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ANALYSIS OF THE IMPACT OF GEOMETRY AND MATERIAL USED FOR THE MAKING ON THE PERFORMANCES OF COUNTER DIRECTING HEAT EXCHANGER

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ABSTRACT: When projecting and building the system of distance heating from central source of heat for supply of heat energy of larger settlements and cities, there is a problem of heat exchange between primary installation of long-distance pipelines and secondary installation of building (block of buildings and settlements). There are several different types of exchangers on market with different performances. The main characteristic of all these exchangers is that the velocities of fluid circulation in primary and secondary are relatively low, thus the process of heat transfer is also developing relatively slow. Apart from this, the existing exchangers which are most frequently in use do not achieve pure counter direction circulation of primary and secondary fluids which is the best solution from the standpoint of heat exchange.
This work contains the proposal for geometry of heat exchanger enabling full counter directing circulation of primary and secondary fluids. Counter directing heat exchanger was used to give an example of comparative analysis in exploitation of copper and steel. Comparative analysis indicated that although copper has a higher heat transmission ratio in relation to steel, by providing a solid construction solution, it is possible to overcome this difference. Construction solution of counter directing heat exchanger enables a high ratio of heat transmission from primary fluid to secondary one, with minimum dependency on material it is made of and achievement of controlled velocity of fluid circulation through exchanger, of both primary and secondary one.
KEYWORDS: heat exchanger, heat energy, distance heating

INTRODUCTION

During the last 50 years, use of copper in technical heat exchangers, particularly in systems of distance heating, has been pushing out more and more other types of material, especially steel pipes. Such trend in the use of copper is probably a result of the fact that the copper as a heat conductor has a conducting ratio of around eight times higher than the heat conducting of steel is. Accordingly, it was concluded that even heat exchangers with the identical heating surface of copper pipes, have to have significantly larger heating capacity in relation to steel pipes. How much such attitude, made out on the grounds of heat conducting ratio can be wrong, is best illustrated by a more comprehensive comparative analysis concerning use of copper and steel pipes at the identical conditions of circulation of primary and secondary fluid with the one and same heat exchanger.

METHODOLOGY

Comparative analysis in the use of copper and steel shall be made by use of counter directing heat exchanger which, in simplified version is shown in Figure 1, consisting of middle pipe 1, through which a primary fluid circulates and external pipe 2 through which secondary fluid circulates, with connectors 3 and 4.

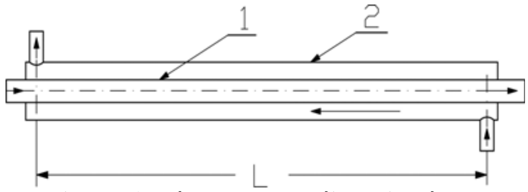

Figure 1. The counter directing heat exchanger - simplified version

As known, heat transmission ratio from primary fluid through the wall of middle pipe 1, to secondary fluid circulating through pipe 2, is given by the followings:

$$K = \frac{1}{\frac{1}{\alpha_p} + \frac{\delta}{\lambda} + \frac{1}{\alpha_s}} \left[W / m^2 K\right]$$ - heat transmission coefficient

α_p – [W/m^2 K] heat transmission coefficient from primary active fluid to internal surface of middle pipe 1,
α_s – [W/m^2 K] - heat transmission coefficient from external surface of middle pipe 1 to secondary fluid circulating through external pipe 2,
$\frac{\lambda}{\delta}$ - heat transmission coefficient through the wall of middle pipe 1, from primary fluid to secondary one,
δ - width of middle pipe wall,
λ - heat transmission coefficient of the material of middle pipe 1.

As can be seen from the heat transmission coefficient formula, the same depends on the three mutualy completely independent coefficients α_p, α_s i δ/λ.

From the same formula, it can be concluded that coefficient K must always be lower than each particular term and that the smallest amount of any of these three terms determines the value of heat transmission coefficient K. If any of these three terms has a low value, thus the heat transmission coefficient K will have even lower value compared to the term with the lowest value. Only in case when all three terms have high values, then the heat transmission coefficient will have a high value. That is the reason why when constructing technical heat exchangers, conditions must be created for all three coefficients participating in forming of heat transmission coefficient, to achieve optimum high values, as only in such circumstance the type and quantity of used material shall be properly exploited.

