Optimization of compact heat exchangers

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The need to develop heat exchangers of small dimensions, high efficiency and relatively low cost has led to the emergence of compact exchangers. These exchangers are made of thin sheets, different materials and are designed for gas-gas systems, where some constructions can also be used for gas-liquid systems. In this paper, the shape and dimensions of compact exchangers are optimized in order to evenly distribute the flow in the apparatus itself. Fluid flow analysis in a compact exchanger was performed for different sheet metal constructions in current channels. The construction of a compact exchanger with external dimensions of 400x400x400mm was adopted. The optimization was performed in the software package "Solidworks", for several variant solutions.

Keywords: compact heat exchanger, fluid flow, optimization

1. INTRODUCTION

Along with the development of industry and technology, there are increased demands for miniaturization - reducing the dimensions of the device, increasing the efficiency while, if it possible, the cost of production should be same or reduced. This trend permeates both the energy segments and the heat exchanger field.

The field of application of heat exchangers is very wide and includes a very large number of industry branches. It would be very difficult to list all the examples of heat exchangers, they are used wherever it is necessary to perform some energy exchange. During technological processes, it is necessary to transfer a certain amount of energy (generated in that process) to another carrier (fluid) in the most efficient way possible in order to minimize energy losses.

Heat exchangers can be divided and classified into different groups and the established division is reduced to the division according to: purpose, functional and technological solutions and operating temperature regime. According to the purpose, heat exchangers are used in industrial applications as: refrigerators and heaters, condensers and evaporators, crystallizers, freezers and defrosters, chemical and biochemical reactors. The most used classification of heat exchangers is according to the method of heat transfer from one fluid to another: recuperative heat exchangers, regenerative heat exchangers, heat exchangers with indirect heat exchanger and contact heat exchangers [1].

This paper presents an analysis of the fluid flow and operation of a compact heat exchanger with defined geometric characteristics, known inlet and outlet temperatures of fluid 1 (combustion products), known inlet temperature of fluid 2 (air) as well as known mass flows of both fluids. The number of channels for both fluids is equal and amounts to seven, whereby the sheets in the channels are bent so as to form an equilateral triangle, as it is shown in Fig. 1. and Fig. 2 Based on the previously mentioned data, the power of a compact heat exchanger of 30 kW was determined. The exchanger is installed in a wood processing plant. During the operation of the compact exchanger, a problem was noticed in the construction, in the way of introducing fluid into the apparatus, which results in uneven fluid flow. In the further part of the paper, modeling and optimization were performed in order to achieve uniformity of fluid flow in the heat exchanger [2], [3].

2. COMPACT HEAT EXCHANGER

The compact heat exchangers are the type of the recuperative exchanger, in the which heat is exchanged between cooled fluid (warmer fluid) and the heated fluid (colder fluid) through a flat surface. The need to develop heat exchangers with high compactness, simple construction and of course the lowest possible price, have led to the development of a compact heat exchangers. These exchangers are made of thin sheets whose thickness ranges from 0.7 mm to 15 mm. The channels are shaped in such a way that the flow of fluid is usually done cocurrent or in countercurrent direction. They are most often used in cases when both fluids are gases, and they can also be used in cases when one fluid is a gas and the other is a liquid. Working pressures in the compact heat exchanger can be up to 16 bar and the fluid temperature range is up to 400°C.

