Systems & Control Transactions

Research Article - Peer Reviewed Conference Proceeding
ESCAPE 35 - European Symposium on Computer Aided Process Engineering
Ghent, Belgium. 6-9 July 2025
Jan F.M. Van Impe, Grégoire Léonard, Satyajeet S. Bhonsale,
Monika E. Polańska, Filip Logist (Eds.)

PSE PRESS

NLP Deterministic Optimization of Shell and Tube Heat Exchangers with Twisted Tape Turbulence Promoters

Jamel Eduardo Rumbo-Arias [a], Fabián Pino [b], Martin Picón-Nuñez [a*], Fernando Israel Gómez-Castro [a], and Jorge Luis García-Castillo [a]

[a] University of Guanajuato, Department of Chemical Engineering, Guanajuato, Guanajuato, Mexico
[b] Universitat Jaume I (UJI), Institute of Advanced Materials (INAM), Castelló de la Plana, Castellón, Spain
* Corresponding Author: picon@ugto.mx

ABSTRACT

This study presents a deterministic optimization methodology for the design of shell-and-tube heat exchangers with twisted tape turbulence promoters, focusing on minimizing the total annualized cost (TAC) while balancing thermal performance and energy consumption. A sensitivity analysis was carried out as Case I (Methanol-Water), it reveals that increasing the twist ratio (TR) reduces flow turbulence, resulting in lower fluid velocity, pressure drop (ΔP_i), and overall heat transfer coefficient (U). Among the turbulence promoters evaluated, twisted tapes with V-cuts achieved a 21.1% increase in U with a 52.27% increase in pressure drop, demonstrating an optimal balance between thermal enhancement and energy cost. In contrast, promoters with circular rings and multiple perforations showed the highest U improvements (26.7% and 25.8%, respectively) but incurred significant pressure drops (93.5% and 97.9%). The optimization problem has been stated as a nonlinear programming (NLP) problem and solved with the CONOPT solver. Results from two case studies emphasize the importance of operating with similar mass flows, directing the smaller flow through the tubes to maximize promoter effectiveness and achieve balanced heat transfer and pressure drop. For Case II (Residue-Water), the TAC was estimated at 11,467 USD/year, with the equipment cost as the major contributor. Case III (Water-Water) demonstrated improved balance in convective coefficients due to lower thermal effectiveness and similar mass flow rates, highlighting the positive impact of turbulence promoters on performance. This work demonstrates the potential of turbulence promoters for enhancing heat exchangers while emphasizing the importance of careful design to optimize performance and cost.

Keywords Deterministic optimization, NLP, thermo-hydraulic design, turbulence promoter, retrofit.

INTRODUCTION

Techniques for enhancing heat transfer in existing designs are frequently utilized in heat recovery systems. One of the most common methods is the incorporation of twisted tape turbulence promoters, which increase thermal efficiency but simultaneously induce flow disturbances that result in higher pressure drops [1]. When designing shell-and-tube (SH&T) heat exchangers with twisted tape turbulence promoters, the design varies depending on the type of promoter used, and it is determined by several geometric variables, including the internal diameter [2]. Among the types of twisted tape inserts, plain twisted tape, perforated tape, tape with circular rings, tape with three centered perforations, and V-cut tape, can be mentioned [3,4,5,6]. The use of these promoters has been reported to enhance the thermo-hydraulic performance of the equipment from 6.3% to 360%, compared to smooth-tube exchangers [7].

Detailed methodologies for designing SH&T heat exchangers are widely available in the literature [8, 9], making their design straightforward. However, when designing with twisted tape turbulence promoter inserts, the calculation of the free-flow cross-sectional area remains an underexplored area, Figure 1 [1].

This study presents a retrofit case (***CASE I:***

Methanol-Water) where a sensitivity analysis is conducted to observe the behavior of heat exchanger design variables as the twist ratio (TR) varies, the twist ratio (TR) is a key geometric parameter in the design of heat exchangers with twisted tapes. It is defined as the ratio between the twist pitch length and the tube diameter. A high TR implies less twisting per unit length, reducing flow turbulence and pressure drop, while a low TR generates higher turbulence, enhancing heat transfer but increasing flow resistance. In heat exchanger design, finding a balance between thermal transfer and pressure drop is crucial for system efficiency. A retrofit case refers to the improvement of an existing design.

