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Review on design optimization in shell and tube type heat exchanger

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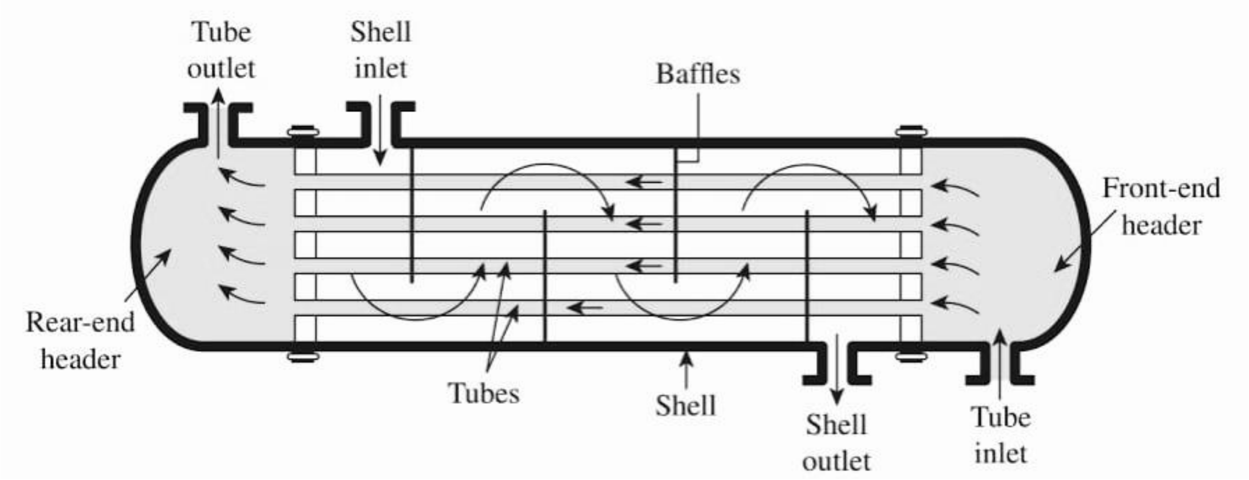
Abstract: This is a review paper based on design optimization of shell and tube type heat exchanger (STHE). It contains numbers of parameters which influence the increased heat transfer of STHE. For designing of STHE, TEMA standards are used to define the main configuration of exchangers and their classification for industry use. They are used along with the ASME code to design and fabricate exchangers, as well as customer specifications. We include the future works suggested to enhance the design to increase the effectiveness of STHE. Required results also included in our paper.The design optimization of STHE is done to achieve the desired heat transfer rate while considering various aspects. This optimization process typically involves minimizing factors like initial cost, operating cost, pressure drop, heat transfer area, weight, or material usage.

1.Introduction:

Shell and Tube heat exchangers are widely used in various industries and applications, including boilers, oil coolers, condensers, pre-heaters, and refrigeration and air conditioning systems .The design of a heat exchanger involves determining the minimum heat transfer area required for a given heat duty, which directly affects the overall cost of the exchanger .The design engineer needs an efficient strategy to search for the global minimum, considering various design variables such as outer diameter, pitch, length of the tubes, tube passes, baffle spacing, and baffle cut .The thermal analysis and design of shell-and-tube heat exchangers are essential topics for mechanical, thermal, and chemical engineering scholars in their curriculum and research activities[11].The paper focuses on the use of graphene nanofluids to enhance the thermal performance of a vertical shell and tube heat exchanger[1]. shell and helically coiled tube heat exchangers (SHCTHEXs) which are compact and have a larger heat transfer area compared to traditional models. The authors collected information on 21 different SHCTHEXs from a catalog for modeling purposes. Artificial neural network structures were created to predict heat transfer coefficient, pressure drop, Nusselt number, and performance evaluation criteria values. Inputs for the network structures included tubing and coil diameters, Reynolds and Dean numbers, curvature ratio, and mass flow rate[2]. The optimization of segmental baffle (STHE) by using combined baffle and ribbed tube configurations. The authors investigate the performance of triangular and circular ribbed tubes in STHE optimization. Considers the heat transfer coefficient, thermal performance, and pressure drop as major factors for evaluating the STHE. The complexity of baffles is found to enhance heat transfer but also results in higher pressure drop, requiring more pumping power and reducing system efficiency. The paper aims to minimize dead zones and pressure drop to improve heat transfer and overall system efficiency[3].Metal foam and fins are commonly used structures to enhance heat transfer in shell-and-tube heat storage units. The optimal structure for energy storage performance is still unclear, and a comparison between metal foam and fins is needed[4].The study aims to address the uncertainties in the inlet and outlet temperatures, pressure drop factor, friction factor, Nusselt number, heat transfer coefficient, and pressure drop in the shell .A multi-criteria decision-making method is applied to select the best solution among the alternatives that satisfy the problem's constraints [5].The rapid growth of the industrial world, especially in the tourism sector, has led to an increased need for energy, with hotels being one of the largest energy users, particularly in terms of electrical energy consumption .Energy efficiency efforts are crucial to mitigate the energy crisis and ensure the sustainability of the tourism industry .One approach to energy recovery in the hotel industry is utilizing wasted heat energy from air conditioning systems, which can be used as additional energy for heating water .The design of a heat exchanger plays a crucial role in this energy recovery process, and technical dimensions, flow patterns, material selection, and heat transfer criteria are key challenges in heat exchanger design[6] .The counterflow configuration is considered the most effective for analysis in STEs. The Tubular Exchanger Manufacturers Association (TEMA) sets the standard for heat exchanger construction. Computational methods, such as CFD simulations, are extensively used to reduce experimental cost and time in analyzing heat exchangers[7].The design of shell and tube heat exchangers involves two parts: the shell side and the tube side, with the shell side being more complex[8].The effectiveness of the design parameters and boundary conditions is evaluated through the CFD simulations. The theoretical analysis results are compared with the CFD predictions to validate the accuracy of the simulation approach[12].Tube layout is identified as a key parameter in the analysis of shell and tube heat exchangers[13].The design of

STHEs traditionally relies on users' experiences, leading to long computing time and suboptimal solutions .To address this issue, a systematic optimization methodology is required for efficient and accurate STHE design[17].The selection of materials and the role of baffles in improving heat transfer capabilities are important factors in the design of these heat exchangers .Copper, aluminum, and steel are considered as materials for the heat exchanger, and their performance in terms of heat transfer is analyzed .copper performs better than aluminum and steel, with minimum baffle spacing, in terms of heat transfer[18].Thermal energy systems (TES) can help mitigate the mismatch between energy supply and demand by shifting load between on-peak and off-peak hours. Phase change materials (PCM) are gaining attention for their ability to provide higher energy storage capacity and efficiency compared to traditional TES systems[19].High-temperature fin-and-tube heat exchangers are widely used in various industries due to their large heat transfer area and compact shape. However, ensuring uniform velocity distribution in all the tubes is crucial to prevent thermal stress and breakdown of the heat exchanger[20].



