Geometric Modeling of Coil Heat Exchanger Based on Spring-Twisted Channel

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Abstract. Heat exchangers are widespread in industry, so it is important to have equipment that meets modern requirements. This raises questions on the improvement and modernization of obsolete and the development of new equipment. The authors proposed a heat exchange element made of tightly wound wire with subsequent welding of turns, called spring-twisted channel.

Also, based on the results of the analysis of scientific and technical literature and modern trends in the development of heat exchange equipment, a whole class of modern heat exchangers based on a spring-twisted channel has been proposed.

According to the authors, at present, conical heat exchangers such as «pipe in pipe» are of particular interest, so the object in this work is a high-speed heat exchanger in the form of a truncated cone on the basis of a spring-twisted channel. The purpose of this work is geometric modeling of the surface of the conical coil spring-twisted channel.

A general method of mathematical description of surfaces of spring-twisted channels, which refer to non-linear surfaces formed by the movement of a continuous closed curve along some curvilinear guide.

Equations for constructing the surface of the conical coil spring-twisted channel are given.

Keywords: Heat transfer · Heat exchanger · Conical coil · Spring-twisted channel

1 Introduction

Heat exchangers have become widespread in many industries. Designs of modern heat exchange equipment must ensure the design level of thermal efficiency, also, it must be technological and reliable during the entire service life, safe at its manufacture, installation and operation, provide for the possibility of cleaning heat exchangers, inspection and repair of the apparatus [1].

In a highly competitive market for heat exchange equipment, modern heat exchangers must be highly efficient, simple in design, have low hydraulic resistance and small weight and dimensions [1–3].

The main problem in the development of heat exchangers is the increase of the heat transfer coefficient k, W/ (m K), the most important characteristic of the device.

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This is possible to achieve this in several ways, which are divided into active, passive and mixed [3–5].

Active methods require direct energy costs from an external source. Such methods include: mixing of the coolant by mechanical means [5, 6], rotation of the heat transfer surface [5, 7], the use of ultrasound [8, 9], electric [10] or magnetic field [11, 12] and others.

Unlike active methods of heat transfer intensification, passive do not need any external force. They affect the flow form of the heat transfer surface. These methods include: the use of insert intensifiers (screw, local and plate flow curlers [5, 13, 14]), finned and other developed heat exchange surfaces on the side coolant with low heat transfer coefficient [15–18].

The analysis of the literature shows that the intensification of heat exchange occurs due to the twisting of the flow, which enhances convective heat transfer by introducing a vortex into the bulk flow and destroying the boundary layer on pipe surface.

According to the authors, the study and development of methods for intensifying heat exchange that are optimal from the point of view of technical and economic indicators is the central issue of modernizing heat exchangers, which becomes especially relevant in conditions of high physical and moral wear and tear of heat exchangers, which are widely used in production processes and housing and communal services.

Considering the fact that today the share of tubular heat exchangers is more than half of the entire fleet of heat exchange equipment, it is advisable to improve the shape of the tubular elements of the heating surfaces.

In this regard, practical interest is developed recently, the class of spring-twisted channels [19]. The straight spring-twisted channel shown in Fig. 1 is a spring of round section, the coils of which are rigidly connected by laser welding [19, 20]. With this technology of manufacturing a heat exchange element, the phenomenon of a sticker is excluded, leading to the embrittlement of the surface layer of metal that occurs in pipes with knurling.

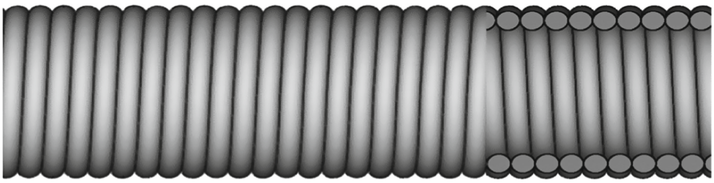

Fig. 1. Straight spring-twisted channel [20]

To intensify heat transfer due to turbulization of the flow of heat carriers, the authors proposed to install intensifiers between the coils of the spring or the flowing part of the spring-coiled pipe to be made in the form of projections 1 and 2 alternating with a given step [19, 21], Fig. 2. Also, the spring-twisted channel can be multi-inbound, Fig. 3 [22]. Wire for the manufacture of a spring-twisted channel may have a round, oval section [19–21] or ovoid [23].

