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Comprehensive review on exergy analysis of shell and tube heat exchangers

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Abstract

Heat exchangers (HEs) are used for several applications including chemical processes, power plants, air conditioning systems, etc. The performance of these devices could be influenced by different constituents such as the mass flow rates and temperatures of streams, characteristics of heat exchanger and thermo-physical properties of the fluid flows. Regarding the importance of entropy generation and second law analysis for heat exchangers, it is crucial to investigate different involving parameters to gain detailed insight into the defects of the system and potentials for performance enhancement. In this article, studies related to entropy generation and exergy analysis of shell and tube heat exchanger (as one of the most common types of HEs) are comprehensively reviewed and discussed. It can be concluded that modification in the thermos-physical properties of the fluids would lead to reduction in the entropy generation and consequently higher exergy efficiency. Furthermore, it is found that operating conditions of the heat exchangers, especially mass flow rates and temperatures of the streams, play key role in entropy generation.

Keywords Heat exchanger · Entropy · Exergy efficiency · Nanofluid · Exergy destruction

List of symbols

A	Heat transfer area
C	Heat capacitance
Q	Heat transfer
T	Temperature
U	Overall heat transfer coefficient
AT_{lm}	Log mean temperature difference
ε	Effectiveness

Subscripts

c	Cold stream
C	Consumed
h	Hot stream
i	Inlet
min	Minimum
max	Maximum
o	Outlet
P	Product

Abbreviations

HE	Heat Exchanger
NTU	Number of transfer unit

Introduction

HEs are the equipment used for heat transfer between two or more fluids with different temperatures [1, 2]. In the majority of the HEs, the streams are separated by using a surface to avoid mixing of the fluids. These devices are utilized for several intentions such as air conditioning, heating and cooling, renewable energy systems and chemical and petrochemical process [3–5]. Typically, HEs are composed of streams' inlets and outlets in addition to surface of heat

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transfer as the core of device. In addition, some other components such as fins, pipes and tanks can be used in HEs. The main advantage of HEs is no requirement for moving parts in their structure. There are various criteria that can be applied for categorizing the HEs such as number of phases, architecture and degree of surface compactness [6].

Similar to other heat transfer media, the performance of HEs depend on different elements [7–9]. The architecture of the components is one of the factors that can influence both pressure drop and heat transfer rate. Arani et al. [10] investigated pressure drop of shell and tube HE with various types of tube bundles. They found that for the same mass flow rate, twisted oval tubes with segmental baffle had much lower pressure loss compared to the ones with elliptical and circular tubes bundles. Abd et al. [11] investigated effects of baffle space on the performance of a HE for different conditions. They found that increment in the cutting space could decrease the heat transfer coefficient and pressure drop. In another work, Son et al. [12] found that the HE with spiral baffle plates could outperform conventional HE from heat transfer point of view. Specification of the streams is one of the most influential factors in performance of HEs. Using nanofluids, with improved thermos-physical properties [13, 14], is one of the attractive approaches implemented in recent years for heat transfer enhancement. For instance, Fares et al. [15] observed that applying graphene/water nanofluid in a HE can enhance the thermal efficiency significantly. It should be noted that the performance of nanofluids as working fluid of HEs depends on different factors such as the concentration, operating condition and configuration of the system [16]. New types of nanofluids, known as hybrid nanofluids that contain more than one nanomaterial [17, 18], are attractive alternatives for the conventional heat transfer fluids. Despite the advantages of using nanofluids in heat transfer improvement in HEs, the pressure loss could be increase as an unfavorable consequence [19]. In a helical shell and tube HE, Singh and Sarkar [20] evaluated the exergy, economics, and energy of a 580 MW nuclear power plant's shell and tube condenser using hybrid nanofluids as coolants. $Al_2O_3 + TiO_2$, $Al_2O_3 + Cu$, $Al_2O_3 + Ag$, and $Al_2O_3 + MWCNT$ were among the hybrid nanofluids studied. They also looked at how the concentration of nanoparticles affected coolant demand, operational costs, and pumping power. CFD was used by Ouellette et al. [21] to perform a detailed analysis on solar-geothermal shell and tube HEs. They also looked at the fluid velocity and temperature in the proposed geometrical designs. They discovered that increasing the mass flow rate on the shell side boosted fluid velocity while minimizing the temperature difference through the HEs. They also discovered that elevating the mass flow rate of the shells-side improves exergetic performance and heat transfer, while decreasing the HE's functionality. With a combination of Organic Rankine Cycle (ORC) and parabolic trough solar collector, Erdogan and Colpan [22] presented a thermal design for the formulation of shell and tube HEs. The mathematical operations on the formulated equations were performed using the Engineering Equation Solver (EES). According to their findings, non-continuous baffles provided a higher heat transfer coefficient, which improved heat transfer across the entire shell side. Abed et al. [23] investigated the existence of electromagnetism in shell and tube HEs using a new optimization method. When comparing different situations of water, kerosene, oil and methanol, they discovered that the area of heat transfer declined by up to 68.4, 17 and 23%, respectively. For all of the case studies, the total expenses are likewise reduced. Shirvan et al. [24] used experimental results to investigate the performance of shell and tube HEs using a cosine wave-like shape. The optimization process was determined using the response surface technique. They discovered that increasing the flow velocity of hot water reduces thermal performance. When compared to smooth tubes, wavy tubes have a larger factor of thermal performance. Shirvan et al. [25] evaluated corrugated-wall shell and tube HEs experimentally. They discovered that in the presence of cold water, heat transfer and effectiveness can be improved. They also discovered that smooth tube is less robust than corrugated tube. Marzouk et al. [26] investigated the efficiency of shell and tube HEs by inserting a circular rod into a tube with an unusual nail shape. The acquired data revealed that thermodynamics and thermal performance had significantly improved, whereas hydraulic performance had suffered a significant disadvantage. In shell and tube HEs, Zahid et al. [27] implemented CFD simulation to optimize performance of the included parameters. They discovered that increased material thermal conductivity, reduced inlet velocity, reduced baffle spacing and the use of triangular tube have a significant impact on the reduction of condensate temperature.

