Investigation of flow non-uniformities in the cross-flow heat exchanger with elliptical tubes

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Abstract. In heat exchangers, especially those with the cross-flow arrangement, it is nearly impossible to achieve the uniform distribution of the working fluid in the tubular space with the currently used inlet and outlet chambers (in some constructions as well). The improper inflow conditions to individual tubes, including those with an elliptical cross-section - often used because of their favorable features compared to round tubes, is the cause of improper heat transfer. In this respect, transitional flow is of particular importance. This flow regime is complex and challenging to model. Therefore, it is necessary to perform experimental verification. For this purpose, an appropriate stand was built, allowing to investigate the flow of the working fluid (water) to the elliptical tubes in the cross-current heat exchanger. The paper presents the results of measurements for manifold geometry, which are currently used in practice (for heat exchanger constructions). The analysis of the measurement data confirms the non-uniform flow distribution to individual tubes of the heat exchanger.

1 Introduction

In many heat exchangers with the cross-flow arrangement, it is nearly impossible to achieve a proper distribution of the working fluid in the tubular space, with currently used inlet and outlet headers [1-3]. In addition, in this type of devices, the flow of liquid in the tubes can belong to various flow regimes including: laminar, transitional and turbulent.

The lack of uniform flow to individual heat exchanger tubes is the reason for improper heat exchange in some of them. This is particularly valid for elliptical tubes - often used because of their advantages compared to round tubes, including lower pressure drop and more favorable heat transfer conditions. The abovementioned flow maldistributions cause unfavorable high stresses, usually leading to damage to the device [3, 4]. The transitional flow regime is of particular importance since the phenomena that characterize it are complex and challenging to mathematical modeling [3-5]. For this purpose, an appropriate stand is developed to allow the measurements of the working fluid (water) flow rate in the elliptical tubes in the cross-flow heat exchanger. The obtained measurement results allow one to investigate the flow maldistribution in the heat exchanger with elliptical tubes.

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2. Test stand

In order to measure the flow of liquid in the cross-flow heat exchanger, a suitable test stand is built as mentioned earlier. Its characteristic feature is the possibility of testing the inlet and outlet headers of various shapes. Also, for each of them, there is a multivariate arrangement of the connectors to it, respectively: supplying and discharging the working medium. This allows investigating the influence of the geometry of heat exchanger chambers and the location of nozzle pipe on the conditions of working fluid flow (uniform or with maldistributions).

The heat exchanger in the test stand is situated vertically and consists of 20 elliptical tubes, placed in two rows (10 tubes per row in the staggered arrangement). To easily change the shape of the inlet and outlet headers, flexible connections between the inlet/outlet nozzle pipe and the feed tank are applied, by using flexible reinforced ducts. The aforementioned headers are connected to sieve plates with a typical flange-screw connection, sealed with a rubber gasket. The scheme of the stand and its general view are shown in Figure 1. It can be added that a more detailed description of this stand is given in [6].

