Influence of the cross-sectional geometry of the heat exchanger element on heat flow and pressure drop

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Abstract. This paper examines the influence of the geometry of the heat exchanger element on heat flow, pressure drop, outlet temperature and energy efficiency. By numerical modeling in a two-dimensional formulation, we solved the problem of convective heat transfer when air flows transversely around one and three rows of heated elements of different cross-sections. The following cross-sectional shapes of heated elements are: circle, trefoil, trefoil (mirrored), quatrefoil, cinquefoil and cinquefoil (mirrored). Calculations were carried out using ANSYS Fluent v. 19.2 at the following air flow velocities: 0.01; 0.05; 0.25 and 1.25 m/s. The research results showed that when flowing around one row of elements, the highest energy efficiency is provided by elements with a trefoil shape in cross-section. When flowing around three rows of elements at lower air flow velocities (0.01, 0.05, and 0.25 m/s), trefoil-shaped elements also have the best energy efficiency values, and only at an air flow velocity of 1.25 m/s elements with a trefoil cross-section inferior by 3.67% to elements with a cinquefoil (mirrored) cross-section.

1 Introduction

Heat exchangers are used in many industries, such as petroleum, chemical and energy [1,2]. Depending on the design, heat exchangers are used for heat recovery [3], electronics cooling [4-6], heat storage, etc. Thanks to their simple and convenient design, shell-and-tube heat exchangers have become widespread [7]. Increasing the efficiency of heat exchangers will improve the overall performance of energy systems. Hence, the research conducted to enhance the characteristics of the heat exchanger holds significant importance [8-10]. To increase the efficiency of heat exchangers, various methods are used to intensify heat transfer and reduce pressure drop. Reducing heat losses to the environment also makes it possible to increase the energy efficiency of the system; various thermal insulation materials are used for this purpose [11,12].

The geometric design of a shell-and-tube heat exchanger has a great influence on the hydraulic and thermal performance, such as pressure drop, temperature difference, heat transfer coefficient and energy efficiency [13,14]. Heat exchangers make extensive use of

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cross flow through a series of tubes. The authors of [15] studied the heat transfer and friction losses of a group of cross-flow tubes with solid and perforated spacer plates with different widths and perforation indexes. The authors concluded that a set of cylindrical tubes with a perforated spacer plate having a spacer plate width ratio (Rw) of 0.5 and a perforation index (Pi) of 1.5 provides maximum thermal and hydraulic performance.

Integrating fins into heat exchangers leads to an increase in heat transfer coefficient [16]. As a result of their research, the authors of [17] concluded that the flow of hot liquid through a coil leads to higher heat transfer values. In addition, research results showed that the highest heat transfer value is achieved by a heat exchanger with round fins. However, the effect of cut round fins on the efficiency and heat transfer of a spiral shell-and-tube heat exchanger is negligible compared to round fins. The numerical calculation results in [18] show that the trefoil hole baffle can effectively improve the heat transfer rate of the shell side, and the maximum average Nusselt number increases by 2.3 times compared with the case of no baffle, while the average pressure loss increases 9.6 times. The heat transfer coefficient per unit pressure drop of heat exchangers with baffles with trefoil holes is higher than that of heat exchangers with baffles with quatrefoil holes [19].