In addition to heat transfer rate and pressure drop as measures of HEs, exergy analysis is a powerful tool to evaluate their performance more deeply [28, 29]. Dizaji et al. [30] examined helical tube-in-tube coiled HEs and gave a detailed analysis of the second law. They investigated the effects of flow behavior, geometrical and thermodynamic parameters on exergetic features (including efficiency and exergy loss) for these types of HEs through experiments. They found that coil pitch had a negligible effect on exergy loss. Furthermore, parallel flow patterns showed the greatest increase in exergy loss. With a dual-pipe HE, Geete [31] presented a thorough examination of entransy-based thermal resistance, entransy and exergy in a variety of pipe materials, including copper, brass, cast iron, aluminum and steel. They discovered that copper tubes have the best performance due to their efficacy. The heat transfer mechanism through circular tubes through internally repeated ribs in ring form was quantitatively studied by Ahmed et al. [32]. They also looked at the exergy and entropy of each of the tubes. They discovered that for ring-type tubes, increased thermal hydraulic efficiency was associated with lower entropy and higher exergy. Shabgard et al. [33] constructed a thermal network model to evaluate HE efficiency, solar thermal power heating, a unit of latent thermal energy storage, and a hot and cold water system made up of tube collectors. They also looked at exergy analysis to see how well the second law performed. They discovered that increasing the number of pipes minimizes temperature swings and improves exergy efficiency due to the reduced temperature drop. Hosseinizadeh et al. [34] investigated the exergy and energy of Ferrofluids in the presence of an extrinsic magnetic field using triple HEs. They discovered that the magnetic field could enhance overall performance. Because of greater Reynolds numbers, the impact of the magnetic field on the thermosfluid characteristics was reduced. When the magnetic field affects all locations, maximum performance is attained. However, because to the existence of magnetic, which tends to increase entropy generation, the effectiveness of the second law is diminished.

Higher entropy generation in a component of a system means more exergy destruction. Due to the dependency of exergy efficiency on the entropy generation of the components, it would be useful to investigate HEs based on entropy generation. Till now, some review studies have been provided on the shell and tube HEs; however, the focus of these works have not been on the exergy and entropy generation. For instance, in a review study by Silaipillayarputhur and Khurshid [35], design of these HEs and the related formulation were reviewed. In another article [36], improvement in shell and tube HEs with helical baffles was reviewed. Salahuddin et al. [37] reviewed advancement made in the field of helical baffles applied in shell and tube HEs and discussed effects of different factors such as spacing and inclination angle. Due to the lack of a comprehensive review on the exergy analysis of these HEs and their entropy generation, this study is designed to focus on this aspect in order to provide required information for the scholars working on this field. In this work, studies on the exergy efficiency of shell and tube HEs, with focus on entropy generation, are reviewed and the findings are represented and discussed. In the following sections, the studies are divided into two groups, conventional and nanofluidic HEs.

Performance evaluation of HEs

Different expressions have been proposed for evaluating the performance of the HEs. Assuming there are two streams, cold and hot, in a HE, temperature of cold stream increases by receiving heat from the hot stream and the temperature of hot stream decreases as shown in Fig. 1. In this section, some of the most important expressions are explained and provided based on Ref [6]. Equation (1) can be used to express the overall heat transfer rate as a differential equation.

$$dQ = U\left(T_{\mathrm{h}} - T_{\mathrm{c}}\right)dA = U\Delta TdA \tag{1}$$

where A, U, T_{c} and T_{h} are heat transfer area, overall heat transfer coefficient, and temperatures of cold and hot streams, respectively. In order to determine heat transfer of streams, Eq. (2) can be used as follows [39]:

$$Q = \int CdT = C_{\mathrm{h}}\left(T_{\mathrm{h,i}} - T_{\mathrm{h,o}}\right) = C_{\mathrm{c}}\left(T_{\mathrm{c,o}} - T_{\mathrm{c,i}}\right) \tag{2}$$

o and i as subscripts refer to outlet and inlet conditions, respectively. C refers to the heat capacitance that equals to the multiplication of specific heat of the fluid and its mass flow rate. Applying heat transfer coefficient, the heat transfer rate can be determined as follows:

$$Q = \int U\Delta TdA = UA\Delta T_{\mathrm{lm}} \tag{3}$$

where U and ΔT_{lm} are the HE heat transfer coefficient and log mean temperature difference (LMTD), respectively. Effectiveness is one of the criteria widely applied for evaluation of HEs, refers to the maximum possible rate of heat that is thermodynamically obtainable. It can be determined as follows [39]:

$$\varepsilon = \frac{Q}{Q_{\max}} \tag{4}$$

where

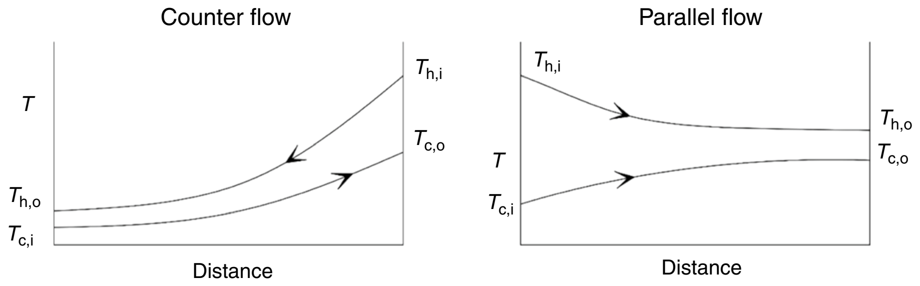


Fig. 1 Temperatures of hot and cold streams in a HE [38]

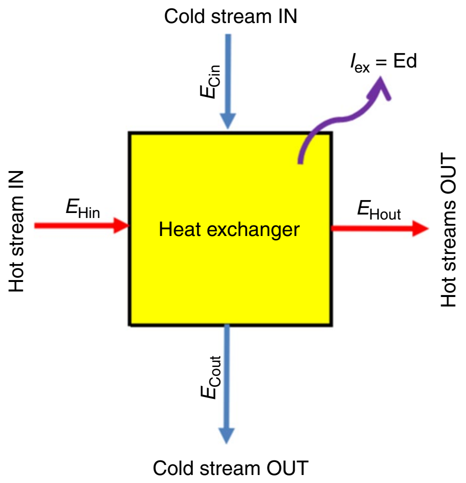


Fig. 2 Exergy flow in a HE [40]

$$Q_{max} = C_{min}\left(T_{h,i} - T_{c,i}\right) = C_{min}\Delta T_{max} \tag{5}$$

In Eq. (5), C_{min} refers to the minimum value of C_c and C_h. By applying both Eqs. (4) and (5), it can be written:

$$\varepsilon = \frac{C_h(T_{h,i} - T_{h,o})}{C_{min}\Delta T_{max}} = \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}\Delta T_{max}} \tag{6}$$

Applying Eqs. (3) and (6) provides following equation:

$$\varepsilon = \frac{UA}{C_{min}}\frac{\Delta T_{lm}}{\Delta T_{max}} \tag{7}$$

NTU (number of transfer units), indicative of the size of the HE and also a good indicative of heat transfer rate in HEs, can be expressed as follows:

$$NTU = \frac{UA}{C_{min}} \tag{8}$$

Exergy destruction due to temperature difference between the streams can be determined by using Eq. (9) as follows [40] (Fig. 2):

$$I_{\Delta T} = \left(1 - \frac{T_0}{T_1}\right)Q - \left(1 - \frac{T_0}{T_2}\right)Q \tag{9}$$

Exergy destruction in a HE is due to the heat transfer of streams with different temperatures and pressure loss. As shown in Fig. 3, the temperatures of streams significantly influence the exergy loss due to heat transfer and consequently the exergy destruction of the HE.

