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Energy Management and Process Improvement of Methanol Production

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Abstract

A heat exchanger network (HEN) for the process of methanol synthesis has been studied by combination of pinch design method and the application of “Twisted Tube” heat exchanger units as a new technology. The HEN is reconstructed based on the full utilization of maximum allowable pressure drops for the process hot and cold streams. An algorithm is developed to generate design procedure for twisted tube application. The algorithm needs to extend and develop correlation among the pressure drops, heat transfer coefficients, and required surface area through a simple relationship for twisted tube exchangers. It is revealed that a great economic, energy savings and process improvement are realized by using pinch analysis and applying twisted tube units in comparison to existing plants. The paper reveals highly potential benefits of this technology in design and replacement of twisted tube heat exchangers with the conventional shell and tubes type. The HEN is reconstructed by adding 4 new twisted tube units with their detail design in methanol process as a case study. The results show that the application of twisted tube exchangers may achieve significant energy saving for the methanol process with a one-year payback. Moreover, these units may result in a great reduction of carbon emission, operational problems such as heat exchanger fouling, and tube bundle vibration of heat exchangers.

Keywords: Twisted Tube Heat Exchanger, Heat Transfer Enhancement, Pinch Analysis, Energy Saving

Introduction

In spite of shortfalls in shell and tube exchangers, still they have been widely used in commercial process plants. The most recent major improvement has been to design twisted tube bundles as a new technology that not only improve flow and heat transfer performance. They are extremely efficient due to induced turbulence in both the shell and tubeside flows. The technology has the added effect of substantially mitigating the amount of fouling. This new design was brought by the Brown Fin Tubes company outside of Scandinavian in 1994. Later, the only institution that allowed to use the product of the Brown Fin Tube company was Koch American Company. The Koch is active in the field of heat transfer devices; however, the advantages of this innovative technology has not been appreciated yet [1].

For the first time the experimental data of twisted tube bundles were obtained by Zukauskas. He compared the results with the data for smooth pipes [2]. Dzybenko et al. tested heat transfer coefficients for different Reynolds numbers using the number of tube with a flow model at that allowable velocity [3]. Brodov et al. showed how replacement of tubes with twisted tubes in a coil condenser could led to an increase in the heat transfer coefficient from 10 to 70 percent [4]. In a comprehensive book Dzyubenko et al. presented numerical methods for calculating heat and mass transfer in heat exchangers equipped with channels formed by twisted tube bundles and porous heat transfer elements. They also investigated the enhancement provided by replacing smooth heat exchanger tubes with helically twisted tubes. They found 10% to 70% improvement in the condensation heat transfer coefficient depending on the operating conditions and tube geometry [5].

In this study, a heat exchanger network (HEN) for the process of methanol synthesis has been studied by the combination of pinch design method and the application of “Twisted Tube” heat exchangers. The HEN is reconstructed based on the full utilization of maximum allowable pressure drops. An algorithm is developed to generate a correlation among the pressure drops, heat transfer coefficients and required surface area through a simple relationship for twisted tube exchangers. It is revealed that a great economic, energy savings and process improvement are realized by using pinch analysis and application of twisted tube units in comparison to existing plants.

Rapid Design Algorithm (RDA) for Twisted Tube Heat Exchangers

Polley et al. have presented design algorithms for the rapid sizing of shell and tube and compact heat exchangers on a more objective basis. These algorithms may be used in conjunction with the detailed rating methods presented in the previous studies as well as programs for mechanical design and tube bundle vibration analysis to achieve an optimal design [6]. The philosophy is to completely utilize the maximum allowable pressure drops on both the hot and cold streams rather than to use these specifications as mere constraints. The full use of both pressure drops ensures that the exchanger is designed for the highest possible velocities and consequently heat transfer coefficients. Thus, the exchanger is the smallest size for a given service and presumably the most economical.

In previous studies rapid design algorithm (RDA) was applied as a new approach to design shell and tube heat exchangers enhancement, compact heat exchangers, and enhanced air-cooled heat exchangers in which the interface among heat transfer coefficients, pressure drops, and heat transfer area have been considered [7,8,9].

The new design algorithm presented in this study is extended to twisted tube heat exchangers while it considers pressure drop constraints that are necessary in heat exchanger design so the outcome is the most economical design in comparison with the traditional methods. This new algorithm is also adaptable when heat transfer enhancement technology such as tube inserts applied [10].