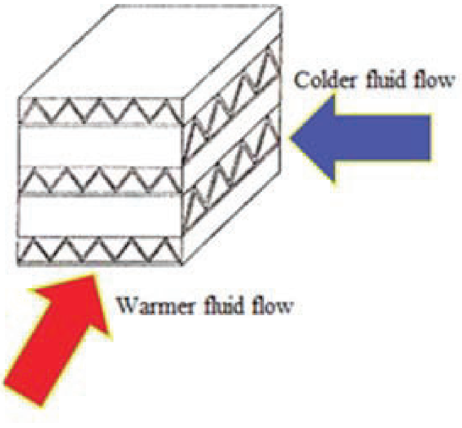

Fig.1 Construction of the compact heat exchanger

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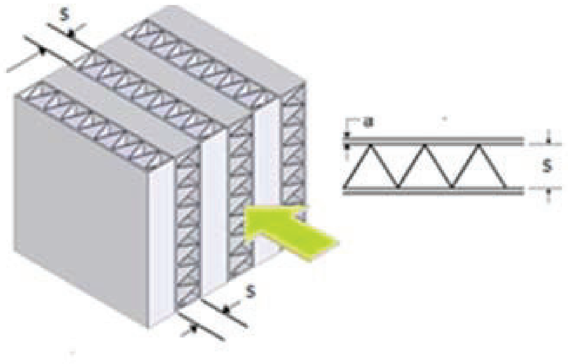

Fig.2 Construction of the compact heat exchanger

In this paper, a compact heat exchanger is considered, in which combustion products are used to heat the air as a colder fluid, with special attention paid to the flow of fluid through the exchanger.

3. MODELING

The design of this type of exchanger is based on the calculation of heat exchange between two fluids taking into account the construction of the exchanger, mass flows and inlet temperature of both fluids, as well as the outlet temperature of one of the fluids.

The energy balance of a heat exchanger is determined from the equation:

$$Q = \dot{m}_1 \cdot c_{p1} \cdot (t_{1\,in} - t_{1\,out}) = \dot{m}_2 \cdot c_{p2} \cdot (t_{2\,out} - t_{2\,in}) = k \cdot A_{exch} \cdot \Delta t_m \tag{1}$$

where are: $\dot{m}_1$-mass flow rate of the combustion products, $c_{p,1}$-specific heat capacity of the combustion products, $t_{1\in}$-temperature of the combustion products at the inlet of the heat exchanger, t_{1out}- temperature of the combustion products at the outlet of the heat exchanger, $\dot{m}_2$-mass flow rate of air, c_{p2}-specific heat capacity of air, $t_{2\in}$-temperature of air at the second inlet of heat exchanger.

The mean logarithmic temperature difference is determined from equation (2) for a heat exchanger with countercurrent flow, taking into account correction factor ε taken from [6], [7] and [8]:

$$\Delta t_m = \varepsilon \cdot \frac{(t_{1\,in}-t_{2\,out})-(t_{1\,out}-t_{2\,in})}{ln\left(\frac{t_{1\,in}-t_{2\,out}}{t_{1\,out}-t_{2\,in}}\right)} \tag{2}$$

Based on known geometry of the compact heat exchanger and on the basis of the known inlet and outlet temperature of the both fluids obtained from (1), the heat transfer coefficient is calculated:

$$\frac{1}{k} = \left(\frac{1}{\alpha_1} + R_1\right)\frac{1}{\eta_1} + \frac{\delta_z}{\lambda_z} \cdot \frac{1}{1-\frac{S_r}{S}} + \left(\frac{1}{\alpha_2} + R_2\right)\frac{1}{\eta_2}, \tag{3}$$

The heat resistance coefficients due to contamination were adopted from [8]:

$$R_1 = 0{,}2 \cdot 10^{-3}\,\frac{m^2K}{W} \text{ и } R_2 = 0{,}1 \cdot 10^{-3}\,\frac{m^2K}{W}. \tag{4}$$

Convective heat transfer coefficient is obtained by the formula:

$$\alpha_i = \frac{Nu_i \cdot \lambda_i}{d_{e,i}} \tag{5}$$

where are: λ_i – the coefficient of the conduction, $d_{e,i}$ – the equivalent diameter, Nu_i – Nusselt number.

Dimensionless numbers, required for determination of the heat transfer coefficient, were calculate from (5) and (6).

$$Nu_i = 0{,}21 \cdot Re_i^{0,6} \cdot Pr_i^{\frac{1}{3}} \tag{5}$$

$$Re_i = \frac{w_i \cdot d_{e,i} \cdot \rho_i}{\mu_i} \tag{6}$$

where are: w_i – the fluid velocity, ρ_i – the fluid density, μ_i – the coefficient of dynamic viscosity of the fluids, $Pr_i -$ Prandtl number, where is $i = 1$ - for combustion product, $i = 2$ – for air.