From the above stated, it is clear that it is necessary to carefully examine factors influencing particular terms of heat transmission coefficient K.

Heat transmission coefficient from primary active fluid to internal surface of middle pipe 1 α_p and heat transmission coefficient from external surface of middle pipe 1 to secondary fluid α_s, circulating through external pipe 2, is illustrated by term established experimentally by Stender and Merkel for turbulent circulation of water in pipes.

$$\alpha_p = 2040\ (1 + 0{,}015\ t_w)\ W_p^{0{,}87}/d_u^{0{,}13} \qquad [\mathrm{W/m^2\ K}]$$

t_w [^{0}C] - average water temperature - $t_w = \frac{t_{wu} + t_{wi}}{2}$
W_p [m/s] - velocity of water circulation of primary in pipes
d_u [m] - diameter of pipes through which the water circulates.

For circulation of secondary fluid through pipes pursuant to Figure 2, the term for heat transmission coefficient is completely identical, only instead of diameter d_u, equivalent of diameter d_e is taken.

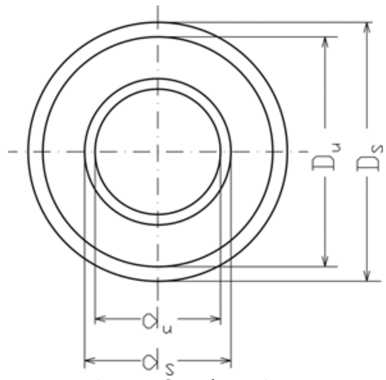

Figure 2. The pipes

$$d_e = \frac{4F_o}{O}\ ;\quad F_o = \frac{\pi}{4}\left(D_u^2 - d_o^2\right)\ ;\quad O = \pi d_s$$

$d_e = \frac{D_u^2 - d_s^2}{d_s}[m]$ - pursuant to Nusselt

$$\alpha_s = 2040\ (1 + 0{,}015\ t_w)\ W_s^{0{,}87}/d_e^{0{,}13}$$

From the terms for α_p and α_s it can be seen that the heat transmission coefficients are higher, when the average temperature of water t_w is higher, velocity of water circulation in pipes is higher while the diameter of the pipes through which the water circulates is smaller. If we bear in mind that the heat energy from water molecules passes to pipe walls generally in direct contact, the heat transmission shall be more accelerated in case when cross section of pipes through which the water circulates is smaller and turbulence of water higher.

For the third term δ/λ participating in forming of heat transmission coefficients K, it is clear that its value for the same thickness of material depends on heat transmission coefficients.

- $\lambda_{\check{c}}$ = 46 [W/mK] - value for carbon steel (37-52)
- λ_b = 372 [W/mK] - value for copper of trading quality

In order to make comparative analysis of heat transmission coefficients K, for middle pipe – seamless steel tubing NO 10 was used , and for external pipe NO 32.

d_s = 17,2 [mm]; d_u = 13,6 [mm]; D_s = 42,4 [mm] ; D_u = 37,2 [mm].

Equivalent pipe diameter shall be

$$d_e = \frac{D_u^2 - d_s^2}{d_s} = \frac{37{,}2^2 - 17{,}2^2}{17{,}2} = 63{,}2558\,[mm]$$

Circulation of primary fluid is given by term

$$q_p = A_p\ W_p[\mathrm{dm^3/s}];\ Ap = \pi d_u^2/4\ [\mathrm{dm^2}];\ \ W_p\ [\mathrm{dm/s}]$$

Circulation of secondary fluid shall be

$$q_s = q_p\ \Delta t_p/\Delta t_s = \pi/4 \cdot d_u^2 \cdot W_p \cdot \Delta t_p/\Delta t_s\ [\mathrm{dm^3/s}]$$

Velocity of secondary fluid

$$W_s = \frac{q_s}{A_s} = \frac{4d_u^2 \pi W_p \Delta t_p}{4\Delta t_s \left(D_u^2 - d_s^2\right)\pi} = W_p \left(\frac{\Delta t_p}{\Delta t_s}\right) \frac{d_u}{D_u^2 - d_s^2} \left[dm/s\right] \text{[dm/s]}$$

