CHEMICAL ENGINEERING TRANSACTIONS Volume 21, 2010
Editor J. J. Klemeš, H. L. Lam, P. S. Varbanov
 ISBN 978-88-95608-05-1 ISSN 1974-9791
DOI: 10.3303/CET102100153

Steam Optimization with Increased Flexibility in Steam Power Island Design

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The importance of the steam island design on steam optimization using site composite curves is demonstrated. Fixed steam headers such as assumed in total site analysis give no allowance for reheating before turbine expansion, which can be valuable to consider when optimizing steam for certain plant configurations. In this work, the effect of reheating, preheating and superheating steam on the shape of the steam composite curve is assessed. By including each heating segment in the steam composite curve, there can be better thermal matching between the process and steam curves in order to improve overall efficiency while minimizing cost. A case study using an IGCC plant with carbon capture is analyzed to assess changes in steam cycle design on the plant efficiency and cost.

1. Introduction

Design of the utility system for a plant is important for any chemical, power or cogeneration plant. Steam is often used to meet the process heating or cooling requirements or used as a medium to transfer heat between processes. Therefore, continued efforts have been placed on optimum steam generation to make plants more efficient, which in turn reduces fuel consumption and increases power generation.

The heating curve followed by water from the pump exit to its final state at the inlet of a turbine requires sensible and latent heating, i.e. water is preheated, boiled and superheated. As steam follows this heating curve, it flows from one heat exchanger to the next, defining the steam path. How cost effective a specified steam path is depends on a balance between the temperature driving force and heat exchanger area. Furthermore, the design of the steam island has an important impact on plant efficiency.

Previous work has examined heat exchanger network synthesis while minimizing the utility system cost using graphical and mathematical techniques. Graphical techniques include pinch analysis (Linnhoff, 1982), and total site analysis (Dhole and Linnhoff, 1993, Klemeš et al., 1997)

In all these methods, steam pressure levels were represented graphically as a constant temperature “plateau” at its saturation temperature. Furthermore, in total site analysis, steam headers of fixed pressure and temperature limit the possible configurations of the steam power island. This work demonstrates the importance of the steam island layout and relaxes the constraint that steam be limited to the headers interacting with each

Please cite this article as: Botros B. B. and Brisson J. G., (2010), Steam optimization with increased flexibility in steam power island design, Chemical Engineering Transactions, 21, 313-318 DOI: 10.3303/CET1021053

process individually but instead, can pass between heat exchangers as it increases or decreases in temperature. This will also require that steam levels not to be approximated as constant temperature plateaus, but including the sensible heating of steam as well the composite curves. The implications of including preheating and superheating makes better use of low temperature waste heat and finds a more accurate lower bound of what heat must be rejected to cooling water.

2. Steam Generation

To target the desired steam configuration in a plant, the entire water/steam isobar is included in the balanced composite curve of the plant, i.e. the subcooled water, boiling and gaseous segments. The approximation of using constant temperature plateaus to represent each steam level breaks down at high pressures, since more heating is required in the sensible heating or cooling of steam than in the latent heat. In Figure 1, the percentage of the total heating required to preheat, boil and superheat steam from 30°C to a given superheat temperature is calculated at different pressures. The maximum superheat temperature for each pressure level is found by taking high pressure (HP) steam at 12.5 MPa and 600 °C (close to current material constraints) and expanding it to sequentially to each pressure level. As can be seen in Figure 1, heat for preheating and superheating is comparable to heat required for boiling at high pressures.

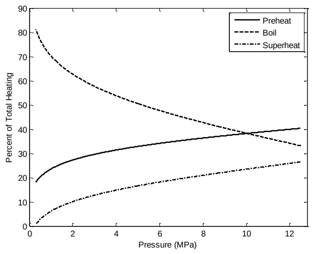


Figure 1 Percent of total heating required to preheat, boil and superheat stream from 30 °C to a desired superheat temperature.

It is important to consider the preheating and superheating segments in the steam curve because of its affect on the heat exchanger network area, because of the differences in the heat transfer coefficient. Advantages of including preheating and superheating in the steam curve are as follows. First, there is better thermal matching of process streams with steam to reduce entropy generation in the heat exchanger. Thermal matching refers to maintaining a constant temperature difference (and as small as possible) between two streams along the length of the heat exchanger. Second, the steam path through the plant is taken into consideration. The composite curve will give the best target of how water can be routed through the plant to pick up waste heat as it is preheated, evaporated and then superheated. This better utilizes waste heat and makes more efficient use of high temperatures such as those available in a heat recovery steam generator (HRSG), since water may be heated to its saturation temperature and potentially evaporated by waste heat streams before entering the HRSG. The HRSG can then be used for high temperature evaporation and/or superheating.

