Journal of Thermal Analysis and Calorimetry (2024) 149:6253–6264
https://doi.org/10.1007/s10973-024-13112-9

Performance analysis of baffle configuration effect on thermo-hydraulic behavior of shell and tube heat exchanger

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Received: 14 November 2023 / Accepted: 16 March 2024 / Published online: 17 April 2024

Abstract
The traditional shell and tube heat exchanger (STHE) is widely utilized in various engineering segments and has found a drawback in limited thermo-hydraulic behavior. This study enriches the STHE thermo-hydraulic performance using different baffle configurations (BC) such as single segment, double segment, single helical, single segment—no tubes in window (NTIW), propeller type and spiral baffle. The influences of BC on thermo-hydraulic behavior are analyzed through heat transfer research Inc. (HTRI) and computational fluid dynamics (CFD). During the analysis, the 60LPM flow rate is fixed under the shell/tube inlet temperature of 30 °C and 80 °C, followed by the counter flow. Additionally, fluid parameters on logarithmic mean temperature difference (LMTD), number of transfer units (NTU), overall heat transfer coefficient (U), effectiveness (η) and exergy efficiency (η_{ex}) of STHE are recorded by both HTRI and CFD analysis. According to the analysis results, the single helical 15° and double segmental BC offered superior LMTD, NTU, U, η and η_{ex} related to others.

Keywords Baffle configuration · CFD · HTRI · STHE · Thermo-hydraulic behavior

Introduction

The system to recover the waste heat from the prime source (heat exchanger) is widely adopted by various industries, which exchange the temperature (heat) between the two bodies with the fluid medium at low processing cost [1]. With the aid of the budding energy consumption of the world's resources and fuels, there is an increase in demand for energy for the modern lifestyle of mankind. So, it is necessary to make the existing thermal power systems more efficient and suited for the present state of life [2]. Among the various systems in heat exchangers, the shell and tube heat exchanger are found to be a trouble-free design, low maintenance charges, efficient, and suitable for oil and gas, food, and other chemical applications [3, 4]. Moreover, the performance of STHE was enhanced by the approaches of baffle segmentation [5].

El-said et al. [6] experimentally investigated the thermal performance of STHE by the approach of curved baffle segment and its results of heat transfer coefficient; the number of transfer units was higher than the conventional STHE with curved baffle segment, as well as the pressure loss to be reduced by 11.22%. Eryener [7] optimized the spacing between the shell and tube in STHE and suggested that the minimum spacing between baffles is about 20% of the shell diameter and a maximum equal to the shell diameter. Ideal baffle spacing is about 0.3–0.6 times the shell diameter. Taher et al. [8] utilized helical baffles and studied the friction factor of these baffles, and tube inserts play a major role in the flow of the medium in the shell and tube

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heat exchanger, which in turn affects the performance of STHE. Anjineyulu et al. [9] analyzed the thermo-hydraulic behavior of STHE by utilizing varied single segment baffle configurations via ANSYS-FLUENT, and they observed that minimum baffle cut has a maximum heat transfer coefficient and improved heat transfer behavior compared to other baffle configurations. The thermo-hydraulic and entropy generation characteristics of STHE were studied by two cross-section approaches of baffle segment and found that 2 baffle cut has maximum entropy generation with enhanced thermo-hydraulic characteristics related to the traditional setup of STHE [10]. The thermal–hydraulic quality of STHE was studied with varied configurations of baffles like traditional single segment, circular ring, circular ring with holes, flower segmental, hybrid segment and staggered single segmental. They noted that the hybrid segment offered an enhanced heat transfer coefficient with reduced frictional loss [11]. Moreover, the heat exchanger thermal–hydraulic quality was enhanced using multiphase nanofluids, which was economical and suitable for conventional heat exchanger systems. The results were compared with finite volume analysis output [12].

The first commercial discontinuous helical baffle-STHE was studied by Master [13] and experimentally investigated by Zhang et al. [14]. Zhnegguo et al. [15] proposed a study on the heat transfer performance and pressure drop in a helical baffle-STHE, which could improve the shell side thermal transfer. According to Lei et al. [16], the ideal helix angle used in the helical baffle plays a major role in the performance of STHE. The helical and segmental baffles are experimentally compared in the study by Zhang et al. [17]. El-Saida et al. [18] conducted an experimental investigation on STHE with segmental baffles and found enhanced thermal characteristics of STHE related to traditional STHE.

With the above literature, the thermal behavior of STHE is enriched by the approaches of baffle configuration segmentation, and no specific report is available for a comparison of thermal performance with HTRI and CFD analysis. The novel research is to study and analyze the different kinds of baffles (single segmental, double segmental, single helical, single segmental NTIW, propeller type, and spiral) used in the STHE and consider the factors determining the thermo-hydraulic performance such as pressure drop, velocity, logarithmic mean temperature difference (LMTD), Overall heat transfer coefficient (U), Number of transfer units (NTU), Effectiveness (η) and exergy efficiency (η_{ex}). The main objective of this study is executed with CFD analysis of different baffle configurations carried out in FLO EFD, and the theoretically calculated values are given as input for the HTRI exchanger. Both the results from the CFD analysis and the HTRI exchanger are considered in this study, and the best baffle configuration for obtaining the optimum thermal performance of STHE is spotted.

