Chemical Engineering Science, Vol. 47, No. 6, pp. 1481–1494, 1992.
Printed in Great Britain.

0009–2509/92 $5.00 + 0.00

A SIMPLE APPROACH FOR MAXIMUM HEAT RECOVERY CALCULATIONS

JACEK JEŽOWSKI†
Institute of Chemical Engineering and Heating Equipment, Wroclaw Technical Univesity, Wroclaw, Norwida 4/6, Poland

and

FERENC FRIEDLER
Research Institute for Technical Chemistry of the Hungarian Academy of Sciences, Veszprém, Egyetem u. 2., H-8201 Hungary

(*First received* 3 *December* 1990; *accepted in revised form* 11 *July* 1991)

Abstract—This paper addresses the problem of calculating the maximum heat energy recovery for a given set of process streams. Simple, straightforward algorithms of calculations are presented that account for tasks with multiple utilities, forbidden matches and nonpoint utilities. A new way of applying the so-called dual-stream approach to reduce utility usage for tasks with forbidden matches is also given in this paper. The calculation mehods do not require computer programs and mathematical programming application. They give the user a proper insight into a problem to understand heat integration as well as to recognize options and traps in heat exchanger network synthesis.

INTRODUCTION

Methods for the maximum energy recovery (MER) or the minimum use of utilities have been developed for nearly 20 years. The problem is of great significance not only for heat exchanger network (HEN) synthesis but also for optimization, analysis and design of heat-integrated chemical systems. It may suffice to mention here the so-called pinch technology [e.g. Linnhoff and Townsend (1982), Linnhoff *et al.* (1983) and Linnhoff and Vredeveld (1984)] that stems from MER calculations and analysis. The maximum energy recovery has been considered the main target for HENs and it can still be seen as the most important item of HENs overall cost (more precisely it is the minimum cost of utilities but in the following we will apply the abbreviation MER).

The problem is stated as follows.

There are NH hot process streams h_i ($i = 1, \ldots,$ NH) to be cooled down from T^1_{hi} to T^2_{hi} and NC cold process streams c_j ($j = 1, \ldots,$ NC) to be heated up from T^1_{cj} to T^2_{cj}. The mass flow rates of these streams (G_{hi}, G_{cj}) are known as well as physical properties required for calculation of their enthalpy changes. It is assumed that there are heating utilities hu_m ($m = 1, \ldots,$ NHU) and cooling utilities cu_n ($n = 1, \ldots,$ NCU) available as well as parameters necessary to calculate their enthalpy changes. The problem to be solved is to find the values of utility heats that minimize goal function (1).

$$E_u = \sum_{m=1}^{\mathrm{NHU}} Q_{hu,m} p_{hu,m} + \sum_{n=1}^{\mathrm{NCU}} Q_{cu,n} p_{cu,n} \qquad (1)$$

where $p_{hu,m}$, $p_{cu,m}$ are unit prices of utility ($/kW a).

If the unit price of kth utility is given ($/kg), the cost of this utility is rated from formula (2).

$$E_{u,k} = G_k \Theta \bar{p}_k \qquad (2)$$

where $\bar{p}_k$ is the unit price of the kth utility ($/kg) and Θ the operation time per annum.

The first correct approach to the above problem was given by Hohmann (1971) but it was not recognized till the late 1970s. For instance, Rathore and Powers (1975) and Grossmann and Sargent (1978) used an inappropriate method to calculate the MER. To date few methods of MER calculation have been developed and the concise summary is given in Table 1. Some of them assumed several simplifications to the general problem formulation such as:

- S1: the use of a single heating utility and a single cooling utility;
- S2: the minimization of utility heat (Q_u) and not the cost;
- S3: the use of the so-called point utilities only, such as those that have a small range of temperature changes, e.g. steam;
- S4: the assumption that each potential match between steams is allowed.

These assumptions are shown in Table 1.

It is also necessary to mention the work of Dolan *et al.* (1987) although it does not consider the MER problem in particular and the paper of Doldan *et al.*

†This work was performed during a scholarship at Research Institute for Technical Chemistry of the Hungarian Academy of Sciences, Veszprém, Hungary.

Table 1. A concise review of MER computation methods

Author	Method, short characteristic, simplifications employed
Hohmann (1971)	Composite curves (CC), graphical: S1, S2, S3, S4
Raghavan (1977)	Heat availability function (HAF) termed later grand composite curves (GCC), graphical: S2, S3, S4
Umeda *et al.* (1978)	Composite curves with exergy losses analysis; graphical: S1, S2, S3, S4
Linnhoff and Flower (1978)	Problem table algorithm (PTA), numerical: S1, S2, S3, S4[†]
Cerda *et al.* (1983)	Transportation task algorithm, linear optimization: S3[‡]
Papoulias and Grossmann (1983)	Transshipment task algorithm, linear programming: S3
Viswanathan and Evans (1987)	Out-of-kilter algorithm, linear programming—network flow: S3[‡]
Quassim and Silveira (1989)	Goal programming[§]

[†]There are references in the literature to certain extensions of the original PTA model—Linnh... off and Turner (1981) report on the inclusion of multiple utilities. However, to the authors' best knowledge, this as well as a method for MER with forbidden matches had not been published in any journal to dat... e.
[‡]The authors addressed the problem of nonpoint utilities but it does not seem that they solve... d it for constant heat capacity flow rate of utility.
[§]The authors discussed the problem of multiple utilities only.

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(1985) that addressed the MER calculation for existing heat and power systems.

It can be concluded from Table 1 that the MER calculation problem (without restrictions S1–S4) is solved. The point is that it can be solved with the use of optimization methods which require special computer programs. These approaches are automatic and do not provide proper insight into the problem as other methods do, e.g. the composite curves (CC) method or the PTA. A designer using such automatic methods does not gain understanding of heat recovery problems. Illustrative simple approaches such as the CC, GCC methods or the PTA yield auxiliary results such as information on temperature approach changes as well as a qualitative "feeling" of a task at hand.

Therefore, the authors see the need for developing a simple approach which in many cases can be applied without computer assistance and will feature all advantages, e.g. of the PTA, whilst restrictions S1, S2, S4 and to some extent S3 are to be eliminated. It is hoped the method presented in this paper meets all these requirements.

The important objective of this paper is to show how the use of a simple model and logical reasoning can help in anticipating effects of certain designer's decisions at the level of synthesis even in complex problems, e.g. dual-stream approach.

THE BASIC MODEL AND SOLUTION ALGORITHMS

The basic model and the solution algorithm are aimed at solving the MER problem with constraints S1–S4. Therefore, the method used has no special advantages as compared to the CC method or the PTA but it can be easily extended to remove these restrictions.

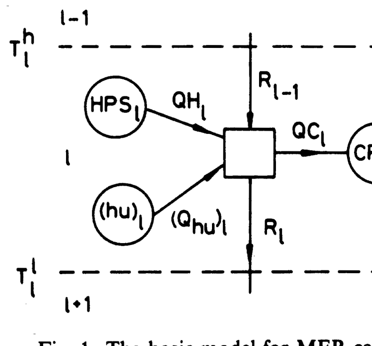
The division of streams for temperature intervals ($l = 1, \ldots, L$) is described, e.g. in Cerda *et al.* (1983). In case of piecewise linearization of temperature-dependent enthalpies of streams the intervals are bounded by the so-called "candidates for pinches", i.e. inlet temperatures of streams and temperatures of

state changes [with certain exceptions fo... hot" temperatures—see Cerda *et al.* (... model we assumed piecewise linariza... sufficient even for industrial problem... increases the number of intervals.

