Solution of conjugate problem in a conical coil heat exchanger

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Abstract. Today, coil heat exchangers are widely used in various industries. A large number of works have been published devoted to the study of the characteristics of helical coil heat exchangers. According to the authors, conical coil heat exchangers have higher efficiency compared to helical ones. The article investigates the influence of the geometric parameters of conical coil heat exchangers on their effectiveness. The object of study is a conical coil heat exchanger with different tube diameters of the inner coil (di = 13, 15, 17 mm) and various number of turns (N = 6, 10, 14). Modeling was carried out in the Ansys Fluent software package. For each combination of the parameters, data were obtained on the temperature and velocity of the coolant at the outlet. It was found that a change in the number of turns by a factor of 2.3 leads to an increase in the temperature of the heated fluid by an average of 9.7 °C. The effect of changing the diameter of the inner coil is non-linear.

Keywords: heat transfer, heat exchanger, conical coil, numerical modeling, conjugate problem, Ansys Fluent.

1 Introduction

Heat exchangers are widely used from department of housing and utilities to nuclear and aircraft industries. Modern heat exchangers must be highly efficient, reliable in operation, have a low cost and size indicators.

Due to its compact size, coil heat exchangers are widely used in industry. The main node is a heat exchange element—a coil, which is a tube, usually of a round cross-section, flat or volumetric configuration. The shape of the coil can be different: flat spiral, zigzag, helical conical, etc. The shape gets out based on the thermal properties of the heat carriers, the required power of the heat exchanger and depending on the interaction scheme of the heat carriers.

A large number of scientific papers are devoted to the study of hydrodynamics and heat exchange processes occurring in helical coil heat exchangers. Thus, first works devoted to the mathematical description of the flow of liquid in a curved tube were published in 1927-1928 by Dean W. R. He noted that the decrease in the flow rate is due to the curvature of the channel and depends on a single variable – K, which is equal to 2 (Re) 2 r/R, for low speeds and small values of the r/R ratio.

The results of numerous studies show that helical coil heat exchangers have higher efficiency due to a higher-pressure drop [1, 2].

Several teams of authors have conducted research to improve the efficiency of heat exchange in helical coil heat exchangers [3, 4], using nanofluids as a coolant [5-8] and studying the influence of geometric dimensions on heat transfer efficiency [6, 9, 10].

The study [11] shows that as tube diameter increases with constant coil diameter, the curvature ratio increases, which increases the intensity of the secondary developed fluid flows and the Nusselt number, Eq. (1):

$$Nu = 265.65 \left( \frac{r}{R} \right)^{0.11}$$ (1)
\( r \) – radius of the tube, mm;
\( R_c \) – radius of the coil, mm.

Therefore, the most effective are helical coils of small diameter with large tube diameter.

The coil pitch is important only in the developing heat exchange area, and in the steady-state mode, the \( \frac{Nu_{loc}}{Nu_{av}} \) ratio is almost independent of the coil parameters and the Dean number.

In [12], the results of three-dimensional modeling of hydrodynamics and heat transfer in a helical coil heat exchanger are shown. The calculation results obtained using the CFD module are consistent with the experimental results within the experimental error. Based on the results obtained, equations were developed for calculating the heat transfer coefficient of a spiral coil.

Works [13, 14] are devoted to the review of scientific articles containing the analysis of flow parameters, assessment of heat exchange characteristics, as well as mathematical modeling of helical coil heat exchangers.

As you can see, the processes of hydrodynamics and heat transfer in a helical coil are well studied, which is not true of heat exchangers with conical coils.

The idea of replacing helical coil heat exchangers with conical ones is that already at the first turns of the coil the temperature of the heated water rises, its kinematic viscosity decreases and, accordingly, the Reynolds number increases, this leads to an increase in the heat transfer coefficient. In this regard, it becomes possible to reduce the area of heat transfer (overall dimensions of the heat exchanger). The growth of the heat transfer coefficient due, among other things, increasing the curvature of the coil.

The team of authors Purandare, Pramod S. et al. [15-17] consider the characteristics of heat transfer and pressure drop of a conical coil placed in a shell with different cone angles and tube diameters. Conical coils with a cone angle 0° (helical coil), 45°, 90°, 135° and 180° (spiral coil) are analyzed experimentally. The study leads to the following conclusions: the Nusselt number has the greatest value for a helical coil and the smallest for a spiral, and for a conical coil, this value decreases with an increase in the angle of the cone.

