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Energy and Exergy Analysis of a Shell and Tube Heat Exchangers Having Smooth and Corrugated Inner Tubes

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Anahtar Kelimeler
Heat exchanger design,
Exergy analysis,
Heat transfer enhancement,
Corrugated tubes

Abstract: Shell and tube heat exchangers are one of the most used heat exchanger types in applications and it is important to predict heat transfer capacity and pressure loss in both design stage. Heat transfer capacity of a heat exchanger can be enhanced by using tubes having enhanced surfaces instead of smooth ones. In this study, the usage of corrugated tubes in a shell and tube heat exchanger is investigated by using ε-NTU method, energy/exergy analysis. The impact of the usage of corrugated tubes on hot and cold fluid outlet temperatures, energy/exergy efficiencies, entropy generation and total exergy destruction are researched for various operation conditions. The results revealed that the difference between fluid outlet temperatures can be decreased by using tubes having corrugated surfaces instead of smooth ones because of fluid mixing and secondary flows obtained by means of the corrugations. Overall heat transfer coefficient of heat exchanger is enhanced up to 8% with the usage of corrugated tube in considered operation conditions. It is exhibited that the energy and exergy efficiencies of heat exchanger can be improved up to 18% and 16% with the usage of corrugated tubes instead of one having smooth tubes. Moreover, the entropy generation because of heat transfer and pressure loss and total exergy destruction of considered heat exchangers are determined to reveal the impact of corrugated tubes.

Pürüzsüz ve Koruge İç Borulara Sahip Bir Gövde Borulu Isı Değiştiricisinin Enerji ve Ekserji Analizi

Keywords
Isı değiştiricisi tasarımı,
Ekserji analizi,
Isı transferi iyileştirilmesi,
Koruge borular

Özet: Gövde borulu ısı değiştiricileri uygulama en çok kullanılan ısı değiştirici türlerinden biridir ve tasarım aşamasında ısı transferi kapasitesi ve basınç kaybının tahmin edilmesi önemlidir. Bir ısı değiştiricisinin kapasitesi pürüzsüz yüzeyler yerinde iyileştirilmiş yüzeye sahip borular kullanılarak arttırılabilir. Bu çalışmada, koruge boruların bir gövde borulu ısı değiştiricisinde kullanımı ε-NTU method, enerji/ekserji analizleri kullanılarak araştırılmıştır. Koruge boru kullanımının sıcak ve soğuk akışkan çıkış sıcaklıklarına, enerji/ekserji verimlerine, entropi üretimine ve ekserji yıkımına etkisi farklı çalışma şartları için incelenmiştir. Sonuçlar koruge yüzeyler kullanılarak elde edilen akışkan karışması ve ikincil akışlar sebebiyle pürüzsüz yüzeyler yerine akışkan çıkış sıcaklıkları arasındaki farkın azaltılabileceğini ortaya çıkarmıştır. Göz önüne alınan çalışma şartlarında toplam ısı transfer katsayısı koruge borular kullanılarak %8'e kadar iyileşmiştir. Pürüzsüz boru yerine koruge boru kullanımıyla ısı değiştiricisinin enerji ve ekserji verimlerinin sırasıyla %18 ve %16'ya kadar arttırılabileceği ortaya konmuştur. Ayrıca, göz önüne alınan ısı değiştiricilerinin ısı transferi ve basınç kaybı kaynaklı entropi üretimi ve ekserji yıkımı koruge boru kullanımının etkisini açığa çıkarmak için belirlenmiştir.

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1. Introduction

Heat exchangers (HEXs) are defined as equipments used for transferring heat between two or more fluids and they are used in many fields such as refrigeration, power production, air conditioning, heat recovery etc. They are generally categorized by construction, fluid number, flow arrangement, etc. [1]. Among the classification according to construction, tubular HEXs are generally preferred because of their high operating pressure/temperature resistance, installation cost and ease of maintenance [2]. In application, it is important to design a HEX having higher heat transfer capacity for constant size so it is necessary to obtain higher overall heat transfer coefficients (HTCs) by considering active and passive heat transfer improvement methods. In active heat transfer improvement methods, it is essential to use an external power such as electric, vibration or acoustic so the usage of this method is not suitable in HEXs because of power consumption. In passive heat transfer enhancement methods, it is necessary to use special geometries (such as extended, rough, coated etc.) or additives for working fluid (such as nanofluid) and this method is generally used in HEX applications [3]. One of the special geometries can used in tubular HEXs is corrugated tubes which have corrugations on the surface. It is known that the heat transfer improvement accompanied by higher pressure loss can be obtained with the usage corrugated tubes instead of smooth ones. It is expected that corrugations make possible to mix boundary layers, reduce thermal boundary layer thickness, generate secondary flows, intensify and increase wet perimeters which are very important parameters in heat transfer enhancement [4]-[7]. With these contributions to fluid flows, corrugated tubes can be used in order to design HEX having smaller size and better thermal performance compared to ones comprised of smooth tubes.

In application, the most used tubular HEX type is shell and tube heat exchangers (STHEX) and their design and thermal performance are generally evaluated with heat transfer and first law of thermodynamics analyses. In these analyses, overall HTC, tube/shell side HTCs, fluid temperatures are determined and design of HEX is generally made by using various methods. In addition, Dincer [8], Bejan et al. [9] and Kotas [10] proposed that second law of thermodynamics, exergy, irreversibility and entropy generation can be used as a good tool for evaluation of thermal system design and equipments such as HEXs. It is known that exergy is not conserved like energy and irreversibilities result in destruction of it. It is also known that heat transfer and pressure loss are causes entropy generation and irreversibilities in HEXs. Some studies on second law analyses of HEXs are given as follows:

Mert and Reis [11] conducted experiments in order to specify performance of a STHEX and performed exergy-based analysis. The variation of tube/shell side exergy, inlet/outlet temperature of fluids and exergy efficiency of HEX with flow rate is investigated. In addition, exergy destruction rates are examined for various flow conditions. Their study showed that exergy efficiency of HEX rises with increment of hot fluid inlet temperature. Sensitivity analysis also revealed that the efficiency of HEX is significantly related to flow rate and temperature. They pointed out that it is necessary to consider exergy analysis for better design of a thermal system.

Naphon [12] presented an experimental study in order to research entropy generation, exergy loss and heat transfer of concentric tube HEX. The impact of hot fluid inlet temperature (40-50^{o}C), cold fluid inlet temperature (15-20^{o}C), hot/cold fluid flow rate (0.02 and 0.20 kg/s) on heat transfer characteristics, entropy generation and exergy loss are investigated and it is observed that entropy generation and exergy loss increase with increasing hot fluid flow rate and inlet temperature. A mathematical model for determination of these parameters is developed. The results of the mathematical model are compared with experimental one and it is seen that this model can predict experimental data for test operation conditions.

Dizaji et al. [13] conducted experiments to research the usage of corrugated tubes in inner and shell sides of a HEX by using exergy analysis as an evaluation method. They considered the tubes having convex and concave corrugations, various diameters and constant corrugation pitch and height. Their study showed that exergy loss increases up to 31% and 81% with the usage of corrugated tube as inner onr and inner/shell ones, respectively. The HEXs comprised of concave corrugated shell and convex corrugated tube have higher exergy loss results compared to other HEXs tested. It also was observed that number of transfer unit increases up to 19% and 60% with the usage of corrugated tube as inner tube and inner/shell tube compared to HEX having smooth inner/shell tubes, respectively.

