Some Remarks on Heat Exchanger Networks Targeting*

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The paper deals with some problems of targeting heat exchanger networks (HENs), such as a choice of the algorithms from Pinch Analysis (PA) technology for targeting HENs of multipass apparatus, and a new approach for calculating heat recovery for nonpoint utilities.

The analysis of approaches from PA was given and examples were presented to show that some algorithms could yield inaccurate or even mistaken results. Comments were formulated on the choice of proper algorithms. In regard to heat recovery for nonpoint utilities a simple graphical approach was developed following concepts from wastewater minimization. The approach requires only basic information for process streams to yield the minimum cost at minimum flow rates of nonpoint utilities. It also provides information on limiting outlet temperatures of utilities that ensure feasible heat recovery with minimal flow rates of utilities.

Heat integration and designing heat exchanger networks (HENs) have reached mature state. There are several commercial and in-home programs available to aid the designer. Almost all are based on Pinch Analysis (PA) technology. Though simultaneous approaches based on superstructure concept are well developed, they have not found industrial applications to date. They are rigorous in frames of their domain, but do not ensure the global optimum solutions for industrial scale problems even with advanced optimization solvers.

Pinch Analysis methods allow the user to keep designing process under the control. Such feature is of great importance while designing HENs since he/she can take into account specific features of the problem at hand in interactive mode.

Due to a wide application of PA technology, it is of great importance to have a full and deep view of its limitations. Approaches developed in frames of PA are focused on providing easy-to-use, usually graphical, tools. Hence, some simplifications are inherent. The user should be aware of such simplifications in order to assess results.

The aim of this paper is to show some limitations of certain methods from PA technology and also to suggest, in some cases, easy-to-use simple tools to overcome some of them.

In particular we will concentrate on the following problems:

1. Targets for HENs consisting of multipass heat exchangers.

2. Maximum heat recovery calculations for nonpoint utilities.

TARGETS FOR HENS WITH MULTIPASS HEAT EXCHANGERS

Existing Approaches and Motivation

The knowledge of the total area and the minimum number of shells targets for HENs with multipass heat exchangers is very important since such apparatuses are usually applied in industry. There were some attempts to develop rigorous methods for calculating these targets. *Briones* and *Kokossis* [1] developed a hybrid method that applies both mathematical programming and concepts from PA. The approach has a complex algorithm and requires some approximations. There is also a possibility of incorporating multipass apparatus into nonlinear mathematical programming targeting method such as that from [2]. However, this would further complicate the optimization process due to additional strong nonlinearities. A simple linear programming-based approach has been developed and implemented in software HX-NET of AEA Technology. The method is only briefly mentioned in [3]. Hence, in practice a designer without commercial computer aids has to apply methods

of PA for targeting HENs of multipass heat exchangers.

The PA algorithms for both minimum units (shells) and minimum area targets have been first presented in [4]. They are also given in the book [5] and monograph [6]. Hence, we omit here detailed description of the calculating procedures. The aim of this paper is to help in choosing the appropriate algorithm from among suggested in the literature.

Number of Shells Target

Ahmad and *Smith* [4] developed two versions of equations for determining the minimum number of shells: the first version is on the stream-wise basis (method *1*), while the second one on the enthalpy intervals basis (method *2*). The authors suggested that the former should yield more accurate results. Similar comments are given in [6]. The main difference of the two versions is that in the first method the number of shells for each stream is rounded-off to the nearest higher integer values, while in the method *2* real numbers of shells in enthalpy intervals are applied. In this paper, stronger arguments against the method based on enthalpy intervals are presented. Example *1*, taken from [7], illustrates drawback of this approach. The corresponding data are gathered in Table 1.

For the example *1* the following targets were calculated for the varying value of HRAT: NA – number of matches (*i.e.* counter-current units), NS1 – number of shells from method *1*, NS2 – number of shells according to method *2*.