The results of numerical and experimental studies show that the shape of the heat exchange elements directly affects the thermal and hydraulic characteristics of the heat exchanger. Optimization of inter-tube fluid flow and heat transfer of heat ex-changers can be achieved by reforming the designs of baffles and tube bundles. The effect of changing tube thickness on heat transfer and pressure drop is that the thicker the tube, the lower the heat transfer efficiency and the higher the pressure drop [20]. By comparing evaluation characteristics such as heat flow to pressure drop ratio and efficiency coefficient for all proposed baffle and tube bundle configurations, the elliptical angular tube bundles in [21] showed superior performance compared to other tube bundle designs studied (vertical and horizontal). The results obtained in [22] demonstrate that the elliptical tube exhibits a higher heat transfer rate with a significant reduction in the coefficient of friction for the Reynolds number range (5000-21000). However, the research results obtained in [23] showed that at the same mass flow rate, stranded oval pipes with a segmented baffle reduced the pressure drop by 53.6% and 35.64% in comparison with bundles of round and elliptical pipes, respectively. Comparing the ratio of the heat transfer coefficient to the pressure drop, we can conclude that a shell-and-tube heat exchanger with a bundle of twisted tubes of oval cross-section (both with a segmental and an inclined partition) has better characteristics than other types of tube bundles and gives a higher coefficient value for performance assessments. The authors of [24] concluded that the butterfly septum, disc septum, helical segmental septum and helical disc septum demonstrate their superiority by 35.12%; 25%; 22% and 12% compared to a conventional segmental septum, respectively. The study showed that among the baffle types presented, disc baffle heat exchangers have the highest heat transfer. The re-search results in [25] showed that under the conditions of the same fluid flow and the same distance between the plates, compared with the segmented baffle heat ex-changer, the overall performance of the quatrefoil perforated plate heat exchanger is improved by 27–41%. The authors of [26] studied the change in pressure drop in a heat exchanger with different types of partitions. The pressure drop across the rod baffle, trefoil baffle, and segmented and pore baffle is reduced by 70.1%, 19.5% and 31.1% compared to the segment baffle. The results obtained in [27] showed that a circular pipe provides a higher heat transfer coefficient of approximately 18% than a flat pipe and produces a moderate pressure drop of approximately 10% higher under the same conditions. Numerical simulation results [28, 29] indicate superior thermal and hydrodynamic performance of teardrop-shaped tube bundles compared to circular pipes and also show that the pressure drop of the studied teardrop-shaped tube bundles is approximately 9.86 ~ 10.88 times less than for round tube bundles.

Thus, we can conclude that the heat transfer of circular pipes has been widely studied in the literature. At the same time, there are few works on studying the influence of other forms of a heated element on the value of the pressure drop and heat flow. In this work, we consider convective heat transfer in the transverse flow of one and three rows of heated elements having the following cross-section: circle, trefoil, quatrefoil, cinquefoil, trefoil (mirrored), and cinquefoil (mirrored). The influence of the geometry of the heated element on the values of heat flow, pressure drop and energy efficiency is studied. The ratio of heat flow to power consumption is proposed as a comprehensive indicator for assessing energy efficiency [30].

2 Materials and Methods

2.1 Formulation of the problem

The objective of this study is to investigate the impact of the heat exchanger element's shape on the pressure drop and heat flow values during convective heat transfer in the case of one and three rows of elements with varying cross-sections (circle, trefoil, quatrefoil, cinquefoil) and transverse flow. The computational areas are channels of rectangular cross-section with one or three rows of heated elements located in them. The length and width of the rectangular section are 5 and 155 mm, respectively (Fig. 1-3).

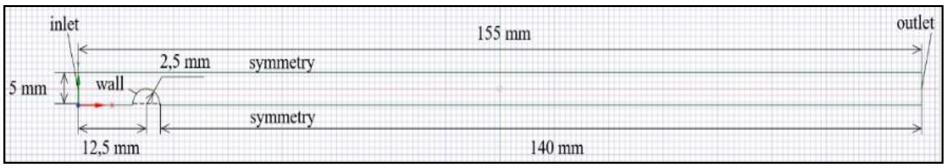

Fig 1. Computational area with one row of circular elements.

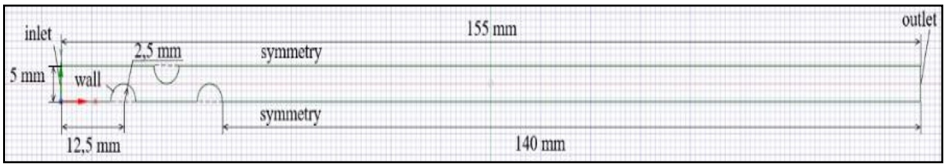

Fig 2. Computational area with three rows of circular elements.

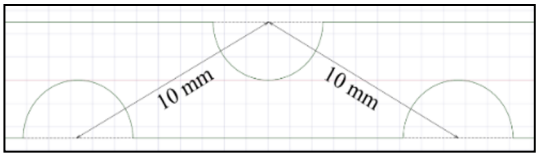

Fig 3. The distance between the centres of circular elements (for the case of three rows).