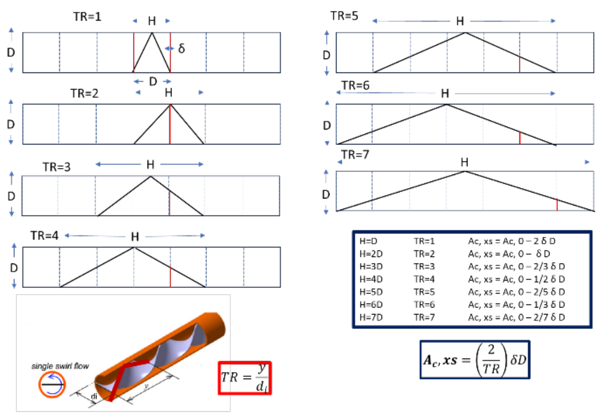


Figure 1. Calculation of the free-flow cross-sectional area with the turbulence promoters.

Additionally, a comparative study among different types of promoters is carried out, evaluating the increase in the overall heat transfer coefficient (U) and the pressure drop within the tubes.

Identifying the best alternative for design and process intensification involves selecting the optimal combination of geometric variables. In literature, optimization techniques have generally been employed to evaluate factors or performance correlations that do not involve costs or a complete equipment design [10, 11].

The primary objective in designing these systems is to minimize total cost, which entails enhancing heat transfer while reducing pumping power. Therefore, determining the optimal combination of parameters for calculating flow velocities, overall heat transfer coefficient (U), and pressure drops within the tubes becomes critical [12].

This work develops a deterministic optimization methodology for solving a nonlinear programming (NLP) problem, where the objective function is to minimize the total annualized cost (TAC) of the equipment and identify the optimal design variables, hence, two cases are studied, ***CASE II: Residue - Water*** and ***CASE III: Water-Water*** [13]. The variables of each case are presented in Table 1.

METHODOLOGY

To carry out the optimization process of the design of heat exchanger with twisted tape inserts, the design methodology followed is shown in Figure 2.

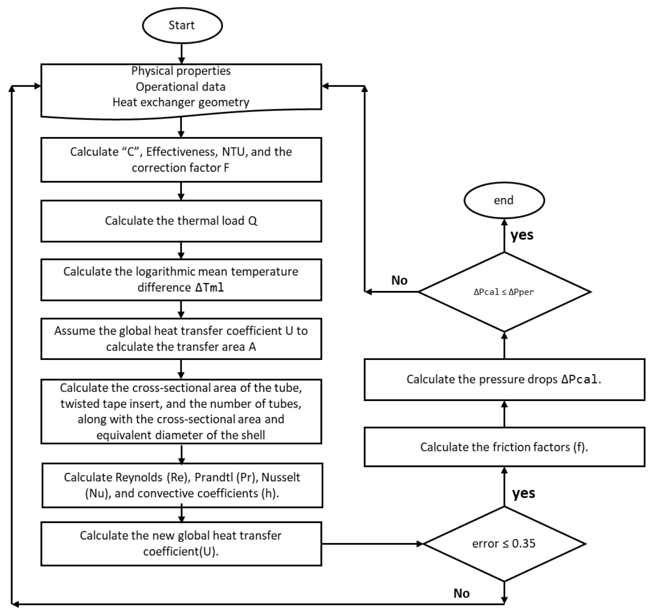


Figure 2. Methodology of design for a T&Sh heat exchanger.

According to Kern's methodology, we assume a starting value for the overall heat transfer coefficient of the system, then, this value is compared with the calculated overall heat transfer coefficient, until the difference between them is within the accepted error range (<35%). Once the condition is reached, the pressure drop is calculated in both sections of the system (tube and shell) [8, 9].

