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Study on Entropy Generation of Multi-Stream Plate Fin Heat Exchanger with use of Changing Variables Thermodynamic and Fluids Flow Rate between Plates and Provide an Optimal Model

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Abstract

Background/Objectives: In this study we have investigated entropy generation of multi-stream plate fin heat exchanger with use of changing variables thermodynamic and fluids flow rate between plates and provide an optimal model. **Methods/Statistical Analysis:** For optimizing the plate thermal exchanger, we get the help of a toolbox (genetic algorithm) which has come with MATLAB software. So it is suitable to point to the logic and essence of this optimization method. Between the optimization methods, genetic algorithm, inspired by nature is one of the most advanced ones with disconnected variables. This algorithm is based on natural progress. **Findings:** The results of calculation were obtained without any change in geometric parameters that was used by air separation unit in APC, thermal exchange coefficient factors are as follows, 1545, 833, 1519, 706 and 2030 W/m^2K; and pressure drop of each of the exchanger feeding fluid is calculated approximately 10.8, 19.0, 12.1, 19.9, 18.6, in KPa Pascal. Also overall pressure drop in suggested plate heat exchanger with simple fins was calculated 80.5 K.Pa which is less than desired figure of air separation unit in petrochemical company but instead, output temperature of passing fluids between plates is reduced. **Application/Improvements:** Optimization was done by using the principal of entropy generation minimization, Entropy Generation Minimization (EGM).

Keywords: Air Separation Unit (ASU), Efficiency, Entropy Generation Minimization, Plate Fin Heat Exchanger (PFHE), Two-Objective Optimization

1. Introduction

Designing a heat exchanger for special usage needs to think of several situations and standards to find a suitable exchanger dimensions. Petrochemical Companies, electric power plants and other industries and any others soon or late need to optimize their internal equipment and among them, heat exchangers[1–4].

State briefly the previous work done related to this study and also justify why the present study is needed. Aim of this study is to attain minimum pressure drop and maximum heat efficiency. For optimization, we use genetic algorithm tool box software produced by MATLAB. Optimization takes place by decision variables which are used to design and operating the system[5–6]. After finding Pareto-Optimality front which is a combination of best optimization answers, the final optimization point will be chosen by policy of making decisions.

2. Methodology

In this study, optimization was done by using the principal of Entropy Generation Minimization. Entropy Generation Minimization (EGM), is the actual thermo dynamical optimization method for real systems that has thermo dynamic defects in transferring heated Fluids cir-

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culation and density problems in transferring the mass. EGM method has the most basic stages in primary thermodynamic course, which consist of; thermal conduction, mass conduction and Fluid mechanics. This method is a connection between thermodynamics, heat transfer and Fluid mechanics[7].

EGM method is different from exergy analysis is a method for analysis of thermo dynamical process that gives the approximate measures of global work potential or (different qualities of energy types in connection with an environment). Using the practice shows balance of exergy and how much of useful work potential which entered to the process is used by itself. This measure of loss in energy is not recoverable. For calculating the Exergy, analyst only needs first and second law and a collection of intensive environment properties.

Main new and important feature of EGM method is minimization in the rate of entropy generation. For minimization in a suggested design, analyst must use the relation between changes in pressure and rate of heat transfer and connection between differences in pressure ant rate of mass flow. He must make connections between different grads of designing a none ideal thermodynamic system, for its physical features, like dimension, figure, material and limit in speed and limited time efficiency. To attain these, he must rely on thermal conduction and bases of Fluid mechanics plus thermodynamics. With changing one or more characteristics of its physical nature, it is possible to be closer to minimization in entropy generation in practical way.

