ANALYSIS OF HEAT EXCHANGER NETWORKS

by

G. G. K. Gaminibandara, M. W. G. N. Gunawardhana and M. R. Chandraratna

Department of Mechanical Engineering,
University of Peradeniya, Peradeniya.

Synopsis:

Heat exchanger networks occur in most of the chemical engineering processes and the computation of their performance arises often during process control, design or plant modification. The steady state performance can be mathematically represented by a sparse system of nonlinear equations and the solution must be attained through some iterative procedure. The objective of this paper is to present a method for an accelerating iterative computation of steady state simulation of heat exchanger networks. The method is formulated into a simple algorithm and this is incorporated into an application orientated computer programme which can be used to analyse complex heat exchanger network systems. Its application is demonstrated by numerical examples.

1. Introduction

The evaluation of operating variables in a process network involving heat exchangers can be time consuming, specially when the number of exchangers involved is high and the units are interconnected. The equations governing the operation of each unit can be easily formulated but when written down for the entire system they form a large set of interconnected nonlinear equations. Whenever possible these equations relating a large number of variables are solved numerically using a computer. Here we will present an efficient method for the performance computation of heat exchanger networks.

2. Types of Equipments

The types of heat transferring equipments in a process network are mainly classified into heat exchangers, coolers using cooling water and heaters using steam. We can assume a mixer with perfect mixing at a place where two or more streams meet and a separator where a stream branches out into several branch streams of the same temperature. Fig. 1 illustrates the functions of the various types of units in a process flow chart.

The network is best identified by giving each unit and the stream connecting any two units unique numbers, namely the node number and the branch number respectively. For example in Fig. 1 branch 1 has the head node 1 and the tail node 2. Each unit, except the separator and mixer, has two different liquid flows, the hot stream $F_h$ and the cold stream $F_c$. The flow rates connected with a separator or a mixer belong to either the hot stream or cold stream only, so the flow rates of the simplest of each unit are again given by two quantities $F_a$ and $F_b$ and third one is obtained by mass balance. In case a separator or a mixer handles more than two streams on one side, it is convenient to form equivalent sub-units having three streams, as the underlined in Fig. 1.

3. Design Equations

Consider the two heat exchangers $j$ and $k$ connected by the cold stream $l$ as shown in Fig. 2. In fact the units shown can in general represent the utilities such as heaters and coolers. The heat capacity flow rates are $F_{hl}$ and $F_{cl}$ associated with the hot and cold streams respectively of the $j$th unit; the inlet and outlet temperatures of the two streams are $(t_{hl}, t_{h0})$ and $(t_{cl}, t_{c0})$.

![Fig. 1. Typical Network.](image)

Dr. G. G. K. Gamin Bandara, BSc (Eng) Hons, PhD, DIC CEng, MIMechE, 1968, graduated from the University of Peradeniya and joined the Faculty of Engineering as Assistant Lecturer, 1976, obtained PhD from Imperial College, London, for his work on "The Optimal Design of Industrial Systems". Presently in the Department of Mechanical Engineering, University of Peradeniya.

Mr. M. W. G. N. Gunawardana, sat the Final Examination (August 1980) in Chemical Engineering (Hons) of the University of PDA and is awaiting results, presently Chemical Engineer at the State Fertilizer Manufacturing Corporation, Sapugaskanda.

Mr. M. R. Chandasena, sat the Final Examination (August 1980) in Chemical Engineering (Hons) of the University of PDA and is awaiting results, presently Chemical Engineer at the State Fertilizer Manufacturing Corporation, Sapugaskanda.
We obtain two equations for the heat exchanger.

- Heat balance:

\[ r_{c_1} (t_{c_3} - t_{c_3}) - r_{c_2} (t_{c_3} - t_{c_2}) = 0 \]

- The other is the design equation, which will be written for the basic counter-current E type heat exchanger. In the analysis of networks it is usual to consider the equivalent E-type exchangers of the existing units.