In the diagram of Figure 2, the expressions to estimate the total heat transfer area are calculated from the thermal load (Q), overall heat transfer coefficient (U), correction factor (F), and logarithmic mean temperature difference (ΔT_{ml}).

$$A = \frac{Q}{U * F * \Delta Tml} \quad (1)$$

$$Q = m * C_p * \Delta T \quad (2)$$

Where, m is mass flow, C_p, is the heat capacity and ΔT is the temperature difference. ΔT_{ml} and the correction factor F are given as:

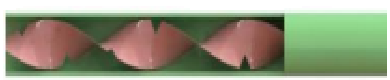
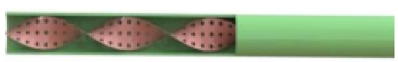
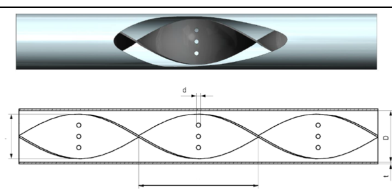
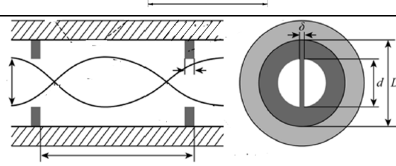
$$\Delta T_{ml} = \frac{\Delta T_1 - \Delta T_2}{Ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \quad (3)$$

$$\mathrm{F} = \frac{Q}{NTU * \Delta T_{ml} * C_{min}} \quad (4)$$

Table 1: Case studies for optimization applications

Case I: Sensibility and Retrofit Analysis			
Variable		Methanol (Shell – hot)	Water (Tube-cold)
Mass Flow	$\left[\frac{Kg}{s}\right]$	27.7	68.9
Inlet temperature	$[^{\circ}C]$	95	25
Outlet temperature	$[^{\circ}C]$	40	40
Effectiveness	$[-]$	0.78	
Case II: Optimization Methodology Application			
Variable		Residue (Shell – hot)	Water (Tube-cold)
Mass Flow	$\left[\frac{Kg}{s}\right]$	47	75
Inlet temperature	$[^{\circ}C]$	131	66
Outlet temperature	$[^{\circ}C]$	79	79
Effectiveness	$[-]$	0.8	
Case III: Optimization Methodology Application			
Variable		Water (Shell – hot)	Water (Tube-cold)
Mass Flow	$\left[\frac{Kg}{s}\right]$	3	3
Inlet temperature	$[^{\circ}C]$	70	9.99
Outlet temperature	$[^{\circ}C]$	40	39.9
Effectiveness	$[-]$	0.49	

Table 2: Thermal-hydraulic correlations for different Twisted Tape promoters

Promotor	**Desing**	**Correlations**
Smooth twisted tape [7]		$Nui = 0.224 * Re_i^{0.66} * Pr^{0.4} * TR^{-0.6}$ $f = 65.4 * Re_i^{-0.52} * TR^{-1.31}$
Smooth twisted tape several perforations [3]		$Nu = a * Re^b$ $f = c * Re_i^d$ $a = 0.0002 * R_p^3 - 0.004 * R_p^2 + 0.033 * R_p + 0.6569$ $b = 0.00005 * R_p^3 - 0.0013 * R_p^2 + 0.0073 * R_p + 0.5501$ $c = -0.0027 * R_p^3 + 0.0583 * R_p^2 + 0.0455 * R_p + 24.536$ $d = 0.00009 * R_p^3 - 0.0013 * R_p^2 + 0.0073 * R_p - 0.6006$
Smooth twisted tape V-cut [14]		$Nu = 0.0296 * Re^{0.853} * Pr^{0.33} * TR^{-0.222} * \left(1 + \frac{d_e}{W}\right)^{1.148} * \left(1 + \frac{w}{W}\right)^{-0.751}$ $fi = 8.632 * Re^{-0.615} * TR^{-0.269} * \left(1 + \frac{d_e}{W}\right)^{2.477} * \left(1 + \frac{w}{W}\right)^{-1.914}$
Smooth twisted tape with three center perforation [5]		$Nu = 0.3528 * Re^{0.62} * Pr^{0.4} * TR^{-0.638} * \left(\frac{l}{di}\right)^{-0.00973}$ $fi = 6.2565 * Re^{-0.404} * TR^{-0.5828} * \left(\frac{d}{di}\right)^{-0.0113}$
Smooth twisted tape with circular ring [4]		$Nu = 0.326 * Re^{0.724} * Pr^{0.4} * TR^{-0.406} * \left(\frac{l}{di}\right)^{-0.475}$ $fi = 13.99 * Re^{0.202} * TR^{-0.619} * \left(\frac{l}{di}\right)^{-0.927}$

NTU is the number of heat transfer units and C_{min} is lower mass flow-heat capacity between the two streams.