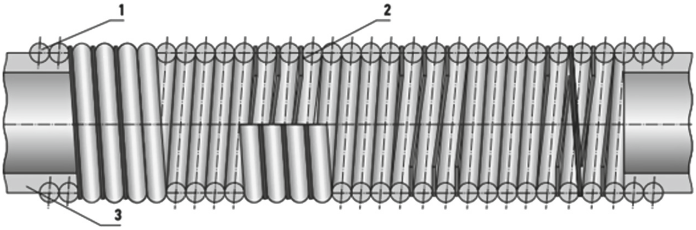

Fig. 2. Straight spring-twisted channel 1 with intensifier 2 [21]

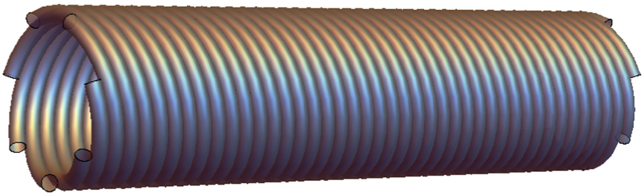

Fig. 3. Heat exchange element in the form of a multi-start helical spiral [22]

On the basis of spring-twisted channels, a number of heat exchangers in the form of a coil, performed in the form of a round truncated cone [24–26], in the exponential curve [27], in the form of a ball [28, 29], oval configuration [30].

Figure 4 shows the appearance of a coil apparatus type «pipe in a pipe» made on a cone, with a heat exchange element in the form of a spring-total channel.

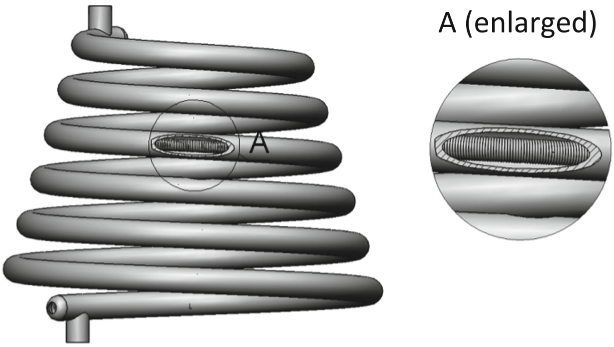

Fig. 4. Coil apparatus type «pipe in pipe» made on cone

According to the data [31–34], conical coil machines have increased efficiency compared to cylindrical heat exchangers such as «pipe-in-pipe».

A heat exchanger is an apparatus with coaxially installed pipes piled into a coil. Moreover, the inner pipe is made in the form of a spring-twisted channel of a round section, and the outer one is made of a smooth cylindrical pipe, Fig. 4.

The conical coil heat exchanger works as follows: with the counter flow of heat transfer, cold water through the fitting enters the inner pipe, simultaneously through the fitting, installed in an external steel coil, hot water is supplied to the annulus space.

With this pattern of motion, the heat agent (liquid) moves along a complex trajectory. First, on the turns of the flow part of the inner coil, where the twisted flow of liquid is realized along the cavities of the spring-twisted channel, and, secondly, along the screw line, determined by the turns of itself coil heat exchanger element.

The heating coolant fed into the intertube space, due to the external screw fining of the inner coil also makes a twisted current characterized by a complex three-dimensional vortex flow structure, which favorably affects heat exchange processes flowing in the annulus space.

When the fluid moves along the curvilinear trajectory of the coil, centrifugal forces appear, the values of which along the cross-section of the channel are different. On the axis of the pipe, where the velocity is maximum, these forces matter most. In the direction to the walls of the pipe, the coolant speed decreases and the effect of the centrifugal effect becomes less. This distribution of forces across the cross-section of the curved canal leads to the emergence of a transverse secondary circulation.

Due to the resulting transverse circulation, the actual fluid velocity in the curved pipe significantly exceeds the average axial flow rate, this results in a significant increase in energy exchange between the flow core and the laminar sublayer and, as a result, to a sharp increase in hydraulic resistance.