The simulation results are shown in Fig. 1. The values of NS1 and NS2 frequently differ from each other and, usually, the values of NS1 are higher than NS2. Moreover, for higher values of HRAT the NS2 value could achieve values smaller than the number of matches (NA). This effect should not been observed, though one can expect that for high HRAT a number of shells will approach the number of matches. In this example, NS2 is lower than NA even for medium values of HRAT. Furthermore, the NS2 value lower than NA was frequently observed for high HRAT in other problems omitted here for brevity sake.

The analysis showed that the higher the value of HRAT, the larger the possibility that the number of shells computed by the method *2* is lower than the number of matches. The effect depends also on profiles of curves on composite curves (CC) plot.

From the above results one can conclude that the method based on enthalpy intervals may lead to serious errors and should not be used.

Area Target for Multipass Heat Exchangers (AT$_{1\text{-}2}$)

The detailed algorithm of PA technology for AT$_{1\text{-}2}$ calculation is given in [6]. More compact descriptions

Table 1. Data for Example *1* according to Ref. [7]

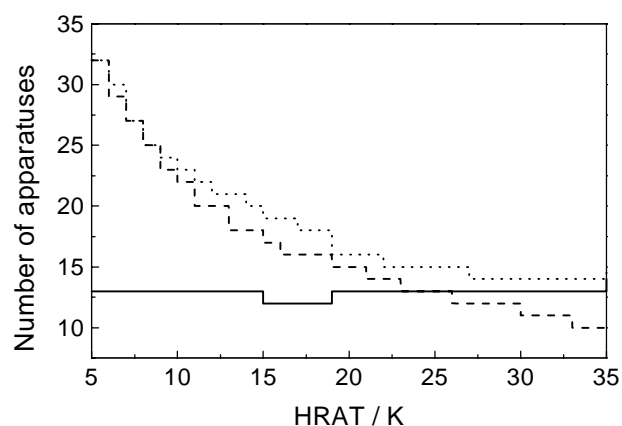| Stream	θ^1/K	θ^2/K	CP/(kW K^{-1})
h_1	393	338	25.0
h_2	353	323	150.0
h_3	408	383	145.0
h_4	493	368	10.0
h_5	408	378	130.0
c_1	338	363	75.0
c_2	348	473	70.0
c_3	303	483	50.0
c_4	333	423	25.0
hu	523	522	–
cu	288	289	–
cu$_1$	278	288	–

Fig. 1. Results from methods for minimum number of units – example *1*. NA – number of matches (——); NS1 – number of shells from method *1* (– – –); NS2 – number of shells from method *2* (···).

can be found in papers [4, 7] and book [5]. The approach is simple and concludes in summing up areas for enthalpy intervals while correction factors for multipass apparatus are calculated with the use of shell number for an interval. *Shenoy* [6] applied shell numbers rounded to the nearest but larger integer, *i.e.* NS = entier [NS]. It seems logical, but it is not correct from the viewpoint of foundation for a method of calculating number of shells presented in [8].

Let us illustrate the problem using example *2*, limited to two streams, hot, *h*, and cold, *c*. To simplify calculations, both streams have the same value of CP, *i.e.* CP equal to 1.0. Temperature profiles of these streams are shown in Fig. 2.

Heat load of the match was divided into 5 equal-size intervals of identical enthalpy and temperature change (see Fig. 2). Mean temperature differences are the same for each interval. Due to parallel profiles of CPs the value of logarithmic mean temperature difference (LMTD) for the total match is equal to LMTD of each interval. For the total match of streams *h* and
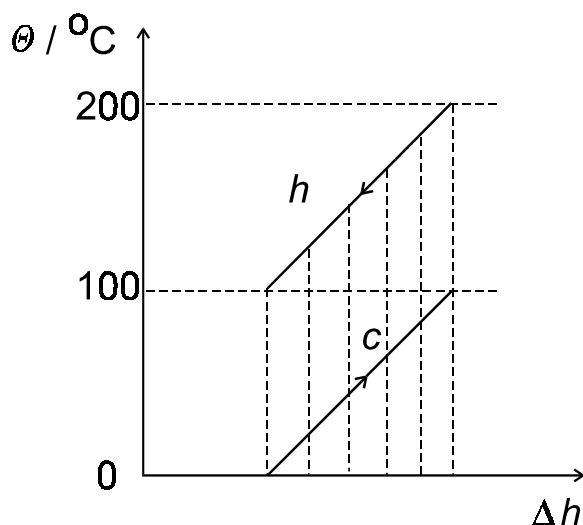
Fig. 2. Heat exchange for streams in example 2.

