Optimization of the boiler using the pinch method and exergy method

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Abstract. The exergy system is the maximum work that can make the system in the transition to a state of equilibrium with the environment. Exergy analysis of heat power and process plants takes into account not only quantitative but also qualitative characteristics of energy resources in various elements of the plants. The pinch method allows solving specific design problems to optimize the parameters of thermal power facilities. The paper presents an exergy analysis of such an object on the example of a boiler using pinch-method. The results show that to improve the energy efficiency of the boiler can change the surface area of the heating economizer and air heater.

1. Introduction

At the moment, for the thermodynamic analysis of the power plants of the system, the balance method is most often used. At the first stage of the structural synthesis of a technical system, the balance (enthalpy) method allows one to roughly determine the power capacity and performance of the system under consideration.

The balance method does not allow determining the qualitative characteristic of energy, that is, questions about the transformation of some forms of energy into others. In practical terms, the balance method is not sufficiently complete to answer the question about the practical possibility of obtaining, converting and using energy.

The enthalpy method does not take into account the most important consequence of the second principle of thermodynamics - the increase in the entropy of an isolated system during the course of real processes in it. This method does not take into account the energy value of heat and cannot serve as a quantitative characteristic of the irreversibility of real processes. However, a system of coefficients is possible, based on all the consequences of both principles of thermodynamics.

The method based on the complex and full use of both principles of thermodynamics, proceeds from the fact that the perfection of any real process should be evaluated according to the degree of its deviation from the reversible process. It is called the thermodynamic method. There are two variations of this method:

1. exergy method (exergy flow method);
2. entropy method (exergy loss method).

Exergy is a part of energy equal to the maximum useful work that a thermodynamic system can accomplish when moving from a given state into a state of equilibrium with the environment.
For heat $Q$ transmitted from a source with temperature $T$ to the environment with temperature $T_0$, the exergy is determined by this formula:

$$E_x = Q \cdot \left(1 - \frac{T_0}{T}\right) = c \cdot m \cdot \left(1 - \frac{T_0}{T}\right)$$ (1)

where:
- $T_0$ - ambient temperature,
- $T$ - the temperature at which heat is transferred;
- $c$ - the specific heat of flow;
- $m$ – the mass flow.

As a practical illustration of the concept of "useful energy" we consider the following example. Steam weighing 300 kg at a temperature of 400 °C, a pressure of 40 bar and water weighing 6 tons at a temperature of 40 °C contain the same amount of energy (compared to the same base temperature) - 1 GJ. Steam at a pressure of 40 bar is capable of performing significant useful work (generation of electricity, actuation of mechanical equipment, etc., but the possibilities for the beneficial use of water with a temperature of 40 °C are extremely limited.

Pinch analysis is a methodology for minimizing the energy consumption of a process by calculating thermodynamically justified amounts of energy consumption and approaching them by optimizing heat transfer between processes. The use of the pinch-method allows one to achieve large financial savings by minimizing the use of external energy sources, both energy supply and discharge, by maximizing the use of heat recovery and its achievement by optimizing the system.

The pinch-analysis is based on enthalpy, which does not take into account the potential of heat. We propose to analyze the sources of thermal energy using exergy, which can better estimate the potential of heat fluxes and shows the dependence of the energy of heat flux on the ambient temperature.

Exergy makes it possible to evaluate the qualitative side of thermal energy, i.e., it is a kind of universal measure of energy resources.

2. Analysis of the boiler using pinch method and exergy method

In the theory of Pinch analysis, all technological flows can be divided into two groups. One of them will include those flows that require cooling before further processing. We will call such streams hot streams. Hot process streams are usually denoted by a vector directed from right to left in temperature – enthalpy coordinates. This is due to the fact that hot heat fluxes decrease their heat content - enthalpy both during cooling and when their phase state changes. Similarly, in cold process streams, when heating or changing their phase state, heat content increases, and therefore in the coordinate plane temperature – enthalpy such flows will be represented by a vector line, directed from left to right.

Presentation enthalpy of flow change depending on changes in the temperature display for a straight line may flow, heat capacity within which temperature changes can be considered constant.

**Figure 1.** Functional relationship between temperature change and flow enthalpy change.
Indeed, the relationship between a change in the temperature of a stream and a decrease in its heat content — enthalpy — will in general be expressed by a nonlinear function (Figure 1). The enthalpy increments of the flow with a change in temperature and be determined as follows:

\[ dH = C_p \cdot M \cdot dT \]  \hspace{1cm} (2)

where \( C_p \) — the specific heat capacity of the substance of the process stream at constant pressure, \( \frac{J}{kg \cdot K} \); \( M \) — the mass flow rate of the substance of the flow, \( kg/sec \); \( T \) — temperature, \( K \); \( H \) — the heat content of the stream, \( W \).