Cross section of stream flow (channel) of secondary fluid

$$A_s = \pi/4 \, (D_u^2 - d_s^2)$$

Relation between heat transmission coefficients is:

$$\alpha_s / \alpha_p = \frac{1 + 0{,}015 \cdot t_{ws}}{1 + 0{,}015 \cdot t_{wp}} \cdot \left(W_p / W_s\right)^{0{,}87} \cdot \left(d_u / d_e\right)^{0{,}13}$$

With known values for D_u, d_p and d relation α_s/α_p will be

$$\alpha_s / \alpha_p = \frac{1 + 0{,}015 \cdot t_{ws}}{1 + 0{,}015 \cdot t_{wp}} \cdot \left(\Delta t_p / \Delta t_s\right)^{0{,}87} \cdot 0{,}17527$$

Third term of heat transmission coefficient K, δ/λ is constant and depends only on the type of material used for heat conducting.

δ/λ = 0,0018/46 = 0,00003913 [m^2K/W] - for steel

δ/λ = 0,0018/372 = 0,000004838 [m^2K/W] - for copper

Heat transmission coefficient shall be

$$K = \frac{1}{\frac{1}{\alpha_p} + \frac{\delta}{\lambda} + \frac{1}{\alpha_s}} \left[W / m^2 K\right]$$

Values α_p, α_s, δ/λ and heat transmission coefficient K, as well as relevant length of pipes L are shown in the Table 1, presented below.

Table 1. Values α_p, α_s, δ/λ and K, as well as relevant length of pipes

Wp	m/s	0,2	0,4	0,6	0,8	1,0	1,2	1,4
120/80 °C ; 90/70 °C ; t_{wp}=100 °C ; t_{ws} = 80 °C ; α_s = α_p 0,281894331								
α_p	$W/m^2 K$	2198,4	4018	5717,4	7343,4	8916,8	10449	11949
α_s	$W/m^2 K$	619,7	1132,6	1611,7	2070	2513,6	2945,6	3068,4
$K_č$	$W/m^2 K$	474,45	854	1198,3	1518,8	1821,1	2108,1	2382,6
K_b	$W/m^2 K$	482,3	879,8	1249,6	1602,3	1942,4	2272,6	2594,6
$\frac{K_b - K_č}{K_č}$	%	1,65	3,02	4,28	5,5	6,66	7,8	8,9
Wp	m/s	0,2	0,4	0,6	0,8	1,0	1,2	1,4
130/80 °C ; 90/70 °C ; t_{wp}=105 °C ; t_{ws} = 80 °C ; α_s = α_p 0,3323338								
α_p	$W/m^2 K$	2264,3	4138,5	5888,9	7563,7	9184,3	10763	12307
α_s	$W/m^2 K$	752,5	1375,3	1957	2513,6	3052	3576,8	4090
$K_č$	$W/m^2 K$	552,5	992,18	1389	1757	2102,3	2429,4	2740,6
K_b	$W/m^2 K$	563,25	1027,1	1459,5	1869,5	2265,6	2650,2	3025
$\frac{K_b - K_č}{K_č}$	%	2,12	3,61	5,07	6,46	7,8	9,12	11
Wp	m/s	0,2	0,4	0,6	0,8	1,0	1,2	1,4
140/80 °C ; 90/70 °C ; t_{wp}=110 °C ; t_{ws} = 80 °C ; α_s = α_p 0,378425								
α_p	$W/m^2 K$	2230	4259	6060,5	7784	9451,8	11076	12666
α_s	$W/m^2 K$	843,8	1611,7	2293,5	2945,6	3576,8	4191,6	4793,2
$K_č$	$W/m^2 K$	597,8	1118	1562,1	1972	2355,6	2717,5	3060,8
K_b	$W/m^2 K$	610,3	1162,6	1650,5	2115	2562,6	2996,8	3419,8
$\frac{K_b - K_č}{K_č}$	%	2,26	4,08	5,72	7,3	8,8	10,3	11,75
Q	W	7297,1	14594	21891	29188	36485	43782	51080
Q_{hi}	W/m	750,18	1398,2	1951	2455,5	2937	3385,8	3811
L	m	9,7	10,4	11,2	11,88	12,4	12,93	13,4
Wp	m/s	0,2	0,4	0,6	0,8	1,0	1,2	1,4
140/80 °C ; 90/70 °C ; t_{wp}=110 °C ; t_{ws} = 80 °C ; α_s = α_p 0,378425								
W	m/s	0,02	0,04	0,06	0,07	0,08	0,09	0,1
α_p	$W/m^2 K$	314,3	574,52	817,53	934,87	1050	1163,3	1275
α_s	$W/m^2 K$	118,95	217,4	309,37	353,77	397,35	440,23	482,5
$K_č$	$W/m^2 K$	86	156,75	222,48	254,1	285	315,4	345,3
K_b	$W/m^2 K$	86,26	157,6	224,2	256,33	287,86	318,8	349,44
$\frac{K_b - K_č}{K_č}$	%	0,3	1,175	1,21	1,26	1,35	1,41	1,48
Q	w	729,71	1459,4	2189,1	2554	2918,8	2383,7	3648,5
Q_{hi}	w/m	125,66	206,05	285,36	3,24	362	399,55	436,48
L	m	5,8	7,08	7,67	7,88	8,06	8,22	8,35