Table 2. Data for $AT_{1\text{-}2}$ Values for Example from Ref. [6]

Stream	$\theta^1/°C$	$\theta^2/°C$	$CP/(kW\ K^{-1})$
h_1	175	45	10
h_2	125	65	40
c_1	20	155	20
c_2	40	112	15
hu	180	179	605
cu	15	25	52.5

$U = 0.1$ kW m^{-2} K^{-1} for all matches, HRAT = 20 °C.

c one can use 1-2 heat exchanger since the value of the correction factor Ft for the apparatus is about 1.0 as found from the well-known plot developed first by Bowman (see *e.g.* [7]) where Ft is given as a function of parameters P and R.

According to the procedure from [6] for calculating $AT_{1\text{-}2}$ target the number of shells for each enthalpy interval has to be 1.0. Correction factors Ft_i for the

enthalpy intervals $(i = 1, \ldots, 5)$ are identical since parameters P and R are the same and denoted by Ft* in the following, *i.e.* Ft* = Ft_i $(i = 1, \ldots, 5)$. Heat transfer area for the 1-2 apparatus $(A_{1\text{-}2})$ is

$$A_{1\text{-}2} = \frac{Q}{U \times \text{LMTD} \times \text{Ft}} \qquad (1)$$

Heat transfer area target is given by

$$\begin{aligned} \text{AT}_{1\text{-}2} &= \sum_{i=1}^{5} \frac{q_i}{(U \times \text{LMTD} \times \text{Ft})_i} = \\ &= \frac{Q}{U \times \text{LMTD} \times \text{Ft}^*} \end{aligned} \qquad (2)$$

Since both $A_{1\text{-}2}$ and $AT_{1\text{-}2}$ values from eqns (1) and (2) should be the same, then, also Ft* should be equal to Ft. However, Ft* from the Bowman's plot is of order 0.8 while Ft is 1.0. Hence, area target $AT_{1\text{-}2}$ will be larger than the real heat transfer area $A_{1\text{-}2}$ of the apparatus.

The reason of this difference is in using rounded-off integer number of shells for intervals. *Ahmad et al.* [7] used similar illustrative example with two streams to show that the additivity feature of shells number is preserved if one applies real, not rounded-off number of shells in intervals. Hence, by rounding-off number of shells for enthalpy intervals one will obtain larger values of total area target for multipass heat exchangers. To show this effect in quantitative manner the example taken from [6] was employed, for which a detailed procedure of calculating $AT_{1\text{-}2}$ target was also presented there. The data are collected in Table 2. The results for area target calculations are gathered in Table 3. This table shows for each interval: S – real number of shells, Ft factors for real and integer number of shells, and area for intervals calculated for real and rounded-off values of S.

For this example, the difference in targets when integer and real numbers were used for shells counting

Table 3. Comparison of $AT_{1\text{-}2}$ Targets for Data from Table 2

Interval	S	Ft		Interval area/m^2	
		for integer number of shells	for real number of shells	for integer number of shells	for real number of shells
1	0.2841	0.9908	0.8566	62.23	53.80
2	0.0237	0.9999	0.7388	18.29	13.52
3	0.1160	0.9973	0.7475	102.38	76.74
4	0.2152	0.9921	0.7861	87.04	68.96
5	1.7304	0.8244	0.7468	1063.16	963.12
6	0.5081	0.9612	0.8177	107.62	91.56
7	0.3944	0.9706	0.7652	76.65	60.30
8	0.0000	1.0000	1.0000	0.00	0.00
9	0.3630	0.9963	0.9652	166.02	160.83
			Σ	1683.41	1488.86

is of order 11.5 %. In some cases, one can expect higher differences, especially for low HRAT values and close curves in CC plot.

