A deterministic algorithm for the synthesis of maximum energy recovery heat exchanger network

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Abstract

This paper presents a general mathematical optimization model and the related deterministic algorithm for synthesizing heat-exchanger networks (HEN). The methodologies commonly used to solve a HEN problem are based on heuristic methods. These algorithms reach a presumed best solution with respect to the investigated set of process streams, whereas our approach determines the optimal configuration.

In this paper the proposed method is applied to the solution of a few simple HEN synthesis problems and the results are compared with those obtained utilizing heuristic or meta-heuristic methods.

HEN’s problem is represented by a general mathematical model that can be applied to small and medium sized problems and is solved by using a deterministic method with a reasonably brief computation time.

Notably, this approach can represent a unique general model of a wide class of heat-exchanger networks, independently of their specific physical configuration.

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1. Introduction

Heat-exchanger network (HEN) synthesis problems have attracted significant research due to the large savings achievable in terms of energy costs. As energy costs continue to increase, industry will have greater incentive to apply heat integration as broadly as possible in its facilities.

In industrial plants there are usually cold process streams that need heating and hot process streams that need cooling, usually achieved using hot and cold utilities such as steam and water, respectively, and consequently increasing energy costs. One way to reduce these costs is by matching the process streams.

The aim of our paper is to obtain the most effective exchange of energy between process streams, in order to reduce the energy costs to a minimum.

Specifying heat capacities and inlet and outlet temperatures for all streams, we can determine how to match them in order to minimize the use of utilities and, therefore, energy costs.

Since the 1970s energy crisis, the research was intensified and now several papers address these kinds of problems.

The “pinch” method, proposed by Linnhoff and Hindmarsh (1983) allows the resolution of HEN problems and achieves in most cases a “nearly optimal” solution. The method was simple enough to be used with manual calculation and by using this method it is possible to find the highest degree of energy recovery with a given number of capital items. This method is easily utilizable, but it is not possible to be sure to achieve the optimal configuration because it is necessary to make heuristic choices. A further problem related to this method is the necessity of high resolution times in the case of large networks that can make this method inappropriate for the aim.

This problem can be overcome by using sequential or simultaneous approaches. The package MAGNETS (Floudas, Ciric, & Grossman, 1986) uses a sequential method that decomposes the original problem into sub-problems within different temperature intervals which are solved sequentially, but often this approach leads to sub-optimal designs. Many researchers,
including Floudas and Cric (1989, 1991), Yee and Grossman (1990a,b), and Adijman, Androulakis, and Floudas (2000), describe simultaneous approaches which seek optimal solutions without decomposition. Most heuristic and meta-heuristic approaches have also adopted a simultaneous approach. Even so, the various heuristic choices can lead to sub-optimal solutions. In the field of heuristic and meta-heuristic methods, Genetic Algorithms (Androulakis & Venkatasubramanian, 1991; Lewin, 1998; Lewin, Wang, & Shalev 1998; Ravagnani et al., 2005a, 2005b) and Tabu Search (Lin & Miller, 2001, 2004) are receiving increasing interest. These methods, used to solve small to medium sized problems, obtain a solution nearly approaching the optimal one, but in order to reach this result they need a significant set of initial values (population).

In a mathematical programming framework, HENs are usually formulated as mixed-integer non-linear programming (MINLP) models, whereby continuous variables represent process parameters (e.g. heat-exchanger duties, stream-split fractions) and integer variables represent discrete decisions (e.g. heat-exchanger matches). Under special circumstances (e.g. the synthesis of maximum energy recovery HENs with no stream splitting), the optimization problem can be posed as a mixed-integer linear program (MILP).

A recent work of Furman and Sahinidis (2001) showed that solving the problem of HENs, either sequentially or with a stage wise-simultaneous formulation is NP-hard giving up in such a way the chance for the existence of a computationally efficient (polynomial) exact solution algorithm for this problem. Their analysis also shows that HENs are NP-hard in the strong sense. Our paper shows that HENs are a difficult class of hard optimization problems, but it is possible to solve these problems using a deterministic method. It is not possible to obtain a polynomial solution algorithm, while it is possible to solve the HEN by using a deterministic algorithm which can find the result for small to medium sized networks with an acceptable solution time.