To introduce and describe the RDA for twisted tube heat exchangers, the thermal and hydraulic characteristics of tube side and shell side are analyzed separately with the following final equations [10, 11]:

$$\Delta P_t = K_{TP3} A h_t^{3.47} \tag{1}$$

$$\Delta P_s = K_{SP1} A h_s^{3.4375} \tag{2}$$

By considering general heat transfer equation, one may obtain:

$$Q = U.AF.(\Delta T_{LM}) \tag{3}$$

while,

$$U = [(1/h_t)(d_{out}/d_{in}) + (1/h_s) + R_{ds} + R_{dt}]^{-1} \tag{4}$$

The equations of (1) to (4) have three unknowns variables, namely ht, hs, and A, which can be combined and rearranged so that it has one unknown variable, i.e. area heat transfer (A);

$$m_1 A^{1/3.47} + m_2 A^{1/3.4375} + m_3 A + m_4 = 0 \tag{5}$$

while,

$$m_1 = \left(\frac{K_{TP3}}{\Delta P_t}\right)^{1/3.47} \frac{d_{out}}{d_{in}}$$

$$m_2 = \left(\frac{K_{SP1}}{\Delta P_s}\right)^{1/3.4375}$$

$$m_4 = R_{dt} + R_{ds}$$

By solving this equation using typical numerical techniques such as the Newton-Raphson iteration, the area required for a twisted tube heat exchanger with a given duty can be calculated straightforward. It should be noted that the calculated area is an optimized value because of the maximum usage of the available pressure drops in the design equation.

Case Study (Methanol Synthesis)

Process section of methanol plant

The stages in the process of methanol production are as follows:

- Natural gas compression for using in feed stream;
- Increasing the pressure of carbon dioxide provided by Razi Petrochemical Complex (RPC) and mixing with carbon dioxide generated from Maroon Petrochemical Complex;
- Hydrocarbon and natural feed gas desulfurization;
- Steam reforming of desulfurizedfeed gas;
- Heat recovery and energy recovery of process gas;
- The process gas will become cool after transferring heat for producing superheat steam, preheating steam, drum feed and steam generation in the evaporator of condensation part by air cooler and cooling tower;
- Process gas compression;
- Methanol synthesis;
- During the circulation, synthesis gas is converted to methanol by passing through three boiling water reactors that are installed in a parallel form. The produced steam by boiling water reactors are utilized to strip in process condensate stripper and then as a process steam in steam reformer;
- A low amount of by-products are produced in methanol reactors. These by-products include high alcohol, amines, ketene, DME (De Methyl Ether), and other materials available in the raw methanol;
- Methanol distillation and purification;
- Distillation is being used to purify raw methanol.

The whole view of this process description is illustrated in Figure 1.

Process Gas Heat Recovery

In order to reduce the load of compressor before entering to synthesis compressor C-3001, the process gas discharges at a temperature of 915 °C and a pressure of 21.4 bars from steam reformer and its temperature should be decreased.

The sensible heat in reformed gas is applied in these cases:

- Steam generation in HHP waste heat boiler by E-2008;
- HHP steam is being super saturated by E-2009;
- Preheating boiling feed water by first section E-2011 and second section E-2010;
- LP tower evaporator by E-5005;
- Stabilizer tower evaporator by E-5001;
- Process gas is cooled by air cooler after heat recovery up to 65 °C and finally it is cooled by E-2014 up to 41 °C;
- Process condensate is separated in these steps:
- The first separator D-5005 is after LP Column Reboiler (E-5005);
- The second separator D-2002 is after stabilizer Column Reboiler (E-5001);