Key wards: STHE, effectiveness, baffles, tube layouts, type of flow

2. Literature review:

1. Mohammad Fares a, Mohammad AL-Mayyahi b , Mohammed AL-Saad c, discusses the use of graphene nanofluids in a vertical shell and tube heat exchanger to enhance its heat transfer performance. The graphene nanofluids were prepared using graphene flakes derived from sugar-based graphite foam. The graphene flakes were characterized using artificial neural networking electron microscopy, X-ray diffraction, atomic force microscopy, and Raman spectroscopy. The effects of nanofluid concentration, flow rate, and inlet temperature on heat transfer coefficient and thermal efficiencies were studied. The results showed that using 0.2% graphene/water nanofluids led to a maximum increase in the heat transfer coefficient of 29% and enhanced the mean thermal efficiency of the heat exchanger by 13.7%.The paper also mentions the use of the Maxwell model to estimate the thermal conductivity of graphene nanofluids.

2. Andaç Batur Çolak, Dogan Akgul, Hatice Mercan d, Ahmet Selim Dalkılıç c,Somchai Wongwises focuses on the estimation of heat transfer parameters of shell and helically coiled tube heat exchangers (SHCTHEXs) using machine learning techniques. The authors collected information on 21 different SHCTHEXs from a catalog for modeling purposes. Two artificial neural network structures were created to forecast the heat transfer coefficient, pressure drop, Nusselt number, and performance evaluation criteria values as outputs. Inputs included tubing and coil diameters, Reynolds and Dean numbers, curvature ratio, and mass flow rate. The training algorithm used in the multi-layer perceptron network models was the Levenberg-Marquardt procedure. The results showed that the created artificial neural network structures accurately estimated the outputs, with a coefficient of determination higher than 0.99 and a mean deviation less than 0.01%.

3. Ali Akbar Abbasian Arania, Reza Moradia focuses on the optimization of segmental baffle shell and tube heat exchangers (STHE) by using combined baffle and ribbed tube configurations. The authors investigate the

performance of triangular and circular ribbed tubes in STHE optimization. The study considers the heat transfer coefficient, thermal performance, and pressure drop as major factors for evaluating the STHE. The complexity of baffles is found to enhance heat transfer but also results in higher pressure drop, requiring more pumping power and reducing system efficiency. The paper aims to minimize dead zones and pressure drop to improve heat transfer and overall system efficiency.

4. Shuai Zhanga, Ziyuan Li b, Yuying Yana, Mark Alstona, Limei TianbThe study compares the heat transfer enhancement performances of metal foam and fins in shell-and-tube heat storage units .Three fin structures (four fins, two vertical fins, and two horizontal fins) are considered, and it is found that increasing the number of fins helps accelerate the melting process .However, the unit enhanced by metal foam has the highest melting rate, and metal foam is shown to be the best thermal enhancer, with an energy storage rate up to 10 times higher than that of the unit enhanced by fins.The study was supported by the National Key RD Program of China, H2020-MSCA-RISE-778104-ThermaSMART, and the China Scholarship Council.

5. Machado-Coelhoc, Gustavo Luís Soares b,∗They investigate multi-criteria decision-making (MCDM) for shell-and-tube heat exchangers (STHX) under uncertainty. While existing research utilizes MCDM for STHX design, incorporating uncertainty adds complexity. addresses this by modeling uncertainties within the mathematical model and utilizing MOPSO, a multi-objective optimization algorithm, to find the best heat transfer area and pumping power balance. It then incorporates a method for decision-making under uncertainty. Overall, the paper contributes to the field by applying MCDM with uncertainty considerations to STHX design optimization.

6. Nanang Apriandi,Yusuf Dewantoro Herlambang,,Abdul Syukur Alfauzi,,Shun ,Ching Lee of the paper "Shell and Tube Heat Exchanger Design: Utilization of Wasted Energy in Air Conditioning Systems "The paper focuses on designing a shell and tube heat exchanger for recovering wasted heat from air conditioning systems in the hospitality industry .The Tubular Exchanger Manufacturers Association (TEMA) standard is used as a reference for the design of heat exchangers .Mathematical calculations based on the technical properties of the working fluid are carried out using Microsoft Excel to obtain values for other parameters in the design .The designed heat exchanger meets the standards in terms of device effectiveness, with an effectiveness value of more than 90% and an impurity factor of 0.014.The paper highlights the importance of energy efficiency in the hotel industry and the potential of utilizing wasted heat energy from air conditioning systems for heating water .The design parameters of the heat exchanger, such as heat transfer rate, overall heat transfer coefficient, number of tubes, and fouling factor, are calculated and meet the specific requirements .The proposed heat exchanger design has a high effectiveness value of 90, which is in line with a previous study .

7. Shuvam Mohanty and Rajesh Arora compares different baffle cuts of a shell and tube heat exchanger (STE) and validates the findings by equating them with existing literature. The counterflow configuration is considered the most effective for analysis in STEs, as suggested by Mohanty et al. The paper aims to generalize between plate baffle heat exchangers and rod baffle heat exchangers using Fluent 6.3 and Gambit 2.3.Pal et al. conducted a CFD simulation study on a shell and tube heat exchanger using ANSYS Fluent, which provided information on flow distribution, heat transfer coefficient, and pressure drop. The paper also refers to another CFD simulation study that analyzed different design parameters such as the number of baffles, baffle cuts, and baffle spacing, and examined output parameters like pressure drop, heat transfer coefficient, and total heat transfer.

8. Risti Ragadhita ,Asep Bayu Dani Nandiyant Shell and tube exchangers are the most commonly used heat exchange equipment in industries due to their larger heat transfer surface per unit volume, good mechanical arrangement, and availability in various construction materials .The fixed tube sheet design is the most basic and least expensive type of shell and tube exchanger .The recommended tube pitch is 1.25 times the tube outside diameter, and the minimum clearance between the tubes is 0.25 in. (6.4 mm) .The heat exchanger design is based on the TEMA (Tubular Exchanger Manufactures Association) standards, and calculations are carried out to analyze heat transfer correction coefficient values, pressure drops, and design effectiveness .Heat exchangers are critical in chemical industries for efficient heat transfer, and the selection of a heat exchanger depends on various factors such as application, available resources, cost, etc.