Design equation:

\[ r_{c_1} (t_{c_3} - t_{c_3}) - r_{c_2} (t_{c_3} - t_{c_2}) = r_{c_1} a_3 \left( \frac{t_{c_3} - t_{c}}{t_{c_3} - t_{c_2}} \right) \]

where \( U_j \) and \( A_j \) respectively are the overall heat transfer coefficient and the heat transfer area. The two equations for heaters using steam have to be slightly modified.

\[ \ln \left( \frac{t_{c_3} - t_{c_2}}{t_{c} - t_{c_2}} \right) \]

So the method of solution is to evaluate the coefficients \( f_1 \) and \( f_2 \) first and then to solve the two linear equations (3) for the two unknown temperatures. As mentioned earlier, a multistream separator or a mixer can be represented by a collection of separator-mixer units, each having not more than three streams. If the \( j \)th mixture has two input streams \( F_{j1} \) and \( F_{j2} \) of temperatures \( t_{j1} \) and \( t_{j2} \) respectively, the outlet stream \( (F_{j1} + F_{j2}) \) will have a temperature \( t_{j3} \) such that

\[ f_3 = \frac{F_{j1}}{F_{j1} + F_{j2}} \]

\[ f_1 = \frac{F_{j1}}{F_{j1} + F_{j2}} \]

\[ f_2 = \frac{F_{j1}}{F_{j1} + F_{j2}} \]

The function of a separator is to provide several streams of the same temperature, and our basic separator would have three streams of equal temperatures, one in and two out. There is no need to write down the heat balance as all stream temperatures are equal. However, to take into account the existence of a unit, one equation to connect the inlet temperature to the outlet temperature is written down. The \( j \)th separator having the inlet temperature \( t_{j1} \) and the outlet temperature \( t_{j3} \) presents the following equation:

\[ \begin{bmatrix} 1 & -1 & -1 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} t_{j1} \\ t_{j2} \\ t_{j3} \end{bmatrix} = 0 \]

4. The Analysis of the General Network

The total number of units involved in a given network is of course the direct summation of the heat exchangers, heaters, coolers, mixers, and separators which are numbered as nodes in any suitable manner as decided by the designer. This we call \( N \). Each branch, i.e. the path of the stream between two nodes is similarly numbered, and the total number of branches thus
obtained is \( N_b \). Referring to equations (3), (5) and (6) we observe that a heat exchanger, a cooler or a heater provides two equations and a mixer and a separator one each. For each branch the temperature leaving the head node is the same as that joining the tail node, so there is a total of additional \( N_b \) equations of the type:

\[
\dot{t}_{i,j} - \dot{t}_{i,k} = 0 \quad \text{(e.g., cold stream)}.
\]

The total number of equations available \( N_{\text{eq}} \) is

\[
N_{\text{eq}} = 2 \times \text{No. of (heat exchangers + coolers)}
+ \text{No. of (mixers + Separators)} + N_b
\]

We have seen that each unit is associated with two streams giving us a total of \( 2 \times N_{\text{tu}} \) \((= N_f, \text{say})\) heat capacity flow rates. If not all, some of these are normally provided. There are also \( N_{\text{tu}} \) continuity equations for the branches, so the actual number of the highest possible unknown flow rates are \( N_f - N_b \) \((= N_{\text{tu}} \text{, say})\).

If \((N_{\text{tu}} - N_f)\) flow rates are specified, further to those that can be obtained from the \( N_b \) branch equations, then there are \( N_f \) unknown flow rates to be found.

A similar analysis is also applicable for the temperature unknowns. It is obvious from equations (3), (5) and (6) that there is a total of \( N_{\text{tu}} \) temperatures where

\[
N_{\text{tu}} = 4 \times \text{No. of (heat exchangers + coolers)}
+ 3 \times \text{No. of mixers} + 2 \times \text{No. of separators}
\]

If \((N_{\text{tu}} - N_f)\) temperatures are specified, then there are \( N_f \) unknown temperatures to be found. Now there is a total of \((N_f + N_b)\) unknowns which are to be evaluated using \( N_{\text{eq}} \) equations. This is in general possible provided that

\[
N_{\text{eq}} = N_f + N_b
\]

and the units are not overspecified in relation to the temperatures and flow rates.