In this work we define a general model to describe the HEN and we solve it by using a deterministic algorithm. The results obtained (duty of energy, number of exchangers and solution time) are compared with the solution found with Genetic Algorithms that represent a recent approach to the HENs solution.

In some cases, the solution time necessary with Genetic Algorithms is shorter than that of our deterministic method, but it must be noted that deterministic algorithms converge to the optimal solution, whereas Genetic Algorithms sometimes give a sub-optimal solution.

2. Problem definition and solution method

A HEN synthesis problem is defined as a system of \(n_H\) hot streams at given hot inlet temperatures that must be cooled to specified outlet temperatures, and \(n_C\) cold streams at given cold inlet temperatures which must be heated to specified outlet temperatures. Fixed flowing heat capacities are supposed and flow rates are specified for these streams. We must define the optimal structure of heat exchangers, together with their heat transfer duties, in order to maximize the heat recovery between hot and cold streams and consequently to minimize the use of external utilities. A HEN which satisfies the thermodynamic lower limit of utility requirements is defined as able to meet the maximum energy recovery (MER).

The basic assumption that will be made for this synthesis problem is that counter-current heat exchangers are used. Furthermore, it will be assumed that a fixed minimum temperature difference \(\Delta T_{\text{min}}\) for matching streams is specified by the design engineer.

In our approach, the HEN synthesis problem is represented by a general model which is efficient for a large class of HEN problems. This model will be solved using a deterministic algorithm. The aim is to simultaneously obtain the MER, the set of process streams matches and the heat loads of the heat exchangers of the network.

The implementation of this model will be described in detail and its application will be demonstrated for three well known case studies already reported in the literature.

The procedure utilized in the present paper is composed by the following two steps:

1. Definition and analysis of the problem, through the individuation of the variables and constraints that these variables must satisfy.
2. Resolution of the mathematical model by using the deterministic algorithm.

3. HEN structure representation

The selection of an appropriate structure representation is important, because it should have a physical meaning and must be easily understood.

The structure representation must generally be described using a generic characterization which is suitable to all problems, when only the number of hot and cold streams is known.

In a HEN structure, the order in which streams are matched is important and therefore the concept of “HEN repetitive unit” (or HEN level) is introduced to allow the increase of all possible matches to be considered. Each unit consists of a block of heat exchangers comprising all possible matches between cold and hot streams. In each further repetitive unit, streams are matched again in the same way. Increasing the number of the units the HEN becomes more complex but all possible matches between the process streams will be increased. Fig. 1 shows the repetitive unit concept by representing a simple HEN involving 2 hot and 3 cold streams with 2 repetitive units.

Increasing the number of repetitive units, at the first we obtain increasing values for the MER until even increasing the number of repetitive units, the value of the MER remains constant.

Each HEN structure can be represented by an incidence matrix of integers, consisting of \(n_H \times n_C\) columns, and \(n_L + 1\) rows, where \(n_L\) is the number of repetitive units or levels. The incidence matrix of the HEN structure represented in Fig. 1 is shown in Fig. 2, where each element \(a_{ijL}\) of this matrix represents the coupling between the hot stream \(i\) and the cold stream \(j\) in the repetitive unit \(L\).

Thus incidence matrix is a physically meaningful representation of the HEN.
Fig. 1. HEN representation with 2 repetitive units.

Fig. 2. Incidence matrix of the HEN represented in Fig. 1.

The utility heat exchangers are not considered in the incidence matrix, because one utility exchanger is automatically added at the end of each stream in order to guarantee the target temperature.

If the difference between the supply temperatures hot \((i)\) and of cold \((j)\) streams is smaller than the minimum fixed temperature difference, this match is not possible and the \(ijL\) element of the incidence matrix is zero.

Each match corresponds to an exchanger that is represented by a number \((k)\) which is related to the hot \((i)\) and cold \((j)\) streams (i.e. \(i(k)\) represents the hot stream in the exchanger \(k\), \(j(k)\) represents the cold stream in the exchanger \(k\). They are supplied in the exchanger \(k\) \((i, j, L)\), where \(L\) represents the repetitive unit).