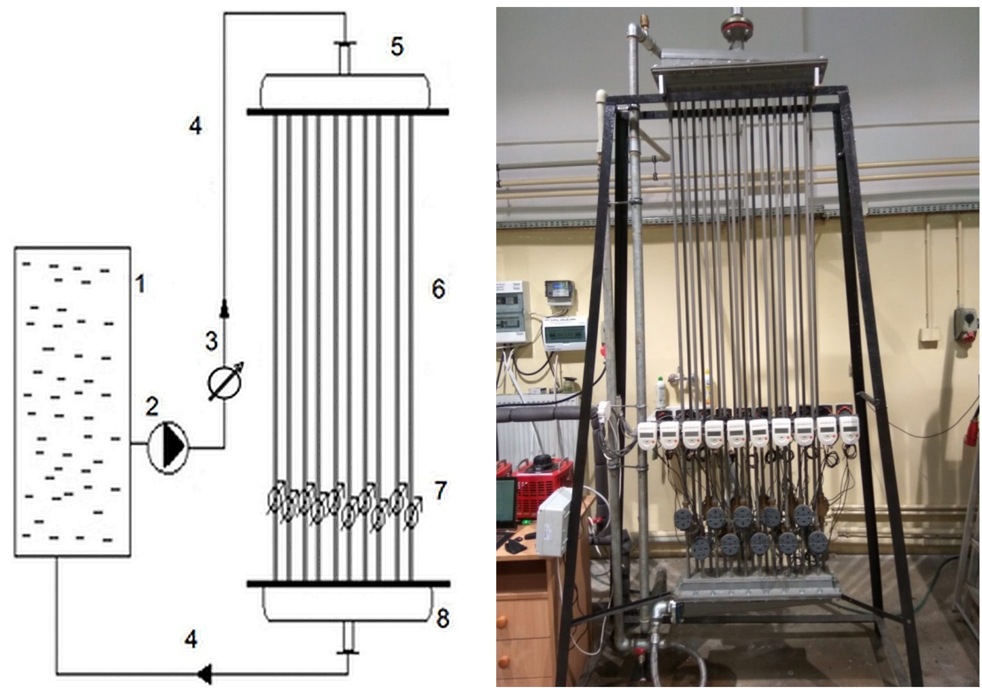

Fig. 1 Scheme and general view of the test stand for the investigation of flow conditions in a heat exchanger (with elliptical tubes) with cross flow: 1 - water supply tank, 2 - feedwater pump, 3 - total volumetric flow rate meter, 4 - connection pipes, 5 - inlet header with a nozzle pipe, 6 – tubular space of heat exchanger (elliptical tubes), 7 - water flow meters in individual pipes, 8 - outlet header with a discharge outlet nozzle.

Measurement of the instantaneous volumetric flow rate in individual tubes is carried out by using an ultrasonic Sontex Superstatic 749 flowmeters with the accuracy of ±0.001 m^3/h. The flowmeters are connected to the data acquisition system. This allowed for automatic verification of independently controlled total liquid flow in the tested system (in Figure 1 this meter was marked as No. 3).

Figures 2 and 3 show examples of the inlet and outlet chambers. In addition to the chamber shape testing, it is possible to study the different positioning of the inlet and outlet nozzle pipe. Figure 4 shows a view of the heat exchanger sieve plate and an example of the inlet chamber assembly phase.

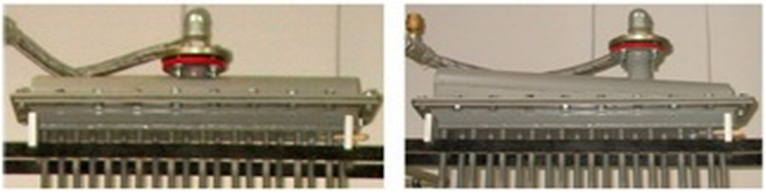

Fig. 2. Exemplary shapes of inlet header with different positioning of the inlet nozzle pipe.

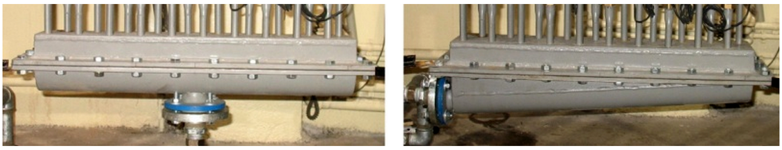

Fig. 3. Exemplary shapes of inlet header with different positioning of the outlet nozzle pipe.

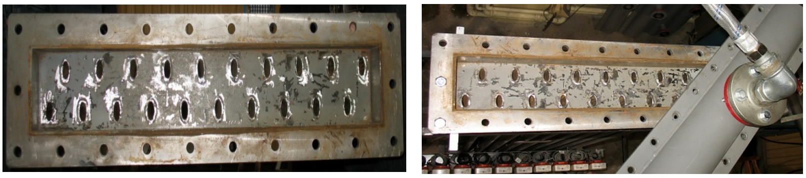

Fig. 4. View of the sieve plate at the assembly stage of the inlet header.