3. The Objective Functions for the Two-Objective Optimization

The objective functions evaluated in this research, the entropy generation in the compact heat exchanger and should be minimization, the objective function is expressible as follows[8]:

$$N_s = N_{s,\Delta T} + N_{s,\Delta P} \tag{1}$$

$$N_{s,\,\Delta T} = \frac{m_a C_{p,a}}{c_{\max}} \ln\left(\frac{T_{a,2}}{T_{a,1}}\right) + \frac{m_b C_{p,b}}{c_{\max}} \ln\left(\frac{T_{\mathrm{b},2}}{T_{\mathrm{b},1}}\right) = \frac{m_a C_{p,a}}{c_{\max}} \ln\left(\frac{1+\dfrac{UA(F.LMTD)}{m_a c_{p,a} T_{a,1} + m_b c_{p,b}}}{c_{\max}}\right) \tag{2}$$

$$N_{s,\,\Delta p} = \frac{-m_a R_a \ln\left(\dfrac{P_{a,2}}{P_{a,1}}\right) - m_b R_b \ln\left(\dfrac{P_{b,2}}{P_{b,1}}\right)}{c_{\max}} = \frac{-m_a R_a \ln\left(1-\dfrac{\Delta P_a}{P_{a,1}}\right) - n m_b R_b \ln\left(1-\dfrac{\Delta P_b}{P_{b,1}}\right)}{c_{\max}} \tag{3}$$

Also, in this study for optimizing the plate thermal exchanger we can get the help of a toolbox named (genetic algorithm) which has come with MATLAB software. So it is suitable to point to the logic and essence of this optimization method. Between the optimization methods, genetic algorithm, inspired by nature is one of the most advanced ones with disconnected variables. This algorithm is based on natural progress. Genetic algorithms are searching ones that are based on natural progress process. These algorithms choose the most suitable threads of the arranged accidental data with human method of search. To form a generation, there is a new combination of artificial threads with the use of bits and most suitable components of last generation. The new part is chosen accidentally and the measure of power or suitability is obtained. In fact in natural genetic algorithm, there is not a simple accidental process, but they inspect the former data with thinking of new searching points, to reach to the aimed progress[9]. In general, genetic algorithm is in class of guided random search algorithms, especially for optimization of complex problems with unknown search environment that normally précised methods cannot find the solution.

As we know there are two general methods for solving heat exchangers thermodynamic problems, one is LMTD and the other is NTU. Each one of these are to be used in specific conditions and have their own blind spots. Usually NTU method is used when the data on input and output of converter is unknown and there is only thermal data of input available. LMTD is useful in analyzing thermal exchanges when thermal degree of input and output is given or is not simply available. Then can easily obtain the amount of LMTD, thermal flow and heat exchange surface and total coefficient of heat exchange. When input and output thermal figures are assigned, mostly you must use try and error method which is subsidiary of logarithmic LMTD[10].

The thermal exchange analyzed in this study is unique for its input and output number of fluids, solving the problem with try and error, like other normal methods, it is not answering us so we are going to use a new design to solve this problem (Figure 1). From the beginning we use the tray and error method that is used in LMTD. For reaching to the final solving stage, we reached to a series of linear and non leaner equations; co efficient of thermal exchange between plates is the result of this equations. The linear and non linear equations which is regnant to this process can be seen in Table 1.

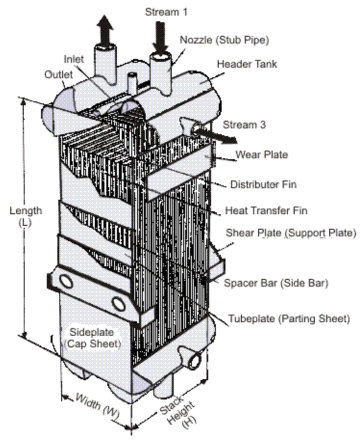

Figure 1. Plate fin heat exchanger core structure.