9. Aulia Rahman,Winarto,Eko Siswanto The paper investigates the optimal baffle design for shell and tube heat exchangers (STHeX) using numerical methods and three-dimensional modeling. It compares the heat transfer coefficient and pressure drop values of STHeX with Inclined-Segmental Baffles to conventional STHeX. The results show that while the heat transfer coefficient is lower in the new design, the pressure drop value is significantly reduced. The overall heat transfer coefficient per pressure loss ($U/\Delta P$) is found to be significantly higher in STHeX with Inclined-Segmental baffles compared to conventional STHeX, indicating an increase in effectiveness. The simulation in the paper is carried out using ANSYS Workbench software, focusing on the relationship between fluid flow, pressure drop, and heat gain coefficient. Water is used as the fluid on both the shell and tube sides. The simulation results are compared with theoretical calculations, showing a 5.8% average deviation. The author also mentions the need to adjust the grid for different mass flow rates and the cost implications of detailed simulations. The research aims to develop an optimal design in terms of total heat coefficient and pressure drop, and further testing is planned for the torsional flow type of STHeX with varying baffles.

10. PETROKIMIA GRESIK,Erwan Adi Saputro,Delfian Lutfiananda, Annisa Kurnia Pratiwi,Sutra Amelia Nugroho The paper focuses on assessing the efficiency of a shell and tube cooler-type heat exchanger in phosphoric acid production at PT. Petrokimia Gresik .It discusses the objective of evaluating the performance of the heat exchanger, determining compliance with design specifications, and identifying the need for cleaning and maintenance .The analysis of the heat exchanger's performance is crucial to prevent any impact on the produced product and ensure optimal heat transfer. The paper highlights the decrease in efficiency of the E-2502 heat exchanger due to scaling caused by the cooled P2O5 Acid solution during the heat transfer process .It emphasizes the importance of initiating a cleaning process for the heat exchanger to optimize the heat transfer mechanism and improve efficiency .The authors provide their findings and recommendations based on the case study at PT. Petrokimia Gresik .The paper is authored by Erwan Saputro, Delfian Lutfiananda, Kurnia Annisa, Pratiwi, Amelia Sutra, Nugroho, and Erwan Adi Saputro.

11. Arjun Kumar Prasad, Mr. Kaushik Anand Shell and Tube heat exchangers are widely used in boilers, oil coolers, condensers, pre-heaters, and refrigeration and air conditioning systems .The design of a heat exchanger involves determining the minimum heat transfer area required for a given heat duty, considering various design variables such as outer diameter, pitch, length of the tubes, tube passes, baffle spacing, and baffle cut .The application of Differential Evolution (DE) has been proposed for the optimal design of shell-and-tube heat exchangers, aiming to achieve the minimum heat transfer area and overall cost .The thermal analysis and design of shell-and-tube heat exchangers are essential topics for mechanical, thermal, and chemical engineering scholars in their curriculum and research activities. The heat exchanger must meet process requirements, be maintainable, and cost-effective, while considering factors such as pressure drops, corrosion, erosion, and vibration .The number of rows crossed in one crossflow section and the Reynolds number based on tube outside diameter and velocity are important parameters in heat exchanger design .Shell and Tube heat exchangers have advantages such as compactness, high pressure handling capability, lower cost, and lower pressure drop across the tubes .

12. Tesfaye Barza1, Mesay Dejene2 Shell and Tube Heat Exchangers (STHE) are commonly used in various industries for heat transfer applications .The use of baffles in heat exchangers has been studied to enhance the flow rate of highly viscous fluids .Computational fluid dynamics (CFD) analysis has been widely used to predict the performance of heat exchangers and optimize their design .ANSYS Fluent and ANSYS CFX are industry-leading CFD software that provides accurate and robust results for fluid and multiphysics applications .The Bell Delaware method is a commonly used approach for rating analysis in heat exchangers, providing accurate predictions of heat transfer coefficients and pressure drops .CFD solvers, such as ANSYS Fluent and ANSYS CFX, extend the limits of what is practical in improving the efficiency and performance of heat exchangers.

13. Sachin Kallannavar ⇑, Suresh Mashyal, Manik Rajangale discusses the importance of optimizing the design of shell and tube heat exchangers to achieve efficient heat transfer .It emphasizes the need for a balanced approach between thermal design and pressure drop in the design of these heat exchangers .The analysis of shell and tube heat exchangers is divided into shell side analysis and tube side analysis, with tube layout being a

key parameter. Experimental analysis is conducted to understand the effect of different tube layouts on the performance of heat exchangers .The tests are conducted for both parallel and counter flow conditions, and the heat transfer rate is calculated for different tube layouts .The obtained results are tabulated and plotted for better understanding .

14. Abdullah Khan 1, Imran Shah 2,* , Waheed Gul 1, Tariq Amin Khan 2 , Yasir Ali 2 and Syed Athar Masood CFD analysis is commonly used to study the characteristics of heat exchangers, allowing for the observation of flow characteristics at inaccessible locations .Previous research has focused on analyzing the flow and heat transfer characteristics of shell and tube heat exchangers using different techniques and geometries .Gurbir Singh et al. conducted CFD analysis of a single shell and tube-type heat exchanger and compared the results with experimental data .Chuncula Babu et al. studied passive techniques that can be applied in the tube of a heat exchanger .Ram Kishan et al. numerically investigated different flow patterns in the tubes of a shell and tube heat exchanger .Sharma et al. examined flow patterns, pressure drop, and heat transfer coefficient in staggered and inline shell-tube heat exchangers .Kumar et al. studied the heat and flow characteristics of double helically coiled tube heat exchangers .However, there is a lack of research on investigating tubes in a turbulent flow regime and optimizing tube geometry for improved heat exchanger efficiency. The present study aims to address this gap by analyzing the performance of shell and tube heat exchangers with round and hexagonal tubes through CFD simulations and experimental analysis.

15. Babak Masoumpour, Mohammad Ataeizadeh, Hassan Hajabdollahi, Mohammad Shafiey Dehaj investigates the effect of mass flow rate recovery (MFRR) on the thermo-economic optimization of a shell and tube heat exchanger (STHE) .The authors consider effectiveness and total annual cost (TAC) as objective functions and analyze nine design parameters related to the STHE parameters, as well as reflux ratio and recovery tube diameter .The results show a significant improvement in both TAC and effectiveness when considering MFRR compared to a conventional heat exchanger without stream recovery .For example, a 5.8% improvement in effectiveness is observed with MFRR compared to the conventional heat exchanger, and the TAC decreases by 24% with MFRR for a fixed effectiveness .The authors also study the effect of MFRR at different mass flow rates of the tube side and find that the best results are obtained at a mass flow rate of 5 kg/s .Additionally, the paper discusses the effect of reflux ratio on the optimum objective functions.