Methodology

With the help of SOLIDWORKS modeling software, the different kinds of baffle configurations (BC) such as single segment, double segment, single helical, single segment—no tubes in window (NTIW), propeller type and spiral baffle modeling are created, and its specific model is exported from SOLIDWORKS and imported to HTRI and CFD. Each solid model's boundary conditions are defined and adopted for further simulation. During the HTRI analysis, the single segment, double segment, single helical, single segment –no tubes in the window (NTIW) made it easier to analyze than others because the more complicated analysis does not generate accurate results. A constant tube layout of shell and tube heat exchanger is maintained for all baffle types except for NTIW. For No Tubes in Window (NTIW), the model geometry varies from the other baffle configurations to accommodate the number of tubes removed from the baffle's window area. The geometric modeling for HTRI and CFD is shown in Figs. 1 (a–d) and 2 (a–f).

The CFD analysis consisted of a shell with an internal diameter of 190 mm and a shell thickness of 5 mm. The tubes are housed inside the shell and have a diameter of 19.05 mm. The total number of tubes in the shell is 28 (7 tubes per pass). There are 4 passes in the tube side of the STHE. The front and rear end parts of the STHE have plates to allow the tube side fluid to flow as 4 passes along the quadrant of the cross-section of the STHE. The length of the tube housed in the shell is 612 mm.

For the NTIW baffle configuration, the internal diameter of the shell is 250 mm. The tube layout is changed, but the number of tubes considered for the study is 28 (7 tubes per pass). The fluid inlet outlet nozzles have an internal diameter of 26.65 mm. For single segmental and double segmental baffle configurations, the baffle cut is 23%. For Single helical baffle configuration, the helix angle is 15°. The baffle cut is maintained at 23% for Single segmental (No Tubes in Window) baffle configuration. Baffle thickness is 6 mm.

The single and double segmental baffles are conventional configurations used in shell and tube heat exchangers. The construction and assembly of these baffles are easier than other baffles. Single helical baffles are complex in geometry, but for ease of assembly, the helical profile of the baffle is created by four baffles covering each quadrant at the helix angle, which will result in the profile of the single helical baffle with continuous swirls.

Propeller-type baffles consist of four quadrant baffles connected to a single sleeve. Spiral-type baffles have a continuous swirling profile. The construction and assembly of propeller and spiral-type baffles are more complicated than the other shell and tube heat exchanger baffle configurations.

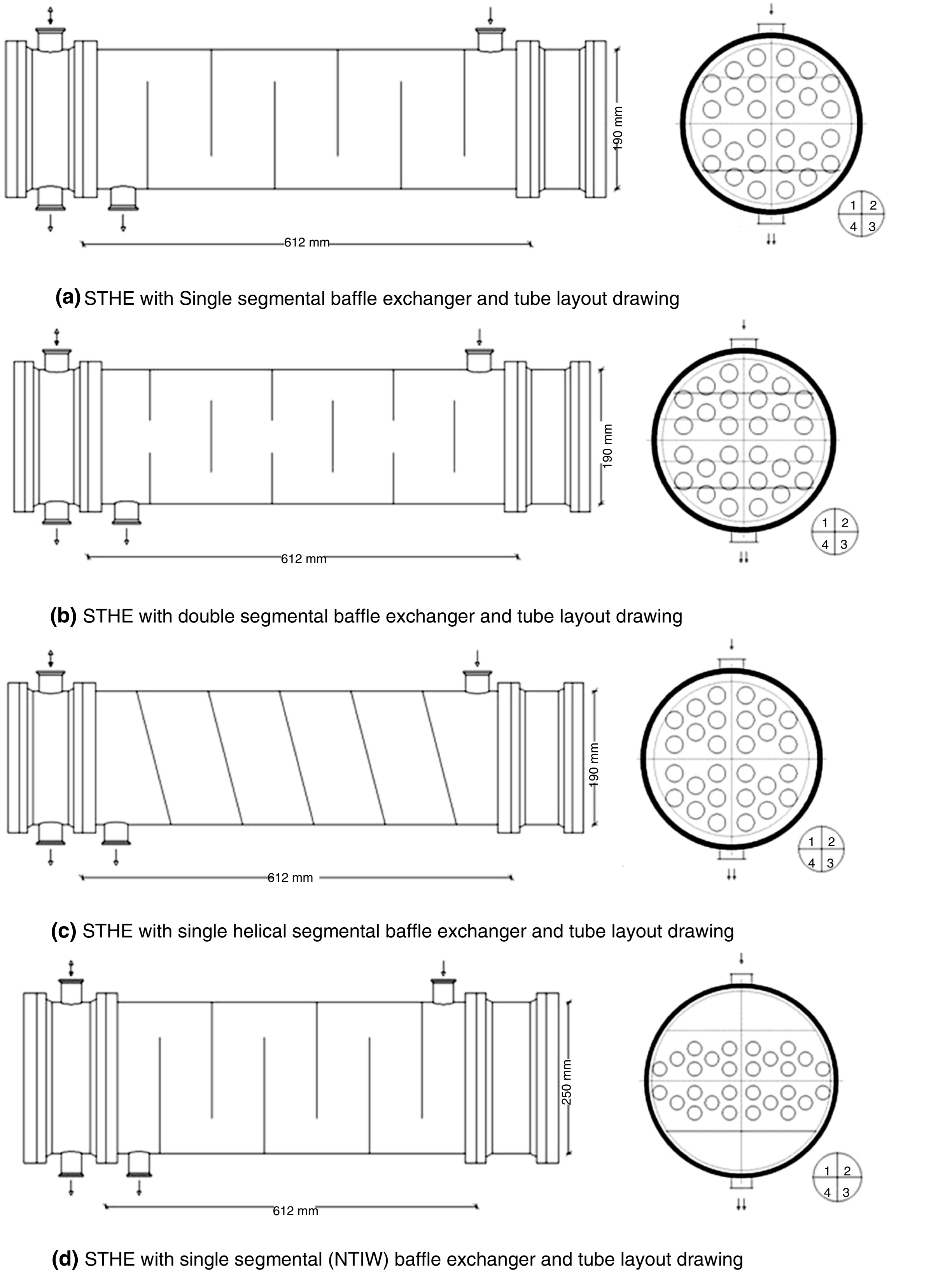


Fig. 1 **a** STHE with Single segmental baffle exchanger and tube layout drawing **b** STHE with double segmental baffle exchanger and tube layout drawing **c** STHE with single helical segmental baffle exchanger and tube layout drawing **d** STHE with single segmental (NTIW) baffle exchanger and tube layout drawing