Experimental studies [16] carried out heat exchanger for cone with cone angle 90° showed that the heat transfer coefficient \( h_i \) increases with increase the Reynolds number \( (Re_i) \) for a constant flow of cold water, but decreases with increasing flow rate of cold water at a constant value number of \( Re_i \).

The analysis shows that the Nusselt number and the coefficient of friction \( f \) are functions of flow rates, tube diameter, curvature coefficient, and cone angle. The Nusselt number increases with increasing flow velocity in the tube space, while it decreases with increasing flow velocity around the coil, with increasing cone angle and tube diameter.

To date, topological application of heat exchangers type "tube in tube", with less hydraulic resistance, and therefore, higher velocities of coolant flow (up to 3 m/s), which provides a higher heat transfer coefficient and a small heat consumption. In addition, the advantage of such a heat exchanger is a variety of layouts, and if necessary, the heat exchange surface can be increased by installing additional sections.

Work [18] is devoted to experimental and numerical studies of heat transfer and characteristics of laminar fluid flow in a conical two-tube coil heat exchanger. The mathematical model is confirmed by the results of the experiment. The results showed that the Dean numbers in the tube and inter-tube space have a significant influence on the Nusselt number. Using a conical heat exchanger instead of a spiral type leads to an increase in the overall heat transfer coefficient, as well as an increase in the coefficient of friction. The highest efficiency of heat exchange is observed in devices with a cone angle from 65 to 85°.

In [19] it is noted that the ratio of tube diameters is the most effective dimensionless variable for determining the efficiency of exergy. The angle of the cone has a significant impact on both the exergy efficiency and the exergy performance coefficient. With an increase in the cone angle from 0 to 65°, the exergy efficiency and the exergy efficiency coefficient decrease by 32.56% and 11.1%, respectively.

The purpose of this work is to study the influence of geometric parameters of a conical coil heat exchanger on the thermal and hydraulic characteristics using the Ansys Fluent software package.
To achieve this goal, the following tasks were completed:
- numerical simulation of heat exchange in the inter-tube space for different diameters of the inner coil tube (d=13, 15, 17 mm) and different number of turns (N=6, 10, 14);
- determination of thermal and hydraulic characteristics;
- evaluation and analysis of the obtained results.

2 Materials and methods
Conical coil heat exchanger (figure 1) works as follows: with a counter-current flow of heat carriers, hot water enters the inner copper tube through a fitting, while cold water is fed into the inter-tube space through a fitting installed in an external steel shell.

![Conical heat exchanger](image)

**Figure 1.** Conical heat exchanger examined in this study, N=10.

For the calculation, the following characteristics were predefined:
- dimensions of the heat exchanger are shown in Table 1.

| №  | Parameter                              | Value             |
|----|----------------------------------------|-------------------|
| 1  | The number of turns, N                 | 6, 10, 14        |
| 2  | Internal tube diameter, mm             | 13, 15, 17       |
| 3  | External tube diameter, mm             | 36                |
| 4  | The coil pitch, mm                    | 70                |
| 5  | Coil diameter at the bottom of HEX, mm | 581               |
| 6  | Coil diameter at the top of HEX, mm    | 324, 153, 92     |
| 7  | Heat exchanger height, mm             | 420, 700, 980    |
| 8  | Wall thickness, mm                    | 2                 |

– parameters of heat carriers are shown in Table 2.
Table 2. Parameters of heat carriers.

| №  | Parameter                                      | Value |
|----|-----------------------------------------------|-------|
| 1  | The inlet temperature of the hot water, °C    | 70    |
| 2  | The inlet temperature of the hot water, °C    | 5     |
| 3  | Hot water consumption, kg / hour              | 945   |
| 4  | Cold water consumption, kg / hour             | 787   |

The computational grid for the model was constructed using the Ansys Meshing hexahedral program for solids and tetrahedral for liquids.

Figure 2 shows the design grid for the conical coil heat exchanger model.

![Figure 2. Calculation grid for the conical coil heat exchanger model.](image)

2.1 Choosing a flow model

To model fluid motion in the apparatus, two turbulence models were used: realizable k-ε model and k-ω SST. According to the data of scientific research, both models have good convergence of the results with experimental data. In this case, both models showed almost identical calculation results, the difference in temperature was less than 0.5 °C and in velocity was less than 0.1 m/s.

In the future, it is planned to solve a similar problem for conical coil heat exchangers based on spring-twisted channels [20-22], the k-ω SST model is preferable.

