

# Engineering Calculation and Experimental Study of a Cone-Shaped Coil Heat Exchanger

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## Abstract

To improve the characteristics of heat and power equipment, it is necessary to develop new designs of heat exchangers, increase the efficiency of heat exchange surfaces, apply modern approaches to the design and calculation of heat exchangers, and create new technologies for their production. The paper proposes modern compact coil heat exchangers of the "pipe in pipe" type with a variable bending radius of the helical spiral and the engineering method calculating the thermohydrodynamic characteristics of such devices. The calculation of a coil heat exchanger with a linearly varying bending radius of a helical spiral (cone-shaped coil heat exchanger) has been performed. They performed the experimental study of heat transfer in a cone-shaped coil heat exchanger of the "pipe-in-pipe" type. They obtained the empirical formulas for the Nusselt number and hydraulic resistance coefficient. It has been established and experimentally confirmed that cone-shaped coil heat exchangers are more compact and efficient in comparison with the known cylindrical coils. It is proposed to modernize the hot water preparation unit in one of the residential buildings in the city of Kazan (Russia) by replacing the outdated shell-and-tube heat exchanger with a compact cone-shaped coil heat exchanger, which made it possible to reduce the duration of hot water preparation significantly, to reduce the costs of the heating medium and, thus, to reduce consumer costs.

## Keywords

*Thermolysis Coefficient; Heat Transfer Coefficient; Heat Exchanger; Heat Exchange Surface; Coil Pipe; Pipe In Pipe*

## Introduction

One of the ways to intensify heat transfer processes is to create small-sized heat exchangers with a developed heat exchange surface. It is known that coil-type channels provide a moulded heat exchange surface and are one of the most efficient and technologically advanced designs of heat exchange elements [5; 11].

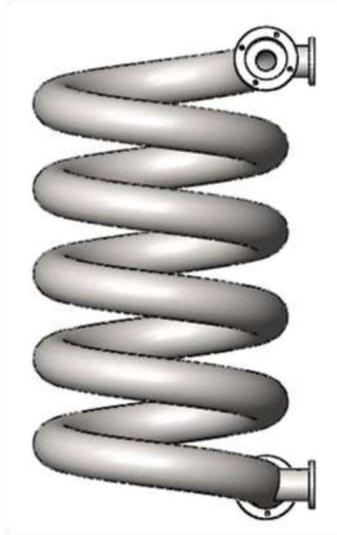
Cylindrical coil pipes immersed in a container with a liquid medium are mainly used in industry nowadays. The methodology for their engineering calculation is widely described in the literature.

The disadvantages of such coil heat exchangers should be attributed to their large volume; therefore, a large metal consumption per unit surface, as well as shallow values of heat transfer coefficients.

A type of coil devices is pipe-in-pipe heat exchangers. One of the first designs of such a heat exchanger (Fig. 1) is described in [17].

The device makes it possible to intensify heat exchange significantly while reducing the length and weight of the device several times as compared to traditional tubular devices and submersible coil heat exchangers.

In order to intensify heat transfer, reduce the weight and dimensions of the apparatus, the authors of [3] proposed innovative two-pipe coil heat exchangers with various configurations of the external circuit.

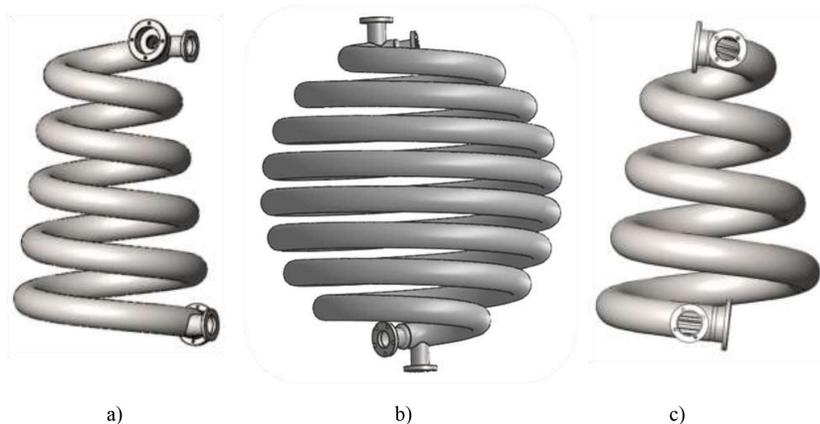


**Fig. 1: Coil Heat Exchanger of "Pipe in Pipe" Type**

The outer contour of the heat exchanger is determined by the law (function) of the helical spiral bending radius change. Individual designs of such devices are shown in Fig. 2. Heat exchangers can be equipped with one or more inner tubes. Fig. 2a demonstrates a cone-shaped coil, 2b - ball-shaped coil, 2c - a sectional cone-shaped coil in which fluid moves through several pipes.