Third, different designs of the steam power island can be considered when forming the steam composite curve, leading to greater efficiency. In the T-ΔH diagram of Figure 2, high pressure (HP) and intermediate pressure (IP) steam are both generated by process heat and are superheated to points 1 and 3 respectively. Both steam levels can be expanded to a lower pressure (not diagrammed here) or HP steam can be expanded to the IP level to mix at point 2 before the combined stream is heated to point 4. Note that the x-axis of the figure is total enthalpy, so that the addition of mass flow at point 2 causes the slope to become shallower (line 2-4) compared to the case if the HP steam were not expanded to the IP level (line 2-3). Depending on the shape of the process composite curve on a T-ΔH diagram, the different slopes in the steam curve that are obtained from flexibility in the steam power island can lead to better thermal matching and recovery of process heat.

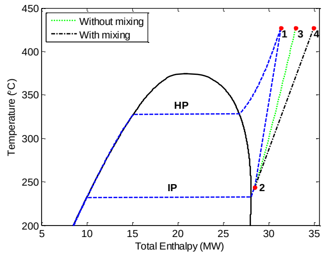


Figure 2 Both HP and IP steam are generated and superheated to points 1 and 3 respectively. HP steam can also be expanded to the IP level to mix at point 2 with generated IP steam, and both streams are heated together to point 4.

In total site analysis, steam headers are assumed to have a fixed superheated temperature and pressure. The thermodynamic state in each steam header is defined by the exit state of the turbine linking the two headers, and can be diagrammed on a temperature-entropy (T-S) diagram as in Figure 3a. In contrast, the steam power island can take various different forms as in Figure 3b,c. In Figure 3b, HP steam is expanded and mixes with IP steam at point 2 and then reheated together to the same maximum temperature as HP steam. In Figure 3c, all streams experience a certain degree of reheat. The steam turbine efficiency is 85 % in all cases. Note that reheat requires more steam piping complexity as opposed to using fixed headers, but if a heat exchanger network can be well-designed, the implication of doing can lead to improved plant efficiency.

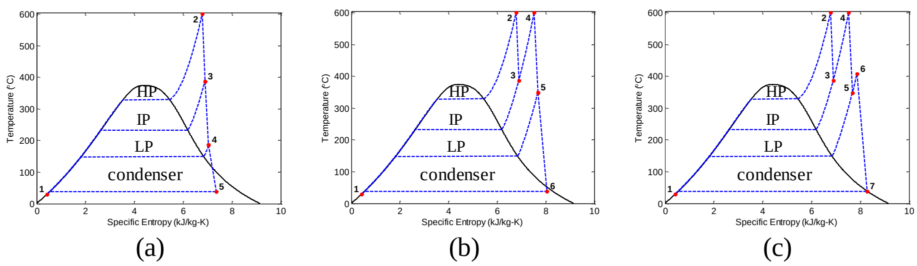


Figure 3 Temperature-Entropy diagram of steam with three steam island configurations (a) No Reheat of IP or LP steam, (b) Reheat of only IP steam, (c) Reheat all

3. Optimization Technique

The optimum steam cycle design will maximize profit. The capital cost of the utility system is considered here to predominantly consist of the cost of the turbines and heat exchangers, while revenues are generated from the work output. The profit per year is:

$$\text{Profit per annum} = W_{gen} * COE - \text{Annualization factor} * \left(C_{HEN} + C_{turb}\right) \quad (1)$$

The first term in equation (1) represents the revenue for generating electricity from power generation, where W_{gen} is the work generated in kWh over one year, and COE represents the cost of electricity per kWh. The second term represents the annualized capital cost of the heat exchangers and the turbines. For the purpose of this work, the assumption is a fixed fuel input, i.e. fixed processes for which we are determining the best steam cycle design to match it.

To choose the optimum steam cycle design, the first step requires forming composite curves of the plant to assess the heating and cooling requirements. Then, multiple steam utility systems can be designed and assessed against each other. Decisions in the steam cycle design include: number and pressure of the steam levels, the degree of superheat or reheat and the turbine layout. In order to select possible steam turbine layouts, a method similar to that outlined by Raissi (1994) can be applied to choose between backpressure or condensing turbines, turbines in sequence or in parallel, extraction turbines or a let-down valve if this reduces capital costs.

The steam heating and cooling curves from each cycle are used to form balanced composite curves. The mass flow rates of steam are varied until the desired pinch point temperatures are achieved. Finally, the targets for the work output, the area of the heat exchanger network, and the cost of the turbines can be calculated, and the most profitable steam cycle design selected.

4. Case Study

An IGCC plant with carbon capture is used to demonstrate efficient steam generation. The layout of the IGCC plant is based on the data from Case 2 (GE Gasifier with carbon capture) of NETL report by Woods et al. (2007). There are predominantly more heat sources than heat sinks in the plant, resulting in steam generation. The system was modeled with Aspen Plus 2006.5 software, and heat transfer coefficients were obtained by exporting the model to Aspen Hx-Net 2006.5. The plant has a net work output of 540 MW, a steam work output of 276 MW, and overall plant efficiency of 31.6 %.