Efficiency of the ribbed surface is calculated based on expressions (8), (9), (10) and (11), taking into account that $\lambda_r = \lambda_p = 20W/mK$ is the coefficient of the conduction for stainless steel plate:

$$\eta_i = 1 - \frac{S_r}{S}(1 - \theta_i) \tag{7}$$

$$\theta_i = \frac{tan\ \mathrm{h}\left(\sqrt{Bi_i}\right)}{\sqrt{Bi_i}} \tag{8}$$

$$Bi_i = \frac{\alpha_i \cdot l_r^*}{\lambda_r} \tag{9}$$

$$l_r^* = l_r \cdot \frac{\mathrm{h}_r^2}{A_r} \tag{10}$$

where are: $h_r = \frac{s}{2}$ -the rib height, s=25mm – the distance between main plates, $l_r = 2h_r + \delta_r$ – the rib circumference, δ_r =1mm – the rib thickness, $A_r = h_r \cdot \delta_r$ – the rib area.

Based on previous, the outlet air temperature and heat transfer coefficient were determined for the given input parameters.

Table 1. Parameters of the basic compact heat exchanger

$\dot{m}_1$[kg/s]	$t_{1\,in}$ [°C]	$t_{1\,out}$ [°C]	c_{p1} [J/kg°C]	Δt_m[°C]
0,712	159	120	1079,5	107.4
$\dot{m}_2$[kg/s]	$t_{2\,in}$ [°C]	$t_{2\,out}$ [°C]	c_{p2} [J/kg°C]	k [W/m^{2}K]
0.634	10	57	1007	64

The parameters that define the operation of the existing heat exchanger, the mass flow rates of the fluid, the inlet temperature of both fluids and the outlet temperature of the fluid 2 were measured in the operating conditions in which the exchanger was installed. The specific heat capacities of the fleece were adopted on the basis of certain mean temperatures from [6], [7] and [8].

4. FLOW ANALYSIS USING SOLIDWORKS FLOW SIMULATION

Based on obtained date, a „digital twin” was formed using SolidWorks software package in which, after defining of the geometry, a Flow analysis of fluid flow through a compact heat exchanger was performed [4], [5].

The data obtained from analytical model were taken as input parameters for the designed digital twin, where the following parameters were taken into account:

- Heat exchange by conduction between fluids,
- Heat exchange by convection between plates and heated fluid (air),
- Model is adiabatic isolated,
- Heat exchanger is made of stainless steel,
- It is adopted that the fluids before entering the exchanger have a fully developed flow,
- The flow of the fluids in the heat exchanger is countercurrent,
- The number of passes of both fluids is equal (seven passes).

