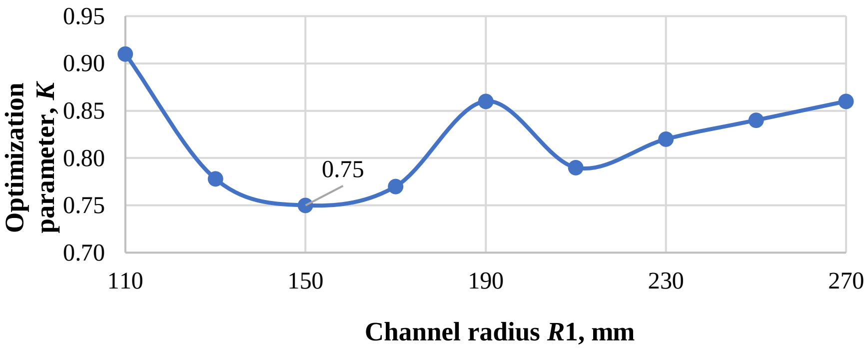

Fig. 6. **Dependence of the optimization parameter *K* when changing pressure and the exit velocity for different values of the radius R1 of the lateral curved wall of the channel**

As a result of the conducted research, it can be concluded that, with other output parameters remaining constant, the optimal value of the channel curvature radius is R1 = 150 mm. The next stage in conducting the research in this direction will be the experimental verification of the obtained theoretical results, using the modern measuring and recording instruments and equipment. The obtained data can be useful when developing equipment for various purposes – the wind generators, turbines, heat exchangers and other energy devices.

Conclusions

1. Two-dimensional parametric optimization was performed of a curved channel with the pre-set geometric dimensions. The influence of various geometric parameters upon the change in the pressure field and channel velocity is analysed in order to improve the aerodynamic characteristics of the curved channel. The conducted calculations of parametric optimization show that, with a radius of curvature of the side walls of the channel 150 mm, the optimal values of the parameter K are determined, which characterizes the smallest values of the pressure drop when changing the flow velocity in the channel.
2. Numerical modelling of the hydrodynamic processes in a channel with curved walls was carried out using the ANSYS Fluent software package. Local distributions of the velocity and pressure fields in a curved channel are obtained. It is shown that the use of curved channels reduces the size of stagnant zones, reduces pressure losses, which improves the aerodynamic and energy properties of the channel of the type under consideration.
3. The obtained data about the optimal geometry of the curved channels of the confusal type can be used in the development of energy devices for various purposes – wind generators, turbines, heat exchangers and other elements of energy equipment.

Author contributions

Conceptualization, V.G., M.T., M.M., D.Z.; methodology, M.T., A.A., A.R., V.T. and V.K.; software, A.B., D.Z.; validation, A.A., V.G.; formal analysis, M.T., M.M., and V.K.; investigation, A.A., V.T. and D.Z.; data curation, V.G.; writing – original draft preparation, V.G., A.A.; writing – review and editing, V.G., A.R., A.A.; visualization, D.Z., A.B. All authors have read and agreed to the published version of the manuscript.

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