The main difficulty of the widespread introduction of this class of heat exchangers is the lack of reliable data on the efficiency of heat exchangers based on spring-twisted channels, research methods, their calculations and design.

The authors of the work [35] on the basis of integral calculus obtained equations for calculation of equivalent diameters of pipe and intertube space in a heat exchanger type “pipe in pipe” with spring-twisted channel. The results of this work can be used in the design and calculation of promising heat exchangers with intense heat transfer.

The purpose of this work is to develop a mathematical description of the geometric model of the conical coil spring-twisted channel with the purpose of further modeling of the heat exchange and hydrodynamic processes.

2 Methods

Surfaces and their geometric description play an important role in the development and design processes of new products.

Currently, in connection with the development and application of computer technology, the analytical method of surface specification has become widespread, allowing relatively easy analysis surface characteristics or quantitative surface - dependent physical characteristics, such as volume, surface area, moment of inertia, etc.

The simplest ways to get a surface are to rotate a two-dimensional object, such as a straight or plane curve around an axis in space, or to move an object, such as a line, polyline, or curve, along some line in space. Such surfaces are called surfaces of revolution and sweeping surfaces, respectively. Examples of surfaces of revolution include a sphere, cone, cylinder, ellipsoid, etc.

Spring-twisted channels refer to non-linear surfaces formed by the motion of a continuous closed curve, along some curvilinear guide. Consider the general method of mathematical description of surfaces of spring-twisted channels, given in the works [19, 21].

Let $\gamma : \ \vec{r} = \vec{r}(s)$ – guide curve, s is a natural parameter in the normal plane of the curve γ.

Let's represent the radius-vector of a surface point as a sum:

$$\vec{r}(s, \varphi) = \vec{r}(s) + \vec{\rho}(s, \varphi), \tag{1}$$

where φ is the polar angle in the normal plane of the curve γ, calculated from the main normal towards the binormal,

$\vec{\rho}(s, \varphi)$ - corresponding "polar radius", Fig. 5.

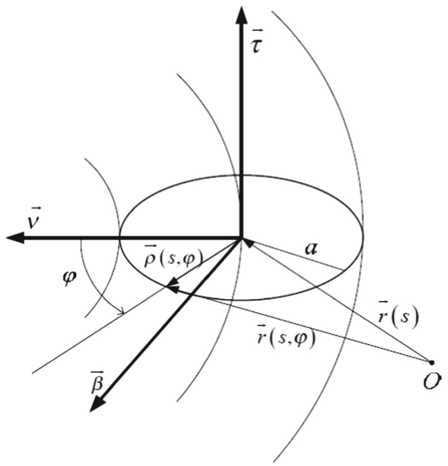

Fig. 5. Surface description scheme [19]

Then

$$\vec{\rho}(s, \varphi) = \rho(s, \varphi)\Big(\vec{\nu}(s)\cos(\varphi) + \vec{\beta}(s)\sin(\varphi)\Big), \tag{2}$$

where $\vec{\nu}(s)$ and $\vec{\beta}(s)$– unit vectors of the main normal and binormal at the point corresponding to the value of the s natural parameter,

$\rho(s, \varphi)$– variable, in general, in two parameters, the radius of the cross-sectional boundary of the channel.

The unit vectors of the tangent, normals, and binormals form a movable orthogonal basis moving along the curve, are computed by the following equations:

$$\vec{\tau}(s) = \vec{r}'(s), \ \vec{\nu}(s) = \frac{1}{k}\vec{r}''(s), \ \ \vec{\beta}(s) = \vec{\tau}(s) \times \vec{\nu}(s), \ k = \left|\vec{r}''(s)\right| \tag{3}$$

Substituting in the Eq. (1) for the radius vector of the $\vec{r}(s, \varphi)$ constraint Eq. (2,3), we get:

$$\vec{r}(s, \varphi) = \vec{r}(s) + \vec{\rho}(s, \varphi) = \vec{r}(s) + \rho(s, \varphi)\left(\vec{\nu}(s)\cos(\varphi) + \vec{\beta}(s)\sin(\varphi)\right)$$
$$= \vec{r}(s) + \rho(s, \varphi)\left(\frac{1}{k} \times \vec{r}''(s)\cos(\varphi) + \vec{\tau}(s) \times \vec{\nu}(s)\sin(\varphi)\right) \quad (4)$$