The proposed coil heat exchangers, compact in size, can be used in hot water supply systems, for residential and industrial facility heating, as well as during storage, transportation and heating of oil and oil products in winter conditions. The heat carrier used to heat oil products from the outer walls of the heat exchanger can simultaneously serve to heat water in the inner pipes of the apparatus, which can be used for the technological and production needs of oil industry facilities.

For the purpose of industrial production of cone-shaped coil heat exchangers of "pipe-in-pipe" type, it is necessary to determine their thermohydrodynamic characteristics and evaluate the efficiency of heat transfer intensification in such devices.



**Fig. 2: Coil Heat Exchangers of the Type "Pipe in Pipe"**

With a changing bend radius of the helix

a) in the form of a cone b) in the form of a ball; c) conical multi-tube

In this regard, it was decided to develop an engineering method to calculate the thermal and hydrodynamic characteristics of cone-shaped coil devices, as well as to conduct an experimental study of the flow and heat transfer in such devices.

Based on the calculation results and experimental data, evaluate the degree of the proposed heat exchanger efficiency in comparison with the known heat exchangers of the "pipe in pipe" type.

## Methods

To study the efficiency of heat exchangers, full-scale and numerical experiments are carried out [15; 7; 2; 8], as well as the methods of engineering calculation are applied.

Calculation of heat transfer in bent pipes and ducts is often carried out using the formulas for straight pipes and ducts with the addition of a factor - a correction for the action of centrifugal forces. For example,  $\alpha_{iz} = \varepsilon \cdot \alpha_{pr}$ , where

$\alpha_{iz}$ ,  $\alpha_{pr}$  – the heat transfer coefficients in a curved and straight channel,  $\varepsilon$  – a correction factor.

For the first time this approach was proposed in [9], where the correction factor was calculated by the following formula:

$$\varepsilon = 1 + 3.54 \frac{d}{D}, \quad (1)$$

where  $d$  is the inner diameter of the channel,  $D$  is the diameter of the curved channel.

In [12], it was proposed to calculate the correction factor by the following formula:

$$\varepsilon = 1 + \frac{1.96}{\text{Re}^{0.088}} \left( \frac{d}{R} \right)^{0.01}, \quad (2)$$

where  $0.01 \leq d/R \leq 1$ ,  $10^4 \leq \text{Re} \leq 10^5$ ,  $R$  – the radius of the channel curvature.

The authors of [19] propose to calculate the correction factor by the following formula:

$$\varepsilon = 1 + \frac{21}{\text{Re}^{0.14}} \left( \frac{d}{D} \right)^c,$$

where the degree ranges from 0.5 to 0.75.

In [20], the authors determine the correction factor by the following formula:

$$\varepsilon = 1 + \frac{21}{\text{Re}^{0.14}} \left( \frac{d}{D} \right)^{0.48}, \quad (3)$$

where  $\text{Re}$  is the Reynolds criterion.

Let's note that at present, there is no generally accepted ratio to calculate the correction factor. In engineering calculations, the expression (1) is used most often.

To calculate cone-shaped coil devices, we use the method of temperature intervals. The essence of the method is the following. The temperature difference along one of the streams is divided into several intervals. The heat balance equation is used to calculate the corresponding temperature intervals for the second flow. Each temperature range corresponds to a certain part of the heat exchanger. The heat transfer is calculated as for the individual device in each interval.

Let us introduce the designations of the quantities that are the initial data for the calculation:

$G_1$  - heating water consumption;

$G_2$  - consumption of heated water;

$t'_{g1}$  - heating water temperature at the inlet;

$t'_{g2}$  - heated water temperature at the inlet;

$t''_{g2}$  - heated water temperature at the outlet.

The result of the engineering calculation is the determination of the heat transfer coefficients, the heat exchange surface area, and the thermal and hydrodynamic characteristics of the device.

