HEAT TRANSFER COEFFICIENT IN ELLIPTICAL TUBE AT THE CONSTANT HEAT FLUX

by

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Cross-flow heat exchangers with elliptical tubes are often used in industrial application. In comparison with round tubes, the elliptical tubes have a better aerodynamic shape, which results in a lower pressure drop of working fluid flowing through the inter-tubular space of heat exchanger. Also, a higher heat flux is transferred from gas to the wall of such a tube due to the more intense heat exchange process. To prove this thesis, the values of the heat transfer coefficient from the wall of the elliptical pipe to the water flowing inside were determined, using the data from the conducted measurements. This study presents also research stand with a vertically positioned tube. In order to obtain a constant heat flux through the wall of elliptical tube, a resistance wire is used, evenly wound on the external surface of tube measuring section. The use of thermal insulation minimized heat loss to the environment to a negligible value. Installed K-type thermocouples allowed one to obtain, for various measurement conditions, the temperature distribution within the elliptical tube wall (for a given cross-section) and the water flowing inside it (in a given cross-section, at different depths, for both axes of the ellipse). The design of the stand allows such measurements in several locations along the length of the measurement section. The measurement results were used to verify numerical calculations. The relative error of the heat transfer coefficient value determined on the basis of CFD calculations using the SST-TR turbulence model in relation to the one determined on the basis of the measurement data is about 11%.

Key words: *heat exchanger, elliptical tube, research stand, heat flux, heat transfer coefficient, numerical calculations, SST-TR turbulence model*

Introduction

Modern power equipment strives both to reduce their dimensions and to optimize their working conditions. The aim of the latter is to maintain the most favourable heat transfer, to intensify the processes of mass, energy and momentum transport. In this regard, no exception is made for heat exchangers. Elliptical tubes are often used in these devices, espe-

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cially in the cross-flow type. Compared to round tubes, they have a more aerodynamically designed shape, which makes the flow of working medium through the inter-tube space, more advantageous. They operate not only with a lower pressure drop, but also the velocity distributions are more advantageous, *i. e*. the stagnant flow zones are reduced [1-5]. An important effect of this is a higher heat transfer rate, *e. g*. from gas to the wall of such a tube, due to a more intense heat exchange process. This fact allows, among other factors, to reduce the size of the device in comparison to the one in which circular tubes are used.

The disadvantage of this type of heat exchangers is the non-uniform distribution of fluids to its individual tubes [6-9]. The reason for this phenomenon is most probably the current shape and the relatively small dimensions of inlet and outlet chambers. The aforementioned fact causes that the velocities of fluid-flow in the pipes of such a heat exchanger may differ significantly from each other, but in some cases it may even be opposite to the desired [8, 10]. This usually results in unfavourable operating conditions, including high thermal compressive stresses caused by overheating of tube walls [6, 8, 11-17].

The analysis of operating conditions of the heat exchangers in question indicates that in their elliptical tubes liquid flows may occur in all regimes, *i. e*.: laminar, transitional and turbulent. This is evidenced by the locations of defects in these devices and the results of numerical simulations of thermal-flow conditions of their operation [8, 10, 11, 14-16]. Especially transitional flow is a very complex phenomenon and difficult to mathematical modelling. It is relatively poorly understood, and possible correlations enabling determination of the heat transfer coefficient, from the fluid-flowing in the tubular space to the wall of the exchanger pipe, are a few [18]. Not always a specific turbulence model, *e. g*. k-ε, k-ω, SST or SST-TR, allows to determine the correct values of heat transfer coefficient (for tube in horizontal arrangement) [19]. Their use in numerical calculations during various analyses requires assessment and confirmation of usability (in the case of the discussed devices, *e. g*. for determination of fluid parameters such as flow velocity or temperature distributions). Therefore, the developed mathematical models require experimental verifications, especially for the aforementioned flow regimes. In this paper the constructed test stand are shown and the measurement data are used to evaluate the results obtained from numerical calculations, especially in the transitional flow regime.

Experimental stand for determining heat transfer coefficient in elliptical tube

To study the heat transfer processes in a vertical elliptical tube a dedicated stand was developed. It was decided that it will work in a closed system and it will enable the measurement of temperatures in cross-sections of the fluid for both axes of the ellipse. This measurement is carried out in several zones along the measuring distance. In addition, the temperature of the elliptical pipe wall on the external surface and near the internal wall is measured at several points around the perimeter and in several zones along the pipe length. One of the important objectives of such measurements is the possibility of obtaining temperature distributions, which allows determining *e. g*. the value of the heat transfer coefficient from the wall of the elliptical pipe to the water flowing inside it.

