ORIGINAL SCIENTIFIC PAPER OPEN ACCESS

Analysis of the performance of the shell and tube heat exchanger: influence of the baffles and the position of fluid inlet and outlet

Stefan Adžić[1], Nenad Stojić[1*], Miljan Marašević[1], Nebojša Bogojević[1], Jovana Bojković[1]

[1] University of Kragujevac, Faculty of Mechanical and Civil Engineering in Kraljevo, Serbia

ARTICLE INFO

[*] **Correspondence:** stojic.n@mfkv.kg.ac.rs

DOI: 10.5937/engtoday2202053A

UDC: 621(497.11) **ISSN:** 2812-9474

Article history: Received 17 June 2022; Accepted 12 July 2022

ABSTRACT

The constant need for heat exchangers that are easy to manufacture and maintain, and that have a standardized and already known manufacturing technology, has led to the fact that shell and tube heat exchangers are one of the most common devices used in the process industry. In this paper, the analytical and numerical models of the basic shell and heat exchanger have presented with dimensions of 3750 x 1000 mm and a nominal heat capacity of 410 kW. Using the flow simulation, the influence of different numbers and arrangement of baffles and the changing the position of the inlet and outlet of warmer fluid are considered. The temperatures of the fluids on the inlet and outlet are taken into account as the main parameters for heat exchanger performance. From obtained results, it can be concluded that with the increase in the number of baffles, the performance of the heat exchanger is increased. The position of the inlet and outlet of the warmer fluid greatly influence the heat exchanger performance.

KEYWORDS

Shell and tube heat exchanger, Simulation, Baffle

1. INTRODUCTION

Heat exchangers are devices in which heat is exchanged between warmer and colder fluids without a fluids mixture [1,2]. There are several groups and subgroups within the division of heat exchangers. The primary division of the heat exchanger is according to the purpose, temperature operating mode of the appliance, and functional-technical solutions. According to the purpose, heat exchangers can be used in industrial processes as heaters and coolers, evaporators and crystallizers, evaporators and condensers, and chemical and biochemical reactors, while the division according to the operating temperature is divided into a low temperature, medium temperature, high temperature, and cryogenic heat exchangers. The most common division of heat exchangers is according to the method of heat transfer from one fluid to another, and this classification was made according to functional-technological solutions. According to the method of heat transfer, we distinguish: regenerative exchangers, recuperative exchangers, exchangers with indirect heat carriers, and contact heat exchangers. Geometric characteristics affect the change in heat flux, primarily by changing the velocity and current flow of the fluid, which makes the geometric characteristics an important parameter when choosing a model of the shell and tube heat exchanger. Experimental examination of different design studies of the heat exchangers requires a lot of time, therefore simulation studies are usually used for the analysis of the influence of parameters on the heat exchanger performance [3]. Bicer et al [4] analyzed the influence of the different baffle designs to reduce the pressure drop and increase the efficiency of the heat exchanger. In their paper, the Taguchi method was used to determine the optimal design of baffles solution. The proposed design leads to a 7.3% increase in the heat transfer rate and a 7.6% pressure drop. Safarian at all [3] considered the influence of the elliptical tube cross-sections on the pressure drop and heat transfer coefficient of the heat exchanger. Abd et al [5] investigate the influence of the shell diameter and tube length on the heat transfer coefficient and pressure drop. Heat transfer coefficient and pressure drop will decrease with increasing the space between the baffles. Increasing the shell diameter, the pressure drop will decrease while an increase in the tube length leads to enhancing the heat transfer coefficient and pressure drop. Labbadlia et al [6] have shown that tube arrangements in the shell and tube heat exchanger have a significant influence on the efficiency. They were investigating four different tube arrangements and show that is possible to achieve better flow distribution as well as better pressure distribution uniformity. Innovative steps in the industry contribute to obtaining better optimization solutions when designing the construction of heat exchangers. The main priority when designing the construction of the heat exchanger is the tendency towards the smallest possible dimension of the device and the highest possible efficiency of the exchanger. Good geometric characteristics achieve more intensive heat exchange between fluids without increasing the size and weight of the device, which affects the manufacturing cost of the heat exchanger.

