Heat Exchanger Network (HEN) costs and performances estimation for multi-period operation

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Abstract

This paper addresses the problem of modeling and estimating the cost of the heat exchanger network (HEN) in multi-period operation using pinch technique concepts. The developed method improves the vertical heat exchanges technique originally proposed by Ahmad *et al.*, by estimating the contribution of each stream to the overall HEN area instead of equally distributing the area between the computed minimum number of exchangers. This method allows to consider the available area for each stream and to manage the fact that some streams may not be active during some particular periods of operation. The method proposed computes the near-optimal $\Delta T_{\min/2}$ contribution, associated to the streams in each of the periods, from one single reference value. This allows to reduce the number of decision variables to one, when computing the energy saving/investment trade-off in thermo-economic optimisation models.

Key words: Pinch analysis, minimum approach temperature, multi-period

1. Introduction

Composite curves are conventionally employed to compute the maximum energy recovery between hot and cold streams and to model the heat exchanger network (HEN) [1] in process systems. In thermo-economic process design of energy conversion systems [2,3], the HEN model based on composite curves computes the heat recovery and the integration of the energy conversion devices in order to close the energy balance of the system. This is done without having to consider and optimise the HEN layout. This approach is particularly attractive when solving process design problems where the operating conditions will result in different pinch points and in the potential selection of

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different integrated energy conversion technologies. In such superstructures, the Heat Recovery Approach Temperature (HRAT or $\Delta T_{\min}$) is the decision variable that is used to represent the trade-off between energy recovery efficiency and the required investment in the heat transfer system. The HEN cost is conventionally estimated considering the vertical heat exchanges in the balanced composite curves and assuming the minimum number of connections calculated by applying the Graph theory. If the validity of the HEN cost estimation using vertical exchange model has been analysed by Ahmad *et al.*[4], there was a need to further study the model and extending it to account for varying heat transfer conditions. We propose in this paper a method which extends the conventional approach to the study of energy systems operating in multi-period conditions. We also propose a mathematical relation allowing to obtain near-optimal $\Delta T_{\min}$ from one single reference value and thus to reduce the number of degrees of freedom of the problem formulation.

2. Background

Considering together the process and the utility system streams, the optimal flowrate of the utility streams u will be computed by solving the transhipment MILP problem originally proposed by Papoulias and Grossmann [5,6]. Equations (1)-(6) are an extended version [7] taking into account the electricity produced by the utilities ($\dot{E}$), sold ($\dot{E}^+_{grid}$) and purchased from the grid ($\dot{E}^-_{grid}$). Two variables are therefore associated with any utility technology u : the integer variables y_u represent the presence of the technology u in the optimal configuration and f_u represents its level of utilisation. $c_{u,1}$, $c_{u,2}$, c^+_{el} and c^-_{el} are constants used for the computation of the operating costs respectively of the utilities and the electricity. The objective function is the operating cost (C_U). This formulation can be easily extended to solve multi-period problems [7].

$$\text{Minimize} \quad C_U = \sum_{u=1}^{N_u} (c_{u,1} y_u + c_{u,2} f_u) + c^+_{el}\dot{E}^+_{grid} - c^-_{el}\dot{E}^-_{grid} \tag{1}$$

$$\text{s.t.} \quad \sum_{u=1}^{N_u} f_u \dot{q}_{u,r} + \sum_{i=1}^{N_i} \dot{Q}_{i,r} + R_{r+1} - R_r = 0 \qquad \forall r = 1 \dots N_{r+1} \tag{2}$$

$$\text{Electricity consumption:} \quad \sum_{u=1}^{N_u} f_u \dot{e}_u + \eta^+ \dot{E}^+_{grid} - \dot{E} \geq 0 \tag{3}$$

$$\text{Electricity exportation :} \quad \sum_{u=1}^{N_u} f_u \dot{e}_u + \eta^+ \dot{E}^+_{grid} - \frac{\dot{E}^-_{grid}}{\eta^-} - \dot{E} = 0 \tag{4}$$

$$\text{Use of technology } u: \quad f_{u,min} \cdot y_u \leq f_u \leq f_{u,max} \cdot y_u \quad \forall u = 1 \dots N_u, y_u \in \{0,1\} \tag{5}$$

$$\dot{E}^+_{grid}, \dot{E}^-_{grid} \geq 0 \qquad R_1 = 0, R_{N_{r+1}} = 0, R_r \geq 0 \qquad \forall r = 1 \dots N_{r+1} \tag{6}$$