The method proposed in [6] gives too conservative results. Targets are commonly considered as "optimal" results that one should try to approach while designing HENs. In our opinion, one should use the real numbers of shells in enthalpy intervals in targeting for area of HENs with multipass heat exchangers.

Maximum Heat Recovery with Nonpoint Utilities

Motivation

Calculation of the maximum heat recovery (MER) and the minimum utility cost (MUC) is a core of heat integration. The methods are well known and range from graphical tools such as the composite curve plot (CC) and the grand composite curves (GCC) presented *e.g.* in [5, 6], to optimization models such as the transportation model developed in [9] and the transshipment model presented first in [10]. The latter is computationally efficient and will be referred to as the standard optimization model for MUC (and for MER as well). It is worth noting that Problem Table (PT) method of *Linnhoff* and *Flower* [11] that is often applied in some software and used in hand calculations is a special case of the standard optimization model for MUC. It is required that a single hot utility and a single cold utility are applied, both with sufficiently high temperature (for hot utility) and sufficiently low temperature (for cold utility).

It is somewhat surprising that all the above-mentioned approaches do not ensure a result that is of great practical importance – "*what are the CP values of nonpoint utilities?*"

By definition, a nonpoint utility is such that its temperature span (from inlet to outlet temperature) exceeds the temperature interval size applied for the problem at hand – see also [3, 12]. Cooling water, hot oil, and hot gas from a furnace are typical representatives of potential nonpoint utilities. Let us notice that one can get the knowledge whether a utility is of nonpoint type only after constructing temperature intervals. If a utility temperature range exceeds a temperature interval, then one knows that it is a nonpoint utility.

To explain this drawback of existing approaches, let us limit for simplicity sake to a case of a single hot (hu) and a single cold utility (cu). The minimum heat of hot or cold utility (u) is the sum of heat loads of the utility applied in temperature intervals (TIs), that is

$$\mathrm{Qu}^{\mathrm{min}} = \sum_i \mathrm{qu}_i \qquad (3)$$

where $u = \mathrm{hu/cu}$; $i =$ number of interval in which

utility is used; qu_i – heat load of utility u in interval i.

Utility u can be used in some intervals, for instance $i = i1, \ldots, i2$. Let $\theta(i1)$ denote the highest temperature of the first interval for utility u and $\theta(i2)$ the lowest temperature of the last interval utility u. It is important to note that values of $\theta(i1)$, $\theta(i2)$ can differ from θ_u^1, θ_u^2 of the utility given in data.

After applying one of the existing methods a designer is provided with the following results: $\mathrm{Qu}^{\mathrm{min}}$, $\theta(i1)$, $\theta(i2)$. Moreover, he knows the values of θ_u^1, θ_u^2.

Hence, CP of utility u can be calculated either from eqn (4) or (5).

$$\mathrm{CPu}^a = \frac{\mathrm{Qu}^{\mathrm{min}}}{\mathrm{abs}[\theta(i1) - \theta(i2)]} \qquad (4)$$

$$\mathrm{CPu}^b = \frac{\mathrm{Qu}^{\mathrm{min}}}{\mathrm{abs}[\theta_u^1 - \theta_u^2]} \qquad (5)$$

Since the denominators in eqns (4, 5) can differ, then also CPu^a and CPu^b can be different. Moreover, both values of CPu can be invalid, *i.e.* when one applies utility u, CPu^a or CPu^b does not ensure sufficient heat load of the utility.