The paper presents an analysis of three variant solutions for optimizing the construction of a shell and tube heat exchanger by changing the arrangement and number of baffles and changing the position of the warmer fluid inlet and outlet. Before the simulation and analysis of the basic model of the exchanger, the geometrical characteristics, mass flows of the fluid, inlet and outlet temperatures of fluid 1 (warmer fluid-water) and fluid 2 (colder fluid-water) were determined. The length of the active part of the appliance is 3750 mm, the diameter of the appliance is 1000 mm, the number of pipes in the pipe register is 81 and they are arranged to correspond to the circular arrangement, as shown in Figure 1. Based on the input parameters, the rated power of the basic model of the heat exchanger is 410 kW. During the simulation of the operation of the shell and tube heat exchanger, uneven fluid flow and low outlet temperature of the colder fluid were observed. In the continuation of the paper, three optimization geometric solutions are presented, which aim to achieve a more uniform fluid flow and as high an output temperature of the colder fluid as possible. The basic geometric characteristics and input parameters of the fluid are the same in all optimization solutions. [7], [8].

2. SHELL AND TUBE HEAT EXCHANGER

Shell and tube heat exchangers are a type of recuperative heat exchangers and have a wide representation in the process industry [1,8,9]. They have been used for more than 14 decades, while in the last few decades they have appeared as standardized and standardized constructions. One of the most well-known standardized constructions is, according to the TEMA standard, within the framework of the American Tubular Exchanger Manufacturers Association (TEMA). The shell and tube heat exchanger can be of robust construction, the surface of the heat exchanger can be up to 5000 m2, while the length of the heat exchanger can reach up to 12 m. The maximum temperature difference between the pipe register and the shell is from 20 ˚C to 600 ˚C. Due to their high rigidity, they are suitable for operation at high pressures and in a vacuum. Shell and tube heat exchangers have two basic parts, one of which is the inner part which consists of a pipe register, and the outer part which consists of the shell, the front and the rear head. During construction and construction solutions, it is possible that the inner and outer parts can be separated. The front head on the shell and tube heat exchanger is always fixed, while the rear head can be positioned so that it is fixed or floating. The liquid that is introduced into the apparatus can achieve its flow along the pipe or at the same time along and transversely on the pipe if baffles are placed. Baffles on the shell and tube heat exchanger theoretically represent external elements but are often placed in the pipe register. The connection of the pipe to the pipe plate in a shell and tube heat exchanger is usually achieved by welding. The fluid flowing through the pipes has an inlet and outlet connection on the heads, while the fluid flowing around the pipe has its connections on the exchanger shell itself, Fig. 1.

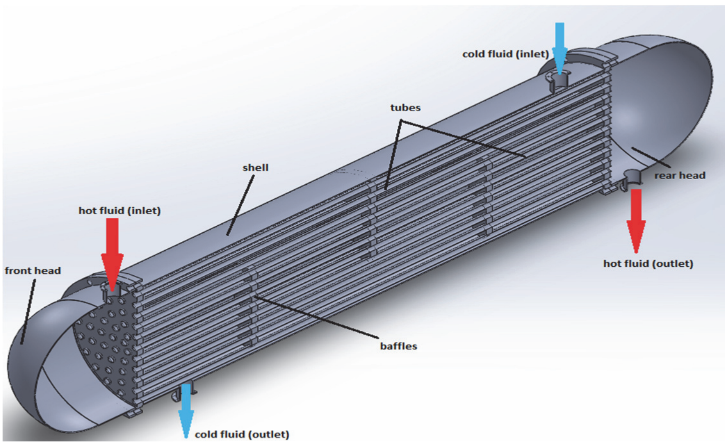

Figure 1: The basic construction of the shell and tube heat exchanger

Several important rules determine the distribution of fluid in a shell and tube heat exchanger. Fluids of higher pressure in most cases flow through a pipe. Small pipe diameters and nominal wall thickness withstand high pressures more easily and give a lower construction cost. Also, the fluid with a higher coefficient of contamination should be placed in the pipe register because the pipes are easier to clean by mechanical methods. Since water is used in the simulation for both fluids in the tubular exchanger, the main reason for adopting this fluid position is flow analysis, i.e. fluid with the lower flow is more adequately placed in the tubular register because it enables greater heat transfer from the register tube (increase in flow rate). [7]

