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Improvement Approaches of Steam System Based on the Grand Composite Curves

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The steam system in petrochemical plants is composed of steam under various pressure levels. The imbalance between the demand and supply of steam at various levels generally exists, which causes large amount of steam transformed from the upper level to the lower one through the temperature and pressure reducing valves, and abundant low-pressure steam. Both of them result in the degradation loss of energy. In order to improve the steam system and to reduce the energy degradation loss, this paper analyses various situations of steam mismatch at different pressure levels by the Grand Composite Curve. By using the adjustable range of steam turbines as boundaries, the operation improvement and specific retrofit schemes, such as using steam turbines, steam ejectors, or absorption refrigeration, have been proposed to show the improvement opportunities for matching the demand and supply of steam at each level.

1. Introduction

A steam system is an important part of the utility system in a petrochemical process. It converts primary energy (fuel, etc.) into steam at different pressure, at the same time, generates power with the pressure difference. So the steam system in nature is a combined heat and power system. Safety and stable operation of a steam system are the basis of the enterprise's security, stability, long period operation. Whether the steam system is reasonable or not, determines the energy consumption level of the enterprise directly, and further affects the enterprise's economy. Therefore, improvement and efficient operation of the steam system play an important role in a petrochemical plant to reduce energy consumption and enhance economic efficiency.

A steam system is composed of steam under various pressure levels to meet the thermal demand at different levels. However, because most of petrochemical plants in China were built early and have been expanded many times, the steam system is not in the best match with the process system, which results in unreasonable utilization of energy. Such mismatch is mainly reflected in two aspects, one of which is that a large amount of steam is converted to the lower level by the temperature and pressure reducing valves, and the other is surplus low-pressure steam. These cause energy degradation. Therefore, effective analysis and improvement of the existing steam system is of great significance to improve the energy utilization efficiency of petrochemical plants.

Much work has been done for optimization and analysis of steam systems. Dhole and Linnhoff (1993) put forward total site profiles for the description of the process system and the utility system. By making use of Pinch Analysis of total site composite curves, Yin et al. (1999) proposed to increase steam levels above and below the original pinch point, to increase the heat recovery amount or the cogeneration capacity. The various uses of the Grand Composite Curves by developing the Pinch method were summarized and expanded, which has been extensively applied in many industrial to save energy problems (Kemp, 2007).

Papoulias and Grossman (1982) proposed a mathematical programming model to design utility systems and optimize the structure and parameters of flexible utility systems under uncertain demands. Iyer and Grossman (1997; 1998) established a MILP model for a steam system to optimize the operating parameters of the multi-period system. Francisco and Matos (2004) expanded the multi-period optimal design and operation model (MSOP), in which aiming at minimization of the investment, operating cost, and emission penalty cost, the environmental pollution caused by fuel combustion. Shang and Kokossis (2004) presented an optimization method for steam levels of a total site utility system satisfying varying demands, based on the total site profiles

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combined with the comprehensive boiler hardware model (BHM) and THM models, to estimate equipment efficiency. Luo and Hua (2009) established a large mixed integer linear programming (MILP) model for the flexible optimization design of a steam power system, on the goal of optimal synthesis of economy and operability.

He et al. (2000) analysed the modulability of a steam system with back pressure and condensing steam turbines based on the Grand Composite Curve, and pointed out that in the actual industrial process, the back-pressure steam turbine has high efficiency, but it has less flexibility. In order to determine the economic and reasonable range of a steam turbine, Wang et al. (2012) proposed an economic evaluation equation to determine the critical economic point of a turbine and discussed the change of the critical point at different price ratio of steam and electricity.

Modesto et al. (2016) has proposed the potential to increase electricity generation with backpressure steam turbine and condensing steam turbine in sugarcane cogeneration plants, also a cogeneration plant based on a BIGCC (Biomass Integrated Gasification Combined Cycle). Guo et al. (2017) proposed a data based leading factor modelling method of a steam turbine regenerative system, enabling the model to update operation data online, which can be used for power plant performance monitoring.