Hajabdollahi et al. [14] presented exergy-based optimization study for a one shell two passes HEX by determining exergy efficiency and cost as objective functions. They aimed the specify best and optimum design parameters of considered HEX by using genetic algorithm. According to performed analysis, it can be understood that exergy destruction is an essential parameter in design of a HEX and the efforts for reduction of it increases cost. They also stated that the improvement in exergy efficiency of a STHEX results in cost increment. As another result of the study, tube layout has not significant parameter for HEX design compared to other ones.

Wang et. al [15] experimentally researched the usage of sealer in STHEX in order to minimize shell-baffle leakage flow. They used oil in shell side and water in tube side, respectively. The experiments showed that overall and shell side HTCs can be increased up to 19.7% and 25.5% with the usage of sealers in application, respectively. Although the pressure loss of shell side fluid is higher up to 48.8% compared to design having no sealer, they stated that it is reasonable increment compared to heat transfer improvement. In addition, it is pointed out that exergy efficiency of considered HEX can be improved up to 14.4%.

Esfahani and Languri [16] investigated the impact of usage graphene oxide/water nanofluid in a STHEX, experimentally. They specified thermal conductivity and viscosity of nanofluid for weight concentration of 0.01% and 0.1% and determined exergy loss of nanofluid for various flow rates and temperatures. The experiments revealed that the nanofluid thermal conductivity is increased 9% and 20% for weight concentration of 0.01% and 0.1% compared to distilled water. In addition, a HEX operated with distilled water and graphene/water nanofluid having weight concentration of 0.01% and 0.1% is compared and it is seen that with usage of nanofluid instead of distilled water augments exergy loss up to 109% in tested conditions.

Pethkool et al. [17] researched heat transfer of smooth and nine corrugated tubes having various geometrical specifications for single phase flow conditions. In the study, a concentric tube HEX is used and water is selected as working fluid both sides of it. The experiments revealed that the Nusselt number (Nu) and friction factor can be increased up to 3.01 and 2.14 times with usage of corrugated tube instead of smooth one, respectively. It is also noted that theses parameters increase with rise of the rib-height ratio and pitch ratio. As another result of the study, they developed Nu and friction factor correlation having deviations of 9% and 4%, respectively.

Shirvan et al. [18] experimentally studied effectiveness of STHEX having corrugated inner tube by using means of response surface methodology. In this methodology, various cold water flow rates (11-19 L/min), hot water flow rates (7-11 L/min), wavy wavelengths (0-80 mm) and wavy starting lengths (0-120 mm), are considered and it is aimed to achieve the highest values of the overall HTC and effectiveness. It is seen that overall HTC and effectiveness reduces with improvement of the wavy starting lengths. The levels of cold-water flow rates, hot water flow rates, wavy and wavy starting lengths for maximization of HEX effectiveness and HTC are determined. Moreover, they defined new sustainability index by means of exergy efficiency and it concluded that the smooth tube is less sustainable than corrugated one.

Dizaji et al. [19] researched heat transfer characteristics and effectiveness of concentric tube HEX having corrugated tubes in various wall tube configurations which smooth, convex and concave. In conducted experiments, they kept inlet temperatures of hot and cold water at 40°C and 8°C, respectively. They observed the heat transfer characteristics of a HEX is significantly affected with the usage of concave and convex profile corrugated tubes and HEX made of concave corrugated outer tube and convex corrugated inner tube has maximum effectiveness. In addition, they stated that friction factor and Nu increases up to 117% and 254% with the usage of the tube having corrugated profile in both side of HEX.

The main aim of the current study is to perform energy and exergy analysis of two STHEXs each of them having inner smooth and corrugated tubes. In literature, the performance of this type HEXs is generally determined with first law of thermodynamics and conducted for DPHEXs. In this study, two STHEXs having smooth and corrugated tubes are designed and the impact of hot and cold flow rates on HTC, pressure loss, outlet temperatures and energy efficiency is studied in the view of first law of thermodynamics. Moreover, the variation of exergy efficiency, exergy destruction, entropy generation due to temperature difference and pressure loss and with flow fluid rates are investigated by using the Engineering Equation Solver Software [20]. Since there are limited number of studies on evaluation of the usage of corrugated tubes in STHEX by using second law of thermodynamics, it is expected that current investigation will fill the gap in the literature.

2. Design Methodology

In the analysis, one shell and one pass STHEXs are considered and the geometric dimensions of it given in Table 1. It should be noted that HEX is operated for the various hot fluid flow rates (12-24 kg/s), hot fluid inlet temperature (90-70°C) cold fluid flow rate (in the range of 12-24 kg/s), and cold fluid inlet temperature (30-50°C). To improve thermal performance of these HEXs, smooth and corrugated tube having equivalent outside/inside diameter of 28.5/24 mm and length of 6 m are selected. The schematic representation of corrugated tube can be seen Figure 1 and it can be seen that corrugation pitch (p), corrugation height (e), helix angle (θ), outside diameter (Do) and inside diameter (Di) are the main geometric parameters of a corrugated tube. Schematic representation of considered STHEX, tube arrangement, and isometric view of are given as a in Figure 2a), Figure 2b) and Figure 2c), respectively.

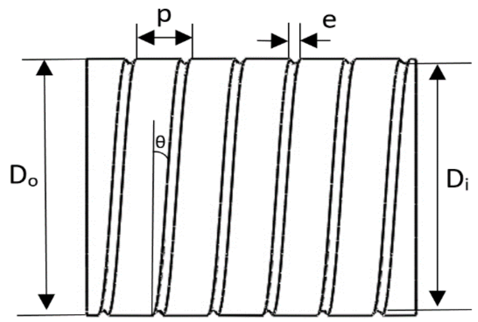
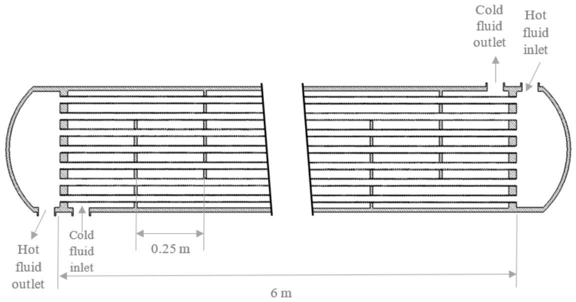


Figure 1. The schematic representation of corrugated tube



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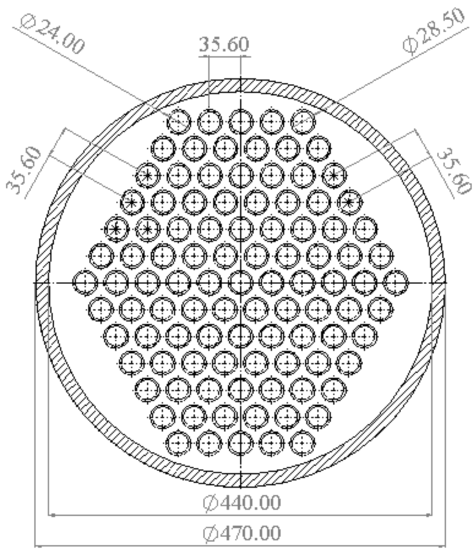