To calculate the overall heat transfer coefficient (U) the thermal-hydraulic correlations for Nusselt number and friction factor presented in Table 2 were employed.

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_s}} \tag{5}$$

The pressure drop in the tube is calculated by equation 6.

$$DPi = N * \left[8 * fi * \frac{L}{di} * \left(\frac{\mu}{\mu_w}\right)^{-0.14} + 2.5\right] * \frac{\rho * v_i^2}{2} \tag{6}$$

The expression for pressure drop in the shell side is:

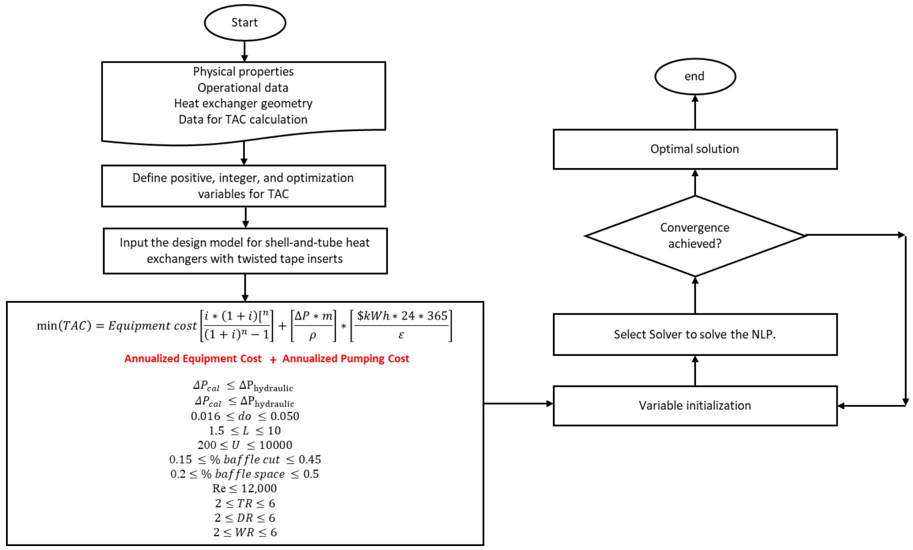
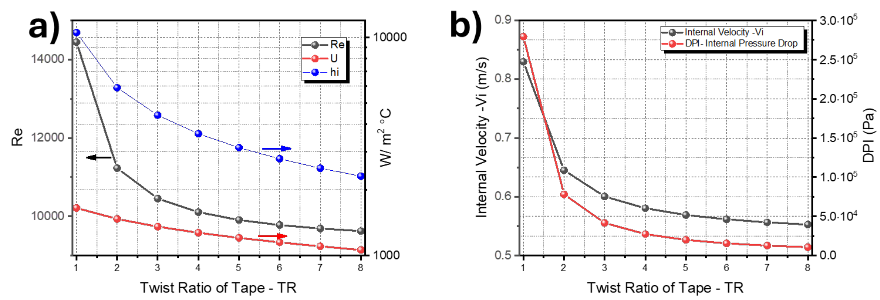
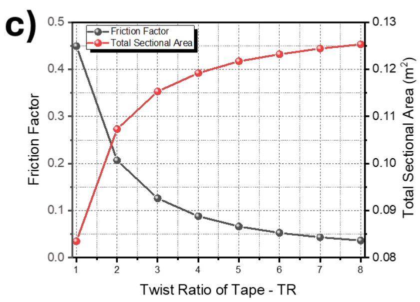


Figure 3. Methodology of optimization with twisted tape





d)