The scheme of the stand, previously referred, is shown in fig. 1, while its general view and approximation to the measuring section are shown in fig. 2. The fundamental part of the stand is an elliptical tube, and the remaining elements are: water tanks, feed pump, radiator, fittings and switching fittings, electrical heating supply, and measurement equipment.

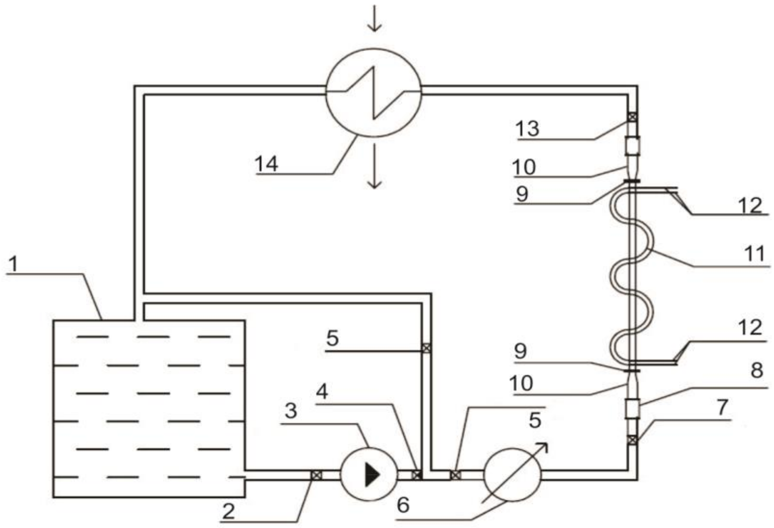

Figure 1. Scheme of the stand for determining the heat transfer coefficient at the inner surface of elliptical tube; *1 – supply water tank, 2 – shut-off valve, 3 – supply pump, 4 – non-return valve, 5 – flow limiter valve towards the elliptical pipe, 6 – flow meter, 7 – measurement section shut-off valve, 8 – connecting element (coupler), 9 – flanged connection of the fitting with elliptical pipe, 10 – fitting (transition from round to elliptical pipe), 11 – heating element (resistance wire), 12 – clamp for electrical connection, 13 – shut-off valve behind the measuring section, 14 – air-cooled heat exchanger*

Figure 2. General view of the stand for determining the heat transfer coefficient on the inner surface of the elliptical tube and a view of the measuring section

The test stand consists of: the elliptical tube with dimensions: 36 × 14 × 2 mm, fittings allowing the *transition* from elliptical to round and *vice versa*, a circulating water tank, a cross-flow heat exchanger (for cooling the water by air), a circulating pump (with a variable speed), and an electronic flow meter. It can be added that the use of the above mentioned heat exchanger in the system allowed cooling down the circulating water and keeping its temperature at the inlet to the tested tube at a constant value. At the same time, such a solution, *i. e*. construction of a closed-circuit system, allowed to save the working medium (water). In the system, as in the case of the pilot stand, the connection of the supply pipeline to the tank was applied. This made it possible to reduce the mass-flow rate of the medium, especially during measurements for laminar flows.

The heating system of the measuring section consists of two resistance wires, wound on an elliptical pipe next to each other and connected in parallel. The autotransformer was used for power supply. To measure the temperature of water flowing inside the elliptical tube and the wall of this tube, thermocouples of the K type with an external diameter of 0.5 mm are used. The zones where the thermocouples are installed along the length of the measuring section are shown in figs. 3 and 4. It can be seen that the thermocouples covered the inlet, middle and outlet points of the measuring section, which is 1200 mm long. It should also be added that the tube itself has inlet and outlet sections with lengths, respectively equal to: 500 mm and 300 mm. Flanged connections (with loose flanges) have been used between these sections and the measuring section. The spacers here, made of insulating material, are designed to limit the longitudinal heat transfer.