It is important to describe a HEN by using a general model, and it is important to describe the system with a set of equality and inequality constraints and to identify a proper objective function to maximize.

Generally an optimum problem must have:

- An objective function with the aim of optimizing the performance of the system.
- A set of inequality or equality constraints, which define variables and describe the physical features of the problem.

### 3.1. Objective function

In typical HEN synthesis problems, the objective function can be addressed to energy targeting, by achieving the MER between process streams, or to simultaneous area and energy targeting to minimize the total annual cost.

In this study we considered only energy targeting and thus the objective function is given by

\[
\max Z = \sum_{k=1}^{n_E} X_k
\]

where \(X_k\) is the duty of the heat exchanger \(k\) and \(n_E\) is the number of heat exchangers (not utility units) in a given HEN problem.

A HEN optimization problem involves \(n_C + n_H\) equality constraints (formulated in terms of energy balances, related to the hot and cold streams in order to satisfy the target temperatures), a pair of inequality constraints for each heat exchanger \(k\) in the HEN, and a pair of logical constraints for each heat exchanger \(k\) in the HEN.

### 3.2. Equality constraints

The total load necessary to heat the cold stream \(j\) from the supply temperature to the target temperature must correspond to the sum of the heat transferred in the exchangers of the network in which the stream \(j\) is supplied:

\[
C_p c(j)(T^l_{c(j)} - T^s_{c(j)}) = \sum_{L=1}^{r_p} \sum_{l=1}^{n_H} X_{k(ljL)} + H_j, \quad j = 1, \ldots, n_C
\]

where \(T^s_{c(j)}\), \(T^l_{c(j)}\) and \(C_p c(j)\) are, respectively, the supply and target temperatures and the flowing heat capacity for the cold stream \(j\), \(r_p\) the number of repetitive units used to describe the HEN and \(H_j\) is the hot utility duty for the cold stream \(j\).

Consequently, the total load necessary to cool the hot stream \(i\) from the supply temperature to its target temperature has to correspond to the sum of the heat transferred in the exchangers

\[
C_p h(i)(T^s_{h(i)} - T^l_{h(i)}) = \sum_{L=1}^{r_p} \sum_{l=1}^{n_H} X_{k(liL)} + H_i, \quad i = 1, \ldots, n_H
\]

The table shows an example of the incidence matrix:

<table>
<thead>
<tr>
<th>cold stream</th>
<th>1</th>
<th>1</th>
<th>2</th>
<th>2</th>
<th>3</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>levels 1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>levels 2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
of the network in which the stream \( i \) is supplied:

\[
CP_{H(i)}(T_{H(i)}^{s} - T_{H(i)}^{l}) = \sum_{k=1}^{n} \sum_{j=1}^{nC} X_{k(i)L} + C_i, \quad i = 1, \ldots, n_H
\]

where \( T_{H(i)}^{s}, T_{H(i)}^{l} \) and \( CP_{H(i)} \) are, respectively, the supply and target temperatures and the flowing heat capacities for the hot stream \( i \) and \( C_i \) is the cold utility duty for the hot stream \( i \).

3.3. Logical constraints

Logical constraints and binary variables are needed to determine the existence of a process match to eliminate the constraints without physical meaning.

Using these constraints, it is possible to write a general incidence matrix that includes all the possible matches and allows the algorithm to choose the optimum configuration between the possibilities present in the general model.

The 0–1 binary variables represented by \( \delta \) are related to each exchanger \( k \) (\( \delta_{k(i)L} \)). An integer value of 0 or 1 of the binary variable, means that the match is, respectively, present or not, in the optimal network:

\[
X_{k(i)L} = 1 \rightarrow \delta_{k(i)L} = 0
\]

\[
X_{k(i)L} = 0 \rightarrow \delta_{k(i)L} = 1
\]

Further, it is necessary to introduce two new constraints for each exchanger in the mathematical model:

\[
X_{k(i)L} - \epsilon(1 - \delta_{k(i)L}) \leq 0, \quad k = 1, \ldots, n_E
\]

\[
X_{k(i)L} + \epsilon(\delta_{k(i)L} - 1) \geq 0, \quad k = 1, \ldots, n_E
\]

where \( G \) and \( \epsilon \) are the greatest and smallest values that the heat duty of a heat exchanger can assume.