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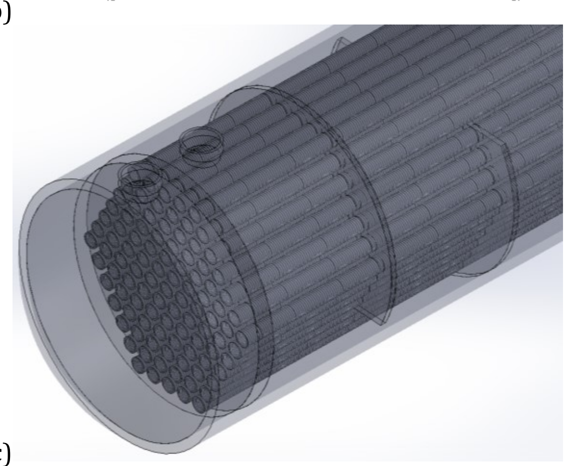


c)

Figure 2. Schematic representation of a) considered STHEX, b) tube arrangement, and c) isometric view of STHEX

The design procedure of considered STHEX is obtained from [21], the equations are used in the calculations given as follows:

The heat transfer capacity of a HEX is estimated as follows:

$$\dot{Q} = \varepsilon \dot{Q}_{max} \tag{1}$$

The maximum heat transfer capacity of a HEX can be estimated as follows:

Table 1. Geometric specifications of the considered HEX

Parameter	Value
Smooth tube outside diameter	28.5 mm
Smooth tube inside diameter	24 mm
Corrugated tube outside diameter	28.5 mm
Corrugated tube inside diameter	24 mm
Corrugation pitch	5.5 mm
Rib height	1 mm
Number of tubes	101
One tube length	6000 mm
Tube side fouling factor	0.000176 m²K/W
Shell side fouling factors	0.000176 m²K/W
Distance between tube center	0.03563
Baffle distance	250 mm
Inner surface area increment of tube compared to smooth one	%120
Outer surface area increment of tube compared to smooth one	%133

$$\dot{Q}_{max} = C_{min}(T_{h,i} - T_{c,i}) \tag{2}$$

The heat capacities of hot and cold fluids are calculated as follows:

$$C_h = \dot{m}_h c_{p,h} \tag{3}$$

$$C_c = \dot{m}_c c_{p,c} \tag{4}$$

Minimum and maximum heat capacities are determined by using calculated values of hot and cold fluid heat capacities.

The energy efficiency (effectiveness) of a STHEX is calculated as follows:

$$\varepsilon = \frac{2}{1 + C + (1 + C^2)^{1/2} \frac{1+\exp(-NTU(1+C^2)^{1/2})}{1-\exp(-NTU(1+C^2)^{1/2})}} \tag{5}$$

The heat capacity ratio is calculated as follows:

$$C = \frac{C_{min}}{C_{max}} \tag{6}$$

Number of transfer unit is calculated as follows:

$$NTU = \frac{U_o A_o}{C_{min}} \tag{7}$$

Overall HTC is calculated as follows:

$$\frac{1}{U_o A_o} = \frac{1}{h_i A_i} + \frac{R_{fi}}{A_i} + \frac{\ln(D_o/D_i)}{2\pi L_{total} k_{tube}} + \frac{R_{fo}}{A_o} + \frac{1}{h_s A_o} \tag{8}$$

HTC of hot water flowing in smooth tube is estimated as follows:

$$h_{i,smooth} = \frac{\left(\frac{f_{smooth}}{8}\right) Re_{i,smooth} Pr_i}{1.07 + 12.7\left(\frac{f_{smooth}}{8}\right)^{0.5} (Pr^{2/3} - 1)} \frac{k}{D_i} \quad (9)$$

In the Eq. (9), friction factor and Reynolds numbers are determined as follows:

$$f_{smooth} = (0.79 \ln Re_{i,smooth} - 1.64)^{-2} \quad (10)$$

$$Re_{i,smooth} = \frac{\rho_i V_i D_i}{\mu_i} \quad (11)$$

HTC of hot water flowing in corrugated tube is estimated by using correlation of Pethkool et al. [7] and given as follows:

$$h_{i,corrugated} = 1.579 Re_{i,corrugated}^{0.639} Pr_i^{0.3} \left(\frac{e}{D_i}\right)^{0.46} \left(\frac{p}{D_i}\right)^{0.35} \frac{k}{D_i} \quad (12)$$

HTC of shell side estimated as follows:

$$h_{shell} = 0.36\, Re_{shell}^{0.55} Pr^{1/3} \left(\frac{\mu_b}{\mu_{shell}}\right)^{0.14} \frac{k}{D_e} \quad (13)$$

Reynolds number is determined as follows:

$$Re_{shell} = \frac{G\, D_e}{\mu_{shell}} \quad (14)$$

The equivalent diameter of shell is estimated for triangular pitch tube layout as follows:

$$D_e = \frac{4\left(\frac{P_T^2\sqrt{3}}{4} - \frac{\pi D_o^2}{8}\right)}{\frac{\pi D_o}{2}} \quad (15)$$

Mass flux is determined as follows:

$$G = \frac{\dot{m}}{A_{shell}} \quad (16)$$

Shell side area is calculated as follows:

$$A_{shell} = \frac{D_{shell}(P_T - D_o)B}{P_T} \quad (17)$$

Shell diameter of HEX is estimated as follows:

$$D_{shell} = 0.637\sqrt{\frac{CL}{CTP}\left[\frac{A_o (P_T/D_o)^2 D_o}{L}\right]^{0.5}} \quad (18)$$

In Eq. (18), CTP is equal to 0.93, 0.90, 0.85 for HEX having one, tube and three passes, respectively. Also, CL is equal to 1 and 0.87 for tube layout 45°-90° and 30°-60°, respectively.

Outlet temperature of both fluids are estimated as follows:

$$T_{h,o} = \frac{\dot{Q}}{\dot{m}_h c_{p,h}} - T_{h,i} \quad (19)$$

$$T_{c,o} = \frac{\dot{Q}}{\dot{m}_c c_{p,h}} + T_{c,i} \quad (20)$$

Tube side pressure loss for smooth tube is calculated as follows:

$$\Delta P_{i,smooth} = \left(4\, f_{smooth} L \frac{N_p}{D_i} + 4N_p\right) \rho \frac{V_i^2}{2} \quad (21)$$

Tube side pressure loss for corrugated tube is calculated as follows:

$$\Delta P_{i,corrugated} = \left(4\, f_{corrugated} L \frac{N_p}{D_i} + 4N_p\right) \rho_i \frac{V_i^2}{2} \quad (22)$$

Friction factor of fluid flowing in corrugated tube by using correlation of Pethkool et al. [7] and given as follows:

$$f_{corrugated} = 1.15 Re^{-0.239} \left(\frac{e}{D_H}\right)^{0.179} \left(\frac{P}{D_H}\right)^{0.164} \quad (23)$$

Shell side pressure loss is calculated as follows:

$$\Delta P_{shell} = \frac{f_{shell} G^2 (N_b + 1) D_{shell}}{2 \rho_{shell} D_e \emptyset} \quad (24)$$