16. Umer Zahid, Ahmad Hanan, Tariq Feroze & Sohaib Khan discusses the performance analysis and design optimization of a shell and tube heat exchanger using computational fluid dynamics (CFD) .It compares the performance of different models of the heat exchanger by varying parameters such as inlet velocity, thermal conductivity of the heat exchanger material, baffle spacing, and tube bundle arrangement .The study shows that a decrease in inlet velocity, an increase in thermal conductivity, a reduction in baffle spacing, and the use of a triangular tube bundle arrangement have a significant influence on reducing the condensate temperature .The effects of these parameters on temperature distribution and heat transfer rate are also discussed .The literature review conducted in the paper highlights the research efforts in achieving design and performance optimization of heat exchangers, considering factors such as design configuration and operating parameters.

17. Zekun, Yang, Yingjie, MaNan, Zhang, Robin, Smith presents a generalized disjunctive programming (GDP) model for the optimization of shell and tube heat exchanger (STHE) design, aiming to improve the performance of STHEs .The model is formulated as a mixed integer non-linear programming (MINLP) problem, considering 12 technology combinations for tube-side and shell-side techniques .The model is applied to minimize the total capital cost of the heat exchanger .The results show that the developed method provides a better design solution compared to conventional STHE design procedures .The constraints for the STHE design include geometric constraints and process constraints .The geometric constraints involve the selection of tube sizes, which are determined based on popular sizes .The process constraints consider factors such as the application of helical baffles to reduce shell-side pressure drop.

18. Erica Jacqueline Fernandes and Sachidananda Hassan Krishanmurthy the paper discusses the design and analysis of shell and tube heat exchangers, focusing on the selection of materials and the role of baffles in improving heat transfer capabilities. The authors used PTC Creo parametric for design and modeling, and

ANSYS Fluent for CFD analysis. They considered copper, aluminum, and steel as materials for the heat exchanger. The study found that copper performed better than aluminum and steel, with minimum baffle spacing, in terms of heat transfer. However, due to its high cost, copper may not be suitable for all parts of the heat exchanger but can be used for baffles. Aluminum, being lightweight, can be an alternative option. Material selection is crucial for long-term heat transfer efficiency, as poor choices can lead to leaks, fluid mixing, and pressure loss. The research emphasizes the significance of baffle spacing in determining the heat transfer rate in shell and tube heat exchangers.

19. Haobin Liang, Jianlei Niu, Yixiang Gan discusses the use of phase change materials (PCM) in thermal energy storage systems (TES) to address the increasing demand for renewable energy and stable system operation. It explores the design factors of a shell-and-tube latent heat thermal energy storage (LHTES) system using PCM, including the tube length-diameter ratio, PCM volume ratio, effective thermal conductivities, and flow conditions of the heat transfer fluid (HTF).The study aims to optimize the PCM volume ratio by maximizing the effective energy storage ratio (Est) through over 500 sets of parametric studies. The paper also discusses the challenges posed by the low thermal conductivity of PCM and explores methods to enhance heat transfer, such as combining high thermal conductivity materials with PCM or encapsulating PCM. The properties of the PCM used for the parametric studies are listed in Table 1, and the effective specific heat capacity of PCM varying with temperature is shown in Figure.

20. Paweł Ocłon , Stanisław Łopata , Tomasz Stelmach , Mingjie Li , Jian-Fei Zhang Hocine Mzad , Wen-Quan Tao High-temperature fin-and-tube heat exchangers are widely used in industries such as petrochemical, automotive, and energy sectors .The major advantage of these heat exchangers is their large heat transfer area within a compact shape .Ensuring uniform velocity distribution in all the tubes is crucial to prevent thermal stress and breakdown of the heat exchanger .The small volume of collectors in the heat exchangers can lead to improper flow conditions inside the tubes, causing unsuitable distribution of thermal and mechanical loads .The paper focuses on the design optimization of a high-temperature fin-and-tube heat exchanger manifold to improve flow distribution and reduce thermal stress .Particle Swarm Optimization and Continuous Genetic Algorithms are used for the design optimization .Computational fluid dynamics (CFD) simulations and structural analysis using ANSYS are performed to evaluate flow distribution and thermal stresses .The new design of the heat exchanger manifold significantly reduces tube wall temperature and compressible stresses compared to traditional designs.

3. Components of STHE:

Shell: The shell is the outer cylindrical component of the heat exchanger that contains the tube bundle and the process fluid. It provides structural support and houses the tubes.

Tubes: Tubes are the main heat transfer surface in a shell and tube heat exchanger. They are typically made of copper or steel alloys and provide a pathway for the process fluids to flow. The heat is transferred between the fluids through the tube walls.

Tube Sheets: Tube sheets are metal plates that are used to support and seal the ends of the tubes. They are typically located at both ends of the shell and provide a secure attachment for the tubes.

Baffles: Baffles are plates or rods that are placed inside the shell to direct the flow of the process fluids. They enhance heat transfer by creating turbulence and preventing fluid bypass. They also provide support to the tubes and prevent sagging.

Shell Side and Tube Side Fluid Inlets and Outlets: These are the points where the process fluids enter and exit the heat exchanger. The shell side fluid flows outside the tubes, while the tube side fluid flows inside the tubes.

Tube Support Plates: Tube support plates are used to hold the tubes in place and prevent them from sagging or vibrating. They are typically located at regular intervals along the length of the tubes.

Shell Side and Tube Side Passes: Shell and tube heat exchangers can have multiple passes on both the shell side and the tube side. Passes refer to the number of times the fluid flows through the exchanger before exiting. Multiple passes increase the heat transfer efficiency.

Shell Side and Tube Side Flow Directors: Flow directors, such as baffles or flow plates, are used to control the flow direction and velocity of the process fluids. They help optimize heat transfer and prevent fluid bypass.

Shell Side and Tube Side Fluids: Shell and tube heat exchangers have two separate fluid streams - the shell side fluid and the tube side fluid. These fluids can be of different types, such as liquids or gasses, and they exchange heat through the tube walls.

Support Structure: The heat exchanger is supported by a structure that holds it in place and provides stability. This structure can be made of steel or other suitable materials.[11]

4. Parameters :

Heat transfer coefficient: It uses machine learning models to estimate the heat transfer coefficient of shell and helically coiled tube heat exchangers (SHCTHEXs) .

