TECHNICAL ECONOMIC MODEL OF ENERGY UTILIZATION AND ENERGY SAVING FOR CENTRAL HEATING SYSTEM

by

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Chinese heating method has gradually shifted from small fragments to centralized regional heating. This heating method has achieved obvious energy-saving benefits. The article establishes an economic model of the energy utilization rate of the central heating system and installs the system exergy balance equation at the same time. The simulation found that the energy utilization coefficient of the heating system is high and has a high energy-saving potential. The effect of energy utilization is poor, and it has great potential for energy saving.

Key words*: central heating energy analysis, exergy analysis, energy efficiency, exergy efficiency, economic benefits*

Introduction

In 2011, the heating energy consumption of northern cities and towns in my country was 166 millionns of standard coal, accounting for 24.2% of building energy consumption [1]. At the same time, the energy utilization efficiency of most heating systems in my country is low, and a large amount of energy is wasted every year. Compared with developed countries such as the USA and Japan, the heating energy per unit area of urban buildings in my country is two to three times that of countries at the same latitude. Therefore, analyzing the energy utilization status of each link of the urban heating system and finding and solving existing problems play an important role in improving the energy utilization efficiency of the heating system and reducing energy consumption.

Some scholars used the exergy analysis method to evaluate the performance of solar heating systems and district heating systems. They analyzed the exergy efficiency of collectors, heat exchangers, and circulating pumps in solar heating systems. They found that collectors' exergy efficiency was the lowest and had excellent potential for improvement [2]. The paper established the energy analysis and exergy analysis model of the geothermal central heating system, and drew the system energy flow diagram and exergy flow diagram according to the actual operating data, determined the energy efficiency and exergy efficiency of the system, and proposed improvement measures. The paper analyzed the energy loss and exergy loss of the heating system pipe network, pointed out that the supply and return water temperature was an important factor affecting exergy loss and proposed measures to reduce the system energy loss and exergy loss. Some scholars have conducted energy analysis and exergy analysis on industrial boilers. They pointed out that the combustion chamber and heat exchanger are the main parts that produce exergy loss. The exergy efficiency of the system is significantly lower

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than the energy efficiency, pointing out that flue gas heat recovery is an essential measure for boiler energy saving.

From the existing literature, energy analysis and exergy analysis have been widely used in engineering practice, especially in heating and air conditioning. However, most of the research focuses solely on heating or cooling subsystems, cold and heat sources, and pipe networks and rarely involves analyzing and evaluating the performance of heat sources and heat pipe networks in urban central heating systems from the perspective of exergy [3]. For this reason, this paper takes a typical central heating system as the research object and focuses on the heat supply and heat pipe network. The energy utilization status of the heat supply and heat pipe network is analyzed by establishing the energy analysis exergy and analysis model. And research, evaluate its energy utilization efficiency, and provide a theoretical basis for energy-saving and transformation of heating system.

Analysis of energy utilization of central heating system

This paper adopts energy analysis and exergy analysis theory to establish a gray box model of a central heating system. We analyze and compare the energy difference between the import and export and the exergy difference of each part of the system. The overall energy consumption of the central heating system is evaluated, and the weak links are determined.

Energy analysis method

Energy analysis uses the principle of thermal balance, with thermal efficiency as the primary criterion, to analyze and evaluate the effective utilization of energy equipment and systems, reflect the balance of energy, and consider the degree of utilization of energy. The hot water in the central heating system as a medium mainly passes through the heat source, water supply pipe-line, heat user and return water pipe-line [4]. According to its process, that is, the direction of energy flow, a series-connected energy analysis gray box model of the system is established, as shown in fig. 1.