2.2 Cross-sections of heat exchange elements

The cross sections of the heat exchanger elements used in the calculations are presented in Fig. 4.

Checking the mesh partition is carried out by refining the computational mesh, during which there is no further change in the calculated parameters, or they change with a slight error.

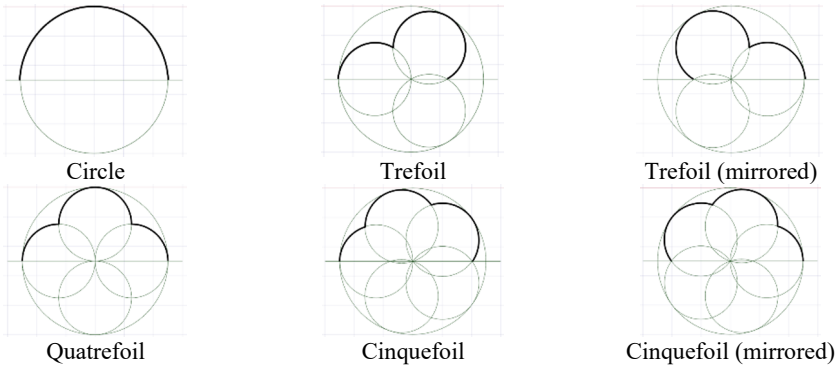

Fig. 4. The distance between the centres of circular elements (for the case of three rows).

2.3 Calculation of Reynolds number and energy efficiency indicator

The Reynolds number is determined by the following relations:

$$\mathrm{Re}=\upsilon d/\nu=\upsilon d\rho/\mu, \tag{1}$$

where υ – flow velocity, m/s; d – hydraulic diameter, m; ν – kinematic coefficient of medium viscosity ($\nu=\mu/\rho$), m^2/s; ρ –density of the media, kg/m^3; μ – dynamic coefficient of viscosity of the media, kg/(m·s).

Reynolds number values for four flow velocities are given in Table 1.

Table 1. Reynolds number for different flow velocities.

υ	0.01	0.05	0.25	1.25	0.01
Re	3.423	17.115	85.573	427.867	3.423

When flowing around an element of circular cross-section, the turbulent regime begins already at a Reynolds number greater than 1. Consequently, the air flow regime is turbulent.

The energy efficiency indicator is calculated using the formula [31]:

$$E_F=Q/\delta P, \tag{2}$$

where Q – heat flow from the surface of the heat exchange element, W; δP – power spent on pumping coolant (air), W [31]:

$$\delta P=G_V\cdot\Delta p=G/\rho\cdot\Delta p, \tag{3}$$

where G_V – volumetric air flow, m^3/s; Δp – pressure drop, Pa; G – mass air flow, kg/s; ρ – air density, kg/m^3.

2.4 Calculation settings

The calculation is carried out for the following air flow velocities: 0.01; 0.05; 0.25; 1.25 m/s. The mesh is refined to a single cell size of 0.000025 (the number of cells is approximately the same and is equal to ~1220000 and ~1320000 for one and three rows of elements,

respectively). The air flow mode is laminar. The following residual values are specified: continuity – $1 \cdot 10^{-6}$; x-velocity, y-velocity, energy – $1 \cdot 10^{-13}$.

3 Results and Discussion

3.1 Study of convective heat transfer during flow around one row of elements

Figure 5 shows a graph of the dependence of heat flow on air flow velocity when flowing around one row of elements with different geometries. At air flow velocities of 0.01 m/s and 0.05 m/s, the heat exchanger elements of all studied sections showed similar heat flow values. At higher air flow velocities, elements with a round cross-section have the best heat flow indicators; the lowest values were shown by elements with a trefoil (mirrored) shape in cross-section.

Figure 6 shows a graph of the dependence of the pressure drop on the air flow velocity when flowing around one row of elements with different geometries. At low air flow velocities (0.01 m/s; 0.05 m/s; 0.25 m/s), the elements of all studied cross-sections showed similar pressure drop values. At higher air flow velocities, the highest pressure drop values were shown by elements with a quatrefoil shape in cross-section. The lowest pressure drop values were shown by elements with a trefoil-shaped cross-section.

