

Design Considerations In Steam System Debottlenecking Using Process Integration

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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. 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 linear programming (LP) model have been developed to obtain the minimum steam flowrate, as well as the network layout. Furthermore, a mixed integer linear programming (MILP) model was developed which does the targeting and design simultaneously. In an illustrative example, the steam flowrate was reduced by 20.5% using the graphical targeting method and LP model, as well as with the MILP model. However, by using the graphical targeting method, the designer gains more insight to the overall design as opposed to the MILP model which is treated as black box approach. Furthermore, the effect of pressure drop (in the pipes and heat exchangers) on the return temperature to the steam boiler was found to be that as the overall pressure drop increased, the return temperature became less than the value obtained from the graphical targeting method and the MILP model.

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 (Linnhoff and Hindmarsh, 1983) is commonly used in maximizing process-process heat integration, thereby minimizing external utility duties. Most industries worldwide have adopted Pinch Analysis as the most powerful tool in achieving a design with optimal usage of external utilities.

Methodologies developed thus far to further reduce the flowrate of the external utilities, for a fixed duty, have only catered in reducing the external cold utilities (Majozi and Moodley, 2007; Kim and Smith, 2001).

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 cost of the heat exchanger network (HEN). For an existing HEN, reducing the steam flowrate (retrofit-design) debottlenecks the existing steam boiler, thereby, indirectly reducing the capital cost of the HEN.

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 ΔT_{\min} 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 heat duty requirement of each heat exchanger.

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 reuse of hot liquid from other units. The hot utility curve is constructed using the ΔT_{\min} , after which graphical targeting for the minimum steam flowrate is done. Figure 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 Equation 1.

$$Q = \dot{m} \lambda_v + \dot{m} c_p \Delta T \quad (1)$$

Where Q is the total energy supplied by the saturated steam and saturated liquid in kW

\dot{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

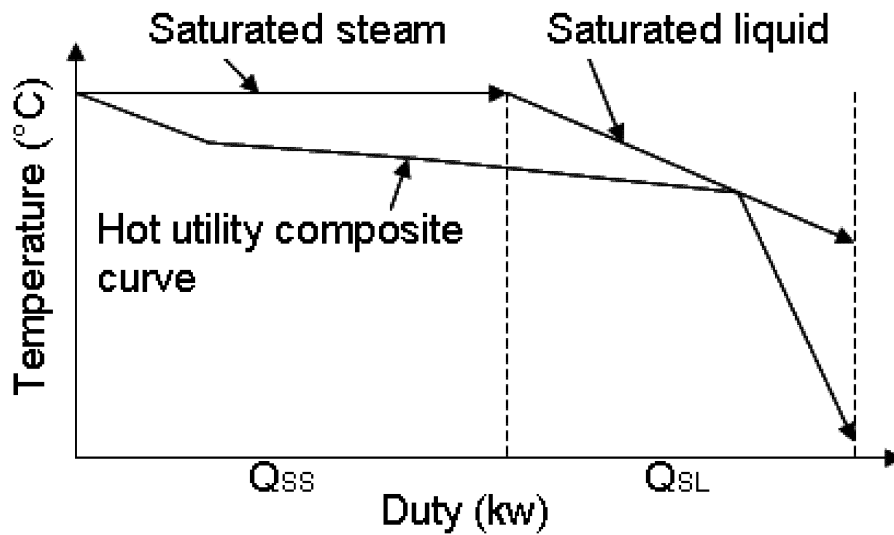


Figure 1: Targeting using saturated steam as well as saturated liquid.

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 Figure 1 can be divided into four regions of interest as shown in Figure 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.

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 Figure 2, a HEN that meets the target steam requirement can be developed.

It is evident that 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, i.e., region 3.

