COMBINING PINCH AND EXERGY ANALYSIS FOR PROCESS MODIFICATIONS

X. Feng* and X. X. Zhu*†

*Department of Chemical Engineering, Xi'an Jiaotong University, Xi'an, 710049, P. R. China; and
†Department of Process Integration, University of Manchester Institute of Science and Technology (UMIST), Manchester, M60 1QD, UK

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Abstract—The strength of pinch analysis is that system information can be represented using simple diagrams (e.g. composite curves, grand composite curves) and thus targets for the system under consideration can be readily obtained prior to design. In contrast, the power of exergy analysis is that it can identify the major causes of thermodynamic imperfection of thermal and chemical processes and thus promising modifications can be determined effectively. By combining the strengths of both methods, the proposed method can represent a whole system, including individual units on one diagram, which helps to screen the promising modifications quickly for improving a base case design. It has been realised that the major limitation of pinch analysis is that it can only deal with heat transfer processes, not the processes involving changes in pressure or compositions, which are very common in power and chemical processes [1, 2]. To overcome this limitation, a generic diagram is introduced, which is the so-called $\Omega$-$H$ diagram, where $\Omega$ indicates the energy level and $H$ states the amount of energy. Both energy and exergy balances for a whole system can therefore be represented simultaneously on this diagram. Using this diagram, the major advantages of both pinch and exergy analysis are combined since the diagram enables one to view the performance of a system and set targets for improvement. Meanwhile, the inefficient processes and equipment can be identified and thus promising modifications can be obtained by revealing the actual potential, which is determined by applying the concepts of inevitable and avoidable exergy losses. The analysis of avoidable exergy losses indicates the maximum potentials (modification targets) which are achievable in current technical and economic conditions. A combined-cycle power station is used to demonstrate the effectiveness of this new method. Copyright © 1996 Elsevier Science Ltd.

Keywords—Pinch analysis, exergy, energy efficiency, processes.

NOTATION

AVO avoidable exergy loss
E exergy
EL total exergy loss
$H$ enthalpy
INE inevitable exergy loss
$S$ entropy
$T$ temperature
$W$ work

Greek letters

$\eta_c$ Carnot factor
$\Omega$ energy level

Subscripts

C condenser, cold stream
Com compressor, combustion
Gas gas turbine
in input
out output
ST steam turbine
T turbine
0 environment state

*Author to whom correspondence should be addressed.
Pinch analysis has become a general methodology for targeting and design of thermal and chemical processes and associated utilities [3]. The composite curves (CC) and the grand composite curve (GCC) are two basic tools in pinch analysis, and they are constructed using temperature versus enthalpy axes [4]. The energy targets set by the CC and GCC are mainly in terms of heat loads. To deal with systems involving heat and power, the concepts of both the composite curves and the grand composite curve have been extended. As a result, the exergy composite curves (ECC) and the exergy grand composite curve (EGCC) were proposed which are based on Carnot factor ($\eta_c$) versus enthalpy [1, 2].

As shown in Fig. 1, the composite curves ($T$–$H$ diagram) for a heat transfer system can be converted into the exergy composite curves and the grand composite curve ($\eta_c$–$H$ diagram). The shaded areas indicate the exergy loss associated with the heat transfer process. By combining pinch analysis and exergy analysis in such a manner, it is possible to predict the shaftwork requirement or generation for both power systems and refrigeration systems with a certain accuracy [5, 6]. It must be noted that this combined pinch and exergy analysis was developed mainly for the purpose of shaftwork targeting. When dealing with process modifications, it has severe limitations. Particularly, only processes related to heat transfer can be represented on the $\eta_c$–$H$ diagram but not the processes associated with pressure and composition changes, since the diagram is constructed based on temperatures:

$$\eta_c = 1 - \frac{T_c}{T}.$$  \hspace{1cm} (1)

As a consequence, the $\eta_c$–$H$ diagram cannot represent the core processes (e.g. a turbine system involving the expansion process for a combined power station and a compression system with throttling processes for a refrigeration plant). This limitation may miss promising modifications since changes to core processes usually have a great impact on the improvement of a system performance [7].