If the guide curve $\gamma : \ \vec{r} = \vec{r}(t)$ is a function of some parameter *t,* then unit vectors tangent, normals, and binormals are computed by the equations [19, 21]:

$$\vec{\tau} = \frac{d\vec{r}/dt}{|d\vec{r}/dt|}, \ \vec{\nu} = \frac{d\vec{\tau}/dt}{|d\vec{\tau}/dt|}, \ \vec{\beta} = \vec{\tau} \times \vec{\nu}. \quad (5)$$

In this case, the position of surface points can be determined by equality:

$$\vec{r}(t, \varphi) = \vec{r}(t) + \rho(t, \varphi)\left(\vec{\nu}(t) \times cos(\varphi) + \vec{\beta}(t) \times sin(\varphi)\right), \quad (6)$$

3 Results and Discussion

Geometric modeling of a cylindrical coil spring-twisted channel is described in detail in the book [21].

On the basis of the above model, the surface of the coil spring-twisted channel formed by a circle of constant radius *r* with a center on the helical line is made.

In this case, the guide curve is a bishelix located on the surface of a round cone with the lower base *R*.

Then we get the following system of equations:

$$\vec{r}(t) = \begin{pmatrix} ((R - bt \cdot \tan\psi) + r \cdot \cos\omega t) \cdot cost \\ ((R - bt \cdot \tan\psi) + r \cdot \cos\omega t) \cdot sint \\ bt + rsin\omega t \end{pmatrix}, \quad 0 \le t \le 2\pi n; \quad (7)$$

$$\vec{\rho}(t, \varphi) = r_0\left(\cos\varphi\vec{\nu}(t) + \sin\varphi\vec{\beta}(t)\right), \quad 0 \le \varphi \le 2\pi \quad (8)$$

Where *R* –radius of the lower base of the coil,

r_0– spring coil wire radius,

n – number of turns of a double helical line,

ω –number of turns of the bishelix, falling on one turn of the central helical line,

ψ – cone angle.

Calculating the unit vectors of tangent, normals and binormals according to Eq. (5) and substituting the resulting expressions in Eq. (6), we get parametric equations of the conical surface coil spring-twisted channel:

$$\vec{r}(t, \varphi) = \begin{pmatrix} ((R - bt \cdot \tan\psi) + r \cdot \cos\omega t)cost \\ ((R - bt \cdot \tan\psi) + r \cdot \cos\omega t)sint \\ bt + rsin\omega t \end{pmatrix} + r_0\cos\varphi \cdot \vec{\nu}(t) + r_0\sin\varphi \cdot \vec{\beta}(t), \quad (9)$$

In order to check the conformity of Eq. (9) geometry of the coil spring-twisted channel under consideration, the surface is constructed in the MatLab system, Fig. 6.

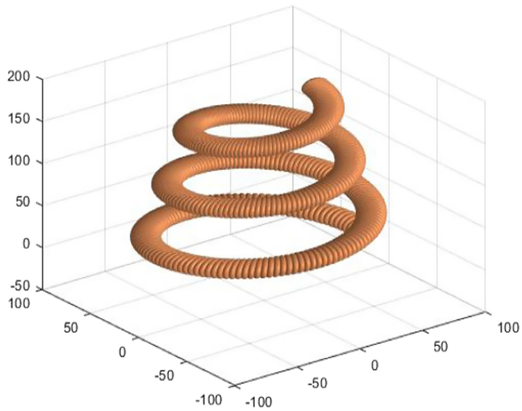

Fig. 6. Conical coil spring-twisted channel built at MatLab

4 Conclusions

Mathematical modeling is widely used in scientific disciplines, due to low costs compared to the rare nature experiment.

One of the stages of design development of innovative heat exchangers is the development of their geometric model.

In this paper, a mathematical description of the geometric model of the surface of the conical coil spring-twisted channel is given.

In the future, the results can be used for mathematical modeling of thermal engineering processes occurring in a conical coil heat exchanger based on a spring-twisted channel.

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