In Eq. (18), friction factor is estimated as follows:

$$f_{shell} = \exp\left(0.576 - 0.19 \ln(Re_{shell})\right) \quad (25)$$

The performance evaulation criteria (PEC) is determined as follows:

$$PEC = \frac{\left(Nu_{i,corrugated}/Nu_{i,smooth}\right)}{\left(f_{corrugated}\ /f_{smooth}\right)} \quad (26)$$

Flow exergy of hot fluid inlet, hot fluid outlet, cold fluid inlet and cold fluid outlet is estimated as follows, respectively:

$$\dot{Ex}_1 = \dot{m}_h((h_1 - h_0) - T_0(s_1 - s_0)) \quad (27)$$

$$\dot{Ex}_2 = \dot{m}_h((h_2 - h_0) - T_0(s_2 - s_0)) \quad (28)$$

$$\dot{Ex}_3 = \dot{m}_c((h_3 - h_0) - T_0(s_3 - s_0)) \quad (29)$$

$$\dot{Ex}_4 = \dot{m}_c((h_4 - h_0) - T_0(s_4 - s_0)) \quad (30)$$

Exergy efficiency is calculated as follows:

$$\eta_{ex} = \frac{Ex_4 - Ex_3}{Ex_1 - Ex_2} \quad (31)$$

Entropy generation because of heat transfer for both fluids is estimated as follows, respectively [22]:

$$S_{gen,ht,h} = \dot{m}_{hot} c_{p,hot} \ln \frac{T_{h,o}}{T_{h,i}} \quad (32)$$

$$S_{gen,ht,c} = \dot{m}_{c} c_{p,c} \ln \frac{T_{c,o}}{T_{c,i}} \quad (33)$$

Entropy generation because of pressure loss for hot and cold fluids is estimated as follows, respectively [22]:

$$S_{gen,\Delta P,h} = \frac{\dot{m}_h}{\rho_h} \Delta P_h \quad (34)$$

$$S_{gen,\Delta P,c} = \frac{\dot{m}_c}{\rho_c} \Delta P_c \quad (35)$$

Total entropy generation is estimated as follows [22] :

$$S_{gen,total} = S_{gen,ht,h} + S_{gen,ht,c} + S_{gen,\Delta P,h} + S_{gen,\Delta P,c} \quad (36)$$

Exergy losses both fluids are determined as follows:

$$Ex_{loss,h} = (S_{gen,ht,h} + S_{gen,\Delta P,h}) T_0 \quad (37)$$

$$Ex_{loss,c} = (S_{gen,ht,c} + S_{gen,\Delta P,c}) T_0 \quad (38)$$

Total exergy loss of HEX is calculated as follows:

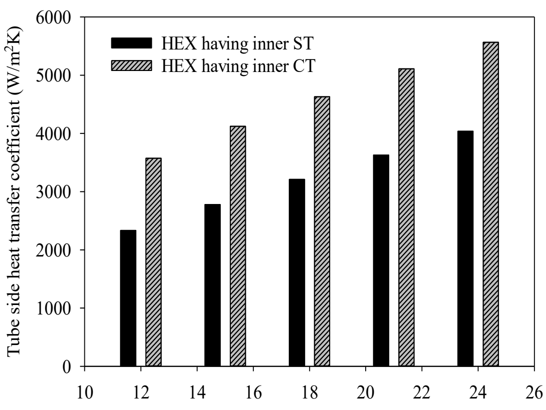
$$Ex_{loss,t} = Ex_{loss,h} + Ex_{loss,c} \quad (39)$$

3. Results and Discussion

In HEX design, the usage of the tubes having enhanced surfaces are preferred in order to improve thermal performance of HEX. For this purpose, it is necessary to increase HTC of working fluids with various active and passive heat transfer enhancement methods. The analysis of a HEX is generally presented with the consideration of the first law of thermodynamics with the calculation of fluid temperatures and pressure losses. In addition, it is very important to take into consideration of irreversibilities or entropy generation in the view of the second law of thermodynamics. It should be noted that temperature difference, fluid mixing and pressure loss are the main reasons of entropy generations for a HEX [1]. In the evaluation of a HEX performance, it is also important the determine these parameters by means of second law of the thermodynamics. To determine thermal performance of a STHEX having smooth and corrugated inner tubes, various parameters such as HTCs, pressure loss, efficiency, entropy generation due to heat transfer/pressure loss and exergy losses are estimated by using equations given previous section and the results are compared following paragraphs.

Figure 3a) shows the variation of tube side HTC of inner smooth and corrugated tubes for various hot fluid flow rates which are corresponding to Reynolds number of 17969-35397. Tube side HTC of smooth and corrugated tubes are estimated by using Eq. (9) and Eq. (12), respectively. It should be noted that cold fluid flow rate and velocity is kept constant as 18 kg/s and 0.87 m/s, respectively. It is observed that HTC augments with increment of fluid flow rate because of rise in the fluid velocity. Also, it can be concluded that tube HTC rises in the range between 38%-53% with increasing flow rate and with the usage of corrugated inner tube instead of smooth one. This increment can be explained with fluid mixing and secondary flows obtained by means of the corrugations. Also, Figure 3b) represents the impact of hot fluid flow rate overall HTC of HEX. It is determined by considering outer diameter area of tubes and by means of Eq. (8).

Since tube side HTC is improved with the usage of corrugated tube instead of smooth one, overall HTC is also increased with the rise of hot fluid flow rate. The improvement in overall HTC has the maximum value of 9% for the lower hot fluid flow rate.



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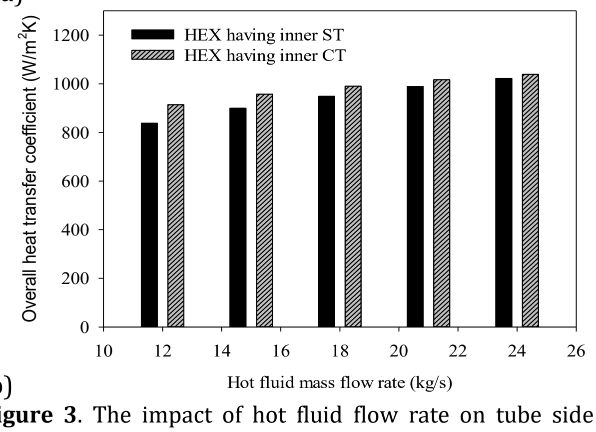


b)

Figure 3. The impact of hot fluid flow rate on tube side convective HTC and overall HTC for HEX operation conditions of a) m_c= 18 kg/s, $T_{c,i}$=30°C, m_c= 18 kg/s, b) m_c= 18 kg/s, $T_{h,i}$=90°C, m_c= 18 kg/s

Figure 4 illustrates the variation of tube side pressure loss of inner smooth and corrugated tubes for various hot fluid flow rates. Tube side pressure loss for smooth and corrugated tubes are calculated by means of the Eq. (21) and Eq. (22), respectively. It is shown that the usage of corrugated inner tube instead of smooth one is resulted in higher pressure loss and it increases with the increment of flow rate. It is specified that pressure loss of corrugated tube has 1.6 times higher pressure loss compared to smooth one for the highest flow rate because of increased friction surfaces of corrugation where the cold fluid pressure loss is constant value of 32 kPa.