To overcome this limitation, the method proposed in this paper extends the current combined pinch and exergy analysis [1, 2] by introducing a new diagram, so called the $\Omega$–$H$ diagram, which can represent a whole system, including both heat transfer processes and core processes and provide targeting information. Meanwhile, major directions and promising modifications for system improvement can be identified effectively.

While the strength of pinch analysis has been accepted in terms of representing main features of a system graphically and providing targeting information for process modification, the advantages of exergy analysis are also adopted in this work, in that the application of exergy analysis makes it possible for the proposed method to deal with any energy systems and clearly

![Fig. 1. Exergy transformation from CC to ECC and EGCC.](image-url)
Combining pinch and exergy analysis

indicates the locations of energy degradation and the causes of thermodynamic inefficiency of a system. Moreover, the idea of having different levels of analysis is proposed. The top level of analysis features conceptual analysis and shows the overall performance of a system. At same time, the major directions for system improvement are indicated. When the level of analysis moves on, the method requires more data to identify the promising modifications following the directions suggested.

To determine the maximum potential which is achievable for each modification, the exergy loss, in this work, is divided into inevitable and avoidable losses. The inevitable exergy loss is defined as the minimum exergy loss which can not be avoided for a process to take place with both technical and economic constraints. With this definition, the avoidable exergy loss gives the practical maximum potential for process improvement. Using this proposed method, a system can be quickly analyzed and major causes for imperfections of a system can be identified. Then promising modifications and the practical maximum potentials for these modifications can be determined by analyzing the avoidable exergy losses incurred in different processes and equipment.

NEW EXERGY-ENERGY (Ω-H) DIAGRAM

Definition

In order to deal with any energy system, we use the energy level Ω as the ordinate. The energy level is defined as

\[ \Omega = \frac{\text{exergy}}{\text{energy}} \, . \]  \hspace{1cm} (2)

Thus, for work

\[ \Omega = 1 \, . \]  \hspace{1cm} (3)

and for heat

\[ \Omega = \eta_c = 1 - \frac{T_2}{T} \, . \]  \hspace{1cm} (4)

and for a steady-state-flow system

\[ \Omega = \Delta E/\Delta H \, . \]  \hspace{1cm} (5)

When we analyze a system only concerning heat and work, we choose \( \eta_c \) as the ordinate, which is same as the current combined pinch and exergy analysis [1, 2]. When a steady-state-flow system involves changes in pressure and/or composition, the definition \( \Omega = \Delta E/\Delta H \) should be used. For the systems not falling into the above two categories, such as magnetic refrigeration, thermoelectric converter and so on, the general definition \( \Omega \) defined in equation (2) must be used. The abscissa of the graph is energy. For steady-state-flow systems, enthalpy (\( H \)) can be used as the abscissa.
**Representation of basic processes**

**Heat transfer process.** In Fig. 2, a heat transfer process can be represented by the hot and cold exergy composite curves. The area below the hot composite curve is the exergy released by hot streams, and the area below the cold composite curve is the exergy obtained by cold streams. So the area between these two curves gives the exergy loss incurred during the heat transfer process. This exergy loss for either hot or cold streams generally consists of two components. The first one is the thermal component, which is caused by the heat transfer over finite temperature difference, and the second is the pressure component, which is related to the pressure drops. In the $\eta_c-H$ diagram, the second component of the exergy loss can not be represented since $\eta_c$ is defined only based on temperature.

