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Minimum heat transfer area for Total Site heat recovery

Stanislav Boldyryev [a,*], Petar Sabev Varbanov [b], Andreja Nemet [b], Jiří Jaromír Klemeš [b], Petro Kapustenko [c]

[a] Centre for Energy Saving Process Integration, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine
[b] Centre for Process Integration and Intensification – CPI[2], Research Institute of Chemical and Process Engineering – MŰKKI, Faculty of Information Technology, University of Pannonia, Veszprém, Hungary
[c] AO Spivdruzhnist-T Company, Kharkiv, Ukraine

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ABSTRACT

In this paper a further development of methodology for decreasing the capital cost for Total Site heat recovery by use of different utility levels is proposed. The capital cost of heat recovery system is estimated for certain temperature level of intermediate utility applying Total Site Profiles. Heat transfer area is reduced by selection of appropriate temperature of intermediate utility. Minimum of heat transfer area depends on slopes of Total Site Profiles in each enthalpy interval. This approach allows estimating the minimum of heat transfer area for heat recovery on Total Site level. Case study is performed for fixed film heat transfer coefficients of process streams and intermediate utilities. It indicates that the total heat transfer area of heat recovery can be different up to 49.15% for different utility temperatures.

1. Introduction

Heat Integration is a key tool for energy saving achieved by heat recovery in process industries [1]. Energy saving has an important role in achieving a sustainable future development. Heat recovery at Total Site level can provide a considerable potential for energy saving as presented in [2]. Use of excess heat can provide a way to reduce the use of primary energy and to contribute to global CO_2 mitigation. Viklund and Johansson [3] presented different measures for the recovery and utilization of industrial excess heat and to investigate how the development of the future energy market can affect which heat utilization measure would contribute the most to global CO_2 emissions mitigation. Exergo-economic and exergo-environmental evaluations are performed in [4]. The environmental impacts obtained by life cycle assessment are apportioned to the exergy streams, identifying the main system components with the highest environmental impacts and possible improvements associated with these components. For the heat recovery at Total Site level heat exchangers with large area may be needed resulting in complex networks with numerous units and matches. Therefore the heat recovery system would have a significant input to capital cost. Nemet et al. [5] developed a general approach for estimation of heat transfer area required for Total Site heat recovery applying intermediate utility. In that approach the temperature of the intermediate utility was assumed constant during the heat recovery. However, a proper selection of the intermediate utility temperature has an influence on heat transfer area and consequently also on the capital cost. Heat transfer area targeting for Heat Exchangers Networks has been well described in [6]. De Ruyck et al. [7] proposed virtual heat exchangers that convert the considered components into equivalent heaters and coolers where the stream compositions remain unchanged. In this way, they are automatically taken into consideration in the current pinch analysis packages, which may lead to different and better optimisation. In [8] a methodology has been presented for calculation of heat transfer area for heat recovery. It focuses mainly on individual processes and steady state pinch analysis as can also be seen in the work by Wan Alwi et al. [9]. A total cost targeting method based on pinch technology for Heat Exchanger Network (HEN) synthesis is presented in [10]. It combines existing targeting methods for the grass-roots design problem with a new method for simultaneous targeting of network area and pumping power cost (i.e., optimum pressure drops of streams). In [11] an optimisation methodology has been presented for a Heat Exchanger Network design over its entire lifespan. Consideration of fluctuating energy prices is essential for achieving an optimal HEN design. The objective function presented a trade-off between investment and operating costs.

The previous works reviewed here establish a representative picture of the state of the art. Hey all have achieved a high level of accuracy and if used well, can help HEN designers finding optimal solutions. However, none of these methods are suitable

* Corresponding author.
E-mail addresses: stas.boldyryev@gmail.com (S. Boldyryev), varbanov@cpi.uni-pannon.hu (P.S. Varbanov), nemet@cpi.uni-pannon.hu (A. Nemet), klemes@cpi.uni-pannon.hu (J.J. Klemeš), sodrut@gmail.com (P. Kapustenko).

