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# Application of pinch analysis in waste heat recovery system of slag dry centrifugal granulation

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ABSTRACT

The liquid slag of 1450°C has a massive output in the iron and steel industry, and its efficient recovery is an important measure to achieve energy saving and consumption reduction. At present, centrifugal granulation has become an essential means to recover high-temperature waste heat in the iron and steel industry. The recovery rate of waste heat and the reduction of energy consumption are the indexes to judge the system's advantages and disadvantages. The pinch analysis can optimize the heat recovery system and reduce energy consumption by calculating thermodynamically feasible energy targets (or minimum energy consumption). Aiming at the problem of waste heat recovery in the slag centrifugal granulation system design, the problem table method in pinch analysis method was used to analyze the design system's data to optimize the heat recovery system. This paper presented the corresponding material balance and energy balance and used the heat cascade table to extract and analyze the cold and hot material flows. Finally, the pinch temperature was 145°C. The utility system can be designed to provide the minimum heating and cooling heat of 20895.74kJ/s and 1108.75kJ/s respectively to achieve the function of energy saving and consumption reduction

**Keywords:** slag, process system, pinch analysis

**NONMENCLATURE**

| *Symbols* | |
|---|---|
| h | enthalpy |
| ΔH | Heat transfer |
| $q_m$ | mass flow |

## 1. INTRODUCTION

With the increasing shortage of resources and the gradual aggravation of environmental pollution, reducing energy and resource consumption is a major challenge for industry. Pinch analysis is based on thermodynamics to analyze the distribution of energy flow and the temperature in the processing system from a macro point of view. It can find out the bottleneck of the system and energy consumption and solve the bottleneck. Because the pinch technology takes the whole system as an integrated whole, it can optimize the overall design, and achieve the minimum energy consumption, minimum cost, and environmental pollution[1].

Pinch technology was first proposed by Professor B.Linnhoff and his colleagues at the University of science and technology in Manchester, UK[2]. At present, this method has been used in many large-scale projects in Europe and America and significant economic benefits have been achieved.

Some materials need to be heated or be cooled in the slag centrifugal granulation system. From the perspective of comprehensive utilization of energy, it is naturally expected that these cold and hot materials will be reasonably matched to improve the heat recovery rate of the process and reduce the heat load and cooling

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load of public utilities. Determining the structure of matching heat transfer between cold and hot materials and the corresponding heat transfer load distribution is a problem to be solved in heat exchange network synthesis. Aiming at the problem of waste heat recovery, this paper used the problem table method in pinch analysis method to find the bottleneck of the system to optimize the system and reduce the energy consumption in the system.

## 2. APPLICATION AND RESEARCH

### *2.1 Technological process*

This paper mainly analyzed the pinch point of waste heat recovery system of centrifugal granulation liquid slag. The waste heat recovery process included slag process, water vapor process, and air process. Waste heat recovery equipment included granulation bin, moving bed, superheater, evaporator, and economizer. The high-temperature waste heat of slag transferred heat to water and air in waste heat recovery equipment through the system.

Slag process: the high-temperature slag first entered the granulation bin and cooled with the air in the granulation bin and the water on the granulation bin's water-cooled wall. Then it entered the moving bed to exchange heat with the air in the moving bed and the water in the water-cooled wall of the moving bed.

Air process: air at room temperature entered granulation bin and moving bed by the blower in two ways. The air entered the waste heat recovery system after heat exchange with high-temperature slag particles in the moving bed and granulation bin.

Water vapor process: the high-temperature air after heat exchange entered the subsequent waste heat boiler to exchange heat with the medium in superheater, evaporator and economizer. The feed water pump will send water into the economizer, which will be heated in the economizer and then enter the steam drum.

### *2.2 Pinch analysis method*

The pinch design method often uses graph theory (composite temperature and enthalpy line) or problem table algorithm to describe the process system's energy flow and distribution. The position of pinch point can be determined directly by compound temperature and enthalpy line. However, when there are many material flows, the compound temperature and enthalpy line are cumbersome and inaccurate. In this case, the problem table method is often used to accurately calculate and determine the location of the pinch point [3]. The specific process of the problem table method is as follows.