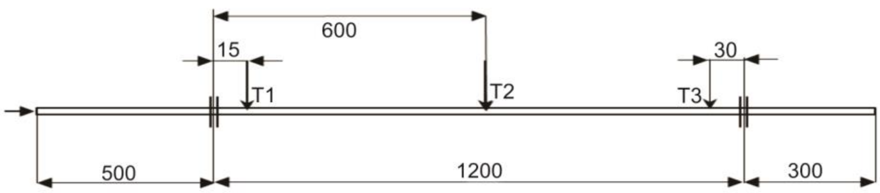

Figure 3. Location areas of thermocouples (T1-T3) for temperature measurement of medium flowing through the elliptical pipe

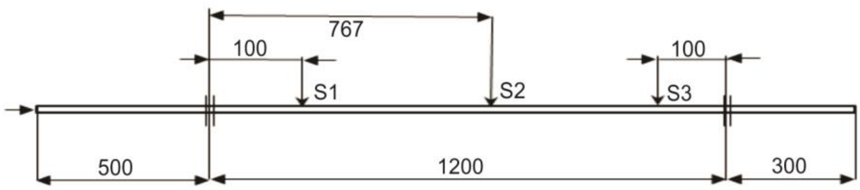

Figure 4. Location zones of thermocouples (S1-S3) for measuring the wall temperature of an elliptical tube

The location of thermocouples allows controlling the water temperature in the cross-section of a given zone in several places for both half-axis of the ellipse: smaller and larger. For one of them, the view of the measuring unit consisting of 4 thermocouples placed in a capillary tube is shown in fig. 5 (such units are glued into the holes drilled in the wall of the elliptical tube, in the given zones of its measuring section). On the other hand, the distances of *hot* thermocouple welds from the inner wall of the elliptical tube are given in tab. 1.

Thermocouples, designed to measure temperature in individual zones of the elliptical tube wall, fig. 4, on its external surface and at a distance of about 0.3 mm from the internal surface, have been installed respectively: in prepared grooves (their length is about 20 mm

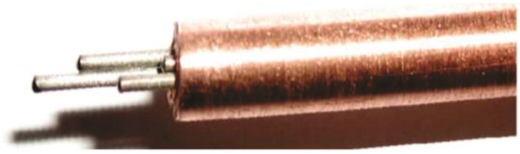

Figure 5. Thermocouples unit (for water temperature measurement) prepared for installation in elliptical tube (for lower half axis)

and depth about 0.25 mm) and in radially drilled holes in the tube wall. In each zone, 3 or 4 thermocouples were installed along ¼ of the ellipse circumference, two of which are located in the directions of the ellipse axis. Adhesives and high temperature silicones were used for the assembly. In the system of the test stand, all sensors for temperature and flow measurement of the circulating medium were included in the computer data acquisition system. The thermocouples are calibrated to ensure the measurement accuracy of ±0.1 °C.

Table 1. Location of thermocouples for measuring the temperature of water flowing inside the elliptical tube

Distance of the *hot shell thermocouple weld* from the inner surface	
For the major semi-axis [mm]	For the minor semi-axis [mm]
0,5	0,5
4,4	2,1
8,8	3,6
12,4	5,2

Experimental results

This section presents the experimental results for the transitional flow. For the elliptical tube it corresponds to the volumetric flow rate equal to $V = 0.15$ m^3/h and Reynolds number Re = 2908. The measurements are performed for the condition, for which the temperature of water on the feed system is about 20 °C. The values corresponding to the established state are considered as reliable. The results obtained for the given conditions are presented in figs. 6 and 7, which show, respectively, the values of temperatures obtained for fluid and wall of elliptical tube.