In fig. 1 Q_f [kJh^{-1}] is the heat brought into the boiler by the fuel of the heat source boiler room, W_s [kJh^{-1}] – the electric power of the heat source auxiliary machine and the circulating

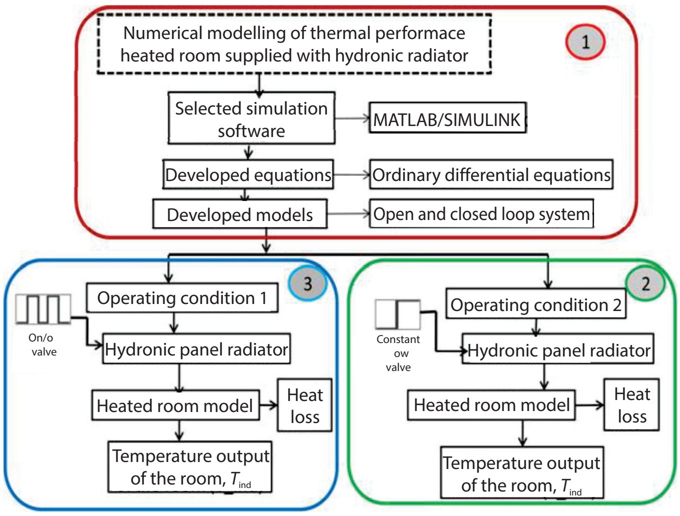

Figure 1. Heat flow model of central heating system

water pump, Q_1, Q_4 [kJh^{-1}] – the heat supply and return water heat, Q_{1s}, Q_{2s}, Q_2, Q_3 [kJh^{-1}] – the system heat source, water supply pipe network, and return water pipe network, E_{fs} [kJh^{-1}] – the fuel exergy provided for the fuel of the heat source boiler room, E_{ps} [kJh^{-1}] – the electrical exergy of the heat source auxiliary machine and circulating water pump, E_{2s}, E_{3s} [kJh^{-1}] – the heat respectively exergy, E_{4s} [kJh^{-1}] – the user's incoming and outgoing water, and I_{1s}, I_{2s}, I_{3s} [kJh^{-1}] – the heat source backwater [5].

The energy difference between the entrance and exit of each part in fig. 1 is compared and analyzed, and the energy balance equation of the heating system is obtained as:

$$W_s + Q_f = Q_2 - Q_3 + \sum Q_{is} \tag{1}$$

where $\sum Q_{is}$ [kJh^{-1}] is the total energy loss of the system. The thermal efficiency of the heating system is the ratio of the effective use of heat-by-heat users to the actual heat consumption of the system. From eq. (1) and fig. 1, the thermal efficiency η_s of the system:

$$\eta_s = \frac{Q_2 - Q_3}{W_s + Q_f} \tag{2}$$

Exergy analysis method

The exergy analysis method is an analysis method that uses exergy as an energy indicator to evaluate the energy use process from the perspective of thermal power conversion. It considers the amount of energy, pays more attention to animation quality, and pursues the best energy level match, revealing more deeply. The nature of energy degradation and the causes and locations of various losses in the process of energy transfer and conversion indicate the direction for the rational use of energy [6]. The exergy analysis method has been proven to be the most effective energy analysis method. Figure 1 shows the exergy flow of the central heating system. According to the exergy flow during operation, the system exergy balance equation is established:

$$E_{fs} + E_{ps} = E_{2s} - E_{3s} + \sum I_{is} \tag{3}$$

where $\sum I_{is}$ is the total exergy loss of the system.

– The fuel exergy belongs to the chemical exergy, which can be calculated by the Z·Rant method according to the calorific value of the fuel. The calculation formula for solid fuel:

$$e_{xf}^0 = Q_1 + r\omega \tag{4}$$

where e_{xf}^0 [kJkg^{-1}] is the fuel ratio exergy, Q_1 [kJkg^{-1}] – the low heating value of the fuel, r [kJkg^{-1}] – the latent heat of vaporization of water, and ω – the mass percentage of water in the fuel. For the coal used in the heat source plant, the mass percentage of water is relatively low, so the ratio of coal burning to exergy can be approximately taken $e_{xf}^0 - Q_1$.

– Electric exergy belongs to the power source exergy. Since electric energy has 100% work capacity, this type of exergy can be directly converted into mechanical work, so the exergy value of electric energy is equal to its energy value:

$$e_{e1}^0 = e_{e1} \tag{5}$$

where e_{e1}^0 [kJkg^{-1}] is the ratio of electric energy, exergy, e_{e1} [kJkW^{-1}h^{-1}] – the ratio of electric energy.