3. MODELING AND CALCULATION

When creating a model of the exchanger, it is necessary to perform calculations of the amount of heat exchanged between two fluids, taking into account the following parameters: mass flow, inlet temperatures of both fluids, and 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 fluid 1, $c_{p,1}$ -specific heat capacity of the fluid 1, $t_{1\,in}$ - inlet temperature of the fluid 1, t_{1out} - outlet temperature of the fluid 1, $\dot{m}_2$ -mass flow rate of the fluid 2, c_{p2} - specific heat capacity of the fluid 2, $t_{2\,in}$ - inlet temperature of the fluid 2, t_{2out} - outlet temperature of the fluid 2.

The mean logarithmic temperature difference is determined from equation (2) for a heat exchanger with counterflow, taking into account correction factor ε taken from [9, 10,11]:

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

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

$$k = \frac{1}{\left(\frac{1}{\alpha_1} + R_{f1}\right)\frac{A_2}{A_1} + R_{wall} + \frac{1}{\alpha_2} + R_{f2}} \tag{3}$$

where: α_i-heat transfer coefficients, A_i-heat transfer areas, R_{f1} - fouling resistances, R_{wall} -thermal resistance of the separating wall. [12]

The heat resistance coefficients due to contamination were adopted from [11]:

$$R_{f1} = 0{,}2 \cdot 10^{-3}\,\frac{m^2K}{W} \quad \text{and} \quad R_{f2} = 0{,}1 \cdot 10^{-3}\,\frac{m^2K}{W} \tag{4}$$

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 [8].

Dimensionless numbers, required for determination of the heat transfer coefficient, were calculated from (6) and (7).

$$Nu_i = 0{,}21 \cdot \mathrm{Re}_i^{0{,}6} \cdot Pr_i^{\frac{1}{3}} \tag{6}$$

$$\mathrm{Re}_i = \frac{w_i \cdot d_{e,i} \cdot \rho_i}{\mu_i} \tag{7}$$

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

Based on previous, the outlet temperature of the fluids and heat transfer coefficient were determined for the given input parameters. The specific heat capacities of both fluids were adopted based on the mean temperatures from [9, 10, 11].

Table 1: Parameters of the basic design of shell and tube heat exchanger obtained by analytical calculations

$\dot{m}_1$ [kg/s]	$t_{1\,in}$ [°C]	$t_{1\,out}$ [°C]	c_{p1} [kJ/kg°C]	Δt_m [°C]
1,67	180	123	4,3075	94,11
$\dot{m}_2$ [kg/s]	$t_{2\,in}$ [°C]	$t_{2\,out}$ [°C]	c_{p2} [kJ/kg°C]	k [W/m^{2}K]
2,9	40	73.8	4,1833	118,89

4. MODEL VALIDATION

Validation of the numerical model was performed by comparison of the results obtained from analytical calculations and results from flow simulations for the basic construction of the shell and tube heat exchanger. The mass flow of the fluids, the inlet temperatures of the both fluids are the same in analytical and flow analysis. The outlet temperature of the colder fluid was the parameter that was used for model validation. The temperature obtained from analytical model was 73.8 °C, while the temperature from flow simulation was 70.57 °C. Regarding that difference between the temperatures on the outlet of the colder fluid is 4.4% the simulation model is able to predict the temperature exchange in the heat exchanger.

5. FLOW ANALYSIS USING SOLIDWORKS FLOW SIMULATION

Using the known input parameters and geometrical characteristics of the exchanger, a simulation of fluid flow in the shell and tube heat exchanger, which is the basic model of the exchanger and on which the analysis will be performed. Fluid flow simulation of the basic model of the heat exchanger has shown uneven fluid flow during operation, which was the main reason for further analysis of the heat exchanger efficiency. For all proposed designs of the heater exchanger, the following parameters were taken into account: the system is adiabatically isolated, fluid flow is countercurrent, fluids entering the apparatus have a fully developed flow, heat exchanger is made of steel, number of inlets and outlets for warmer and the colder fluid is the same in all variant solutions. Fluid flow simulation in the basic model of the heat exchanger and the shown temperature fields indicate an uneven fluid flow in the tubular register of the exchanger. The cause of uneven fluid flow is the inadequate position of the inlet and outlet openings of the warmer fluid, as well as the layout and number of baffles within the pipe register, as shown in Fig. 2.