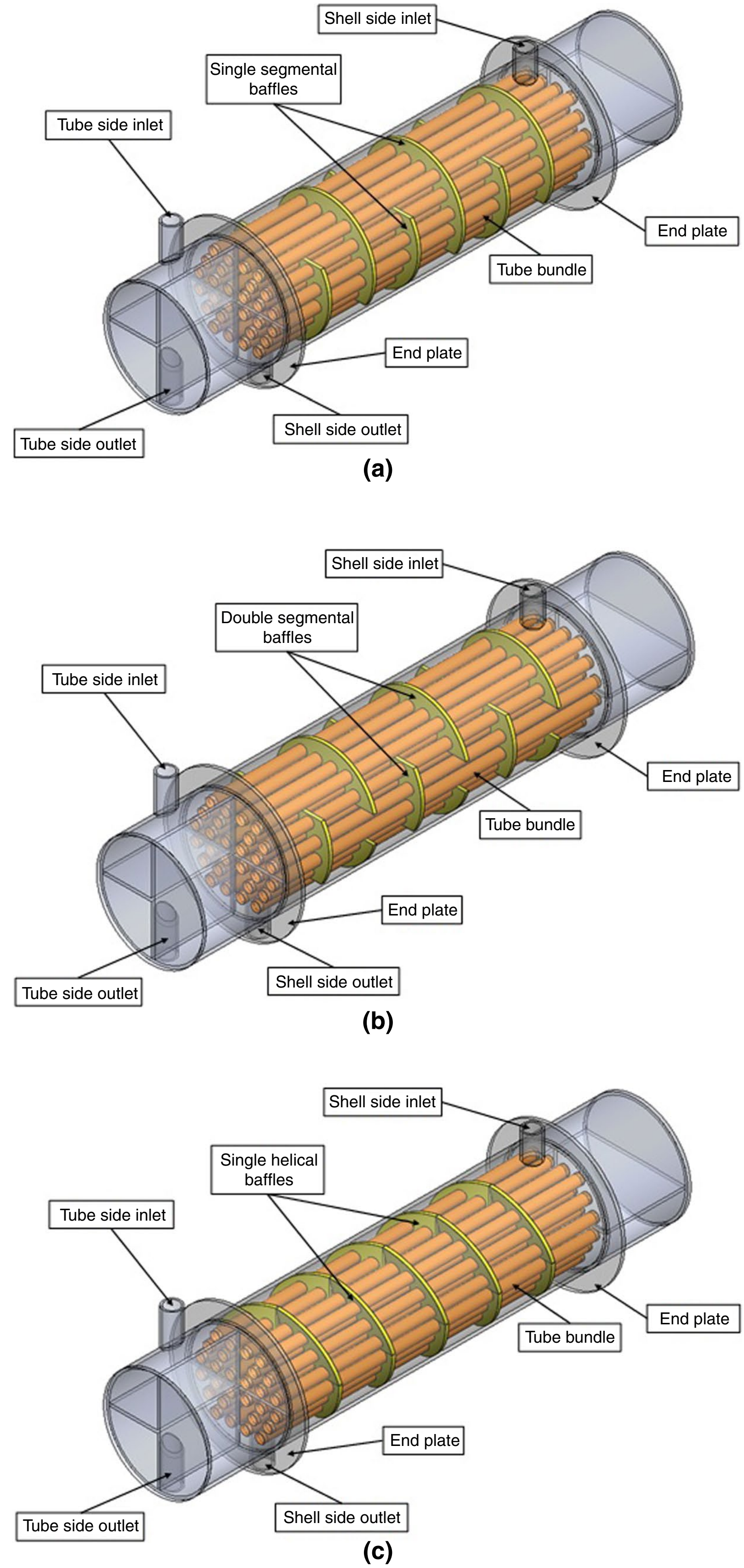
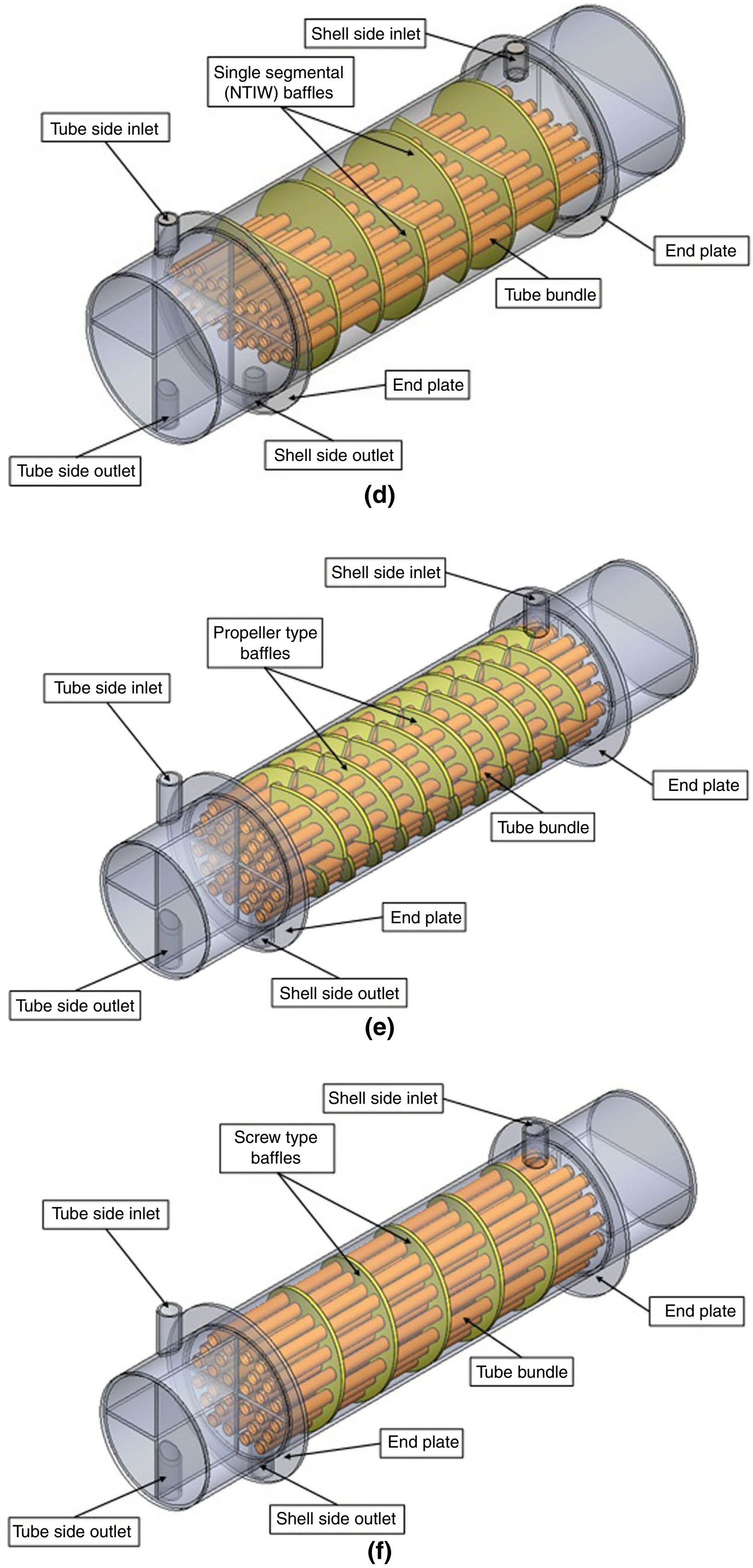