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Nomenclature

CW	cooling water (MW)
HW	hot water (MW)
LP	low pressure steam (MW)
MP	middle pressure steam (MW)
HP	high pressure steam (MW)
$Q_{cooling}$	cooling duty (MW)
$Q_{RECOVERY}$	heat recovery (MW)
Q_{LOSS}	heat losses (MW)
Q_{FUEL}	heat of flue gas (MW)
W	power (MW)
T_{TFT}	combustion temperature of flue gas (°C)
T	temperature (°C)
TS	supply temperature (°C)
TT	target temperature (°C)
T_{IM}	temperature of intermediate utility (°C)
T_{IM1}	low temperature of intermediate utility (°C)
T_{IM2}	high temperature of intermediate utility (°C)
h_{IM1}	film heat transfer coefficient of intermediate utility on source side (W/(m^2 °C))
h_{IM2}	film heat transfer coefficient of intermediate utility on sink side (W/(m^2 °C))
CP	heat capacity flowrate (MW/°C)
H	enthalpy (MW)
A	heat transfer area (m^2)
A_{total}	heat transfer area of heat recovery (m^2)
$A_{min,EI}$	minimum heat transfer area of enthalpy interval (m^2)
$A_{min,Rec}$	minimum heat transfer area of heat recovery (m^2)
A_{Source}	heat transfer area of source side (m^2)
A_{Sink}	transfer area of sink side (m^2)
A_{EI}	total heat transfer area of enthalpy interval (m^2)
ΔT_{min}	minimal temperature difference between two process streams (°C)
ΔT_1	minimal temperature difference for source side (°C)
ΔT_2	minimal temperature difference for sink side (°C)
ΔT^H_{LM}	logarithmic temperature difference for source side (°C)
ΔT^C_{LM}	logarithmic temperature difference for sink side (°C)
ΔT_{LM}	logarithmic temperature difference (°C)
Q_i	heat of i hot stream (MW)
Q_j	heat of j cold stream (MW)
Q_{IM}	heat of intermediate utility (MW)
h_i	film heat transfer coefficient of i process stream (W/(m^2 °C))
h_j	film heat transfer coefficient of j process stream (W/(m^2 °C))
h^C_{IM}	film heat transfer coefficient of intermediate utility (W/(m^2 °C))
n	number of hot streams in enthalpy interval
m	number of cold streams in enthalpy interval
k	number of enthalpy intervals

or treat the heat transfer area targeting for the Total Site heat recovery. The present paper provides a methodology for minimisation of heat transfer area of Total Site heat recovery systems. It is an important step on the way to achieve capital cost reduction for Total Site Heat Integration on the way to enabling the systematic selection of the most optimal values for the minimum allowed temperature differences for the process-to-process heat exchanges as well as for the utility generation or use heat exchanges.

2. Methodology development

The procedure for estimating heat transfer area, which depends on a certain temperature levels of intermediate utility consists of two main steps:

- Selection of number of intermediate utilities available.
- Determination of intermediate utility temperature levels.

Intermediate utility transfers the heat from process to process in Total Site. It can be steam with different pressure level, hot water, thermal oil, refrigerants, etc. The selection of intermediate utility depends on temperature level on which it is used. The Total Site Sink and Source Profiles should be plotted together on the T–H diagram applying individual ΔT_{min} specifications for heat exchange between process streams in order to present the streams with their real temperatures [5]. Dhole and Linnhoff [12] presented the Total Site targets for fuel, turbine loads, emissions and cooling. The modified Total Site targets with use of intermediate utility heat recovery are shown in Fig. 1.