A shifted scale of tempeature is use... atures of hot streams are decreased by ... of a stream to Δt^{min} and temperatures o... are increased by individual stream cont... Saboo and Morari (1984)]. The basic m... to the transshipment model developed... and Grossmann (1983), thus, the detail... of the division and of the basic model is... After creating L temperature intervals, ... ment model depicted in Fig. 1 is envisag... can be interpreted as the shipment of a ... sources: HPS_l—set of hot process st... interval l; $(hu)_l$—hot utility in lth inter... the interval $l-1$ by stream R_{l-1} thr... house to two sinks; CPS_l—set of cold p... in the lth interval and (by stream R_l) t... $l+1$. [Streams R_{l-1}, R_l will be called... flows.]

For each interval ($l = 1, \ldots, L$), a b... can be written.

$$R_{l-1} + QH_l + (Q_{hu})_l = QC_l + \ldots$$



lculation.

Fig. 1. The basic model for MER ca...

where

$$\mathrm{QH}_l = \sum_{h_i \in \mathrm{HPS}_l} G_{hi} * \Delta i_{hi} \Big|_{T_l^l}^{T_l^h} \tag{3a}$$

$$\mathrm{QC}_l = \sum_{c_j \in \mathrm{CPS}_l} G_{cj} * \Delta i_{cj} \Big|_{T_l^l}^{T_l^h} \tag{3b}$$

$$R_{l-1}, R_l \geqslant 0 \quad \text{for } l = 2, \ldots, L \tag{3c}$$

$$R_0 = 0. \tag{3d}$$

For temperature-dependent enthalpies of streams, integrals in eqs (3a) and (3b) can be used if proper division for intervals has been performed. Our experience with targeting programs [Jezowski and Friedler (1991)] is that it is often enough to divide at "traditional" candidates for pinches. The bounds of integrals have to be changed into "normal" temperature scale. Example 2 illustrates the use of integrals for calculating enthalpy change in temperature intervals.

To solve the MER problem invoking S1–S4 it is necessary to find $(Q_{hu})_l$ $(l = 1, \ldots, L)$ such that

$$Q_{hu}^{\min} \equiv \sum_{l=1}^{L} (Q_{hu})_l \rightarrow \min. \tag{4}$$

The value of $Q_{cu}^{\min}$ will result from heat balance for L intervals and is given by

$$Q_{cu}^{\min} = R_L. \tag{5}$$

In each eq. (3) for $l = 1, \ldots, L$ there are two unknown parameters R_l and $(Q_{hu})_l$ (except for $l = 1$ where $R_0 \equiv 0$). To calculate $(Q_{hu})_l$ $(l = 1, \ldots, L)$ that fulfils eq. (4) it is enough to use constraint (3c).

Namely, in each interval, $(Q_{hu})_l$ has to be added to ensure eq. (3c) but only in such an amount as to satisfy demands for heat of streams $c_j \in \mathrm{CPS}_l$. Provided that the intervals are ordered downwards from the highest temperature (i.e. $T_l^h > T_{l+1}^h$) the following solution algorithm is suggested (the basic algorithm):

(1) for $l = 1, \ldots, L$ calculate Δ_l according to

$$\Delta_l = R_{l-1} + \mathrm{QH}_l - \mathrm{QC}_l \tag{6}$$

if $\Delta_l < 0$ then $R_l = 0$ and $(Q_{hu})_l = |\Delta_l|$

if $\Delta_l > 0$ then $R_l = \Delta_l$ and $(Q_{hu})_l = 0$

(for $\Delta_l = 0$ both R_l and $(Q_{hu})_l$ are equal to 0);

(2) calculate $Q_{hu}^{\min}$ from (4) and $Q_{cu}^{\min}$ from (5).

Remarks:

(1) The basic algorithm does not account for temperatures of *hu* and *cu*. For the use of a single heating utility *hu* it is necessary that

$$T_{hu}^1 \geqslant T_K^h \tag{7}$$

where K is the number of the first intervals in which Δ_l [redacted] additional calculations are necessary and these are performed in the next section.

(2) Pinches caused by process streams (called process pinches) can be detected by the following procedure:

(a) find the first interval (K') such that

$$(Q_{hu})_{K'} = 0 \tag{8a}$$

(b) find all intervals such that

$$R_l = 0 \qquad \text{for } l = K', K' + 1, \ldots, L \tag{8b}$$

lower temperatures of the intervals are pinches.

The basic model presented above seems to have simpler interpretation than the model used in the PTA. The solution algorithm requires less computations than the PTA.

THE EXTENSION FOR MULTIPLE UTILITIES

It will be assumed in this section that point utilities are to be applied. A point utility is one in which its temperature change is less than the temperature span of an interval in which it is applied.

During division for intervals, inlet temperatures of all hu_m $(m = 1, \ldots, \mathrm{NHU})$ and cu_n $(n = 1, \ldots, \mathrm{NCU})$ should be treated as candidates for pinches too. The only change in the basic model which is required here is the inclusion of utility type in eq. (3):

$$R_{l-1} + \mathrm{QH}_l + (Q_{hu,m})_l = \mathrm{QC}_l + R_l. \tag{9}$$

A rule of assigning an utility to an interval should be aimed at minimizing cost E_u [eq. (1)]. In industrial scenario the following rule is usually valid (termed here the cost–temperature rule):

the higher the temperature of heating utility, the higher the price, and the lower the temperature of cooling utility, the higher the price.

Therefore, the assignment procedure of the utility interval should ensure that costly utility is to be used in these intervals only where it cannot be replaced by a cheaper one. For instance, for two heating utilities hu_p, hu_r such that $T_{hu\,p}^1 > T_{hu\,r}^1$ (and $p_{hu\,p} > p_{hu\,r}$), utility hu_p should not be used in intervals $l < K$, where

$$T_K^h = T_{hu\,r}^1$$

(both values are in the same temperature scale).

Since temperatures of available heating utilities are known it is an easy task to find intervals in which they are to be used.

For assigning heating utilities, we can perform straightforward calculations, i.e. optimal assignment of heating utility type and of its heat is performed in the course of MER calculations from higher to lower temperature intervals. Therefore, eq. (6) of the basic [redacted]

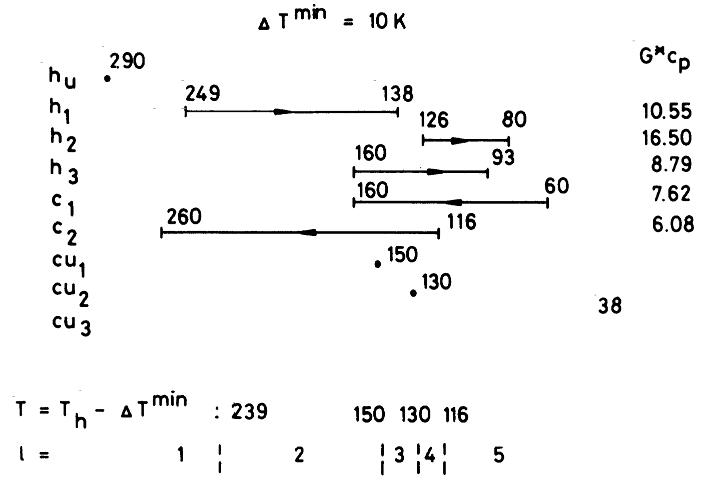


Fig. 2. Data for example 1: the task with multiple utilities.

that we have hu_1 and hu_2 such that: $T^1_{hu\,1} = 300$ K and $T^1_{hu\,2} = 200$ K and hu_2 is cheaper than hu_1 according to the cost–temperature rule. Thus, for all intervals l where $(Q_{hu})_l$ are greater than zero and T^h_l are higher than $T^1_{hu\,2}$ the application of hu_1 is necessary but if T^h_l is less than 200 K utility hu_2 should be used.

In the case of cooling utilities we have to redistribute utilities moving towards increasing temperatures (in order to use cheaper media first), i.e. in the direction opposite to that of calculations in the basic algorithm for MER.