– When the exergy of hot water is reversibly changed from any state to the restricted dead state in the steady flow state, the part of energy that can theoretically be converted into other forms is the physical exergy of 1 kg of steady flow. Also known as enthalpy exergy, the hot water in a central heating system can be regarded as a steady flow working fluid, and the enthalpy exergy per working fluid:

$$e_x = h - h_0 - T_0\left(s - s_0\right) \tag{6}$$

where e_x [kJkg^{-1}] is the enthalpy of the unit working fluid exergy, h [kJkg^{-1}] – the specific enthalpy of the unit working fluid at temperature T and pressure p, h_0 [kJkg^{-1}] – is the specific enthalpy of the unit working fluid at the reference state (temperature T_0, pressure P_0), s [kJkg^{-1}K^{-1}] – the specific entropy of the unit working fluid at temperature T and pressure p, s_0 [kJkg^{-1}K^{-1}] – the specific entropy of the unit working fluid at temperature T_0 and pressure P_0.

From eq. (3), the calculation formula of the heating system model exergy efficiency η_{es} can be obtained:

$$\eta_{es} = \frac{E_{2s} - E_{3s}}{E_{fs} + E_{ps}} \tag{7}$$

Exergy efficiency is between 0 and 1. Exergy efficiency reflects the comparison of homogeneous energy. It demonstrates the influence of the internal loss and external loss of the system, which can truly reflect the completeness of the system. When conducting exergy analysis in the thesis, not only the total exergy loss of the system must be known, but also the exergy loss and the cause of each link included, and the internal links need to be analyzed. The exergy analysis of the internal links of the heating system, such as the heat source and the transmission pipe network, is the same as that of the primary network [7]. The expressions of exergy loss and exergy efficiency of each link are shown in tab. 1.

Table 1. Expressions of exergy loss and exergy efficiency in each link of the heating system

	Exergy loss	Exergy efficiency
Heat source	$I_{1s} = E_{fs} + Q_{ps} + E_{4s} - E_{1s}$	$\eta_{s1} = \dfrac{E_{1s} - E_{4s}}{E_{fs} + Q_{ps}}$
Water supply pipe-line	$I_{2s} = E_{1s} - E_{2s}$	$\eta_{s2} = \dfrac{E_{2s}}{E_{1s}}$
Return line	$I_{3s} = E_{3s} - E_{4s}$	$\eta_{s3} = \dfrac{E_{4s}}{E_{3s}}$
System	$\sum I_{is} = I_{1s} + I_{2s} + I_{3s}$	$\eta_{es} = \dfrac{E_{2s} - E_{3s}}{E_{fs} + Q_{ps}}$

Engineering case analysis

This article mainly analyzes the hot water boiler and hot water pipe network. We selected a central heating system as the research object. Use energy analysis and exergy analysis methods to analyze the energy of the significant heating source (boiler) and the thermal pipe network link. Find out the location and reason of energy loss and exergy loss through research to improve the thermal efficiency and exergy efficiency of the system.

Project overview

Two heat source plants provide the central heating system. The first heat source plant was built in 2005 and the second heat source plant was built in 2009. The hot water boilers are all a 29 MW coal-fired chain-grate boiler. The survey recorded the operating data on January

10, 2019. The test results of the stable operation of the hot water boiler in the heat source plant are shown in tab. 2.

Table 2. Heating system operation test results

	The first heat source plant	The second heat source plant
Inlet water temperature of hot water boiler [°C]	58.94	60
Outlet temperature of hot water boiler [°C]	91.48	101
Inlet pressure of hot water boiler [MPa]	0.572	0.571
Outlet pressure of hot water boiler [MPa]	0.613	0.612
Circulating water volume of hot water boiler [kgh^{-1}]	444800	490500
Fuel consumption [kgh^{-1}]	4250	5550
Input heat (low heating value) [kJkg^{-1}]	19980	19980
Heat source auxiliary machine and water pump power [kW]	272	272

Analysis and discussion

To calculate the exergy value of each part of the central heating system, the base state of exergy must be determined first. Therefore, the environmental status is usually used as the baseline status of exergy. According to the outdoor air calculation parameters in GB50736-2012 *Code for Heating, Ventilation and Air Conditioning Design of Civil Buildings*, the calculated outdoor temperature for heating in winter in Tianjin is –7 °C, and the atmospheric pressure is 101.3 kPa. In the engineering investigation, the hot water temperature, pressure, and flow rate during stable operation of the heating system were recorded [8]. The results are shown in tab. 3.