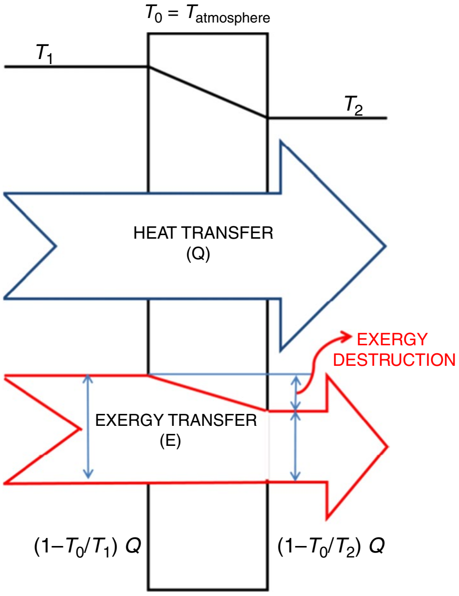


Fig. 3 Exergy destruction in heat transfer process [40]

Exergy analysis of shell and tube HEs

One of the mostly used kinds of HEs is shell and tube type. This type of HE composed of shell with one or more tubes inside it as shown in Fig. 4. The streams flow through the shell and tubes. Regarding the wide applications of shell and tube HEs, this study focuses on the exergy analysis and entropy generation of these types.

The exergy efficiency of the HEs and entropy generation are influenced by different variables [41] as shown in Fig. 5. Mert and Badak [42] investigated the performance of a 1–1 shell and tube HE and used the COMSOL tool to run

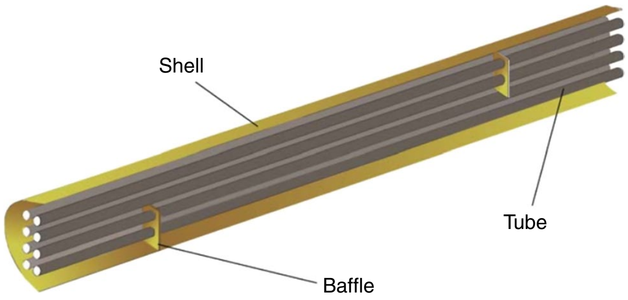
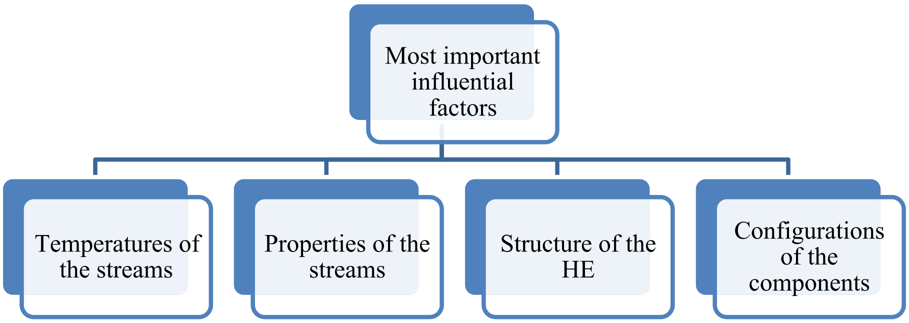


Fig. 4 Schematic of a shell and tube HE [6]

Fig. 5 The most important factors influencing exergy efficiency of HEs



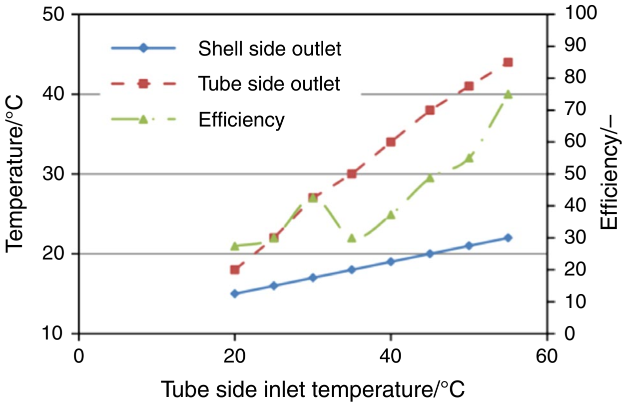


Fig. 6 Effect of tube side inlet temperature on the efficiency and outlet temperatures [43]

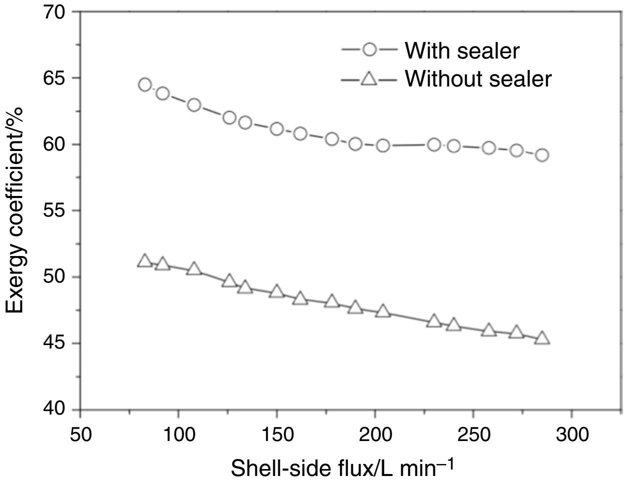


Fig. 7 Effect of installing sealer on the exergy coefficient [44]

an exergetic simulation. They calculated three-dimensional pressure, temperature, and velocity profiles and discovered that exergy destruction is reduced when the shell side velocity temperature is higher, and the tube side velocity temperature is lower. Mert et al. [43] experimentally assessed exergy efficiency of a HE by considering different mass flow