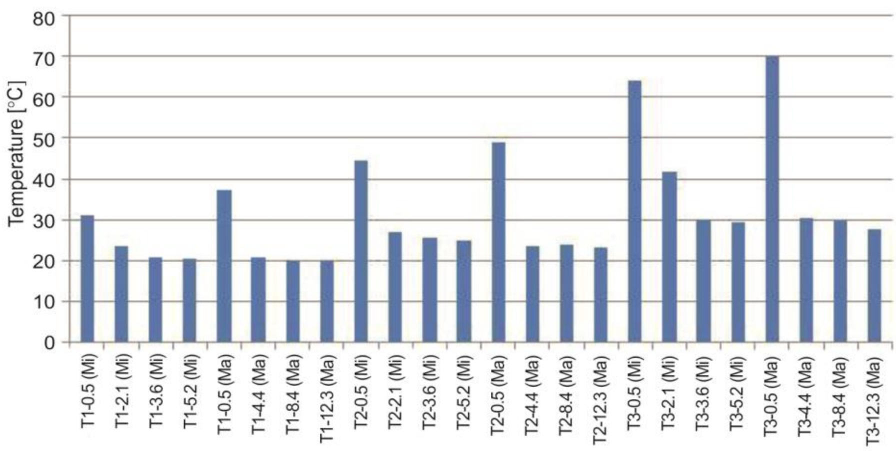

Figure 6. Temperature of the medium at individual measurement locations for the flow in the transitional flow regime V = 0.15 m^3/h (in the description of the cut-off axes the designation of zones T1-T3 and the distance - in [mm] - of the *hot* thermocouple weld from the inner surface of the elliptical tube, adding Mi for the small half axis and Ma for the large half axis)

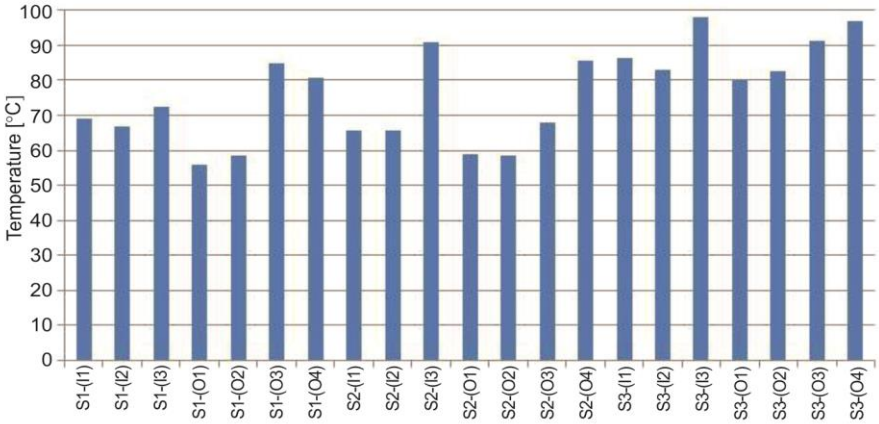

Figure 7. Temperatures of the wall of the elliptical pipe in individual places of measurements within the transitional flow range V = 0.15 m^3/h (in the description of the cut-off axes the designation of zones S1-S3 and the position of the thermocouple in a given zone: along the circumference on the external surface - O1-O4 and at a distance of about 0.3 mm from the internal surface - I1-I3, in both cases it concerns ¼ of the ellipsis circumference)

It should be added that for the purpose of estimating heat losses to the environment, the external surface temperature of the insulation and the ambient temperature are also measured each time. The values of averaged measurement data and calculated values of the density of the generated heat flux, q, and its losses to the environment, q_{loss}, are presented in tab. 2.

Table 2. Measurement data and calculation results for water flow in elliptical tube (in transitional regime, Re = 2908)

V [m^3/h]	T_{wall} [°C]	T_{inlet} [°C]	T_{outlet} [°C]	T_{fluid} [°C]	q [Wm^{-2}]	q_{loss} [Wm^{-2}]
0,15	77,56	23,28	40,37	31,82	33369,00	452,13

On the basis of the data from tab. 2, it can be seen that the heat loss to the environment, q_{loss}, represents only about 1.3% of the generated heat flux, q. It proves that the elements of the stand are well insulated, so that practically the heat is absorbed by the fluid flowing inside the elliptical pipe.

The average value of the heat transfer coefficient from the inner surface of the elliptical tube to the water flowing inside was determined using the relation:

$$h = \frac{q}{(T_{\text{wall}} - T_{\text{fluid}})} = \frac{q}{T_{\text{wall}} - \frac{1}{2}(T_{\text{inlet}} + T_{\text{outlet}})} \tag{10}$$

