A Systematic Numerical Tool Accounting for Boiler Feed Water (BFW) in Total Site Heat Integration

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Abstract

Energy efficiency in industrial field gains very much attention around the world. Total Site Heat Integration (TSHI) is proposed as a solution to increase energy saving opportunities. Graphical method, numerical method and mathematical model are used to benchmark, design and optimise centralised utility system in multiple processes site. Several publications have studied multiple utility targeting with sensible heat in individual plant heat integration. However, most studies done in THSI do not account for the sensible heat for heating up the boiler feed water (BFW) to become steam. In this work, an organised methodology is developed for targeting the minimum utility requirement in a centralised steam system that involves the heating of BFW to saturated steam condition, as often encountered in the process plant with centralised condensate system. An extended Total Site Problem Table Algorithm (TS-PTA) is proposed as a systematic numerical tool for accounting the sensible heat while targeting the Total Site utility requirement. An illustrative example is used to verify the methodology developed, which shown 11 MW of heat has used for heating BFW. TS-PTA also shows that 7 MW and 81 MW of hot and cold utility are minimum required for the TS.

Keywords: Total Site Heat Integration; Pinch Analysis; Problem Table Algorithm; Sensible heat.

1. Introduction

Heat Integration by Pinch Analysis has been applied in the industry for more than 30 years. The increment of fuel price has highlighted the importance of using heat integration as a tool to improve the heat recovery in the heat exchanger network (HEN) of process industry. The implementation of fuel saving strategies has become more essential due to the negative environmental impact from carbon emission. Total Site Heat Integration – TSHI is developed by Dhole and Linnhoff (1993) and extended by Klemeš et al. (1997). The concept considers a site-wide heat integration approach via utility system and offers further energy conservation opportunities for process industry. Graphical tools are frequently used in the TSHI analysis, including Total Site Profile - TSP, Site Composite Curve - SCC, and Site Utility Grand Composite Curve – SUGCC (Klemeš et al., 2010). TSP shows the total heat source and heat sink available in the integrated Total Site (TS) system. SCC is constructed from the TSP by targeting the heat source to be contributed to the steam mains and the heat sink to be fulfilled by
steam mains. The minimum heating and cooling utility required by the TS is determined by SCC. SUGCC indicates the cogeneration potential of the site steam system. The minimum temperature difference ($\Delta T_{\text{min}}$) for graphical targeting methodology has been revisited by Varbanov et al. (2012). Their work suggested the use of different $\Delta T_{\text{min}}$ for heat transfer between processes and between process and utility.

A series of analogous numerical tools for TS targeting have been introduced (Liew et al., 2012). Total Site Problem Table Algorithm (TS-PTA) is proposed to target the minimum multiple utility requirements of the TS system. Total Site Heat Storage Cascade (TS-HSC) has been later introduced to assess the impact of plant operation changes towards the utility system. It also estimates the optimal capacity for utility generation system and determines the intake of external utilities (Wan Alwi et al., 2012). The previous works have only considered the latent heat of steam in the TS system, by assuming the TS has different level condensate treatment system and the condensate is vaporised directly from condensate temperature. However, in the case of site utility system with a centralised condensate system, all types of steam condensate are collected and directed into the same de-aeration tank to produce the BFW at low temperature. BFW is required to be heated up to its saturated temperature prior to the vaporisation. The inclusion of BFW and the corresponding requirement of sensible heat represent the TS problem in a more practical manner.

The extended TS-PTA in this work aims to account the sensible heat while targeting the multiple minimum utility requirements for a site utility system with centralised condensate system. It can also assist the designer to perform a preliminary assessment on the retrofit options of incorporating an individual level steam condensate system. This article is organised as follows. Section 2 describes the terminology behind the development of TS-PTA. Section 3 describes the details of the methodology. In Section 4, the proposed TS-PTA is applied on an illustrative case study to demonstrate its significance. Section 5 concludes the important finding of this research.

2. Terminology

The methodology is proposed for determining the TS multiple utility targets by including the previously neglected sensible heat. It is an extension of TS-PTA methodology. It is aimed to fulfil the heat sink from processes in first place. BFW is required to be heated up to the saturated temperature and vaporised by using the heat sources available in TS system as shown in Fig 1(a). The steam is condensed by supplying heat to the heat sink as illustrated in Fig 1(b). For example, 40 kW of steam is required for heating up process heat sink in Fig 1(b) at $T(\text{sat})$, around 48 kW of process heat source would be required for producing that amount of steam as in Fig 1(a). The sensible heat for heating up BFW would not be able to be used to heat up process heat sink. In short, the energy consumed for heating up the BFW water to the desired saturated temperature is an additional heat sink in the plant that needs to be satisfied by the heat sources. Thus less heat source would be available for producing steam.