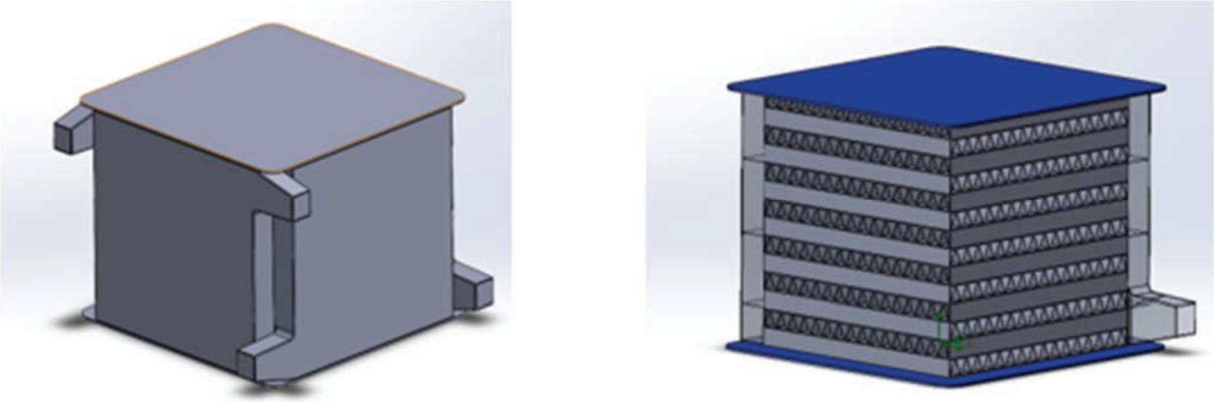

Fig.3. 3D model of the compact heat exchanger

The flow of the fluids inside of heat exchanger is analyzed by Flow Simulation where the results of the simulations are shown on the Fig. 3. Despite the fact that it is assumed that at the entrance in heat exchanger was the fully development flow, fluids tend to go to the first obstacle, which in this case is the back wall of the inlet channel and then are directed through passes of heat exchanger (see Fig. 3.). This flow of the fluids leads to low efficiency of the exchanger, because the fluids do not pass through the entire surfaces, as shown in Fig. 3.

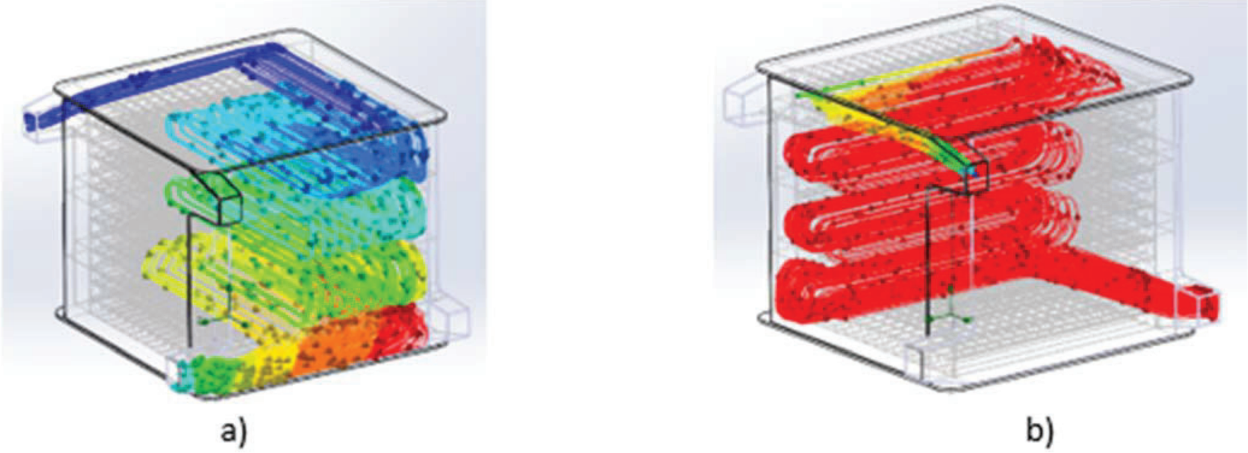

Fig.4. The flow of both fluids thought the heat exchanger, a) air, b) combustion products

In order to better routing the fluid through the exchanger and improve the efficiency, in the inlet channels of the exchanger baffles are placed (See Fig.4.). The height of the first baffle is 1/3 of the height of the inlet channel while the height of the second baffle is 2/3 of the height of the channel, as shown at the right side of Fig. 4.