The calculation of the cone-shaped coil heat exchanger is carried out according to the following algorithm:

1. The temperature difference in the heated liquid is divided into  $n$  of equal intervals.

2. At each temperature interval  $[t_{i-1}; t_i]$  they determine the heat transfer coefficients of the shell and tube space  $\alpha_{1i}$ ,  $\alpha_{2i}$  (taking into account the correction factor), heat transfer  $k_i$ , heat transfer surface area  $F_i$  and pressure drop

$\Delta P_i$ ,  $i = 1, \dots, n$ . At each interval, the bending radius of the heat exchanger is considered constant, i.e. a cylindrical coil is calculated in each interval.

3. The general parameters of the heat exchanger are calculated:

$$\Delta P = \sum_{i=1}^n \Delta P_i \text{ - pressure drop, } F = \sum_{i=1}^n F_i \text{ - heat transfer area, } \alpha_1 = \frac{1}{F} \sum_{i=1}^n \alpha_{1i} F_i \text{ - thermolysis coefficient}$$

during fluid flow in the space between the inner and outer pipes,

$$\alpha_2 = \frac{1}{F} \sum_{i=1}^n \alpha_{2i} F_i \text{ - thermolysis coefficient during fluid flow inside the inner pipe.}$$

Heat transfer coefficient can be calculated using the following formula:

$$k = \frac{1}{F} \sum_{i=1}^n k_i F_i$$

or

$$k^* = \frac{Q}{F \cdot \Delta t_{cr}}$$

The proposed calculation algorithm is implemented in the form of the computer mathematics program "Matlab", which allows to calculate cone-shaped coil heat exchangers of the "pipe-in-pipe" type with one or more inner tubes. A coil with a constant bending radius of the helical spiral (cylindrical coil) was used as a test to check the calculation correctness.

## Results and Discussion

Let's consider a two-tube cone-shaped coil heat exchanger (Fig. 2a). Let the diameter of the outer pipe  $D = 0.048$  m. The diameter of the inner pipe  $d_1 = 0.029$  m, the outer diameter of the inner pipe is  $d_2 = 0.032$  m. The distance between the turns  $h = 1.5D$  m, the smaller diameter of the cone is  $D_{zm}^1 = 0.2$  m. The taper angle is  $\varphi = \pi/10$ .

The heated water moves through the steel pipe and is heated from  $t'_{g2} = 5$  °C to  $t''_{g2} = 55$  °C. Its consumption makes  $G_2 = 1.09$  kg/s.

Heating water moves in counterflow along the annular channel between the pipes and has the inlet temperature  $t'_{g1} = 95$  °C, its flow rate is  $G_1 = 0.549$  kg/s.

The equivalent diameter of the annular space is

$$d_{eqv} = \frac{D^2 - d_2^2}{D + d_2} = 0.014 \text{ m.}$$

We divide the temperature difference into the intervals of  $\Delta t = 10$  °N and on each interval we calculate: correction factors according to the formula (1)

$$\varepsilon_1 = 1 + 3.54 \cdot D / D_{zm}^i \text{ - in the annular space;}$$

$$\varepsilon_2 = 1 + 3.54 \cdot d_1 / D_{zm}^i \text{ - in the tube space;}$$

$$\text{the amount of transferred heat } Q_i = G_2 c_{p2} (t''_{g2} - t'_{g2}) \text{ kW;}$$

heating water temperature at the end of the temperature range

$$t''_{g1} = t'_{g1} - \frac{Q_i}{G_1 c_{p1}};$$

arithmetic mean of temperatures:

$$t_{g1} = 0.5(t'_{g1} + t''_{g1}), t_{g2} = 0.5(t'_{g2} + t''_{g2});$$

the values of the physical properties of water at these temperatures;  
fluid velocities

$$w_1 = \frac{4G_1}{\rho_{g1}\pi(D^2 - d_2^2)} \text{ m/s}, w_2 = \frac{4G_2}{\rho_{g2}\pi d_1^2} \text{ m/s};$$

Reynolds number for heating water  $\text{Re}_{g1} = w_1 d_{eqv} / \nu_{g1}$  ;

Nusselt number for the annular space

$$\text{Nu}_{g1} = 0.017 \text{Re}_{g1}^{0.8} \text{Pr}_{g1}^{0.4} \left( \frac{\text{Pr}_{g1}}{\text{Pr}_{c1}} \right)^{0.25} \left( \frac{D}{d_{eqv}} \right)^{0.18} ;$$

heat transfer coefficient from heating water to the pipe wall

$$\alpha_{1i} = \varepsilon_1 \text{Nu}_{g1} \frac{\lambda_{g1}}{d_{eqv}} \text{ W/(m}^2 \cdot \text{K)};$$

Reynolds number for heated water  $\text{Re}_{g2} = w_2 d_1 / \nu_{g2}$  .