Viswanathan and *Evans* [12] first noticed that CPu^a calculated from eqn (4) with $\mathrm{Qu}^{\mathrm{min}}$ and $\theta(i1)$, $\theta(i2)$ from the standard transshipment model can be invalid. They developed such a method that keeps the flow rate of utility constant within the temperature range in which it is applied and ensures MER. However, the method is iterative and tedious, especially for multiple utilities. *Jeżowski et al.* [3] presented in short generalized transshipment model that properly accounts for nonpoint utilities. The detailed presentation is given also in [13]. The model is complex, since many changes had to be done in standard optimization model found in [10].

In this paper a simple graphical tool that allows accounting for nonpoint utilities is presented. This approach is described bellow.

Graphical Approach for MER/MUC with Nonpoint Utilities

The assumptions used in comparison with the generalized transshipment model from [3, 13] are as follows:

a) Restricted matches (*e.g.* forbidden ones) are not accounted for.

b) Prices of utilities are in accordance with their inlet temperatures, *i.e.* the higher the inlet temperature of hot utility, the higher the price and *vice versa* in case of cooling utilities.

(Let us notice that identical assumptions are imposed when using approaches from PA technology.)

The method makes use of concepts developed in [14] for wastewater minimization.
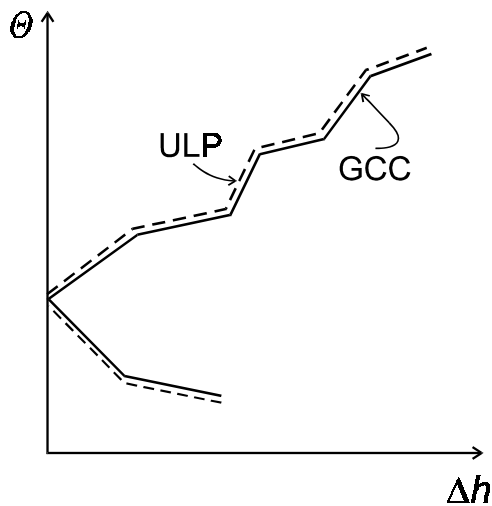
Fig. 3. GCC plot and utility limiting profile (ULP).

Fig. 4. Utility supply lines.

Consider a simple case of one hot (hu) and one cold utility (cu). Let qu_i denote the heat loads calculated by the standard transshipment model or PA approaches. The loads supplied or taken by utility u (u = hu/cu) to/from process streams are the in the temperature intervals $i = i1, \ldots, i2$. CPu_i values of utility u in intervals i can be computed from

$$CPu_i = \frac{qu_i}{\theta^1(i) - \theta^2(i)}; \quad i = i1, \ldots, i2 \qquad (6)$$

These values are minimal CPu values in TIs that ensure the minimum value of the total utility u load. However, they are not of practical meaning since changeable mass flow rates of utility have to be used in each TI and temperature changes of utility in heat exchangers have to be the same as the temperature intervals in which this utility is used. When designing a network, one would account for this applying complex spaghetti structure for utility exchangers which requires a lot of apparatus.

It is important to note that if such CPu values are plotted in GCC plot a curve is obtained that has identical profile as GCC for process streams, *i.e.* both profiles are parallel as shown in Fig. 3. The vertical shift depends on dt contribution to HRAT. If dt contribution for matches of utility-process streams is identical to dt contribution for matches of process streams, GCC profile and CPu profile are identical (see Fig. 3).

In analogy to wastewater minimization, the CPu profile is referred to as the utility limiting profile (ULP). The knowledge of qu_i is not necessary since one can construct ULP from GCC curve for process streams and dt contribution.