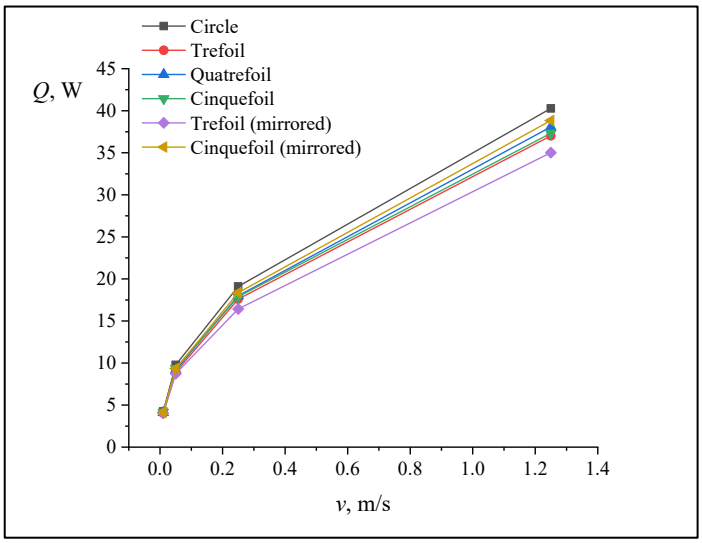

Fig. 5. Dependence of heat flow on air flow velocity when flowing around one row of elements with different geometries.

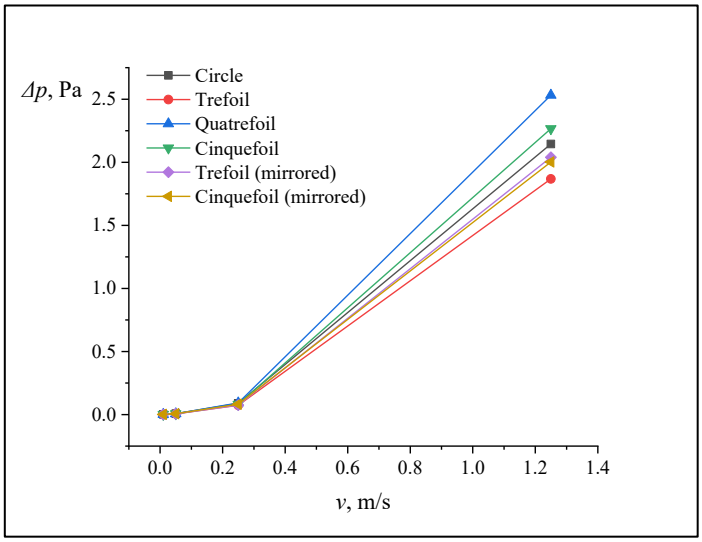

Fig. 6. Dependence of pressure drop on air flow velocity when flowing around one row of elements with different geometries.

Figure 7 shows a graph of the dependence of the outlet temperature on the air flow velocity when flowing around one row of elements with different geometries. The highest temperature values at all studied air flow velocities were shown by elements with a circular cross-section. The lowest temperature at the outlet of the channel was shown by elements with a trefoil (mirrored) cross-section.

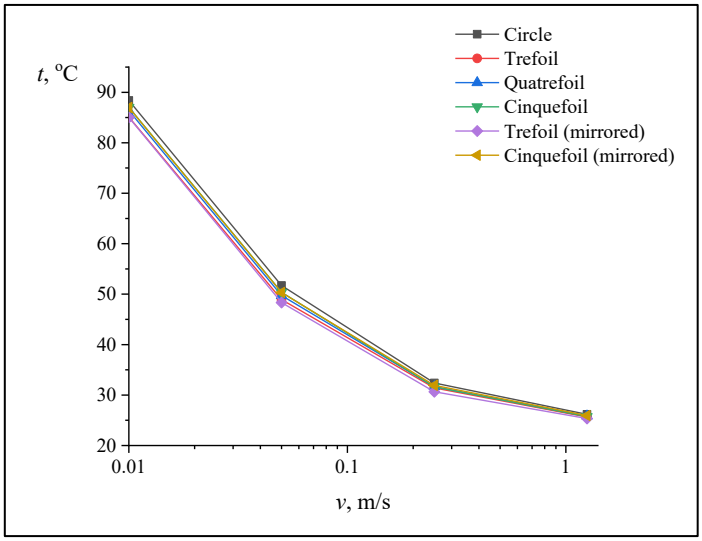

Fig. 7. Dependence of the outlet temperature on the air flow velocity when flowing around one row of elements with different geometries.