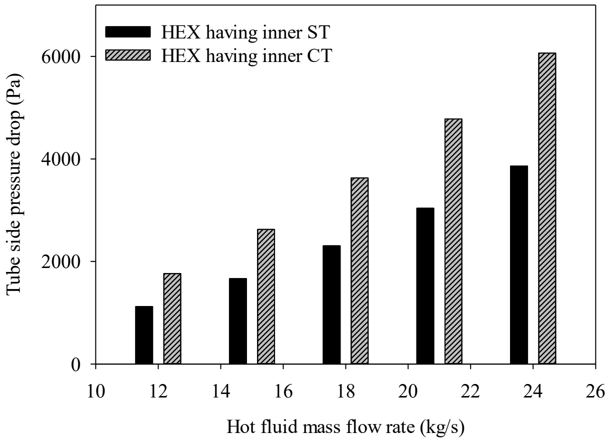
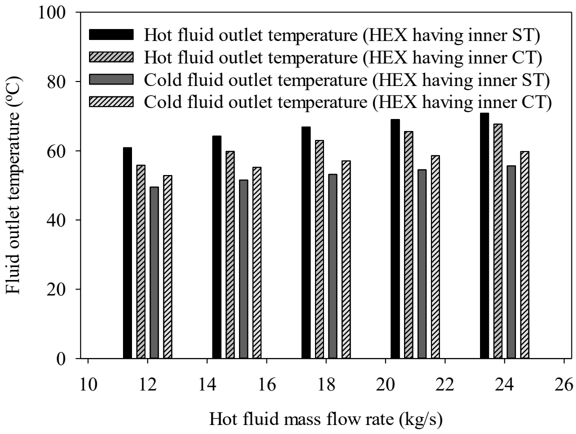


Figure 4. The impact of hot fluid flow rate on tube side pressure drop for HEX operation conditions of m_c= 18 kg/s, $T_{c,i}$=30°C, m_c= 18 kg/s



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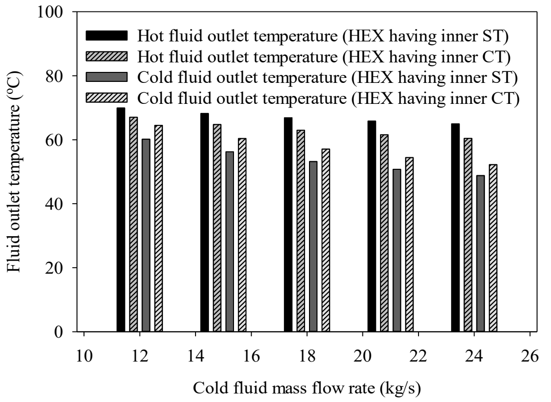


b)

Figure 5. The impactof fluid inlet temperatures on fluid outlet temperature for HEX operation conditions of a) m_c= 18 kg/s, $T_{c,i}$=30°C, m_c= 18 kg/s, b) m_c= 18 kg/s, $T_{h,i}$=90°C, m_c= 18 kg/s

Figures 5a) and 5b) compare the influence of flow rates on fluid outlet temperatures HEXs working constant hot fluid inlet temperature of 90°C and cold fluid inlet temperature of 30°C, respectively. In order to reveal the impact of corrugated tube usage on outlet temperature of HEX, the outlet temperatures of fluids for the HEX having inner smooth and corrugated tubes are determined by means of the Eq. (19) and Eq. (20), respectively. According to Figure 5a), the outlet temperature of hot fluid decreases up to approximately 5°C the usage of corrugated tube instead of smooth one where the outlet temperature of cold fluid rises nearly 4°C for various flow rates of hot fluid. Figure 5b) depict that the outlet temperature of hot fluid decreases up to approximately 4.5°C the usage of corrugated tube instead of smooth one where the outlet temperature of cold fluid rises nearly 4.3°C for various flow rates of cold fluid. It is revealed that the difference between inlet and outlet temperatures reduces with the increment of flow rate for both HEX having smooth and corrugated tubes. These results imply that the energy efficiency of a STHEX can be improved with the usage of corrugated tubes instead of smooth ones.

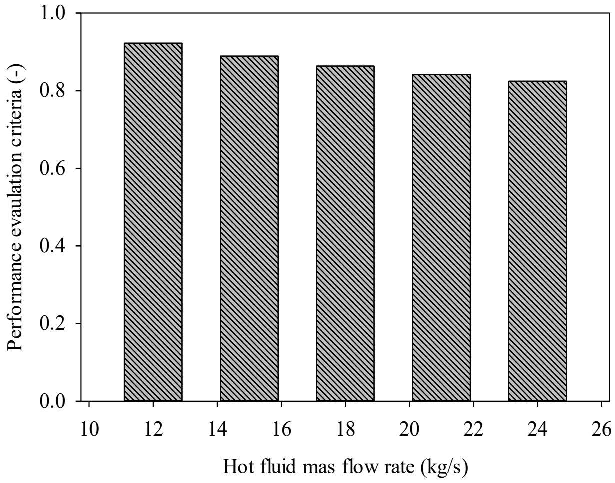
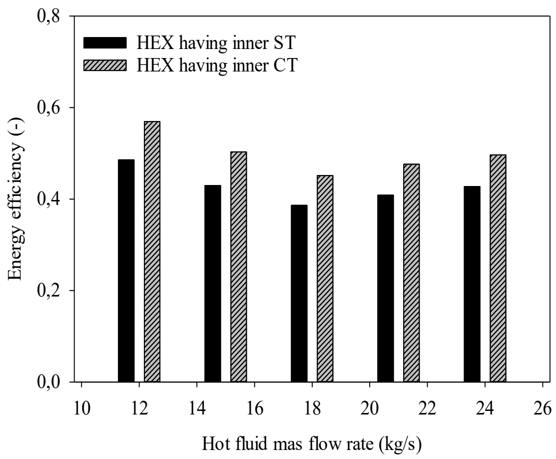


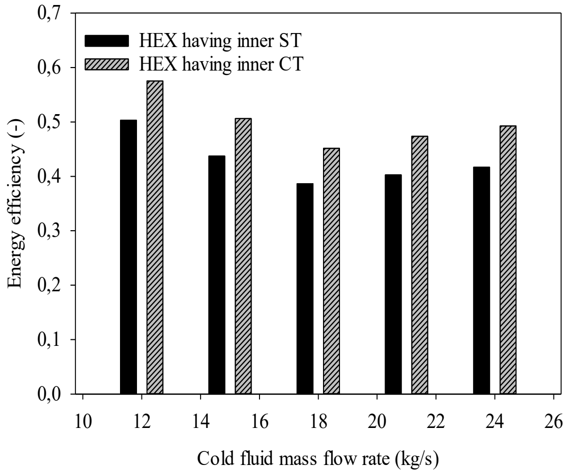
Figure 6. The variation of PEC with hot fluid mass flow rate

Figure 6 depict the variation performance evaluation criteria, which is estimated by using Eq. (26), with hot fluid mass flow rate and it is reduced with rise of mass flow rate. Since the increment of smooth and corrugated tube friction factor ratio value is higher than smooth and corrugated tube HTC ratio for higher mass flow rates, it is decreased from 0.92 to 0.82.