The existing researches on steam systems mainly aim at the following two aspects: (1) optimization of steam systems; (2) optimization of operation parameters under a certain structure of a steam system. Yu et al. (2014) analysed a refinery's steam system, and reformed the medium and low-pressure steam systems in the plant by reducing the steam pressure of steam turbines, optimizing the operation mode of boilers, optimizing the condensate recovery system to reduce energy consumption. However, the work was only effective for this refinery without general guiding significance.

The Grand Composite Curve is an intuitive tool to analyse the utilization of steam at various levels in a process system, because the Grand Composite Curve can express the ideal demand for steam of a process system clearly. Therefore, this paper uses the Grand Composite Curve as the tool to analyse the existing steam system and puts forward improvement opportunities. Specific measures to various cases of mismatched steam systems are proposed in order to reduce mismatch between the demand and supply of steam at each level. Similar study has not yet been reported.

2. Steam system

There are various steam levels in a steam system. In order to simplify the analyses and meanwhile, do not lose its generality, three pressure levels are considered in this paper: high pressure (HP) steam, medium pressure (MP) steam and low pressure (LP) steam. High pressure steam is produced by the boiler of the power plant. Some of high pressure steam is supplied to the users, the other enter the medium pressure steam pipeline through steam turbines and temperature and pressure reducing values. In addition to supplying medium pressure steam users, partial medium pressure steam is converted into low pressure steam through steam turbines and temperature and reducing pressure reducing values. Usually there will be waste heat recovery steam generators (HRSG) to produce low pressure steam. Figure 1 is a simplified structure of a steam system.

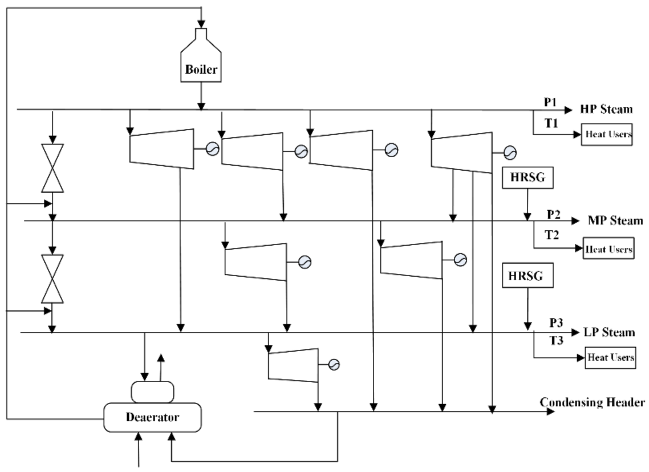

Figure 1: A simplified steam system structure

The upper part above the pinch point of a Grand Composite Curve indicates the ideal heat demand with temperature of a process system. In this paper, it is assumed that the heat exchanger network is reasonable, which means that the upper part of the Grand Composite Curve expresses the actual heat demand with temperature. In this way, the ideal amount of steam demand under different pressure levels can be determined by the Grand Composite Curve. Therefore, through the part above the pinch point of the Grand Composite Curve, the ideal amount of high, medium and low-pressure steam can be determined, as shown in Figure 2, where T is the temperature; H is enthalpy; HP, MP, and LP correspond to steams under T_1, T_2, T_3, and their steam volume is A, B, C, respectively.

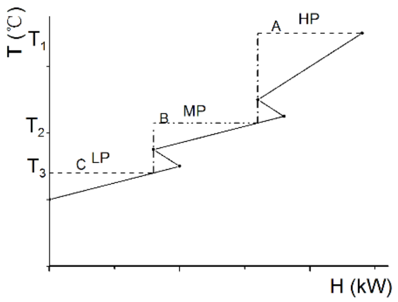

Figure 2: The ideal steam demand under different pressure levels determined by the Grand Composite Curve

The actual steam system is usually not in the ideal condition, often in which there are steam through temperature and pressure reducing values, and surplus steam exists. In order to improve the steam systems, the mismatch between the demand and supply of steam at each pressure level should be reduced.