According to the material flow's initial temperature and target temperature, several temperature ranges are divided. The cold and hot flows transfer completely in each temperature range, and the heat flow transfers from the high-temperature section to the low-temperature section.

Then, the accumulated value of residual heat in each temperature range is calculated. If the accumulated value of residual heat in any temperature range is negative, it means that thermodynamics is impossible

Table 1 Material flow data

| Thermal demand side-cold material flows | | | |
|---|---|---|---|
| Symbol | Material flows | initial temperature(°C) | target temperature(°C) |
| A1 | Air of moving bed | 27 | 800-1000 |
| A2 | Air of granulation chamber | 27 | 800-1000 |
| A3 | Superheater steam | 241 | 435 |
| A4 | Evaporator | 241 | 241 |
| A5 | Economizer | 50 | 224 |
| A6 | Moving bed water wall | 241 | 241 |
| A7 | Water wall of granulation bin | 241 | 241 |
| Thermal supply side-hot material flows | | | |
| Symbol | Material flows | initial temperature(°C) | target temperature（°C） |
| B1 | Slag from granulation bin | 1450 | 1000 |
| B2 | Slag of moving bed | 1000 | 100 |
| B3 | Superheater flue gas | 800-1000 | 600-700 |
| B4 | Evaporator flue gas | 600-700 | 400-500 |
| B5 | Economizer flue gas | 400-500 | 150 |

Finally, the maximum negative value of accumulated residual heat is found in all temperature ranges. The heat of the absolute value of the maximum negative value is added from the first temperature range so that the accumulated residual heat in the temperature range where the maximum negative value is located is zero. This ensures that the accumulated residual heat in all temperature ranges is greater than zero.

The heat added in the first temperature section is the minimum heat utility quantity required by the heat exchange network. The output value of the lowest temperature section is the minimum cold utility quantity required by the network. The point where the output of the temperature section is zero is the pinch point[4, 5].

### 2.3 Calculation

#### *2.3.1 Data extraction*

In the system design, the temperature data of material flow was extracted from each heat exchange node. The heat exchange nodes included the interface between moving bed and granulation bin, the inlet of granulation bin, the outlet of moving bed, the inlet and outlet of superheater, evaporator and economizer. The specific data are shown in Table 1. The material flows were divided between the thermal demand side and the thermal supply side. The initial temperature and target temperature of each material flow were given, including 7 cold material flows and 5 hot material flows. "A" stands for cold material flows, "B" stands for hot material flows. As can be seen from the table, the number of cold material flows is more in the whole design system. Since the moving bed and granulation bin entered the same waste heat recovery system, the required temperature was the same. For the granulation bin and moving bed, the water in the water-cooled wall was at the same temperature. However, due to different dryness, their enthalpy and heat load were different. Therefore, they were regarded as two different fluids. The inlet fluid of the evaporator was water, and the outlet fluid was steam.

#### *2.3.2 Dividing temperature range*

Since the problem table algorithm uses the temperature interval as the unit, it is necessary to establish a unified temperature scale for calculation. However, if the actual temperature flow is used, some heat can not be recovered in time, which will cause data error. Therefore, in order to avoid this problem, a shift temperature △Tmin=10°C was established to re-establish the temperature label. When △Tmin was determined, the energy location and the corresponding displacement of hot and cold flows can be carried out. Heat flow temperature increased by 5°C and the cold flow was opposite. Then divide the temperature range as shown in Table 2. Due to the limited space, the data had been reduced.

#### *2.3.3 Establishment of thermal cascade table*

The heat transfer was calculated in the corresponding temperature range, and the heat cascade table was established according to the heat balance. The corresponding enthalpy of each material flow was multiplied by the corresponding mass flow rate to obtain the heat change. The formula is as follows:

Table 2 Temperature range adjustment table

| Range | Inflow temperature | Outflow temperature | Adjusted inflow temperature | Adjusted outflow temperature |
|---|---|---|---|---|
| | °C | °C | °C | °C |
| A1 | 27 | 800-1000 | 32 | 805-1005 |
| A2 | 27 | 800-1000 | 32 | 805-1005 |
| A3 | 241 | 435 | 246 | 440 |
| -- | -- | -- | -- | -- |
| B3 | 800-1000 | 600-700 | 895 | 595-695 |
| B4 | 600-700 | 400-500 | 595-696 | 395-495 |
| B5 | 400-500 | 150 | 405-505 | 145 |

$$\Delta H = \hbar \times q_m$$

where *ΔH* is the heat change in the temperature range, kJ/s; *h* is the corresponding enthalpy of the material flow, kJ/kg; $q_m$ is the mass flow rate of the material flow, kg/s.