Figure 8 shows a graph of changes in the energy efficiency indicator depending on the velocity of air flow when flowing around one row of elements with different geometries. The energy efficiency indicator was calculated as the ratio of the heat flow value to the pressure drop value (formulas 2 and 3). From the graph (Fig. 8), it can be noted that, despite the lowest heat flow values of all the studied elements of various sections (Fig. 5), the highest energy efficiency was shown by elements having a trefoil (mirrored) shape in the cross-section. This can be explained by the fact that elements with this cross-sectional shape have a fairly low pressure drop (Fig. 6). Elements with a circular cross-section have the lowest energy efficiency values.

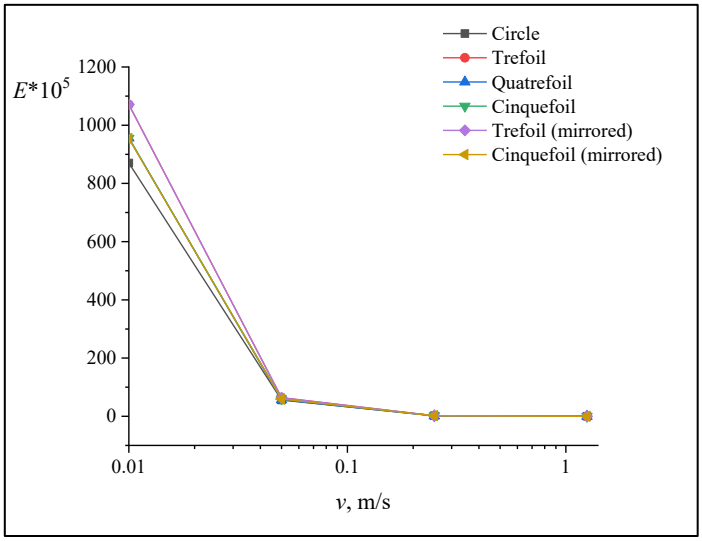

Fig. 8. Change in energy efficiency indicator depending on the air flow velocity when flowing around one row of elements with different geometries.

Figure 9 shows a graph of changes in the energy efficiency indicator depending on the velocity in percent relative to an element of circular cross-section when flowing around one row of elements. At all four velocities, the highest energy efficiency indicator is provided by an element that represents a trefoil in cross-section. The increase in energy efficiency when using an element of this geometry relative to a circular cross-section at velocities of 0.01; 0.05; 0.25; 1.25 m/s is 23.13%; 14.24%; 10.28%; 5.56% respectively. At air flow velocities of 0.01 and 0.05 m/s, an increase in energy efficiency is observed by 23.15% and 13.22%, respectively, relative to an element with a circular cross-section for an element representing a trefoil (mirrored) cross-section.

At air flow velocities of 0.25 and 1.25 m/s, the lowest values of the energy efficiency indicator are characteristic of the element representing a quatrefoil in cross-section. The value of the energy efficiency indicator relative to the circular element in this case decreases by 9.2% and 19.9%, respectively. There is also a decrease in energy efficiency by 8.52% at the velocity of 1.25 m/s for an element representing a trefoil (mirrored) cross-section.