Fig. 2 **a** STHE with single segmental baffles **b** STHE with double segmental baffles **c** STHE with single helical segmental baffles **d** STHE with single segmental (NTIW) baffle. **e** STHE with Propeller type baffles **f** STHE with Spiral baffles

Fig. 2 (continued)



Boundary conditions

During the analysis, the flow of STHE is considered counter flow because of better thermo-hydraulic behavior and efficiency [10]. Moreover, this study fixes the 4 flow passes in the tube side containing 28tubes, and 60LPM flow is maintained due to enriched heat transfer coefficient with superior heat transfer rather than other flow rates. The same technique was reported by Eryener et al. [7] and Anjineyulu et al. [9]. In the meantime, the temperature of the fluid medium at the shell and tube side (inlet) is followed by 30 °C and 80 °C, respectively. The detailed boundary conditions for analysis of the STHE are mentioned in Table 1.

Table 1 Boundary conditions of STHE analysis

Parameters	Boundary conditions	Units	Shell side	Tube side
Inlet	Inlet flow rate	LPM	60	60
Outlet	Pressure measure	mmwc	Outlet	Outlet
Temperature	Inlet Temperature	°C	30	80
Fluid medium	–	–	Water	Water
Material	–	–	Stainless steel	Carbon steel

Results and discussions

HTRI and CFD analysis

According to the analysis report from HTRI and CFD simulation, the following output values of STHE are measured, and their values are tabulated in Table 2.

Logarithmic mean temperature difference (LMTD)

Figure 3 represents the LMTD of STHE under different baffle configurations, and its HTRI and CFD analysis values are compared.

From Fig. 3, the HTRI analysis value of LMTD for STHE is higher than the CFD analysis value, and CFD proves

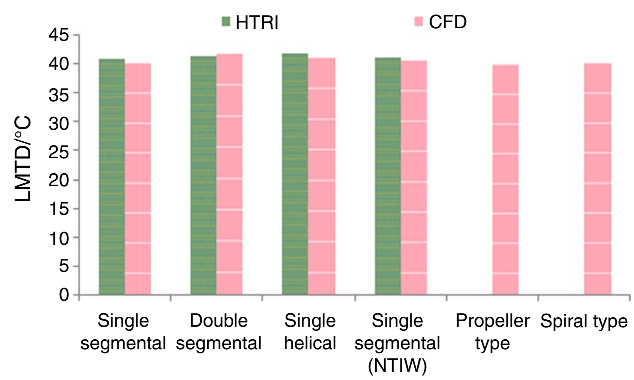


Fig. 3 LMTD of STHE (HTRI and CFD)