Based on Figures 2 and 3, it can be noticed that two design solutions for inlet and outlet headers can be tested. For some, the unchanging shape is characteristic (it is made up of a longitudinal section of the pipe), and for others - the unilateral increase of the internal volume (properly cut wedges are added on both sides in longitudinal direction). The numerical analyzes carried out previously show that this solution improves the flow distribution in the heat exchanger tubes [3, 4].

In addition to the header construction itself, the influence of the supply and outflow nozzles on flow distribution is also examined. In order to ensure a stable inflow of water to the inlet chamber of the heat exchanger, an additional straight pipe section is installed. A similar solution is applied at the outlet header of the heat exchanger.

3 Study of maldistribution of the working medium flow

The paper presents the results of the measurements carried out for one of the described headers design and nozzles located on them. This is a constant (unchanging) longitudinal shape of the collectors, with the location of the nozzles in the middle of the chamber. This type of solution is often used in currently applied heat exchangers. Figure 5 presents the tested header with dimensions, and Figure 6 shows the view and dimensions of the sieve plate, with the numbering of individual tubes.

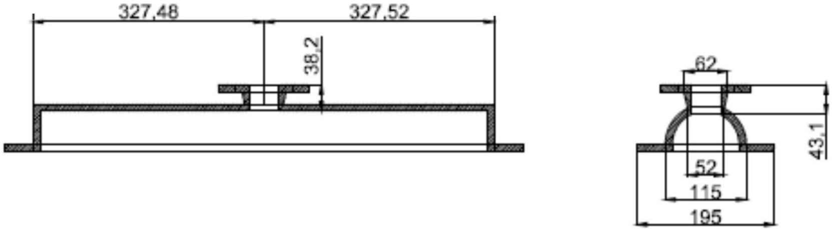

Fig. 5. Shape and dimensions of the inlet and outlet heat exchanger headers

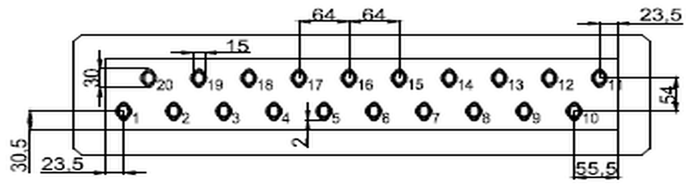

Fig. 6. View of the sieve plate of the heat exchanger with given tube numbering

The measurement results presented in this paper show the flows of working medium (water) in individual heat exchanger tubes, each time for a specified total volumetric flow rate, changed in the range from 1 [m^3/h] to 5 [m^3/h]. The measurement is carried out for a water temperature of 21 [^{o}C]. In each case, the measurement results are acquired after obtaining a steady-state flow distribution (in about 10 minutes period). Afterward, the next value of the total volumetric flow rate is set.

The obtained results are shown in Figures 7 – 15 and in Tables 1 – 9, in the latter together with the determined values of the Reynolds number (Re).

Measurement No. 1 – volumetric flow rate $\dot{V} \approx 1$[m^3/h]:

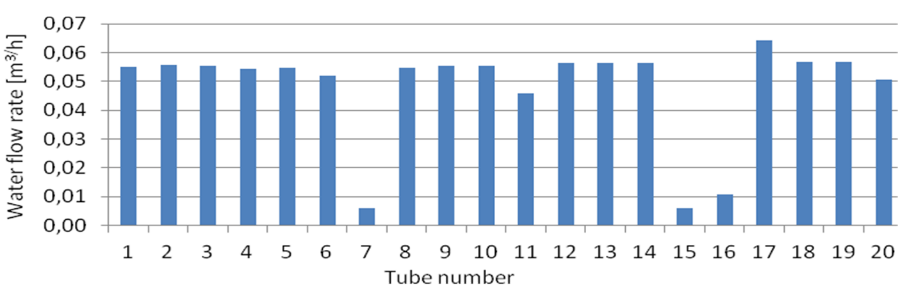

Fig. 7. Volumetric flow rate in individual tubes for total flow rate of $\dot{V}$ = 0,9593 [m^3/h].