Figures 7a) and 7b) show the impact of fluid flow rates on HEX energy efficiency, respectively. The energy efficiency value is estimated by using Eq. (5) and it can be observed from these figures that the energy efficiency of a HEX is significantly affected by fluid flow rates. In Figure 7a), the energy efficiencies of both HEXs having smooth and corrugated tubes is compared and it is seen that the highest energy efficiency values are determined for the hot fluid flow rate of 12 kg/s and obtained as 48% and 56% for HEX having inner smooth and corrugated tubes, respectively.



a)



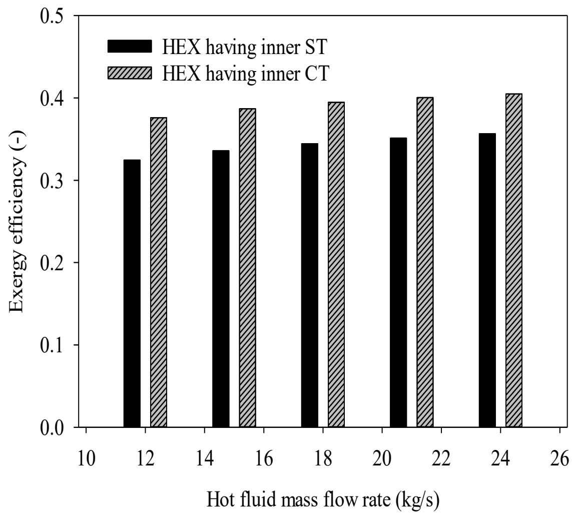
b)

Figure 7. The impact of fluid flow rates on energy efficiency for HEX operation conditions of a) m_c= 18 kg/s, $T_{c,i}$=30°C, m_c= 18 kg/s, b) m_c= 18 kg/s, $T_{h,i}$=90°C, m_c= 18 kg/s

The impact of cold flow rate on energy efficiencies of both HEXs having smooth and corrugated tubes are also evaluated in Figure 7b) and it is observed that the highest energy efficiency values are determined for the cold fluid flow rate of 12 kg/s and obtained as 50% and 57% for HEX having inner smooth and corrugated tubes, respectively. These enhancements can be explained with hot fluid outlet temperature reduction and cold fluid outlet temperature increment in all cases.

Figures 8a) and 8b) represent exergy efficiency of considered HEXs having inner smooth and corrugated tubes, respectively. The exergy efficiency value is estimated by using Eq. (31) and it can be understood from the figures that energy and exergy efficiencies of HEX is increases with the usage of corrugated tube instead of smooth one because of heat transfer improvement. In Figure 8a), the highest values of exergy efficiency are obtained for the hot fluid flow rate of 12 kg/s and obtained as 32% and 37% for HEX having inner smooth and corrugated tubes, respectively. In Figure 8b), the highest values of energy efficiency are obtained for the cold fluid flow rate of 12 kg/s and obtained as 40% and 45% for HEX having inner smooth and corrugated tubes, respectively.

Figures 9a) and 9b) show the impact of flow rates on entropy generation of fluids due to heat transfer for HEXs for constant hot and cold fluid inlet temperatures, respectively. Entropy generation because of heat transfer is calculated by using Eq. (32) and Eq. (33) for fluids flowing in smooth and corrugated tubes, respectively. These figures show that entropy generation of HEXs due to heat transfer and increases with the usage of corrugated tube compared to smooth one since secondary flows formed by corrugations. The entropy generation because of heat transfer of HEXs having smooth and corrugated tubes is increased up to 5% and %6, respectively. This augmentation is the result of variation of outlet temperatures since secondary flows help to reduce thermal boundary layer thickness.



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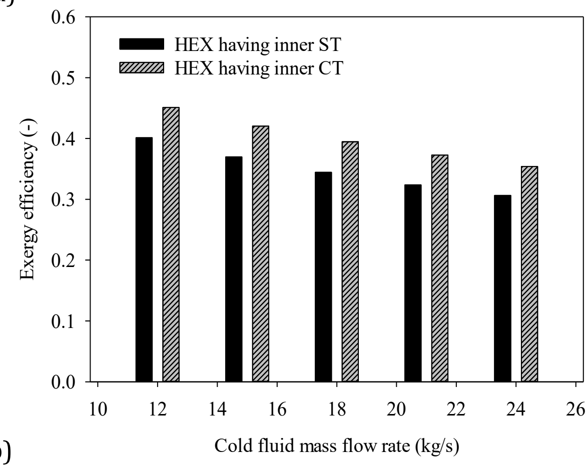

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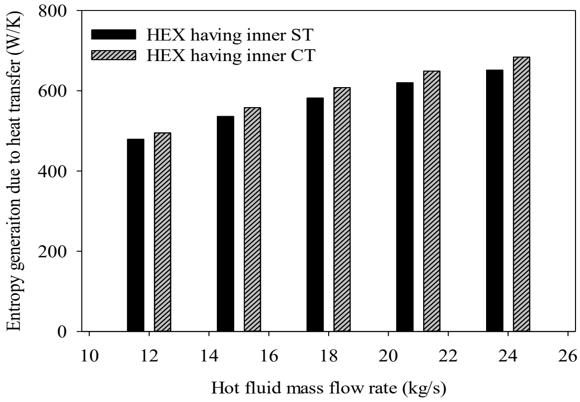
Figure 8. The impact of fluid flow rates on exergy efficiency for HEX operation conditions of a) m_c= 18 kg/s, $T_{c,i}$=30°C, m_c= 18 kg/s, b) m_c= 18 kg/s, $T_{h,i}$=90°C, m_c= 18 kg/s

The variation of the entropy generation of fluids due to pressure loss for considered HEXs is given in Figure 10a) and 10b) for various flow rates of hot and cold fluids, respectively. Entropy generation due to pressure loss is determined by using Eq. (34) and Eq. (35) for fluids flowing in smooth and corrugated tubes, respectively. These figures show that entropy generation of both hot and cold fluid due to pressure



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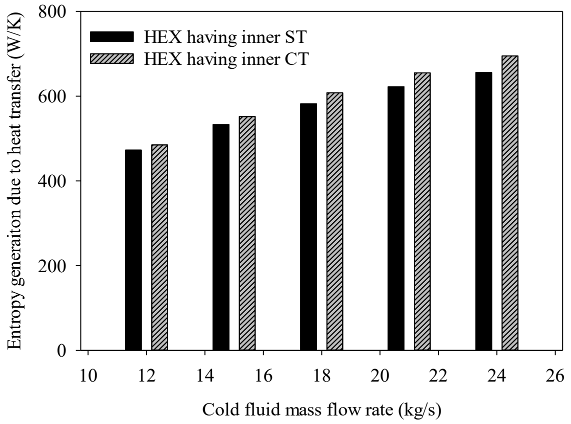

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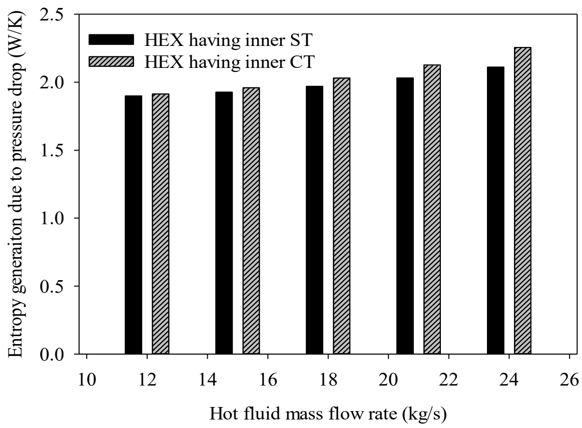
Figure 9. The effect of fluid flow rates on exergy efficiency for HEX operation conditions of a) m_c= 18 kg/s, $T_{c,i}$=30°C, m_c= 18 kg/s, b) m_c= 18 kg/s, $T_{h,i}$=90°C, m_c= 18 kg/s