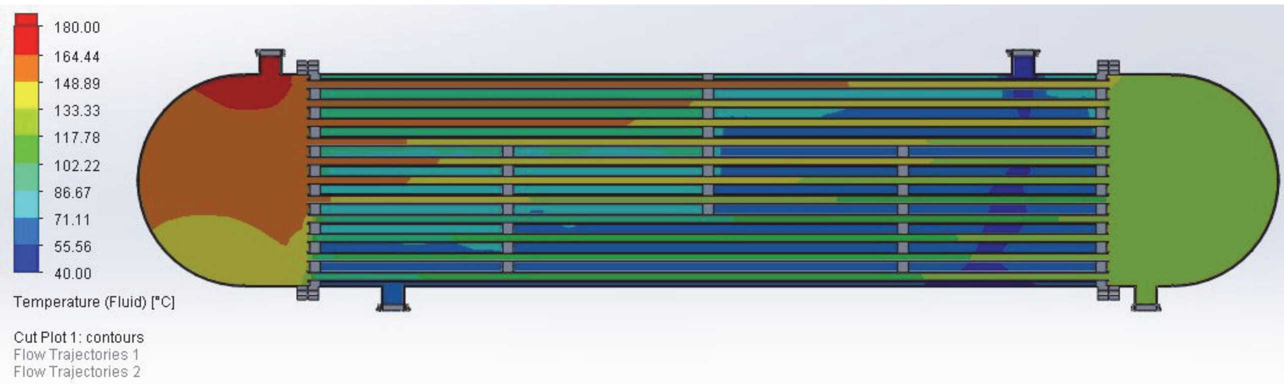

Figure 2: Temperature field for the basic model of shell and tube heat exchanger obtained by simulation

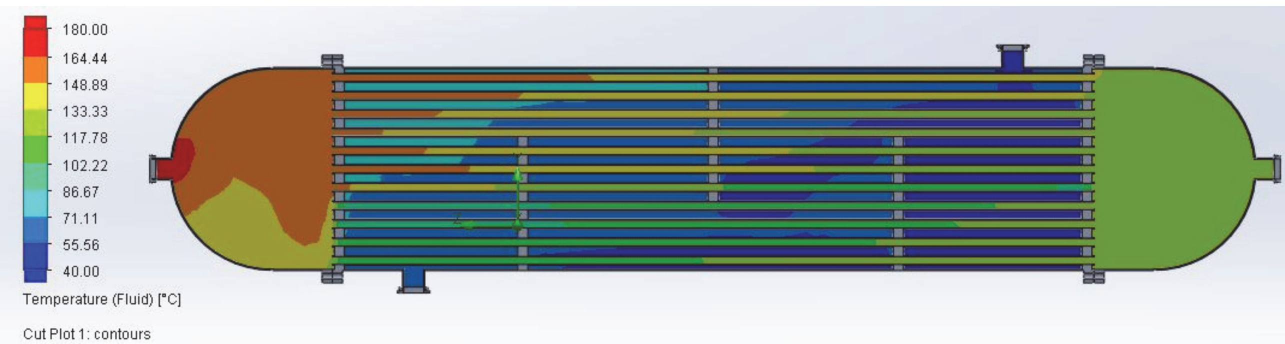

Figure 3: Temperature field for the model with the change of position of warmer fluid inlet and outlet obtained by simulation

In order to increase the effectiveness of the heat exchanger, i.e., in order to transfer as much heat between the two fluids as possible, it is necessary to optimize the geometric characteristics of the heat exchanger. Fluid inlets and outlets have a connection located on the exchanger heads. Changing the position of the inlet and outlet of the warmer fluid allows a more adequate and entry of fluid into the pipe register with higher velocity. Analysis of fluid flow simulation when changing the position of the inlet and outlet of the warmer shows that in addition to more adequate inlet and outlet of fluid from the pipe register, it is necessary to change the geometric structures related to the layout and number of baffles. The disadvantage of a variant solution in optimizations that involves changing the position of the inlet and outlet of the warmer fluid without additional optimization solutions is insufficient long retention of the warmer fluid through the pipe register and uneven flow that reduces heat exchange between the two fluids, as shown in Figure 3.