Desing parameters		
Area	152	m2
N tubes	1704	--
Steps	2X1	--
do	0.018	m
di	0.014	M
L	1.58	M
% baffle space	0.5	--
% baffle cut	0.45	--

Figure 4. Sensibility analysis of design of SH&T varying the twisted tape. a) Re, U and h vs TR; b) Internal velocity and pressure drop vs TR; c) Friction factor and total sectional area vs TR, and d) design parameters.

$$DPs = 8 * fs * \left(\frac{D_s}{d_e}\right) * \left(\frac{L}{l_B}\right) * \frac{\rho * v_s^2}{2} * \left(\frac{\mu}{\mu_w}\right)^{-0.14} \qquad (7)$$

The mathematical model was implemented in GAMS software, as a Non-Linear Programming Model (NLP), and it was solved using the CONOPT solver. The optimization methodology to solve the SH&T heat exchanger with twisted tape inserts is based on reducing cost (TAC), which is in function on the equipment cost and the annualized energy consuming due to pumping. Figure 3 shows the design constraints.

RESULTS AND DISCUSSION

From Figure 4, (a) and (b), it is evident that increasing the twist ratio (TR) of the twisted tape results in wider and less frequent twists, reducing the intensity of flow mixing and turbulence within the tube.

This leads to a decrease in fluid velocity (Vi), as it encounters less resistance, which in turn reduces the pressure drop (DPi) and the overall heat transfer coefficient (U). Higher TR values produce a smoother flow that

Table 3: Thermal-hydraulic comparative performance using different turbulence promoters for case I: Retrofit Methanol-Water.

Type of twisted tape	U $\left[\frac{W}{m^2\ ºC}\right]$	[%]	Dpi $[Pa]$	[%]
Smooth tube	959	0	9445	0
Smooth twisted tape	1127	14.8	66160	85.7
Smooth twisted tape with three center perforation	1149	16.5	33058	71.4
Smooth twisted tape with circular ring	1309	26.7	460044	97.9
Smooth twisted tape several perforations	1292	25.8	146286	93.5
Smooth twisted tape V-cut	1216	21.1	19791	52.27

Table 4: Results of the optimization process for a SH&T heat exchanger with inserts Case II: Residue-Water.

Design varible	Units	Data	Design varible	Units	Data	Design varible	Units	Data
di	[m]	0.0127	**Ds**	[m]	1.498	**Space**	[%]	0.48
do	[m]	0.0167	**As**	$[m^2]$	0.1462	**Q**	[W]	4086
L	[m]	1.5	**LB**	[m]	0.7308	**U**	$\left[\frac{W}{m^2\ ºC}\right]$	430
#-Tubes	[-]	4445	**Vs**	$\left[\frac{m}{s}\right]$	0.3680	**A**	$[m^2]$	350
Ac	$[m^2]$	0.2033	**Res**	$[m^2]$	174	**TR**	[-]	6
Vi	$\left[\frac{m}{s}\right]$	0.3689	**hs**	$\left[\frac{W}{m^2\ ºC}\right]$	475	**Equipment cost**	$\left[\frac{USD}{Año}\right]$	9368
Ri	[-]	11980	**fs**	[-]	0.0664	**Dpi Cost**	$\left[\frac{USD}{Año}\right]$	1460
hi	$\left[\frac{W}{m^2\ ºC}\right]$	4502	**Cut**	[%]	0.45	**DPs Cost**	$\left[\frac{USD}{Año}\right]$	637
fi	[-]	0.0172	**de**	[m]	0.0119	**DP Total cost**	$\left[\frac{USD}{Año}\right]$	2098
DPi	[Pa]	2545	**Dps**	[Pa]	8136	**Cost (TAC)**	$\left[\frac{USD}{Año}\right]$	11467

Table 5. Results of the optimization process for a SH&T heat exchanger with promoters Case III: Water-Water.