Pressure drop: The machine learning models are also used to estimate the pressure drop in SHCTHEXs .

Nusselt number: The Nusselt number, which represents the convective heat transfer coefficient, is estimated using the machine learning models.

Performance evaluation criteria values: The machine learning models are used to estimate various performance evaluation criteria values of SHCTHEXs, which can provide insights into the efficiency and effectiveness of the heat exchangers .These parameters are important in the design and optimization of heat exchangers, as they help in understanding the heat transfer characteristics and performance of the system. By accurately estimating these parameters using machine learning, engineers and researchers can make informed decisions and improve the efficiency of SHCTHEXs[2].The heat transfer coefficient and heat transfer with mass flow rate were studied for five types of shell and tube heat exchangers (STHE) within the range of mass flow rates between 0.5 and 2.0 kg/s. Under the maximum mass flow rate of 2 kg/s, the average value of shell-side heat transfer coefficient for the DB-TR (disk baffle triangular rib) and CSDB-TR(Combined Segmental-Disk Baffle triangular rib) configurations was found to be 26.6% and 31.9% higher than the DB-CR (disk baffle circular rib) and CSDB-CR (Combined Segmental-Disk Baffle circular rib) configurations, respectively .At the referred mass flow rate of 2 kg/s, the average value of shell-side heat transfer for the DB-TR and CSDB-TR configurations was 24% and 19.5% higher than the DB-CR and CSDB-CR configurations, respectively. Heat transfer coefficient, heat transfer, and pressure drop: These parameters all increase with increasing mass flow rate. This is likely because higher flow rates lead to greater fluid movement and interaction with the heat transfer surfaces, but also result in more friction and resistance to flow. Performance evaluation factor (Q/Δp) and performance evaluation criteria (PEC): Both decrease with increasing mass flow rate.[3].

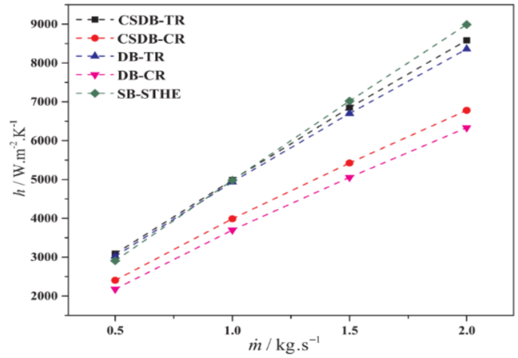


Fig. 7. Heat transfer coefficient vs mass flow rate for five studied types of baffles and tubes combination, CSDB-TR, CSDB-CR, DB-TR, DB-CR and SB-STHE.

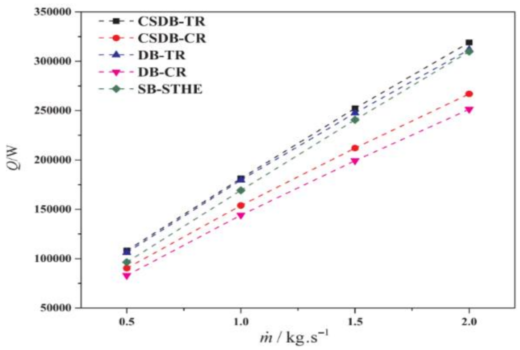


Fig. 8. Heat transfer vs mass flow rate for five studied types of baffles and tubes combination, CSDB-TR, CSDB-CR, DB-TR, DB-CR and SB-STHE.

Two methods for enhancing heat transfer were investigated: metal foam and fins.

Metal Foam: This is a porous metal structure that increases the surface area for heat exchange between the PCM and the working fluid within the storage unit . While metal foam offers superior performance, it might be more complex to integrate into existing thermal storage systems due to its structure. Additionally, manufacturing intricate metal foam shapes can be more challenging and expensive.

Fins: These are thin, projected structures that also increase the surface area for heat transfer. Three different fin configurations were examined. Although fins provide less improvement in heat transfer compared to metal foam, they are likely easier to install and integrate into existing systems. Fins can also be readily manufactured in various shapes and sizes to fit specific needs[4].Mass flow rate: Increasing the mass flow rate of either hot or cold fluid can enhance heat transfer, but it also leads to a higher pressure drop across the exchanger. This requires a balance between maximizing heat transfer and minimize pumping costs.

Temperature difference: A larger temperature difference between the hot and cold fluids at the inlet will result in a greater potential for heat transfer. However, this is often dictated by the specific application of the heat exchanger.

Fluid properties: The thermal conductivity, viscosity, and specific heat capacity of the fluids all influence the rate of heat transfer. Choosing fluids with high thermal conductivity and specific heat capacity can benefit heat transfer. Overall heat transfer coefficient (U): This is a combined parameter that reflects the effectiveness of all the factors transferring heat across the exchanger. A higher U value indicates better heat transfer performance.

Pressure drop: increasing the flow rates or using complex flow paths can lead to a higher pressure drop across the exchanger. This requires more pumping power, which can be an operational cost. Optimizing the design for a balance between heat transfer and pressure drop is crucial[5].

5. Type of flow:

Laminar Flow: Laminar flow refers to a smooth and orderly flow pattern where fluid particles move in parallel layers with minimal mixing or turbulence. It is characterized by low Reynolds numbers and is generally associated with higher effective energy storage ratios in latent heat thermal energy storage (LHTES) systems.

Turbulent Flow: Turbulent flow is characterized by chaotic and irregular fluid motion with high Reynolds numbers. In turbulent flow, fluid particles mix vigorously, resulting in enhanced heat transfer. However, fully turbulent flows in LHTES systems tend to have lower effective energy storage ratios compared to laminar flows.

Transition Region: The transition region refers to the range of Reynolds numbers where the flow behavior transitions from laminar to turbulent. Further experimental studies in the low-Re turbulence transition region would be valuable for understanding the performance of LHTES systems. Laminar flow is favorable for heat exchangers due to its smooth and orderly flow pattern, allowing for efficient heat transfer. Laminar flow minimizes mixing and turbulence, resulting in reduced pressure drop and energy consumption. Laminar flow provides a higher effective energy storage ratio in latent heat thermal energy storage (LHTES) systems compared to fully turbulent flow. Laminar flow allows for better control and predictability of heat transfer performance in heat exchangers. Laminar flow is suitable for applications where precise temperature control and uniform heat distribution are required. Overall, laminar flow is favorable for heat exchangers due to its efficient heat transfer characteristics, reduced pressure drop, and better control over heat transfer performance. It is particularly beneficial in LHTES systems, where it provides higher energy storage ratios[19].