Table 1. The volumetric flow rate and Re number in individual tubes for the total flow rate of $\dot{V}$ = 0,9593 [m^3/h].

Tube No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Flow rate [m^3/h]	0,0551	0,0556	0,0554	0,0543	0,0546	0,0519	0,0060	0,0548	0,0555	0,0555
Re number	656	662	660	646	650	618	71	652	661	661
Tube No.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Flow rate [m^3/h]	0,0460	0,0564	0,0563	0,0565	0,0060	0,0108	0,0644	0,0569	0,0566	0,0507

Re number	548	671	670	673	71	129	767	677	674	604

Measurement No. 2 – volumetric flow rate $\dot{V} \approx 1{,}5$ [m^3/h]:

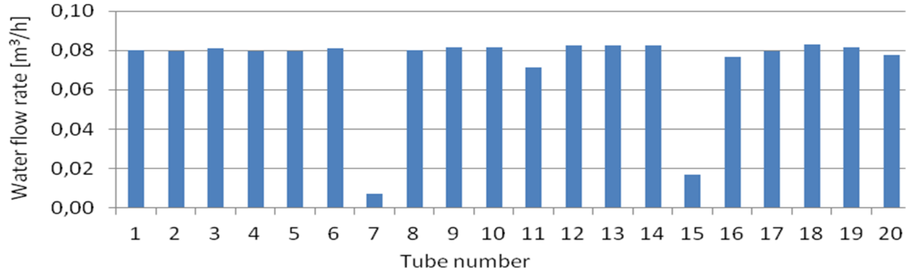

Fig. 8. Volumetric flow rate in individual tubes for total flow rate of $\dot{V} = 1{,}4405$ [m^3/h].

Table 2. The volumetric flow rate and Re number in individual tubes for the total flow rate of $\dot{V} = 1{,}4405$ [m^3/h].

Tube No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Flow rate [m^3/h]	0,0803	0,0798	0,0809	0,0794	0,0795	0,0810	0,0072	0,0799	0,0818	0,0817
Re number	956	950	963	945	946	964	86	951	974	973
Tube No.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Flow rate [m^3/h]	0,0715	0,0824	0,0823	0,0824	0,0169	0,0769	0,0795	0,0830	0,0818	0,0777
Re number	851	981	980	981	201	915	946	988	974	925

Measurement No. 3 – volumetric flow rate $\dot{V} \approx 2$ [m^3/h]:

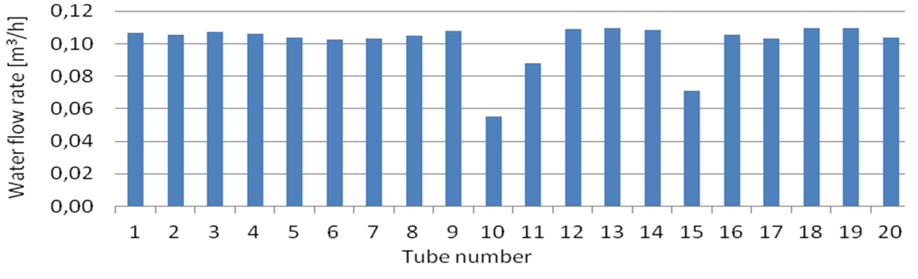

Fig. 9. Volumetric flow rate in individual tubes for a total flow rate of $\dot{V} = 2{,}0207$ [m^3/h].

Table 3. The volumetric flow rate and Re number in individual tubes for the total flow rate of $\dot{V} = 2{,}0207$ [m^3/h].