The heat recovery and the optimal heat exchange between the hot and the cold streams of a system is computed by solving the heat cascade (eq. 2). In order to estimate the HEN investment cost, the overall heat exchange area is calculated considering the vertical heat exchange between the hot and cold composite curves. Considering N_j vertical sections defined by the slope change of the streams, the exchange area A_j associated to the vertical sections j is computed by summing the contribution of all the streams i and their respective heat transfer film coefficient $\alpha_{i,j}$, as shown in equation (7).

$$A_{tot} = \sum_{j=1}^{N_j} A_j = \sum_{j=1}^{N_j} (\frac{\dot{Q}_j}{\Delta T_{lm,j}} (\sum_{i=1}^{N_{i,j}} \frac{1}{\alpha_{i,j}})) \tag{7}$$

In the conventional approach, the overall HEN cost is computed knowing the minimum number of exchangers target $N_{HX,min}$ and assuming that the overall heat exchange area A_{tot} will be equally distributed among the heat exchangers (eq. 8). We propose a new method accounting the contribution of each stream to the overall area, as shown later in equation (19).

$$C_I = N_{HX,min} \left[a_{hx} + b_{hx} \left(\frac{A_{tot}}{N_{HX,min}} \right)^{c_{hx}} \right] \tag{8}$$

To optimize the HEN layout, the annual cost of the system C_{Tot} is minimized, considering the annualized (τ) investment cost and the annual operating cost (eq. 9) and by searching for the optimal $\Delta T_{\min}$ value.

$$C_{Tot} = \frac{1}{\tau} C_I + C_U T_{year} \tag{9}$$

The value of $\Delta T_{\min}$ is obtained by summing the contribution of the hot and the cold stream at the pinch points. The value of $\Delta T_{\min/2_i}$ being related to the heat transfer film coefficient (α_i), the optimization of the exchange area A_{tot} should therefore be performed by considering each $\Delta T_{\min/2_i}$ as decision variable. This optimisation is however difficult to solve since only the $\Delta T_{\min/2_i}$ of the streams creating the pinch points really influence the objective function. Townsend *et al.*. [8] suggested relation (10), that links $\Delta T_{\min/2_i}$ with the corresponding film transfer coefficient α_i where K constant can be derived from a reference state, which is defined by $\Delta T_{\min/2_{ref}}$ and α_{ref}. The optimization of the HEN cost can then be simplified by using K as the only decision variable.

$$\Delta T_{\min/2_i} \cdot \sqrt{\alpha_i} = K \tag{10}$$

3. Optimal $\Delta T_{\min}$ estimation for steady-state conditions

The formulation of Townsend *et al.*. was established considering a linear cost of the heat exchangers. For non-linear cost functions (eq. 8), we propose to replace the K constant with a more complex relation. Let us analyse the definition of the $\Delta T_{\min}$ calculation for one single heat exchanger as described on figure 1(a). The heat exchanged between the hot and cold stream is defined in equation (11).

$$\dot{Q}(\Delta T_{\min}) = \begin{cases} \dot{Q} & \text{if both streams change phase} \\ \dot{m}c_{p,h}(T_{h,i} - (T_{c,i} + \Delta T_{\min})) & \text{if } \dot{m}c_{p,h} \leq \dot{m}c_{p,c} \\ \dot{m}c_{p,h}(T_{c,o} + \Delta T_{\min} - T_{h,o}) & \text{otherwise} \end{cases} \tag{11}$$

According to the relative value of the specific heat of the two streams, the logarithmic mean temperature difference is computed as equation (12).

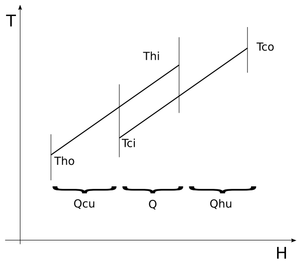
$$\Delta T_{lm} = \begin{cases} \Delta T_{\min/2_h} + \Delta T_{\min/2_c} = \Delta T_{\min} & \text{if} \quad \dot{m}c_{p,h} = \dot{m}c_{p,c} \\ \dfrac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{ln\frac{T_{h,i}-T_{c,o}}{T_{h,o}-T_{c,i}}} & \text{otherwise} \end{cases} \tag{12}$$

Considering c_{cu} and c_{hu} the unitary price of the hot and cold utilities, the cost (eq. 13) to be minimised can be expressed as a function of the heat exchanged. Parameters a_{hx}, b_{hx} and c_{hx} are the cost estimation constants, T_{year} is the yearly working time and τ is the annualisation factor.