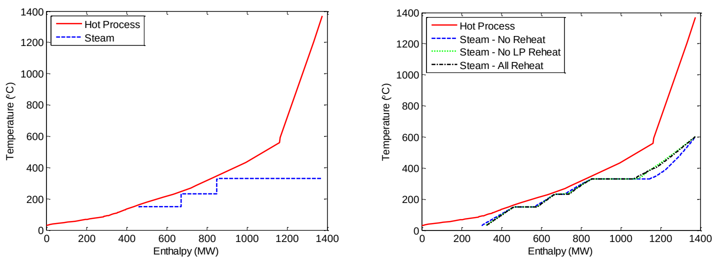
To demonstrate the importance of using preheating and superheating of steam in the composite curve, cold process streams will first be neglected, and steam will be the only cold sink in the system. The steam pressure levels are taken to be: high pressure (HP) of 12.5 MPa, intermediate pressure (IP) of 2.9 MPa, and low pressure (LP) of 0.45 MPa. To compare previous methods to the current approach, three ways to model the steam cycle will be explored:

1. Steam levels modeled in the composite curve as constant temperature plateaus based on saturation temperature – as modeled in works by (Linnhoff, 1982, Linnhoff, 1993, Dhole and Linnhoff, 1993, Klemeš et al., 1997, Raissi, 1994)

2. Headers of fixed temperature and pressure (as in Figure 3a) – assumed in total site analysis, but steam sensible heating was not assessed (Klemeš et al., 1997, Raissi, 1994).
3. Flexibility in steam island design, where streams can be reheated before expanding again (as in Figure 3b,c) – method advocated here.

The results of the first model are given Figure 4a while the second two are plotted together in Figure 4b, following the same steam cycle designs of Figure 3. The heat that that is not used for steam generation will be rejected to cooling water. The pinch temperatures for HP, IP and LP steam are 20°C, 15°C and 12°C respectively. The turbine efficiency in all methods is 85%. The method presented by Dhole and Linnhoff (1993) is used to calculate the work output for Figure 4a, with an exergetic efficiency of 85 %. The condenser pressure for all cases is 7 kPa.

Cold process streams can also be included in the cold composite curve with the same steam cycle designs and pinch temperatures, which results in reduced steam generation and less work output. The work output, heat exchanger network area and profit are given in Table 1. The approximation of the steam curve with constant temperature plateaus results in a lower target for both the work output and the HEN area than including the sensible heating of steam in the composite curve. Interestingly, when some reheat is experienced by either IP or both IP and LP steam, the work output of the steam cycle goes up while the area goes down. The reason for this can be seen in Figure 4. With reheating, the slopes of the curves near the pinch points become steeper causing the two curves to move further apart, reducing the area, even though the hot and cold curves get closer together at high temperatures. The dominant effect of the change in slope near the pinch points causes a net decrease in HEN area.



(a) (b)

Figure 4 Composite curves with (a) steam approximated by its saturation temperature, (b) steam composed of preheating, boiling and superheating.

The case of reheating all steam pressures in this example was not desirable. The work output decreased slightly because more process heat was being used to heat LP steam. The HEN area, however, decreased due to an increasing slope near pinch points although this did not offset the decreased revenue from work output, resulting in a net decrease in profit.

Note that the design of the steam cycle design could have taken a number of different configurations and be comparatively assessed to determine the optimum steam cycle design. The next step is to build a heat exchanger network that would consider utility streams with both sensible and latent heats, either by heuristic methods or mathematical optimization.

Table 1 Targets for an IGCC plant with carbon capture with various steam cycle designs. (The improvement in efficiency is relative to the base value of 31.6 %).

	Work (MW)	HEN Area (m^2)	Profit (M$/y)	η points Improvement
Steam Only				
Plateau Approx.	319.05	5.35e5	244.62	2.52
No Reheat	378.72	8.06e5	288.03	6.01
No LP Reheat	383.86	7.65e5	293.46	6.31
All Reheat	381.78	7.52e5	292.19	6.19
Cold + Steam				
Plateau Approx.	310.34	6.19e5	236.16	2.01
No Reheat	362.27	8.74e5	271.82	5.05
No LP Reheat	368.22	8.19e5	278.39	5.39
All Reheat	366.50	8.08e5	277.46	5.29

5. Conclusion

The goal of the current method is to determine the best design of the steam utility system. Including the sensible heating and cooling of steam in composite curves instead of the latent heating alone results in more accurate cost targets. It takes into account the layout of the steam power island and its effect on the steam composite curve, leading to better optimization of the steam cycle. A method to assess different steam cycle designs was applied to an IGCC plant with carbon capture to show that superheating not only increases work output, but has the effect of reducing the HEN area due to changes in slope of the composite curve.

6. Acknowledgements

The authors would like to thank Randall Field and Robert Brasington (MIT), as well as David Byard and George Huff (BP) for their insight and support. This project was conducted as a part of the BP-MIT Conversion research program.

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