6. Tube layouts:

Tube arrangements in STHE can be organized in equilateral triangular, square, or rotating square patterns, with triangular and rotated square patterns providing higher heat transfer rates but also higher pressure drops. Square arrangements are used for heavily fouling fluids that require mechanical cleaning of the tube exteriors. The recommended tube pitch is 1.25 times the tube outside diameter, and a minimum clearance of 0.25 in. (6.4 mm) is recommended between tubes in a square pattern. Tube-side passes are used to increase the length of the flow channel, with the number of passes determined by the required tube-side design velocity. Exchangers can have one to sixteen tube passes, organized using partition plates. Shell diameters are covered by British standard BS 3274 and TEMA standards, with shells up to 24 in. (610 mm) typically made of tubing and larger shells rolled from plates. The tube-sheet layout is determined by the number of tubes and tube passes, with constants provided for triangular and square tube-sheet layouts[8].with an increase in mass flow rate, there was a decrease in heat transfer.

The tests were conducted for both parallel and counter flow conditions, and it was found that heat transfer was maximum for all tube layouts in the counter flow configuration.

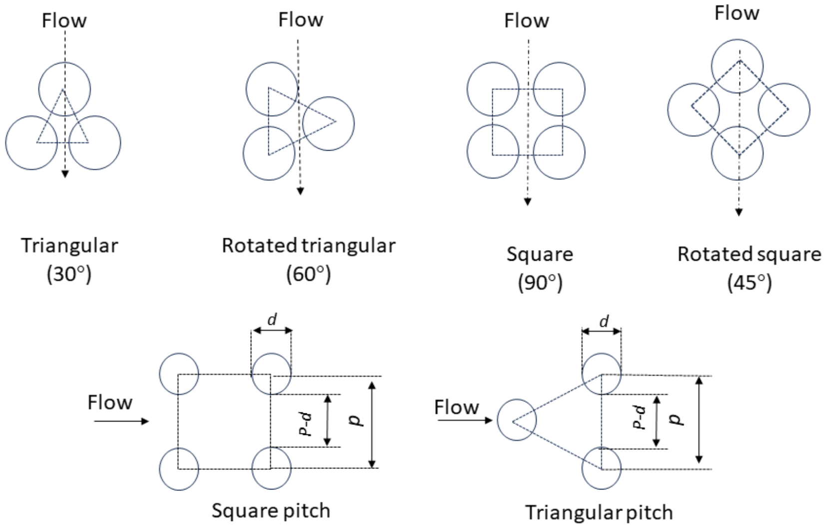
Among the four different tube layouts (30°, 45°, 60°, and 90°), it was observed that the 30° tube layout had better heat transfer compared to the other layouts. Experimental analysis showed that the heat transfer rate decreased with an increase in mass flow rate. Heat transfer was found to be maximum in the counter flow configuration for all tube layouts. Among the four different tube layouts (30°, 45°, 60°, and 90°), the 30° tube layout exhibited better heat transfer performance.

The overall heat transfer coefficient was selected according to TEMA standards for water to water heat exchangers. Triangular layout: This is the most common tube layout and is considered to be the most efficient for heat transfer . In a triangular layout, the tubes are arranged in a triangular pattern, with each tube surrounded by six other tubes. This close packing of tubes allows for a large heat transfer surface area, which promotes efficient heat transfer.

Square layout: In a square layout, the tubes are arranged in a square pattern, with each tube surrounded by four other tubes. This layout is less efficient for heat transfer than the triangular layout, but it can be easier to clean and is less susceptible to fouling.

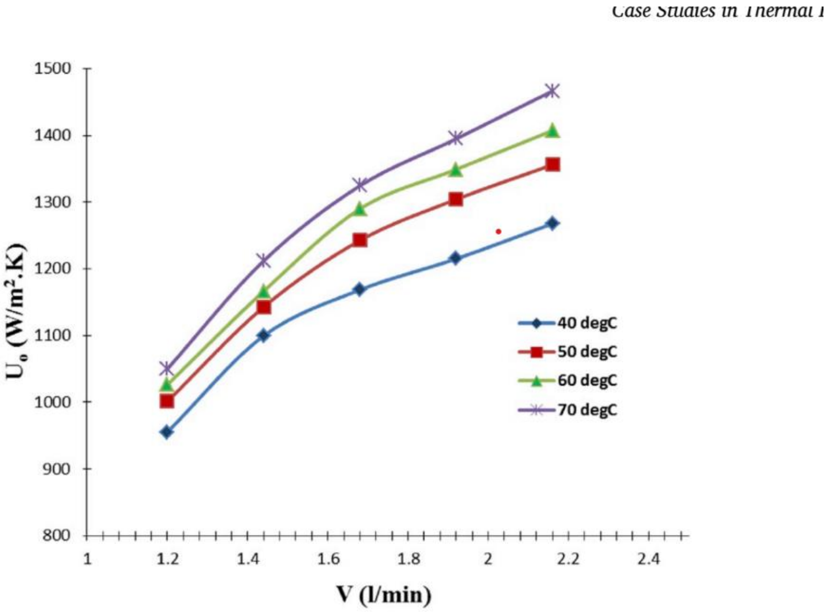
Rotated triangular layout: This layout is a variation of the triangular layout, in which the tubes are rotated by 30 degrees. This can improve heat transfer performance compared to the standard triangular layout, but it can also increase pressure drop.

Rotated square layout: This layout is a variation of the square layout, in which the tubes are rotated by 45 degrees. This layout can offer a balance between heat transfer performance and pressure drop .The selection of the best tube layout for a particular application will depend on a variety of factors, including the desired heat transfer rate, pressure drop limitations, cleaning requirements, and fouling potential[13].The introduction of hexagonal structure tubes in shell and tube heat exchangers resulted in an increased rate of heat transfer due to better flow disruption compared to round tubes[14].



7. Mass flow rate:

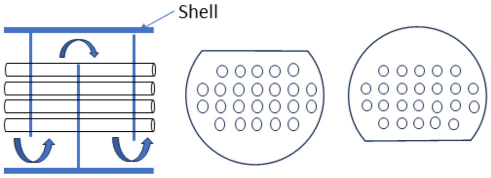
the hot side flow rate increases, the convective heat transfer coefficient also increases. At higher tube side flow rates, the influence of the hot fluid inlet temperature on the heat transfer coefficient is higher. The highest value of the convective heat transfer coefficient (Uo) was 1466 W/m^2×K at a flow rate of 2.16 l/min and an inlet temperature of 70°C.This represents an increase of 15.6% compared to its value at 40 °C[1].