There are three cases to be analysed in this paper: (1) no excess steam, only temperature and pressure reducing values exists; (2) there is excess steam, no temperature and pressure reducing values; and (3) there is excess steam and temperature and pressure reducing values.

3. Improvement of steam system in Case 1

Case 1 is the steam system only with temperature and pressure reducing values without excess steam, as shown in Figure 3. Figure 3(a) shows the steam system only with high-pressure temperature and pressure reducing value, named as case 1-I. The high pressure steam load through the valve is a. Case 1-II is the steam system with only medium-pressure temperature and pressure reducing values, and the steam load through the valve b. Case 1-III is the system with both high-pressure and medium-pressure temperature and pressure reducing values V_1, and V_2, and the steam load through V_1 is a, that through V_2 is b.

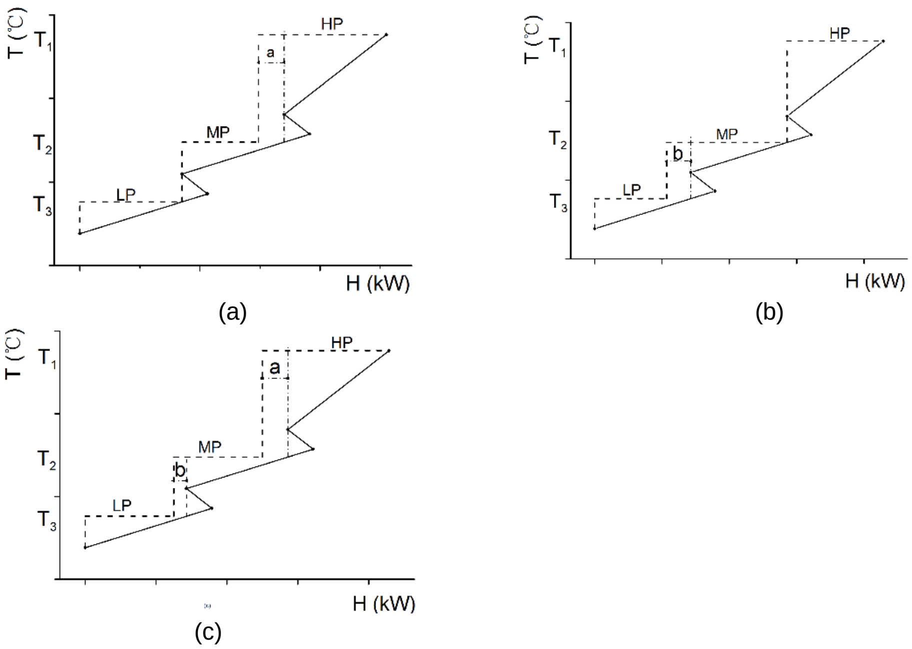

Figure 3: Steam system with temperature and pressure reducing values and without excess steam

When the steam load difference for supply and demand at each level is within the adjustable range of steam turbines, the operation improvement can be performed to achieve the optimal operating state. In case 1-I, the steam a through the temperature and pressure reducing value should be extracted from medium pressure after generating work in a steam turbine. In case 1-II, the steam b through the temperature and pressure reducing value should be extracted from low pressure after generating work in a steam turbine. In case 1-III, the steam a through the value should be extracted from medium pressure after generating work in a steam turbine, and meanwhile the amount of low pressure steam should be adjusted to meet the demand of low pressure steam users.

When the steam load difference for supply and demand at each level is beyond the adjustable range of steam turbines, system retrofit will be need. Back-pressure turbines can be used instead of the temperature and pressure reducing values to recover the energy loss caused by temperature and pressure reduction.

4. Improvement of steam system in Case 2

Case 2 is the steam system with excess steam and without temperature and pressure reducing values, as shown in Figure 4.

