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Pressure Drop Optimization in an Multi-Stream Heat Exchanger using Genetic Algorithms

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In this paper, Genetic Algorithms (GA) has been used to achieve optimum use of stream pressure drops when designing a Heat Exchanger Network comprising of Multi-Stream Heat Exchangers (MSHE). The MSHE consists of several block sections with intermediate entry and exit points along the length of unit, determined by the composite curves. Three different approaches have been used for optimization, in all of which the Total Annual Cost (TAC) is considered to be objective function. In first approach, allowable pressure drop of the critical stream in each section is maximized. However, since full utilization of pressure drop of the critical streams does not necessarily lead to uniform block heights, the allowable pressure drops are not fully utilized. In second approach, the drawback in the first approach is removed and a new procedure is presented to achieve uniform block heights as well as full utilization of critical streams' pressure drops through whole sections. Moreover, fin type is also checked and best fins are selected in order to minimize the objective function. In third approach, a comprehensive optimization is carried out through relaxation of all stream pressure drops, fin types and heat exchanger height and letting all these variables to be optimized simultaneously. It is shown that by applying GA method using the above approaches TAC of the optimized MSHE is improved, compared to those reported in the literature, by 9.5%, 3.9 %, and 10.7 %.

1. Multi-Stream Heat Exchanger Design

In this paper, a new MSHE design was developed based on the method proposed by Picon-Nunez et al. (2002). The design problem of an MSHE can be divided to smaller sections specified by the enthalpy intervals of T-H composite curves. They applied the design procedure of two stream plate-fin heat exchangers (PFHE) in each section. Therefore, in each section, length and width of an MSHE is obtained by calculating the required volume to transfer heat between critical and reference streams in which the critical stream achieves the maximum allowable pressure drop.

Knowing the length and width of an MSHE in each block, the thermal and hydraulic parameters of other streams can be calculated.

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It is important to select suitable fin type for streams in order to achieve uniform ηhA value, where h, A and η indicate the heat transfer coefficient, total heat transfer area and fin temperature effectiveness, respectively. However, this method was lead to design MSHEs with different height. Final design of an MSHE must be done by relaxation of critical stream pressure drop to achieve an MSHE with uniform height owing to the manufacturing requirements (Xie et al., 2001).

The volume of a PFHE can be calculated by the following equation:

$$V_T = \frac{Q}{\Delta T_m}\left(\frac{1}{\eta_1\alpha_1}\left(\frac{1}{h_1}+R_1\right)+\frac{1}{\eta_2\alpha_2}\left(\frac{1}{h_2}+R_2\right)+R_W\right) \tag{1}$$

where Q is the heat load transferred between two streams, ΔT_{LM} is the logarithmic mean temperature difference; α1 and α2 are the ratio of total surface area on sides 1 and 2 to the total exchanger volume, respectively. The thermal and friction performance of plate fins can be correlated as a function of Reynolds number by following equations (Kays and London, 1998)

$$f = a\,\mathrm{Re}^{-b} \tag{2}$$

and

$$j = (St\,\mathrm{Pr}^{2/3}) = x\,\mathrm{Re}^{-y} \tag{3}$$

where,

$$\mathrm{Re} = \frac{\dot{m}\,d_h}{\mu A_C} \tag{4}$$

$$St = \frac{hA_C}{\dot{m}C_P} \tag{5}$$

j is Colburn factor and f is fanning friction factor. In a compact heat exchanger, the pressure drop is related to fin parameters and physical and hydraulic specifications of the fluid by Eq. (6):

$$\Delta P = \frac{2fL\dot{m}^2}{\rho D_h A_C{}^2} \tag{6}$$

In the design of PFHEs, when total volume and total free flow area are known, we can easily calculate the length (L) of exchanger. (Picon-Nunez et al., 2002)

$$L = \frac{V_T}{A_f} \tag{7}$$

The ratio of free flow area to total exchanger frontal area is given:

$$A_{fr} = \frac{4A_C}{\beta d_h}$$

(8)

The only way to calculate all dimensions of an PFHE is fixing either width (W) or height (H) of exchanger. Since width is usually fixed, height can be calculated knowing the number of passages per stream (N_P) by following equation.

$$H_T = \sum_1^i (N_P\delta)_i + \left[1+\sum_1^i (N_P)_i\right]\varepsilon \tag{9}$$

Where

$$N_P = \frac{A_C}{W\delta} \tag{10}$$

2. Developing Two New Approaches for MSHE Design

The current method proposed by Picon-Nunez (2002) suffers from some drawbacks. After pressure drop relaxation, the obtained results deviate from necessary condition for achieving uniform ηhA value and full utilization of pressure drop for the critical stream. In this paper, two new approaches introduced to resolve the problems of the current method. Here, the interactions between variables are considered through a simultaneous design procedure through all sections. Therefore, there is no need to relax the pressure drop of critical stream to achieve uniform height.