**Adiabatic expansion process.** By definition, for an adiabatic expansion process,

$$\Omega = \frac{\Delta E}{\Delta H} = 1 - \frac{T_0 \Delta S}{\Delta H} > 1 \ (\Delta S > 0, \ \Delta H < 0),$$

(6)

$\Delta E$ in equation (6) is the exergy change of the process stream going through the expansion process. This exergy change is the net exergy expense of the process. The equation indicates that the expansion expends exergy ($\Delta E$) more than $\Delta H$ [with $\Omega > 1$ as shown in equation (6)] but the surroundings can only get work ($W$) which equals $\Delta H$ (with $\Omega = 1$). The difference of the exergy expense ($\Delta E$) and the work generated ($W$) gives the exergy loss which is represented by the shaded area in Fig. 3. In this expansion process, the exergy source is the exergy change of the process stream and the exergy sink is the surrounding which receives the work.

**Adiabatic compression process.** For an adiabatic compression process given in Fig. 4,

$$\Omega = \frac{\Delta E}{\Delta H} = 1 - \frac{T_0 \Delta S}{\Delta H} < 1 \ (\Delta S > 0, \ \Delta H > 0).$$

(7)

For this compression process, the exergy input (work) from the surroundings (exergy source) equals $\Delta H$ (with $\Omega = 1$), but the process stream (exergy sink) can only get exergy ($\Delta E$) less than $\Delta H$, thus $\Omega < 1$ which is indicated by equation (7). The difference of the exergy input and the exergy change of the stream is the exergy loss, which is represented by the shaded area in Fig. 4.

It should be noted that the $\eta_c-H$ diagram cannot represent both the expansion and compression processes, since these processes involve changes in both temperature and pressure.

**APPLICATION OF THE $\Omega-H$ DIAGRAM**

**Description of the base case**

Here a combined power station [8] is selected as a case study to show how the system can be represented on the $\Omega-H$ diagram and how a shaftwork target can be set up for the base case. The flowsheet and data of the base case design are given in Fig. 5 and Table 1, respectively. This power station includes an open gas turbine system and a conventional steam turbine system. The gas cycle is a hot air arrangement with indirect heating of the air in the boiler and the steam cycle is a
conventional reheat cycle with three feed water heaters and one economizer. The gas turbine exhaust is used as pre-heated combustion air for the boiler. The major advantage of this system is that it uses coal as fuel, and all elements are made by proven technology.

General analysis

This power station consists of two major components, one is the heat transfer system and the other is the turbine system. The chemical energy in the coal provides the total exergy for the plant, which is the original exergy source. Part of the exergy from the fuel is lost in the heat transfer system, including the boiler, the bleeds heat exchangers, the economizer and the condenser. The rest of the exergy goes into the turbine system as the exergy input for generating power. Some of the exergy input is lost in running the turbines, pumps and compressors. The amounts of these losses are defined by their machine efficiency. Also, a certain amount of the exergy is lost with the exhausted gas. The remaining exergy gives the shaftwork which is received by electrical generators, which becomes the final exergy sink. The exergy flow and distribution is represented in Fig. 6.

The first level of analysis

Construction of the Ω–H diagram. This level of the analysis involves the construction of the hot and cold exergy composite curves and calculations of exergy losses for the heat transfer system. The construction of the exergy composite curves (the Ω–H diagram of Fig. 7) is similar to the construction of the composite curves in pinch analysis. In other words, the hot and cold composite curves are plotted by lumping hot and cold streams together according to their temperatures.