Diagram shows Figure 3 illustrating the change in heat transmission coefficient $K_č$ and K_b as function of change in velocity of primary fluid circulation Wp.

Bold line displays heat transmission coefficient K for steel, and interrupted line Kb for copper, for the following $\Delta t_p = 40\ ^0C$, $\Delta t_p = 50\ ^0C$, $\Delta t_p = 60\ ^0C$

As can be seen from diagram containing Figure 3, heat transmission coefficients progressively increase with the increase of velocity in fluid circulation. The same diagram displays that the heat transmission coefficients K hardly increase with the type of material. With low velocity in fluid circulation, type of material has an influence of 2-4%, and only with high velocity of W_p>1,0 [m/s] it reaches the range of 10-12%.

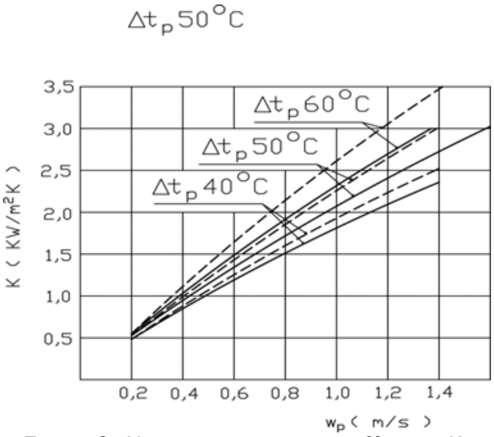

Figure 3. Heat transmission coefficient $K_č$ and K_b as function of change in velocity of primary fluid circulation Wp

Calculated heat transmission coefficients K displayed in diagram, Figure 3, proceed from the condition that due to the length of pipe L, Figure 1, adequate difference in temperature is achieved Δt_p, thus for every calculated heat transmission coefficient, length of pipe has to have its proper value L.

Transmission of heat of a meter long pipe, pursuant to Figure 1 and 2 shall be as following:

$$Q_{hl} = \frac{\pi \cdot \Delta t_m}{1/d_u \cdot \alpha_p + 1/d_s \cdot \alpha_s + 1/2\lambda \cdot \ln\left(d_s/d_u\right)} [W]$$

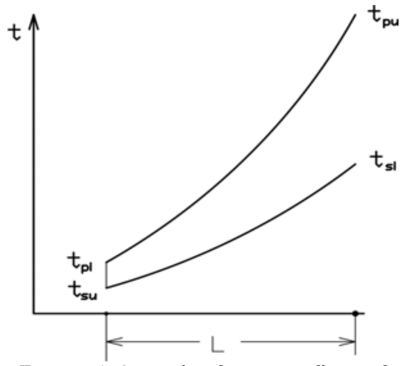

Figure 4. Length of stream flow of primary and secondary

Δt_m [^{0}C] - average logarithm temperature as per Figure 4;
t_{pu} - temperature of primary fluid – entry; t_{pi} - temperature of primary fluid – exit; t_{su} - temperature of secondary fluid – entry;
t_{si} - temperature of secondary fluid – exit.

$$Q = q_p\ C\ \Delta t_p\ 36000 = 1\ Q_{h1}$$

Length of stream flow of primary and secondary shall be:

$$l = Q/\ Q_{h1}\ [m]$$

C - [W/kg] - specific heat of fluid

For accepted parameters of active fluid of primary $t_{pu} = 140\ ^0C$, $t_{pi} = 80\ ^0C$ and secondary fluid $t_{su} = 70\ ^0C$, $t_{si} = 90\ ^0C$ and steel pipes will be $\Delta t_m = 24{,}85$ [m] - average logarithm difference in temperature.