2.1 First Approach

We have designed the MSHE by solving the following non-linear set of equations in order to achieve uniform ηhA value and full utilization of pressure drop for one stream.

$$\begin{aligned} &f_1(x) = H_1(x) - H_2(x) \\ &f_2(x) = H_2(x) - H_3(x) \\ &\vdots \\ &f_{n-1}(x) = H_{n-1}(x) - H_n(x) \\ &f_n(x) = \Delta P_{allowable,i} - \sum_{j=1}^{n} dP_{i,j} \qquad i = stream\ , \quad j = enthalpy\ section \end{aligned} \tag{11}$$

If the whole heat recovery region is divided to n enthalpy intervals, H1, H2,…,Hn depict the height of an MSHE in section 1,…, n, respectively.

ΔPi,j is pressure drop of ith stream in jth section. This stream can be the critical stream or any other streams. A modified Newton-Raphson Method was used to solve this set of equations.

2.2 Second Approach

In this approach, the design of an MSHE is started by an initial guess for height of heat exchanger. Then, the fin type of streams in one section is selected in which the height of MSHE reach to the guessed value. If pressure drop of all streams is remained less than its maximum allowable pressure drop and uniform ηhA is achieved, the design could be finished; otherwise the procedure will be continued until the all constraints are satisfied.

3. Optimization of MSHE using GA

There is a strong trade-off between pressure drop of streams and required surface heat transfer in design of an MSHE. Therefore, we need to use a powerful optimization tool to exploit of this trade-off. Whereas the TAC comprises of operating and maintenance cost and capital cost as a function of pressure drop and heat transfer surface, TAC would have the role of a controlling function.

$$Total\ Annual\ Cost\ (TAC) = Capital\ Cost + Operating\ and\ Maintenance = IC + OMC \tag{12}$$

The capital costs and operating and maintenance costs are determined from (Peng, and Ling 2008):

$$IC = (f_c + A \times u_c) \times C_1 \tag{13}$$

$$C_1 = \frac{(1+i)^{t_P}}{t_P} \tag{14}$$

$$OMC = \frac{(E_c + E_h) \times AH \times fe}{3600 \times 1000} \tag{15}$$

Fin selection plays an important role in designing of MSHE by changing heat transfer surfaces and pressure drops and considered as a GA variable. Considering different fins, will allow the model to trade-off heat transfer areas against pressure drops to get the minimum TAC. Specifications of plate fins have been saved in an Excel file, which is linked to GA program. Moreover, fins are specified by integer numbers between 1 and 57, which provide an array of integer variables in GA Program which is written in Visual Basic platform. Finally, the model completed at the second approach, can obtain the minimum TAC without enforcing full pressure drop utilization for any stream.

4. Case Study

The new methodology is now applied to a nine-stream problem, six liquid streams, and three gaseous streams, cited by Khorrammanesh et al (2007) as shown in Table 1. The objective of this example is to demonstrate the ability of new methodology for design and optimization of an MSHE. A minimum temperature approach of 18 °C is used to construct the composite curves and enthalpy intervals.

Table 1 : Process data of case study

Stream	Ts (°C)	Tt (°C)	Mass (kg/s)	ΔP (Pa)	ρ (kg/m^3)	Cp (J/kg.K)	μ (N.s/m^2)	k (W/m.K)	R_W (m^2°C/W)
H1	220	60	26.6	62000	730	2250	0.0003	0.12	0.000053
H2	327	40	47.6	86000	700	2120	0.0004	0.12	0.000053
H3	160	60	160	20000	11.5	2500	0.000016	0.049	0.000053
H4	220	160	74.4	45000	920	2150	0.0003	0.12	0.000053
C1	85	138	125	10000	17.5	2800	0.0000075	0.03	0.000053
C2	140	300	133	65000	850	1500	0.0005	0.12	0.000053
C3	35	164	25	55000	810	2800	0.0003	0.12	0.000053
C4	60	170	35	32000	14.5	1715	0.000012	0.0516	0.000053
C5	100	300	47.6	97000	800	2100	0.0004	0.12	0.000053