<table>
<thead>
<tr>
<th>Points</th>
<th>Temperature (°C)</th>
<th>Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.7</td>
<td>101.4</td>
</tr>
<tr>
<td>2</td>
<td>365.0</td>
<td>1165.2</td>
</tr>
<tr>
<td>3</td>
<td>926.7</td>
<td>1082.5</td>
</tr>
<tr>
<td>4</td>
<td>460.2</td>
<td>108.2</td>
</tr>
<tr>
<td>5</td>
<td>540.6</td>
<td>16648.7</td>
</tr>
<tr>
<td>6</td>
<td>337.9</td>
<td>4410.5</td>
</tr>
<tr>
<td>7</td>
<td>537.8</td>
<td>4965.8</td>
</tr>
<tr>
<td>8</td>
<td>203.9</td>
<td>239.2</td>
</tr>
<tr>
<td>9</td>
<td>177.2</td>
<td>177.2</td>
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<tr>
<td>10</td>
<td>75.9</td>
<td>40.0</td>
</tr>
<tr>
<td>11</td>
<td>38.7</td>
<td>6.8</td>
</tr>
<tr>
<td>12</td>
<td>128.9</td>
<td>19406.7</td>
</tr>
<tr>
<td>13</td>
<td>143.0</td>
<td>101.4</td>
</tr>
</tbody>
</table>
Assume that the maximum chemical exergy contained in the coal fuel is provided in full as the exergy input, so $\Omega = 1$. After combustion in the boiler, the chemical energy of the fuel is converted into heat exergy received by the flue gas and a large amount of exergy loss is incurred in combustion, which is indicated by the shaded area between the $\Omega = 1$ line and the flue gas curve in Fig. 7. Then, in the boiler the heat of the flue gas is used to raise the high-pressure (HP) steam, reheat the HP turbine exhaust and heat the air. Therefore, in these heat transfer processes taking place in the boiler, the flue gas becomes the heat source and two water streams and one air stream become the heat sink. The source and the sink can be represented by both the hot and cold exergy composite curves (Fig. 7). The shaded area between these two composite curves gives the total exergy loss incurred in the heat transfer processes.

Similarly, the hot and cold composite curves for the bleed heat exchangers (feed heaters), the condenser and the economizer can be constructed, which are also shown in Fig. 7. The exhaust flue gas in the stack is also shown. The corresponding shaded areas indicate the exergy losses occurred in the three bleed heat exchangers, the condenser, the economizer and the stack.
Combining pinch and exergy analysis

Analysis and process modifications. Once the $\Omega-H$ diagram is constructed, the general performance of the base case can be predicted effectively. First let us look at the exergy balance for the problem. The entire area of the diagram gives the total exergy input of 614.4 MW provided from the chemical exergy of the fuel. By subtracting all the exergy losses (the shaded areas in Fig. 7), the remaining exergy (white area) gives the net exergy input of 316.3 MW to the turbine system. In contrast, the energy balance can be derived from the abscissa of the $\Omega-H$ diagram. The full length of the abscissa is the total amount of the heat input from the fuel, which is equal to 614.4 MW. The heat loss in the stack can be measured from the diagram which is 32.4 MW and the heat loss in the condenser 314.3 MW. The difference between the heat from the fuel and the heat losses in the condenser and the stack gives the net shaftwork of 267.7 MW. Then the exergy efficiency of the whole plant can be calculated as 43.57% ($= 267.7/614.4$). And the exergy efficiency for the turbine system, including the gas and steam cycles, is 84.63% ($= 267.7/316.3$).

By exploring the $\Omega-H$ diagram, it is found that a very big exergy loss occurs in the boiler. Thus from this level of analysis, the major direction to improve the base case is obviously to reduce the exergy losses in the boiler as much as possible. Graphically, the cold exergy composite curve should lift upwards. Also, the $\Omega-H$ diagram shows the inefficiency in the water feed heaters. The detailed discussions for process modifications are given later in this paper.

Second level of analysis

Construction of the $\Omega-H$ diagram. After analyzing the $\Omega-H$ diagram for the heat transfer component, we have achieved a better understanding of the exergy loss distribution in different heat transfer processes and can identify major directions to improve the base case. In the second level of analysis, we are going to describe the performance of the turbine system, which is the core component in the power plant. From this level of analysis, the $\Omega-H$ diagram of Fig. 7 is modified to give Fig. 8, which includes the turbine system.

In order to show the energy and exergy balance for the turbine system clearly, we shift the exergy losses for work-making equipment (turbines) featuring $\Omega > 1$ to the bottom of the diagram, as the amount of exergy losses incurred in any equipment is relative.