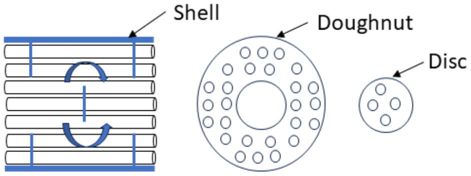
Higher flow rates lead to greater fluid movement and interaction with the heat transfer surfaces, but also result in more friction and resistance to flow. Performance evaluation factor (Q/Δp) and performance evaluation criteria (PEC): Both decrease with increasing mass flow rate. These metrics consider the trade-off between heat transfer (Q) and the pumping power required to overcome pressure drop (Δp). As the pressure drop increases disproportionately with flow rate, the overall performance (Q/Δp and PEC) suffers[3].mass flow rate recovery in the design and optimization of shell and tube heat exchangers, leading to improved efficiency and cost-effectiveness[15].

8. Types of baffles :

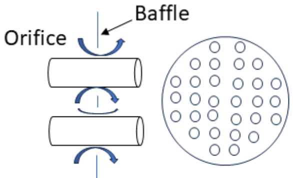
Combined Segmental-Disk Baffle (CSDB) has a greater impact on heat transfer than adding ribs, and triangular ribs are more effective than circular ribs in enhancing heat transfer. The heat transfer coefficient is a measure of how efficiently heat is transferred from the tube to the fluid. Based on the study, CSDB-STHE has the highest heat transfer coefficient, followed by DB-TR (triangular rib), CSDB-CR (circular rib), and finally DB-STHE (smooth tube).Segmental Baffle STHE (SB-STHE) experiences the highest pressure drop due to the sudden changes in flow direction and presence of dead zones[3].Baffles in a heat exchanger can alter the flow patterns and turbulence, impacting the fluid flow. The arrangement and design of baffles can change the direction and velocity of the fluid flow. Baffles create gaps and obstructions in the flow path, leading to non-uniform flow and variations in flow velocity. The presence of baffles can cause blockage of fluid flow in certain sections, resulting in lower flow velocity in those areas. Different baffle configurations, such as inclined-segmental baffles, can affect the flow characteristics and distribution of fluid flow. The impact of baffles on fluid flow can be studied using computational fluid dynamics (CFD) simulations, which provide insights into the flow behavior and velocity distribution[9].Reducing the space between baffles and using more baffles significantly improves heat transfer. This is because it forces the hot fluid to take a more winding path, mixing it up more and increasing contact with the cooler fluid. Imagine a complex maze; it takes longer to get through but allows for more interaction with the surroundings. The material of the baffles and tubes plays a role. Materials with higher thermal conductivity, like copper, transfers heat more efficiently than those with lower conductivity, like stainless steel [16].The Tubular Exchanger Manufacturers Association (TEMA) publishes standards that provide guidelines for baffle design and placement in shell and tube heat exchangers[17].Baffles are plates or rods placed inside the shell of a shell and tube heat exchanger to direct the flow of process fluids. Baffles create turbulence in the shell side fluid, enhancing heat transfer by promoting better mixing and increasing the contact between the fluid and the tube surface. They prevent fluid bypass, ensuring that the shell side fluid flows across the entire tube bundle, maximizing heat transfer efficiency. Baffles also provide support to the tubes, preventing sagging or vibration during operation[11].



Cut-Segmental baffle



Disc and Doughnut baffle



Orifice baffle

9. Effectiveness and efficiency of STHE:

The results indicate that using these nanofluids can improve the thermal efficiency of both the hot (tube side) and cold (shell side) fluids. In this experiment, a 0.2 wt% concentration of graphene nanofluid led to a 24.4% and 7.3% increase in thermal efficiency for the hot and cold sides, respectively, but only applicable for vertical types of heat exchanger[1].Heat transfer coefficient: The paper uses machine learning models to estimate the heat transfer coefficient of shell and helically coiled tube heat exchangers (SHCTHEXs) .Pressure drop: The machine learning models are also used to estimate the pressure drop in SHCTHEXs .Nusselt number: The Nusselt number, which represents the convective heat transfer coefficient, is estimated using the machine learning models .Performance evaluation criteria values: The machine learning models are used to estimate various performance evaluation criteria values of SHCTHEXs, which can provide insights into the efficiency and effectiveness of the heat exchangers[2].Using materials with high thermal conductivity for the heat transfer surfaces will improve heat transfer between the fluids. Common choices include copper, aluminum, and stainless steel[5]. Effectiveness in heat exchangers refers to the ability of the heat exchanger to transfer heat efficiently between the hot and cold fluids. It is a measure of how well the heat exchanger performs in terms of heat transfer efficiency. The effectiveness of a heat exchanger depends on the temperature difference between the inlet and outlet of the fluids. A higher effectiveness value indicates a better performance of the heat exchanger in transferring heat. In the designed heat exchanger, the effectiveness value is reported to be high, with a value of 90, meeting the standards set by the Tubular Exchanger Manufacturers Association (TEMA).The effectiveness of the heat exchanger is an important parameter in designing an efficient heat recovery system for air conditioning systems, as it determines the amount of wasted heat that can be recovered and utilized. The design of the heat exchanger, with its specific dimensional specifications and arrangements, ensures efficient heat transfer and minimizes energy losses[6]. Increase baffle cut for better heat transfer. Use 50 baffle cuts for improved performance. Implement double segmental baffles to overcome future issues[7]. Optimize baffle cuts for good heat transfer rates. Use equilateral triangular or square tube arrangements for higher rates. Consider shell and tube passes to enhance efficiency[8].Presence of deposits or scaling on the interior surfaces of the heat exchanger introduces additional resistance to heat flow, leading to fouling .Fouling can occur due to the deposition of solids carried by the flowing fluid .Corrosive chemical processes can also contribute to fouling in heat exchangers. Scaling, particularly from the cooled P2O5 Acid solution, is a significant factor contributing to fouling in the E-2502 Heat Exchanger .The accumulation of fouling diminishes the heat transfer rate and reduces the efficiency of the heat exchanger. Regular cleaning of the heat exchanger, such as through mechanical methods like hydro jetting, is necessary to remove the accumulated deposits and maintain optimal heat transfer[10]. Increasing the thermal conductivity can be achieved by combining materials with high thermal conductivity, utilizing additives or encapsulation techniques, and incorporating fins or nanoparticles to enhance heat transfer. A higher tube length-diameter ratio is recommended for better energy storage performance, but the specific optimal values should be determined based on system requirements and constraints [19].The effectiveness depends on factors like pressure drop limitations. In this case, helical baffles were less effective due to this constraint[17]. mass flow rate recovery in a shell and tube heat exchanger, leading to improved effectiveness and reduced total annual cost. The optimization process considers various design parameters and the influence of the reflux ratio, providing valuable insights for the design and operation of heat exchangers[15].