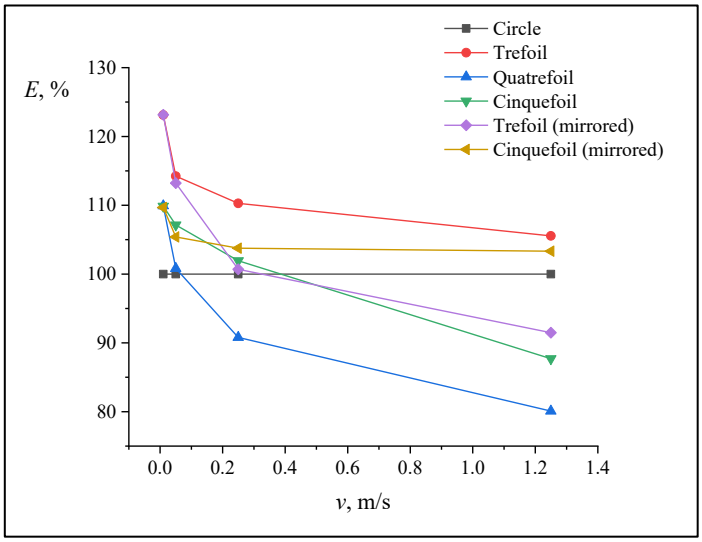

Fig. 9. Change in the energy efficiency indicator depending on the air velocity in percent relative to a circular element when flowing around one row of elements.

3.2 Study of convective heat transfer in flow around three rows of elements

Figure 10 shows a graph of the change in heat flow versus velocity during flow around three rows of elements. As in the case of flow around one row of elements, the greatest heat flow is observed in elements with a circular cross-section, the smallest in elements with a trefoil and trefoil (mirrored) shape in cross-section. Elements with a quatrefoil-shaped cross-section showed higher heat flux values when flowing around three rows of elements than when flowing around one row of elements. The opposite picture is observed for elements with a cinquefoil (mirrored) shape in cross-section.

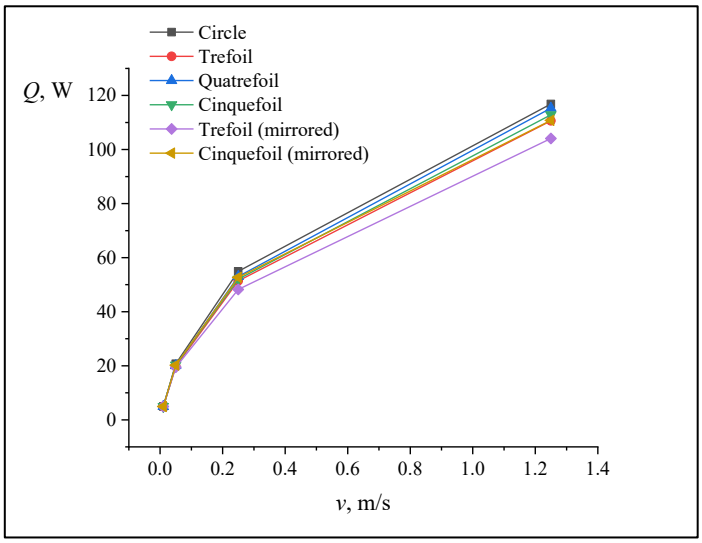

Fig. 10. Dependence of heat flow on air flow velocity when flowing around three rows of elements with different geometries.

Figure 11 shows a graph of changes in pressure drop versus velocity during flow around three rows of elements. We can see that elements with a circular cross-section have the highest pressure drop. The lowest pressure drop was shown by elements with a cinquefoil (mirrored) cross-section. Compared to the case of flow around one row of rows, an increase in the pressure drop is observed for elements with a circular cross-section and a trefoil-shaped cross-section.

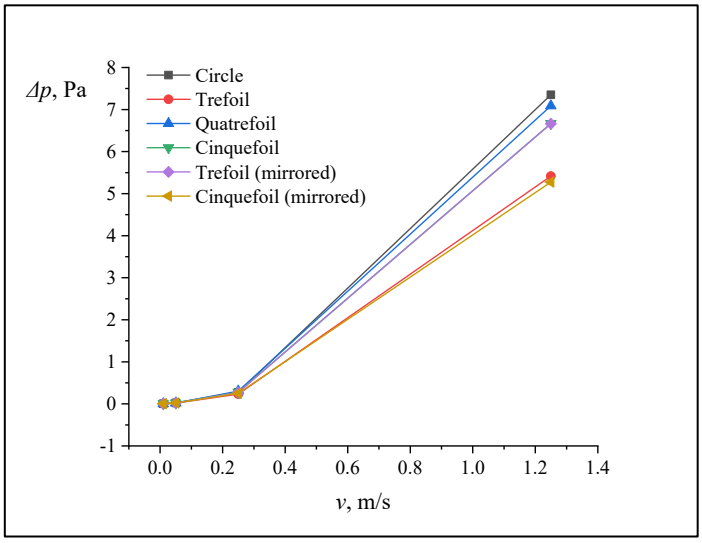

Fig. 11. Dependence of pressure drop on air flow velocity when flowing around three rows of elements with different geometries.