The exergy loss of the gas turbine system should be explained in more detail. This system consists of a compressor and a gas turbine, which are represented in Fig. 9. Assume the shaftwork generated by the gas turbine is $W_g$, the shaftwork required to drive the compressor is $W_{com}$ and thus the gas cycle produces the net shaftwork $W_{gas} (= W_g - W_{com})$. To show the energy balance for the whole system clearly, we draw the gas turbine system at a scale of $\Delta H = W_{gas}$ as shown in Fig. 8.
Analysis and process modifications. From the $\Omega-H$ diagram (Fig. 8) obtained from the second level of analysis, the net exergy inputs to both the steam and gas cycles can be calculated as 252.9 MW and 63.4 MW, and the net shaftwork generated by the steam and the gas cycles is 218.6 MW and 49.1 MW, respectively. Thus the exergy efficiency for the steam cycle and the gas cycle is 86.4 and 77.4%. Similar calculations can be done for individual turbines.

From Fig. 8, the exergy loss contribution in the turbine system can be clearly viewed and it indicates that the biggest exergy loss in the turbine system occurs in the LP (low-pressure) turbine and the second biggest loss is from the IP (intermediate-pressure) turbine. Furthermore, the interactions between the heat transfer and the turbine systems can be revealed to some extent. For example, the inefficiency of the LP turbine may be caused by the wetness of the LP turbine exhaust. The essential modification to reduce the wetness of the exhaust is to increase the steam reheating temperature (point 7 in Fig. 5). Meanwhile, raising the steam reheating temperature can also reduce the exergy loss in the boiler. These interactive effects can be identified from the corresponding $\Omega-H$ diagram after the modification of raising the steam reheating temperature is made.

Remarks and significance

The first level of analysis shows the outer layer of the whole problem, i.e. the heat transfer processes. As a result, the major cause of inefficiency of the heat transfer system is revealed, which exists in the boiler. Thus, the major directions for improvement are identified. When moving into the core of the problem, which is the turbine system in this case, the second level of analysis is required. The $\Omega-H$ diagram of Fig. 8 from these two levels of analysis shows the overall picture of the power plant, including the two major components, the heat transfer system and the turbine system.

The results of the second level of analysis tell the performance of the core system and show the inefficiency of the system, which mainly exists in the LP turbine. More importantly, the analysis also reveals the interactions between the outer layer of processes (e.g. heat transfer system) and the inner layer of processes (turbine system). When the level of analysis moves on, the data requirement increases, the sophistication of analysis increases and the details of analysis results increase as well.

It should be noted that in this case study, the heat transfer system is dominant in exergy losses and thus modifications in this system are bound to produce more significant benefits towards the improvement of the whole plant. However, in many chemical processes, situations may be completely different and modifications in core processes may generate more or equally significant impact to the whole system than those made in heat transfer processes. Thus, the second level of analysis can play a very important role.

The essence of this analysis method is the proper combination of pinch analysis and exergy loss analysis. In the conventional exergy analysis, the exergy loss analysis is based on individual units, from which one cannot see the interactions of different units and systems. This problem is overcome by applying the concepts of composite curves in pinch analysis, which makes it possible to graphically represent both the whole system and individual units clearly. As a result, the major
directions and promising modifications for improvement can be determined effectively. The other significant benefit of the $\Omega-H$ diagram is that the base case design can be quickly evaluated in terms of thermo-efficiency. If any modification is made which results in a modified $\Omega-H$ diagram, then the impact of such modification to the whole system can be predicted from the diagram effectively.

Although the overall picture of a system can be shown and major directions for improving the system performance can be identified from the above two levels of analysis, the maximum potential or the limit of improvement for individual units and processes are still uncertain, since the exergy loss analysis so far is based on the concept of total exergy loss. In some cases, the suggestions for promising modifications based on the total exergy loss may be misleading, since they do not consider the minimum exergy loss which is required to operate a process.