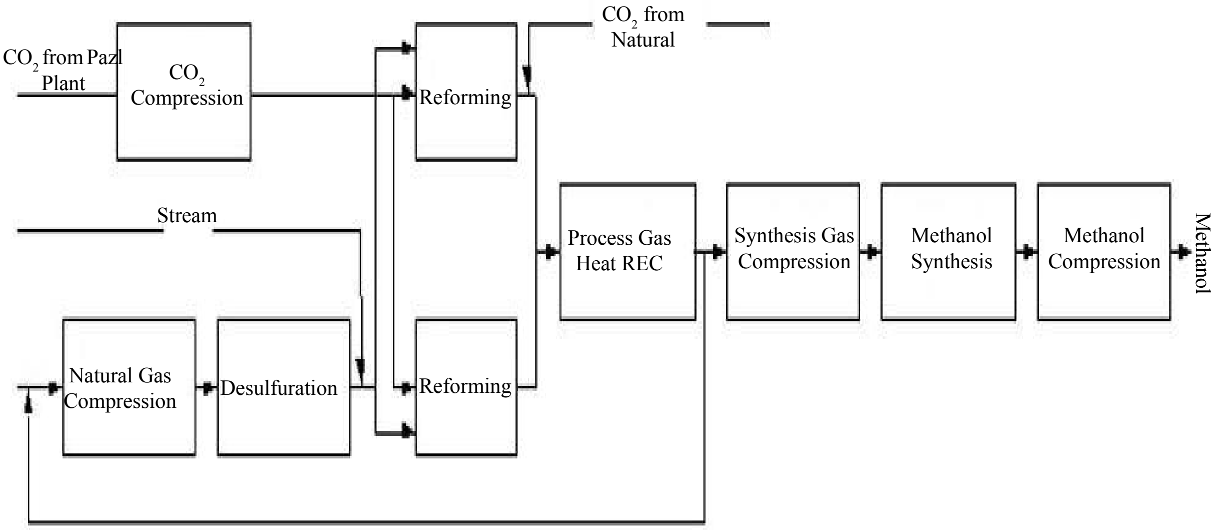

Figure 1: The main process block diagram of a methanol plant

- Process condensate is collected in D-2003 and then sent by P-2001 A/B pumps into process condensate stripper T-6101;

Data Extraction and Process Fluid Properties

Table 1 gives the basic stream data for the methanol synthesis process presented in Figure 2 [12].

It should be mentioned that in this study the only streams which hare significant contribution in network optimization results have been considered.

As shown in Figure 3 the plant includes eight to process to process heat exchangers. This has only two heaters E-5006 and E-5015 those import the whole required stream from outside of the plant.

For further analysis composite curve Figure 4 and grand composite curve Figure 5 can be extracted from selected stream data with consideration to existing minimum temperature different ΔTmin = 32 °C.

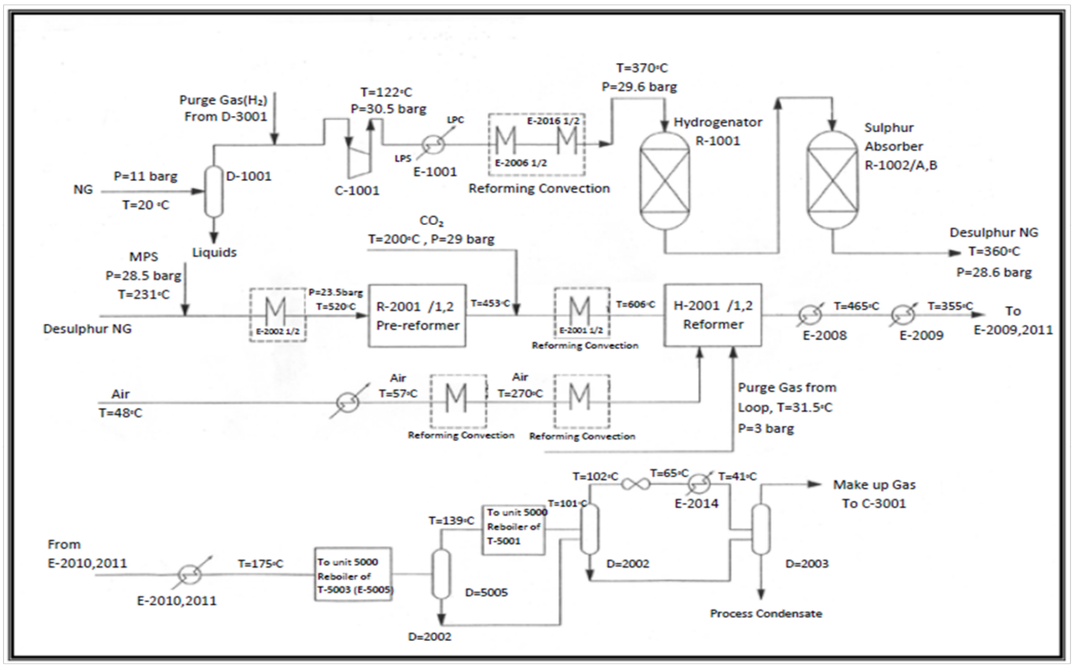

Figure 2: The simplified process flowsheet of a methanol synthesis plant

Table 1: Final data calculation of existing heat exchanger streams for methanol plant [12]