5. Method of Solution

The \( N_{\text{eq}} \) equations mentioned earlier, written over all the units, can be arranged in the matrix formation as shown below:

\[
\begin{bmatrix}
\dot{t}_{1,c} & \dot{t}_{1,t} & \cdots & \dot{t}_{1,n} \\
\dot{t}_{2,c} & \ddots & \ddots & \ddots \\
\vdots & \ddots & \ddots & \ddots \\
\dot{t}_{n,c} & \cdots & \dot{t}_{n,t}
\end{bmatrix}
\begin{bmatrix}
\dot{t}_{c,c} \\
\dot{t}_{c,t} \\
\vdots \\
\dot{t}_{c,n}
\end{bmatrix}
= \begin{bmatrix}
0 \\
0 \\
\vdots \\
0
\end{bmatrix}
\]

The \( A \) matrix formed is a large sparse matrix and in most configurations of heat exchanger arrangements the non-zero elements are scattered closely around the diagonal. Some of the non-zero elements are unity and the rest are by no means constants but functions of the flow rates. Hence the system (7) in general represents a large set of nonlinear equations. There is however a special case when all the flow rates are known, whence all the non-zero elements in the matrix become constants, so now we have a linear system. We will first seek a solution method for this linear system.

5.1 All Flow-rates Specified

When all the heat capacity flow rates in the network are specified, \( N_f \) becomes zero and \( N_{\text{eq}} \) becomes \( N_f \) and the system (7) in general provides a unique solution. The storing of all the elements of \( A \) indiscriminately is obviously an inefficient use of storage available and also a possible waste of computing time, so a standard packed form storage of sparse matrices is recommended. In this method only the non-zero elements are retained—its value and the position. The information of the branch equations occupy a portion in the lower half of the matrix \( A \), the non-zero elements being either \(+1\) or \(-1\). This means that two temperatures in the vector \( t \) are equal and therefore it may be worthwhile to drop one of them. In this connection we choose to drop the tail node (say \( j \)) temperature and to keep the head node (say \( i \)) temperature. This will in turn reduce the size of the vector \( t \) by one, and the row of \( A \) containing the corresponding \(+1\) and \(-1\) and the \( j \) th column of \( A \) are removed, having modified all the \( i \) th column elements as follows:

\[
a_{ki} = a_{ki} + a_{ij} \quad \text{all } k
\]

Note that some of the elements in the vector \( t \) may have been of specified values and if we encounter one of them as the tail node temperature to drop, this special case must be recorded separately.

This eliminating procedure is repeated until all the branch equations have disappeared from \( A \), and the dimensions of \( A \) at the end of the process is \((N_{\text{eq}} - N_b) \times (N_{\text{tu}} - N_b)\) and \( t \) is a \((N_{\text{tu}} - N_b)\) vector. It now remains to deal with the specified temperatures in \( t \). If the \( j \) th element of \( t \) shows a specified temperature the elements \( b_k \) of a vector \( b \) are computed such that

\[
b_k = b_k - \sum_j a_{kj} t_j \quad \text{all } k
\]

and the \( j \) th column of \( A \) is removed at the same time to obtain the final set of equations

\[
A t - b = 0
\]

Of course at the beginning of the operation all \( b_k \) are zeros and it is only necessary to adjust the \( b_k \) which are associated with the non-zero \( a_{kj} \) thus saving the comp-
puting time. The resulting system (8) should have a full rank square matrix $A$ and can be solved for $t$ by any standard method. Once again, in this connection, it is recommended to use the Gaussian Elimination applied to sparse matrices written in packed form. (Ref. 1).