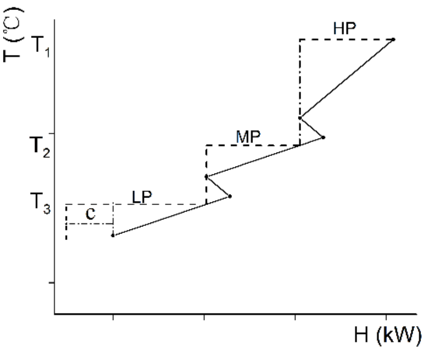

Figure 4: Steam system with excess steam and without temperature and pressure reducing values

When the steam load difference for supply and demand at each level is within the adjustable range of steam turbines, the steam system can be improved by reducing the intake quantity and the low-pressure extraction quantity c of the steam turbine, or by increasing the steam amount c in the condensing part of the steam turbine. The former will reduce fuel consumption as well as power generation, with the cold-end loss unchanged. Therefore the former has a higher energy efficiency and less economic performance than the latter. The latter can increase power generation, but the cold-end loss also is enlarged, so it has a lower energy efficiency but better economic performance.

When the excess load of low pressure steam c is larger than the adjustable range of steam turbines, which usually occurs when abundant low-pressure steam is produced by HRSG, especially in summer, the system needs to be retrofitted to recover energy by approaches are as follows: (1) using condensing steam turbines to generate work; (2) for domestic heating; (3) absorption refrigeration; (4) using steam ejectors to obtain the medium-pressure steam with the high-pressure steam as the driving steam.

Approach (1) has the highest investment cost, but is not restricted by seasons. Approach (2) should be given priority for its lowest investment cost. However, it is greatly influenced by seasons, whose heat load is large in winter and small in summer, and the excess heat is not recovered enough in summer. Approach (3) has higher investment cost. It is a good way when there is a stable cooling demand with not too low temperature (such as the temperature with air conditioning), otherwise the recovery would be limited by seasons when it is used only for living air conditioning. Approaches (2) and (3) can be combined to supply heating in winter and air conditioning in summer. For Approach (4), the investment cost is lower and not limited by seasons, but it is required that the high-pressure steam has a rich amount, and the reduction of the medium pressure steam is within the adjustable range of steam turbines

5. Improvement of steam system in Case 3

Case 3 is the steam system with excess steam and temperature and pressure reducing values, as shown in Figure 5. Case 3-I in Figure 5(a) is the steam system with excess steam and high-pressure temperature and pressure reducing value V_1, and the high pressure steam load through the valve is a. Case 3-II is the system with excess steam and medium-pressure temperature and pressure reducing value V_2, and the steam load

through the valve is b. Case 3-III is the system with excess steam and both high-pressure and medium-pressure temperature and pressure reducing values V_1 and V_2, and the steam load through V_1 is a, that through V_2 is b.
When the steam load difference for supply and demand at each level is within the adjustable range of steam turbines, the operation improvement can be performed to achieve the optimal operating state. In case 3-I, the steam load a through the value should be extracted from medium pressure after generating work in the steam turbine, meanwhile the amount of low pressure steam should be reduced. In case 3-II, the steam load b through the value should be extracted from low pressure after generating work in the steam turbine, meanwhile the amount of low pressure steam should be reduced. In case 3-III, the steam load a through the value V_1 should be extracted from medium pressure after generating work in the steam turbine, meanwhile the amount of low pressure steam should be reduced too.