No.	Stream	T_S(°C)	T_T(°C)	Δh (kW)	CP (KW/°C)	HTC (W/m²K)
1	Reformer outlet up to D-5005	915	140	176712	228	4507.9
2	D-5005 outlet up to D-2002	140	103	31763	858.45	6807.9
3	Separator outlet (D-5005)	103	41	17979	289.98	6830
4	C-3001-E-1 Interstage Cooler	157	43	11564	101.4	3890
5	HP column product cooler	128	43	3068	36.09	1120
6	Reactor outlet	250	41	179989	861.2	1289
6	Reactor outlet	250	41	179989	861.2	1289
7	LP column oh condenser	64.8	43	1383	63.4	1219
8	Water Preheater	133	270	45600	332.8	4966.4
9	Steam generation	270	324	102600	1900	447.9
10	Super heater	324	389	23940	368.3	1009.9
11	T-5001 Reboiler	87	88	31763	31763	4253.3
12	LP column Reboiler(T-5003)	117	118	4560	4560	6255.6
13	Reactor Feed Reheater	63.2	225	120568	745.16	1909
14	HP column Reboiler(T5002)	135	138	67245	22415	6718.9
15	Combustion Air Preheater	48	57.3	1278	137.5	4120

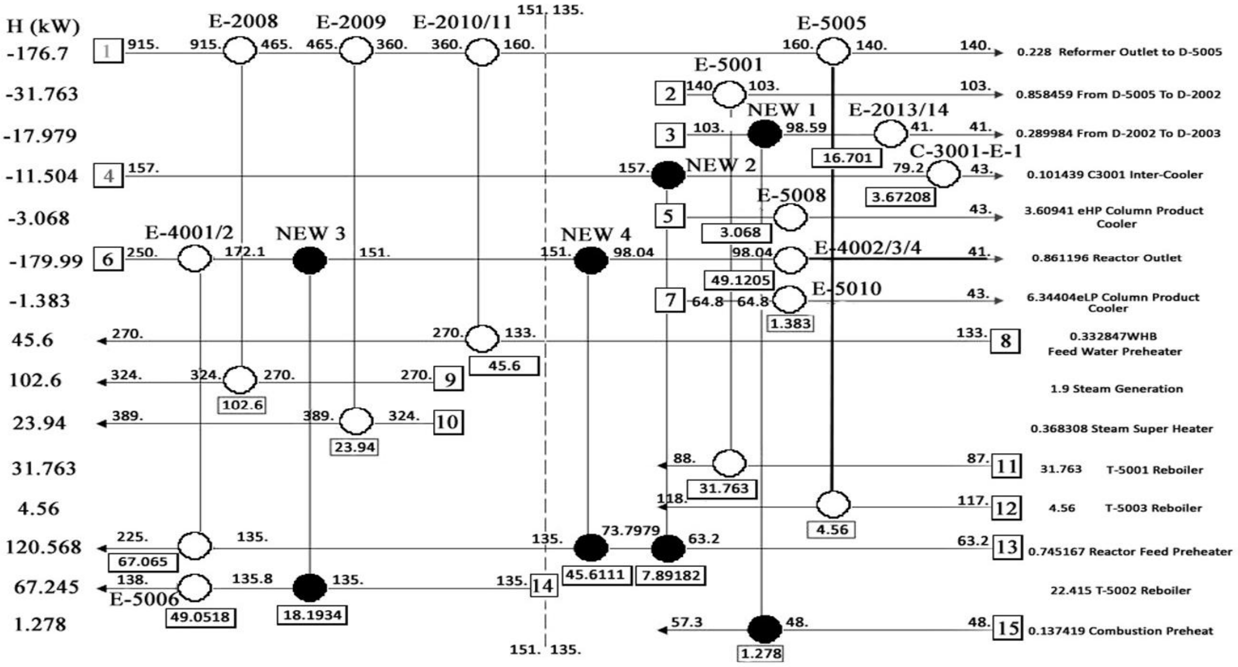

Figure 3: Grid diagram of heat exchanger network after modification (The heat loads of heat exchangers and temperatures are in MW and °C respectively) [13].