Table 2 HTRI and CFD analysis numerical values for STHE

Parameters	Descriptions	Baffle configuration					
		Single segmental	Double segmental	Single helical	Single segmental (NTIW)	Propeller type	Spiral type
		23% baffle cut	23% baffle cut	θ = 15°	23% baffle cut		
Shell side temperature (Coldwater) in°C	Inlet	30	30	30	30	30	30
	Outlet-HTRI	39.21	38.69	38.16	38.86	–	–
	Outlet-CFD	39.53	38.12	38.14	39.03	39.92	39.49
ΔT in°C	Shell side-HTRI	9.21	8.69	8.16	8.86	–	–
	Shell side -CFD	9.53	8.12	8.41	9.03	9.92	9.49
Pressure drop in mmwc	Shell side	117.8	82.57	337.39	373.37	413.07	365.3
Tube side temperature (Hot water) in°C	Inlet	80	80	80	80	80	80
	Outlet-HTRI	70.78	71.3	71.83	71.13	–	–
	Outlet-CFD	69.7	71.42	70.51	69.99	69.49	69.68
ΔT in°C	Tube side-HTRI	9.22	8.7	8.17	8.87	–	–
	Tube side-CFD	10.3	8.58	9.49	10.01	10.51	10.32
Pressure drop in mmwc	Tube side	397.35	198.85	429.03	194.72	433.13	432.65

their significance with enriched results related to HTRI. The LMTD for HTRI analysis value of single, double, single helical, and NTIW shows 40.785, 41.305, 41.835, and 41.135 °C, respectively. Amid the different baffle configurations the HTRA reports, the single helical baffle owns higher LMTD than others and improved by 3% related to single segmental. The uniform heat transfer due to improved turbulence mixing is the reason for enhancing LMTD. The CFD analysis value illustrates the variation in LMTD due to the configuration of the baffle plate. The LMTD for single segmental baffle is spotted by 40.084 °C and improved by 41.65 °C on double segmental due to improved heat transfer with reduced bypass fluid flow. The LMTD for single helical is exposed nearer to the double segmental value and spot 41.048 °C. The single segmental (NTIW), propeller, and spiral type exploited downtrend of LMTD like 40.478, 39.784, and 40.094 °C, respectively. The uneven distribution of fluid flow and bypass fluid flow causes a reduction in LMTD [6 and 11]. Among the various baffle configurations, the double segment and single helical baffle configurations found the optimum LMTD value in the HTRI and CFD analysis. This was due to the action of segmental partition, which enhanced the thermal quality of STHE with improved heat transfer performance [7 and 10].

Overall heat transfer coefficient (*U*)

Figure 4 bar chart indicates the 60LPM operated counter flow action on the overall heat transfer coefficient of STHE analyzed via HTRI and CFD. Based on analytical results, the overall heat transfer coefficient for CFD is higher than the value of HTRI, which is proved in Fig. 4. During this analysis, the lowest value of the overall heat transfer coefficient for STHE was found superior thermo-hydraulic performance [15]. The result of *U* from HTRI of a single segmental baffle is exposed to 1053.472, a higher value than other baffle configurations. The *U* of double segmental and single helical is recorded by less than 1000 due to temperature difference and the conversion of laminar to turbulent. The single segmental (NTIW) is noted that the *U* is 1004.837. Moreover, the *U* value evaluated by HTRI in varied baffle segments showed that the single helical baffle configuration found the lowest value of 910.007Wm^{-2} K^{-1} and limited by 15.76 as related to single baffle configuration. Moreover, the helical baffle configuration was optimal thermal behavior [16].

The analytical report of CFD shows the fine variation in each baffle configuration. The *U* value of the single segmental is 1153.327, and the double segmental baffle configuration found an optimum overall heat transfer coefficient of 934.769 Wm^{-2} K^{-1}. The single helical baffle is exposed to 1016.631 of its *U*, and single segmental (NTIW), propeller, and spiral type is exhibited by 1096.594, 1197.168, and 1151.882. Moreover, the CFD results of various baffles explored minimum variations in overall heat transfer coefficient due to boundary conditions, fluid flow, and baffle design. However, based on HTRI and CFD, the single helical and double segment baffle configuration is suggested for optimum thermo-hydraulic quality measure.

Number of transfer units (NTU)

The number of transfer units of STHE analysis via HTRI and CFD comparison bar chart is shown in Fig. 5

With the baffle configuration in STHE, the NTU is varied, and a minor difference is noted when comparing HTRI and CFD analysis reports. The HTRI analysis of NTU for single, double, single helical, and NTIW shows 0.243, 0.226, 0.21, and 0.232, respectively. Meantime, the CFD analysis report for single, double, single, helical, NTIW, propeller, and spiral-type baffle configurations indicates 0.266, 0.216, 0.234, 0.253, 0.276, and 0.266, respectively. The variations in NTU were due to the baffle configuration, flow rate and pressure drop [6]. However, the optimum value from HTRI is 0.21 (single helical), and CFD is 0.216 (double segment), which is the optimum value compared to the past reported value (0.22) [10].

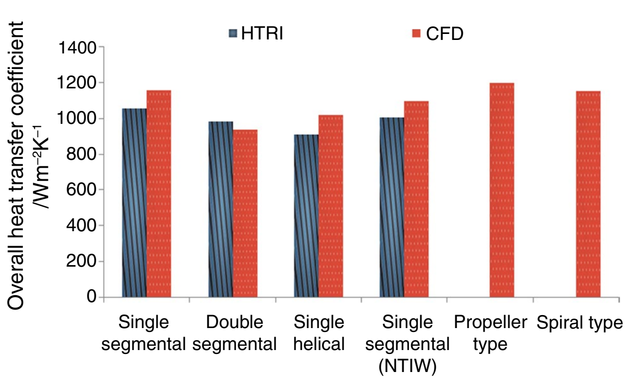


Fig. 4 Overall heat transfer coefficient of STHE (HTRI and CFD)