We will conduct an exergy analysis of a straight-through boiler BKZ-35-40 using the pinch method. Let us take for analysis only part of the boiler: economizer and air heater.

![Figure 2. Scheme of the boiler section BKZ-35-40.](image)

In calculations and graphs, instead of heat content, we will use exergy of the flow. In this case, waste gas, which gives off heat to the economizer, will be called “Hot stream 1”. The waste gases, heating the air preheater, will be called “Hot Stream 2”. The second group of streams will include those streams that need to be heated - cold streams. In this boiler unit, the economizer water is “Cold Stream 1”, the heating air of the air heater is “Cold Stream 2”.
Table 1. Boiler parameters.

|                | Initial temperature, °C | Final temperature, °C | Specific heat capacity, kJ / kg K | Mass flow rate, kg / s | Exergy, kW |
|----------------|-------------------------|-----------------------|-----------------------------------|------------------------|------------|
| Cold Stream 1  | 145                     | 249                   | 4.1                               | 10.2                   | -1812      |
| Cold Stream 2  | 30                      | 160                   | 1.009                             | 8.956                  | -294       |
| Hot stream 1   | 655                     | 360                   | 1.16                              | 13.35                  | 2951       |
| Hot Stream 2   | 360                     | 180                   | 1.16                              | 15.68                  | 1612       |

In the conditions of stationary operation of technical systems it is not difficult to determine exergy. For example, at constant temperatures of the source of heat and the environment, the exergy function of the heat $\text{Ex}$ is determined by formula (1). However, when the flow temperature changes, the exergy function of the heat of power plants looks different.

Thus, the heating water (cold stream 1) is in the economizer has an initial temperature and the final temperature. Then the equation (1) in differential form is written as:

$$d(\text{Ex}) = c \cdot m \cdot \tau \cdot dT = c \cdot m \cdot \left(1 - \frac{T_0}{T_1}\right) \cdot dT.$$  \hspace{1cm} (3)

Integrating this equation (3) in the temperature range from $T_1$ to $T_2$, we obtain the dependence of the exergy function:

$$\text{Ex} = \int_{T_1}^{T_2} c \cdot m \cdot \left(1 - \frac{T_0}{T_1}\right) \cdot dT = c \cdot m \cdot [T_1 - T_0 \cdot \ln(T_1) - T_2 + T_0 \cdot \ln(T_2)] = c \cdot m \cdot \left[T_1 - T_2 - T_0 \cdot \ln \left(\frac{T_1}{T_2}\right)\right].$$ \hspace{1cm} (5)

Let us calculate the exergy for “cold flow 1” by the formula (5). The ambient temperature taken for calculations is 0 ° C.

$$\text{Ex} = 4.1 \frac{kJ}{kgK} \cdot 10.2 \frac{kg}{s} \cdot \left[418K - 522K - 273K \cdot \ln \frac{418K}{522K}\right] = -1812 \ kW.$$  

Heat flows can be represented in the coordinate system "exergy-temperature" (Figure 3).

![Figure 3](image-url)

Figure 3. Hot and cold flows in the coordinate system "exergy-temperature".

We transform the graphs using the pinch method (Figure 4).
Figure 4. The converted heat flows in a coordinate system "exergy - temperature".

The projections of the curves on the axis of exergy overlap. This means that the heat removed from the hot compound curve (a set of hot streams) can be used to heat a cold compound curve (a set of cold streams) by organizing heat transfer between the streams.

The theory of pinch analysis reports that for each of the composite curves there is a section whose projection on the axis of enthalpy does not overlap with the projection of the second curve. This means that in its upper part the cold composite curve needs an external heat source (power $Q_{H_{\text{min}}}$), and the hot composite curve in its lower part needs an external cooling source (power $Q_{C_{\text{min}}}$). These values are theoretical needs for hot and cold energy [2].

Conclusions are based on graphs:

1) Hot streams overlap completely cold streams; therefore, the cold composite curve does NOT need an external heat source (this can be seen from the top of the graphs). And the exergy is still 2457 kW. At the same time, the hot streams in the upper part of the graph have a high temperature, hence a large potential that can be used.

2) There are opportunities for the transfer of exergy between processes (recovery), 2106 kW of exergy.

The point at which the distance between the curves along the temperature axis is minimal is called a "pinch point". At the pinch point, the temperature difference between the curves reaches a minimum - $\Delta T_{\text{min}}$. In this case, the recovery is maximum, and the theoretical need for external energy carriers is minimal. In our case, $T_{\text{min}} = 60 ^\circ \text{C}$ - this will be the pinch point.

Conclusion

Exergy analysis using the pinch method showed that the boiler had unused exergy equal to 2457 kW. To improve efficiency, based on the calculations, we can increase the heating surface area of the economizer or air heater, thereby increasing the efficiency of the boiler.

This exergy method is oriented towards the environment, i.e. takes into account the operating conditions of technological equipment (ambient temperature).

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