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Using Process Integration for Steam System Network Optimization with Sustained Boiler Efficiency

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Abstract

The traditional steam system comprises of a steam boiler and the associated heat exchanger network (HEN). Most research published in literature tends to address both the elements of the steam system as separate entities instead of analyzing, synthesizing and optimizing the overall system in a holistic manner. This paper presents a process integration technique using conceptual and mathematical analysis without compromising boiler efficiency. It was found that the steam flowrate could be reduced whilst maintaining boiler efficiency by utilizing sensible heat from the high pressure steam leaving the boiler. In the event of too little sensible energy being available a compromise in either minimum steam flowrate or boiler efficiency must be made.

Keywords: steam system, heat exchanger network, boiler efficiency

1. Introduction

Pinch analysis has found numerous applications in a wide range of process integration areas, most specifically mass and heat integration. In heat integration, pinch analysis has the ultimate goal of reducing external utilities by maximizing process to process heat exchange but can also be used in the optimal placement of utilities (Linnhoff and Hindmarsh, 1983).

The work on steam network synthesis by Coetzee and Majozi (2008) encompasses finding a minimum steam flowrate for the steam system and designing the corresponding HEN. The authors presented two methods, the first involved a graphical targeting technique as well as a mathematical LP model for the network design. The second method constituted an MILP model that targeting minimum flowrate and designing the network simultaneously.

However, the effects of minimising the steam flowrate on the entire steam system have not been considered. The efficient operation on the steam boiler is dependent on the condensate return flowrate and temperature. Reducing the steam flowrate affects both of these areas. The advantages of reducing the steam flowrate in steam systems include decreased water consumption in retrofit operations and a smaller boiler for the grassroot design of plants.

2. Problem Statement

The problem addressed in this investigation can be formally stated as follows.

Given:
a steam boiler with known efficiency,
a set of heat exchangers directly connected to the boiler with limiting temperatures and fixed duties,
steam turbines with fixed power output and
background heat exchangers directly connected to the steam turbine exhaust,

determine the minimum steam flowrate and corresponding HEN while maintaining boiler efficiency. In the event that the minimum steam flowrate cannot be achieved without compromising the boiler efficiency two situations arise. Firstly the boiler efficiency is maintained whilst the minimum steam flowrate is compromised slightly or secondly the minimum steam flowrate is achieved at the expense of the boiler efficiency.

3. Paper Approach

Figure 1(a) shows a typical steam system. Superheated high pressure steam is produced inside the steam boiler. A portion of this steam is sent to a high pressure steam turbine where energy is recovered in the form of shaft work. The rest of the steam from the boiler is sent directly to a process through a let down valve for pressure reduction and to remove the sensible heat.

3.1. Boiler Efficiency

Equation (1) relates boiler efficiency, η_b, to the effects of changing steam load, capacity and operating conditions as would be encountered in a realistic situation (Shang and Kokossis, 2004).

$$\eta_b = \frac{q\left(M/M^{\max}\right)}{\left(c_p \Delta T_{sat} + q\right)\left[(1+b)\left(M/M^{\max}\right)+a\right]} \tag{1}$$

In Equation (1), q is the heat load of the steam (i.e. the latent and sensible heat), M is the steam load raised by the boiler which consists of the condensate return from all the steam using processes in the system and M^{max} is the capacity of the boiler. The parameters a and b are taken from a study by British Gas in work done by Pattison and Sharma (1980).

3.2. Methodology

The first part of the objective is to reduce the steam flowrate to the HEN. The model from Coetzee and Majozi (2008) forms the basis of the work presented in this study. The model comprises simple mass and energy balances based on a supersturcture found in the work by Coetzee and Majozi (2008).

To calculate the boiler efficiency as defined in Equation (1) several variables are required. The outlet temperature of the process must be known and can be calculated by Equation (2). The return flowrate to the boiler form any heat exchanger *i* is represented by the two terms, FRS_i and FRL_i, the first being saturated condensate and the other subcooled condensate form the process. The total mass flow to the boiler, TS and M_{turb}, must be considered by Equation (3), where the temperature before preheating, T_{pump}, is also calculated. Using these variables the total return temperature to the boiler, T_{boil} can then be calculated with Equation (4). Then the efficiency can be calculated using Equation (5).

