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Steam system design using a novel graphical targeting method and MILP model

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Abstract

Steam boilers are used to generate steam in order to meet cold process requirements. The most common steam heat exchanger network layout found on chemical plants is that of a pure parallel design which implies that each heat exchanger is directly connected to the boiler. This implies that the flowrate of steam needed for the system can be reduced, while maintaining the required duty, simply by changing the layout of the network. Phase change of saturated steam to saturated liquid plays a vital role in the targeting method as well as the design of the network layout. A graphical targeting method and a mathematical model have been developed to obtain the minimum steam flowrate, as well as the network layout. Furthermore, a mathematical model was developed which does the targeting and design simultaneously. Steam savings of 20.5% were obtained.

Keywords: steam boiler, graphical targeting, pinch technique, LP, MILP

1. Introduction

Very common in most chemical plants are process streams that need to be cooled or heated. To save on energy costs, heat is initially exchanged between hot and cold process streams via heat exchangers, and then cooling water and steam are used for the remaining process streams. Pinch Analysis [1] is commonly used in maximizing process-process heat integration, thereby minimizing external utility requirements. Most industries worldwide have adopted Pinch Analysis as the most powerful tool in achieving a design with optimal usage of external utilities. Cooling towers, steam boilers and process-process heat exchangers all form part of a heat exchanger network (HEN).

In the past minimization of the amount of the external steam needed in the system has been accomplished by optimizing the steam boiler, or optimizing each heat exchanger individually. However, in this work it is demonstrated that by optimizing the steam system as one entity instead of individual components, better results are obtained, as was proven by Kim and Smith [2] for cooling water system design.

The reduction of the steam flowrate also influences the capital cost of the steam boiler. When designing in the grass-root phase, reducing the steam flowrate results in the reduction of the capacity of the required steam boiler, thereby, directly reducing the capital costs of the HEN. For an existing HEN, reducing the steam flowrate (retrofit-design) debottlenecks the existing steam boiler, thereby, indirectly reducing the capital costs of the HEN in the case of future expansions.

The aim is to demonstrate that the steam flowrate can be significantly reduced by consideration of an integrated system.

2. Problem statement

The problem addressed in this paper can be stated as follows, given:

i) a set of heat exchangers,
ii) the fixed duties of each heat exchanger,
iii) the limiting data for each heat exchanger, and
iv) the minimum driving force ΔTmin for the overall network,

determine the minimum amount of steam required to satisfy the heat exchanger network, as well as the steam utility network layout without compromising the minimum heat duty requirement.

3. Methodology

Saturated steam is used first to transfer the latent heat to cold process streams. The resulting saturated liquid is then further used to transfer heat to the remaining cold process streams, together with re-use of hot liquid from other units. The hot utility curve is constructed using the ΔTmin, after which, graphical targeting for the minimum steam flowrate is done. Fig. 1 shows the combination of the saturated steam, saturated liquid and hot utility composite curve on a Temperature vs. Duty diagram. The energy supplied by the saturated steam as well as the saturated liquid is given by Eq. (1).

$$Q = m\lambda_v + mc_p\Delta T \qquad (1)$$

Where Q is the total energy supplied by the saturated steam and saturated liquid in kW
m is the water flowrate in kg/s
λ_v is the latent heat of vaporization of the saturated steam in kJ/kg
c_p is the specific heat capacity of the water in kJ/kg°C
ΔT is temperature difference in °C