2.1. Intermediate utility levels definition

The extent of heat recovery should be divided into enthalpy intervals. For each enthalpy interval the intermediate utility level can be selected. This level corresponds to minimum heat transfer area for that enthalpy interval. Fig. 2 illustrates such a partitioning into enthalpy intervals with their utility levels. This picture is based on previous works which analysed the heat transfer for process integration level and process-utility level [13]. In [5] it was used for estimation of heat transfer area for one intermediate utility of Total Site heat recovery. But minimisation of heat transfer area can be achieved by applying compilation of methods described in [13] as general approach and further development in [5].

The sum of minimum heat transfer area targets of all enthalpy intervals produces the total minimum area requirement for Total Site heat recovery.

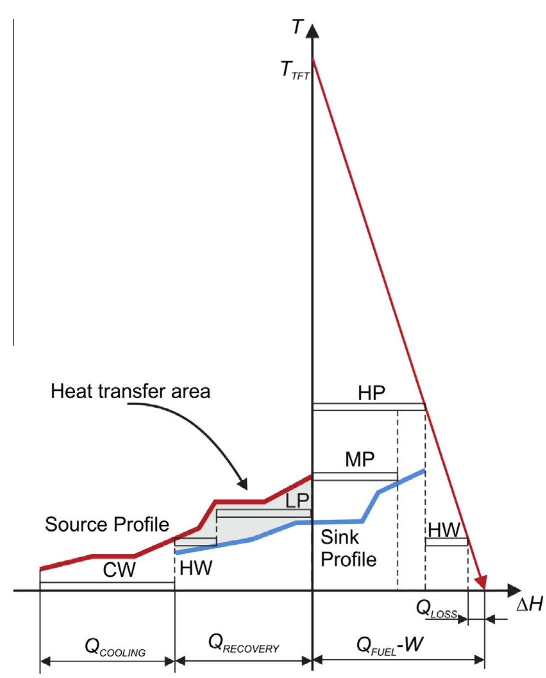

Fig. 1. Heat recovery potential on Total Site level (developed after [12]).

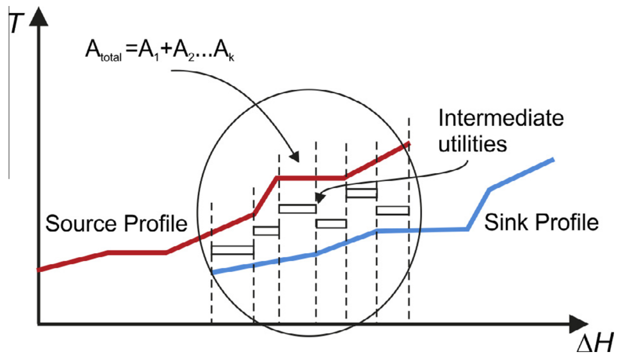

Fig. 2. Total Site heat recovery region divided on enthalpy intervals (developed after [12]).

2.2. Selection of ΔT_{min}

Calculation of heat transfer area in enthalpy intervals for Composite Curves was firstly proposed in [13]. Modification of this approach allows estimating heat transfer area by using of intermediate utility (source-intermediate utility and intermediate utility-Sink). Heat transfer area of each temperature interval consists of two competitive areas of source-intermediate and Sink-intermediate heat exchange. Mean logarithmic temperature difference changes for each level of the intermediate utility. The temperature of the intermediate utility is varied between the lower and upper bounds which are limited by minimal temperature difference on source-intermediate T_1 and intermediate-Sink sides T_2 (Fig. 3). The equation for heat transfer area estimation presented in [13] should be modified for applying it to the enthalpy intervals for each level of intermediate utility; assuming that h_{IM} are equal for each level of intermediate utility, but it is different for each intermediate utility:

$$A_{EI} = \frac{1}{\Delta T^{H}_{LM}}\left(\sum_{i=1}^{n}\frac{Q_i}{h_i} + \frac{Q_{IM}}{h^{H}_{IM}}\right) + \frac{1}{\Delta T^{C}_{LM}}\left(\sum_{j=1}^{m}\frac{Q_i}{h_i} + \frac{Q_{IM}}{h^{C}_{IM}}\right) \quad (1)$$

In Eq. (1) the first term estimates the heat transfer area required to exchange heat between the hot streams (i) and the intermediate utility (IM), while the second term stands for the required surface area to transfer heat from the intermediate utility (IM) to the cold streams (j) in a certain enthalpy interval (EI).