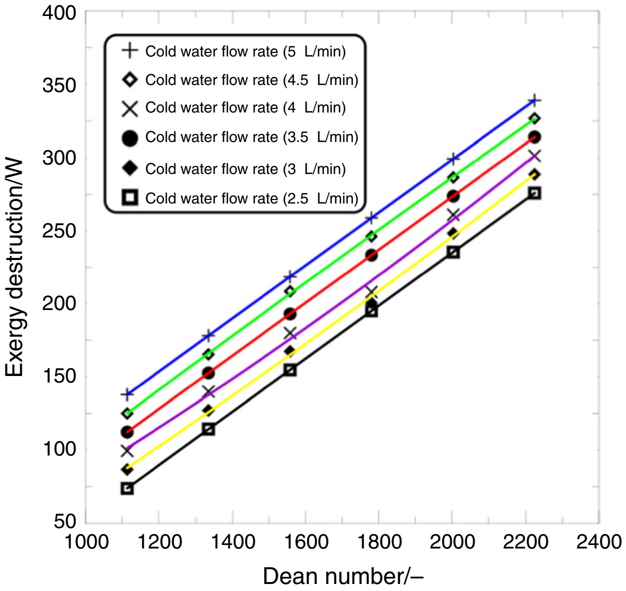


Fig. 8 Effect of mass flow rates of streams on the exergy destruction [45]

rates of the streams and tube side inlet temperature. In their setup, hot stream flows through the tubes while the cold stream flows via the shell side. They found that increase in tube side inlet temperature from 20 to 55 °C leads to increase in the exergy efficiency by around 40% as shown in Fig. 6. Some modifications in the structure of HEs can lead to improvement both in energy and exergy efficiencies. For instance, Wang et al. [44] installed sealers on the shell side of a HE in order to block the gaps between the shell and baffle plats. It was observed that installation of the sealers increased exergy coefficient by up to more than 10% in cases of high shell side flow rate as shown in Fig. 7. Similar to simple shell and tube HEs, exergy analysis can be applied for shell and helical coil tube HEs. For example, Abbas et al. [45] applied exergy analysis for this type of HE by considering the effects of mass flow rates of streams on exergy destruction. They observed that increase in the mass flow rates caused higher exergy destruction, as illustrated in Fig. 8, which was attributed to the higher heat transfer or in other word, higher temperature difference. In another work [46], effect of temperature at the inlets of shell (cold stream) and tube (hot stream) sides of a shell and coiled tube HE was investigated. They observed that exergy loss increased by increment in the temperature at the inlet of coil side and reduction in the inlet temperature of shell side. Moreover, they found that increase in the coil pitch of the HE led to higher exergy loss. In another work [47], focused on helically coiled HE by applying exergy analysis, it was found that using the coil with the highest number of turns and the lowest diameter was the most efficient structure among the applied coils with the same length. Exergy analysis has been performed on the other types of shell and tube HEs in some studies. As an example, Kumar et al. [48] investigated as HE with triple meshed helical coil in different operating conditions. They observed that by increase in the inlet temperature of hot, and consequently increase in the temperature difference between the streams, exergy loss increased. Moreover, they noticed that increase in the mass flow rate of hot stream caused increment in the exergy loss.

Modification on the structure of components is one of the approaches useful for improving the heat transfer rate of HEs; however, it may cause exergy losses. In a study by Dizaji et al. [49], investigated the effect of corrugating the shell and tube of a HE on the exergy loss. They observed that corrugation existence on the shell and tube sides of the HE led to increase in exergy loss. They observed that existence of corrugation causes secondary flow creation which reduces the thickness of the boundary layer on the outer surface of the tube. Moreover, the turbulence of the fluid and mixing of thermal boundary layer along the HE increases. All of these phenomena led to improvement in heat transfer coefficient which results in higher Number of Transfer Unit (NTU). Increment in NTU causes increase in irreversibility of heat transfer which means higher exergy loss of the HE. In another study [50], HE with helically plained coil tube and helically corrugated coil tubes were compared by applying exergy analysis and it was observed that using helically corrugated coiled tube led to more than 20% reduction in exergy loss compared with helically plained coiled tube. The structure and configuration of baffle are other factors that could affect the exergy efficiency of HEs. In a study by Said et al. [51], different baffle configurations were investigated in HE and the exergy efficiency of the system was compared under various operating conditions. The considered baffle configurations in their study were conventional single segmental baffle (CSSB), flower segmental baffle (FSB), staggered single segmental baffle (SSSB) and hybrid segmental baffle (HSB). As shown in Fig. 9, structure of baffle affects the exergy efficiency of the HE and using HSB led to the highest exergy efficiency among the applied baffles. In another work [52], effect of fin geometry on the exergy loss of a shell and helically coiled finned tube was investigated. They found that for constant velocity and number of fins, higher height of fins led to increment in exergy loss. This increment in the exergy loss was attributed to the higher pressure loss in cases of increased fins height. The same trend was observed for increasing the number of fins in the HE. In another work [53], Taguchi analysis was applied on the basis of exergy loss for a HE with helically grooved shell. They found that the minimum exergy loss obtained in case of lowest height of groove and flow rate and the maximum input temperature (cold stream). According to their findings, the height of the grooves influence exergy loss of the HE. DETHE software was used by Zueco and Ayala- Miñano [54] to determine the exergy analysis and irreversibility on shell and tube HEs. They discovered that changing tube pitch had a higher impact on irreversibility, implying that increased tube pitch causes greater irreversibility.

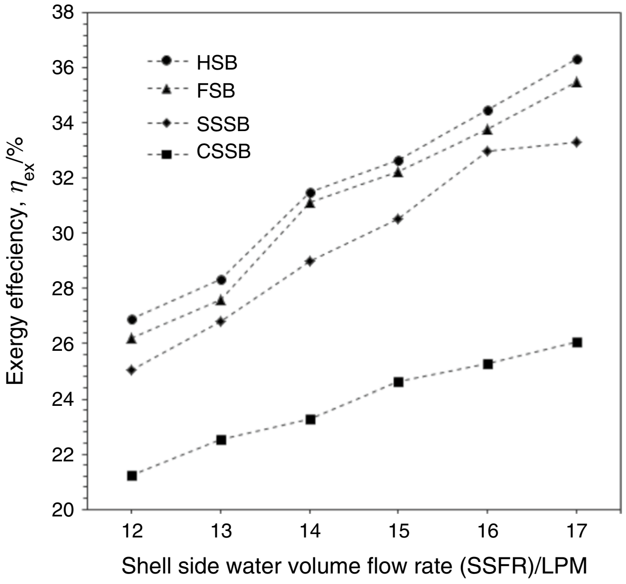


Fig. 9 Exergy Efficiency of HE for different configurations of baffle [51]

Exergy concept and entropy generation are applicable for optimization of HEs [55]. Minimization of entropy generation, which means higher exergy efficiency, is widely used for modeling and optimization of thermal mediums such HEs [56, 57]. By applying optimization on the HEs, it would be possible to improve the effectiveness and decrease the pumping power [58]. In addition to exergy, other factors such as economic indicators can be used for multi objective optimizations of HEs [59]. In a study by Hajabdollahi et al. [60], both exergy and cost were considered as the objectives of an optimization problem on a HE. They observed conflict between the objective function which means that any modification on the geometrical parameters that reduces the exergy loss led to higher cost of the system. Moreover, they found that pressure drop and temperature difference between the