The SST turbulence model provides a more accurate solution in the parietal layer. The hybrid SST model uses the k-ω model for the near-wall region and the k-ε model for the external flow, which allows one to combine the strengths of each of the combined models.

To solve this problem, a Pressure-Based solver was chosen, an energy equation was connected, a k-ω SST turbulence model, a SIMPLEC numerical solution algorithm were set.

3 Results

A stationary problem for different geometric models of a conical coil heat exchanger is considered. Table 3 shows the results obtained.

| Number of turns N | 6  | 10 | 14 |
|-------------------|----|----|----|
| Internal tube diameter, mm | 13 | 15 | 17 |
| The outlet temperature of the hot water, °C | 41.7 | 39.7 | 37.9 | 38.47 | 33.6 | 37.3 | 34.5 | 28.1 | 31.9 |
| The outlet temperature of the cold water, °C | 39.5 | 41.3 | 44.15 | 43.5 | 49.4 | 45.2 | 47.9 | 54.6 | 51.6 |
| Velocity in the inner coil, m/s | 2.0 | 1.7 | 1.2 | 1.77 | 1.5 | 1.17 | 1.6 | 1.35 | 1.28 |
| Velocity in the annulus, m/s | 0.38 | 0.48 | 0.56 | 0.34 | 0.39 | 0.5 | 0.32 | 0.45 | 0.51 |
The flow of heating water is turbulent, \(3.9 \times 10^4 \leq \text{Re} \leq 5.2 \times 10^4\). The heated water is transient and turbulent flow, \(0.83 \times 10^4 \leq \text{Re} \leq 11.3 \times 10^4\).

The adequacy of the results obtained is confirmed by the results of calculating the heat balance. Figure 3 shows an example of temperature distribution over the surface of the coil.

![Figure 3](image)

**Figure 3.** The temperature distribution of heat carriers on the surface of the coil:
   a) general form, b) in the XY plane.

According to Table 3 the maximum temperature difference is 50°C for a cold water conical coil heat exchanger with 14 turns and an internal coil tube diameter of 15 mm.

![Figure 4](image)

**Figure 4.** Changing the flow rate along the length of the coil: a) general form; b) in the XY plane.

From figure 4 it is seen that the speed and temperature of the cold carrier practically do not change, and the core of the flow is distributed in the inter-tube space at a distance from the walls. The temperature of the cold water increases 3 times after the second coil turn.

Consider the influence of the number of turns and the diameter of the inner coil on the efficiency of heat exchange, the results are shown in figure 5.

Let's analyze each of the factors separately. When the number of turns increases, the heat exchange area increases, which leads to an increase in the output temperature of the heated coolant. It is worth noting that when the number of turns increases by 2.3 times, the average temperature increases by 9.7°C.

As for the influence of changes in the diameter of the inner coil, the nonlinear nature of the relationship can be seen. It can be assumed that there is an optimal ratio between the diameters of the external and internal coil. Initially, there is an increase in heat transfer efficiency (with a change in diameter from 13 to 15 mm), and then a slight decrease (with a change in diameter from 15 to 17 mm), in general, an increase in the diameter of the inner coil tube leads to an increase in the heat transfer efficiency. In this work, the maximum value of the temperature of the cold coolant at the outlet, regardless of the number of turns, was obtained for a diameter of 15 mm.
In this paper, a numerical method was used to model the stationary mode of heat transfer and fluid dynamics of heated water in the inter-tube space of a coil-type conical heat exchanger. The k-ω SST model was chosen as the turbulence model. The main purpose of this study was to determine the influence of such parameters as the number of coils of the coil and the diameter of the inner coil tube on the efficiency of heat exchange.

It was found that:

a) it is possible to heat a cold coolant at 50°C in a conical coil heat exchanger with 14 turns and a diameter of the inner coil tube of 15 mm;

b) number of turns increases by more than 2 times, the temperature at the outlet of the cold coolant increases by an average of 9.7%;

c) change in the diameter of the inner coil tube has a stronger effect on the change in the final temperature of the cold coolant;

d) this effect is non-linear, the authors assume that the optimal ratio between the diameters of the external and internal coil, in this work, is equal to 2.3.

4 Discussions

The analysis of the results shows the need to intensify the heat exchange process in a conical coil heat exchanger by using surface finning of the inner coil walls [21] or creating coil heat exchangers in the form of truncated cones with tubes per cone [22].

Figure 5. Dependence of the outlet temperature of the cold water on the geometry of the conical coil.

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