The minimal heat transfer area is selected within each enthalpy interval, as shown in Eq. (2).

$$A_{min,EI} = \min(A_{1,EI}, A_{2,EI}, \ldots, A_{l,EI}) \quad (2)$$

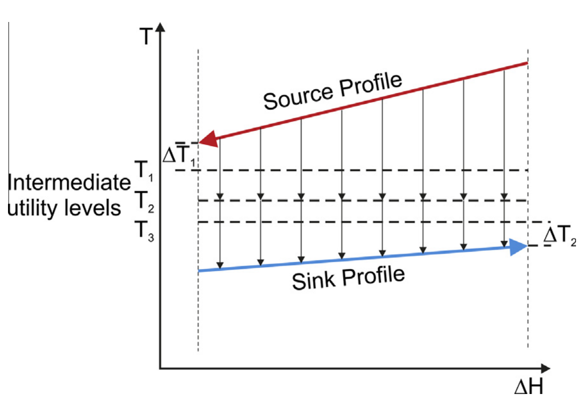

Fig. 3. Selection of temperature of intermediate utility (developed after [13]).

The sum of minimal heat transfer area of all enthalpy intervals forms the total minimal area of heat recovery (Eq. (3)) and allows calculating the optimal temperature for intermediate utilities.

$$A_{min,Rec} = \sum_{p=1}^{k} A_{min,EI} \quad (3)$$

The algorithm has been demonstrated on a case study.

3. Case study

3.1. Process description

There are three processes in this case study (A, B, C) considered in the Total Site and their streams are accounted for when plotting Total Site Profile, described by Nemet et al. [5]. There are six process streams with specific phase and thermo-physical properties. These streams were collected in Table 1. Total Site Profiles were built with use of data in Table 1 and shifted to create heat recovery area (Fig. 4a). In order to perform heat recovery an intermediate utility is needed (see (3a) and (3b) in Fig. 4a). The overlapping part representing the heat recovery was distributed by enthalpy intervals. Numbers of enthalpy intervals depend on numbers of kinks of Sink and Source Profiles. There are two kinks on the Source Profile and 3 kinks of the Sink Profile on heat recovery of this case study. These breakpoints form 2 enthalpy intervals as presented in Figs. 4a and b. The temperature range of the intermediate utility is limited by the Sink and Source Profile temperatures e.g. for (3a) it is between 105 and 125 °C, while for (3b) it is between 115 and 145 °C (Fig. 4b).

Table 2 represents the initial data of intermediate utilities for selected enthalpy intervals.

3.2. Decreasing the heat transfer area

The heat transfer area for each enthalpy interval is calculated using Eq. (1). Temperature of intermediate utility is varied between the lower (T_{IM1}) and the upper bound (T_{IM2}). The lower temperature boundary for enthalpy interval E1 it is 105 °C and the upper is 125 °C. The lower boundary for enthalpy interval E2 is 115 °C and the upper is 145 °C (see Fig. 4b). The results of heat transfer area calculations are presented in Figs. 5 and 6.

Minimal heat transfer area is obtained for temperatures 105 °C and 125 °C of intermediate utilities for the first and second enthalpy intervals. Appropriate placement of intermediate utility is shown in Figs. 4a and b. Detailed results of the case study are presented in Table 3.