When *ΔH* was positive, it meant that heat flow was dominant and there was surplus heat. On the contrary, when *ΔH* was negative, it meant that the cold mass flow was dominant and the heat supply was insufficient. The results are shown in Table 3. Due to the limited space, the data had been reduced. Each value in the rightmost column represented the accumulated heat added in two temperature intervals. When the accumulated heat was negative, it meant that thermodynamics was impossible. It can be seen that when the temperature was 145°C, the absolute value of the accumulated heat was the largest.

In order to realize the thermodynamic possibility of the whole system, the negative value of accumulated heat corresponding to 145°C must be treated at the lowest possible cost. The 145°C was the pinch point of thermal system. The minimum heat load corresponding to pinch temperature was -20895.74kJ/s. Then add the heat load of - 20895.74kJ/s to the last column of Table 3 to get Table 4. Due to the limited space, the data had been reduced. At this time, the heat load was 0 when the pinch temperature was 145°C, which realized the thermodynamic possibility of the whole system.

Table 3 Thermal cascade table

| Temperature (°C) | Excess heat in temperature range（kJ/kg） | Accumulated heat（kJ/s） |
|---|---|---|
| 1445 | | 0 |
| | 7694.05 | |
| -- | | -- |
| 246 | | -1928.17 |
| | -17818.49 | |
| 229 | | -19746.67 |
| | -1149.08 | |
| 145 | | -20895.74 |
| | 1596.5 | |
| -- | | -- |
| | -329.16 | |
| 32 | | -19786.99 |

Table 4 Adjusted thermal cascade table

| Temperature (°C) | Excess heat in temperature range（kJ/kg） | Accumulated heat（kJ/s） |
|---|---|---|
| 1445 | | 20895.74 |
| | 7694.05 | |
| -- | | -- |
| 246 | | 18967.57 |
| | -17818.49 | |
| 229 | | 1149.08 |
| | -1149.08 | |
| 145 | | 0 |
| | 1596.5 | |
| -- | | -- |
| | -329.16 | |
| 32 | | 1108.75 |

### *2.4 Summary*

According to the pinch analysis, the pinch temperature was 145°C when the minimum temperature difference between hot and cold materials △Tmin was 10°C. The minimum common heating or cooling consumption were 20895.74kJ/s and 1108.75kJ/s. In pinch technology, the larger the △Tmin value is, the more cold and hot utilities are required, which increases the operation cost of heat exchanger network. The smaller the it is, the larger the heat exchange area is required, which increases the equipment investment cost of the heat exchange system. In the later stage, the minimum total cost can be taken as the objective to optimize the system by selecting △Tmin.

### *2.5 Conclusions*

Because of its clear principle, simple process, and easy to understand, pinch analysis technology has been applied in various industries to optimize the process. In this paper, the pinch point analysis method was used to analyze the cold and hot material flow data of each process of the slag centrifugal granulation waste heat recovery system. It was found that the pinch temperature was 145°C. The pinch points divided the engineering system into upper and lower systems. The upper part of the pinch point was a heat supply network, which needed utility heating, and the lower part was a cold network, which needed utility cooling. This fully shows that pinch points limit the further energy recovery of engineering system and form the bottleneck of energy recovery. Under the design conditions, the minimum common heat required for heating above the pinch temperature was 20895.74kJ/s, and that for colding below the pinch temperature was 1108.75kJ/s. In the design system of slag waste heat recovery, it can be considered to establish a utility system to provide the minimum heat and cooling capacity of 20895.74kJ/s and 1108.75kJ/s respectively to achieve the purpose of energy saving and consumption reduction.

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