Again, the analogy with wastewater minimization is used with the aim to construct a nonpoint utility supply line (USL). The USL for utility u has to be a straight line in the range of utility's temperature
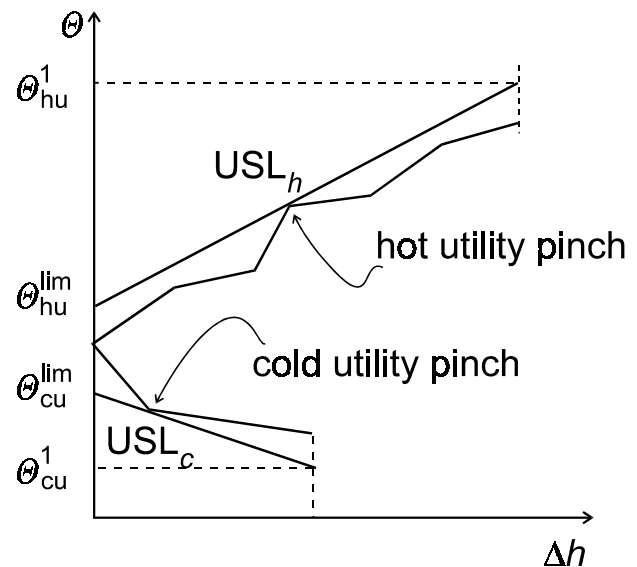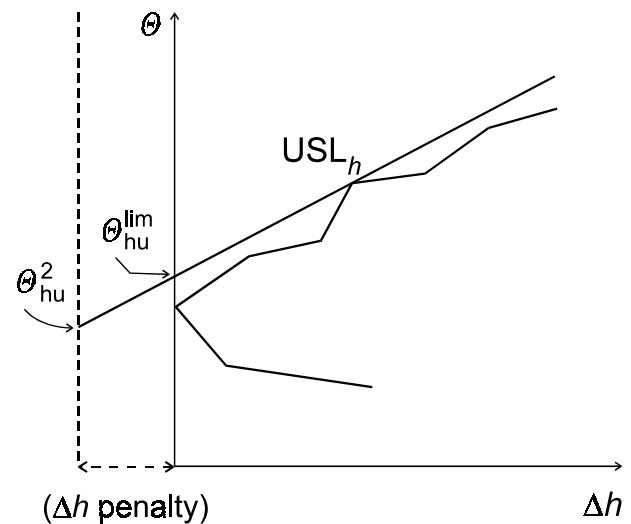

Fig. 5. Energy penalty caused by the too low value of outlet hot utility temperature.

change to maintain the mass flow rate of the utility constant. Such lines are shown in Fig. 4 for hot and cold utility.

The lines ensure minimal values of CP (*i.e.* mass flow rate) for nonpoint utility cu and nonpoint utility hu. Both lines feature at least one utility pinch at the point where they touch GCC curve (see Fig. 4). There are also two characteristic points, θ_{hu}^{lim} and θ_{cu}^{lim} shown also in Fig. 4, where utility supply lines cross the θ axis. Let θ_{hu}^2 given by the designer in data be lower than θ_{hu}^{lim}. This will affect in additional energy penalty (double penalty) as illustrated in Fig. 5. Let us notice that in general θ_{hu}^2 that causes energy penalty can be higher than the temperature of the process pinch. Hence, the knowledge of the process pinch is insuffi-
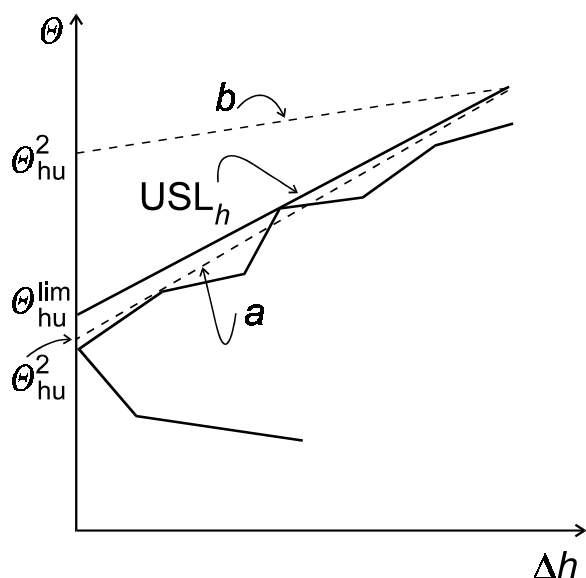
Fig. 6. Illustration of the effect of outlet temperature of utility hu on CP_{hu}. Line a – CP_{hu} calculated from eqn (5) for $\theta^2_{hu} < \theta^{lim}_{hu}$; line b – CP_{hu} calculated from eqn (5) for $\theta^2_{hu} > \theta^{lim}_{hu}$.