Nusselt number for tube space

$$\text{Nu}_{g2} = 0.021 \text{Re}_{g2}^{0.8} \text{Pr}_{g2}^{0.43} \left( \frac{\text{Pr}_{g2}}{\text{Pr}_{c2}} \right)^{0.25} ;$$

heat transfer coefficient from the pipe wall to the heated water

$$\alpha_{2i} = \varepsilon_2 \text{Nu}_{g2} \frac{\lambda_{g2}}{d_1} \text{ BT/(m}^2 \cdot \text{K)};$$

heat transfer coefficient  $k_1 = \left( \frac{1}{\alpha_{11}} + \frac{\delta_c}{\lambda_c} + \frac{1}{\alpha_{21}} \right)^{-1} \text{ W/(m}^2 \cdot \text{K)};$

heating surface area  $F_i = \frac{Q_i}{k_i (t_{g1} - t_{g2})} \text{ m}^2;$

the length of one turn  $l_v = \sqrt{(\pi D_{zm}^i)^2 + h^2} \text{ m};$

pipe length  $l_i = \frac{F_i}{\pi d_1} \text{ m};$

number of turns  $s = \frac{l_i}{l_v};$

pressure drop in the annular space

$$\lambda_{1i} = \frac{0.316}{\text{Re}_1^{0.25}},$$

$$\Delta P_{1i} = \varepsilon_1 \lambda_{1i} \frac{l_{1i}}{d_{eqv}} \cdot \frac{\rho w_1^2}{2} \text{ Pa};$$

pressure drop in the tube space:

$$\lambda_{2i} = \frac{0.316}{\text{Re}_2^{0.25}},$$

$$\Delta P_{2i} = \varepsilon_2 \lambda_{2i} \frac{l_i}{d_1} \cdot \frac{\rho w_2^2}{2} \text{ Pa.}$$

The diameter of the larger diameter of the cone for the considered temperature range is

$$D_{zm}^{i+1} = D_{zm}^i + 2s \cdot h \cdot \text{tg } \varphi \text{ m.}$$

Temperature ranges and calculation results in each range are shown in Table 1.

**Table 1: Characteristics of the Heat Exchanger by Temperature Intervals**

Numerical indicators	55–45 °C	45–35 °C	35–25 °C	25–15 °C	15–5 °C
$\varepsilon_1$	1.8496	1.5525	1.4443	1.3834	1.3428
$\varepsilon_2$	1.5664	1.3683	1.2962	1.2556	1.2286
$Q_i$ , kW	22.915	22.912	22.937	22.985	23.05
$w_1$ , m/s	1.186	1.1814	1.1778	1.1755	1.1744
$w_2$ , m/s	0.70967	0.70715	0.7047	0.70238	0.70016
$Re_{g1}$	54131	51124	48148	45213	42338
$Re_{g2}$	40844	34338	28014	22342	17155
$Nu_{g1}$	155.49	149.93	144.39	138.81	133
$Nu_{g2}$	192.67	186.29	179.4	172.64	165.68
$\alpha_{1i}$ , W/(m <sup>2</sup> ·K)	13511	10893	9715	8606	8249
$\alpha_{2i}$ , W/(m <sup>2</sup> ·K)	6111	5058	4491	4058	3651
$k_i$ , W/(m <sup>2</sup> ·K)	3690	3098	2786	2551	2334
$F_i$ , m <sup>2</sup>	0.14616	0.1559	0.15709	0.15707	0.15843
$l_i$ , m	1.4533	1.5507	1.5626	1.5625	1.5759
$\Delta P_{1i}$ , Pa	1182	1069	1014	986	982
$\Delta P_{2i}$ , Pa	867	841	842	860	903
$\Delta P_i$ , Pa	2049	1910	1856	1846	1885
$D_{zm}^{i+1}$ , m	0.30756	0.38245	0.44319	0.49563	0.54293