To illustrate this we will solve example No. 1 where three cooling utilities are available:

$$cu_1:\quad T_{cu\,1} = 150\text{ K},\ p_{cu,1} = 0.4$$

$$cu_2:\quad T_{cu\,2} = 130\text{ K},\ p_{cu,2} = 0.5$$

$$cu_3:\quad T_{cu\,3} = 38\text{ K},\ p_{cu,3} = 1.0.$$

The single heating utility is to be used and its inlet temperature is 290 K. The data are shown in Fig. 2 as well as temperature intervals for $\Delta T^{min} = 10$ K (the contribution for all hot streams is 10 K and 0 K for cold streams).

The results of calculations from the basic algorithm are gathered in the first two rows of Table 2.

Pinch is in interval No. 1 [see eqs (8a) and (8b)]. Total heat of cooling utilities equals R_5, i.e. 1009.1 units. We look for the minimum residual heat flow from intervals starting from the first interval below pinch—this is $R_2 = 321.6$ units. This demand for cooling can be accomplished by the cheapest utility cu_1. Now it is necessary to reduce residual heat flows (below the last pinch) by the value of $(Q_{cu\,1})$, i.e. 321.6 units. The current values of R_1, termed now R'_1, are in the third row of Table 2. Let us note that a new pinch was created in interval No. 2—utility pinch.

We can repeat the above procedure once more; the minimum residual heat flow (but now below the current utility pinch) is in interval No. 4: 65.16 units. This cooling demand cannot be accomplished by cu_1, but the next utility cu_2 can be applied.

The subtraction of $Q_{cu\,2}$ from R'_1 gives new residual heat flows—R''_1, values in the 4th row of Table 2. The next pinch was created in interval No. 4. We are left with 622.34 units of heat in interval No. 5—the only possibility is to use cu_3.

The total cost of utilities applied is:

$$E^{min}_{cu} = 321.6 * 0.4 + 65.16 * 0.5 + 622.34 * 1.0 = 783.56$$

whilst for the use of cu_3 only the cost would be 1009.1.

The information on two additional pinches which were created by the optimal (in terms of energy cost) redistribution of cooling utilities is of great importance for the designer.

Table 2. Results of calculations for example 1—multiple cooling utilities

	Interval No.	1	2	3	4	5
			239 K	150 K	130 K	116 K
1	Q_{hu}	127.68	0.0	0.0	0.0	0.0
2	R_l	0.0	321.6	434.43	386.76	1009.1
3	R'_l	—	0.0	112.83	65.16	687.5
4	R''_l	—	—	47.67	0.0	622.34
			← cu_1	← cu_2		← cu_3

Investment cost of a HEN with three pinches will be, in general, higher than for the single, process pinch. It is possible to eliminate the third pinch caused by cu_2 which has relatively small heat load. The final decision can be taken on the basis of targeting calculations for energy as well as capital cost.

Now, we can formulate the algorithm of calculations of minimum cost of utilities:

(1) apply eq. (6) of the basic algorithm but with assignment of heating utilities from the rule: use hotter heating utility if and only if temperature of a lower-temperature utility is too low;
(2) redistribute cooling utilities;

(a) find the interval with zero residual heat flow—interval No. K';
(b) find $R^* = \min\ (R_l)$ for $l = K',\ K'+1, \ldots, L$;
(c) use the cheapest cooling utility possible, i.e. the utility which has the temperature closest to, but not higher than the temperature of this interval in which R^* had been found; heat of this utility equals R^*;
(d) reduce all residual flows from intervals $l = K', \ldots, L$ by R^* and go to point (a) till the last interval.

From Table 2, it is easy to see that an increase of heat of any cooling utility (above R^*) has to increase the heating utility usage. If we use e.g. 400 kW for $Q_{cu\,1}$ (the cheapest utility) instead of 321.6 kW we cause negative heat flows R'_2, R'_4 which have to be compensated by additional Q_{hu}. The same effect can be shown for heating utilities.

Therefore, it is possible to state that any increase of a cheap utility usage does not influence the use of more costly utility but increases the required amount of heat of utilities of "opposite" type. This proves that the algorithm yields optimal cost of utilities provided that the temperature–cost rule is valid.

The algorithm is quite easy and gives the user the proper insights into the task at hand. He can observe in the course of calculation how much heat and of which utility to apply. The next example (No. 2) will be given here to show this advantage. This is an industrial task from crude-oil refinery. The data and division for intervals are shown in Fig. 3.

The enthalpy changes of streams were calcuated from Watson's formula [eq. (10)] according to Berghoff (1968):

$$\Delta i = \int_{t^1}^{t^2} \left[\frac{0.403}{\rho} K_1 + \frac{0.009}{\rho} K_1 t \right] \mathrm{d}t \qquad (10)$$

where

t = temperature (°C)
Δi = enthalpy (kcal/kg)
ρ = relative density of a stream
K_1 = Watson factor for a stream.

(This is an example where the division at "traditional" candidates for pinches can be proper for problems with temperature-dependent enthalpies of streams.)

Crude-oil stream c_2 is usually heated up in a furnace, but also high pressure steam ($T = 503$ K) is available in this system, as cooling utility water is used that can be heated up from 293 K to 323 K.

Let apply at first the basic algorithm. The results from it are as follows:

$$(Q_{hu})_1 = 55{,}688.48 \quad (Q_{hu})_2 = 2167.74$$
$$(Q_{hu})_3 = 37{,}926.10 \quad (Q_{hu})_4, \ldots, (Q_{hu})_9 = 0.0$$
$$(Q_{hu})_{10} = 20{,}712.98 \quad R_{10} = Q_{cu} = 0.0.$$

(The values of Q are in MJ/h.)

The results show clearly that heat is needed at temperatures higher than 553 K and in the temperature range 394–293 K (interval No. 10). The more dense division of streams, e.g. using outlet temperatures, also reveals that heat is required below 323 K. It is a very important piece of advice for a designer

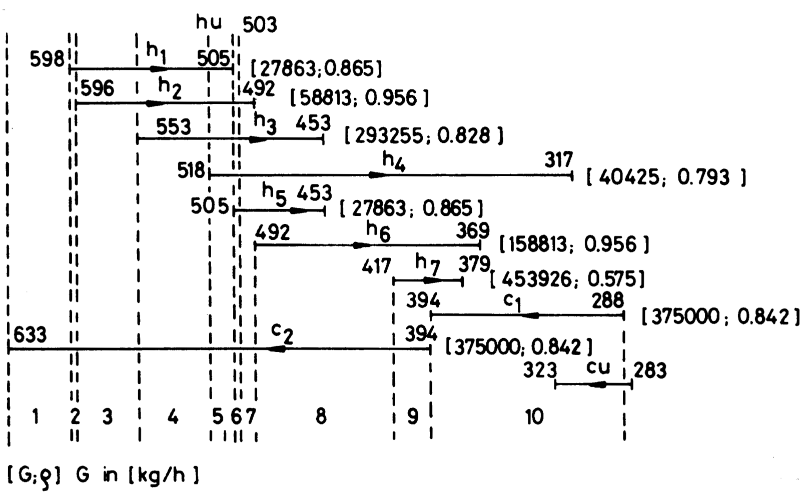


Fig. 3. Data for example 2.

that instead of using expensive HP steam, it is possible to apply LP steam or even hot water (e.g. cooling water heated up in another subsystem).

FORBIDDEN MATCHES

In industrial problems, matches between certain streams may be forbidden, e.g. because of safety reasons. They usually cause an increase of utility usage. In this section we will present the extension of the basic algorithm which enables a simple, "by hand" solution of the MER problem with forbidden matches.

Let us define for a forbidden match between h_x and c_y the following sets:

$$H1 = \text{HPS}—h_x; \quad H2 = \{h_x\}$$

$$C1 = \text{CPS}—c_y; \quad C2 = \{c_y\}$$

where HPS = the set of all hot process streams, h_i ($i = 1, \ldots, \text{NC}$), and, CPS = the set of all cold process streams, c_j ($j = 1, \ldots, \text{NC}$).