Table 1. Thermal energy balance linear and non linear equation that are obtained from try and error method by LMTE

Unknown	Obtained equation	Column
$q_{12} h_2 h_1$	$\left(\frac{1}{h_1}+\frac{1}{h_2}\right)=\frac{a}{q_{12}}$	1
$q_{15,} q_{12}$	$q_1 = q_{12} + q_{15}$	2
$q_{15} h_5 h_1$	$\left(\frac{1}{h_1}+\frac{1}{h_5}\right)=\frac{b}{q_{15}}$	3
q_{23}, q_{12}	$q_2 = q_{12} + q_{23}$	4
$q_{23} h_3 h_2$	$\left(\frac{1}{h_2}+\frac{1}{h_3}\right)=\frac{c}{q_{23}}$	5
q_{23}, q_{34}	$q_3 = q_{23} + q_{34}$	6
$q_{34} h_4 h_3$	$\left(\frac{1}{h_3}+\frac{1}{h4}\right)=\frac{d}{q_{34}}$	7
q_{34}, q_{45}	$q_4 = q_{34} + q_{45}$	8
$q_{45} h_5 h_4$	$\left(\frac{1}{h_4}+\frac{1}{h_5}\right)=\frac{e}{q_{45}}$	9
q_{15}, q_{45}	$q_5 = q_{45} + q_{15}$	10

Which in them amount of a, b, c, d, e are:

$$a = (L_{ex}W_{ex}N[1 + (2n(H - t))]) * (LMTD_{12}) \quad (4)$$

$$b = (L_{ex}W_{ex}N[1 + (2n(H - t))]) * (LMTD_{15}) \quad (5)$$

$$c = (L_{ex}W_{ex}N[1 + (2n(H - t))]) * (LMTD_{23}) \quad (6)$$

$$d = (L_{ex}W_{ex}N[1 + (2n(H - t))]) * (LMTD_{34}) \quad (7)$$

$$e = (L_{ex}W_{ex}N[1 + (2n(H - t))]) * (LMTD_{45}) \quad (8)$$

This equations can be solved by fsolve command which is in MATLAB software for solving none linear equations, it is written in main text, two lines in bottom is used for solving non linear equations and then in an m-file linear and nonlinear equations are written to be solved, which from output of this code will be written to main code for optimization (Figure 2).

Options = optimset (maxFunEvals,1000);
[x.fval, exitflag] = fsolve@non linear function1, x0, options);

4. Decision Making Variables

In this study, variables of decision making with respect to geometric dimensions of air separation unit in APC can't be changed, and only with use of alterations in thermodynamic variables and amount of Fluid passing between plates the optimization is done. Decision making variables with their abbreviation forms and range of changes, the parameters for design of exchanger and two-objective optimization are seen in Table 2.

5. Results

Pareto-Optimality front diagram obtained by Two-objective optimization

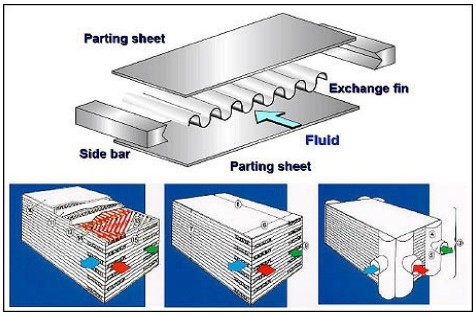

Figure 2. Structure and arrangement plates and fins in the plate fin heat exchanger.

Table 2. Decision making variables for two-objective optimization

Scope of the change	Abbreviation	Decision making parameters	No.
$150 \le T_{o1} \le 190$	T_{o1}	Air1.Outlet temperature	1
$280 \le T_{o2} \le 320$	T_{o2}	Nitrogen1.Outlet temperature	2
$80 \le T_{o3} \le 120$	T_{o3}	Air2.Outlet temperature	3
$280 \le T_{o4} \le 320$	T_{o4}	Nitrogen2.Outlet temperature	4
$280 \le T_{o5} \le 320$	T_{o5}	Oxygen Outlet temperature	5
$1000 \le h_1 \le 1800$	h_1	Heat transfer coefficient 1	6
$600 \le h_2 \le 950$	h_2	Heat transfer coefficient 2	7
$1300 \le h_3 \le 1700$	h_3	Heat transfer coefficient 3	8
$300 \le h_4 \le 800$	h_4	Heat transfer coefficient 4	9
$1600 \le h_5 \le 2500$	h_5	Heat transfer coefficient 5	10
$2000 \le Q_1 \le 3500$	Q_1	Fluid1.Volumetric flow rate	11
$7500 \le Q_2 \le 9000$	Q_2	Fluid2.Volumetric flow rate	12
$15000 \le Q_3 \le 19000$	Q_3	Fluid3.Volumetric flow rate	13
$7000 \le Q_4 \le 9000$	Q_4	Fluid4.Volumetric flow rate	14
$3000 \le Q_5 \le 5000$	Q_5	Fluid5.Volumetric flow rate	15

The following Pareto-Optimality front diagram is drawn by MATLAB which recommends 79 optimized points as desired ones in design. Result of the final point of optimization will be displayed in the following Figure 3 and Figure 4.