The TS targeting becomes more challenging when the number of steam levels is more than one. Fig 2(a) shows the required multiple steam levels for heating up a process heat sink. Two steam headers are available in the TS system - Steam 1 and Steam 2. The simplified targeting of sensible heat and latent heat required for raising the needed steam is illustrated in Fig 2(b), in which the BFW is being heated up continuously into saturated vapour. However, the heat source at high temperature should be used to produce high pressure steam. The targeting of sensible heat for saturated Steam 1 could be divided into two parts. The BFW water for Steam 2 could be heated up together with
the BFW for Steam 1 to T(sat 2) by using low temperature heat source, as shown in Fig 2(c). The BFW for producing Steam 1 continues then to be heated up until T(sat 1) by heat source at higher temperature. This targeting method would decrease the utility requirements at high temperature. However, the heat recovered with lower temperature difference would increase the heat transfer area required by heat exchanger.

3. Methodology

The proposed methodology for targeting the minimum multiple utility requirements that accounts sensible heat for BFW is defined as below:

3.1. STEP 1: Total individual plant multiple utility targets determination

Starting with the total multiple utility targets from Site Source Profile and Site Sink Profile in TSP (Klemeš et al. 1997). An alternative approach is using a numerical method, Multiple Utility Problem Table Algorithm - MU-PTA (Liew et al., 2012). The heat sink represents the heat required to heat up process streams. The minimum amount of heat required for the processes is determined through multiple utility targets. The available heat source is determined based on temperature of utility available. The heat would be used to heat up BFW or vaporise BFW at saturated temperature.

3.2. STEP 2: TS multiple utility targets determination

This methodology is an extension from TS-PTA, with the incorporation of additional steps to obtain sensible heat to heat up BFW toward its saturation temperature.

a) Determining the net utility requirement for different type of utility

Total multiple utility targets from all individual plant are listed as heat sink and source in the TS-PTA (Column 3, 4 of Table 2). The targeted utility above the Pinch is a heat sink that requires heating by hot utility. Heat sources located below Pinch temperature require cold utility.
b) Determining the minimum steam flow

The required steam flow to satisfy TS heat sink is determined in this step based on the MU targets on heat sink. The steam flow rate (F) is obtained by dividing the targets (H_{sink}) with the heat of vaporisation (h_{fg}) of steam at respective utility condition as shown in Equation (1)

\[ F = \frac{H_{sink}}{h_{fg}} \]  

(1)

c) Identifying additional heat sink

This is a newly developed step in TS-PTA. The additional heat sink includes the sensible heat of different types of steam level. The sensible heat of steam is segregated into different segments by depending on the temperature level, to ensure the heat source is being utilised efficiently. Otherwise, the huge temperature difference in the heat exchange process can lead to energy wastage, as described in Section 2. Eq (2) is used for determining the segregated sensible heat required for heating up BFW.

\[ H_i = \sum_{i=1}^{j} F_i C_{pi}(T_i - T_{i-1}) \]  

(2)

Where

- \( H_i \) = Sensible heat of steam at temperature level \( i \) [kW]
- \( F_i \) = Flow rate of required steam at temperature level \( i \) [kg/s]
- \( C_{pi} \) = Heat capacity of water at temperature between temperature level \( i \) and \( i-1 \) [kW/(kg/s)/°C]
- \( T_i \) = Temperature level \( i \) [°C]
- \( T_{i-1} \) = Temperature level \( i-1 \) [°C]

d) Targeting TS multiple utility requirement

The net utility requirement (Column 6 of Table 2) at different utility level is determined by computing the differences between the heat source (Column 3 of Table 2) and heat sink (Columns 4, 5 of Table 2) as done in TS-PTA. The calculated final net heat is then cascaded from the highest utility level towards the lowest utility level. Multiple utility cascade is then performed to determine the minimum utility requirements (Column 10 of Table 2). The heat at above TS pinch is cascades from highest level towards the Pinch. External utility is added when there is a energy deficit, which denoted by the negative value in the cascade to obtain “zero” cascade. At below TS Pinch, multiple utility is cascaded from the lowest level towards the Pinch. Cooling utility (negative value) is added when there is positive value appears in the cascade. The detail explanation can be found in Liew et al. (2012).

4. Illustrative Case Study

The case study consists of a simplified industry process data to illustrate the proposed algorithm. The TS system has three types of steam available, which are High Pressure Steam (HPS), Medium Pressure Steam (MPS) and Low Pressure Steam (LPS). Other available utilities on the site are in Table 1. The steam properties for HPS, MPS and LPS are also identified in Table 1. The sensible heat is determined by calculating the enthalpy difference between BFW and saturated liquid, while the heat capacity (Cp) is identified by dividing the calculated sensible heat with the temperature difference between BFW and saturated steam.

The work starts by identifying the total heat source and sink at different temperature levels for the TS. Table 2 shows the extended TS-PTA with the inclusion of sensible heat of steam production from BFW. MU-PTA is used in this case study to identify multiple utility for all individual process. The summation of heat source and sink are calculated based on different type of utility levels (Columns 3, 4 of Table 2). The methodology is aimed to satisfy the heat sink by heat source. To prevent the excess
production of steam, the flow rate of minimum steam requirement (Column 2 of Table 2) is determined by available heat sink using Eq (1).