Design variable	Units	Data	Design variable	Units	Data	Design variable	Units	Data
di	[m]	0.0189	**Ds**	[m]	0.3734	**Space**	[%]	0.2
do	[m]	0.0229	**As**	$[m^2]$	0.0149	**Q**	[W]	375.5
L	[m]	1.5	**LB**	[m]	0.0747	**U**	$\left[\frac{W}{m^2\ ºC}\right]$	1438
#-Tubes	[-]	84	**Vs**	$\left[\frac{m}{s}\right]$	0.2017	**A**	$[m^2]$	9.07
Ac	$[m^2]$	0.0094	**Res**	$[m^2]$	3638	**TR**	[-]	2.6
Vi	$\left[\frac{m}{s}\right]$	0.3252	**hs**	$\left[\frac{W}{m^2\ ºC}\right]$	2129	**Equipment cost**	$\left[\frac{USD}{Año}\right]$	1369
Ri	[-]	12000	**fs**	[-]	0.040	**Dpi Cost**	$\left[\frac{USD}{Año}\right]$	22.01
hi	$\left[\frac{W}{m^2\ ºC}\right]$	4434	**Cut**	[%]	0.45	**DPs Cost**	$\left[\frac{USD}{Año}\right]$	30.08
fi	[-]	0.0287	**de**	[m]	0.0162	**DP Total cost**	$\left[\frac{USD}{Año}\right]$	52.10
DPi	[Pa]	2163	**Dps**	[Pa]	2991	**Cost (TAC)**	$\left[\frac{USD}{Año}\right]$	1420.6

is less efficient in heat transfer, as the ability to effectively induce turbulence is diminished.

Figure 4(c) shows that the friction factor decreases as TR increases. The tape causes less obstruction, which reduces the fluid velocity and consequently lowers the pressure drop. Additionally, with higher TR, the tape occupies less space in the cross-section tube, increasing the available free cross-sectional area and allowing the fluid to flow more easily.

According to the results shown in Table 3, smooth twisted tape turbulence promoters with circular rings and multiple perforations provide the highest percentage increase in the heat transfer coefficient (U), achieving improvements of 26.7% and 25.8% compared to a smooth tube. However, these results also exhibit the highest pressure drop increase (DP_i) of 97.9% and 93.5%, indicating a significant energy cost. In contrast, twisted tapes with V-cuts achieve a 21.1% increase in U while maintaining a lower pressure drop of 52.27%, positioning them as a more balanced option.

From case II (Table 4), TAC was estimated at 11,467 USD/year, where the largest contribution comes from the equipment cost (9,368 USD/year), while the pumping costs are 2,098 USD/year. This analysis shows that the convective heat transfer coefficient of the shell side (h_s) is significantly lower compared to that of the tubes (h_i), indicating that the heat transfer is controlled by the fluid flowing through the shell. This situation causes the improvement in heat transfer coefficient on the tube side, not being significant in the overall heat transfer coefficient. This prevents the inserts from achieving the intended operational performance. In this case, a better design configuration is to send the fluid with the lowest mass flow rate through the tubes. Yet, another operating feature that affects the magnitude in which a promoter enhances heat transfer is thermal effectiveness. Higher effectiveness heat exchangers tend to dampen the increment in heat load.

The results of the optimization methodology applied to Case III are presented in Table 5. It can be observed that the convective heat transfer coefficients, h_i (4,434 W/m²°C) and h_s (2,129 W/m²°C), are slightly more balanced compared to Case II. In this configuration, the mass flow rates are equal, which does not constrain the increase in the overall heat transfer coefficient. This is because heat transfer is more evenly distributed, attributed to the heat exchanger exhibiting a balanced thermal effectiveness and *C* relation average.

CONCLUSIONS

Based on the sensitivity analysis results, it can be concluded that an increase in the twist ratio (TR) of the twisted tape promoter causes the twists to become wider. This reduces flow turbulence, which inversely affects fluid velocity, decreasing speed (Vi), pressure drop (ΔP_i), and the overall heat transfer coefficient (U). The twisted tape with V-cuts shows a 21.1% increase in the overall heat transfer coefficient (U) and a 52.27% increase in the pressure drop (ΔPi) compared to the smooth tube without promoters, making it the best option to maximize heat transfer with minimal impact on energy consumption.