10. Future works suggested :

- Graphene Nanofluids:
    - Conduct experiments to study the effects of different concentrations of graphene nanofluids on convective heat transfer in a shell and tube heat exchanger.
    - Explore the influence of flow rate and inlet temperature on the heat transfer coefficient and thermal efficiencies using these nanofluids.
- Baffle and Tube Configurations:
    - Investigate the performance of different baffle and tube configurations (e.g., helical, segmented) to optimize thermal performance and pressure drop within the STHE.
    - Analyze the effects of ribbed tubes (e.g., longitudinal triangular) on heat transfer and overall system efficiency compared to smooth tubes.
    - Machine Learning for Heat Transfer:
    - Develop and train artificial neural network structures to estimate heat transfer parameters for various STHE designs.
    - Incorporate additional input parameters into the machine learning models that might impact heat transfer performance (e.g., surface roughness, fluid properties).
    - Increase the size and diversity of the training data for machine learning models to improve prediction accuracy.
    - Conduct comparative studies to evaluate the performance of machine learning approaches against traditional methods for heat transfer parameter estimation.

Optimization Strategies:

- MOPSO Algorithm Improvement:
    - Further develop or compare the Multi-Objective Particle Swarm Optimization(MOPSO) algorithm used with other optimization algorithms (e.g., Genetic Algorithm, Simulated Annealing) to enhance its performance in solving STHE design problems.

- Uncertainty and Multi-Criteria Decision Making:
    - Investigate the impact of uncertainties in factors like flow rates or material properties on the optimization results for a more comprehensive understanding of the solution's robustness.
    - Explore the application of multi-criteria decision-making methods under uncertainty to evaluate and select the best STHE design solutions considering multiple objectives (e.g., heat transfer, pressure drop, cost) and uncertainties.

Real-World Applications:

- Air Conditioning System Optimization:
    - Design and optimize STHEs specifically for air conditioning systems in the hospitality industry, considering factors like flow patterns, material types, construction methods, and long-term performance with regards to fouling and maintenance requirements.
- Cleaning Techniques:
    - Develop new techniques or technologies for efficiently cleaning the outside of tubes in STHEs to minimize maintenance needs and improve overall efficiency.
- System Integration:
    - Explore the integration of STHEs with other systems or processes (e.g., waste heat recovery systems) to improve overall energy efficiency and promote sustainability in industrial applications.

Flow and Performance:

- Torsional Flow Optimization:
    - Conduct further testing on STHEs with varying baffle configurations to achieve a torsional flow design that optimizes the total heat transfer coefficient and pressure drop.
- Baffle Arrangement Analysis:
    - Analyze the flow characteristics of baffle arrangements in more detail, particularly focusing on non-uniform flow caused by gaps between baffles.
    - Investigate the effect of different baffle angles on flow direction, velocity, and potential blockage of fluid flow in specific sections of the STHE.
- Inclined-Segmental Baffle Improvement:
    - Conduct research on optimizing the heat transfer coefficient in STHEs with Inclined-Segmental Baffles, as they were found to have lower values compared to conventional designs.

Flow-Heat Transfer Relationship:

- Perform further analysis and experimentation to understand the relationship between the fluid flow characteristics on the shell side of the STHE and the resulting pressure drop and heat gain coefficient.

Material Exploration for Heat Storage:

- Research and develop new materials or structures like metal foams with enhanced porosity and fin designs to improve heat transfer and energy storage capacity in thermal storage units.
- Study the effect of different parameters like porosity and metal volume fraction on the heat transfer enhancement of these materials.
- Explore the impact of different fin structures and arrangements on the melting process and energy storage rate within the unit.

11. Conclusion:

1. Nanofluids for Enhanced Heat Transfer:

- Impact: The addition of graphene nanofluids to water-based coolants significantly increases the heat transfer coefficient of STHEs. Studies show a maximum improvement of 29% using 0.2% graphene nanofluid concentration.
- Mechanism: This enhancement is attributed to the exceptional thermal properties of graphene compared to water. Graphene's high thermal conductivity allows for more efficient heat transfer within the exchanger.

2. Machine Learning for Heat Transfer Prediction:

- Technique: Artificial neural networks (ANNs) are employed to accurately predict crucial heat transfer parameters for STHE designs.
- Performance: ANNs demonstrate remarkable precision with a coefficient of determination exceeding 0.99 and minimal mean deviation (less than 0.01%).
- Benefits: This level of accuracy allows engineers to design STHEs with targeted heat transfer performance, optimizing their efficiency for specific applications.

3. Optimized Baffle and Tube Configurations:

- Conventional vs. Optimized Designs: The research identified baffle and ribbed tube configurations that outperform traditional designs in terms of heat transfer efficiency.
- Effective Configurations: Configurations like disk baffles with triangular ribbed tubes (DB-TR) and circular segmental disk baffles with triangular ribbed tubes (CSDB-TR) showed a significant improvement of 39% compared to conventional STHEs.
- Mechanism: These optimized configurations promote better fluid mixing and turbulence within the heat exchanger, leading to more efficient heat transfer between the hot and cold fluids.

4. Metal Foam for Superior Thermal Enhancement in Heat Storage:

- Comparison: Metal foam proves to be a more effective thermal enhancer than fins in shell-and-tube heat storage units, especially at higher metal volume fractions (around 3%).
- Performance: Studies indicate that metal foam can achieve up to 10 times higher energy storage rates compared to units with fins.
- Reasoning: The intricate structure of metal foam provides a larger surface area for heat transfer and reduces thermal resistance within the unit, leading to faster and more efficient heat storage.

5. Multi-Objective Optimization for STHE Design:

- Optimization Approach: Multi-objective particle swarm optimization (MOPSO) algorithms are successfully used to optimize STHE design by considering multiple factors simultaneously.
- Factors Considered: These factors include heat transfer area, pumping power required for fluid circulation, and uncertainties associated with various design parameters.
- Decision-Making: Additionally, a multi-criteria decision-making method is employed to select the optimal design solution that satisfies all the problem constraints.
- Benefits: This multi-faceted approach ensures a well-balanced STHE design that achieves both high heat transfer efficiency and minimal energy consumption for pumping.

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