Number of thermodynamic subsidiaries of final optimization point from the view of reduction in production of entropy and thermal conditions are in the following Table 3-6.

In the following diagram the changes of pressure and heat entropy that is obtained in 79 points of optimization is presented (Figure 5. and Figure 6).

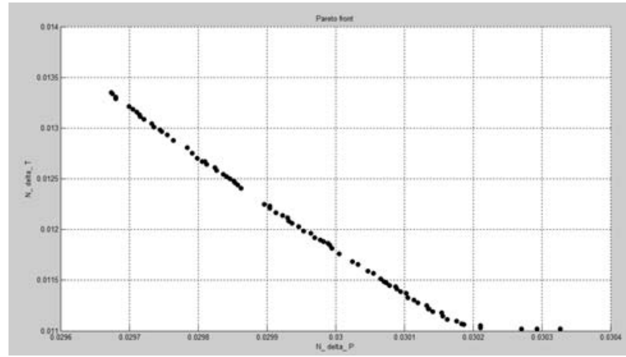

Figure 3. Obtained pareto-optimality front diagram.

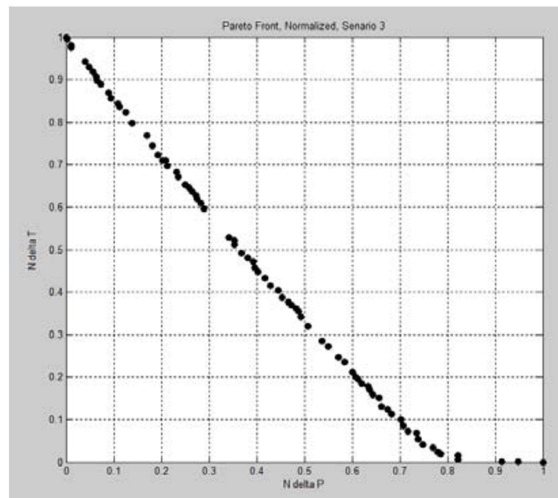

Figure 4. Normalized diagram of obtained pareto-optimality front.

Table 3. Number of thermodynamic subsidiaries for final optimization

Number of compatible optimization points for final optimization drawing method	Abbreviation	Description	No.
169 K°	T_{o1}	Air1.Outlet temperature	1
285 K°	T_{o2}	Nitrogen1.Outlet temperature	2
91 k°	T_{o3}	Air2.Outlet temperature	3
281 K°	T_{o4}	Nitrogen2.Outlet temperature	4

(*Continued*)

283 k°	T_{o5}	Oxygen Outlet temperature	5
1545 W/m^2K	h_1	Heat transfer coefficient 1	6
833 W/m^2K	h_2	Heat transfer coefficient 2	7
1519 W/m^2K	h_3	Heat transfer coefficient 3	8
706 W/m^2K	h_4	Heat transfer coefficient 4	9
2030 W/m^2K	h_5	Heat transfer coefficient 5	10
2001 Nm³/hr	Q_1	Fluid1.Volumetric flow rate	11
7996 Nm³/hr	Q_2	Fluid2.Volumetric flow rate	12
15501 Nm³/hr	Q_3	Fluid3.Volumetric flow rate	13
7478 Nm³/hr	Q_4	Fluid4.Volumetric flow rate	14
3137 Nm³/hr	Q_5	Fluid5.Volumetric flow rate	15

Table 4. Number of pressure and temperature entropy compatible with final optimization points