An optimization methodology was developed for the design of shell and tube heat exchangers with turbulence promoters. The results indicate two key issues that determine the magnitude of performance improvement achievable with turbulence promoters: (1) a larger overall performance increase is observed when the lower mass flow rate fluid passes through the tube, and (2) higher increases in heat load are achieved when turbulence promoters are used in units with low thermal effectiveness.

ACKNOWLEDGEMENTS

Authors wish to express their gratitude to the Mexican Council of Science, Humanities and Technology (CONAHCyT) for the grant provided to Jamel Eduardo Rumbo-Arias during this research.

REFERENCES

1. Crespo-Quintanilla, J.A., García-Castillo, J.L., I. Minchaca-Mojica, J., Picón-Núñez, M.: Enhancing heat exchanger performance with combined twisted tubes and twisted Tapes: Design and retrofit strategies. Therm. Sci. Eng. Prog. 54, 102817 (2024). https://doi.org/10.1016/j.tsep.2024.102817
2. Picón-Núñez, M., Minchaca-Mojica, J.I., Durán-Plazas, L.P.: Selection of turbulence promoters for retrofit applications through thermohydraulic performance mapping. Therm. Sci. Eng. Prog. 42, 101876 (2023). https://doi.org/10.1016/j.tsep.2023.101876
3. Bhuiya, M.M.K., Chowdhury, M.S.U., Saha, M., Islam, M.T.: Heat transfer and friction factor characteristics in turbulent flow through a tube fitted with perforated twisted tape inserts. Int. Commun. Heat Mass Transf. 46, 49–57 (2013). https://doi.org/10.1016/j.icheatmasstransfer.2013.05.012
4. Eiamsa-ard, S., Kongkaitpaiboon, V., Nanan, K.: Thermohydraulics of Turbulent Flow Through Heat Exchanger Tubes Fitted with Circular-rings and Twisted Tapes. Chin. J. Chem. Eng. 21, 585–593 (2013). https://doi.org/10.1016/S1004-9541(13)60504-2
5. Gunes, S., Karakaya, E.: Thermal Characteristics in a Tube With Loose-Fit Perforated Twisted Tapes. Heat Transf. Eng. 36, 1504–1517 (2015). https://doi.org/10.1080/01457632.2015.1024985
6. Eiamsa-ard, S., Promvonge, P.: Thermal characteristics in round tube fitted with serrated twisted tape. Appl. Therm. Eng. 30, 1673–1682 (2010). https://doi.org/10.1016/j.applthermaleng.2010.03.026
7. Eiamsa-ard, S., Thianpong, C., Eiamsa-ard, P.: Turbulent heat transfer enhancement by

counter/co-swirling flow in a tube fitted with twin twisted tapes. Exp. Therm. Fluid Sci. 34, 53–62 (2010). https://doi.org/10.1016/j.expthermflusci.2009.09.002
8. Sadik, K.: Heat Exchanger. CRC Press, 6000 Broken Sound Parkway NW, Suite 300 Boca Raton, FL 33487-2742 (2012)
9. Sinnott, R.: Chemical Engineering Design: Chemical Engineering Volume 6. Elsevier Science & Technology, Jordan Hill (2005)
10. Keklikcioglu, O., Günes, S., Senyigit, E., Akcadirci, E., Ozceyhan, V.: The optimization of the thermal and hydraulic characteristics of a tube with twisted tapes using Taguchi-based-AHP-TOPSIS approach. J. Therm. Anal. Calorim. 147, 13711–13723 (2022). https://doi.org/10.1007/s10973-022-11518-x
11. Kola, P.V.K.V., Pisipaty, S.K., Mendu, S.S., Ghosh, R.: Optimization of performance parameters of a double pipe heat exchanger with cut twisted tapes using CFD and RSM. Chem. Eng. Process. - Process Intensif. 163, 108362 (2021). https://doi.org/10.1016/j.cep.2021.108362
12. Picón-Núñez, M., Rumbo-Arias, J.E.: Improving thermal energy recovery systems using welded plate heat exchangers. Energy. 235, 121373 (2021). https://doi.org/10.1016/j.energy.2021.121373
13. Sebastian anak Sidi, Feasibility study on the replacement of tradisional heat exchanger by alfa laval compabloc, 2009