Tube No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Flow rate [m^3/h]	0,1068	0,1057	0,1070	0,1062	0,1036	0,1025	0,1031	0,1051	0,1079	0,0555
Re number	1271	1258	1274	1264	1233	1220	1227	1251	1285	661
Tube No.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**

Flow rate $[m^3/h]$	0,0882	0,1088	0,1094	0,1084	0,0708	0,1053	0,1032	0,1098	0,1094	0,1040
Re number	1050	1295	1302	1290	843	1254	1229	1307	1302	1238

Measurement No. 4 – volumetric flow rate $\dot{V} \approx 2{,}5$ $[m^3/h]$:

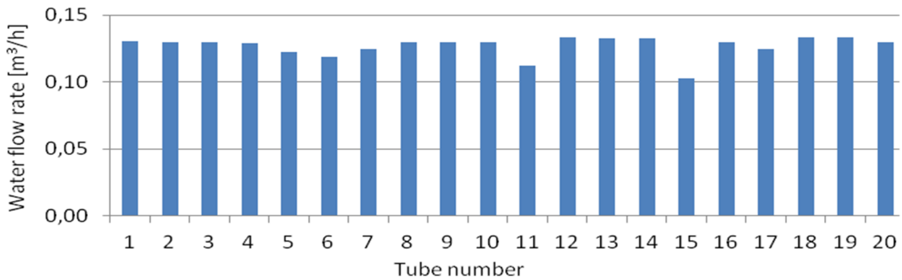

Fig. 10. Volumetric flow rate in individual tubes for total flow rate of $\dot{V} = 2{,}5356$ $[m^3/h]$.

Table 4. The volumetric flow rate and Re number in individual tubes for the total flow rate of $\dot{V} = 2{,}5356$ $[m^3/h]$.

Tube No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Flow rate $[m^3/h]$	0,1303	0,1295	0,1296	0,1290	0,1220	0,1188	0,1249	0,1293	0,1300	0,1295
Re number	1551	1542	1543	1536	1452	1414	1487	1539	1548	1542
Tube No.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Flow rate $[m^3/h]$	0,1120	0,1330	0,1327	0,1325	0,1027	0,1299	0,1248	0,1334	0,1330	0,1296
Re number	1333	1583	1580	1577	1223	1546	1486	1588	1583	1543

Measurement No. 5 – volumetric flow rate $\dot{V} \approx 3$ $[m^3/h]$:

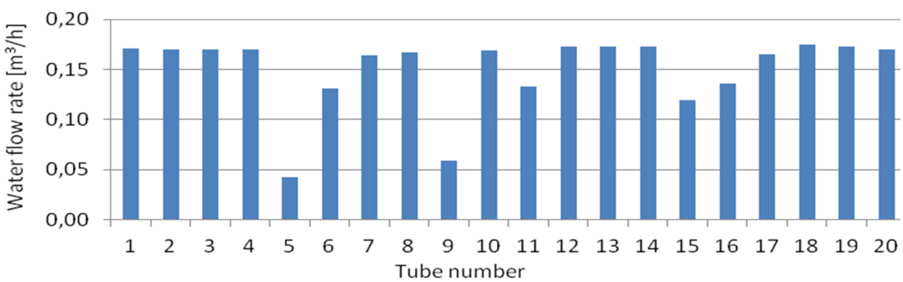

Fig. 11. Volumetric flow rate in individual tubes for a total flow rate of $\dot{V} = 3{,}0164$ $[m^3/h]$.

Table 5. The volumetric flow rate and Re number in individual tubes for the total flow rate of $\dot{V} = 3{,}0164$ $[m^3/h]$.