Let's calculate the general parameters of heat exchanger:

$$\Delta P = 9546 \text{ Pa}; F = 0.7747 \text{ m}^2;$$

$$\alpha_1^* = \frac{1}{F} \sum_{i=1}^5 \alpha_{1i} \cdot F_i = 10204 \text{ W/(m}^2 \cdot \text{K)};$$

$$\alpha_2^* = \frac{1}{F} \sum_{i=1}^5 \alpha_{2i} \cdot F_i = 4651 \text{ W/(m}^2 \cdot \text{K)};$$

$$k^* = \frac{1}{F} \sum_{i=1}^5 k_i \cdot F_i = 2879 \text{ W/(m}^2 \cdot \text{K)}.$$

Thus, the coil length is  $l = 7.706$  m, the device height – 0.3559 m, the number of turns is 5, the diameter  $D_{zm}^1$  of the smaller base of the cone-shaped coil is 0.2 m, the diameter of the larger base  $D_{zm}^6$  – 0.54293 m.

The proposed method of temperature intervals is universal and can be used to calculate the hydrodynamic characteristics of not only cone-shaped coils, but also heat exchangers with a curvilinear configuration of the external

circuit.

Currently, a fairly large number of methods for heat exchanger comparison are considered in the literature, various methods for their efficiency evaluation are proposed [4; 10; 14; 1].

Let us compare cone-shaped coil heat exchangers of the "pipe-in-pipe" type with cylindrical coils in terms of their efficiency, using the criterion proposed in [10]. The authors of [10], use the volumes or heat exchange surfaces of two devices at the same heat capacities and the capacities spent on the coolant pumping as the criterion for heat exchange efficiency.

$$\frac{F}{F_0} = \frac{(\xi/\xi_0)_{\text{Re}}^{0,4}}{(\text{Nu}/\text{Nu}_0)_{\text{Re}}^{1,4}} \quad (4)$$

The purpose of heat transfer intensification is to reduce the heat transfer surface. Therefore, it is possible to compare heat exchangers by this parameter. Since the intensification of heat transfer, as a rule, increases the velocities of the coolants and, accordingly, the resistance coefficients, it is necessary to compare the devices with equal costs for pumping, provided that the input and output temperatures of the coolants are equal. In this case, the flow rates of the coolants must be in the same ratio.

Let the temperature of the heated water varies from 5 °C to 55 °C. Heating water has the inlet temperature of 95 °C, and the outlet temperature of 70 °C. Equality of pressure drops is achieved by changing the flow rates of the coolants in the device under consideration.

Let us calculate the characteristics of one-pipe devices at different values of the taper angle. The calculation results are shown in Table 2.

**Table 2: Characteristics of Coil Heat Exchangers**

Parameter	Cylindrical coil	Conical coil			
		$\varphi = \pi/10$	$\varphi = \pi/12$	$\varphi = \pi/18$	$\varphi = \pi/20$
$d_i$ , m	0.032	0.032	0.032	0.032	0.032
$D$ , m	0.048	0.048	0.048	0.048	0.048
$D_{zm}^I$ , m	0.6	0.2	0.2	0.2	0.2
$D_{zm}^N$ , m	0,6	0.54	0.4945	0.4095	0.3814
$G_1$ , kg/s	1,108	1.09	1.089	1.085	1.078
$G_2$ , kg/s	0,558	0.549	0.548	0.546	0.543
$Q$ , kW	117	114.8	114.6	114.17	113.54
$\alpha_1$ , W/(m <sup>2</sup> ·K)	8774	10204	10396	10782	10828
$\alpha_2$ , W/(m <sup>2</sup> ·K)	4181	4651	4713	4843	4857
$k$ , W/(m <sup>2</sup> ·K)	2585	2879	2919	3000	2994
$F$ , m <sup>2</sup>	0.877	0.775	0.763	0.7393	0.7333
$l$ , m	8.72	7.706	7.586	7.354	7.29

Calculations show that the heat exchange surface of tapered coils is reduced by 13 - 19%. Consequently, they are more efficient than widespread cylindrical coils.