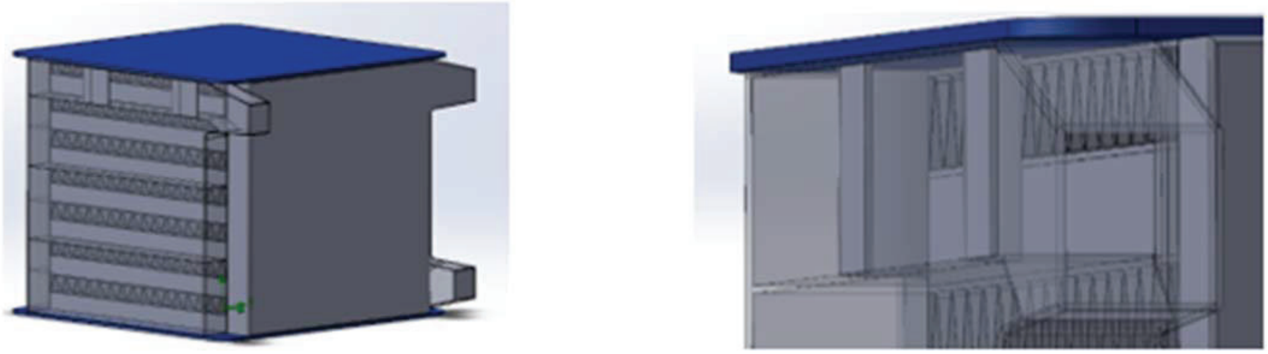

Fig.5. The position of the baffles at the inlet channel of heat exchanger

After obtained analysis of this solution, it can be concluded that in this case there has been improvement in fluid flow but there are still parts of exchanger in which we have very little or no fluid flow at all, as shown in Fig. 5. In this case the efficiency is improved in comparison with the basic construction of the heat exchanger given in Fig.3.

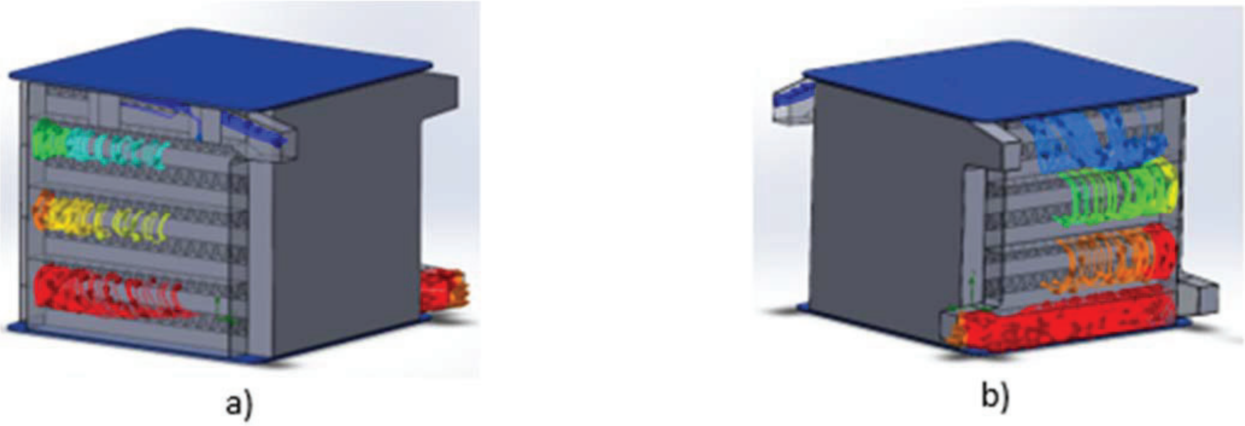

Fig. 6. Simulation of the fluid flow through heat exchanger with baffles, a) air, b) combustion products

Despite the added baffles, the flow analysis shows that the flow of both fluids in heat exchanger can be improved and that we still have a large part of the exchanger through which there is almost no fluid flow, and therefore no heat exchange between fluids, as shown in Fig.6.

In order to further improve the flow of fluids in the exchanger, a constructive change was made on the fluid inlets and outlets of the exchanger were the entrance and exit of the fluid is given along the entire sidewalls, as shown in Fig. 7. The assumption during flow simulation is that the flow at the inlet is fully developed. This assumption requires that the fluids be fed to the exchanger at a constant flow rate through a corresponding cross-section of a channel of similar geometry as inlet ports [4], [5].