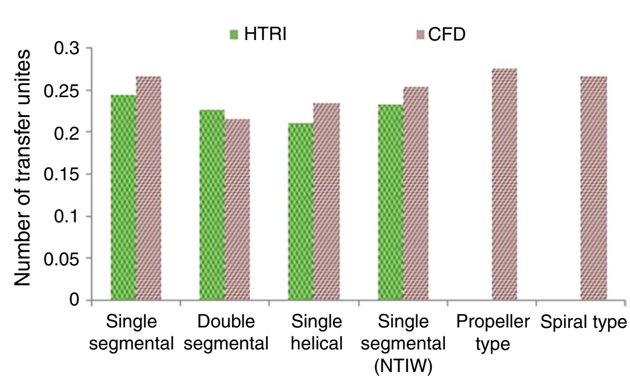


Fig. 5 Number of transfer units of STHE (HTRI and CFD)

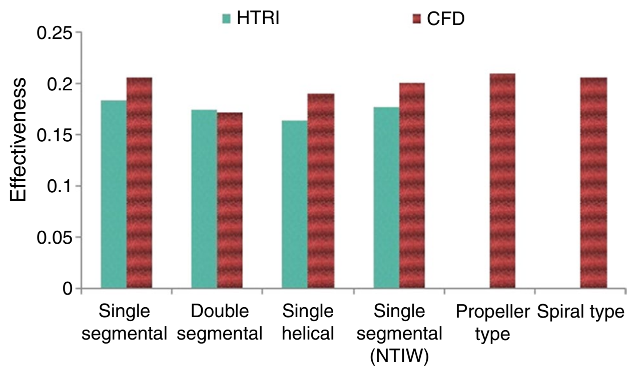


Fig. 6 Effectiveness of STHE (HTRI and CFD)

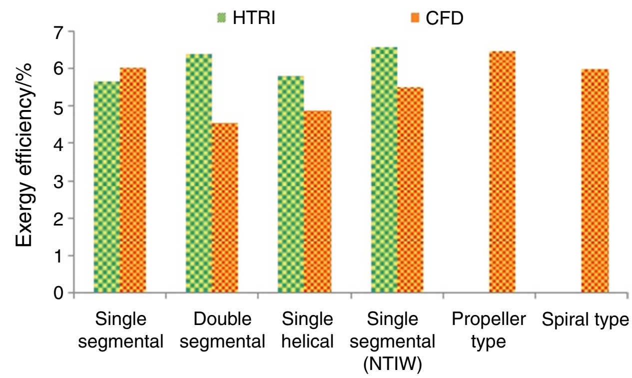


Fig. 7 Exergy efficiency of STHE (HTRI and CFD)

Effectiveness (η)

Figure 6 bar chart illustrates the effectiveness of STHE analyzed by HTRI and CFD under a constant flow rate of 60LPM with varied baffle configurations. Based on the HTRI analysis, the effectiveness of STHE under single, double, single helical, and NTIW is shown by 0.184, 0.174, 0.163, and 0.177. Among this configuration, the single helical baffle configuration is the least effective at 0.163, and the single segment baffle configuration notes the maximum due to improved velocity distribution and increased heat transfer area. In the same way, the CFD analytical reports the variations in effectiveness value due to the configuration of baffle design and single segmental, which shows the major variations compared to HTRI results. The single helical and double segmental baffles are exposed to better effectiveness values of 0.19 and 0.172, respectively. The highest effectiveness is noted by propeller type, and its value is 0.21.

Moreover, the nearest value of 0.17 is taken from both analyses, which showed that the least error between the HTRI and CFD, which is the optimum effective amount, could not affect the hydraulic flow rate and found good thermal properties [13, 14]. Here, The analysis of HTRI chooses single helical, and double segment is fixed based on HTRI and CFD analysis showed the better value with the least variations.

Exergy efficiency (η_{ex})

The exergy efficiency of STHE is calculated from the analytical value of HTRI and CFD, which is compared, and its values are graphically represented in Fig. 7. During the HTRI analysis of STHE, the exergy efficiency of baffle configuration is varied according to the single segment, double segment, single helical, and NTIW like 5.633%, 6.383%, 5.779, and 6.587%, respectively.

Moreover, the exergy efficiency of STHE during CFD analysis, the propeller-type NTIW, and the single helical baffle configuration offered good exergy efficiency, which is more than 4.8%. The reason for the improved exergy efficiency of STHE was the baffle configuration and constant flow rate of 60LPM. The optimum flow rate, fluid medium, and inlet temperature-based exergy efficiency were varied [10]. The exergy efficiency of single helical 15° is lower than the propeller type due to enriched turbulence mixing leading to frictional loss with the fluid flow. But the single helical 15° and double segmental baffle configuration offered better optimum logarithmic mean temperature difference (LMTD), reduced overall heat transfer coefficient (U), optimum number of transfer units (NTU), and effectiveness (η) reasons, the single helical 15° is recommended for STHE specific applications.

Based on the HTRI and CFD analysis results for STHE, the single helical 15° and double segmental baffle configuration offers optimum logarithmic mean temperature difference (LMTD), reduced overall heat transfer coefficient (U), optimum number of transfer units (NTU), effectiveness (η), and lower exergy efficiency (η_{ex}). The design features of a single helical 15° baffle configuration (geometric model is presented in Figs. 1 c and 2c) prevent the fouling action during the continuous sweeping, ensuring the heat transfer is uniform, enriching the turbulence mixing results improved thermal performance. The enriched turbulence mixing is evidenced in Fig. 10. Likewise, the design features of double segmentation promote the turbulence flow with improved fluid mixing, resulting in improved heat transfer rate and limiting the bypass fluid flow. So, the contact surface area is increased and attains maximum heat transfer compared to other methods. The dead zone of STHE is limited. The detailed CFD justification is addressed below.

