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Numerical Studies into Hydrodynamics and Heat Exchange in Heat Exchangers Using Helical Square and Oval Tubes

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Increase in efficiency of heat exchangers is an urgent task which facilitates development of compact heat exchangers for various industries. The efficiency can be increased by various methods: superficial intensification, use of insertion made of twisted tapes, use of membranes in intra-tube space, flow whirl etc.. One of the approaches to flow whirl is the use of helical tubes of various cross sections. This work investigates into heat exchange and hydrodynamics of heat exchanger with helical tubes of square and oval cross sections. The range of studies of flow modes has been selected involving the most widely applied in practice Re numbers from 3000 to 20000. Numerical studies have been aided with ANSYS CFX solver technology and the calculated Menter's Shear Stress Transport Turbulence Model. As a consequence, the hydraulic resistance and heat efficiency of helical tubes of square and oval cross sections have been obtained as a function of flow mode. The use of helical tubes of square cross section makes it possible to increase heat transfer from 80 % at lower Re = 3000 to 40 % at Re = 20000. More promising is the application of oval tubes, for which the heat transfer increases by 90-100 % in all studied range of Re numbers. Analysis of heat thermal-hydraulic efficiency demonstrates dominancy of oval helical tubes at higher Re numbers (from 10000), at lower Re numbers (3000-7500) square helical tubes provide higher thermal-hydraulic efficiency. In addition, the flow structure has been determined in tubes and in intra-tube space. Analysis of liquid flow structure in intra-tube space demonstrates better miscibility upon application of helical tubes of oval cross section, which permits to increase heat transfer by 90 %. The flow structure with helical tubes of square cross section is close to flow around of plain tubes.

Key words: Helical tubes, oval tubes, square tubes, heat exchange, simulation, heat transfer, flow structure.

Application of intensifiers of heat exchange in shell-in-tube heat exchangers is vital for power engineering, housing and utility facilities and chemical industry. Costs, weight and dimensions, convenience of operation and maintenance, reliability and log operation lifetime are of great importance. Experience of development and operation of various heat exchangers demonstrated that the developed up till now methods of intensification of heat exchange can provide decrease in dimensions in 1.5...2 times in comparison with similar serial units with plain tubes at equal thermal capacity, however, the power for pumping of heat carriers increases. While using intensifiers of heat exchange it is necessary to select optimum balance between the increase in thermal flow and increase in hydraulic resistance. One of the limiting factors of implementation of new types of intensifiers involves significant financial and technical expenditures for scientific

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researches of their efficiency and engineering availability of their subsequent implementation. The optimum solution is application of numerical simulation, facilitating significant expansion of applied r4eseraches, as well as decrease in their costs. The performed analysis of various tools of numerical simulation of heat exchange and hydrodynamics demonstrated that the most reasonable results can be achieved by means of ANSYS CFX solver technology.

General physical principles related in the literature with flow turbulization, forming the basis of intensification mechanism of heat transfer by means of intensifiers of heat exchange, are well known. However, quantitative relations for thermal-hydraulic computation of channels in wide range of variation of geometrical parameters and hydrodynamic conditions of flow have not been determined yet to the fullest extent. It can be attributed to the absence of strict analytical models and computation methods, as well as insufficient development of approximating computations. In addition, there is a deficit of experimental results, as well as relatively detailed study in the essence of intensification mechanism of heat exchange, and possible poorly studied hydrodynamic flow modes in intra-tube space of heat exchangers.

Analysis of published data on research into helical channels and tubes of square cross section[1-8] and helical tubes of oval cross section[9-24] made it possible to obtain experimental data for comparison and verification of numerical computations.

EXPERIMENTAL

Numerical simulation of liquid flow makes it possible to obtain data on flow structure both in tubes, and in intra-tube space of heat exchanger. In addition it is possible to visualize fields of pressure, temperature and coefficients of heat transfer. This method makes it possible to optimize weight and dimensions of heat exchanger and supplements experimental studies.

This work upon numerical studies of liquid flow and heat transfer applied ANSYS CFX solver technology (certificate No. ANS2011-S015), well behaved in solution of similar tasks.

The most popular in Russian municipal services shell-and-tube heat exchanger was selected as a prototype. Water-cooled heater has the following characteristics: number of tubes: 4, with the diameter of 20 mm, shell diameter: 57 mm, length: 500 mm. Heat carrier motion: counter-flow. Working medium: water-water. Flow rate varies both for internal and for external circuit of heat carriers from 0.1 to 0.7 kg/s with increment of 0.1 kg/s. Cold heat carrier flow inside the tubes and its inlet temperature is 8°C. Hot heat carrier flows in intra-tube space and its temperature is 95°C. Modernized helical tubes of square and oval cross sections are designed so that the pitch of complete circulation is 100 mm, and the profile is fitted into 20 mm circumference, as illustrated in Fig. 1.