cient to assume proper outlet temperature of the utility but USL provides necessary information. Similar effect is observed if θ^2_{cu} is higher than θ^{lim}_{cu}.

Further, an effect of calculating CPu from eqn (5) can be visualized and explained. Let θ^2_{hu} be lower than θ^{lim}_{hu}. Line a in Fig. 6 shows that CP_{hu} calculated from (5) will lie below USL, *i.e.* CP_{hu} is insufficient. If θ^2_{hu} is higher than θ^{lim}_{hu} (line b in Fig. 6) a value of CP_{hu} has to be higher than that derived from USL, *i.e.* one has to use the flow rate of utility larger than the minimum.

In certain cases a designer has some freedom in choosing value of the utility outlet temperature. Value of θ^{lim}_{cu} provides the upper limit for θ^2_{cu} while θ^{lim}_{hu} the lower limit of θ^2_{hu}. In fact, one should try to approach these borders in order to minimize mass flow rates of utilities, especially in case of cooling water, since minimal flow rate means lower cost of cooling tower, piping, and pumping.

It is important to note that this implies serial arrangement of coolers in HENs. In fact, many HENs presented in the literature as optimal solutions use parallel arrangement of coolers. To approach minimal cooling water flow rates the requirement of serial connection of coolers should be imposed on designing approaches for HENs. Care has to be taken, however, since this increases the heat transfer area of coolers. Also, if the minimum CPu is used, a utility pinch is created even for a single utility. This effect is clearly visible in the plot of USL and ULP.

The method of constructing USL can be extended for multiple utilities, *i.e.* to calculate MUC, following the way of developing minimum fresh-water usage in case of various fresh-water sources in [15]. Let a

set of hot utilities be available so that unit price of hotter one is higher than the price of colder utility: hot utilities hu_i with temperatures and unit prices: $\theta^1_{hu1} > \theta^1_{hu2} > \cdots$; $p_{hu1} > p_{hu2} > \cdots$. Similarly, for cold utilities we have a set of cold utilities cu_i with temperatures and unit prices: $\theta^1_{cu1} > \theta^1_{cu2} > \cdots$; $p_{cu1} > p_{cu2} > \cdots$.

For hu_1 one should construct USL_1 up to temperature θ^1_{hu2}, then USL_2 for hu_2 up to θ^1_{hu3} and so on. In the case of cold utilities this procedure will start from the lowest temperature cold utility, *i.e.* from cu_1.

The procedure outlined above ensures minimal utility flow rates in cases of multiple nonpoint or mixed-type utilities.

The graphical method for heat recovery in the case of nonpoint utilities is simple and does not require additional calculations. Only GCC curve for process streams is needed – the construction is shown in Fig. 7.