**Table 1. Utilities temperature and pressure**

<table>
<thead>
<tr>
<th>Type of Utility</th>
<th>Temp. °C</th>
<th>Pres. bar</th>
<th>Cp (liq) kW/(kg/s)/°C</th>
<th>h_fg kW/(kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure Steam (HPS)</td>
<td>275</td>
<td>58.4</td>
<td>4.3951</td>
<td>1574.52</td>
</tr>
<tr>
<td>Medium Pressure Steam (MPS)</td>
<td>200</td>
<td>17.8</td>
<td>4.0538</td>
<td>1938.02</td>
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<tr>
<td>Low Pressure Steam (LPS)</td>
<td>130</td>
<td>2.70</td>
<td>3.1895</td>
<td>2173.70</td>
</tr>
<tr>
<td>Boiler Feed Water (BFW)</td>
<td>125</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tempered Water (TW)</td>
<td>45-70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling Water (CW)</td>
<td>30</td>
<td></td>
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</table>

The sensible heat for heating up the BFW to its saturated temperature is calculated and tabulated as the “additional heat sink” (Column 5 of Table 2). Eq (2) is used to determine the required sensible heat between two temperature levels to produce a specific type steam. In this paper, two temperature levels of steam are produced from BFW, i.e., MPS and HPS. For both the production of MPS and HPS, additional heat is required at temperature level of MPS to heat up the BFW into the steam at MPS temperature level. In the case of HPS, the additional heat is required at the HPS temperature level to heat up the steam to achieve HPS temperature. At such, Eq (3), (4) and (5) are derived from Eq (2) to account the additional heat sink at MPS and HPS temperature level. The result shows 4.0 MW of HPS, 6.3 MW of MPS and 0.6 MW of LPS are consumed in heating up BFW to achieve its desired temperature.

\[ H_{LPS} = F_{LPS} \cdot C_{P,LPS} \cdot (T_{LPS} - T_{BFW}) + F_{MPS} \cdot C_{P,MPS} \cdot (T_{LPS} - T_{BFW}) \]

\[ H_{MPS} = F_{MPS} \cdot C_{P,MPS} \cdot (T_{MPS} - T_{LPS}) + F_{HPS} \cdot C_{P,HPS} \cdot (T_{LPS} - T_{LPS}) \]

\[ H_{HPS} = F_{HPS} \cdot C_{P,HPS} \cdot (T_{HPS} - T_{MPS}) \]

**Table 2. TS-PTA for the case study**

<table>
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<tr>
<td>HPS</td>
<td>275</td>
<td>12.25</td>
<td>30,213</td>
<td>19,291</td>
<td>4,039</td>
<td>6,884</td>
<td>1,931</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>6,884</td>
<td>13,987</td>
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<td>0</td>
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<td></td>
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<tr>
<td>MPS</td>
<td>200</td>
<td>9.06</td>
<td>11,842</td>
<td>17,557</td>
<td>6,340</td>
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<tr>
<td>LPS</td>
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<td>10.48</td>
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<td>22,781</td>
<td>620</td>
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<td></td>
<td></td>
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<td>74,101</td>
<td>81,204</td>
<td>0</td>
</tr>
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</table>

The final net heat available in TS is computed by deducting the heat sink from heat sources. The initial and final heat cascade (Column 7, 8 of Table 2) are constructed to obtain the location of TS Pinch point, the minimum hot and cold utility requirement. The results show that the TS Pinch is located between the LPS and TW. Hot utility of 7.1 MW and 81.2 MW of cold utility are required the TS system in this case study.
Hot utilities at higher temperature level are usually more costly compared to the hot utilities at lower temperature level. Multiple utilities cascade is performed to determine the amount of different types of utility. For above Pinch, it is done by cascading the utility from higher temperature to lower temperature level. For below Pinch, the utility is cascaded from lower temperature to higher temperature level. The final cascade consists of 5.2 MW of MPS and 1.9 MW of LPS as shown in Column 10 (Table 2). The cool requirements in the TS are 76.5 MW of TW and 4.7 MW of CW. The result also shows that the accounted additional heat sink is more than the final heating utility required. In addition, the utility consumed for satisfying sensible heat of BFW is located at higher utility level compared to the final multiple hot utility requirements. Hot utility consumption could be eliminated if the current steam system is changed to individual level condensate treatment system. In the case of excess steam, the steam could be further utilised to generate power. Alternatively, the steam generated from the boiler could reduce the fuel gas cost, subject to the economic feasibility of each retrofit option.

5. Conclusion
TS-PTA has been extended to target the steam production for a site utility system that incorporated with centralised condensate system. The proposed methodology is simple and accurate in accounting the additional heat sink, i.e., sensible heat, while targeting for the TS multiple utilities requirement. The tool plays an important role in retrofitting process plant that involves, the heating of BFW by process heat, as often encounter in the centralised condensate system. The application of the proposed tool on the case study reveals that 13.6 MW of heat is consumed for sensible heat, which is more than the utility required by the TS after TSHI.

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