Figure 12 shows a graph of the outlet temperature change during flow around three rows of elements.

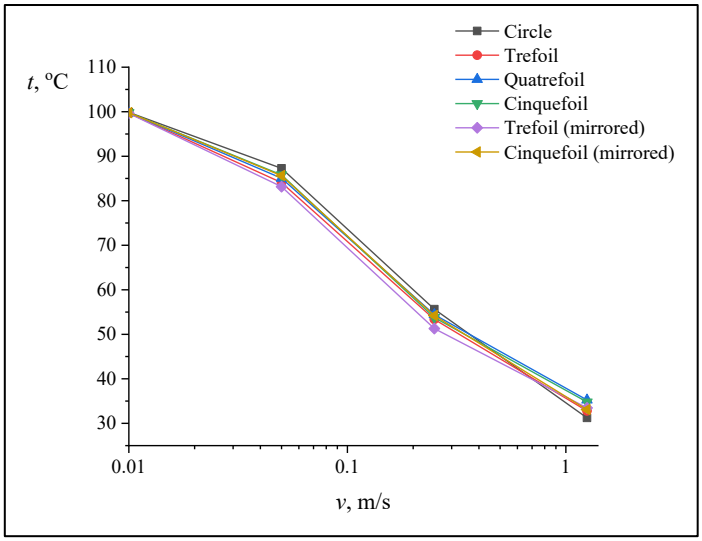

Fig. 12. Dependence of the outlet temperature on the air flow velocity when flowing around three rows of elements with different geometries.

At air flow velocities of 0.01 m/s; 0.05 m/s; 0.25 m/s, the highest outlet temperature is observed for elements with a circular cross-section. At an air velocity of 1.25 m/s, the highest

temperature is observed in elements with a quatrefoil cross-section, and elements with a circular cross-section at this velocity showed the lowest outlet temperature.

Figure 13 shows a graph of the change in energy efficiency indicator when flowing around three rows of elements. As in the case of flowing around one row of elements, the highest values of the energy efficiency indicator were observed in elements with a trefoil (mirrored) cross-section and the lowest values in elements with a circular cross-section.

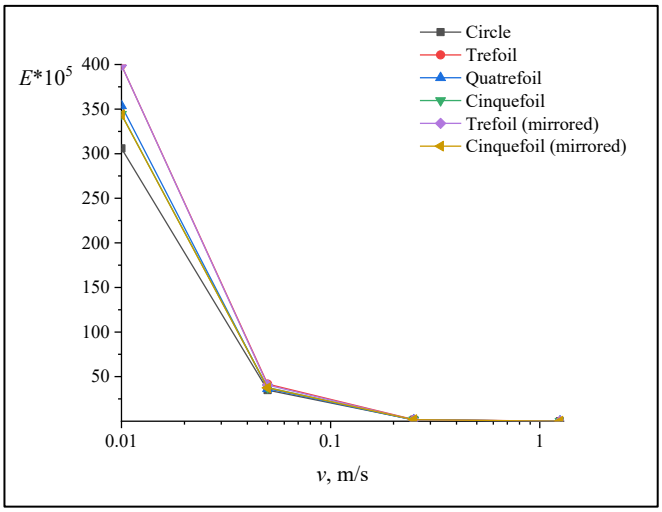

Fig. 13. Change in energy efficiency indicator depending on the air flow velocity when flowing around three rows of elements with different geometries.

Figure 14 shows graph of changes in the energy efficiency indicator depending on the air flow velocity in percent relative to the element with circular cross-section when flowing three rows of elements.