5.2 All Flow-rates not specified

Here the elements of the matrix $A$ in (7) are not constants, but functions of some flow rates and we are left with a set of nonlinear equations. With the help of continuity equations written for every node, it is possible to express the heat capacity flow rate in each branch as a linear function of the $N_t$ parameters of flow unknowns. All of some or all of the $a_{ij}$ in $A$ are thus nonlinear functions of some or all of this $N_t$ variables; the nonlinear system must necessarily be solved by some iterative method. Some approximate but realistic values are assumed for the $N_t$ heat capacity flow rates and the $N_t$ temperatures at the beginning of iteration, non-zero $a_{ij}$ are computed, and the equations are simultaneously solved for the new $N_t$ temperatures. The $N_t$ flow rates are now corrected and this procedure is continued until convergence. We must develop a suitable correction procedure for the flow rates to give rapid and guaranteed convergence.

Take the $a_{ij}$ element at the $r$ th iteration, $a_{ij}^{r}$ is a function of in most $N_t$ flow unknowns $F_{1r}, F_{2r}, \ldots, F_{N_t}$.

We approximate

\[
\begin{align*}
\frac{\partial a_{ij}^{r}}{\partial F_{k}} & = a_{ij}^{r-1} \sum_{j=1}^{N_t} \frac{\partial s_{ij}}{\partial F_{k}} b_{ij}^{r-1} \\
& + \frac{a_{ij}^{r-1}}{s_{ij}^{r-1}} \frac{\partial s_{ij}}{\partial F_{k}} b_{ij}^{r-1} + \sum_{j=1}^{N_t} \frac{\partial s_{ij}}{\partial F_{k}} b_{ij}^{r-1} b_{ij}^{r-1} b_{ij}^{r-1} \\
& = a_{ij}^{r-1} \frac{\partial s_{ij}}{\partial F_{k}} + a_{ij}^{r-1} \frac{\partial s_{ij}}{\partial F_{k}} + \sum_{j=1}^{N_t} \frac{\partial s_{ij}}{\partial F_{k}} b_{ij}^{r-1} b_{ij}^{r-1} b_{ij}^{r-1}
\end{align*}
\]

where $s_{ij}^{r-1}$ and $b_{ij}^{r-1}$ are the corrections on the flow rates

\[
\begin{align*}
\frac{\partial s_{ij}}{\partial F_{k}} & \text{ and } \frac{\partial b_{ij}}{\partial F_{k}}
\end{align*}
\]

Using (11) in (10) we can extend the range of $j$ from 1 to $(N + N_t)$

\[
\sum_{j=1}^{N_t} \frac{\partial s_{ij}}{\partial F_{k}} b_{ij}^{r-1}
\]

where the correction $b_x$ from 1 to $N_t$ are for the unknown temperatures and from $(N + 1)$ to $(N + N_t)$ are for the heat capacity flow rates. We now have the linear system:

\[
\begin{align*}
\begin{bmatrix}
\frac{\partial R}{\partial F_{1}} \\
\frac{\partial R}{\partial F_{2}} \\
\vdots \\
\frac{\partial R}{\partial F_{N_t}}
\end{bmatrix}
\begin{bmatrix}
\frac{\partial s_{ij}}{\partial F_{k}} \\
\frac{\partial s_{ij}}{\partial F_{k}} \\
\vdots \\
\frac{\partial s_{ij}}{\partial F_{k}}
\end{bmatrix}
= \begin{bmatrix}
\frac{\partial s_{ij}}{\partial F_{k}} b_{ij}^{r-1} \\
\frac{\partial s_{ij}}{\partial F_{k}} b_{ij}^{r-1} \\
\vdots \\
\frac{\partial s_{ij}}{\partial F_{k}} b_{ij}^{r-1}
\end{bmatrix}
\]
\]

At each iteration the heat capacity flow rates are updated as $F = F + \Delta F$, the non-zero elements of $A$ are recomputed, and the current temperature $N_t$ are retained. The non-zero elements of the sub matrix $A$ are then computed according to (11), which needs the derivatives $\frac{\partial s_{ij}}{\partial F}$ and the evaluation of these shall be investigated into in the next section.

Once the two sub matrices $A$ and $A^r$ have been generated equation (12) can be solved for the unknown temperatures and the corrections of flow rates, using the same solution procedure described in the previous section. Convergence is said to have achieved when there is no significant deviation in the last two set of temperatures, or when $\Delta F \to 0$ for all $k$.