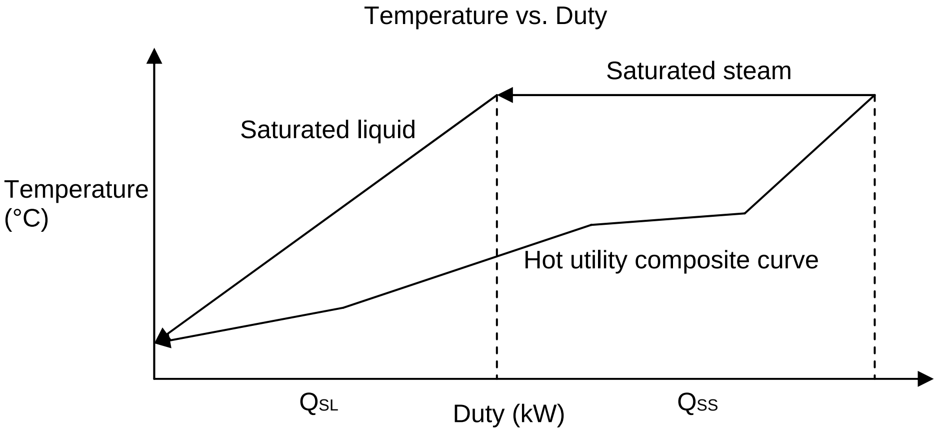

Figure 1: Targeting using saturated steam as well as saturated liquid.

After the steam target has been set, the heat exchanger network that meets the target is designed. As stated previously, saturated steam and saturated liquid are used as utilities in the HEN. Therefore, the diagram in Fig. 1 can be divided into four regions of interest as shown in Fig. 2. The composite curve divides the diagram into regions 1 and 2. Region 1 is a feasible region since all the utility streams within this region obey the thermal driving forces. Region 2, on the other hand, involves utility streams that violate the thermal driving forces and is, therefore, an infeasible region. The vertical dashed line separates the diagram into regions 3 and 4.

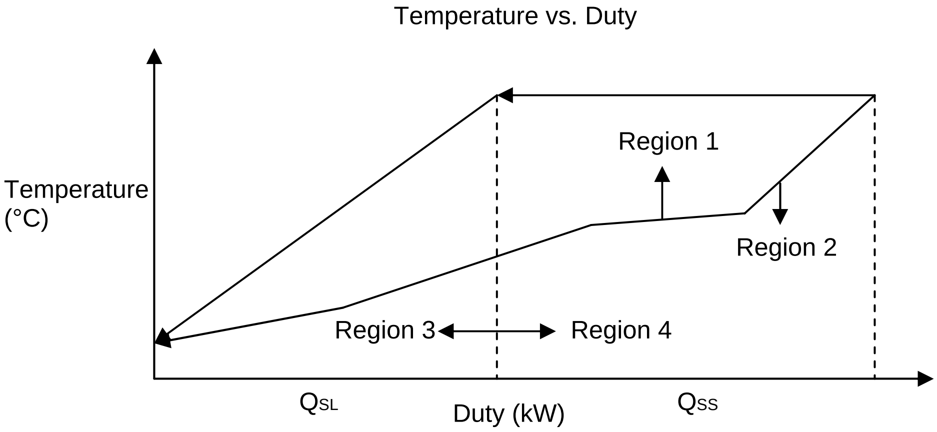

Figure 2: The four regions.

In region 3, heat transfer takes place through sensible heat whereas in region 4 heat transfer involves latent heat, i.e. phase change. By exploiting the structure of Fig. 2, a HEN that meets the target steam requirement can be developed.

In the region where only saturated steam is required, i.e. region 4, the layout will always be a parallel connection, therefore, one only needs to determine the layout of the rest of the heat exchangers for the saturated liquid region.

In the saturated liquid region the layout can be parallel, series or both. The Temperature vs. Duty diagram gives a visual representation of the targeted solution. However, the diagram does not show the layout of the HEN in the saturated liquid region. A mathematical model is then used to obtain the HEN layout in the saturated liquid region. The mathematical model, which is a linear programming (LP) model, entails mass and energy balances as well as design constraints that should not be violated.

A mathematical model can also be used to target for the minimum steam flowrate, as well as obtain a network layout for targeted value. The model developed for this, takes the form of a mixed integer linear programming (MILP) model. To prove the applicability of the developed methodology, an illustrative example will be used.

3.1. Illustrative example

The utility data is given in Table 1. Saturated steam is provided at 160°C (6.18 bar) with a latent heat capacity of 2081.3 kJ/kg. The specific heat capacity of the resulting saturated liquid is 4.22 kJ/kg°C. Fig. 3 shows the results of targeting using saturated steam, as well as saturated liquid.

Table 1: Utility data for the illustrative example.