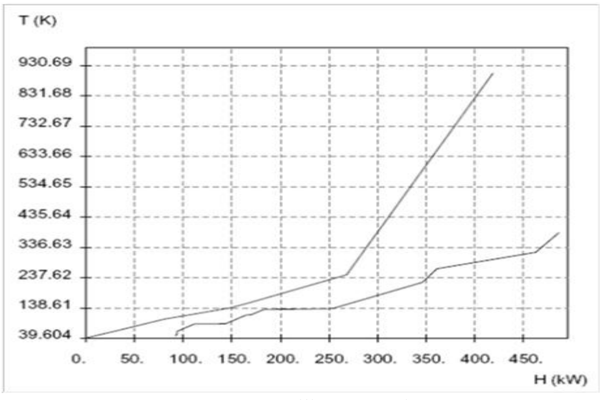

Figure 4: Process utility composite curve

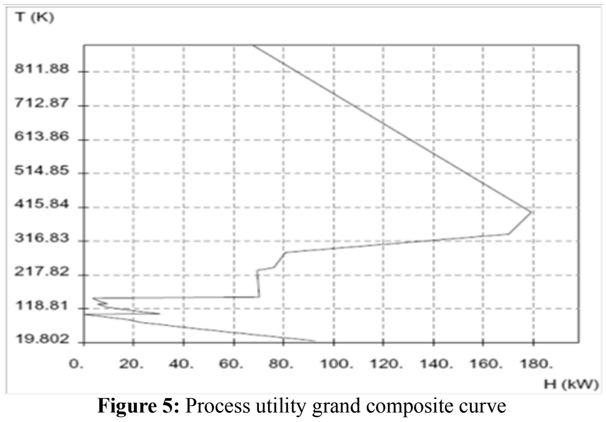

Figure 5: Process utility grand composite curve

Replacement of Existing Heat Exchangers with Twisted Tube Unit

To reduce the amount of network energy consumption, based on pinch analysis and the retrofit study of the process, four heat exchangers (NEW 1, 2, 3, 4) are needed to be replaced with twisted tube units [13,14]. This leads to the following results given in Table 2.

Tables 2 and 3 show the input and output conditions of four plain and twisted tube heat exchangers respectively.

Table 4 shows the input and output conditions of four plain tube heat exchangers.

Results and Discussion

The replacement of heat exchanger units with twisted tube bundle gives the following results. The detailed of calculations can be found in reference 14:

1- Operating cost for hot utility is 42.34 \$/kW.Yr

2- Operating cost for cold utility is 36.9 \$/kW.Yr

3- Heat transfer area of twisted tube unit can be calculated based on a rapid design algorithm (RDA) (explained in section 2)

4- The cost function of twisted tube is calculated as follows [10]:

Capital (construction) cost function of twisted tube heat exchanger:

$$\text{Cost } \$ = 43.74\, A^{1.27} + 15180 \qquad (6)$$

where, A is heat transfer area.

Tube replacement cost function of twisted tube HEX:

$$\text{Cost } \$ = 267.64\, A_{\text{shell}} + 468.47 \qquad (7)$$

where, A_{Shell} is area shell.

Table 4 shows the input and output conditions of four twisted tube heat exchangers.

Total investment is \$754,249 which is the sum of the investment for construction of plain tube (\$42,688) and the investment for twist tube replacement (\$711,561) [13].

Table 4 shows the traditional conditions of hot and cold utility with shell and plain tube heat exchangers.

Table 5 shows the input and output conditions of four twisted tube heat exchangers.

Table 5 shows the conditions of hot and cold utilities with shell and twisted tube heat exchangers and therefore it can remove E-5006 utility.

Impact of Clean Development Mechanism (CDM)

The calculation of the income due to the reduction of CO_2 green house gas emission in (kg) for each Tera Joule of fuel consumption according to net heat value is [12]:

1 Tera Joule =56.1 (ton) CO_2.

In order to estimate the amount of heat in terms of Tera Joule per year the following calculation has been made:

Since 8.95 MJ is being saved as hot utility thus:

$(8.95(\text{MJ/s})\times 3600(\text{s/hr})\times 8000(\text{hr/year}))\times 10^{-6}=257.76(\text{TJ/Yr})$

The amount of the reduction of CO_2 per year is given by:

Year =257.6×56.1=14460.33(ton/Yr)

Since each ton of CO_2 costs ten dollars, then:

Income due to the reduction of CO_2 is equal to 144603 (\$/Yr).