The obtained results were also used to verify the numerical simulations carried out. CFD calculations were performed by using the ANSYS CFX software [20]. The shear stress transport flow model with transitional turbulence (SST-TR) is used, which reflects quite well the flow and thermal phenomena in the transient range. This more complex model of transient turbulence (the so-called Gamma-Theta model) [21] is an interesting alternative to the two equations models of turbulence. In comparison with the classical SST model, new transport equations for the so-called intermittency were introduced into the model. It determines the way in which the turbulent flow passes into the laminar flow. The views of computational grid of the model which was analysed and the obtained temperature distribution in the cross-section of the elliptical tube with water flowing through it are shown in figs. 8(a) and 8(b), respectively. The numerical grid (with 550000 nodes and 720000 elements) was refined in such a way that the difference in the results of calculations of the heat transfer coefficient at two successive compactions does not differ by more than 1%. The values of flow rate, heat flux and inlet temperature are set taking into account the measurement data. At the inflow to the tube, the inlet boundary condition with a specified velocity and temperature was applied. At the outer surface of the tube the heat flux boundary condition is applied based on the indication of the current and voltage of the autotransformer. The value of heat flow calculated as: $Q = IU$ [19], were Q [W] is heat flow, I [A] – the electric current in a resistance wire, and U [V] – the voltage over a resistance wire, was divided by the inner surface area of the tube. Due to the insulation of the tube, the heat losses to environment are considered as negligible. The outlet boundary condition, with relative pressure of 0 Pa was given at the outlet surface of the flow domain.

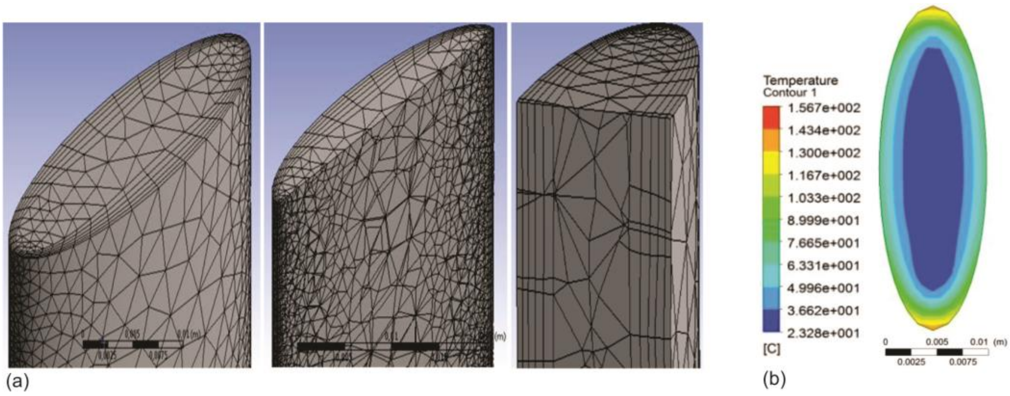

Figure 8. Computational grid of the analysed model (a) and the temperature distribution in the cross-section (b) of a heated elliptical tube

The measurement data used in the calculations and the results obtained, including the use of dependence (1) and the CFD simulation, are shown in tab. 3 (for data given in figs. 6 and 7).

Table 3. Results from the thermal measurements of elliptical tube for flow conditions in the transitional regime, Re = 2908 (measurement data and results of CFD calculations)

V [m^{3}h^{-1}]	$\dot{m}$ [kgs^{-1}]	w [ms^{-1}]	T_{fluid} [°C]	T_{fluid} (Ansys) [°C]	Relative error [%]
0.15	0.04	0.16	31.82	30.94	2.77
			T_{outlet} [°C]	T_{outlet} (Ansys) [°C]	Relative error [%]
			40.37	38.60	4.37
			$T_{\text{wall (S3-I)}}$ [°C]	$T_{\text{wall (S3-I)}}$ (Ansys) [°C]	Relative error [%]
			89.18	90.04	0.96

In tab. 3 $\dot{m}$ and w denote mass-flow rate and velocity of water in the elliptical pipe, respectively, $T_{\text{wall (S3-I)}}$ is the average temperature of the wall of the elliptical tube near its inner surface, in zone S3 (see fig. 4).

Heat transfer coefficient at the inner wall of elliptical tube for transitional flow regime, *i. e.* for Re = 2908, is: h = 729.57 [Wm^{-2}K^{-1}], calculated using dependence (1), and h = 649.88 [Wm^{-2}K^{-1}] (calculated using ANSYS). The relative error has reached 10.92%.