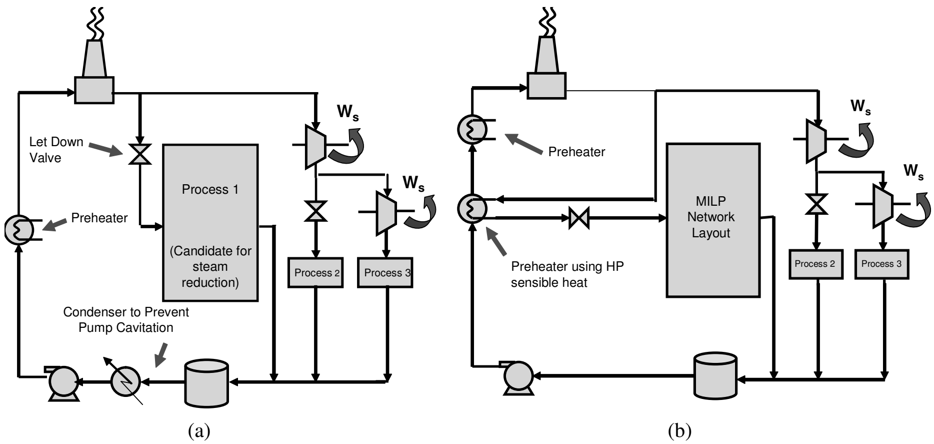

Figure 1: Steam system layouts.

$$T_{proc} = \frac{\sum_{i\in I} FRS_i Tsat + \sum_{i\in I} FRL_i Tout_i^L}{TS} \qquad (2)$$

In Equation (2), T_{proc} is the process outlet temperature.

$$T_{pump} = \frac{(T_{proc} TS) + (T_{turb} M_{turb})}{(TS + M_{turb})} \qquad (3)$$

In Equation (3), T_{turb} and M_{turb} are the turbine outlet temperature and mass flowrate respectively.

$$T_{boil} = T_{pump} + \frac{Q_{preheat}}{(TS + M_{turb})c_p} \qquad (4)$$

In Equation (4), $Q_{preheat}$ is the heat added by the preheater.

$$\eta_b = \frac{q\left((TS + M_{turb})/M^{\max}\right)}{\left(c_p(T_{sat} - T_{boil}) + q\right)\left[(1+b)\left((TS + M_{turb})/M^{\max}\right) + a\right]} \qquad (5)$$

Since the steam flowrate reduction causes a decrease in the return boiler temperature a means of reheating the boiler feed must be found. It is suggested that the boiler return condensate be heated by the sensible heat of the superheated steam from the boiler. In most instances this energy is lost during the pressure let down. Thus the energy can be reclaimed and used to maintain the boiler efficiency. Figure 1(b) shows a simple diagram of this alteration.

The new boiler return condensate temperature is calculated using Equation (6):

$$T_{boil} = T_{pump} + \frac{TS\left(h_{\mathrm{sup}} - h_{sat}\right)\theta}{\left(TS + M_{turb}\right)c_p} \tag{6}$$

In Equation (6), h_{sup} is the enthalpy of the superheated steam leaving the boiler, h_{sat} is the enthalpy of saturated steam at the boiler outlet conditions and θ is the fraction of this energy that can be used safely without the risk of condensation.

Equations (2) to (6) can be used to create a second part to the mathematical model, the first part being the formulation by Coetzee and Majozi, (2008). Two cases can be considered, each focusing on different objectives.

3.2.1. Case 1:Maintain boiler efficiency with slight compromise in minimum flowrate

Firstly the primary objective can be to maintain boiler efficiency. This may mean that the minimum steam flowrate may not be reached if there is not enough sensible heat available. The method of Coetzee and Majozi, (2008) is first used to find the minimum steam flowrate. The boiler efficiency is then fixed while the deviation from the minimum steam flowrate is minimised.

3.2.2. Case 2:Maintain minimum flowrate with slight compromise in boiler efficiency

Secondly the minimum flowrate must be achieved with the smallest possible decrease in boiler efficiency. The method of Coetzee and Majozi, (2008) is once again used to find the minimum steam flowrate. With this value fixed the deviation in boiler efficiency is then minimised.