Table 6 demonstrates a better evaluation of project with CDM mechanism as follows:

Table 7 shows the comparison of adding four heat exchangers in two scenarios: (i) shell and plain tube with baffles (ii) shell and twisted tube bundle. As shown, the application of this technology can results in a significant reduction in CO_2.

Table 2: Input and output of heat exchanger with plain tubes [14]

Straight Tube	Inlet Temp. (Tube) (°C)	Outlet Temp. (Tube) (°C)	Inlet Temp. (Shell) (°C)	Outlet Temp. (Shell) (°C)	Heat Transfer Area (m²)	Shell Area (m²)	Heat Recovery (MW)
HEX 1	103	98.59	48	57.3	443.5	36.8	1.28
HEX 2	157	79.2	63.2	73.8	605	37.2	7.9
HEX 3	172.1	151	135	135.8	2420	37.2	18.1
HEX 4	151	98.04	73.8	135	3629	41.3	45.6

Table 3: Input and output of heat exchanger with twisted tubes [14]

Twisted Tube	Inlet Temp. (Tube) (°C)	Outlet Temp (Tube) (°C)	Inlet Temp (Shell)(°C)	Outlet Temp (Shell) (°C)	Heat Transfer Area (m²)	Cost ofTube Replacement (\$)	Heat Recovery (MW)
HEX.1	103	95.75	48	63.28	620.9	10330.1	2.1
HEX.2	157	72.61	63.2	74.68	847	10417.7	8.56
HEX.3	172.1	146.07	135	136	3388	10417.7	25.6
HEX.4	146.07	92.94	73.8	136.24	5080.6	11533.4	46.53

Table 4: Traditional conditions of hot and cold utility with plain tubes

Utility	Inlet Temp. (°C)	Outlet Temp. (°C)	M.CP (kW/°C)	Energy Consumption (MW)
E-2013	98.59	41	0.289984	16.7
C-3001	79.2	43.1	0.101439	3.7
E-4002	98.04	41	0.861196	49.1
E-5006	135.8	138	22.415	49.3

Table 5: Conditions of hot and cold utility with twisted tubes

Utility	Inlet Temp (°C)	Outlet Temp (°C)	M.C_P (kW/°C)	Energy Consumption (MW)	Saving Energy (MW)
E-2013	95.75	41	0.289984	15.88	0.82
C-3001	72.61	43.1	0.101439	2.99	0.7
E-4002	92.04	41	0.861196	43.96	5.14
E-5006	136.2	138	22.415	40.35	8.95

Table 6: Project comparison due to payback period time for two scenarios

	Project evaluating without considering CDM	Project evaluating with considering CDM
	International price cost ($)	International price cost ($)
Investment ($)	754249	754249
Income due to saving ($/Yr)	624697	769300
Payback period time (year)	1.21	0.98

Table 7: Conditions of hot and cold utility with twisted tubes

HEX Type	Plain Tube with Baffle [13]	Twisted Tube Bundle
Investment ($)	711561	754249
Income due to saving ($/Yr)	1854024	769300
Payback period time (year)	0.38	0.98

Conclusion

This study reveals that how the application of pinch technology combined with twisted tube heat exchangers could lead to a significant energy saving in a typical petrochemical plant. It is seen that by adding four new process-to-process twisted tube heat exchangers heat transfer area increases by about 40%; however, energy can be recovered up to 35% for cold utility and 18% for hot utility. The payback period time will be around 1 year for such a case study.

Nomenclature

ΔH: Change in enthalpy, kW
ΔP_t: Pressure drop in tube, bar
ΔP_s: Pressure drop in shell, bar
Cp: Heat capacity, kW/ °C
ΔT_{min}: Minimum temperature difference, °C
HTC: Overall heat transfer coefficient, W/m^2 °C
M: Mass flow rate, kg/s
M: $=10^6$ w
Ts: Supply temperature, °C
T_T: Target temperature, °C
N_b: Number of baffle
R_{ds}: Shell side fouling resistance, m^2 °C /W
R_{dt}: Tube side fouling resistance, m^2 °C /W
D_e: Equivalent diameter tube, m
$d,_{in}$: Inlet diameter twisted tube, m
d_{out}: Outlet diameter twisted tube, m
h_s: Shell heat transfer coefficient, W/m^2 °C
h_t: Tube heat transfer coefficient, W/m^2 °C
F: Temperature correction factor

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