Table 2 : MSHE Dimensions

	Length(m)	Height(m)	Volume(m^3)
Base Case	1.18	4.391	5.2
Approach 1	0.613	5.18	4.12
Approach 2	0.97	3.48	4.39
Approach 3	0.58	4.68	3.53

Table 3 : Total Annual Cost

	TAC($/y)
Base Case	5752799.08
Approach 1	5207077.47
Approach 2	5530536.84
Approach 3	5137152.52

Tables 2, 3 and 4 compare the effect of fin types on heat transfer area (volume), TAC and stream pressure drops of the three approaches with those of the base case solution, respectively. As it can be seen, the fin types and stream pressure drops have all been changed during full optimization, and as a result, TAC of the optimized MSHE reduced from base case value by 9.5 %, 3.9 %, and 10.7 %, respectively.

Table 4 : Total Stream Pressure Drops (Pa)

Stream	Allowable	Current Method	Approach 1	Approach 2	Approach 3
Hot 1	47880	1235.08	418.21	573.2	481.722
Hot 2	69063	2294.98	834.7155	1320.57	1018.05
Hot 3	12700	12125.07	8149.68	12700.01	9807.87
Hot 4	45000	98.89	83.68	110.03	179.94
Cold 1	9999	8326.61	2584.81	7202.14	4326.45
Cold 2	36964	454.73	149.82	1612.43	412.64
Cold 3	54995	151.4187	236.05	208.81	681.62
Cold 4	31996	3896.22	7167.83	7765.10	1995.58

5. Conclusions

1. In previous methods for MSHE design, the main focus is on pressure drop maximization over critical streams, while pressure drop values for other stream are calculated consequently. This is somehow a conservative design policy, because there is a strong trade-off between stream pressure drops and exchanger size, which cannot be exploited in this manner.
2. Type of fins has an effect on the rate of heat transfer and pressure drop utilization, and hence, it should be taken into account when designing a MSHE. Therefore, we need to take care of fin selection and pressure drop optimization for every single stream, simultaneously.
3. The Genetic Algorithm proved to be a powerful optimization tool for design and optimization of MSHE's when fin selection and pressure drop optimization are to be considered at the same time.

Nomenclature

A: heat transfer area (m^2)
A_C: free flow area (m^2)
A_{fr}: frontal area (m^2)
AH: annual operating period ($/y)
a: coefficient in heat transfer vs. Re correlation
b: exponent in heat transfer vs. Re correlation
Cp: heat capacity (J/kg °C)
d_h: hydraulic diameter (m)
E: pumping power (W)
f: friction factor
fe: electric cost ($/kWh)
fc : fixed cost ($)
H_T: exchanger height (m)
h: heat transfer coefficient (W/m^2 °C)
i :Interest rate (%)
IC: capital cost ($)
j: Colburn factor (St $Pr^{2/3}$)
k: fluid thermal conductivity (W/m °C)
L: exchanger length (m)
$\dot{m}$: mass flow rate (kg/s)

MSHE: Multi-Stream Heat Exchanger
n: number of sections
N_F: fin type number
N_P: number of passages per stream
OMC: operating and maintenance cost ($)
Pr: Prandtl number
Q: heat load (J)
R: thermal resistance due to fouling (m^2 °C/W)
Re: Reynolds number
R_W: wall thermal resistance (m^2 °C/W)
St: Stanton Number
tp: operating period (y)
uc: unit cost of PFHE per area ($/$m^2$)
V_T: total volume of heat exchanger (m^3)
W: Exchanger width (m)
x: coefficient in friction factor vs. Re correlation
y: exponent in friction factor vs. Re correlation
α: total heat transfer area of one side of exchanger to total exchanger volume (m^2/m^3)
β: total heat transfer area of one side of exchanger to volume between plates in that side (m^2/m^3)
δ: plate spacing (m)
ε: plate thickness (mm)
η: fin temperature effectiveness
μ: viscosity (kg/m s)
ρ: density (kg/m^3)
ΔP: pressure drop (Pa)

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