An experimental device was developed to verify the adequacy of the calculations and to confirm the effectiveness of the cone-shaped coil heat exchanger. The experimental device allows to determine the flow rate of cold water, the flow rate of hot water; the pressure in the tubular and annular space; the temperature of cold and hot water at the inlet and outlet; the temperatures of the outer and inner walls of the inner pipe.

The main element of the device is a two-tube cone-shaped coil heat exchanger. The outer tube with the diameter of 0.048 m is made of stainless steel. Wall thickness makes 0.002 m, the taper angle is  $\varphi = \pi/10$ . The inner pipe diameter is 0.032 m, the wall thickness is 0.0015 m.

An asbestos cord and a heat-resistant polymer film are used as heat-insulating material for the outer tube of the heat exchanger.

The flow rates were set in the range of Re numbers: from 15,000 to 50,000. The temperature of the fluids was constant at the inlet.

The hydraulic resistance coefficient  $\xi = \frac{2d}{\rho lw^2} \Delta P$  was determined by the measured pressure drop  $\Delta P$ .

Numerical calculations and the results of physical experiments made it possible to determine the parameters of hydrodynamics and heat transfer (Table 3).

**Table 3: The Results of Numerical Calculations and Physical Experiments**

$Re$	numerical calculation		experimental result	
	$Nu$	$\xi$	$\overline{Nu}$	$\overline{\xi}$
48239	548	0.0213	515	0.0241
42315	497	0.0220	464	0.0250
38083	460	0.0226	431	0.0258
33852	421	0.0233	392	0.0267
29620	381	0.0241	356	0.0277
25389	340	0.0250	315	0.0290
21157	297	0.0262	275	0.0305
16926	252	0.0277	230	0.0325
15233	233	0.0284	215	0,0335
14387	223	0.0289	206	0.0341

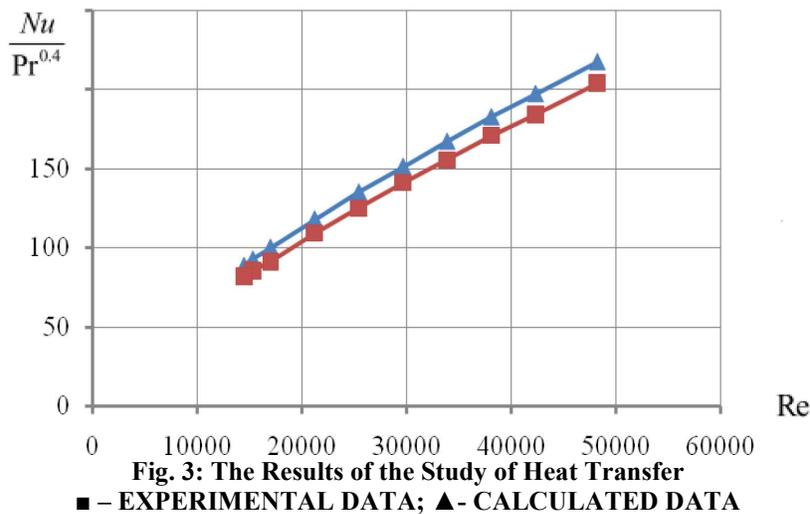
The results of the physical experiment were generalized by criterion equations. At  $Re = 15000 \div 50,000$  and  $Pr = 2.5 \div 10$

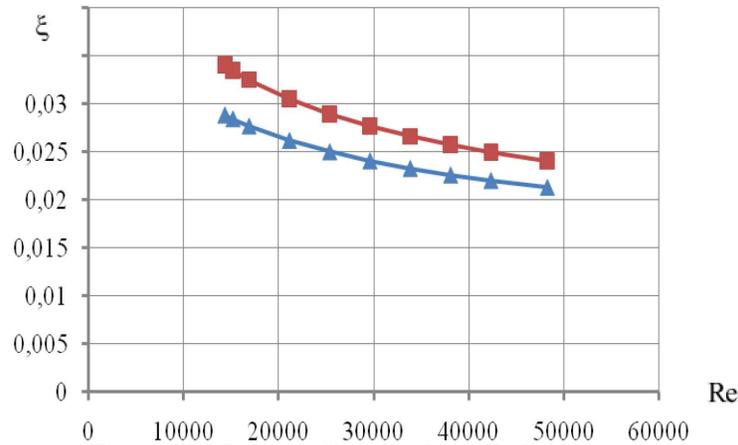
$$\frac{Nu}{Pr^{0.4}} = 0.056 Re^{0.759}; \xi = 0.527 Re^{-0.28}.$$

The results of the numerical study were approximated by the following dependences:

$$\frac{Nu}{Pr^{0.4}} = 0.072 Re^{0.742}; \xi = 0.318 Re^{-0.25}.$$

The results of the study of hydrodynamics and heat transfer are shown on Fig. 3-4.