### Inevitable (INE) and Avoidable Exergy Losses (AVO)

The previous analysis is based on the concept of the total exergy loss, which cannot state whether or not the possible improvement is practical and economic. Obviously, there is no possibility to recover the full amount of a total exergy loss for a process, since the minimum amount of exergy loss is required as the minimum driving force to operate the process at a desirable rate. These kinds of exergy losses are defined as inevitable exergy losses. A process with smaller exergy losses than the inevitable losses will either not meet the requirement of a desirable production rate, or cannot be accomplished technically and economically. The requirement of the minimum exergy loss to drive a process at a certain rate varies from process to process and also changes with technical advancement and economic conditions.

Therefore, any total exergy losses can be decomposed into two parts: avoidable exergy loss and inevitable exergy loss:

$$EL = AVO + INE.$$  \hspace{1cm} (8)

The inevitable exergy loss can be defined as the minimum exergy loss which cannot be avoided technically and economically. The calculations of inevitable exergy losses for different units can be found in ref. [9]. Given the inevitable exergy loss, the avoidable exergy loss can be calculated according to equation (8). As a consequence of the analysis for inevitable and avoidable exergy losses, we can know exactly which process or equipment incurs the biggest avoidable exergy loss and can then identify practical and valuable modifications.

To explain how to distinguish the inevitable and avoidable exergy losses, we use an indirect heat transfer process as an example. For simplicity, let us assume that the heat transfer process involves hot and a cold streams with the same heat capacity flow rate. The minimum or inevitable exergy loss is determined by the minimum temperature difference between these two streams. In an ideal case, when the minimum temperature difference is equal to zero, the minimum exergy loss becomes zero as well. However, the zero temperature difference corresponds to an infinite surface area, which is clearly not economical. Practically, the heat transfer process with a zero temperature difference is thermodynamically infeasible. Hence, a minimum temperature difference is required to account for the thermodynamic feasibility and this temperature difference is called the exchanger minimum approach temperature (EMAT). For a heat transfer process to take place, the minimum exergy loss defined from EMAT is inevitable. However, the heat transfer process may have different total exergy losses when the process is integrated into a system in different ways, but the minimum exergy loss remains the same, since this loss is determined by the EMAT.

In summary, the total exergy loss is calculated based on operation conditions of a given process and the minimum or inevitable exergy loss is determined by the best thermodynamical performance which can be achieved with the process. The difference of the total loss and the inevitable exergy loss gives the avoidable exergy loss, which defines the potential for improvement. Therefore, the avoidable exergy loss may differ for a given process, which depends on how the process is integrated into a system, while the minimum exergy loss associated with the process remains the same. More detailed discussions about the concepts of inevitable and avoidable exergy losses can be seen from ref. [9].
Table 2. The exergy balance of the base case

<table>
<thead>
<tr>
<th>Component</th>
<th>$E_a$ (MW)</th>
<th>$E_{out}$ (MW)</th>
<th>EL (MW)</th>
<th>AVO (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler</td>
<td>614.4</td>
<td>268.2</td>
<td>76.6</td>
<td></td>
</tr>
<tr>
<td>Economizer</td>
<td>10.7</td>
<td>5.7</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Flue gas exhaust</td>
<td>-93.8</td>
<td>5.9</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Compressor</td>
<td>142.9</td>
<td>8.4</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Gas turbine</td>
<td>51.5</td>
<td>4.5</td>
<td>14.2</td>
<td></td>
</tr>
<tr>
<td>HP turbine</td>
<td>104.8</td>
<td>12.4</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>IP turbine</td>
<td>66.8</td>
<td>16.9</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td>LP turbine</td>
<td>51.5</td>
<td>4.5</td>
<td>14.2</td>
<td></td>
</tr>
<tr>
<td>Condenser</td>
<td>12.1</td>
<td>1.4</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Feed heaters</td>
<td>3.3</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td>-4.5</td>
<td>0.5</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>614.4</td>
<td>267.7</td>
<td>349.3</td>
<td></td>
</tr>
</tbody>
</table>

APPLICATION OF THE CONCEPT OF THE AVOIDABLE EXERGY LOSS—THIRD LEVEL OF THE COMBINED PINCH AND EXERGY ANALYSIS

Construction of the $\Omega$–$H$ diagram

First, the inevitable exergy losses are calculated for different processes and then the avoidable exergy losses are determined. The calculation results are listed in Table 2. Then the $\Omega$–$H$ diagram of Fig. 8 is modified considering both inevitable and avoidable exergy losses to give the $\Omega$–$H$ diagram of Fig. 10, in which the blackened areas indicate the avoidable exergy losses and the shaded ones inevitable losses.