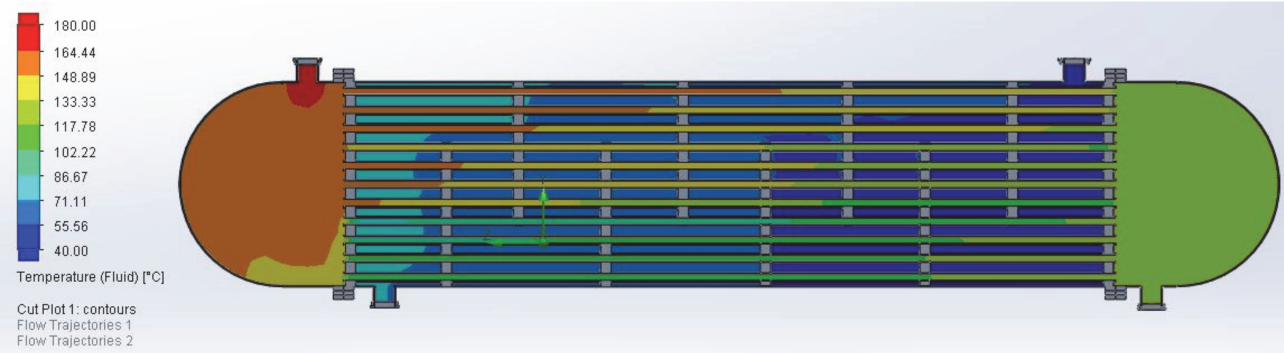

Figure 4: Temperature field for the model with changed number and layout of baffles obtained by simulation

In order to achieve the most even flow of fluid in the pipe register, the number and arrangement of baffles were optimized. In addition to the existing number baffles, optimization was performed and the number of baffles in the pipe register was increased. The variant solution includes the installation of a total of 8 baffles with equal lengths and distances, as shown in Figure 4. The increase in the number of baffles resulted in a more uniform fluid flow in the cervical register and a greater heat exchange between the warmer and colder fluids. By simulating the fluid flow when applying this variant of the solution, the results were obtained which show that by increasing the number of baffles, a higher outlet temperature of the colder fluid and thus a larger temperature difference is obtained.

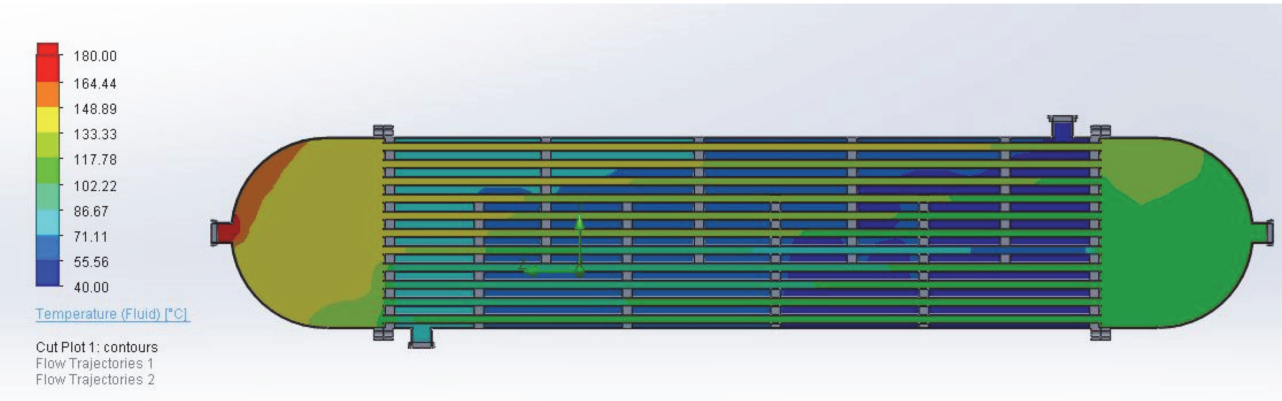

Figure 5: Temperature field for the model with changed the number and layout of baffles and position of warmer fluid inlet and outlet obtained by simulation

Despite the optimization solution that includes changing the layout and number of baffles, analyzes of fluid flow simulation and temperature fields show that the flow of warmer fluid in the pipe register can still be improved. For greater heat exchange, it is necessary to apply optimization solutions which, in addition to changing the layout and number of l baffles, also include changing the position of the warmer fluid inlet and outlet, as shown in Figure 5. The optimization solution, which includes a change in the layout and number of baffles, as well as a change in the position of the warmer fluid inlet and outlet, achieves a uniform fluid flow and a more adequate entry of the warmer fluid into the pipe register.