Computational fluid dynamics (CFD)–shell side flow trajectories

Single segment baffle configuration of STHE

The Shell side flow trajectories for single segmental baffle-STHE are represented in Fig. 8. During the analysis, the 60LPM constant flow rate was fixed, and the CFD analysis shows the detailed simulation report of fluid velocity varied from 0 to 1 ms^{-1}. Initially, the velocity of a fluid is 0.778 ms^{-1}. After passing to a single segment baffle, the fluid velocity decreased to 0.111 ms^{-1}. However, the baffle configuration of a single segment reduces the velocity and increases the thermal performance. It is observed from Fig. 8 that the trajectories show the U and inverted U flow do contact the side wall of the shell, leading to decreased thermal convective quality [9].

Double segment baffle configuration of STHE

Figure 9 illustrates the CFD simulation plot for the double baffle configuration of STHE analyzed by 60LPM flow rate with the temperature of shell and tube at 30 °C and 80 °C. It shows the C and inverted C curves, improving the surface contact area. During this analysis, the fluid velocity is higher (1 ms^{-1}) and crossing the double segment shows the optimum velocity level of 0.222 ms^{-1}.

Compared to the segment baffle configuration, it shows the maximum contact area between the shell and tube, which results in enhanced heat exchange between the shell and tube and progressively increased efficiency [10].

Single helical baffle configuration of STHE

Figure 10 represents the CFD analytical simulation plot for a single helical baffle configuration of STHE under a 60LPM flow rate. Its trajectory profile shows the maximum contact area and maintains the optimum fluid velocity of 0.333 ms^{-1}. It shows efficient trajectories with high contact area between shell and tube, related to single and double segment baffle configuration. It results in a good overall heat transfer coefficient and increased exergy efficiency. Moreover, the helical baffle configuration has facilitated good thermo-hydraulic behavior compared to the single segment reported by Zhnegguo et al. [15].

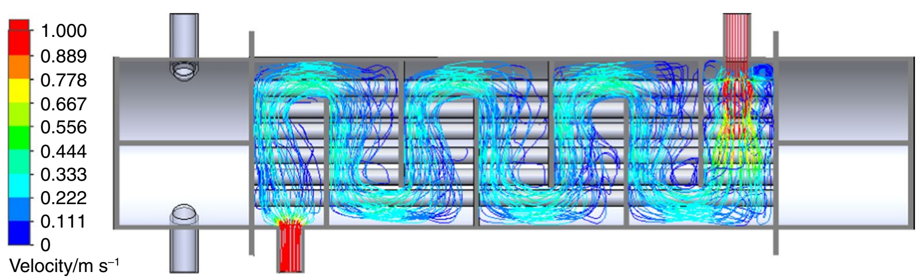


Fig. 8 Shell side flow trajectories for Single segmental baffle-STHE

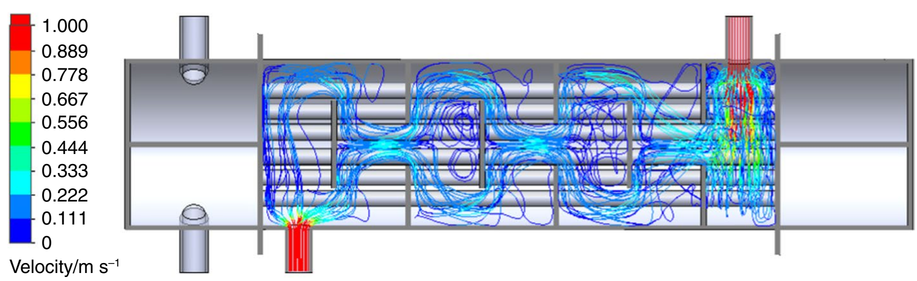


Fig. 9 Shell side flow trajectories for Double segmental baffle-STHE

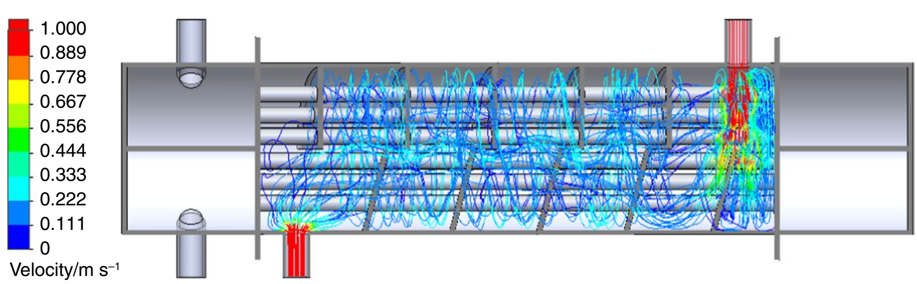


Fig. 10 Shell side flow trajectories for Single helical baffle-STHE

Single segmental (NTIW) baffle of STHE

The Shell side flow trajectories of single segmental (NTIW) baffle the ideal flow pattern in an STHE, shown in Fig. 11. The flow is fully developed without any dead spots or fouling in the shell side of the heat exchanger. It shows that the baffle spacing chosen for the study is proportional to the baffle spacing between baffles.

However, the NTIW baffle configuration shows a profile similar to that of the single baffle configuration, and the value of 0.111 ms-1 limits the flow velocity.

The propeller-type baffle of STHE

The flow pattern for propeller-type baffle configuration of STHE operated under 60LPM flow is analyzed via CFD simulation, and its trajectories are shown in Fig. 12. The trajectories show the velocity range between 0.111 to 0.333 ms-1 during the fluid flow. The propeller mode approach found significant contact between the shell and the tube, which increased thermal performance and exergy efficiency by 6.464%. However, the overall heat transfer coefficient is much higher than the nominal value of a single segment.

Spiral-type baffle of STHE

The shell side flow trajectories show that the flow in the shell side of the shell and tube heat exchanger is fully developed without any fouling, and its fluid velocity pattern shown in Fig. 13 indicates the spiral-type baffle configuration. Fouling or misdistribution can lead to inefficient heat transfer between the shell side and tube side medium [12].