As can be noted from Figure and diagram, Figure 3, with the change in velocity of water circulation in pipes, heat transmission coefficient K also changes, and with that length of stream flow L. Thus this leads to conclusion that counter directing heat exchangers, pursuant to Figure 1, have specifically defined lengths L, for particular parameters of primary and secondary fluids, which are changing with the change in velocity of water in primary fluid W_p, which practically means that the length of such heat exchangers cannot be standardized. Only if the counter directing heat exchanger shown in Figure 1 has a precisely defined length of stream flow of primary and secondary, calculated heat transmission coefficients may have real value and the material installed shall be exploited in the most rational manner.

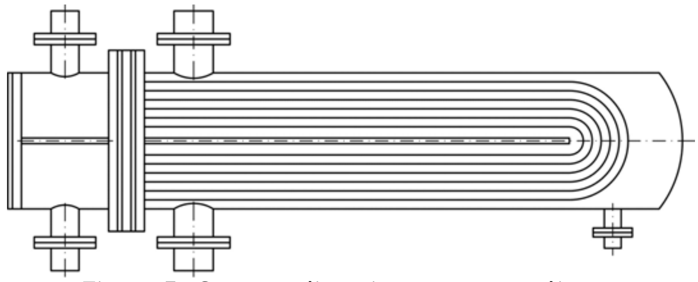

Figure 5. Counter direction stream appliance

In heating system with the distance heat transmission, heat exchangers with pipes in the shape of letter U are usually applied, generally called "counter direction stream appliances" displayed in Figure 5. In regarding to that exchanger, primary fluid circulates in counter direction from secondary fluid, thus the name counter direction stream appliances. They are made of steel, mostly with copper sheaf's/shafts of pipes. Because of their construction, they cannot be considered as identical to heat exchangers shown in Figure 1, where the fluid circulation is from entry to exit under counter direction and controlled. With counter direction stream appliance displayed in Figure 5, velocities of circulation of primary fluid depend on the length of pipe in shaft, which vary for each pipe in shaft. Velocity of circulation of secondary fluid is not evenly distributed around pipe U in shaft, but mainly depends on placing of pipes in section of circulation of counter direction stream appliance. With usual standard sizes of counter direction stream appliances, the lengths of U pipes in shaft l_u, as shown in Figure 5, are in the range off 1-3 [m], being, in average, of total length of U pipe l_{uk} = 2,0 – 6,0 [m]. Such small lengths of U pipes in shaft, in order to achieve planned decrease in temperature Δt_p, create low velocity in fluid circulation, thus immediately causing relatively low heat transmission coefficient K. As an example of circulation in primary – secondary system, Figure 1, diagram displays heat transmission coefficients K and total length of pipe L for velocity range of circulation of primary fluid W_p = 0,02-1,4 [m/s]. The fact that can be seen from the displayed, is that for primary hot water being 140/80 ^{0}C and secondary hot water 90/70 ^{0}C, the length of pipe is in the range of L = 5,8-13,4 [m], and heat transmission coefficients K = 86-3060 [W/m^{2}K]. Short length of pipes in shaft of counter direction stream appliances result in low heat transmission coefficients K which, according to Reknagel, page 638, are somewhere in the range of K = 450-700 [W/m^{2}K] for the average velocities of water. In order for higher heat transmission coefficient K to be achieved, it is necessary that the technical solution of counter directing heat exchanger has adequate length of pipes L, Figure 1, which would, together with U pipes significantly increase the length of counter direction stream appliances.

ADEQUATE TECHNICAL SOLUTION

Adequate technical solution for counter directing heat exchangers with necessary length of pipes, requiring a high heat transmission coefficient K, and parameters of primary and secondary fluids, are displayed in Figure 6. This technical solution has, instead of U pipe, snake like pipe making a single flow of primary and secondary fluid, enabling, with high heat transmission coefficient K, achievement of adequate decrease in temperature in primary fluid Δt_p. By using right length of legs for snake like pipe, desired length for heat exchanger can be realized.