The following remarks are valid:

(1) the possible heat flow among sets of streams: $H1$, $H2$, $C1$, $C2$ is depicted by di-graph in Fig. 4 ($H1$, $H2$ = sources; $C1$, $C2$ = sinks);

(2) a demand for heat of $C1$ can be supplied from $H1$ and $H2$ whilst $C2$ from $H1$ only—thus $C2$ should be supplied at first.

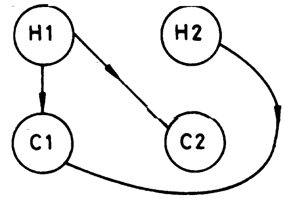


Fig. 4. Graphical illustration of heat flow for a task with forbidden match.

The above remarks help to build a model (Fig. 5) and an algorithm of solution. The model involves in a single interval two "basic" models connected by heat flow R_{12} and consists of two eqs (11) and (12) and constraints (13a)–(13c).

$$(Q^1_{hu})_l + \text{QH1}_l + R1_{l-1} = \text{QC2}_l + R1_l + R_{12} \quad (11)$$

$$(Q^2_{hu})_l + \text{QH2}_l + R_{12} = \text{QC1}_l + R2_l \quad (12)$$

$$R1_l \geqslant 0; \quad R1_0 \quad l = 1, \ldots, L \quad (13a)$$

$$R2_l \geqslant 0; \quad R2_0 = 0 \quad l = 1, \ldots, L \quad (13b)$$

$$R_{12} \geqslant 0. \quad (13c)$$

$$Q^{\min}_{hu} \equiv \sum_{l=1}^{L} \left[(Q^1_{hu})_l + (Q^2_{hu})_l \right] \rightarrow \min. \quad (14)$$

The value of $Q^{\min}_{cu}$ results from heat balance for the problem:

$$Q^{\min}_{cu} = R1_L + R2_L. \quad (15)$$

The solution algorithm is based on similar concepts as the basic algorithm, the differences being that eq. (11) is solved prior to eq. (12) since QH1_l can be used to heat up cold stream in $C2$.

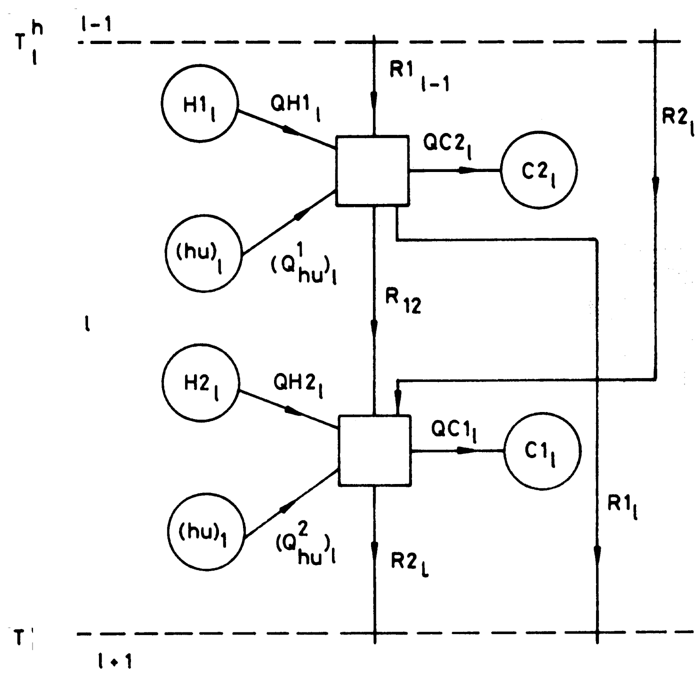


Fig. 5. The model for lth interval for the MER problem with forbidden match.

The algorithm of calculations for lth interval is given in Fig. 6, where

$$\Delta 1 = R1_l + QH1_l - QC2_l \quad (16)$$

$$\Delta 2 = R2_l + QH2_l - QC1_l. \quad (17)$$

To illustrate the use of the algorithm two examples are solved:

—example—task 4SP1 with forbidden match h_2–c_1 [Viswanathan and Evans (1987)]

—example—task 5SP1 with forbidden match h_2–c_1 [Linnhoff and Flower (1978), Grimes *et al.* (1982)].

The data are shown in Figs 7 and 8, respectively.

Results of the calculation, and values of the variables in eqs (11) and (12) are given in Tables 3 and 4, respectively.

The extension of this algorithm for several forbidden matches in the same temperature intervals seems to be difficult. It is however, possible to apply any standard, widely available linear programming subroutine to solve the model [eqs (11)–(14)] developed.

THE USE OF PREHEATING/PRECOOLING FOR INCREASING ENERGY RECOVERY IN PROBLEMS WITH FORBIDDEN MATCHES

The problem to be considered in the following is a way of reducing excess utility usage caused by forbidden matches. Grimes *et al.* (1982) were the first to apply the so-called dual-stream approach.

The dual-stream approach means the use of a cold stream from a forbidden match to cool down another cold stream (dual stream) or a hot stream from a forbidden match to heat up another hot stream.

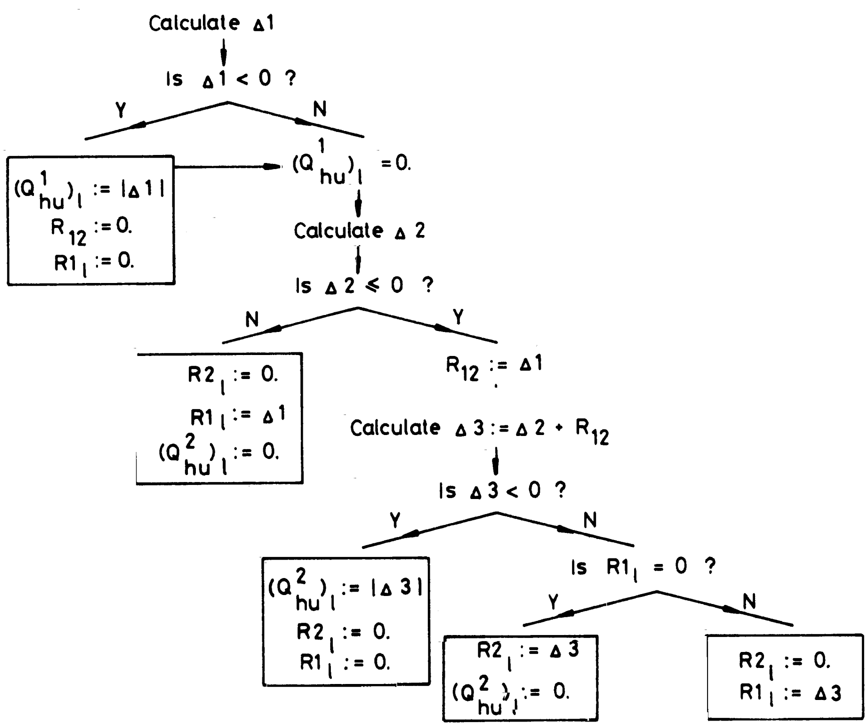


Fig. 6. The algorithm of MER calculation for the problem with forbidden match (interval No. 1).

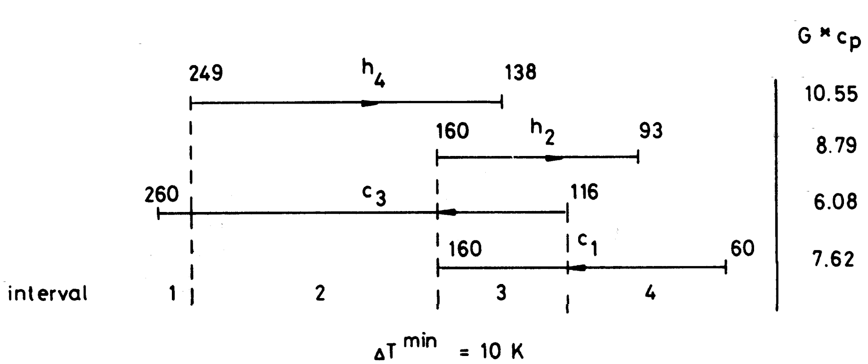


Fig. 7. Data for example 3 [from Viswanathan and Evans (1987)]: the task with forbidden match.