Table 1 Summaries of the studies on exergy analysis and entropy generation of shell and tube HEs

Reference	Architecture of HE	Working Fluid	Important Findings
Mert et al. [43]	Simple shell and tube HE	Water	Increase in tube side temperature and mass flow rate caused higher exergy efficiency
Wang et al. [44]	Shell and tube HE with and without sealers on the baffles	Water and oil	Installation of sealers led to improvement in the exergy coefficient
Abbas et al. [45]	Shell and helical coiled tube HE	Water	Increase in mass flow rates of streams led to higher exergy destruction
Dizaji et al. [46]	Shell and coiled tube HE	Water	Increase in coil pitch led to higher exergy loss
Alimoradi [47]	Shell and helical coiled tube HE	Water	Among the tested coils with the same length, using coil with the minimum diameter and the maximum number of turns led to the highest efficiency
Kumar et al. [48]	Tripled meshed helical coil with shell HE	Water	Increase in the temperature of hot stream caused exergy loss increase
Dizaji et al. [49]	Corrugated shell and tube	Water	Corrugation on the shell and tube sides led to increment in exergy loss
Said et al. [51]	Shell and tube HE with different baffle configurations	Water	The baffle configuration affects the exergy efficiency of the HE
Heydari et al. [50]	Helically corrugated coiled and helically plained coiled with shell HEs	Water	Using helically corrugated coiled led to lower exergy loss compared with helically plained coiled
Wang et al. [52]	Shell and helically coiled tube with fin	Water and air	Increase in fin height and number led to increase in exergy loss
Miansari et al. [53]	Helically grooved shell with tube HE	Water	Height of the grooves affects the exergy loss of the HE
Zueco and Ayala-Mi ñ ano [54]	Shell and tube HE	Water	Greater irreversibility occurs due to greater tube pitch
Guo et al. [57]	Simple shell and tube HE	Water	Applying multi objective optimization led to more favorable design compared with the single objective optimization
Guo et al. [58]	Simple shell and tube HE	Water	Applying optimization led to improvement in the effectiveness of the HE and reduction in pumping power
Ozcelik [59]	Simple shell and tube with baffle	Water	An algorithm was proposed to find the optimum or near optimum configuration of the HE
Hajabdollahi et al. [60]	Heat recovery shell and tube HE	Water	Modification on the structure for exergy destruction reduction led to increment in cost
Arivazhagan et al. [61]	Shell and tube HE with porous medium inside tube	Water	There is an upper limit for Reynolds number and higher values causes irreversibility
Elias et al. [67]	Simple shell and tube	Boehmite alumina/ water-ethylene glycol and flue gas	Using spherical shape particles led to the lowest entropy generation
Esfahani et al. [68]	Simple shell and tube	Water and graphene oxide/water	Using the nanofluid led to reduction in exergy loss of HE for the same volume flow rate of hot stream
Bahiraei et al. [69]	Shell and tube HE with helical baffles	Boehmite nanofluids	Platelet nanoparticle suspension produces the most thermal entropy. Oblate spheroid particles produce the least thermal entropy

streams caused irreversibility which means higher exergy destruction. In another work [57], minimization of entropy generation was applied for multi objective optimization of a HE. In their work, objectives were minimization of the dimensionless entropy generation that was related to the heat conduction with finite temperature difference and friction of fluid for finite pressure drop. Compared with single objective optimization, this approach led to reduction in pumping power for the same effectiveness of the HE. Exergy and entropy concepts can be applied for optimization of HEs with more complex structure. For instance, Arivazhagan et al. [61] optimized a HE with porous medium on its tube based on entropy generation. According to their optimization, there was an optimum value for Reynolds number and higher values led to increment in the irreversibility.

Heat transfer rate in the HEs could be enhanced by applying nanofluids [9, 62]. Generally, increment in the concentration of solid structures of nanofluids lead to heat transfer and pressure loss improvement [63, 64]. As an example, Sridhar et al. [65] investigated heat transfer efficiency in shell and tube HEs employing Ag-water and SnO_2-water nanofluids. Because of the unique intrinsic properties of the nanoparticles, they discovered that thermal conductivity was enhanced by 29 and 39 percent, respectively. Increases in thermal conductivity tend to increase the coefficient of heat transfer but rises in nanofluid density and viscosity boosted the friction factor. Furthermore, they discovered that Ag had a sharper pressure drop than SnO_2 due to the nanofluid's stronger thermos-physical characteristics. Improvement in the performance of HEs in cases of using nanofluids is dependent on different specifications of nanofluids such as shape of nanomaterials [66]. Existence of nanostructures in the working fluid can cause reduction in entropy generation and consequently lower exergy destruction. The reduction in the entropy generation of nanofluidic HEs could be under the influence of different constituents such as the particle shape or concentration of solid phase. For instance, Elias et al. [67] compared entropy generation of a HE with boehmite alumina with various particle shapes including brick, cylindrical, platelet, blade and spherical shapes and found that using the spherical shape particles causes the lowest entropy generation. In another work, Esfahani et al. [68] compared the exergy destruction of a HE by using water and graphene oxide/water in 0.01% and 0.1 mass% concentrations in hot stream while water was used as the cold stream. They found that increase in mass flow rate of hot stream caused increment in exergy loss while increase in the concentration of the nanofluid resulted in lower exergy loss. Bahiraei et al. [69] investigated nanofluid flow through shell and tube HE with new type of ladder helical baffles using the second law. They employed Boehmite nanofluids with a variety of nanoparticle shapes contained in a heated fluid with a constant Reynolds number. They discovered that platelet nanoparticle suspension produces the most thermal entropy, whereas oblate spheroid particles suspended in fluid produce the least thermal entropy.

In Table 1, the reviewed works are summarized.

Recommendations for upcoming studies

In the previous parts of the manuscript, works on the exergy and entropy generation of the shell and tube HEs are reviewed. Despite the existence of several valuable works in this field, there are some suggestions for the next studies in this area. First of all, it will be useful to develop some models based on data-driven methods. By using these methods, due to their ability in forecasting and modeling of complicated problems [70–74], it would be possible to predict exergy efficiency of the HEs in a more time-saving way. In addition to benefits of data driven methods in exergy analysis of HEs in term of time consumption, it would be possible to develop comprehensive models based on these approaches by applying proper inputs [75]. Regarding the better performance of nanofluidic HEs, it is recommended to apply exergy analysis for HEs with other types of nanofluids, especially the ones with carbonic nanostructures. Moreover, the HEs with hybrid nanofluids, as promising heat transfer fluids [76–78], would be attractive cases for exergy analysis. In addition, in cases there is significant difference between the inlet and outlet temperatures of the streams, considering the properties of the fluids as a function of temperature would lead to more accurate and realistic outputs.