3.4. Inequality constraints

For a counter-current heat exchanger, the temperature differences between hot and cold streams must satisfy the following minimum driving force constraints:

- At hot side of the exchanger:
  \[
  T_{hotin} - T_{coldout} \geq \Delta T_{min}
  \]

- At cold side of the exchanger:
  \[
  T_{hotout} - T_{coldin} \geq \Delta T_{min}
  \]

where the minimum driving force \( \Delta T_{min} \) is a design parameter.

These constraints are written in the mathematical model, in the following modified way:

- At hot side of the exchanger:
  \[
  T_{hotin} - T_{coldout} \geq \delta_k M + \Delta T_{min}
  \]

- At cold side of the exchanger:
  \[
  T_{hotout} - T_{coldin} \geq \delta_k M + \Delta T_{min}
  \]

where \( M \) is a negative value small enough to annul the constraint.

If \( \delta_k \) is zero, the exchanger exists and the constraint must be satisfied; otherwise if \( \delta_k \) is 1, the exchanger does not exist and the constraint must be annulled.

To better clarify the proposed procedure, let it apply to the simple network represented in Fig. 1. The incidence matrix of the HEN, represented in Fig. 2, leads to the following constraints:

\[
CP_{H(1)}(T_{H(1)}^{s} - T_{H(1)}^{l}) - (X_{12} + X_{10} + X_8 + X_6 + X_4 + X_2 + C_1) = 0
\]

\[
CP_{H(2)}(T_{H(2)}^{s} - T_{H(2)}^{l}) - (X_{11} + X_9 + X_7 + X_5 + X_3 + X_1 + C_2) = 0
\]

\[
CP_{C(1)}(T_{C(1)}^{s} - T_{C(1)}^{l}) - (X_7 + X_8 + X_2 + X_1 + H_1) = 0
\]

\[
CP_{C(2)}(T_{C(2)}^{s} - T_{C(2)}^{l}) - (X_10 + X_9 + X_4 + X_3 + H_2) = 0
\]

\[
CP_{C(3)}(T_{C(3)}^{s} - T_{C(3)}^{l}) - (X_{12} + X_{11} + X_6 + X_5 + H_3) = 0
\]

Moreover, \( 2 \times n_E \) logical constraints must be generated. In our case, 2 constraints will be generated for each of the 6 heat exchangers in each level of the HEN. For example, for the heat exchanger \( k=8 \) the following two logical constraints must be satisfied:

\[
X_8 - G(1 - \delta_8) \leq 0
\]

\[
X_8 + \epsilon(\delta_8 - 1) \geq 0
\]

Finally, \( 2 \times n_E \) inequality constraint must be generated:

- At hot side of the exchanger:
  \[
  \sum_{f=1}^{k-1} \sum_{i(k)=i(f)}^{k-1} X_f \cdot \frac{C_P_{f(h)}^{(k)}}{C_P_{H(k)^{(k)}}^{(k)}} \geq \Delta T_{min} + \delta_k M - T_{H(k)^{(k)}}^{S} + T_{C(i)}^{S}, \quad k = 1, \ldots, n_E
  \]

- At cold side of the exchanger:
  \[
  \sum_{f=1}^{k} \sum_{i(k)=i(f)}^{k} X_f \cdot \frac{C_P_{H(k)^{(k)}}^{(k)}}{C_P_{C(j)}^{(k)}} \geq \Delta T_{min} + \delta_k M - T_{H(k)^{(k)}}^{S} + T_{C(j)}^{S}, \quad k = 1, \ldots, n_E
  \]
At hot side of the exchanger:
\[
\frac{C_1}{C_{pH(1)}} + \frac{1}{C_{pH(1)}}(X_2 + X_4 + X_6) - \frac{1}{C_{pC(1)}}(X_1 + X_7) \\
\geq \Delta T_{\text{min}} + \delta_8 M - T_{H}^{T}(1) + T_{C}^{S}(1) \quad (21)
\]

At cold side of the exchanger:
\[
\frac{C_1}{C_{pH(1)}} + \frac{1}{C_{pH(1)}}(X_2 + X_4 + X_6 + X_8) - \frac{1}{C_{pC(1)}}(X_1 + X_7 + X_8) \\
\geq \Delta T_{\text{min}} + \delta_8 M - T_{H}^{T}(1) + T_{C}^{S}(1) \quad (22)
\]