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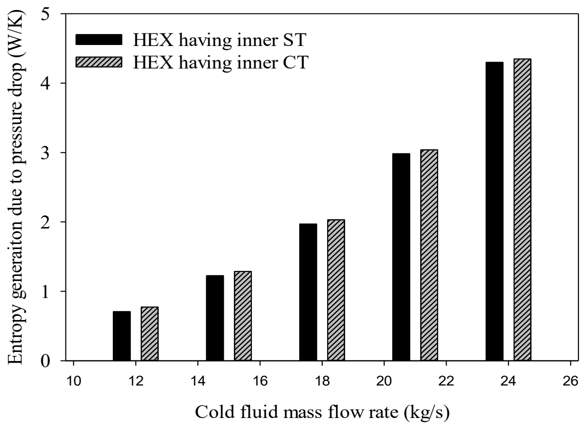
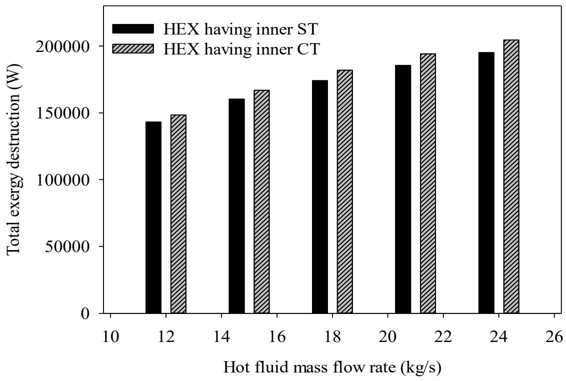


b)

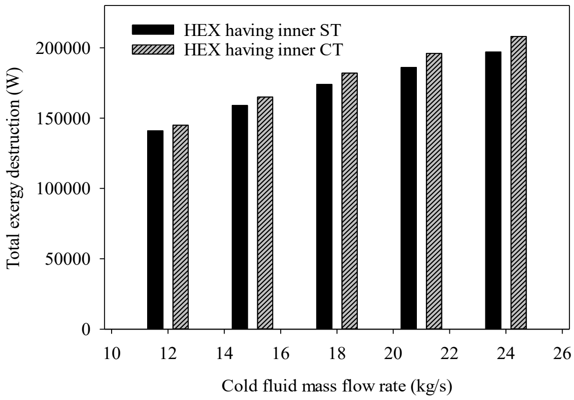
Figure 10. The effect of fluid flow rates on entropy generation due to a) heat transfer and b) pressure drop for HEX operation conditions of a) m_c= 18 kg/s, $T_{c,i}$=30°C, m_c= 18 kg/s, b) m_c= 18 kg/s, $T_{h,i}$=90°C, m_c= 18 kg/s

loss augments with the usage of corrugated tube compared to smooth one since corrugations contribute turbulence and mixing flow. It is seen that entropy generation of hot and cold fluids due to pressure loss increases up to 7% and 9%, respectively. It also can be understood that entropy generation due to pressure loss is much lower than entropy generation due to heat transfer so it can be neglected in the second law analyses of HEXs.

Figures 11a) and 11b) depict the impact of fluid flow rates on total exergy destruction for HEXs for constant hot and cold fluid inlet temperatures, respectively. It is determined by using Eq. (39) and considering entropy generation due to heat transfer and pressure loss of hot and cold fluids. These figures present that total exergy destruction of HEX increases with the usage of corrugated tubes instead of smooth ones and it can be explained with the higher entropy generation results for corrugated tubes. In addition, the impact of fluid inlet temperature on total exergy destruction results are given in Table 2.



a)



b)

Figure 11. The impact of fluid flow rates on exergy destruction for HEX operation conditions of a) m_c= 18 kg/s, $T_{c,i}$=30°C, m_c= 18 kg/s, b) m_c= 18 kg/s, $T_{h,i}$=90°C, m_c= 18 kg/s

4. Conclusion

In HEX design and sizing, it is important to use tubes having enhanced surfaces in order to reduce HEX size and effectiveness. Besides calculations heat transfer characteristics, exergy analysis can be used as key parameter in the performance determination of a HEX. In the current study, the usage of corrugated tubes, which is one of the tubes having enhanced surfaces, in a STHEX is parametrically investigated. The points which can be concluded from current study given as follows:

- The HEX having corrugated tubes has 1.53 times higher tube side HTC compared to smooth ones since fluid mixing and secondary flows obtained by means of the corrugations.
- The HEX having corrugated tubes has 1.6 times higher tube side pressure loss compared to smooth ones.
- The difference between hot and fluid outlet temperature of HEXs having both smooth and corrugated inner tubes are compared and it is observed that the difference can be diminished with the application of corrugated tubes instead of smooth ones.
- The performance evaluation criteria value is determined between 0.92 and 0.82 and it can be increased by using corrugated tubes having higher heat transfer area and lower friction factor value.
- Both the energy and exergy efficiencies of the HEX can be improved up 17% and 18%, respectively.
- The improvements in heat transfer, energy and exergy efficiencies of considered HEXs can be explained with the fluid mixing and secondary flows obtained by means of the corrugations rather than heat transfer area increment.
- The entropy generation due to pressure loss can be ignored in the second law analysis of HEXs.
- The total exergy destructions of HEXs having smooth and corrugated tubes are compared and it is seen that the HEX having corrugated tubes has higher the total exergy destruction compared to smooth ones.
- Although higher entropy generation and total exergy destruction results of the HEX having corrugated tubes, it is very important to use enhanced surfaces since they decrease difference between hot and cold fluid outlet temperatures which is directly related to performance of it.