Description	Abbreviation	Optimized amount
Pressure entropy Dimensionless	N_S^{deltaP}	0.0299
Thermal entropy Dimensionless	N_S^{deltaT}	0.0120

Table 5. Number of pressure and thermal entropy compatible with minimum pressure

Description	Abbreviation	Optimized amount
Pressure entropy Dimensionless	N_S^{deltaP}	0.0296
Thermal entropy Dimensionless	N_S^{deltaT}	0.0133

Table 6. Number of pressure and thermal entropy compatible with temperature minimum point

Explanation	Abbreviation	Optimized amount
Pressure entropy Dimensionless	N_S^{deltaP}	0.0303
Thermal entropy Dimensionless	N_S^{deltaT}	0.0110

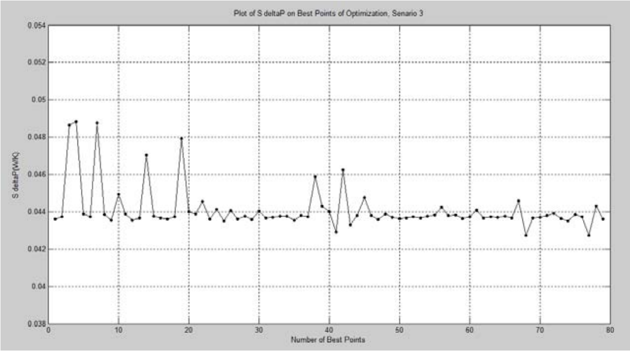

Figure 5. Diagram of change in pressure entropy in optimized points of Pareto-Optimality Front.

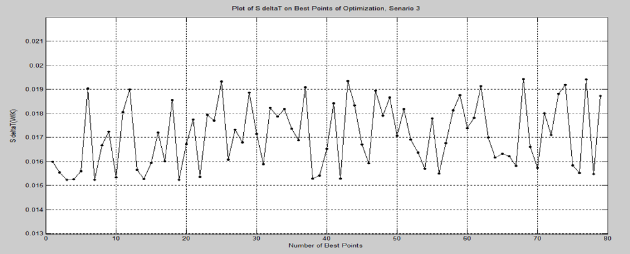

Figure 6. Diagram of change in temperature entropy in optimized points of Pareto-Optimality Front.

5.1 Final Results of Drop in Pressure

According to calculations, pressure drop diagrams of each fluid that is used in suggested plate heat exchanger are as follows (Figure 7).

6. Comparison, Summation and Conclusion

According to the Table, Figures and obtained results, a comparison is made between desired pressure drop of design in air separation unit in APC and drop in pressure of proposed optimized plate heat exchanger is made in the following Table 7.

Following Figure shows the total pressure drop (Figure 8).

As can be seen the results of calculation was obtained without any change in geometric parameters that was used by air separation unit in APC, thermal exchange coefficient factors are as follows, 1545, 833, 1519, 706 and 2030 W/m^2K; and pressure drop of each of the exchanger feeding fluid is calculated approximately 10.8, 19.0, 12.1, 19.9, 18.6, in KPa Pascal. Also overall pressure drop in suggested