4. Results and discussion

A methodology for estimating minimum heat transfer area with a pre-defined rate of heat recovery on Total Site level with use of intermediate utility has been developed. The implementation can lead to reduced heat transfer area and consequently capital cost of heat exchangers on the Total Site. As can be seen from Table 3, the minimal heat transfer area in the first enthalpy interval is at 105 °C equal 240.08 m^2, while in the second enthalpy interval is at 125 °C equal 291.48 m^2. Those two observations lead to the conclusion that the smallest area required for the heat recovery for this case study can be 531.56 m^2. Without the presented methodology the heat transfer area on Total Site can be as high as 1045.37 m^2. It demonstrates that proper selection of the temperature level of the intermediate utility the area can be decreased in this case study to 49.15%.

This considerable decrease in heat transfer area reduces the investments for retrofit as well as save the operation cost for utility

Table 1
Stream data of Total Site analysis.

No.	Stream	Type	TS (°C)	TT (°C)	CP (kW/°C)	ΔH (kW)	h (kW/(m² C))
1	A1 liquid	Hot	100	40	50	3000	0.80
2	B2 gas	Hot	180	130	30	1500	0.11
3	C2 liquid	Hot	80	40	20	800	1.00
4	A3 liquid	Cold	80	120	30	1200	0.70
5	B4 liquid	Cold	100	140	40	1600	0.90
6	C3 gas	Cold	150	240	20	1800	0.15

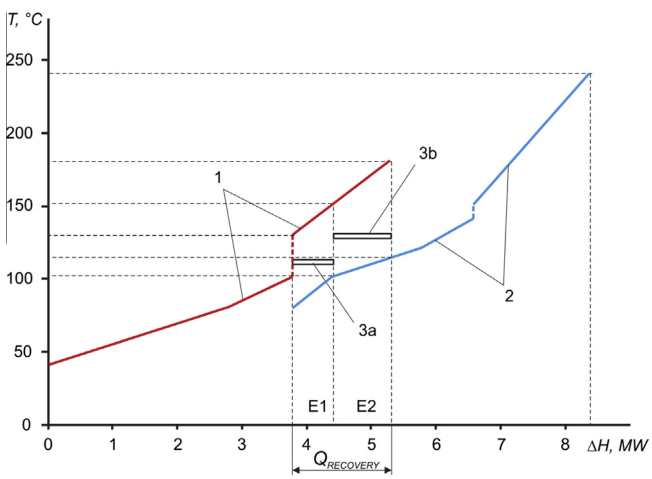

Fig. 4a. Case study – Total Site Profiles. (1) Source Profile; (2) Sink Profile; (3) intermediate utilities; (3a) intermediate utility of enthalpy interval E1; and (3b) intermediate utility of enthalpy interval E2; E1, E2 – enthalpy intervals.

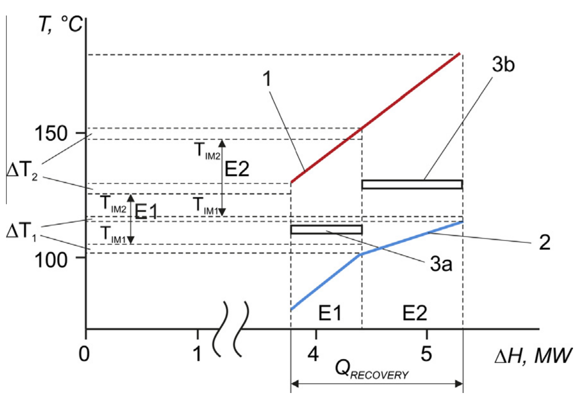

Fig. 4b. Case study – Heat Recovery of Total Site. (1) Source Profile; (2) Sink Profile; (3) intermediate utilities; E1, E2 – enthalpy intervals.

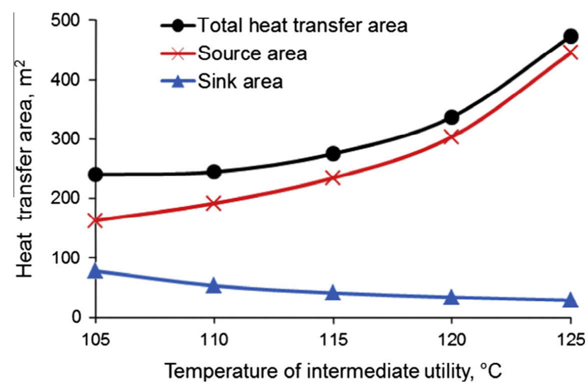

Fig. 5. Heat transfer area for enthalpy interval E1.