For the optimization studies, it would be useful to develop the optimization algorithms and applying more recent approaches [79]. Hybridization of optimization approaches would be useful to provide novel algorithms [80]. In addition, different optimization methods can be applied and compared their performance [81–83]. Moreover, it is recommended to consider more objectives for optimization of these HEs by using different criteria such as environmental ones in addition to exergy efficiency and entropy generation.

Conclusions

In the current article, works on the exergy analysis and entropy generation of shell and tube HEs are reviewed and their results are discussed and represented. The main findings from these studies are summarized as follows:

- Different operating conditions such as inlet temperature and mass flow rates of the streams affect the exergy efficiency of the HEs. For instance, by increase in inlet temperature of tube side of a HE from 20 to 55 °C, exergy efficiency can be increased significantly.

- Modifications on the structure of the HEs, such as installing sealers, can be useful in term of exergy coefficient; as an example, up to more than 10% increase in exergy coefficient has been observed in a study.
- Modification on the geometry of shell and tubes could lead to improvement in exergy efficiency.
- In addition to the cores of HEs, the additional components of the HEs such as the baffles and their architecture can influence the exergy efficiency.
- Applying nanofluids in HEs can decrease the entropy generation and consequently enhance the exergy efficiency.
- Exergy concept and entropy generation are applicable for optimal design of shell and tube HEs.
- In addition to single objective optimization, other objectives such as cost, can be used for optimal design of HEs.
- Optimal design of HEs by employing exergy concept can lead to reduction in pumping power and increase in effectiveness.

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Declarations

Conflict of interest The authors declare no conflict of interest.

References

1. Sahota L, Tiwari GN. Exergoeconomic and enviroeconomic analyses of hybrid double slope solar still loaded with nanofluids. Energy Convers Manage. 2017;148:413–30.
2. Pantzali MN, Mouza AA, Paras SV. Investigating the efficacy of nanofluids as coolants in plate heat exchangers (PHE). Chem Eng Sci. 2009;64(14):3290–300.
3. Mohanty DK. Application of firefly algorithm for design optimization of a shell and tube heat exchanger from economic point of view. Int J Therm Sci. 2016;102:228–38.
4. Wang K, Cheng L. Numerical modeling and multi-objective optimization of a novel cross-flow heat exchanger with rotated aligned tube bank. Sci China Technol Sci. 2018;61(7):982–93.
5. Wang Y, Huai X. Heat transfer and entropy generation analysis of an intermediate heat exchanger in ADS. J Therm Sci. 2018;27(2):175–83.
6. Assad M, Rosen MA (Eds.) Design and performance optimization of renewable energy systems. Academic Press (2021).
7. Wang C, Cui Z, Yu H, Chen K, Wang J. Intelligent optimization design of shell and helically coiled tube heat exchanger based on genetic algorithm. Int J Heat Mass Transf. 2020;159: 120140.
8. Ghanei A, Assareh E, Biglari M, Ghanbarzadeh A, Noghrehabadi AR. Thermal-economic multi-objective optimization of shell and tube heat exchanger using particle swarm optimization (PSO). Heat Mass Transf. 2014;50(10):1375–84.
9. Mansoury D, Ilami Doshmanziari F, Rezaie S, Rashidi MM. Effect of Al2O3/water nanofluid on performance of parallel flow heat exchangers. J Therm Anal Calorim. 2019;135(1):625–43.
10. Arani AAA, Uosofvand H. Different tube bundles effect on the shell-and-tube heat exchanger performance. Int J Numer Meth Heat Fluid Flow. 2021;31(12):3661–88.
11. Abd AA, Kareem MQ, Naji SZ. Performance analysis of shell and tube heat exchanger: parametric study. Case Stud Ther Eng. 2018;12:563–8.
12. Son YS, Shin JY. Performance of a shell-and-tube heat exchanger with spiral baffle plates. KSME Int J. 2001;15(11):1555–62.
13. Hemmat Esfe M, Motallebi SM. Optimization, modeling, and prediction of relative viscosity and relative thermal conductivity of AlN nano-powders suspended in EG. The Eur Phys J Plus. 2021;136(1):1–19.
14. Esfe MH, Motallebi SM, Bahiraei M. Employing response surface methodology and neural network to accurately model thermal conductivity of TiO2–water nanofluid using experimental data. Chin J Phys. 2021;70:14–25.
15. Fares M, Mohammad AM, Mohammed AS. Heat transfer analysis of a shell and tube heat exchanger operated with graphene nanofluids. Case Stud Ther Eng. 2020;18: 100584.
16. Plant RD, Saghir MZ. Numerical and experimental investigation of high concentration aqueous alumina nanofluids in a two and three channel heat exchanger. Int J Thermofluids. 2021;9: 100055.
17. Amani M, Amani P, Kasaeian A, Mahian O, Pop I, Wongwises S. Modeling and optimization of thermal conductivity and viscosity of MnFe2O4 nanofluid under magnetic field using an ANN. Sci Rep. 2017;7(1):1–13.
18. Li Z, Shahsavar A, Niazi K, Al-Rashed AA, Rostami S. Numerical assessment on the hydrothermal behavior and irreversibility of MgO-Ag/water hybrid nanofluid flow through a sinusoidal hairpin heat-exchanger. Int Commun Heat Mass Transfer. 2020;115: 104628.
19. Karimi S, Heyhat MM, Isfahani AHM, Hosseinian A. Experimental investigation of convective heat transfer and pressure drop of SiC/water nanofluid in a shell and tube heat exchanger. Heat Mass Transf. 2020;56(8):2325–31.
20. Singh SK, Sarkar J. Energy, exergy and economic assessments of shell and tube condenser using hybrid nanofluid as coolant. Int Commun Heat Mass Transfer. 2018;98:41–8.
21. Ouellette D, Erdogan A, Colpan CO, CFD analysis of a solar-geothermal shell and tube heat exchanger. In Exergetic, energetic and environmental dimensions (pp. 307–322). Academic Press (2018).
22. Erdogan A, Colpan CO, Thermal design and modeling of shell and tube heat exchangers combining PTSC and ORC Systems. In Exergetic, Energetic and Environmental Dimensions (pp. 279–305). Academic Press (2018).
23. Abed AM, Abed IA, Majdi HS, Al-Shamani AN, Sopian K. A new optimization approach for shell and tube heat exchangers by using electromagnetism-like algorithm (EM). Heat Mass Transf. 2016;52(12):2621–34.
24. Shirvan KM, Mamourian M, Esfahani JA. Experimental investigation on thermal performance and economic analysis of cosine

wave tube structure in a shell and tube heat exchanger. Energy Convers Manage. 2018;175:86–98.