The predetermined task of turbulent flow of strongly whirled flows was solved using the most suitable Shear Stress Transport Turbulence Model [25]. The SST Turbulence Model is presented in ANSYS CFX by means of 15 prismatic sublayers in order to simulate laminar sublayer on tube wall. Finite-element model of heat exchanger is formed of three computation domains. Total number of cells in the three computation domains is 5 million pieces. The finite-element model is illustrated in Fig. 2.

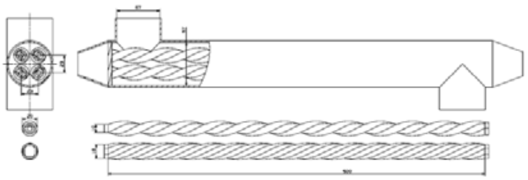
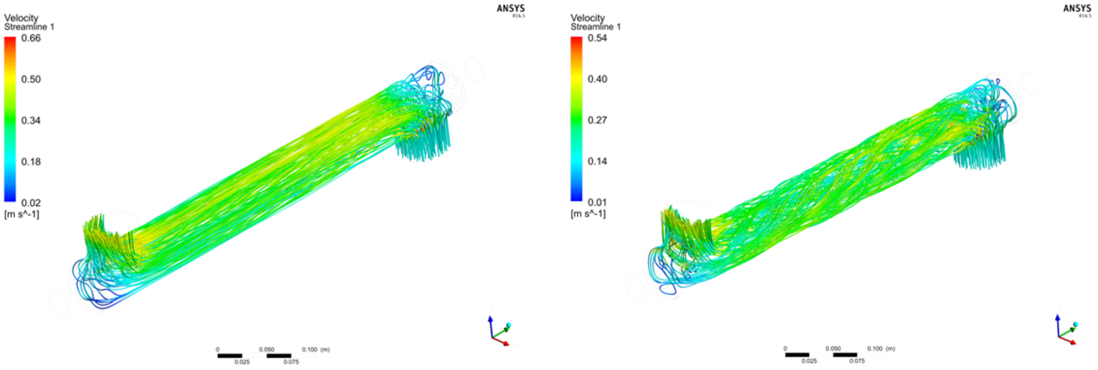


Fig. 1. Heat exchanger and tubes

Fig. 2. Finite-element model of heat exchanger.

RESULTS AND DISCUSSION

The performed numerical studies made it possible to obtain the flow structure in intra-tube space, illustrated in Fig. 3a for helical tubes of square cross section and Fig. 3b for helical tubes of square cross section.



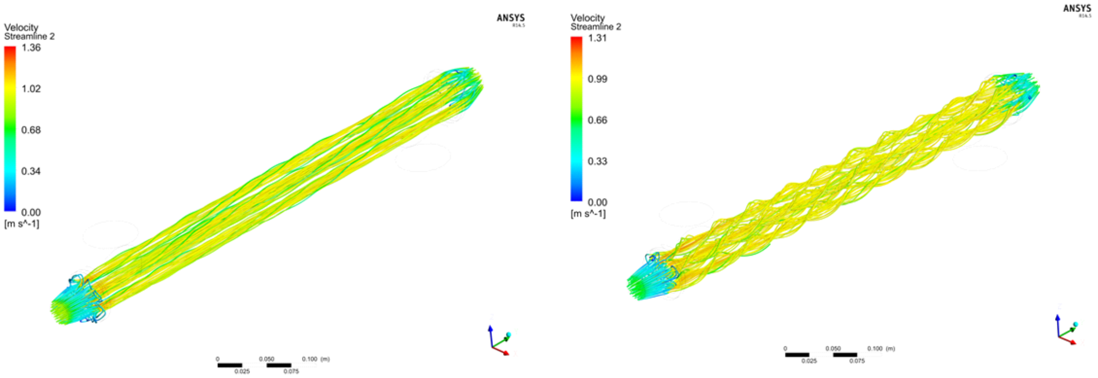
a) for helical tubes of square cross section b) for helical tubes of oval cross section

Fig. 3. Flow structure in intra-tube space in heat exchanger

For helical tubes of square cross section there exists insignificant flow perturbation in intra-tube space and low rate of flow whirl. The flow structure is close to the case of plain tubes, which lead to achievement of low values of friction factor. Helical tubes of oval cross section provide good flow whirl along the total length of heat exchanger, thus facilitating increase in heat efficiency, though, hydraulic resistance increases both in tubes, and in intra-tube space.