Moreover, the trajectories show the spiral concave profile and lead to an increase in the thermo-hydraulic behavior compared to the single segment baffle configuration. The baffle configuration, flow rate, and design of the shell and tube determine the thermo-hydraulic performance of STHE [10].

According to the CFD analysis, the various baffle functioned STHE's flow trajectories are analyzed, and it is noted that the single segmental baffle shows a decreased velocity and less contact area. Implementing a double baffle configuration showed better fluid flow with improved

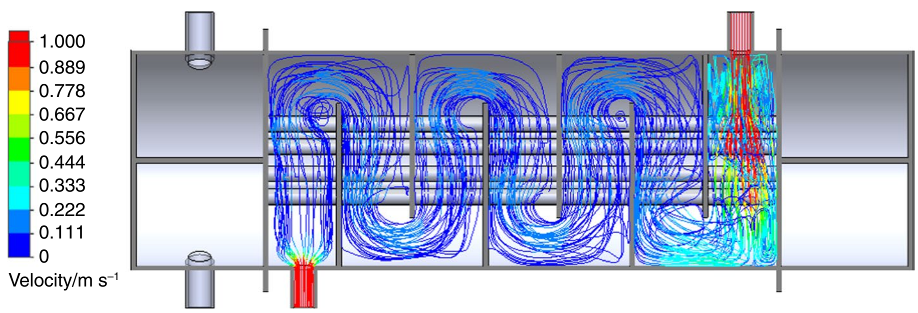


Fig. 11 Shell side flow trajectories for Single segmental (NTIW) baffle-STHE

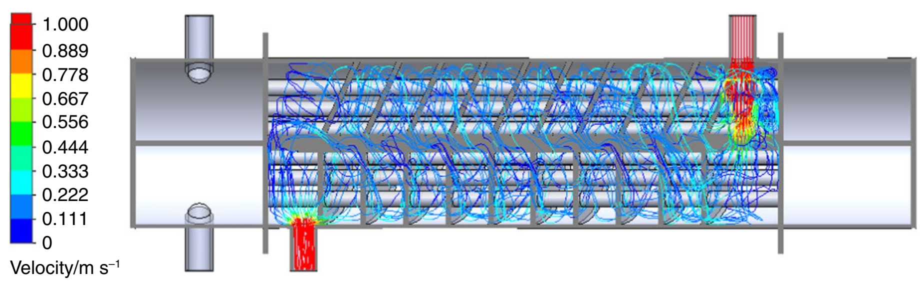


Fig. 12 Shell side flow trajectories for Propeller-type baffle-STHE

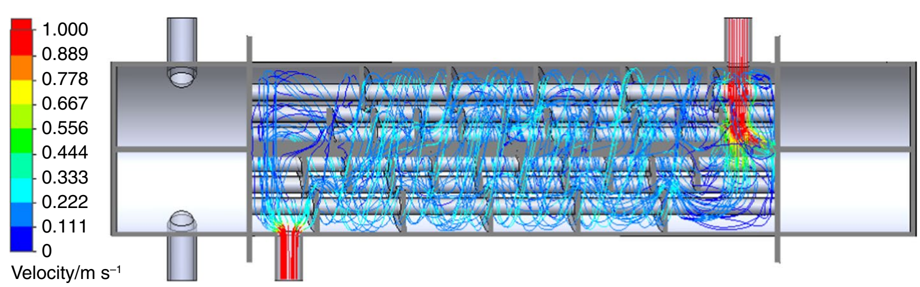


Fig. 13 Shell side flow trajectories for Spiral-type baffle-STHE

surface contact than single segmental. However, the configuration of single helical, propeller, and spiral-type baffles proved their significance with improved surface contact and high energy loss spotted in spiral and propeller baffle configuration due to the maximum pressure drop of 413.07 and 365.3mmwc. This is evidenced in Table 2.

Conclusions

The shell and tube heat exchanger (STHE) with different baffle configurations, (a) Single segmental, (b) Double segmental, (c) Single helical, (d) Single segmental (NTIW), (e) Propeller type, and (f) Spiral-type baffles are considered for investigation in this research study using HTRI and CFD. The thermo-hydraulic parameters of the STHE with different baffle configurations are articulated, and the conclusion is as follows.

- The analysis of HTRI and CFD showed the optimum LMTD value for single Helical 15° and double segmental Baffle configurations like 41.305 and 41.048 °C
- The overall heat transfer coefficient for single Helical 15° and double segmental Baffle configuration is lower than other baffle configurations analyzed by HTRI and CFD.
- Based on heat transfer performance, number of transfer units, and effectiveness, a single Helical 15° is optimum heat transfer performance related to all others. However, the exergy efficiency is low compared to the propeller-type baffle configuration (6.464).
- Similarly, the CFD shell side fluid velocity trajectories analysis proved the significance of single helical, propeller, and spiral-type baffle configurations having a good contact area between the shell and tube.

Authors contributions All authors contributed to the study's conception and design. Material preparation, data collection and analysis were performed by CD, NSS, KVR, and RV. The first draft of the manuscript was written by CD, and all authors provided language help, writing assistance and proofreading. All authors read and approved the final manuscript.

Funding The authors did not receive support from any organization for the submitted work. No funding was received to assist with the preparation of this manuscript. No funding was received for conducting this study. No funds, grants, or other support were received.

Data availability All the data required are available within the manuscript.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare relevant to this article's content. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Ethical approval This is an observational study. Performance Analysis of baffle configuration effect on thermo-hydraulic behavior of shell and tube heat exchanger: The Research Ethics Committee has confirmed that no ethical approval is required.

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