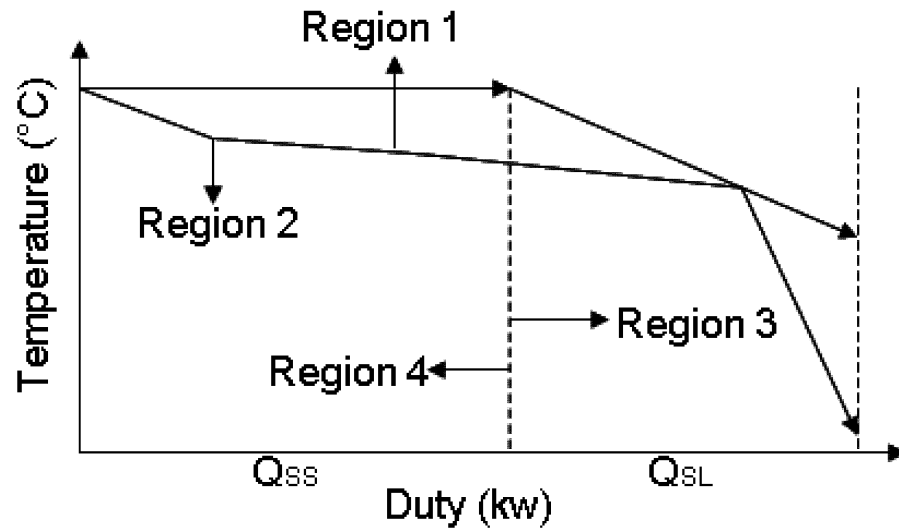


Figure 2: The four regions.

In the saturated liquid region the layout can be parallel, series or both. This can be problematic for the designer to try and find the layout that adjusts to the obtained flowrate. Furthermore, the Temperature vs. Duty diagram only gives a visual representation of the targeted solution; therefore, 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 simultaneously 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.

4. 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. Figure 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 Figure 4.

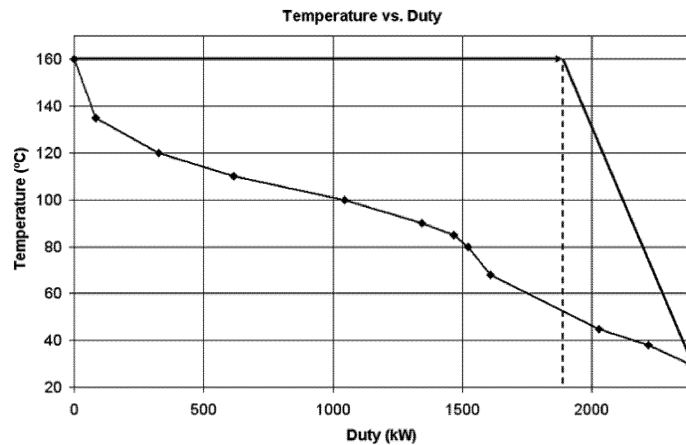


Figure 3: Targeting for the minimum steam flowrate.

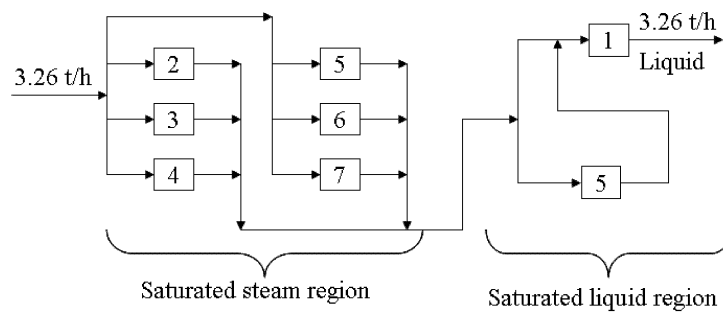


Figure 4: Network layout using the graphical method and LP model.

The MILP model resulted in the same flowrate of 3.26 t/h, although a different network layout was obtained. A simulated flow sheet using Aspen was obtained to see the effects of pressure drop on the return temperature to the steam boiler. It was found that as the pressure drop for the network increased, the return temperature to the steam boiler decreased to become less than the specified return temperature obtained by the graphical targeting method and the MILP model.

5. 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 HE layout in the saturated steam region will always be of parallel design.
- The HE 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.
- Pressure drop in the network decreases the return temperature to the steam boiler.

6. Acknowledgements

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7. References

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