The flow structure inside tubes is illustrated in Fig. 4. For helical tubes of square cross section the flow is also slightly whirled, and helical tubes of oval cross section whirl the flow well, the velocity in both cases is equal.

The fields of heat transfer coefficients are illustrated in Fig. 5, it is possible to observe uniform distribution of heat transfer coefficient for helical tubes of square cross section.



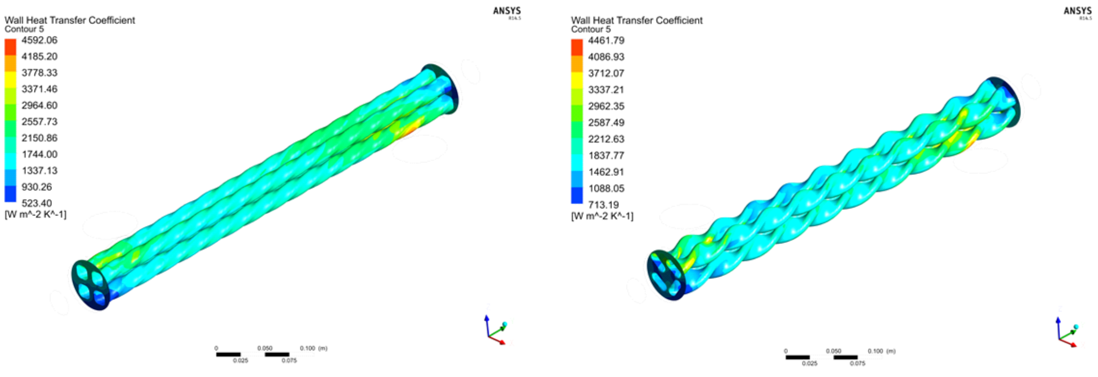
a) for helical tubes of square cross section b) for helical tubes of oval cross section

Fig. 4. Flow structure inside the tubes in heat exchanger

In order to estimate the efficiency of the methods of heat exchange intensification the applied variants methods are compared by one or several criteria of optimality. This work estimates increase in heat flow (1) and increase in hydraulic resistance (2) as a function of flow mode in comparison with heat exchanger with regular plain tubes. Equation (1) estimates the rate of increase in thermal efficiency of the considered intensifier with regard to the thermal efficiency of plain tubes.

$$(Nu/Nu_{st}) = f(\mathrm{Re}) \qquad ...(1)$$

In addition, it is also required to consider for increase in hydraulic resistance. Equation (2) estimates the rate of increase in hydraulic resistance of the considered intensifier with regard to that of plain tubes.



a) for helical tubes of square cross section b) for helical tubes of oval cross section.

Fig. 5. Field of heat transfer coefficients on external surface of tubes in heat exchanger

$$(f/f_{st}) = f(\mathrm{Re}) \quad ...(2)$$

Reasonably selected parameters of heat exchange intensifiers provide more beneficial ratio between the conveyed heat amount Q and power of pumping of heat carriers N in intensified apparatus with regard to the case of plain tubes. Respectively, the energy efficiency of intensified heat exchanger also increases, E = Q / N – the main index of (thermal-hydraulic, economic) efficiency of heat exchangers. Therefore, in order to compare total thermal-hydraulic efficiency of various designs of intensifiers it would be reasonable to apply Eq. (3), which characterizes relative increase in intensity of heat exchange in tube with intensifier per unit of additionally consumed energy.

$$E(\mathrm{Re}) = (\overline{\mathrm{Nu}}/\overline{\mathrm{Nu}_{st}})/(f/f_{st}) \quad ...(3)$$

If *E(Re)* is more than 1, then the increase in heat transfer is higher than the increase in hydraulic resistance in comparison with the case of plain tubes. The higher is *E(Re)*, the more efficient is the heat exchange intensifier.

The Nu number as a function of flow mode is illustrated in Fig. 6, where it can be seen that oval tubes have better increase in thermal efficiency both in absolute value, and in the increase rate.

In comparison with plain tubes the increase in thermal efficiency equals for helical tubes of square cross section of heat transfer from 80 % at lower Re = 3000 to 40 % at Re = 20000. The efficiency of oval tubes is better in comparison with plain tubes, the heat transfer increases by 90-100 % in all the considered range of Re numbers. (Fig. 7).

Estimation of friction factor (Fig. 8) demonstrates that helical square tubes have lower hydraulic resistance by 20 % in all the considered range of Re numbers.