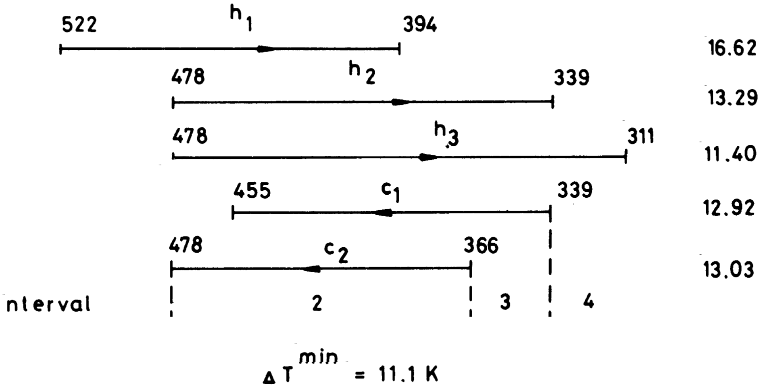


Fig. 8. Data for example 4 [from Linnhoff and Flower (1978)]: the task with forbidden match.

Table 3. Results of MER calculations for example 3

Interval No.	1	2	3	4
$\Delta 1$	− 127.68	862.75	294.65	− 132.07
$\Delta 2$	0.0	− 541.12	92.14	− 382.21
$\Delta 3$	0.0	− 321.63	—	—
R_{12}	0.0	862.75	—	0.0
$R1$	0.0	321.63	294.65	0.0
$R2$	0.0	0.0	92.14	382.21
Q_{hu}^1	127.68	0.0	0.0	132.07
Q_{hu}^2	0.0	0.0	0.0	0.0

$Q_{hu}^{min} = 127.68 + 132.07 = 259.75$; $Q_{cu}^{min} = 382.21$ [according to Viswanathan and Evans (1987) $Q_{cu}^{min} = 382$, $Q_{hu}^{min} = 260$].

Table 4. Results of MER calculations for example 4

Interval No.		2	3	4
$\Delta 1$	731.28	705.92	− 307.8	− 319.2
$\Delta 2$	− 271.173	− 1123.646	9.99	157.509
$\Delta 3$	460.107	− 417.726	—	—
R_{12}	731.28	705.92	0.0	0.0
$R1$	460.107	0.0	0.0	0.0
$R2$	0.0	0.0	9.99	157.509
Q_{hu}^1	0.0	0.0	307.8	319.2
Q_{hu}^2	0.0	417.726	0.0	0.0

$Q_{hu}^{min} = 417.726 + 307.8 + 319.2 = 1044.726$; $Q_{cu}^{min} = 157.509$ [according to Linnhoff and Flower (1978) $Q_{hu}^{min} = 1044$, $Q_{cu}^{min} = 159$].

This concept was used in a systematic way by Dolan *et al.* (1987) as well as by Viswanathan and Evans (1987).

The dual-stream approach causes a reduction of Q_u^{min} since a part of "unavailable" heat is shifted from stream h_x/c_x ($h_x \in H2$, $c_x \in C2$) to stream h_k/c_k ($h_k \in H1$, $c_k \in C1$) where it is more "useful". The same effect can be obtained by preheating or precooling of c_k/h_k ($h_k \in H1$, $c_k \in C1$) by h_x/c_x ($c_x \in C2$, $h_x \in H2$). The use of preheating/precooling for the dual-stream approach has not been reported to date.

Figure 9 is given to illustrate the difference between the traditional way of matching streams in the dual-stream approach (traditional dual-stream match) and the use of precooling.

In terms of heat recovery there is no principal difference between traditional dual-stream match and a match with preheating/precooling. Both cause that heat is moved from streams in sets $H2/C2$ to streams in sets $H1/C1$ and thus increasing potential for heat recovery.

The difference is in the possibility of designing new topologies of HENs. The concept of preheating/precooling gives structures which cannot be reached by traditional dual-stream matches. We do not claim that these new structures are always better in terms of total cost (for instance, preheating/precooling yields, in general, more units), but we think that they should be investigated, too.

Furthermore, the use of traditional dual match can be impossible in certain cases where preheating/precooling can be applied—see example below.

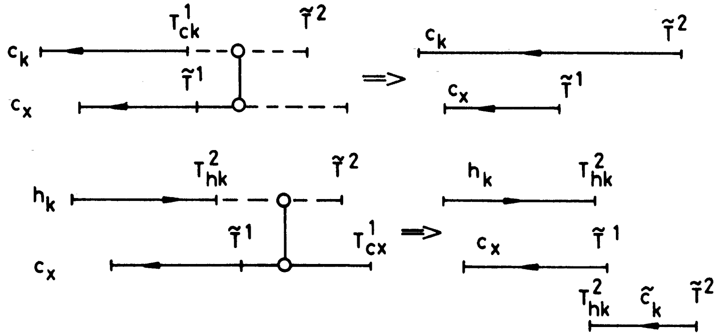


Fig. 9. Illustration of traditional dual-stream approach and dual-stream approach by precooling.

In the following we will show that concept of preheating/precooling yields the same reduction of utility usage as traditional dual-stream match does and that solutions can be advantageous in terms of investment cost. Also, we will show that a selection of heat load in dual-stream match can be predicted from the results of MER calculations for forbidden matches. And finally we will prove that the heuristic approach suggested by Viswanathan and Evans (1987) for selection of streams for traditional dual-stream matches and their heat loads fails in certain cases.

The example of applying precooling hot stream in the dual-stream approach will be shown for task 4SP1 (Fig. 7) in which match h_2–c_1 is not allowed. Viswanathan and Evans (1987) and Dolan *et al.* (1987) used stream c_3 as the dual stream. Here, we apply c_1 to precool h_4.

Let us note that for lower inlet temperature of stream c_3, e.g. 60°C, traditional dual-stream match with streams c_3 and c_1 would be impossible while precooling of h_4 can be used.

The highest heat load for this match equals 518.16 whilst for traditional dual approach (match c_3–c_1) it is equal to 279.68 [see Fig. 10(a) and (b)]. But, in the case of the dual-stream approach not only heat load is important but temperature range of the new stream as well. The analysis of the MER calculation results in Table 3 reveals that heat demand in interval 4 equals 132.07 and that stream c_1 requires this heat. Thus, by shifting heat load 132.07 from c_1 to c_3 in dual-stream match c_1–c_3, we will reduce Q_{hu} to zero and also Q_{cu} by the value 132.07 [match with heat load 132.07 is shown in Fig. 10(c)]. The reduction of dual-stream match influenced investment cost of a HEN. For comparison, two HENs with dual-stream match c_1–c_3 but with different heat loads of this match are shown in Fig. 11(a) and (b); the network with lower heat load features higher-temperature approaches in almost each unit.