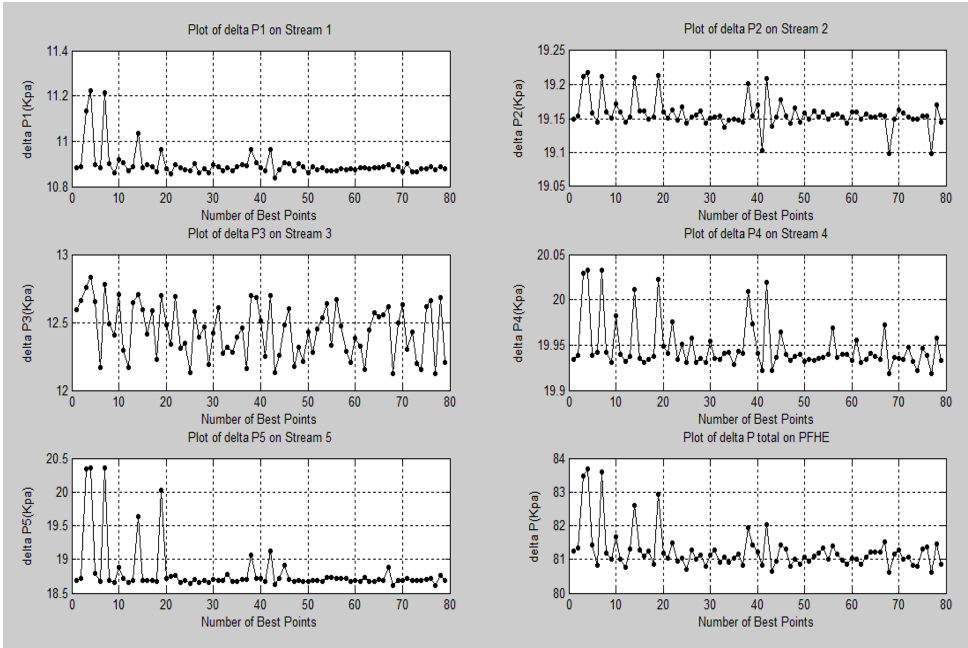

Figure 7. Diagram of change of pressure drop in optimized points in each thermal exchanger in general state.

Table 7. Comparison between measures of optimization in presented exchanger and measures of desired exchanger design in air separation unit in APC.

Minimum pressure drop in optimized exchanger presented (Kpa) in this study	Desired pressure drop design in air separation unit of (Kpa) APC	Desired output pressure design in Air separation (bar) Unit of APC	Desired input pressure design in Air separation (bar) Unit of APC	Fluid
10.839	30	7.2	7.5	1
19.098	16	0.3	0.14	2
12.121	20	4.9	4.7	3
19.918	15	0.25	0.1	4
18.608	10	0.3	0.2	5
80.584	91	---	---	total

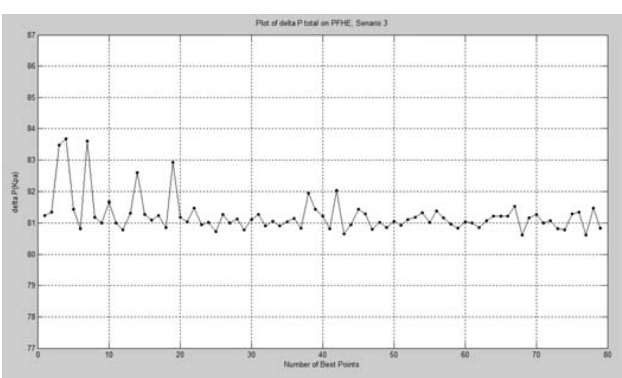

Figure 8. Diagram of optimized total pressure drop in design.

plate heat exchanger with simple fins was calculated 80.5 KPa which is less than desired figure of air separation unit in petrochemical company but instead, output temperature of passing fluids between plates is reduced.

7. Nomenclature

APC: Arvand Petrochemical Company.
ASU: Air Separation Unit.
PFHE: Plate Fin Heat Exchanger.
EGM: Entropy Generation Minimization.
LMTD: Logarithmic mean temperature difference.
NTU: Number of Transfer Units Method.

L_{ex}: length of passing current (m).
W_{ex}: Width of passing current (m).
N: Number of fin layers.
N: Fin frequency [fins/m].
H: Height of outside to next fin layer (outside length) (mm).
T: Fin thickness (mm).
T_o: Outlet temperature (K).
H: Heat transfer coefficient(W/ (K. m^2)).
Q: Volumetric flow rate (Nm^3/hr).
Q: Rate of heat transfer (W).
$N_S^{delta\ P}$: Dimensionless Pressure entropy.
$N_S^{delta\ P}$: Dimensionless Thermal entropy.
A: Heat transfer area (m^2).
P: Pressure (KPa).
DP: Pressure drop (KPa).
R: Specific gas constant (J/kg.K).
U: Overall heat transfer (W/m^2.K).
C_p: specific heat of fluid (W/ kg.K).

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