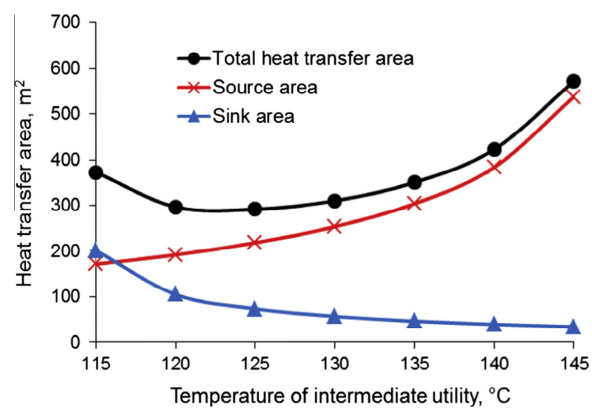

Fig. 6. Heat transfer area for enthalpy interval E2.

reduction. However, this methodology has also some limitations which are connected with technological issues.

They are estimation of changes of film heat transfer coefficient for different temperatures of intermediate utility. The use of heat exchangers of different construction needs the estimation of film heat transfer coefficient too. Different levels of intermediate utility can require different types of heat exchangers that lead to changes (in some case increasing) of capital cost.

The flow rate of intermediate utility in an enthalpy interval can be too small and transportation of this stream to another process may not be economic. Further, if the number of enthalpy intervals is high, this would define too many options for intermediate utility levels. Combined with the well known fact that each additional utility header requires one more set of piping to most of the processes, indicates that there are other capital cost trade-offs. Therefore additional analysis should be performed to account for these factors as well.

However, this methodology still offers a step ahead to estimation of the capital cost for Total Site heat recovery. The further development should deal with investigate the disadvantages listed. Number of enthalpy intervals should be investigated as well

Table 2
Data of intermediate utilities.

Enthalpy interval	ΔH (kW)	T_{IM1} (°C)	T_{IM2} (°C)	ΔT_{min} (°C)	h_{IM1} (kW/(m² C))	h_{IM2} (kW/(m² C))
E1	600	105	125	5	8.1	5.6
E2	900	115	145	2	8.0	5.4

Table 3
Results of heat transfer area calculation.

T_{IM} (°C)	ΔT_{LM} (°C)	A_{Source} (m^2)	A_{Sink} (m^2)	A_{EI} (m^2)
Enthalpy interval E1				
105	34.03	162.48	77.60	240.08
110	28.85	191.61	52.97	244.58
115	23.60	234.22	40.85	275.07
120	18.20	303.69	33.42	337.11
125	12.43	444.90	28.34	473.24
Enthalpy interval E2				
115	48.46	171.15	201.74	372.89
120	43.28	191.64	105.11	296.75
125	38.05	217.99	73.49	291.48
130	32.74	253.33	56.87	310.20
135	27.31	303.74	46.49	350.23
140	21.64	383.28	39.35	422.63
145	15.42	538.00	34.13	572.13

accounting for heat exchange placement and installation cost. Additional enthalpy interval needs installation and repiping cost. This point is also connected with pipe length between the Site processes. Pipe length has considerable contribution to capital cost and even running cost (pressure drop, pumping) for Total Site heat recovery system and should be optimised as well.