Equations (3), (4) and (5) show that the coefficients $a_{ij}$ are explicitly expressed in terms of the flow rates connected with the unit concerned, and we saw that these flow rates would appear as linear combinations of the $N_t$ unknown flow rates. We therefore obtain explicit formulae for the derivatives and then in turn for the elements $a_{ij}$ in $A^r$. For each unit we can form a constant matrix $G_F$ whose non-zero elements are either $+1$ or $-1$.

\[
\begin{bmatrix}
\frac{\partial F_{1}}{\partial F_{1}} & \frac{\partial F_{1}}{\partial F_{2}} & \cdots & \frac{\partial F_{1}}{\partial F_{N_t}} \\
\frac{\partial F_{2}}{\partial F_{1}} & \frac{\partial F_{2}}{\partial F_{2}} & \cdots & \frac{\partial F_{2}}{\partial F_{N_t}} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial F_{N_t}}{\partial F_{1}} & \frac{\partial F_{N_t}}{\partial F_{2}} & \cdots & \frac{\partial F_{N_t}}{\partial F_{N_t}}
\end{bmatrix}
\]
for a heat exchanger; for mixer or separator $F_H$ and $F_C$ are replaced by $F_a$ and $F_b$. The $k$th row of $A_{N_i}$ is now given by

$$\begin{bmatrix}
\frac{\partial n_k}{\partial t} \\
\frac{\partial n_k}{\partial x} \\
\vdots \\
\frac{\partial n_k}{\partial T_b}
\end{bmatrix} = 0$$

Matrix $C_k^T$

The few non-zero elements in $C_k^T$ can be explicitly expressed by the formulae derived from (3), (4) and (5) and then computed by substituting the current values of the parameters. In fact $C_k^T$ for mixer is a null matrix.

7. The Computer Programme

A computer programme was developed to read the information of the process network and then to solve the resulting problem for the unknown flow rates and temperatures. The network is defined to the programme by the node characteristic data and the branch characteristic data. The node data are the unit number, its type, the given or the initial approximate temperatures and heat capacity flow rates, the overall heat transfer coefficient and the heat transfer area. The branch data are the branch number, the head and tail node numbers, and the type of stream in the branch, i.e. whether the stream is hot or cold. The programme is made compact and efficient in terms of the computing time by defining the specific type of the problem, i.e. whether the network is analysed for the temperatures only or temperature and flow rates. An answer will be sought within the given accuracy and the maximum number of iterations allowed. The main steps of the algorithm is given below:

1. Read node characteristics, branch characteristics accuracy and the maximum number of iterations.
2. Check whether the problem is determinate.
3. Scan through node characteristics identifying each node and generating the non-zero coefficients of the matrix $A$ as in equations (3), (4), (5) and (6).
4. If the problem is to find the temperatures only then go to 6.
5. Compute the non-zero coefficients of the sub matrix $A_{N_i}$.
6. Scan through branch characteristics. Remove duplicate temperatures thus dropping the lower portion of the matrix $A$ as in equation (7) and making corrections on the remaining $a_{ij}$ accordingly.

7. Substitute the values for the specified temperatures, generate the $b$ vector as in equation (8). Drop the corresponding columns in $A$.
8. Solve the equation (8). If the problem is to find the temperatures only then go to (11).
9. If the solution is within the given accuracy or if the maximum number of iterations is exceeded, print relevant message and then go to (11).
10. Update flow rates and temperatures and go to (3).
11. Print solution and STOP.

8. Numerical Examples

Consider the network illustrated in Fig. 1. The unit or the node number is encircled and the branch number is written adjacent to the branch. Only the branch numbers 1 to 9 are necessary for our computation; the terminal numbers 10 to 21 are included only for the purpose of stating the problem particulars completely. The following table gives the operational data.