The general model proposed can be solved using efficient algorithms for MIP (mixed-integer programming) problems such as “Branch and Bound” (Hillier & Lieberman, 1999) or cutting plane techniques (Bertsekas, 2003). Different computing tools for MIP are available. We adopted two of them having different features by different point of view: the Lindo–Lingo package is an easy to use tool that can be employed by any user and can be downloaded as a free light version, at http://www.lindo.com and the CPLEX packages (CPLEX Optimization Inc., 1993), one of the best state-of-the-art computer codes in the field of mathematical programming. The first one can be adopted for medium size problems and/or with a reduced budget available. The second one can reach a very high computational precision. It is to point out that with both the computing tools adopted, a tolerance parameter can be set to balance the accuracy of the solution and the necessary computation time.

Testing phases were carried out using a single P-IV CPU (2.8 GHz) with 1 GB RAM, and both XP-Microsoft and Linux-Redhat environment.

4. Application of the method to the HEN synthesis

The proposed approach will be demonstrated by considering a few typical case studies reported in the literature.

### Table 1

<table>
<thead>
<tr>
<th>Repetitive units</th>
<th>MER (MW)</th>
<th>(Q_C) (MW)</th>
<th>(Q_H) (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>371</td>
<td>99</td>
<td>59</td>
</tr>
<tr>
<td>2</td>
<td>427</td>
<td>43</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>430</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>430</td>
<td>40</td>
<td>0</td>
</tr>
</tbody>
</table>

4.1. Case study 1

This example is taken from Linnohff (1984). In Fig. 3 the solution provided by the Linnohff, that involves 6 exchangers and 2 coolers, is reported together with the duty, the inlet and outlet temperatures of each exchanger, and the flowing heat capacity of each stream.

Linnohff fixed a value of 20 \(^\circ\)C for \(\Delta T_{\text{min}}\) and obtained a hot pinch temperature of 100 \(^\circ\)C and a MER of 430 MW.

To apply the model proposed in this work it is necessary to consider an increasing number of repetitive units in order to reach the MER for the HEN. This number is an important optimization parameter for achieving the MER value.

Table 1 shows the MER, the duty of the cooler (\(Q_C\)) and the duty of the heater (\(Q_H\)) as a function of the number of repetitive units, obtained by applying our method to this case study.

As can be seen from Table 1, the maximum MER is reached with 3 repetitive units. The corresponding network that we obtained is reported in Fig. 4.

The configuration presents 9 process exchangers plus 2 utility exchangers, but if we introduce the further constraint, reported in the Eq. (23), related to the maximum number of exchangers \(N_{\text{max}}\) allowed in the configuration:

\[
\sum_{i=1}^{n_E}(1 - \delta_i) \leq N_{\text{max}} \quad (23)
\]

we can evaluate the minimum number of exchangers necessary to have the same value of the MER previously obtained.

Table 2 reports the MER variation, as a function of the number of heat exchangers obtained for this case study, by considering 3 repetitive units.

![Fig. 3. HEN configuration provided by Linnohff (1984) for the case study 1.](image-url)
As can be seen from Table 2, the optimal value for the MER is obtained by using 6 exchangers (plus 2 coolers). The corresponding network is reported in Fig. 5. The solution was obtained with a computation time of 5 s.

By considering 4 repetitive units and the constrain of the maximum number of exchangers we obtain, with a computation time of 6 s, the same configuration found by Linnhoff (1984) and reported in Fig. 3.

Since only energy recovery is considered here, both the above solutions must be considered optimal in the sense that both achieve maximum energy recovery (MER). Thus, the alternative solutions must be further tested considering other parameters such as total annualised cost, controllability, operability, etc. in order to identify the best solution that satisfy one or more of the cited parameters.

### 4.2. Case study 2

This example is the well known aromatics plant problem that considers 5 cold and 4 hot streams and was studied many times in the literature. Linnhoff and Ahmad (1990) solved this example using the pinch technique with a ΔTmin fixed at 26 °C, and with a hot pinch temperature of 126 °C; the obtained MER is 61.14 MW, realized by splitting the hot stream 4 and by employing 11 exchangers, 3 coolers and 3 heaters.