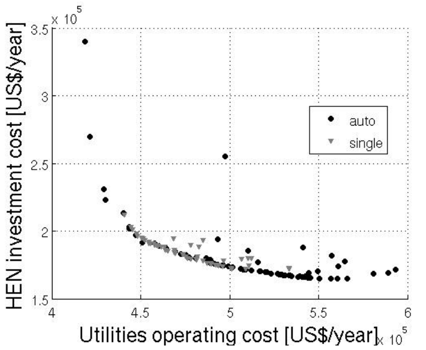
$$C_{Tot} = \frac{1}{\tau}\left[a_{hx} + b_{hx}\left(\frac{\dot{Q}\cdot(\frac{1}{\alpha_c}+\frac{1}{\alpha_h})}{\Delta T_{lm}}\right)^{c_{hx}}\right] - T_{year}(c_{cu}Q_{cu} + c_{hu}Q_{hu}) \tag{13}$$

The optimal value of $\Delta T_{\min}$ is obtained by solving equation (14).

$$\frac{\delta C_{Tot}}{\delta \Delta T_{\min}} = 0 \tag{14}$$



(a) Single heat exchanger definition.



(b) Results of the problem optimization.

Figure 1. Heat exchanger definition and optimization results.

Assuming that $\Delta T_{\min/2_c} = \Delta T_{\min/2_h} = \frac{\Delta T_{\min}}{2}$ and that the optimal value of $\Delta T_{\min/2_{ref}}$ has been found for a given reference stream with given heat transfer coefficient (α_{ref}), the optimality condition (eq. (14)) will be used to compute the value of $\Delta T_{\min/2_i}$ for any stream i knowing the value of its heat transfer coefficient α_i.

When considering a heat exchanger that operates with a temperature difference equal to $\Delta T_{\min}$ during all the heat exchange (i.e. the two streams involved in the heat exchange have the same specific heat and $\Delta T_{lm} = \Delta T_{\min}$, equation (14) simplifies into equation (15).

$$\frac{\Delta T_{\min/2_i}}{\Delta T_{\min/2_{ref}}} = \left(\frac{(T_{h,i} - T_{c,i} - 2\Delta T_{\min/2_i})}{(T_{h,i} - T_{c,i} - 2\Delta T_{\min/2_{ref}})}\right)^{\frac{c_{hx}-1}{c_{hx}+1}} (\frac{\alpha_{ref}}{\alpha_i})^{\frac{c_{hx}}{c_{hx}+1}} \tag{15}$$

In this case, when $T_{h,i} - T_{c,i} \gg \Delta T_{\min/2_i}$ and $T_{h,i} - T_{c,i} \gg \Delta T_{\min/2_{ref}}$, equation (15) is simplified to equation (16).

$$\Delta T_{\min/2_i} \cong \Delta T_{\min/2_{ref}} \cdot (\frac{\alpha_{ref}}{\alpha_i})^{\frac{c_{hx}}{c_{hx}+1}} \tag{16}$$

When the investment cost function (eq. 8) is linear (i.e. $c_{hx} = 1$), the relation given by equation (16) is identical to the one presented by Townsend et. al (eq. 10).

In the situation where the cold stream evaporates and the hot stream condenses, the energy saving does not continuously depend on the value of $\Delta T_{\min}$. The exchange is either acceptable or not if the annual investment cost is higher than the energy saving benefit. However, if a reference $\Delta T_{\min/2_{ref}}$ is known, the dependence of the heat transfer coefficient remains given by equation (16).

4. Extension to multi-period operation

Applying the heat cascade model in multi-period situations reveals another difficulty since the value of the $\Delta T_{\min/2_i}$ should be updated to represent the fact that the available area is constant for all the N_p periods even if the operating conditions of the streams are changing. To do so, a reference area $A_{i,p_{ref}}$ will be attributed to each stream. Assuming the more constrained situation where the stream is exchanging with a stream of similar temperature variation and heat transfer coefficient, equation (17) will be used to establish the relation between the $\Delta T_{\min/2_{i,p}}$ in any period p by comparison with the $\Delta T_{\min/2_{i,p_{ref}}}$ computed for the attributed area $A_{i,p_{ref}}$ in the reference period.

$$A_{i,p} = A_{i,p_{ref}} = \frac{\dot{Q}_{i,p} \cdot \alpha_{i,p}}{4 \cdot \Delta T_{\min/2_{i,p}}} = \frac{\dot{Q}_{i,p_{ref}} \cdot \alpha_{i,p_{ref}}}{4 \cdot \Delta T_{\min/2_{i,p_{ref}}}} \tag{17}$$

As given in equation (16), $\Delta T_{\min/2_{i,p_{ref}}}$ can be computed from a global reference $\Delta T_{\min/2_{ref,p_{pref}}}$. Equation (17) can then be rearranged into equation (18).