6. RESULTS AND ANALYSIS

The following table shows the values of fluid inlet and outlet temperatures in the simulation of the operation of shell and tube heat exchanger in which three optimization geometry solutions were made. Based on the simulation and analysis of fluid flow, it is concluded that the most adequate optimization solution is the one in which the largest temperature difference is obtained. In all optimization solutions, the values of the mass flows of colder and warmer fluids did not change, as did the inlet temperatures of the fluid. Therefore, by increasing the number of baffles and changing the position of the warmer inlet and outlet, the most uniform flow in the pipe register is achieved, that is, this variant solution achieves the greatest heat exchange between the colder and warmer fluid.

Table 2: Inlet and outlet temperatures depending of type construction obtained by simulation

Fluid	**Fluid 1 - water (warmer)**		**Fluid 2 - water (colder)**	
Temperature	t_{1in} [°C]	t_{1out} [°C]	t_{2in} [°C]	t_{2out} [°C]
Basic design	180	120,30	40	70,57
Basic design with changing the position of the warmer fluid inlet and outlet	180	126,40	40	67,67
Basic design with eight baffles	180	123,47	40	71,38
Basic design with eight baffles and changed the position of the warmer fluid inlet and outlet	**180**	**115,76**	**40**	**74,31**

Bearing in mind the same values of the inlet temperature of the colder and warmer fluid in all variant cases, we conclude that the amount of heat exchanged in the exchanger depends on the temperature differences. The table shows the values of the inlet and outlet temperatures of the hotter and colder fluid in all variant solutions. The outlet temperatures of the colder and warmer fluid depend on the application of the optimization solution of the geometric characteristics.

Effectiveness ε is a measure of thermal performance of a heat exchanger. It is defined for a given heat exchanger of any flow arrangement as a ratio of the actual heat transfer rate from the hot fluid to the cold fluid to the maximum possible heat transfer rate q_{max} thermodynamically permitted:

$$\varepsilon = \frac{q}{q_{max}} \tag{8}$$

where: q -total or local heat transfer rate in the exchanger, q_{max} - thermodynamically maximum possible heat transfer rate in a counterflow heat exchanger.

An overall energy balance for the two fluid streams is [13]:

$$q = C_h \cdot \left(t_{1,in} - t_{1out}\right) = C_c \cdot \left(t_{2,out} - t_{2in}\right) \tag{9}$$

$$q_{max} = C_{p1} \cdot \left(t_{1,in} - t_{2in}\right) = C_{p1} \cdot \Delta t_{max} \tag{10}$$

where: $C_h = m_1 \cdot c_{p1}$ - hot fluid capacity rate, and $C_c = m_2 \cdot c_{p2}$ - cold fluid capacity rate.

Table 3: Effectiveness of the analyzed designs of the heat exchanger

Effectiveness [%]			
Basic design	Basic design with changing the position of the fluid inlet and outlet	Basic design with eight baffles	Basic design with eight baffles and changing the position of the fluid inlet and outlet
36.82	33.26	37.76	41.39

7. CONCLUSION

The paper presents the analysis of geometric characteristics in the operation of shell and tube heat exchanger with two floating heads. Fluid flow simulation of the basic model of the heat exchanger with the required input parameters was performed. Based on the obtained results, the design of the exchanger was improved in order to achieve higher heat exchange between the two fluids. Simulations were performed in the software package "Solidworks" for three variant solutions. Higher heat exchange between the two fluids was achieved by the adjusting the number of the baffles and changing the position of the wormer fluid inlet and outlet, which gave a more uniform fluid flow in the exchanger. The nominal heat flux of the heat exchanger before the improvement was 410 kW. By applying the proposed design, for the same input parameters, the nominal heat flux of the heat exchanger has increased and reach 465 kW, which represents an increase of heat exchange between fluids for more than 13%.