By using Genetic Algorithms (GA) employing 3 repetitive units, Lewin (1998) obtained a MER of 60.58 MW (99% of the MER target) with the configuration reported in Fig. 6 that uses 11 exchangers, 3 coolers, 3 heaters.

Table 3 shows the solutions found by Lewin (1998) using the Genetic Algorithm with 1, 2 or 3 repetitive units.
By applying the deterministic model, with the constraint $N_{\text{max}}$, we obtained, depending on the numbers of repetitive units considered, the different solutions reported in Table 4.

As can be seen from Tables 3 and 4 with 1 repetitive unit both methods achieve only the 92% of the MER target was achieved.

With 3 repetitive units both methods obtain the same result in terms of MER, but with a main difference in the procedure: our deterministic method is based on a general model for the HEN, while by using a Genetic Algorithm it is necessary to write a new model for each HEN analysed.

Furthermore Genetic Algorithms are not deterministic and there is no certainty that the solution is the optimal one. By using the general model described in this work, it is possible to use a deterministic algorithm, and to be certain of obtaining the optimal solution. Additionally, it is not necessary to create an initial family like using a Genetic Algorithm.

Moreover, as outlined in Section 3, the computation time can be reduced by setting a lower tolerance factor. More precisely, the computation time in the third row of Table 4 can be reduced by a factor of $10^2$ with a required precision of $10^{-4}$ instead of $10^{-8}$ as fixed in all the reported results.

Fig. 7 shows the solution found using our deterministic model with 3 repetitive units.

This configuration involves 11 exchangers, 3 coolers and 2 heaters, 1 heater less with respect to the solutions founded by Linnhoff and Ahmad (1990) and by Lewin (1998).

4.3. Case study 3

This example is the 10SP1 problem, as originally defined by Pho and Lapidus (1973), analysed also from other researchers (Lewin, 1998; Lewin et al., 1998; Linnhoff and Flower, 1978).

In this case a HEN with 5 hot streams and 5 cold streams is considered and Fig. 8 shows the network that we found by using the deterministic algorithm with a fixed $\Delta T_{\text{min}}$ of 10°C. The MER is 6149 kW and it was achieved by employing 6 exchangers and 4 coolers with a computational time of 29 s.
Exactly the same number of units was also found by Lewin et al. (1998) utilizing a Genetic Algorithm but with a computation time of 78 s.

5. Conclusions

This paper describes a general model for the HEN which can be solved with a deterministic algorithm to design the network of heat exchangers which recovers the maximum amount of energy. Because the general model described in this paper can be solved by using a deterministic algorithm the network found is surely, in terms of MER, the best one. To solve the HEN the concept of repetitive units, useful for ordering the heat exchangers, is utilized.

The first part of the paper describes the mathematical representation of the HEN by using a general model. To solve the model the only data necessary are the supply and target temperatures and the flowing heat capacities of each stream in the network.

In the second part, three different case studies are considered and the results obtained with the deterministic algorithm are compared with those achieved by using the Pinch
method and heuristic methods, specifically based on Genetic Algorithms.

The results reported for the case studies analysed show that the general model and the deterministic algorithm proposed in this work allow to achieve the MER for the HENs design with an equal or minor number of exchangers than by applying the Pinch method or Genetic Algorithms. Another advantage of the method, besides the certainty to have found the optimal solution, is that it is not necessary to consider an initial configuration of the network.

It must be also pointed out that this paper is specifically addressed to energy conservation and thus the objective function of the optimization procedure considers only the MER, with no reference to the total cost of the network and in particular to the influence to this regard of the total transfer area of the heat exchangers utilized. To introduce this parameter in our model, the objective function must be modified and thus a non-linearity, due to the dependence of the transfer area from the logarithmic mean temperature difference ($\Delta T_{\text{min}}$) in the design equation of the heat exchangers, will be introduced. Future work in this field will be addressed to consider this case by reducing the non-linearity to a linear problem or to a quadratic form easier to be solved, or by construct efficient algorithms devoted to solve non-linear cases.

References