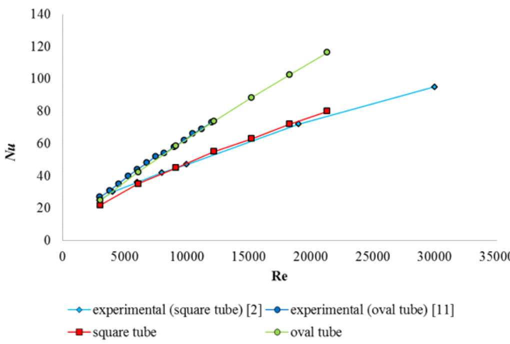


Fig. 6. Nusselt number as a function of flow mode

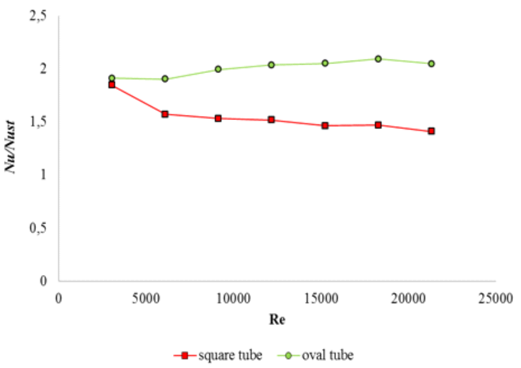


Fig. 7. Nusselt number as a function of flow mode

Thermal-hydraulic efficiency according to Eq. (3) as a function of flow mode is illustrated in Fig. 9.

Complex index of efficiency of helical tubes of square cross section at lower Re numbers (3000-5000) exceeds the efficiency index of helical tubes of oval cross section as a consequence of lower hydraulic resistance, but at higher Re numbers (10000-20000) oval tubes have better efficiency.

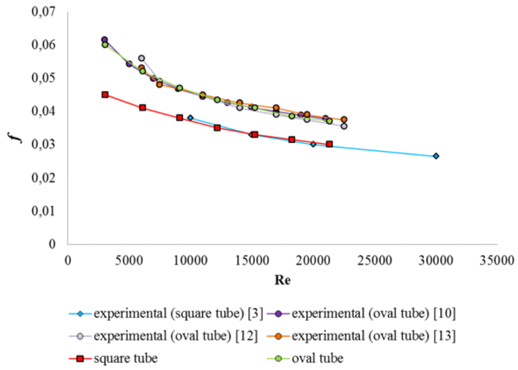


Fig. 8. Friction factor as a function of flow mode

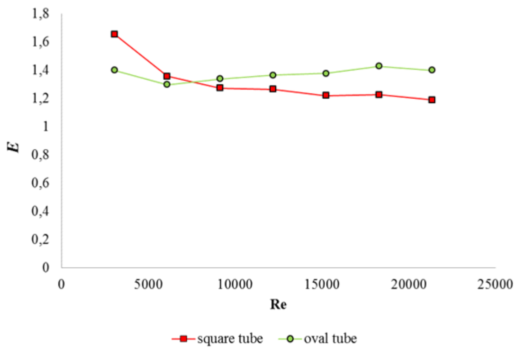


Fig. 9. Thermal-hydraulic efficiency as a function of flow mode

CONCLUSIONS

This work presents the results of nunerical studies in intesigication of heat tranfer using helical tubes of square and oval cross section. The numerical studies have been performed using ANSYS CFX solver technology and the Shear Stress Transport Turbulence Model, aided by arrangement of 15 prismatic sublayers. The studied range of flow modes Re was from 3000 to 20000.

Increase in heat transfer of helical square tubes in comparison with plain ones at low Re numbers (3000) is 80 % and decrease to 40 % at Re=20000. When using helical tubes of oval cross section the increase in heat transfer in all considered range is from 90 to 100 %. Using helical tubes of square cross section the friction factor in all considered range is lower by 20 % than with the use of helical tubes of oval cross section.

In terms of complex index of increase in heat transfer with regard to increase in hydraulic resistance the highest efficiency is that of helical tubes of square cross section at low Re numbers (3000 to 5000), however, at high Re numbers the helical tubes of oval cross section are more efficient. Analysis of liquid flow structure in intra-tube space demonstrates that the best heat efficiency of helical tubes of oval cross section is achieved due to higher whirl of the flow both in tubes, and in intra-tube space, as a consequence of which additional hydraulic resistance appears. Flow structure of helical tubes of square cross section creates low degree of flow whirl both in tubes, and in è intra-tube space, which permits to achieve high efficiency at moderate Re numbers.

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