Due to the small amount of calculation this time, the loss of supplemental heat caused by the system *running, emitting, dripping, and leaking* was not considered. Table 4 shows that the thermal efficiency of the first heat source plant is only 32.56%. The thermal efficiency of the second heat source plant is relatively high, reaching 57.03%. The heat loss of the heating system mainly comes from the heating pipe network. The transmission efficiency of the first heat source plant's supply and return pipe network is 89.62% and 87.98%, respectively. The heat transmission efficiency of the pipe network is lower than JGJ/T132-2009. The heat transmission efficiency of the outdoor pipe network of the heating system specified in the *Testing Standards for Energy Conservation of Residential Buildings* shall not be less than the standard value of 90%, and the heat loss in the heat transmission link is relatively large.

The first heat source plant was established earlier, and the outdoor heating pipe network is insulated with rock wool with a thickness of 60 mm and laid directly in a direct burial method. Due to the long-term corrosion of pipelines, the aging and damage of the waterproof layer of the pipe network. With the strong water absorption of rock wool in rainy and snowy weather or when the groundwater level is high, the thermal conductivity of the insulation material increases significantly after absorbing water, the insulation performance deteriorates. The heat dissipation loss increases large, resulting in lower transmission efficiency of the pipe network. The thermal pipe network of the second heat source plant adopts polyurethane insulation with a thickness of 60 mm and is laid in direct burial. The thermal insulation layer has low thermal conductivity and low water absorption, with good insulation effect and high pipe network transmission efficiency [9]. Therefore, the thermal pipe network should use insulation materials with sound thermal insulation effects, such as calcium silicate tiles + polyurethane composite

Table 3. Node parameters of heating system

	The first heat source plant			
	Heat source water supply	User water	User water	Heat source backwater
Temperature [°C]	91.48	82	67	58.94
Pressure [MPa]	0.613	0.6	0.59	0.572
Flow [kgh^{-1}]	444800	444800	444800	444800
Specific enthalpy [kJkg^{-1}]	383.58	343.75	280.87	247.12
Specific entropy [kJkg^{-1}K^{-1}]	1.21	1.1	0.92	0.82
Exergy [kJkg^{-1}]	58.14	47.57	32.57	25.42
Exergy rate 1 [GJh^{-1}]	25.861	21.159	14.487	11.307
	The second heat source plant			
	Heat source water supply	User water	User water	Heat source backwater
Temperature [°C]	101	95	64	60
Pressure [MPa]	0.612	0.6	0.59	0.571
Flow [kJh^{-1}]	490500	490500	490500	490500
Specific enthalpy [kJkg^{-1}]	423.66	398.38	268.31	251.55
Specific entropy [kJkg^{-1}K^{-1}]	1.32	1.25	0.88	0.83
Exergy [kJkg^{-1}]	68.96	62.3	30.65	27.19
Exergy rate 1 [GJh^{-1}]	33.825	30.558	15.034	13.337

Table 4. Heat balance of heating system

	Link	Heat loss [GJh^{-1}]	Effectiveness [%]	Percentage of total heat loss [%]
Second heat source plant	Boiler Room	25.197	70.67	43.5
	Water supply network	17.716	89.62	30.58
	Backwater pipe network	15.012	87.98	25.92
	Heating system	57.925	32.56	–
First heat source plant	Boiler Room	27.448	75.46	57.1
	Water supply network	12.4	94.03	25.8
	Backwater pipe network	8.221	93.75	17.1
	Heating system	48.069	57.03	–

insulation. Reasonably adjust the operation of the pipe network to increase the load rate of the pipe network, reduce the loss along with the pipe network, and improve the pipe network transportation effectiveness. The thermal efficiency of the boiler room of the heat source plant is relatively high, reaching 70.67% and 75.46%, respectively, and the effect on the quantity of energy is better. The results of the thermal balance test of the hot water boiler in the boiler room are shown in tab. 5.