The calculations of inevitable exergy losses are based on the following assumptions:

- The highest temperature of the gas 1000°C [10].
- The lowest condensing temperature 37°C [11].
- The lowest temperature of the flue gas 143°C [11].
- The highest equipment efficiency $\eta_T = \eta_{st} = \eta_{con} = 0.90$ [12].

Practical maximum potential (target) for improvement

The results from the avoidable exergy loss analysis would be very different from the total exergy loss analysis. For example, the total exergy loss of the IP turbine is almost the same as that of the condenser, but the avoidable exergy loss in the IP turbine is much higher than that of the condenser, which means that there is a big potential for improving the IP turbine performance and little potential in the condenser. In other cases, one may find that some processes with a large total exergy loss are difficult to improve, since the majority of the total loss is unavoidable [9]. Therefore, the avoidable exergy loss indicates the maximum potential which is achievable and practical.

![Fig. 10. Avoidable exergy losses from the third level of analysis.](image-url)
The full amount of the avoidable exergy loss for each unit or process defines the practical maximum potential for improvement and it sets the limit for process modifications. The calculation of avoidable exergy losses indicates that although the boiler incurs the biggest total exergy loss, which is 268.2 MW, the avoidable exergy loss is only 76.6 MW (28.56%). In contrast, the LP turbine has a small amount of the total exergy loss (16.9 MW) but it has a high percentage of the avoidable loss of 9.7 MW (57.40%) and the second highest percentage of avoidable exergy loss occurs in the economizer. There is virtually no potential for improvement in the condenser, since the temperature approach difference in the condenser is very close to the minimum approach. The calculations also reveal that there is little or no potential in the pump and the stack.

**Significance of the concept of the practical maximum potential**

There are three significant advantages of knowing the practical maximum potential and limit for improvement. First, the performance of a process and equipment can be evaluated based on the maximum potential which is achievable in current technical and economical conditions. The practical maximum potential for improvement defined as such distinguishes itself from the theoretical maximum potential, which cannot be realized either technically or economically. Therefore, the practical maximum potential indicates what can be done and what cannot be done in current conditions. Secondly, by knowing the practical maximum potential for improvement, a designer sets the target for improvement by making modifications. Different modifications can then be compared in terms of how much benefit can be achieved and what is the capital cost involved. Thirdly, any processes or units with very small potential for improvement can be immediately ruled out from consideration.

**ANALYSIS AND PROMISING MODIFICATIONS**

The objective of using this proposed analysis method is to evaluate the performance of a base case design, reveal inefficient processes and equipment and thus identify the major directions and promising modifications for improving the base case effectively. From the above three levels of analysis, we can achieve the following analysis and promising modifications for the power plant.

By exploring the Ω–H diagram of Fig. 10, it is found that the avoidable exergy losses incurred in the boiler are dominant in the whole plant, which suggests that the major direction to improve the base case is to reduce the exergy loss in the boiler and the main idea to achieve this task is to increase the exergy conversion from the fuel and bring the exergy cold composite curve of H₂O and air upward.

To have a better understanding of the heat transfer in the boiler, the Ω–H composite curves for the boiler (Fig. 11) are constructed. It is noticed that the pinch point is in the left border of the curves, i.e. at the economizer, which restricts the increase of the water temperature at the
The following promising modifications may possibly reduce the exergy losses in the boiler: increase the air flow rate, raise steam reheating temperature (point 7 in Fig. 5) and/or increase the air outlet temperature (point 3 in Fig. 5) and reduce the water flow rate.