In the case of dual-stream match h_4–c_1 such an analysis is difficult since a new candidate for pinch is introduced with precooled part of stream h_4. Thus, for the MER calculation it is necessary to use the maximum heat load of dual match h_4–c_1 but in the synthesis of a HEN this load can be reduced to design a better network. Figure 11(c) shows the HEN for example 3 which includes dual-approach match h_4–c_1 with heat load less than maximum. The solution has only 5 matches, that is, the same number as for the task without forbidden match h_2–c_1 (the use of the dual-stream approach yields an additional match). The reason is that by reducing heat load of match

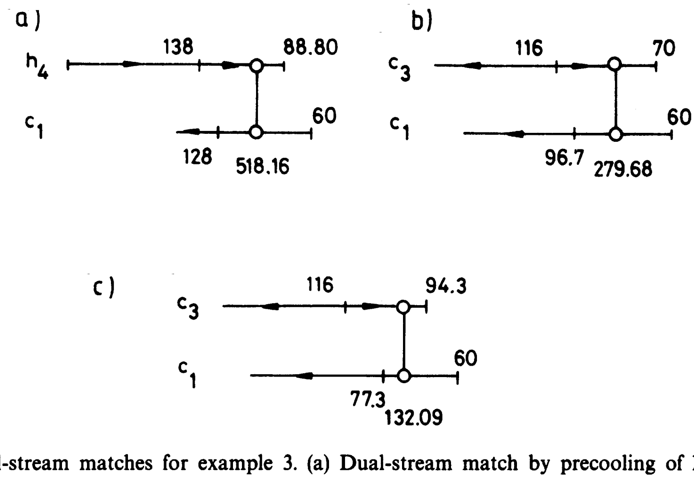


Fig. 10. Dual-stream matches for example 3. (a) Dual-stream match by precooling of hot stream; (b) traditional dual-stream match with maximum heat load; (c) traditional dual-stream match with reduced heat load.

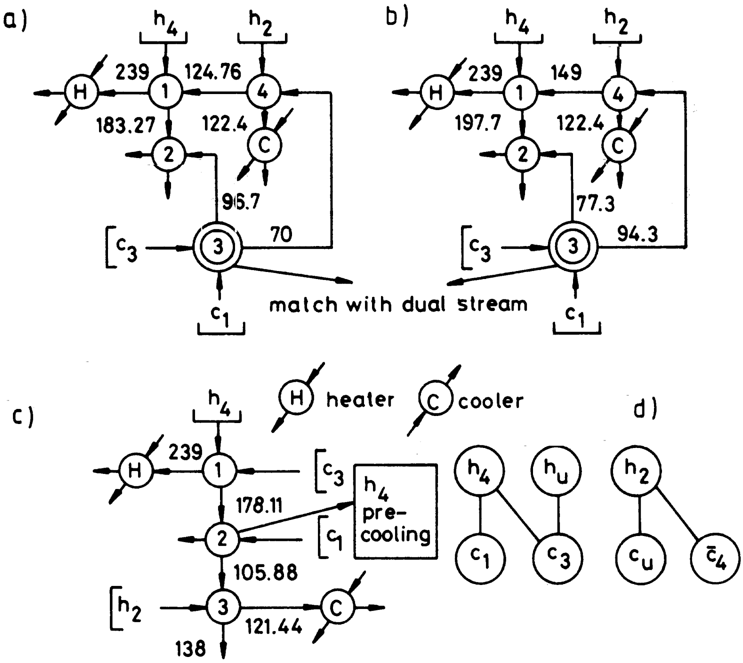


Fig. 11. Networks for example 3 with application of the dual-stream approach. (a) Network for example 3 with match from Fig. 10(b); (b) network for example 3 with match from Fig. 10(c); (c) network for example 3 with dual match by hot stream precooling and with reduced heat load of this match; (d) graph representation for network in Fig. 11(c).

h_4–c_1 we formed two subgraphs [see Fig. 11(d) where the precooled part of h_4 is termed $\bar{c}_4$]. For another example from Viswanathan and Evans (1987), task 4SP1 with forbidden match h_4–c_3, it is possible to preheat c_1 by h_4 instead of using dual stream h_2. The solution with preheating is shown in Fig. 12; it features the same level of heat recovery as with the use of the traditional dual-stream approach.

The question arises which stream should be used as the dual stream and whether to apply the traditional dual-stream approach or that suggested in this paper. Viswanathan and Evans (1987) suggested the heuristic "use as the dual stream the one that has the maximum heat load in the dual match". We proved, however,

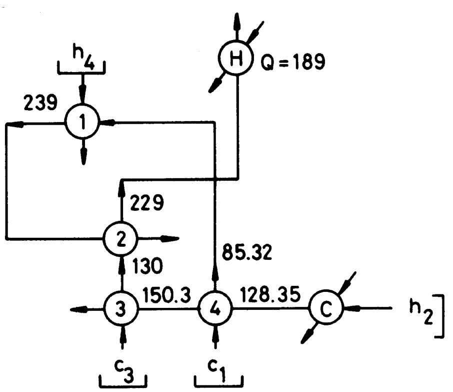


Fig. 12. Network for example 4 with application of the dual-stream approach by preheating stream c_1.

that it is an inappropriate rule in terms of total cost. In our opinion, the analysis of results of MER calculations as well as the composite curves can give valuable advice. The former was illustrated by example 3 but it cannot be used, e.g. for dual-stream approach by precooling.

Composite curves can give an additional insight. Let us consider example 4 in which there are two options:

(a) to use dual-stream match c_3–c_1
(b) to preheat h_4 by c_1.

To consider which is better, one can calculate the dual-stream match for both cases and use new parameters of streams (after dual-stream match) to draw composite curves or to calculate the MER. For option (b), the higher utility usage than for option (a) will result. Therefore, it is possible to foresee that option (b) will not reduce the utility usage and the rigorous calculation proves this conclusion.

ON MER CALCULATION FOR NONPOINT UTILITIES

The methods of calculating the MER for nonpoint utilities (that is such utilities that have range of temperature changes larger than temperature range of intervals in which they are used) have been suggested by Cerda *et al.* (1983) and Viswanathan and Evans (1987). If outlet temperatures of these utilities are also decision variables the MER task is a nonlinear optimization task and cannot be solved (in a general way) by methods listed in Table 1.

In the case of a single nonpoint utility an important question is how to redistribute mass flow rate of the utility.

The redistribution should meet the following conditions:

(1) the minimum heat/cost of the utility is to be reached;
(2) serial connections of heaters/coolers should be possible in a HEN.

To illustrate the way of redistributing utility we will employ the example from Viswanathan and Evans (1987). It is a modified task 4SP1 (see Fig. 7) in which hot utility with $T^1_{hu} = 270°C$ and $T^{2,\min}_{hu} = 140°C$ is used and stream c_3 has a value of (Gc_p) equal to 10.08.

Figure 13(a) shows the values of $(Q_{hu})_l$ and R_l (for $l = 1, 2, 3$) calculated from the basic algorithm as for point utility; (Gc_p) values necessary to supply the required heats are furnished in brackets. It is clear that the minimum (Gc_p) required is equal to the value for the first interval. This value is, however, too high for the second interval but the surplus of heat flows *via* stream R_2, satisfying the heat demand of interval 3 [Fig. 13(b)]. Therefore, heating utility cannot be used in the third interval and its outlet temperature should be adjusted from

$$Q^{\min}_{hu} = (Gc_p)_1(T^1_{hu} - T^2_{hu}).$$

If the value of (Gc_p) for interval 1 is too low for a certain interval k it is necessary to repeat calculations from interval 1 using $(Gc_p)_k$. This reasoning has been used by Viswanathan and Evans (1987) to develop a very complex algorithm. It seems that the use of results from the basic algorithm for the MER described in Section 2 together with simple conclusions are sufficient to redistribute nonpoint heating utility.

This redistributon yields constant mass flow rate of nonpoint utility but causes the decrease of its temperature change.

In order to reach the minimum possible outlet temperature (or maximum for cooling utility) it is necessary to use mass flow rate that changes from interval to interval. It is clear that (Gc_p) values in Fig. 13(a) are of no practical use since (Gc_p) in higher temperature interval (No. 1) is smaller than in lower temperature interval (No. 3).

The approach of Cerda *et al.* (1983) provides a proper redistribution of flow rates for nonpoint utility that also reaches the maximum allowable temperature change.

Figure 13(c) shows the results of calculations according to their method.

The approach of Cerda *et al.* (1983) can also be simplified; it is not necessary to use the transportation algorithm with prices for point utilities formed from nonpoint utility—the results of the basic algorithm are sufficient. To prove this we will solve the example from Cerda *et al.* (1983) (data are given in Table 5).