As example *3* the problem used first in [12] and then in [3] to illustrate the results from the generalized transshipment model was applied. The data are shown in Table 4 (HRAT is 10 °C). *Jeżowski et al.* [3] showed that limiting outlet temperature of a stream that does not cause energy penalty is 225 °C. For this temperature the CP value for the stream equals 10.08 kW K^{-1}. When using the graphical approach, one has
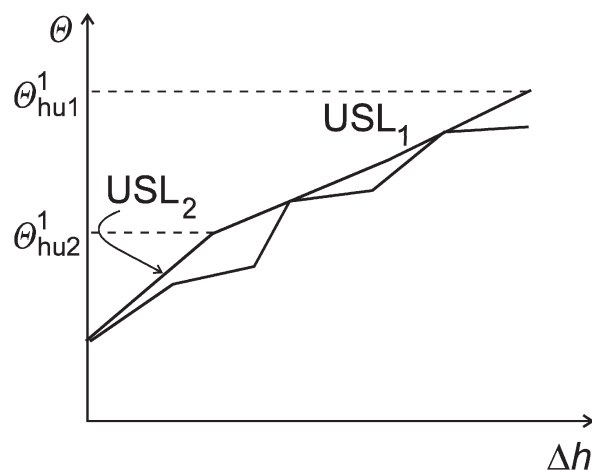

Fig. 7. Example for construction of utility supply lines for two hot utilities.

Table 4. Data for Example *3*

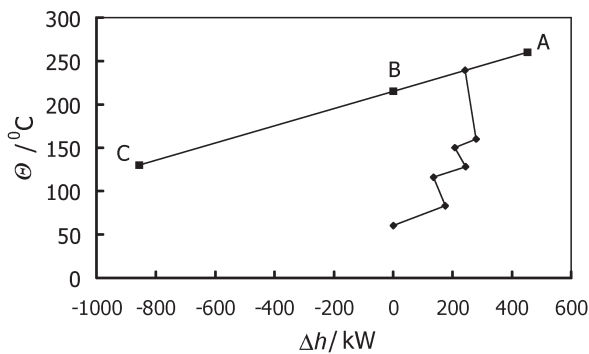| Stream	$\theta^1/°C$	$\theta^2/°C$	CP/(kW K^{-1})
h_4	249	138	10.55
h_2	160	93	8.79
c_1	60	160	7.62
c_3	116	260	10.08
Steam	270	140*	–
Water	38	82	–

*Minimum value.

Fig. 8. GCC plot with USL for example *3*. AB – USL from the developed method, AC – steam profile for the minimum outlet steam temperature in data (140 °C).

first to draw GCC plot shown in Fig. 8 by the standard method described *e.g.* in [6]. Then it is sufficient to draw utility supply line that touches the GCC along the segment AB in Fig. 8, *i.e.* utility pinch is in the range AB. USL crosses θ axis at 225 °C (notice that θ axis is in the shifted scale).

CP calculated for $\theta_{\mathrm{hu}}^1 \approx 225$ °C is 10.08 kW K^{-1}. Extending USL to the minimum outlet temperature 140 °C, given in data one will obtain the energy penalty for the hot utility equal to 856.5 kW, *i.e.* the same result as calculated in [3] with the use of the generalized transshipment model. This example shows the easiness of the use of the graphical method.

SYMBOLS

$A_{1\text{-}2}$	heat transfer surface area of 1-2 heat exchanger
AT$_{1\text{-}2}$	area target for HEN of 1-2 heat exchangers
c	cold process stream
cu	cooling utility
CP, CPu	heat capacity flow rate (product of mass flow rate and specific heat capacity), CP of utility u
dt	contribution to HRAT value
Ft	correction factor to LMTD for multipass heat exchanger
h	hot process stream
hu	hot utility
HRAT	heat recovery approach temperature
LMTD	logarithmic mean temperature difference
NA	number of matches, *i.e.* 1-1 heat exchangers
NS	number of shells

P	parameter for calculating Ft; $P = \dfrac{\theta_h^1 - \theta_h^2}{\theta_h^1 - \theta_c^1}$
q, Q	heat load
qu, Qu	heat load of utility u
R	parameter for calculating Ft; $R = \dfrac{\mathrm{CP}_h}{\mathrm{CP}_c}$
U	overall heat transfer coefficient
Δh	enthalpy change, J
θ	temperature

Subscripts

c, h	refers to cold, hot stream
cu, hu, u	refers to utility cu, hu, u

Superscripts

1, 2	refers to inlet, outlet
min	refers to minimum
lim	refers to limiting value

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