Tube No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Flow rate $[m^3/h]$	0,1712	0,1696	0,1703	0,1702	0,0426	0,1314	0,1637	0,1674	0,0589	0,1694
Re number	2042	2026	2023	2035	548	1495	1950	1999	688	2017

Tube No.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Flow rate [m³/h]	0,1333	0,1727	0,1730	0,1733	0,1191	0,1356	0,1653	0,1747	0,1728	0,1699
Re number	1587	2056	2060	2063	1573	1614	1968	2080	2057	2031

Measurement No. 6 – volumetric flow rate $\dot{V} \approx 3{,}5$ [m³/h]:

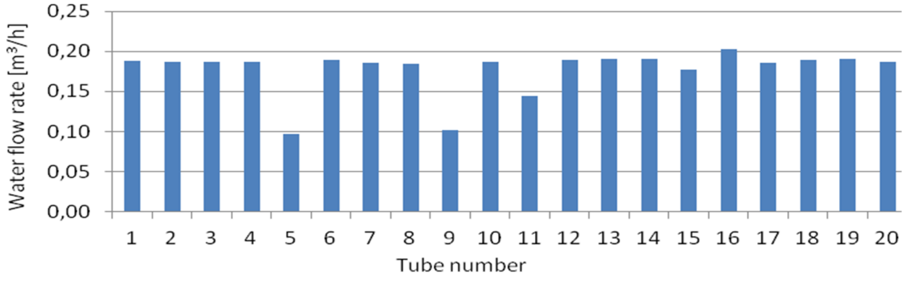

Fig. 12 Volumetric flow rate in individual tubes for total flow rate of $\dot{V} = 3{,}5385$ [m³/h].

Table 6. The volumetric flow rate and Re number in individual tubes for the total flow rate of $\dot{V} = 3{,}5385$ [m³/h].

Tube No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Flow rate [m³/h]	0,1878	0,1863	0,1865	0,1869	0,0971	0,1887	0,1859	0,1842	0,1019	0,1864
Re number	2236	2218	2220	2225	1156	2246	2213	2193	1213	2219
Tube No.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Flow rate [m³/h]	0,1444	0,1888	0,1900	0,1905	0,1770	0,2022	0,1860	0,1898	0,1909	0,1872
Re number	1719	2248	2262	2268	2107	2407	2214	2260	2273	2229

Measurement No. 7 – volumetric flow rate $\dot{V} \approx 4$ [m³/h]:

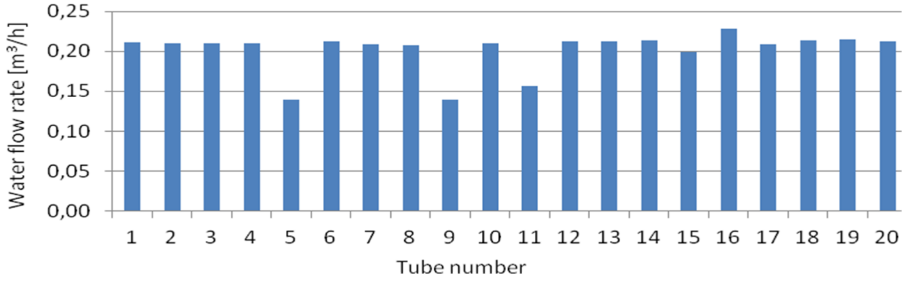

Fig. 13. Volumetric flow rate in individual tubes for a total flow rate of $\dot{V} = 4{,}0290$ [m³/h].

Table 7. The volumetric flow rate and Re number in individual tubes for the total flow rate of $\dot{V} = 4{,}0290$ [m³/h].

Tube No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Flow rate [m³/h]	0,2114	0,2094	0,2102	0,2098	0,1391	0,2125	0,2093	0,2073	0,1388	0,2094

Re number	2517	2493	2502	2498	1656	2530	2492	2468	1652	2493
Tube No.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Flow rate [m³/h]	0,1562	0,2129	0,2119	0,2134	0,1993	0,2282	0,2093	0,2133	0,2149	0,2124
Re number	1860	2535	2523	2540	2373	2717	2492	2539	2558	2529

Measurement No. 8 – volumetric flow rate $\dot{V} \approx 4{,}5$ [m³/h]:

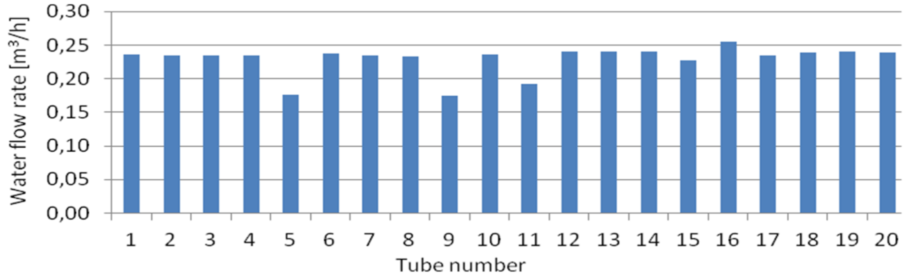

Fig. 14. Volumetric flow rate in individual tubes for a total flow rate of $\dot{V}$ = 4,5793 [m³/h].

Table 8. The volumetric flow rate and Re number in individual tubes for the total flow rate of $\dot{V}$ = 4,5793 [m³/h].

Tube No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Flow rate [m³/h]	0,2358	0,2351	0,2349	0,2348	0,1759	0,2373	0,2348	0,2326	0,1749	0,2362
Re number	2807	2799	2796	2795	2094	2825	2795	2769	2082	2812
Tube No.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Flow rate [m³/h]	0,1927	0,2403	0,2401	0,2400	0,2273	0,2544	0,2339	0,2394	0,2406	0,2383
Re number	2294	2861	2858	2857	2706	3029	2785	2850	2864	2837

Measurement No. 9 – volumetric flow rate $\dot{V} \approx 5$ [m³/h]:

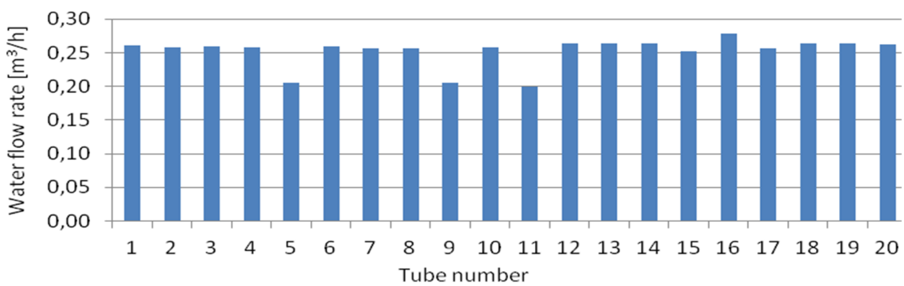

Fig. 15. Volumetric flow rate in individual tubes for total flow rate of $\dot{V}$ = 5,0446 [m³/h].

Table 9. The volumetric flow rate and Re number in individual tubes for the total flow rate of $\dot{V}$ = 5,0446 [m³/h].

Tube No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Flow rate [m³/h]	0,2603	0,2583	0,2593	0,2584	0,2052	0,2600	0,2566	0,2560	0,2054	0,2583
Re number	3099	3075	3087	3076	2443	3095	3055	3048	2445	3075
Tube No.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Flow rate [m³/h]	0,1999	0,2643	0,2630	0,2639	0,2517	0,2779	0,2568	0,2632	0,2643	0,2618
Re number	2380	3146	3131	3142	2996	3308	3057	3133	3146	3117

In addition to the data presented above, it can be added that a certain, minimal discrepancy between the set flow rate (measured with the flowmeter marked in Figure 1 as 3) and actually obtained (calculated as the sum of readings from flowmeters installed on the tubes) results mainly from measurement error of the applied ultrasonic meters, which is 0.0060 [m^3/h].

4. Analysis of measurement results

The presented measurement results illustrate the flow of the working fluid (water) in individual tubes of the cross-flow heat exchanger, for the laminar, transitional and turbulent regimes. The value of the Reynolds number determines the flow type. In practice, for round tubes, the following ranges are usually accepted: Re < 2100 – laminar flow, 2100 < Re < 3000 – transitional flow, Re > 3000 – turbulent flow [7].