5. Conclusions

This article provides a procedure which shows a considerable potential for energy saving on Total Site level by heat recovery improvement by using intermediate utilities as well as capital cost reduction via minimum heat transfer area calculation. In the case study the heat recovery is increased by 1.5 MW. The overall heat recovery scope was divided into two enthalpy intervals through the Total Site Source and Sink Profiles. Minimum heat transfer area was obtained for each enthalpy interval and appropriate temperatures of intermediate utility were identified. Heat transfer area for enthalpy interval E1 is 240.08 m^2 and temperature of intermediate utility is 105 °C. The enthalpy interval E2 has minimum heat transfer area on 291.48 m^2 and temperature of intermediate utility is 125 °C. Total minimum heat transfer area for this case study on Total Site heat recovery is 531.56 m^2.

The proposed extended methodology indicates potential of capital cost reduction for heat exchangers network design on Total Site level. It allows making a general recommendation for selection of heat exchangers design and selection and decreases the investment. The results can be used in different industrial applications, but additional analysis is required due to the need to account for more factors as identified in the discussion. The results may be used for estimation of investments for Total Site integration.

This paper proposes a method for reduction of heat transfer area and investment cost. Heat exchangers network design is going to be the next step of the research, which need further analysis. It is connected with different constructions of heat exchangers, forbidden matches and numbers of other limitations (e.g. material). Further development of this methodology can be connected with selection of optimal temperature difference between Total Site Curves [14].

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References

[1] Klemeš JJ, Varbanov PS. Heat integration including heat exchangers, combined heat and power, heat pumps, separation processes and process control. Appl Therm Eng 2012;43:1–6.
[2] Klemeš J, Dhole VR, Raissi K, Perry S, Puigjaner L. Targeting and design methodology for reduction of fuel, power and CO_2 on total sites. Appl Therm Eng 1997;17(8–10):993–1003.
[3] Viklund SB, Johansson MT. Technologies for utilization of industrial excess heat: potentials for energy recovery and CO_2 emission reduction. Energy Convers Manage 2014;77:369–79.
[4] Khoshgoftar Manesh MH, Navid P, Baghestani M, Khamis Abadi S, Rosen MA, Blanco AM, et al. Exergoeconomic and exergoenvironmental evaluation of the coupling of a gas fired steam power plant with a total site utility system. Energy Convers Manage 2014;77:469–83.
[5] Nemet A, Varbanov PS, Kapustenko P, Boldyryev S, Klemeš JJ. Capital cost targeting of total site heat recovery. Chem Eng Trans 2012;29:1447–52.
[6] Ahmad S, Linnhoff B, Smith R. Cost optimum heat exchanger networks: 2. Targets and design for detailed capital cost models. Comput Chem Eng 1990;14(7):751–67.
[7] De Ruyck J, Lavric V, Baetens D, Plesu V. Broadening the capabilities of pinch analysis through virtual heat exchanger networks. Energy Convers Manage 2003;44(14):2321–9.
[8] Townsend DW, Linnhoff B. Surface area targets for heat exchanger networks. In: IChemE 11th Annual Research Meeting, Bath, UK; 1984. [lecture 7a].
[9] Wan Alwi SR, Manan ZA, Nam SK. A new method to determine the optimum heat exchanger network approach temperature. Comput Aid Chem Eng 2012;31:190–4.
[10] Serna-González M, Ponce-Ortega JM. Total cost target for heat exchanger networks considering simultaneously pumping power and area effects. Appl Therm Eng 2011;31(11–12):1964–75.
[11] Nemet A, Klemeš JJ, Kravanja Z. Optimising entire lifetime economy of heat exchanger networks. Energy 2013;57:222–35.
[12] Dhole VR, Linnhoff B. Total site targets for fuel, co-generation, emissions, and cooling. Comput Chem Eng 1993;17:S101–9.
[13] Ahmad S, Linnhoff B, Smith R. Cost optimum heat exchanger networks – 2. Targets and design for detailed capital cost models. Comput Chem Eng 1990;14(7):751–67.
[14] Klemeš JJ, Kravanja Z. Forty years of heat integration: pinch analysis (PA) and mathematical programming (MP). Curr Opin Chem Eng 2013;2(4):461–74.