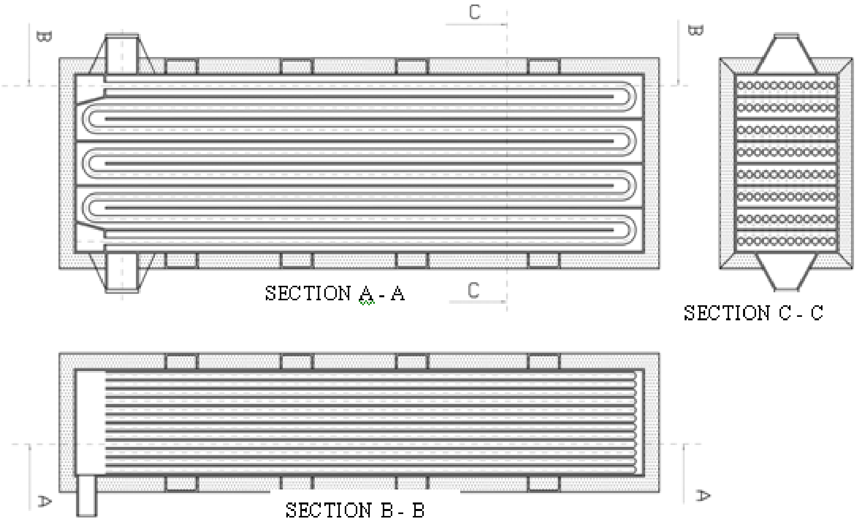

Figure 6. Adequate technical solution

As can be seen from the above stated, counter directing heat exchangers displayed in Figure 6 will lead to high heat transmission coefficient K at higher velocities of circulation, and cause planned decrease in temperature in primary fluid, only in the conditions of specific length of stream flow. This leads to the idea that with particular parameters of fluids in any change of velocity in circulation, the length of snake like pipe in exchanger, Figure 6, has to be replaced.

However, if the total length of snake like pipe for higher velocity of circulation, for example W_p = 1,0 [m/s], is accepted, it means that for all velocities lower than W_p<1,0 [m/s], snake- like pipe shall lead to higher decrease in temperature t_p than planned, thus bringing closer temperatures t_{su} and t_{pi}, as well as average temperature of primary fluid $t_{su,}$, as well as average temperature of secondary fluid t..., which will affect the decrease in heat transmission ratio K. Practically, this means that the longer length of snake like pipe will not evenly affect and significantly increase heat capacity of exchanger and that standard length of snake like pipe can be used, while the length and height of exchanger, as shown in Figure 6, would be permanent.

Change in capacity of heat exchanger is solved by the number of snake like pipes in heat exchanger, as shown in cross section in Figure 6. Stream channels of secondary fluid form a distance between partitions/compartments h and distance between pipes b, as seen in Figure 6. In this way stream flow of fluid has been provided from entry to exist from heat exchanger. By standardizing the length and height of counter directing heat exchanger, a high heat transmission coefficient K has been achieved, with certain higher heat surface i.e. higher consumption of pipes.

CONCLUSION

Entire above analysis clearly establish that the use of copper, i.e. copper made pipes in heat exchanger is not technically justified. As can be seen from tabular review, with low velocity of fluid, effect of type of material on heat transmission coefficient K is irrelevant. Increase of heat transmission coefficient K should be made through increase of velocity and controlled circulation from entry to exit from heat exchanger. This can be achieved by technical solution of counter directing heat exchanger displayed in Figure 6, exclusively made of steel pipes. Steel pipes through which a primary fluid circulates enables active pressures P = 25 (bar), while a constant length of snake like pipes results in circulation resistance of primary and secondary fluid to exclusively depend on selected velocity of fluid circulation. A somewhat unusual rectangular cross section of heat exchanger makes it unfavorable in regard to pressure of secondary fluid, but it is subject to controlled stream channels of secondary active fluid. However, active pressures of secondary fluid are far lower than the pressures by primary fluid, and usually follow the active pressures of heating equipment of radiators.

Unfavorable section of counter directing heat exchanger is compensated by increased resistance of internal circulation compartments (plates and external stiffening made of NP profile (cross section) which at the same time has a tin casing of thermal insulation. Copper pipes in heat exchanger, whether with U pipes shown in Figure 5 or with snake like pipes in Figure 6, decrease active pressure of primary part of exchanger, hindering the way of linking of various material of pipes and pipe castings, causing the occurrence of galvanic power and electro corrosion in the place of joints.

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