25. Milani Shirvan K, Mamourian M, Abolfazli Esfahani J. Experimental study on thermal analysis of a novel shell and tube heat exchanger with corrugated tubes. J Therm Anal Calorim. 2019;138(2):1583–606.
26. Marzouk SA, Abou Al-Sood MM, El-Said EM, El-Fakharany MK. Effect of wired nails circular–rod inserts on tube side performance of shell and tube heat exchanger: experimental study. Appl Therm Eng. 2020;167: 114696.
27. Hanan A, Zahid U, Feroze T, Khan SZ. Analysis of the performance optimisation parameters of shell and tube heat exchanger using CFD. Austr J Mech Eng. 2021. https://doi.org/10.1080/14484846.2021.1914890.
28. Jafarzad A, Heyhat MM. Thermal and exergy analysis of air-nanofluid bubbly flow in a double-pipe heat exchanger. Powder Technol. 2020;372:563–77.
29. Sokhal GS, Dhindsa GS, Sokhal KS, Ghazvini M, Sharifpur M, Sadeghzadeh M. Experimental investigation of heat transfer and exergy loss in heat exchanger with air bubble injection technique. J Therm Anal Calorim. 2021;145(3):727–37.
30. Dizaji HS, Khalilarya S, Jafarmadar S, Hashemian M, Khezri M. A comprehensive second law analysis for tube-in-tube helically coiled heat exchangers. Exp Thermal Fluid Sci. 2016;76:118–25.
31. Geete A. Exergy, entransy, and entransy-based thermal resistance analyses of double-pipe heat exchanger with different pipe materials. Heat Transfer Res. 2017;48(18):1625–36.
32. Ahmed SAES, Ibrahim EZ, Ibrahim MM, Essa MA, Abdelatief MA, El-Sayed MN. Heat transfer performance evaluation in circular tubes via internal repeated ribs with entropy and exergy analysis. Appl Therm Eng. 2018;144:1056–70.
33. Shabgard H, Song L, Zhu W. Heat transfer and exergy analysis of a novel solar-powered integrated heating, cooling, and hot water system with latent heat thermal energy storage. Energy Convers Manage. 2018;175:121–31.
34. Hosseinizadeh SE, Majidi S, Goharkhah M, Jahangiri A. Energy and exergy analysis of ferrofluid flow in a triple tube heat exchanger under the influence of an external magnetic field. Thermal Sci Eng Prog. 2021;25: 101019.
35. Silaipillayarputhur K, Khurshid H. The design of shell and tube heat exchangers–a review. Int J Mech Prod Eng Res Dev. 2019;9(1):87–102.
36. Wang Q, Chen G, Chen Q, Zeng M. Review of improvements on shell-and-tube heat exchangers with helical baffles. Heat Transfer Eng. 2010;31(10):836–53.
37. Salahuddin U, Bilal M, Ejaz H. A review of the advancements made in helical baffles used in shell and tube heat exchangers. Int Commun Heat Mass Transfer. 2015;67:104–8.
38. Spalding DB, Types of temperature change pattern. HEDH multimedia - heat exchanger design handbook, multimedia edition [Internet]. New York: Begell House Inc. (2016). https://hedhme.com/content_map/?link_id=63&article_id=90
39. Chahartaghi M, Eslami P, Naminezhad A. Effectiveness improvement and optimization of shell-and-tube heat exchanger with entransy method. Heat Mass Transf. 2018;54(12):3771–84.
40. Mehdizadeh-Fard M, Pourfayaz F. Advanced exergy analysis of heat exchanger network in a complex natural gas refinery. J Clean Prod. 2019;206:670–87.
41. Cheng X, Liang X. A comparison between the entropy generation in terms of thermal conductance and generalized thermal resistance in heat exchanger analyses. Int J Heat Mass Transf. 2014;76:263–7.
42. Hu D, An introductory survey on attention mechanisms in NLP problems. In Proceedings of SAI intelligent systems conference (pp. 432–448). Springer, Cham (2019).
43. Mert SO, Reis A. Experimental performance investigation of a shell and tube heat exchanger by exergy based sensitivity analysis. Heat Mass Transf. 2016;52(6):1117–23.
44. Wang S, Wen J, Li Y. An experimental investigation of heat transfer enhancement for a shell-and-tube heat exchanger. Appl Therm Eng. 2009;29(11–12):2433–8.
45. Al-Abbas AH, Mohammed AA, Hassoon AS. Exergy analysis of Shell and helical coil heat exchanger and design optimization. Heat Mass Transf. 2021;57(5):797–806.
46. Dizaji HS, Jafarmadar S, Hashemian M. The effect of flow, thermodynamic and geometrical characteristics on exergy loss in shell and coiled tube heat exchangers. Energy. 2015;91:678–84.
47. Alimoradi A. Investigation of exergy efficiency in shell and helically coiled tube heat exchangers. Case Stud Ther Eng. 2017;10:1–8.
48. Kumar R, Chandra P. Thermal analysis, pressure drop and exergy loss of energy efficient shell, and triple meshed helical coil tube heat exchanger. Energy Sour, Part A: Recov, Util Environ Effects. 2020;42(8):1026–39.
49. Dizaji HS, Jafarmadar S, Asaadi S. Experimental exergy analysis for shell and tube heat exchanger made of corrugated shell and corrugated tube. Exp Thermal Fluid Sci. 2017;81:475–81.
50. Heydari O, Miansari M, Arasteh H, Toghraie D. Optimizing the hydrothermal performance of helically corrugated coiled tube heat exchangers using Taguchi's empirical method: energy and exergy analysis. J Therm Anal Calorim. 2021;145(5):2741–52.
51. El-Said EM, Abou Al-Sood MM. Shell and tube heat exchanger with new segmental baffles configurations: a comparative experimental investigation. Appl Therm Eng. 2019;150:803–10.
52. Wang J, Hashemi SS, Alahgholi S, Mehri M, Safarzadeh M, Alimoradi A. Analysis of Exergy and energy in shell and helically coiled finned tube heat exchangers and design optimization. Int J Refrig. 2018;94:11–23.
53. Miansari M, Valipour MA, Arasteh H, Toghraie D. Energy and exergy analysis and optimization of helically grooved shell and tube heat exchangers by using Taguchi experimental design. J Therm Anal Calorim. 2020;139(5):3151–64.
54. Zueco J, Ayala-Miñano S. Exergy analysis of a shell and tube heat exchanger using DETHE software. Int J Exergy. 2020;33(2):198–213.
55. Petinrin MO, Bello-Ochende T, Dare AA, Oyewola MO. Entropy generation minimisation of shell-and-tube heat exchanger in crude oil preheat train using firefly algorithm. Appl Therm Eng. 2018;145:264–76.
56. Rodríguez MBR, Rodríguez JLM, Fontes CHDO. Thermo ecological optimization of shell and tube heat exchangers using NSGA II. Appl Therm Eng. 2019;156:91–8.
57. Guo J, Cheng L, Xu M. Multi-objective optimization of heat exchanger design by entropy generation minimization. J Heat Trans. 2010;132(8):081801.
58. Guo J, Cheng L, Xu M. Optimization design of shell-and-tube heat exchanger by entropy generation minimization and genetic algorithm. Appl Therm Eng. 2009;29(14–15):2954–60.
59. Özçelik Y. Exergetic optimization of shell and tube heat exchangers using a genetic based algorithm. Appl Therm Eng. 2007;27(11–12):1849–56.
60. Hajabdollahi H, Ahmadi P, Dincer I. Exergetic optimization of shell-and-tube heat exchangers using NSGA-II. Heat Transfer Eng. 2012;33(7):618–28.
61. Arivazhagan M, Lokeswaran S. Entropy generation minimization of shell and tube heat exchanger with porous medium. Exp Tech. 2013;37(5):74–82.
62. Shahsavar Goldanlou A, Sepehrirad M, Papi M, Hussein AK, Afrand M, Rostami S. Heat transfer of hybrid nanofluid in a shell