The nonpoint utility is divided into three intervals and the basic algorithm yields the values of R_l ($l = 1, 2, 3$) shown in Fig. 14(a).

The minimum heat capacity flow rate of cooling utility we can apply in order not to obtain negative values of R_l ($l = 1, 2, 3$) is given by

$$(Gc_p) = \frac{R_1}{70 - 67} = 10.0.$$

This value is, however, too small [see Fig. 14(b)]. Additional 0.5 units of (Gc_p) have to be used starting from the second interval to remove heat [Fig. 14(c)].

Table 5. Data for example 5 [from Cerda *et al.* (1983)]

Stream	T^1 (°C)	T^2 (°C)	(Gc_p)
h_1	70	60	
h_2	67	62	
h_3	65	60	
cu	37	$\leqslant$ 50	

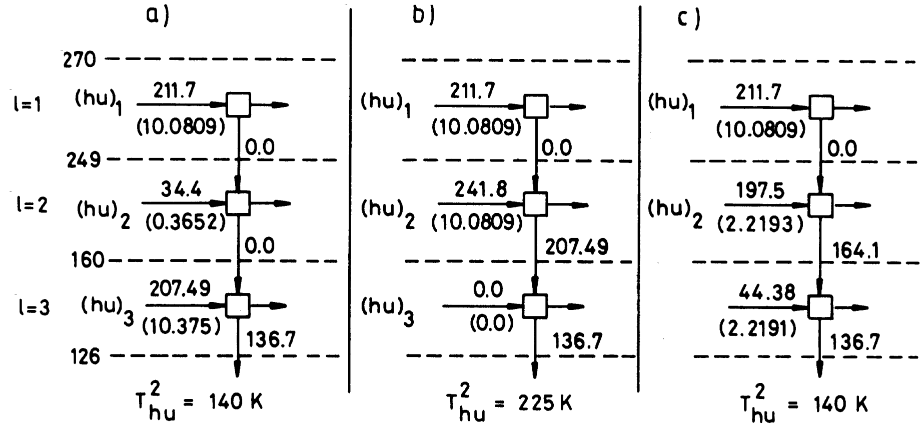


Fig. 13. Heat flows for three first interval in modified task 4SP1 [from Viswanathan and Evans (1987)]. (a) Before nonpoint utility redistribution; (b) nonpoint utility redistribution with change of its outlet temperature; (c) nonpoint utility redistribution by method of Cerda *et al.* (1983).

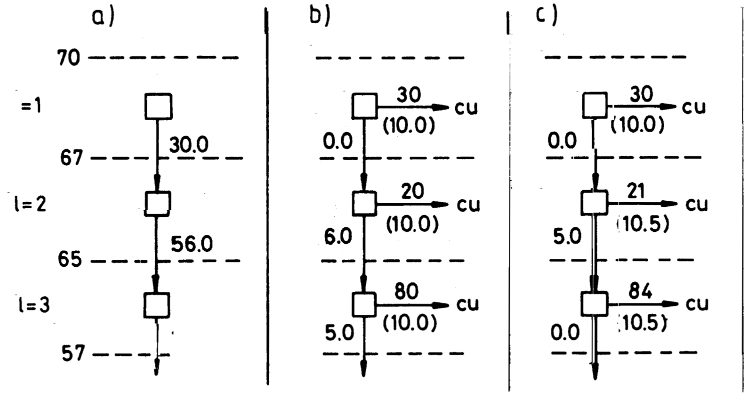


Fig. 14. Heat flows in intervals for example 5 [from Cerda *et al.* (1983)]. (a) Before cooling utility redistribution; (b) after redistribution with (Gc_p) equal to 10.0; (c) after final redistribution.

In this way we obtain that 10.5 units of *cu* have to be applied from 37°C to 47°C but 10.0 units can be used in the temperature range 47°C–50°C—the same result has been obtained by Cerda *et al.* (1983).

It is questionable, however, to what extent changeable mass flow rates of an utility will be applied in industrial HENs.

It is worthwhile noting that calculations performed for example 5 are very similar to those for distribution of heats for multiple-point cooling utilities. In the latter the value of heat of *m*th utility used in interval No. *k* has been subtracted from R_l $(l = k + 1, \ldots, L)$ whilst in case of nonpoint utility it is necessary to subtract also heats added to other intervals in which the utility is used.

MAXIMUM ALLOWABLE RESIDUAL HEAT FLOWS FOR REDUCED TEMPERATURE APPROACH

Recently, several synthesis methods addressed the question of reducing EMAT, i.e. minimum temperature approach in matches below HRAT, heat recovery approach temperature [see e.g. Gunderson and Grossmann (1988), Trivedi *et al.* (1989), Ciric and Floudas (1990) and Jezowski (1991)]. The knowledge of allowable residual heat flows (especially across pinches) in networks which feature energy recovery level fixed by HRAT and have temperature approaches in units less than HRAT is, thus, important, e.g. in analysis and retrofit designs.

Ciric and Floudas (1990) developed both graphical and analytical methods for calculating maximum allowable residual heat flows from temperature intervals in networks that feature EMAT less than HRAT. (In fact, they introduced the third type of minimum temperature approach called TIAT from "temperature interval approach temperature". The use of TIAT seems superfluous; thus, we will apply EMAT and HRAT, assuming that EMAT equals TIAT.)

We will show that the basic algorithm described here (as well as the PTA) can be used to calculate the values of maximum residual heat flows, too.

Let us note that for both HRAT and EMAT the utility usage is the same (MER is fixed by HRAT). Therefore, if we calculate the residual heat flows for HRAT and apply the necessary heat of heating utilities Q_{hu}^{min} [HRAT] as the additional heating utility in the same problem but with EMAT we should obtain the maximum, allowable residual heat flows for EMAT (including pinch-crossing flow).

Similarly, we can use another approach. At first, let us calculate Q_{hu}^{min} for HRAT, then, Q_{hu}^{min} for EMAT. By adding the difference

$$\Delta Q = Q_{hu}^{min}[\text{HRAT}] - Q_{hu}^{min}[\text{EMAT}]$$

to the residual heat flows for EMAT we will obtain the maximum residual heat flows for EMAT.

Example 6 [data in Fig. 15 according to Ciric and Floudas (1990)] illustrates the latter approach.

For HRAT = 30 K the residual heat flow across 80 K (in temperature of hot streams) is zero; the task is pinched at 80/50 K. Value of Q_{hu}^{min} for HRAT equals 450 kW.

We will calculate here cross-pinch heat flows for EMAT = 25 K and EMAT = 5 K for comparison with results from Ciric and Floudas (1990) who obtained 50 kW and 375 kW, respectively.

—EMAT = 25 K Q_{hu}^{min}[EMAT] = 400 kW; difference ΔQ = 50 kW, residual heat flow across 80 K is 0.0 kW → thus maximum cross-pinch heat flow is: 0.0 + 50 = 50 kW.

—EMAT = 5 K Q_{hu}^{min}[EMAT] = 375 kW; difference ΔQ = 75 kW, residual heat flow across 80 K is now 300.0 kW → thus maximum cross-pinch heat flow is: 300.0 + 75.0 = 375 kW.

The amount of work to calculate maximum residual heat flows across several temperatures seems comparable to that entailed in the suggested approach and methods of Ciric and Floudas (1990).