**Fig. 4: The Results of the Study of Hydrodynamics**

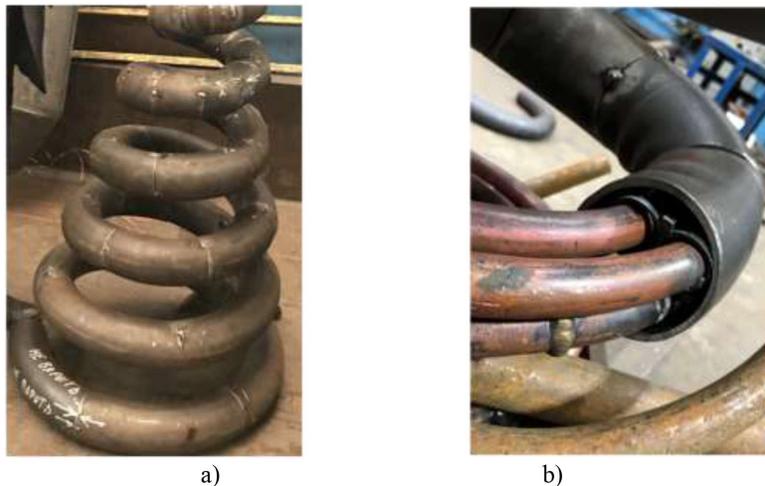
■ – EXPERIMENTAL DATA; ▲ - CALCULATED DATA

The discrepancies between theoretical and experimental values do not exceed  $\pm 10\%$ . Consequently, the proposed calculation method can be used to determine the thermal and hydrodynamic characteristics of cone-shaped devices. Thus, the complex of computational and experimental studies carried out has confirmed that conical coil devices are more efficient in comparison with the known cylindrical coils.

At present, a pilot industrial sample of a four-pipe cone-shaped coil heat exchanger of the "pipe in pipe" type has been manufactured in the Republic of Tatarstan (Russia). The manufacturing process is shown on Fig. 5a, 5b.

The apparatus is made in the form of a truncated cone [13], the lower base of which is 0.65 m, the upper one is 0.33 m, the height is 1.04 m, the heat exchange surface of the apparatus is 2.97 m<sup>2</sup>.

A bundle of tubes is mounted inside the outer tube with the diameter of 0.88 m, made of stainless steel, consisting of four copper coil heat exchange elements with an inner diameter of 0.02 m and the wall thickness of 0.0015 m. The ends of the bundle elements are fixed in the holes of the tube sheets along a hexagon using tight seam welding.



**Fig. 5: The Process of Making Heat Exchanger Coil**  
a) The Outer Tube; b) The Coil Fragment

On the basis of the performed theoretical and experimental studies, it was proposed to modernize the hot water preparation unit in one of the residential buildings of Kazan. In order to save energy and heat carrier, it was proposed to replace the morally and physically obsolete shell-and-tube heat exchanger with an efficient four-tube cone-shaped coil heat exchanger (Fig. 6).

This made it possible to reduce significantly the duration of hot water preparation, reduce the costs of heating coolant, electricity and metal consumption of equipment and, thus, to reduce the costs of consumers (the residents of a residential building).



**Fig. 6: Coil Heat Exchanger**

### Summary

The results of the study showed that, with equal costs for pumping heat transfer fluids, cone-shaped coil heat exchangers are more efficient in comparison with known cylindrical coils, since they have a smaller heat exchange surface to achieve the required thermohydrodynamic parameters.

The obtained results in this work are consistent with the conclusions of the authors [21; 6; 18; 16], who assert that cone-shaped coil units have an advantage over cylindrical coils, since they have higher heat transfer coefficients.

### Conclusion

The offered heat exchangers can be recommended for use in hot water supply systems, for heating of residential and industrial facilities.

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