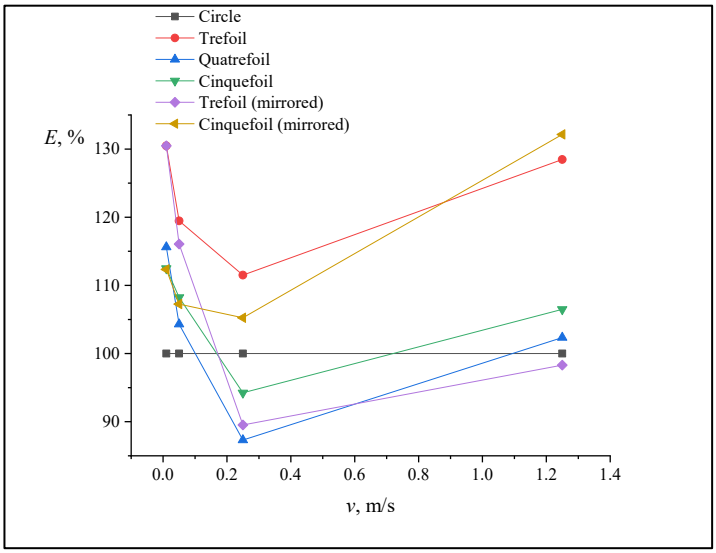

Fig. 14. Change in the energy efficiency indicator depending on the velocity in percent relative to a circular element when flowing around three rows of elements.

4 Conclusion

The present investigation aimed to examine the effect of the geometry of the heated element on the values of heat flow, pressure drop, and energy efficiency. Calculations were carried out for two cases: 1) transverse flow around one row of heat ex-change elements; 2) transverse flow around three rows of heat exchange elements. The following cross-sectional shapes of the elements were studied: circle, trefoil, trefoil (mirrored), quatrefoil, cinquefoil and cinquefoil (mirrored). Calculations were carried out at the following air flow velocities: 0.01; 0.05; 0.25; 1.25 m/s. The re-search results showed that with transverse flow around both one and three rows of heat exchange elements, the highest value of heat flow is typical for an element with a circular cross-section. Elements representing trefoil and trefoil (mirrored) cross-sections provide the lowest heat flow values.

The smallest value of the pressure drop was observed when using heat exchange elements representing a trefoil in cross-section in the case of flowing around one row of elements. When flowing around three rows of elements at an air flow velocity of 1.25 m/s, the pressure drop at the trefoil is only 1.94% higher than the pressure drop at the element representing a cinquefoil (mirrored) cross-section.

A decrease in pressure drop leads to a decrease in power consumption for pumping coolant and, accordingly, increases energy efficiency. Thus, when flowing around one row of elements, the increase in energy efficiency when using an element that represents a trefoil in cross-section, relative to an element with a circular cross-section for velocities of 0.01; 0.05; 0.25; 1.25 m/s is 23.13%; 14.24%; 10.28% and 5.56%, respectively. At air flow velocities of 0.01 and 0.05 m/s, an increase in energy efficiency is observed by 23.15% and 13.22%, respectively, relative to an element with a circular cross-section for an element representing a trefoil (mirrored) cross-section. However, at a velocity of 1.25 m/s, the trefoil (mirrored) shows a decrease in energy efficiency by 8.52% relative to the circular element, due to the lower heat flow value.

When flowing around three rows of elements, the increase in energy efficiency when using an element with a trefoil cross-section relative to a circular element at velocities of 0.05 and 0.25 m/s is 19.47% and 11.51%, respectively. At a velocity of 0.01 m/s, the increase in energy efficiency is 30.47%, the same as for the trefoil (mirrored). The increase relative to an element of circular cross-section in the case of a cinquefoil (mirrored) at a speed of 1.25 m/s is 32.14%, which is only 3.67% higher than the increase in energy efficiency of an element with a trefoil cross-section.

Thus, we can conclude that the use of heat exchange elements representing a trefoil in cross-section (using the example of shell-and-tube heat exchangers) may be preferable to the use of elements with a circular cross-section.

Acknowledgements

The research was funded by the Russian Science Foundation, grant number 21-79-10406, https://rscf.ru/en/project/21-79-10406/

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