$$\Delta T_{\min/2_{i,p}} = \frac{\dot{Q}_{i,p} \cdot \alpha_{i,p_{ref}}}{\dot{Q}_{i,p_{ref}} \cdot \alpha_{i,p}} \Delta T_{\min/2_{ref,p_{ref}}} \left(\frac{\alpha_{ref,p_{ref}}}{\alpha_{i,p_{ref}}} \right)^{\frac{c_{hx}}{c_{hx}+1}} \tag{18}$$

In order to estimate the HEN cost, all the streams appearing in the problem formulation must be taken into account. Eq. (7) must be adapted to account for streams that would be active only in some periods. We consider therefore a contribution of each stream to the total area and, at the same time, a contribution to the HEN overall investment cost. This can be deduced again from the analysis of the heat exchanger with identical temperature variations. In this case, the investment cost (C_I) is the sum of the contribution of the costs of the hot and the cold streams. Assuming that both streams have the same heat transfer coefficient α_i half of the exchanger price will be attributed to each stream. We obtain then equation (19) which defines the cost attributed to a given stream i. In this equation, $\dot{Q}_{i,j,p}$ is the heat load of stream i in the vertical section j of period p.

$$C_I = \sum_{i}^{N_i} \frac{a_{hx}}{2} + b_{hx} \cdot 2^{c_{hx}-1} \cdot \left(\max_{p \in \{1 \cdots N_p\}} \sum_{j=1}^{N_{j,p}} \frac{\dot{Q}_{i,j,p}}{\alpha_{i,p} \cdot \Delta T_{lm,j,p}} \right)^{c_{hx}} \tag{19}$$

5. Application

In order to demonstrate the method, we applied it to the problem 1 of Floudas *et al.*. [9]. This simple problem presents two hot and two cold streams and three periods of operation. Figure 1(b) reports the results of two multi-objective optimizations realised using an evolutionary algorithm. The figure represent the energy savings/investment trade-off by two objective functions: the HEN investment cost and the operating cost of the utilities.

auto refers to the calculation where the only decision variable is $\Delta T_{\min/2_{ref,p_{ref}}}$ and where the other $\Delta T_{\min/2}$ have been computed using equation (18).

single refers to the optimization where all the $\Delta T_{\min/2_{i,p}}$ are considered as decision variables. This generates a variable per stream and per period. Only evolutionary algorithms are efficient to solve such problems, since only $\Delta T_{\min/2_{i,p}}$ involved in pinch points are really influencing the objective functions.

The two Pareto frontiers do coincide, which demonstrates the validity of the approach.

6. Conclusions

A method to estimate the HEN area and cost has been proposed to solve multi-period problems using pinch techniques. The method includes a technique allowing to estimate a near-optimal $\Delta T_{\min/2}$ contribution of all the streams of the problem as a function of the operating conditions in the different periods of operation. This technique requires a reference state where the optimal relationship between $\Delta T_{\min/2_{ref}}$ and α_{ref} is known. This modelling method will be used to model HEN in thermo-economic design of energy conversion systems.

References

[1] Z. Kravanja, P. Glavic, Cost targeting for hen through simultaneous optimisation approach: a unified pinch technology and mathematical programming design of large hen., Computers and Chemical Engineering 21 (1997) 833–853.

[2] M. Gassner, F. Marechal, Thermo-economic optimisation of the integration of electrolysis in a wood to methane process, ECOS 2006 proceedings, Greece, 12-14 July 2006 2 (2006) 553–561.

[3] F. Marechal, F. Palazzi, J. Godat, D. Favrat, Thermo-economic modelling and optimisation of fuel cell systems, Fuel cells - From Fundamentals to Systems 5 (1) (2005) 5–24.

[4] S. Ahmad, B. Linnhoff, R. Smith, Cost optimum heat exchanger networks–2. targets and design for detailed capital cost models, Computers & Chemical Engineering 14 (7) (1990) 751–767.

[5] S. A. Papoulias, I. E. Grossmann, Structural optimization approach in process synthesis - i., Computers And Chemical Engineering 7 (6) (1983) 695–706.

[6] S. A. Papoulias, I. E. Grossmann, Structural optimization approach in process synthesis - ii., Computers And Chemical Engineering 7 (6) (1983) 707–721.

[7] F. Marechal, B. Kalitventzeff, Targeting the integration of multi-period utility systems for site scale process integration, Applied Thermal Engineering 23 (2003) 1763–1784.

[8] B. Linnhoff, D. Townsend, et al., A user guide on process integration for the efficient use of energy., The Institution of Chemical Engineers.

[9] C. Floudas, I. Grossmann, Automatic generation of multiperiod heat-exchanger network configurations, Computers And Chemical Engineering 11 (2) (1987) 123 – 142.