$A = 1000 \, f^2$ for all exchangers.
$U_1 = 85, U_2 = 90, U_4 = 105, U_5 = 120, U_7 = 200,$
$U_6 = 100 \, (\text{BTU}/\text{hr}/\text{f}^2/\text{F})$

<table>
<thead>
<tr>
<th>Stream No.</th>
<th>Heat capacity flow rate ($X 10^{-3}$)</th>
<th>Temperature of F (specified)</th>
<th>Solution</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>233.4</td>
<td></td>
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<tr>
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<td>435.0</td>
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</table>

We notice that the route 10, 1, 2, 3, 5 and 4, 6, 7, 21 belongs to the cold stream and the route 15, 8, 9, 20 to the hot stream. The problem is of type 1 and the solution giving the remaining temperatures is obtained in one iteration. There must be a temperature rise in the cold stream and a temperature drop in the hot stream when they leave an exchanger; in addition the branch temperatures of the hot stream must be above those of the cold streams. It is seen that the solution satisfies these conditions and hence can be accepted as a feasible one.
Next the problem is slightly modified by making two heat capacity flow rates unknown and this is compensated by fixing two temperatures in addition to the ones already specified in the previous problem. Let the flow rates in the branches 3, 5 and 15, 8, 9 be found out, and the temperatures of the branches 10 and 14 be 170°F and 292.8°F respectively. This problem is of type 2 where one seeks a solution for a system of nonlinear equations, and approximate values must be given for the unknown flow rates and temperatures at the start of iteration. The initial estimate of the flow rates and the temperatures is taken from the solution to the previous example with the answers to the unknown variables having been given a displacement of 5 per cent from their values. Convergence is achieved in six iterations to an accuracy of 0.1 per cent in the temperature.

Next we take a larger network with seventeen exchangers and no separators or mixers as illustrated in Fig. 3. The operational data are given in Table 2 and Table 3. Once given the problem is of type 1 and the solution obtained is admissible to the conditions governing the terminal temperatures of a heat exchanger. Next the values of flow rates in the cold stream 1, 2, 3, 4, 5, 6 and the hot streams 22, 23, 31, 32, 35, 11, 12, 13, 27 are withdrawn, but the temperatures 16, 20, 27, 6 are given the values of the previous solution. Starting from an initial estimate of the unknown flow rates and temperatures determined by adjusting their values as in the second examples, it took ten iterations for convergence. The criterion of convergence is the same as the one in the second example.

9. Conclusion

The computational procedure described here is suitable to analyse complicated networks, and when the number of units involved is large it is essential to use a powerful storing technique for matrix A. The evaluation of temperatures is straightforward and in this case a unique solution is usually obtained. When the problem has unknown flow rates the resulting nonlinear system may have multiple solutions, so one should take special precautions not to start with a non-feasible set of values as this may lead to an undesirable or non-feasible solution. If a particular configuration is thought to be too large in the storage, it is worthwhile investigating the network for possible breaking down into several sub-systems which can be treated independently. If totally independent sub-systems cannot be found then the ones interconnected by the smallest number of variables are selected. The sub-systems are solved individually until the common variables assume the correct values to satisfy all the sub-systems simultaneously.

The selection of the economically optimal exchanger for the process is receiving the highest priority among the design criterions. The location of the exchanger in the process network and the different ways the exchanger may be connected to the flow paths lead to a number of feasible solutions. The objective should be to minimise the capital cost of the processing equipment as well as the unnecessary wastage of energy which will indirectly lower the running costs.

The computer programme developed here for the analysis of heat exchanger networks can be employed for simulation, to obtain the feasible solutions and to examine them for the optimal one. In the ideal situation the programme provides a suitable subroutine for a general optimization routine so that the optimal solution can be attained in one attempt.

References

<table>
<thead>
<tr>
<th>Node</th>
<th>( U/\theta T U/(Hr/ft^2°F) )</th>
<th>( A(\theta) )</th>
<th>Heat Capacity</th>
<th>Temperature °F</th>
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<td></td>
<td></td>
<td>(Btu/h/ft²°F)</td>
<td>(specified)</td>
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**TABLE 2**
Problem Specification for Example 3

**TABLE 3**
Problem Specification and the Solution for Example 3