Nomenclature

A_o	Heat transfer surface area based on outside diameter of tube, m²
B	Baffle distance, m
C	Heat capacity ratio
$c_{p,c}$	Specific heat capacity of hot fluid, J/kgK
$c_{p,h}$	Specific heat capacity of hot fluid, J/kgK
C_c	Heat capacity of cold fluids, W/K
C_h	Heat capacity of hot fluids, W/K
C_{min}	Minimum heat capacity of fluids, W/K
Do	Smooth tube outside diameter, m
Di	Smooth tube outside diameter, m
De	Corrugated tube equivalent diameter, m
Ds	Shell side diameter, m
Ex	Exergy of fluid, W
$Ex_{loss,h}$	Exergy loss of hot fluid, W
$Ex_{loss,c}$	Exergy loss of cold fluid, W
$Ex_{loss,t}$	Total exergy loss of heat exchanger, W
e	Rib height, m
f_{smooth}	Friction factor for smooth tube
f_{shell}	Friction factor for shell side
$f_{corrugated}$	Friction factor for corrugated tube
G	mass flux, kg/m²s
h	enthalpy of fluid, J/kg
h_i	Tube side heat transfer coefficient, W/m²K
$h_{i,corrugated}$	Tube side heat transfer coefficient for corrugated tube, W/m²K
$h_{i,smooth}$	Tube side heat transfer coefficient for smooth tube, W/m²K
h_{shell}	Shell side heat transfer coefficient, W/m2K
k_{tube}	Thermal conductivity of tube, W/mK
L	One tube length, m
L_{total}	Total tube length, m
$\dot{m}_c$	flow rate of cold fluid, kg/s
$\dot{m}_h$	flow rate of hot fluid, kg/s
$Nu_{i,smooth}$	Nusselt number of smooth tube
$Nu_{i,corrugated}$	Nusselt number of corrugated tube
N_p	number of pass of heat exchanger
n	Number of tubes
$Re_{i,smooth}$	Tube side Reynolds number of flow for smooth tube
Re_{shell}	Shell side Reynolds number of flow
p	Corrugation pitch, m
Pr_i	Tube side Prandtl number of fluid
P_T	Distance between tube center, m
R_{fi}	Tube side fouling factor, m²K/W
R_{fo}	Shell side fouling factor, m²K/W
s	entropy, J/kgK
$\dot{Q}$	Heat transfer capacity of a HEX, kW
$\dot{Q}_{max}$	Maximum heat transfer capacity of a HEX, kW
$S_{gen,ht,h}$	Entropy generation due to heat transfer hot fluid, W/K
$S_{gen,ht,c}$	Entropy generation due to heat transfer hot fluid, W/K
$S_{gen,\Delta P,h}$	Entropy generation due to pressure loss for hot fluid, W/K
$S_{gen,\Delta P,c}$	Entropy generation due to pressure loss for cold fluid, W/K
$S_{gen,total}$	Total entropy generation, W/K
$T_{c,i}$	Cold fluid inlet temperature, °C
$T_{c,o}$	Cold fluid outlet temperature, °C
$T_{h,i}$	Hot fluid inlet temperature, °C
$T_{h,o}$	Hot fluid outlet temperature, °C
U_o	Overall heat transfer coefficient based on outside area of tube
V_i	Velocity of tube side fluid, m/s
ε	Effectiveness of HEX
ρ_i	density of tube side fluid, kg/m³
ρ_{shell}	density of shell side fluid, kg/m³
η_{ex}	Exergy efficiency
μ_b	Viscosity of tube side fluid for bulk temperatue, Ns/m²
μ_i	Viscosity of tube side fluid, Ns/m²
μ_{shell}	Viscosity of shell side fluid, Ns/m²
$\Delta P_{i,smooth}$	Tube side pressure loss for smooth tube, Pa
$\Delta P_{i,corrugated}$	Tube side pressure loss for corrugated tube, Pa
ΔP_{shell}	Shell side pressure loss, Pa
ΔP_h	Pressure loss of hot fluid, Pa
ΔP_c	Pressure loss of cold fluid, Pa

Declaration of Ethical Code

In this study, we undertake that all the rules required to be followed within the scope of the "Higher Education Institutions Scientific Research and Publication Ethics Directive" are complied with, and that none of the actions stated under the heading "Actions Against Scientific Research and Publication Ethics" are not carried out.

References

[1] Shah, R. K., Sekulić, D. P. 2003. Fundamentals of Heat Exchanger Design. Hoboken, NJ: John Wiley & Sons.

[2] Serth, R. W. 2007. Process heat transfer: Principles and applications. Amsterdam: Elsevier Academic Press.

[3] Ralph L Webb, L. R. 1994. Principles of enhanced heat transfer, Wiley New York.

[4] Laohalertdecha, S., Wongwises, S. 2010. The effects of corrugation pitch on the condensation heat transfer coefficient and pressure drop of R-134a inside horizontal corrugated tube. International Journal of Heat and Mass Transfer, 53(13-14), 2924-2931

[5] Kareem, Z. S., Jaafar, M. M., Lazim, T. M., Abdullah, S., Abdulwahid, A. F. 2015. Passive heat transfer enhancement review in corrugation. Experimental Thermal and Fluid Science, 68, 22-38.

[6] Ajeel, R. K., Salim, W. I., Hasnan, K. 2018. Thermal and hydraulic characteristics of turbulent nanofluids flow in trapezoidal-corrugated channel: Symmetry and zigzag shaped. Case Studies in Thermal Engineering, 12, 620-635.

[7] Darzi, A. A. R., Farhadi, M., Sedighi, K. 2014. Experimental investigation of convective heat transfer and friction factor of Al2O3/water nanofluid in helically corrugated tube. Experimental Thermal and Fluid Science, 57, 188-199.

[8] Dincer, I. 2002. The role of exergy in energy policy making, Energy Policy ,30, 37–49.

[9] Bejan, A., Tsatsaronis, G., Moran, M. 1996. Thermal Design & Optimization; Wiley: New York.

[10] Kotas, T.J. 1995. The Exergy Method of Thermal Plant Analysis; Krieger Publishing Company: Malabar, FL, USA.

[11] Mert, S. O., Reis, A. 2016. Experimental performance investigation of a shell and tube heat exchanger by exergy-based sensitivity analysis. Heat and Mass Transfer, 52(6), 1117-1123.

[12] Naphon, P. 2006. Second law analysis on the heat transfer of the horizontal concentric tube heat exchanger. International Communications in Heat and Mass Transfer, 33(8), 1029-1041.

[13] Dizaji, H. S., Jafarmadar, S., Asaadi, S. 2017. Experimental exergy analysis for shell and tube heat exchanger made of corrugated shell and corrugated tube. Experimental Thermal and Fluid Science, 81, 475-481.

[14] Hajabdollahi, H., Ahmadi, P., Dincer, I. 2012. Exergetic optimization of shell-and-tube heat exchangers using NSGA-II. Heat Transfer Engineering, 33(7), 618-628.

[15] Wang, S., Wen, J., Li, Y. 2009. An experimental investigation of heat transfer enhancement for a shell-and-tube heat exchanger. Applied Thermal Engineering, 29(11-12), 2433-2438.

[16] Esfahani, M. R., Languri, E. M. 2017. Exergy analysis of a shell-and-tube heat exchanger using graphene oxide nanofluids. Experimental Thermal and Fluid Science, 83, 100-106.

[17] Pethkool, S., Eiamsa-Ard, S., Kwankaomeng, S., Promvonge, P. 2011. Turbulent heat transfer enhancement in a heat exchanger using helically corrugated tube. International Communications in Heat and Mass Transfer, 38(3), 340-347.

[18] Shirvan, K. M., Mamourian, M., & Esfahani, J. A. 2019. Experimental study on thermal analysis of a novel shell and tube heat exchanger with corrugated tubes. Journal of Thermal Analysis and Calorimetry, 138(2), 1583-1606.

[19] Dizaji, H. S., Jafarmadar, S., Mobadersani, F. 2015. Experimental studies on heat transfer and pressure drop characteristics for new arrangements of corrugated tubes in a double pipe heat exchanger. International Journal of Thermal Sciences, 96, 211-220.

[20] S. A. Klein, Engineering Equation Solver (EES), F-Chart Software,Middleton.

[21] Kakaç, S., Liu, H., Pramuanjaroenkij, A. 2012. Heat Exchangers Selection, Rating, and Thermal Design, Third Edition.

[22] Manjunath, K., Kaushik, S.C. 2014. Second law thermodynamic study of heat exchangers: A review. Renewable and Sustainable Energy Reviews, 40, 2014, 348-374.