As shown in Fig. 11, increasing the air flow rate in the gas cycle could have the effect of flattening the hot composite curve (flue gas). The benefit of this modification is that more exergy from fuel can be converted into the heat exergy received by the flue gas and thus more shaftwork can be generated from the turbine system, given the unchanged conditions of the turbine system.

Raising the steam reheating temperature may have two effects: one is the reduction of the exergy loss in the boiler and the other is the increase of the steam dryness for the LP turbine exhaust, which in turn improves the LP turbine efficiency. The other modification is to reduce the water flow rate in the steam cycle, which can steepen the cold composite curve.

In addition, the other promising modifications include optimizing feed heating conditions by closing pinches in the feed heaters and optimizing the bleed levels [2]. These modifications can reduce the exergy losses in both the LP turbine and the feed heaters.

Assume the above suggested modifications are made, the shaftwork increases from 267.7 to 278.4 MW under the same fuel input and thus the overall thermal efficiency is increased by 1.74%. The Ω–H diagram for the improved system is constructed and is shown in Fig. 12, where the dotted lines represent the base case and the solid lines the improved design.

The above analysis is based on the following assumptions: the fuel and boiler's metallurgy remain unchanged and we take $t_3 = 954^\circ\text{C}$ [9] and $t_s = t_5 = 560^\circ\text{C}$ [13].

**CONCLUSIONS**

The proposed method combines the pinch and exergy analysis on a rational basis for process modifications. Pinch or exergy analysis alone can not fulfil the task for effective process modification, since they have their own intrinsic advantages and disadvantages.

The power of pinch analysis is in showing the main features of a system on simple diagrams. Based on such diagrams, e.g. the composite curves and the grand composite curve, conceptual analysis can be done very effectively and targets can be set up for design. The weakness of pinch analysis is that it can not deal with processes which involve changes in pressure and composition. However, these processes are usually the core processes in thermal and power systems. If these processes are not considered in process modification, it is very possible that promising modifications can be missed.

In comparison, exergy analysis can deal with any systems of different features and is powerful in quantitative analysis for any elements of a system. Furthermore, the exergy loss analysis can
indicate the major causes of imperfections of a system. However, exergy analysis cannot represent the overall picture of a system information as clearly as pinch analysis does. Therefore, the proper combination of these two methods from this work has brought significant benefits for process modifications, since it is vital to display the system information graphically for one to visualize the performance of a system and quantitatively identify major directions for improvement. This task has been achieved by introducing the Ω-H diagram. In contrast, the application of exergy analysis, particularly the concept of the avoidable exergy loss, allows one to carry out quantitative analysis to identify the major problems and then promising modifications based on the concept of the practical maximum potentials or limits for improvement.

The strategy for process modifications proposed in this work considers the different levels of analysis for modification. It starts from heat transfer processes, which requires limited data to construct the exergy composite curves for these processes. The results of the first level of analysis give the general performance of the heat transfer system and indicate the inefficient processes. The second level of analysis involves the core system and requires more data to construct the exergy loss distribution for the core processes. This level of analysis evaluates the whole system, including subsystems, in more detail, so that the thermal efficiencies for all the subsystems can be predicted. As a result, major problems in the whole system can be identified. Finally, the third level of analysis is based on the concept of avoidable and inevitable exergy losses, by which one can identify promising modifications and determine targets (the practical maximum potential) for improvement.

The justification behind this strategy for modifications with different complexity levels is that a designer can decide at which level he/she may stop. If the results from the first level of analysis show a very good overall efficiency or performance of a base case, it may not be necessary to go further. Otherwise, the second level of analysis may be needed for a more detailed analysis, which can give process-wise and unit-wise analysis for different processes and equipment. Hence, one can identify which process or equipment suffers the worst performance. To set up targets or the practical maximum potentials for modifications, the third level of analysis is required to reveal the actual bottlenecks or major problems based on the analysis of avoidable exergy losses. Therefore, practical promising modifications can be determined effectively to improve the whole system.

REFERENCES

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