Heat Exchanger	T_{supply}	T_{target}	**Duty (kW)**	**CP (kW/°C)**
1	45	30	300	20.0
2	135	100	450	12.9
3	68	45	250	10.9
4	120	90	159	5.30
5	120	38	600	7.32
6	110	85	350	14.0
7	160	80	270	3.38
Total			**2379**	**73.8**

If only saturated steam was used as a hot utility, i.e., assuming a parallel design, the flowrate would be 4.11 t/h. However, by using the methodology described above, the flowrate needed is only 3.26 t/h, reducing the original flowrate by 20.5%. After targeting for the minimum flowrate, the network layout was obtained by using the LP model, as seen in Fig. 4.

Note that heat exchanger 5 has been split, meaning that a part of the cold utility stream's duty has to be met by saturated steam, while the remaining duty is met by hot liquid. Whether a heat exchanger should be allowed to split is a decision that rests with the designer, since a split increase the capital cost of the network. It should be noted however, that by not allowing a split to occur, the flow rate of the steam increases.

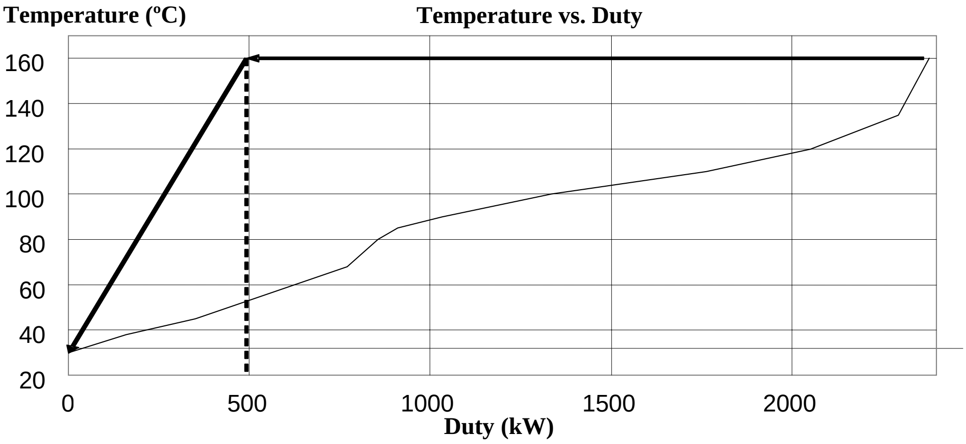

Figure 3: Targeting for the minimum steam flowrate.

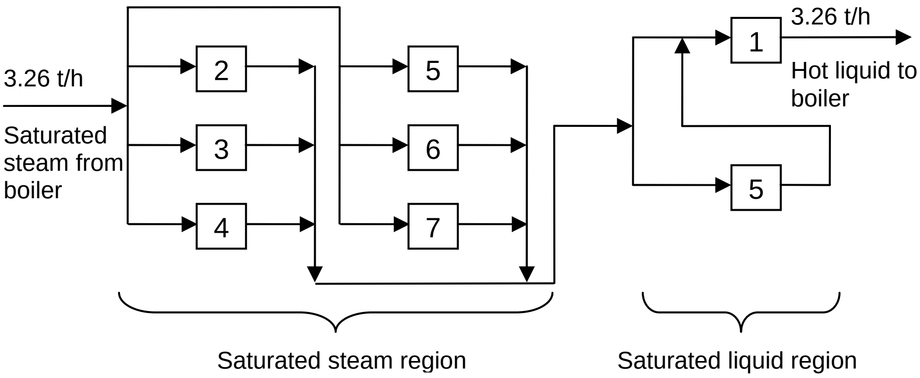

Figure 4: Network layout using the graphical method and LP model.

The MILP model resulted in the same flowrate of 3.26 t/h, although a different network layout was obtained.

4. Conclusions

The following conclusions can be made from the foregoing analysis:

- From the targeting, four regions are encountered, namely the feasible, infeasible, saturated steam and saturated liquid region.
- The heat exchanger layout in the saturated steam region will always be of parallel design.
- The heat exchanger layout in the saturated liquid region can be parallel, series or both.
- An LP model can be used to determine the network layout of the saturated liquid region.
- An MILP model can be used for targeting the minimum steam flowrate, as well as the network layout.

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