and tube heat exchanger equipped with blade-shape turbulators. J Therm Anal Calorim. 2021;143(2):1689–700.

63. Leong KY, Saidur R, Khairulmaini M, Michael Z, Kamyar A. Heat transfer and entropy analysis of three different types of heat exchangers operated with nanofluids. Int Commun Heat Mass Transfer. 2012;39(6):838–43.
64. Said Z, Rahman SMA, Assad MEH, Alami AH. Heat transfer enhancement and life cycle analysis of a Shell-and-Tube Heat Exchanger using stable CuO/water nanofluid. Sustain Energy Technol Assess. 2019;31:306–17.
65. Sridhar SV, Karuppasamy R, Sivakumar GD. Experimental investigation of heat transfer enhancement of shell and tube heat exchanger using SnO2-water and Ag-water nanofluids. J Thermal Sci Eng Appl. 2020;12(4): 041016.
66. Hajabdollahi H, Hajabdollahi Z. Numerical study on impact behavior of nanoparticle shapes on the performance improvement of shell and tube heat exchanger. Chem Eng Res Des. 2017;125:449–60.
67. Elias MM, Miqdad M, Mahbubul IM, Saidur R, Kamalisarvestani M, Sohel MR, Amalina MA. Effect of nanoparticle shape on the heat transfer and thermodynamic performance of a shell and tube heat exchanger. Int Commun Heat Mass Transfer. 2013;44:93–9.
68. Esfahani MR, Languri EM. Exergy analysis of a shell-and-tube heat exchanger using graphene oxide nanofluids. Exp Thermal Fluid Sci. 2017;83:100–6.
69. Bahiraei M, Naseri M, Monavari A. A second law analysis on flow of a nanofluid in a shell-and-tube heat exchanger equipped with new unilateral ladder type helical baffles. Powder Technol. 2021;394:234–9.
70. Kumararaja K, Khiran Kumar CS, Sivaraman B. A convolutional neural network analysis of a heat pipe with Hybrid Nanofluids. Int J Ambient Energy. 2021. https://doi.org/10.1080/01430750.2021.2014959.
71. Ramezanizadeh M, Ahmadi MH, Nazari MA, Sadeghzadeh M, Chen L. A review on the utilized machine learning approaches for modeling the dynamic viscosity of nanofluids. Renew Sustain Energy Rev. 2019;114: 109345.
72. Dadsetani R, Sheikhzade GA, Goodarzi M, Zeeshan A, Ellahi R, Safaei MR. Thermal and mechanical design of tangential hybrid microchannel and high-conductivity inserts for cooling of disk-shaped electronic components. J Therm Anal Calorim. 2021;143(3):2125–33.
73. Zhang L, Bhatti MM, Michaelides EE, Marin M, Ellahi R, Hybrid nanofluid flow towards an elastic surface with tantalum and nickel nanoparticles, under the influence of an induced magnetic field. The Eur Phys J Special Top, 2022;231:521–533.
74. Bhatti MM, Beg OA, Abdelsalam SI. Computational framework of magnetized MgO-Ni/water-based stagnation nanoflow past an elastic stretching surface: application in solar energy coatings. Nanomaterials. 2022;12:1049.
75. Ahmadi MH, Hajizadeh F, Rahimzadeh M, Shafii MB, Chamkha AJ, Lorenzini G, Ghasempour R. Application GMDH artificial neural network for modeling of Al2O3/water and Al2O3/ethylene glycol thermal conductivity. Int J Heat Technol. 2018;36(3):773–82.
76. Kamel MS, Al-Oran O, Lezsovits F. Thermal conductivity of Al2O3 and CeO2 nanoparticles and their hybrid based water nanofluids: An experimental study. Periodica Polytech, Chem Eng. 2021;65(1):50–60.
77. Esfe MH, Alirezaie A, Rejvani M. An applicable study on the thermal conductivity of SWCNT-MgO hybrid nanofluid and price-performance analysis for energy management. Appl Therm Eng. 2017;111:1202–10.
78. Wole-Osho I, Okonkwo EC, Kavaz D, Abbasoglu S. An experimental investigation into the effect of particle mixture ratio on specific heat capacity and dynamic viscosity of Al2O3-ZnO hybrid nanofluids. Powder Technol. 2020;363:699–716.
79. Alshammari N, Asumadu J. Optimum unit sizing of hybrid renewable energy system utilizing harmony search, Jaya and particle swarm optimization algorithms. Sustain Cities Soc. 2020;60: 102255.
80. Jahannoosh M, Nowdeh SA, Naderipour A, Kamyab H, Davoudkhani IF, Klemeš JJ. New hybrid meta-heuristic algorithm for reliable and cost-effective designing of photovoltaic/wind/fuel cell energy system considering load interruption probability. J Clean Prod. 2021;278: 123406.
81. Patel VK, Rao RV. Design optimization of shell-and-tube heat exchanger using particle swarm optimization technique. Appl Therm Eng. 2010;30(11–12):1417–25.
82. Garoosi F, Hoseininejad F, Rashidi MM. Numerical study of heat transfer performance of nanofluids in a heat exchanger. Appl Therm Eng. 2016;105:436–55.
83. Othman MI, Said S, Marin M. A novel model of plane waves of two-temperature fiber-reinforced thermoelastic medium under the effect of gravity with three-phase-lag model. Int J Numer Meth Heat Fluid Flow. 2019;29(12):4788–806.