SUMMARY

Simple algorithms are presented in this work to calculate the MER for problems with multiple heat and cooling utilities as well as forbidden match. T algorithms require neither any computer progra

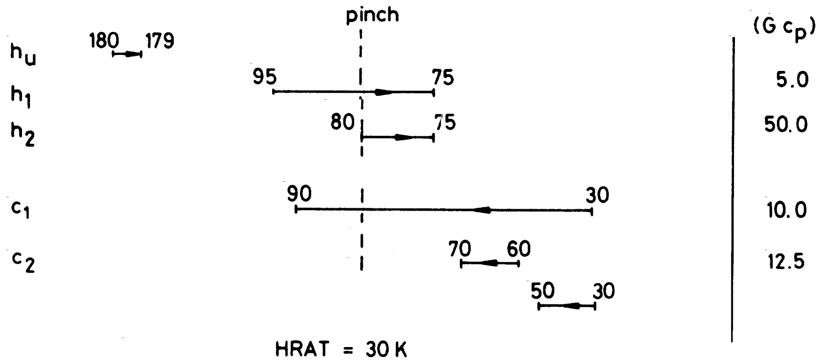


Fig. 15. Data for example 6 [from Ciric and Floudas (1990)].

nor optimization methods, although for large-scale complex problem the automatization of calculations can be necessary. The examples given illustrate the way of applying results of calculation for revealing features of tasks that are important for heat exchanger network synthesis and heat integration.

The extension of dual-stream approach for problems with forbidden matches is suggested. Furthermore, the heuristic approach of Viswanathan and Evans (1987) for selection of dual-stream match heat load is proved inappropriate in terms of investment cost.

It is also shown that simple reasoning based on the results of the algorithms developed can be used to solve the MER problem for nonpoint utilities.

Finally, the application of the basic algorithm for MER to calculate maximum residual heat flows for EMAT less than HRAT is given.

It is not claimed that the method suggested in the paper is better than the PTA, CC or GCC for all cases. It is rather an alternative for other designer-driven approaches. The use of the suggeted approach by hand is rather restricted to simple problems. However, the understanding of this method is, in the authors' opinion, necessary for the designer to solve complex industrial-size problems with the help of available mathematical programming based programs.

NOTATION

c_j	jth cold process stream
c_p	heat capacity
cu	cooling utility
CC	composite curves
$C1$, $C2$	sets of cold process streams in transshipment model for a task with forbidden matches
CPS	set of cold process streams in MER task
CUS	set of cooling utilities available
E	cost of utility/utilities
EMAT	exchanger minimum approach temperature
G	mass flow rate
GCC	grand composite curves
h_i	ith hot process stream
hu	heating utility
$H1$, $H2$	sets of hot process streams in transshipment model for a task with forbidden matches
HEN	heat exchanger network
HPS	set of hot process streams in MER task
HRAT	heat recovery approach temperature
HUS	set of heating utilities available
	enthalpy
L	number of the last (lowest temperature) interval
MER	maximum heat energy recovery (minimum use of utilities)
NC	number of cold process streams
NCU	number of cooling utilities available
NH	number of hot process streams
NHU	number of heating utilities available
p	unit price of utility, \$/kW a
$\bar{p}$	unit price of utility, \$/kg
PTA	the problem table algorithm of Linnhoff and Flower (1978)
Q	heat
QH/QC	heat flow to/from a warehouse in transshipment model
Q''_{min}	minimum heat flux
$R/R1$, $R2$	heat flow between intervals in the transshipment model for a task with no forbidden matches/with forbidden matches
R_{12}	heat flow between warehouses in an interval in the transshipment model for a task with forbidden matches
T^h/T^l	higher/lower temperature of an interval
T^1/T^2	inlet/outlet temperature of a stream

Greek letters

α	heat transfer coefficient
Δ, $\Delta 1$, $\Delta 2$, $\Delta 3$	difference of heats, auxiliary variables in the algorithm

$\Delta T^{min}/ \Delta T^{min} \times (h_k, c_1)$	minimum temperature approach in MER calculations/for streams h_k, c_1
θ	time of operation per annum, h/a

Subscripts

cu/cu, n	refers to cooling utilities/*n*th cooling utility
hu/hu, m	refers to heating utilities/*m*th heating utility
i	refers to hot process stream or temperature interval
j	refers to cold process stream
m	refers to *m*th heating utility
n	refers to *n*th cooling utility
u	refers to heating and cooling utilities

REFERENCES

Berghoff, W., 1968, *Erdölverarbereitung und Petrolchemie—Taffeln und Tabellen.* VEB, Leipzig.

Cerda, J., Westerberg, A. W., Mason, D. and Linnhoff, B., 1983, Minimum utility usage in heat exchanger network synthesis—a transportation problem. *Chem. Engng Sci.* **38**, 373–387.

Ciric, A. R. and Floudas, C. A., 1990, Application of the simultaneous match-network optimization approach to the pseudo-pinch problem. *Comput. chem. Engng* **14** 241–250.

Dolan, W. B., Cummings, P. T. and LeVan, M. D., 1987, Heat exchanger network design by simulated annealing, in *Foundations of Computer-aided Process Operations* (Edited by G. V. Reklaitis and H. D. Spriggs), p. 639. CACHE, Elsevier, New York.

Doldan, O. B., Bagajewicz, M. J. and Cerda, J., 1985, Designing heat exchanger networks for existing chemical plants. *Comput. chem. Engng* **9**, 483–498.

Grimes, L. E., Rychener, M. D. and Westerberg, A. W., 1982, The synthesis and evolution of networks of heat exchange that feature the minimum number of units. *Chem. Engng Commun.* **14**, 339–360.

Grossmann, I. E. and Sargent, R. W. H., 1976, Optimum design of heat exchanger networks. *Comput. chem. Engng* **2**, 1–7.

Gunderson, T. and Grossmann, I. E., 1988, Improved optimization strategies for automated heat exchanger network synthesis through physical insights. Paper 81g, AIChE Annual Meeting, Washington D.C., 27 November–2 December.

Hohmann, E. C., 1971, Optimum networks for heat exchange. Ph.D. thesis, University of Southern California.

Jezowski, J., 1991, A note on the use of dual temperature approach in heat exchanger network synthesis. *Comput. chem. Engng* (to be published).

Jezowski, J. and Friedler, F., 1991, A note on targeting in the design of cost optimal heat exchanger networks. *Chem. Biochem. J.* (to be published).

Linnhoff, B. and Flower, J. R., 1978, Synthesis of heat exchanger networks. I. Systematic generation of energy optimal networks. *A.I.Ch.E. J.* **24**, 633–642.

Linnhoff, B. and Turner, J. A., 1981, Heat-recovery networks: new insights yield big savings. *Chem. Engng* **88**, 56–80.

Linnhoff, B. and Townsend, D. W., 1982, Designing total energy systems. *Chem. Engng Prog.* **78**, 72–80.

Linnhoff, B., Dunford, H. and Smith, R., 1983, Heat integration of distillation columns into overall process. *Chem. Engng Sci.* **38**, 1175–1188.

Linnhoff, B. and Vredeveld, D. R., 1984, Pinch technology has come of age. *Chem. Engng Prog.* **80**, 33–40.

Papoulias, S. A. and Grossmann, I.E., 1983, A structural optimization approach in process synthesis—2. Heat recovery networks. *Comput. chem. Engng* **7**, 707–721.

Qassim, R. Y. and Silveira, C. S., 1989, Heat exchanger network synthesis: the goal programming approach. *Comput. chem. Engng* **12**, 1163–1165.

Raghavan, S., 1977, Heat exchanger network synthesis. Ph.D. thesis, Purdue University.

Rathore, R. N. and Powers, G. J., 1975, A forward branching scheme for the synthesis of energy recovery systems. *Ind. Engng Chem. Process Des. Dev.* **14**, 175–181.

Saboo, A. K. and Morari, M., 1984, Design of resilient processing plants. 4. Some new results on heat exchanger network synthesis. *Chem. Engng Sci.* **39**, 579–592.

Trivedi, K. K., O'Neill, B. K., Roach, J. R. and Wood, R. M., 1989, A new dual-temperature design method for the synthesis of heat exchanger networks. *Comput. chem. Engng* **13**, 667–685.

Umeda, T., Itoh, J. and Shiroko, K.., 1978, Heat exchange system synthesis. *Chem. Engng Prog.* **74**, 70–76.

Viswanathan, M. and Evans, L. B., 1987, Studies in the heat integration of chemical process plants. *A.I.Ch.E. J.* **33**, 1781–1790.