The analysis of the data in tab. 3 shows that the relative error of the average water temperature at the outlet from the heated section does not exceed about 4.4%. The error is calculated based on the results of CFD simulation and experimental results. In the case of the average wall temperature of an elliptical tube near its inner surface (in the outlet zone), the error is lower and amounts to approximately 1%. However, the relative error of the numerically determined average value of the heat transfer coefficient is higher, reaching about 11%. It should be added here that in both cases the values determined on the basis of measurement data are the reference. The reason for the observed increase in error is most probably the overlapping of errors related to the determination of the wall and fluid temperature. However, in a case of heat transfer coefficient determination, this is a satisfactionary agreement.

Figure 9 presents the values of heat transfer coefficient determined by the experimental procedure (Method I), CFD simulation and two well-known heat transfer correlations by Gnielinski and Dittus Boelter [22] (for V = 0.15-0.42 m^3/h corresponding to Re = 2908-7756).

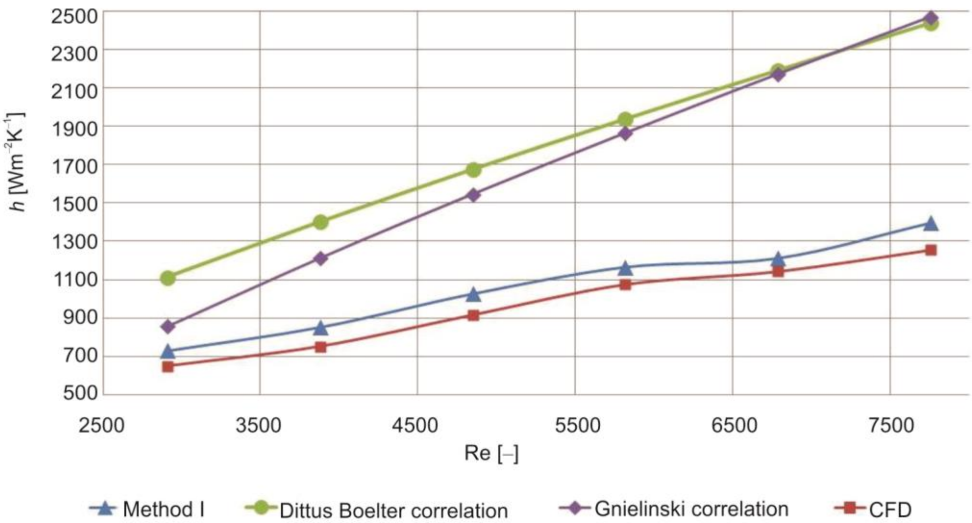

Figure 9. Comparison of the experimental results, and CFD simulation results with Dittus Boelter and Gnielinski correlation on heat transfer coefficient

From our measurements we can see that in the transitional flow regime, the Gnielinski and Dittus Boelter formulas overpredict heat transfer coefficient of the internal flow. It was expected, since those correlations are suitable for the turbulent flow regime. The CFD simulation and experimental results are in a quite good agreement.

Conclusions

The fluid-flow phenomena the transitional range is very complex and difficult in mathematical modelling. This applies especially to elliptical tubes. In this case it is still relatively little recognized. That is why such a flow was tested on a test stand built especially for this purpose. The verification, i.e. comparison of measurement data with values determined by numerical methods covered temperatures of: elliptical tube wall in a given section, water at the outlet from such a pipe and average for water flowing through it, taking into account its entire length.

In the case of elliptical tube, the use of the turbulence model SST-TR in thermo-flow CFD calculations gives a relative error, the value of which, when determining the aforementioned values, reaches up to approximately 4.4%. This error increases to about 11% when estimating the average value for the entire length of the elliptical tube for the heat transfer coefficient from the inner surface to the water flowing in it, in the transitional regime.

The turbulence model SST-TR can be used for the entire fluid-flow regime. As shown in the study, the numerical calculation of the internal flow heat transfer coefficient in elliptical tube allows obtaining results which, in the transitional flow range, are sufficiently satisfactory in comparison with the measurement data.

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Nomenclature

h – heat transfer coefficient from the inner surface of the elliptical tube to the water flowing inside, [Wm^{-2}K^{-1}]
q – heat flux, [Wm^{-2}]
T_{wall} – inner surface temperature (averaged along the tube length), [°C]
T_{fluid} – water temperature within the elliptical tube (the average value taking into account the entire length of the measuring distance), [°C]
T_{inlet} – temperature of the fluid at the inlet to the measuring section (the value averaged in the entire cross-section), [°C]
T_{outlet} – temperature of the fluid at the outlet of the measuring section (the value averaged in the entire cross-section), [°C]

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