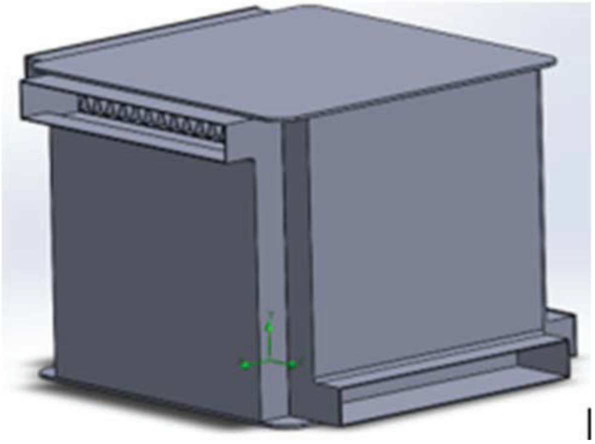

Fig.7. Compact heat exchanger with redesign inlet and outlet ports

After the flow analysis of fluid flow through redesigned heat exchanger, efficiency is improved due to better fluid flow along the entire surfaces of the exchanger, as shown in Fig 8.

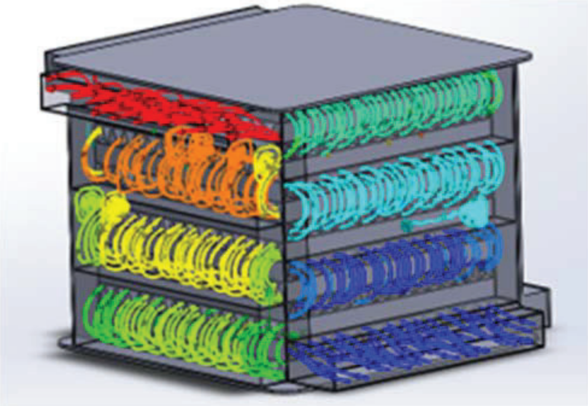

Fig.8. Simulation of the fluid flow through heat exchanger with redesign inlet and outlet ports

5. RESULTS

Based on the performed analyzes of all models and shown fluid output temperatures, it can be seen that in the case of exchanger with redesigned inlet and outlet ports, the highest degree of heat transfer from one fluid to another is achieved. In all cases the input parameters were the same. The obtained results for all models are given in the Tab.2

Table 2. Inlet and outlet temperatures depending of type construction

Fluid	Fluid 1 -combustion product		Fluid 2 -air	
Type of construction	$t_{1\in}$ [°C]	t_{1out}[°C]	$t_{2\in}$[°C]	t_{2out}[°C]
basic	159	120	10	57
basic with baffles	159	118	10	60
basic with redesigned ports	159	114	10	64

The modification of the inlet and outlet ports on the heat exchanger leads to the higher amount of the exchanged heat, which can be seen from lower temperature of the combustion products and higher temperature of the air at the outlet ports. With reconstruction of the inlet ports, both fluids have better flow over plates, which directly means better efficiency of heat exchanger.

In all three analyses, the mass flow of the combustion products and the air on the inlet ports has the same value. Due to different surface area for exchange, it is clear that in first two analysis the velocity of the air and combustion products has higher values compared to the velocities in the third analysis. This change of the velocity of the fluids on inlet ports may have significant influence on the fluids flow inside the heat exchanger. Regarding that, the future analyses should take into account and fluid velocity in the heat exchanger, in order to increase the amount of the exchanged heat and increase the efficiency of the heat exchanger.

6. CONCLUSION

In this paper optimization of the compact heat exchanger is performed, for defined geometry, mass and energy parameters in order to achieve uniformity of fluid flow in the heat exchanger. The modeling and fluid flow simulation of the existing (basic) heat exchanger is performed. Based on obtained results, optimization of the heat exchanger construction in order to achieved uniformity of the fluids over the entire surfaces was performed. The obtained solution does not require a change in the arrangement of the plates in the exchanger, but a correction is needed in the part where the fluids are introduced into the apparatus.

The analytical design process of the exchanger does not take into account the fluid flow inside the exchanger and does not consider the actual efficiency. Most often, when design, degree of security is taken into account, which leads to oversizing of the required power of the heat exchanger. Using Flow simulation, as shown in this paper, it is possible to analyze the fluid flow inside the exchanger and perform optimizations of operation, or increase the efficiency of the exchanger. When designing new types of exchangers, the dimensions of the exchanger can be significantly reduced and the efficiency can be increased using this type of analysis.

ACKNOWLEDGEMENT

This research was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Grant No. 451-03-9/2021-14/200108).

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