The effectiveness of the proposed design solution has been calculated and increase of the 4.57 % achieved in the case of the heat exchanger with eight baffles and revised position of the warmer fluid inlet and outlet.

Proposed design solution would include the installation baffles and change of the position of the inlet and outlet of the warmer fluid, which will not have effect on the manufacturing costs of the heat exchanger. The proposed design has retained the dimensions of the basic heat exchanger, also the arrangements of the tube register have no changes as well as tubes length.

ACKNOWLEDGMENT

This research has been supported by the Serbian Ministry of the Education, Science and Technology Development under grant 451-03-68/2022-14/200108.

REFERENCES

[1] S. H. Gawande, S. D. Wankhede, R. N. Yerrawar, V. J. Sonawane and U. B. Ubarhande, "Design and Development of Shell & Tube Heat Exchanger for Beverage", Modern Mechanical Engineering Vol. 2 No. 4, p.121, https://doi.org/10.4236/mme.2012.24015, (2012)

[2] Liang-YuChen, V. S. K. Adi and R. Laxmidewi, "Shell and tube heat exchanger flexible design strategy for process operability", Case Studies in Thermal Engineering, 102163, https://doi.org/10.1016/j.csite.2022.102163

[3] M. R. Safarian, F. Fazelpou and M. Sham, "Numerical study of shell and tube heat exchanger with diferent cross-section tubes and combined tubes", nternational Journal of Energy and Environmental Engineering,Vol. 10, pp. 33–46, https://doi.org/10.1007/s40095-019-0297-9, (2019)

[4] N. Biçer, T. Engin, H. Yas¸ E. Büyükkaya, A. Aydın and A. Topuz, "Design optimization of a shell-and-tube heat exchanger with novel three-zonal baffle by using CFD and taguchi method", International Journal of Thermal Sciences, Vol. 155, p. 106417, https://doi.org/10.1016/j.ijthermalsci.2020.106417, (2020)

[5] A. A. Abd, M. Q. Kareem and S. Z. Naji, "Performance analysis of shell and tube heat exchanger: Parametric study", Case Studies in Thermal Engineering, Vol. 12, pp. 563-568, https://doi.org/10.1016/j.csite.2018.07.009, (2018)

[6] O. Labbadlia, B. Laribi, B. Chetti and P. Hendrick, "Numerical study of the influence of tube arrangement on the flow distribution in the header of shell and tube heat exchangers" Appl. Therm. Eng, Vol. 126, pp. 315–321, https://doi.org/10.1016/j.applthermaleng.2017.07.184, (2017)

[7] M. Rikalović, Dobošasti razmenjivači toplote, Savez mašinskih i elektrotehničkin inženjera i tehničara Srbije, Beograd (2002)

[8] M. Marašević, N. Bogojević, N. Stojić, S. Adžić and D.Šimunović, "Optimization of compact heat exchanger ", Proceedings of X International Conference "Heavy Machinery HM 2021", Vrnjačka Banja (Serbia), 22 June 25 June 2021, pp. 497-502, (2021)

[9] B. Jaćimović, S. Genić, Toplotne operacije i aparati – Deo 1: Rekuperativni razmenjivači toplote, Mašinski fakultet, Beograd, (2016)

[10] S. Genić, B. Jaćimović, M. Jarić and N. Budimir, Svojstva procesnih fluida, Savez mašinskih i elektrotehničkih inženjera i tehničara Srbije, Beograd, (2014)

[11] B. Jaćimović, S. Genić, M. Nagi and J. Laza, Problemi iz toplotnih operacija i aparata, SMEITS i Mašinski fakultet, Beograd, (1996)

[12] VDI Heat Atlas, C4 Fouling of Heat Exchanger Surfaces, Springer-Verlag Berlin Heidelberg, https://doi.org/10.1007/978-3-540-77877-6_7, (2010)

[13] R. K. Shah and D. P. Sekulić, Fundamentals of Heat Exchanger Design. John Wiley & Sons, Inc, https://doi.org/10.1002/9780470172605, (2003)