3.3. Case Study

The case study presented by Coetzee and Majozi, (2008) is used here to show how boiler efficiency is affected by a reduction in steam flowrate and how the formulations above can be used to maintain the original efficiency.

Using Equation (5) the boiler efficiency was calculated as 0.6349. The HEN was a parrallel configuration. After steam reduction the steam flowrate was reduced from 10.90kg/s to 7.69kg/s. Figure 2(a) shows the network layout using this flowrate. This reduction in flowrate and consequently outlet temperature corresponds to a new boiler efficiency of 0.5991, a 5.6% reduction.

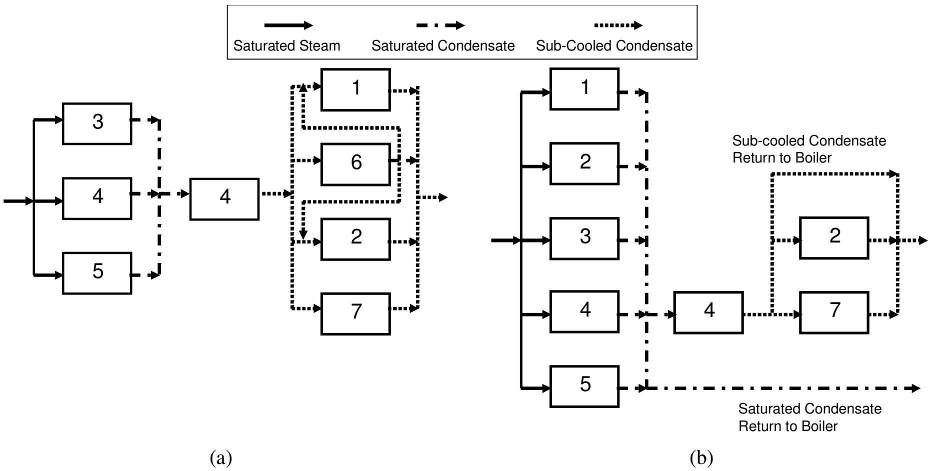

Figure 2: Network layouts obtained using the formulation.

Using the first premise it was found that the boiler efficiency could be sustained without compromising the steam flowrate by using 79.2% of the available sensible heat. With the reduction in steam flowrate, the return temperature had to be increased from 113°C to 117.7°C. Given that the steam flowrate was not changed the heat HEN remains as Figure 2(a).

Both formulations gave the same result since there was enough sensible energy available. If the amount of sensible energy was reduced the models may show how they compromise either efficiency or flowrate. For this purpose the amount of sensible heat available was reduced to 30% of the original available amount.

To maintain boiler efficiency the minimum steam flowrate was indeed compromised. The solution resulted in a flowrate of 8.32kg/s, which still yielded a 23.7% reduction from the original, parallel HEN. This new flowrate did require a new HEN to shown in Figure 2(b).

Using the second objective the new boiler efficiency was calculated as 0.6130, a decrease of 3.5%. The network required for this flowrate is the same as that of Figure 1(a), since there is no change in flowrate.

4. Conclusions

The following conclusions can be made about reducing steam flowrate while maintaining boiler efficiency:

Preheating the return flow to the boiler can maintain efficiency for a reduced steam flowrate.

In the event of there not being enough sensible heat available a compromise in either the boiler efficiency or the minimum flowrate must be made.

References

[1] Coetzee, W.A. and Majozi, T. (2008) Steam System Network Design Using Process Integration, Ind. Eng. Chem. Res 2008, 47, 4405-4413.

[2] Shang, Z. and Kokossis, A. (2004), A transshipment model for the optimisation of steam levels of total site utility system for multiperiod operation, Computers and Chemical Engineering 28, pages 1673-1688.

[3] Linnhoff, B. and Hindmarsh, E. (1983) The pinch design method for heat exchanger networks, Chemical Engineering Science 38, No. 5, pages 745-763.

[4] Pattison, J. R. and Sharma, V. (1980) Selection of boiler plant and overall system efficiency. Studies in energy efficieny in buildings, British Gas.