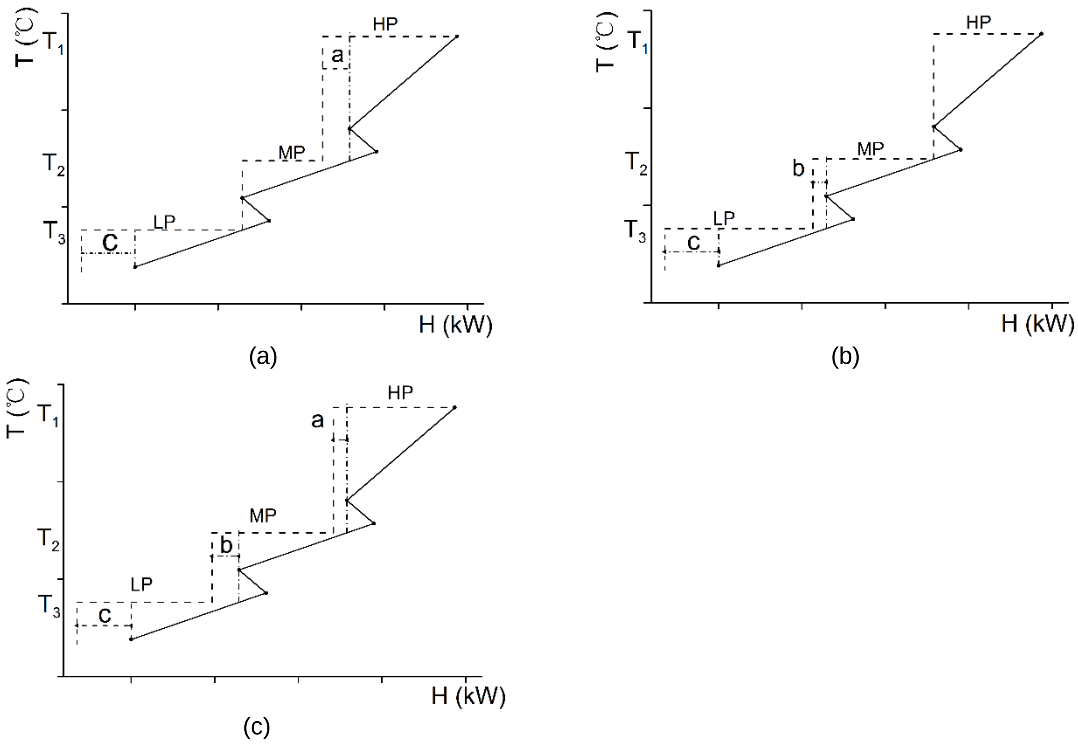

Figure 5: Steam system with excess steam and temperature and pressure reducing valves

If there is surplus low pressure steam after the adjustment, the improvement approaches at this time is similar to case 3, which is no longer repeated here. This situation is often found in enterprises with massive low-pressure steam from waste heat recovery.
When the steam load difference for supply and demand at each level is beyond the adjustable range of steam turbines, the ideal condition of the steam system cannot be achieved only by adjusting the intake and exhaust quantity of the steam turbines. The system needs to be retrofitted at this time. The improvement ways are as follows: (1) steam turbine scheme, that is, using back-pressure turbines to replace the temperature and pressure reducing values, and using condensing steam turbines to recover the energy of excess low-pressure steam; and (2) steam ejector scheme, that is, using ejectors to eject the excess low-pressure steam by using high-pressure steam through the temperature and pressure reducing values as driving steam, and obtaining the medium-pressure steam eventually.
Scheme 1 can fully recover the energy, but the investment cost is high. Although the investment of scheme 2 is low, the steam quantities at three pressure levels must meet a certain relationship determined by the steam ejector. Sometimes, the amount of high pressure steam through the value may be larger than the amount required, or the amount of high pressure steam through the value is not enough to eject the low-pressure steam. At the same time, due to the large increase of medium pressure steam, there will be another constraint that the amount decrease of medium pressure steam in turbines should be within the adjustable range.

6. Conclusion

The Grand Composite Curve represents the ideal demand for utility (steam in this paper) consumption at different temperature levels by the process system, so that it can clearly and intuitively describe the difference between the steam supply in the actual process and the one in the ideal situation. In this paper the Grand Composite Curve was used to analyze three possible kind mismatches for steam supply and demand at different pressure levels in existing steam systems.

The three cases are: (1) there is no excess steam, and only temperature and pressure reducing values exist in the steam system; (2) there is excess steam, but no temperature and pressure reducing values in exist in the steam system; and (3) there is excess of steam and temperature and pressure reducing values in the steam system.

System regulation should be considered first for no capital cost is needed, which includes adjusting the inlet, outlet and extracting steam amount of steam turbines. When the steam load difference for supply and demand at each level is beyond the adjustable range of steam turbines, system retrofit will be need. According to the qualitative analysis for each case, some suitable retrofit approaches were put forward, which might be adding new steam turbines, using steam ejectors, using absorption refrigeration, domestic heating, etc. The advantages and disadvantages of different measures were compared.

Acknowledgments

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