Considering the abovementioned flow regimes, it can be noted that the first of the flow regimes (laminar) occurs in heat exchanger tubes for measurements No. 1 – 5, where total flows is in the range from 1 [m^3/h] to 3 [m^3/h]. Correspondingly for these flows, Reynolds numbers are in average of Re_{av} = 571 ÷ 1796, at maximum value of Re_{max} = 767 ÷ 2080, and the minimum value Re_{min} = 71 ÷ 1223. Excluding tubes with low flow rate (i.e. marked No. 7, 15 and 16 for measurement No. 1 or No. 5, 9 and 15 for measurement No. 5), mean value of Re_{av} = 656 ÷ 1947. For the transitional flow regime, the total flow rates from 3.5 [m^3/h] to 4.5 [m^3/h] are obtained, corresponding to measurements No. 6 ÷ 8. In these cases, Reynolds numbers are, respectively: Re_{av} = 2106 ÷ 2726, Re_{max} = 2407 ÷ 3029, Re_{min} = 1156 ÷ 2082. Excluding flows, with the lowest values (i.e., in tubes No. 5, 9 and 11 – for measurements No. 6, 7 and 8) Re_{av} = 2238 ÷ 2826. The third flow type, turbulent flow, is obtained in measurement No. 9, for total flow are approx. 5 [m^3/h]. In this case: Re_{av} = 3027, Re_{max} = 3308, Re_{min} = 2380. Excluding flows with low values (in tubes No. 5, 9 and 11) the average Re number is Re_{av} = 3105.

The measurement results confirm the assumption that maldistributions characterize the flow of the working fluid in the tubular space of the cross-flow heat exchanger. The presented measurement results indicate that the most considerable flow differences concern the tubes located under the supply nozzle pipe. In the examined heat exchanger, in tubes No. 5, 6 and 7 in the first row and No. 15 and 16 in the second row.

Visible significant flow maldistributions occur mainly for laminar and transitional flows. In the case of the latter (measurements No. 6 ÷ 8), in some tubes of the numbers above, the flow rate of the water is so low that the flow should be classified as laminar. A similar situation can be observed in the case of measurement No. 9, in this case in the majority of the tubes the flow is turbulent, but in several tubes, it belongs to the transitional flow regime. In their case, the differences in flow rate are lower compared to the remaining tubes and do not exceed 20%

The measurement data obtained for the transitional flow is of great importance because this kind of regime is insufficiently studied. The obtained experimental data will be used to verify CFD simulations. Currently, further investigations of other heat exchanger headers are under development (taking into account the different location of the inlet nozzle pipe). It is planned to broaden the scope of research for turbulent flow. Additional research is also carried out to optimize the shape of the headers, aimed at improving the conditions of flow distribution in the heat exchanger. The result of this work will ensure a more uniform distribution of liquid to individual tubes of the heat exchanger.

5 Conclusions

The paper presents a test stand for testing water flows in a single-pass cross-flow heat exchanger with elliptical tubes. This developed setup enables the measurement of the volumetric flow rate in each of the twenty tubes of the analyzed exchanger. The results of the research are presented for laminar, transitional and turbulent flow regimes which allowed one to confirm the occurrence and to assess the maldistributions of the flow of the working medium (water) for individual tubes of the device.

For a typical cross-flow heat exchanger with straight headers in the shape of a longitudinal section of the pipe (in practice the most commonly used), with the nozzle pipe placed in their central part of the heat exchanger, it was observed that the most significant flow maldistribution occurs for the laminar flow regime. In this case, the volumetric flow rates in individual tubes of the tested heat exchanger differ up to six times. For transitional and turbulent flows, these differences are much smaller, and their maximum value, between the highest and the lowest flow rates in heat exchanger tubes, does not exceed 80%.

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