Table 5. Boiler heat balance test results

	First heat source plant	Second heat source plant	GB/T17954-2007 regulations
Boiler output [MW]	16.87	23.39	78 (1st class), 76 (2nd class), 74 (3rd class)
Load factor [%]	58.17	80.66	
Air coefficient of exhaust	1.86	1.61	<1.75
Exhaust smoke temperature [°C]	134	152	<180
Carbon content of slag [%]	14.5	17.61	<12

It can be seen from tab. 5 that the boiler operation effect of the first heat source plant is average. It's thermal efficiency is 73.79%, which is lower than the third-class operating thermal efficiency requirement of 74% in GB/T17954-2007 *Economic Operation of Industrial Boilers*. The air coefficient and the carbon content of the slag in the smoke exhaust area exceed the standard requirements. The boiler operating load is 58.17% of the rated load, which deviates from the economic burden and the rated load. The operating conditions of the hot water boiler in the second heat source plant are better. The functional limitation of the boiler is 80.66% of the rated load. Although the boiler's thermal efficiency, the air coefficient of the exhaust gas, and the exhaust gas temperature all meet the standard requirements, the carbon content of the slag is relatively high. Therefore, we need to match the boiler's drum and induced draft fan and adjust the operating speed of the grate for the hot water boiler. At the same time, we need to control the air coefficient of the exhaust gas and the carbon content of the slag within the allowable range to reduce exhaust gas loss and mechanical incomplete combustion loss while improving boiler output and thermal efficiency.

Although the energy utilization of the system can be seen from the calculation result of thermal efficiency (transport efficiency), it cannot get the utilization of adequate energy. If it is evaluated from the thermal efficiency (transport efficiency), it will also cause the illusion that the energy utilization is relatively good. Therefore, we must perform exergy analysis. The exergy analysis model of the central heating system and the data in tab. 2 are combined with the calculation formula in tab. 1 to obtain the exergy loss and exergy efficiency of each link of the heating system. The specific results are shown in tab. 6.

Table 6. Exergy balance of central heating system

	Link	Exergy loss [GJh^{-1}]	Exergy efficiency [%]	Percentage of total exergy loss [%]
First heat source plant	Boiler room	71.34	16.94	90.05
	Water supply network	4.702	81.82	5.94
	Backwater pipe network	3.18	78.05	4.01
	Heating system	79.222	7.77	–
Second heat source plant	Boiler Room	91.38	18.31	94.85
	Water supply network	3.267	90.34	3.39
	Backwater pipe network	1.697	88.71	1.76
	Heating system	96.344	13.88	–

Therefore, to reduce the loss of the boiler and improve the efficiency, the boiler should be operated strictly according to the rated working condition of the boiler during use. In the case of good mixing with fuel, minimize the excess air coefficient and reduce the exhaust smoke loss; increase the initial air temperature and return water temperature, increase the combustion temperature, reduce the heat transfer temperature difference between the flue gas and the boiler water, and reduce the exhaust smoke loss; and an automatic control system is adopted to adapt to changes in load, and timely adjust the thickness of the coal seam, the speed of the grate, and the amount of blasting air to match each other to ensure that the boiler operates in an optimized state [11].

The power loss of water pump and fan is mainly due to the irreversible throttling process when air and flue gas-flow through the drum, induced draft fan baffle, and water flowing through the pump and valve. The smaller the opening, the greater the loss. To reduce power loss, high efficiency and energy-saving pumps and fans with a large adjustment range that match the design parameters and the pipe network should be used to adapt to load changes; at the same time, the pumps and fans with the largest power consumption should be equipped with variable frequency speed control devices to adjust the pump and the speed of the fan changes the air volume and circulating water volume to reduce power consumption.

We compared tabs. 4 and 6. It can be seen that the loss of the heat pipe network of the first and second heat source plants accounted for 9.95% and 5.15% of the total loss of the heating system, respectively. The loss is relatively small. The proportions reached 56.5% and 42.9%, respectively, and the heat loss of pipe network transportation was relatively large. From the perspective of heat loss, the heating power pipe network is to increase the heat supply. The main link of efficiency, but from the analysis, it can be seen that the system losses are 90.05% and 94.85%, respectively, in the boiler room. The heat pipe network losses only account for 9.95% and 5.15%. The boiler room is the only way to increase the main link of system efficiency. Thermal efficiency is often unintuitive and even misleading. There are inequalities between different grades of energy. Energy with the same quantity but different quality has different actual utility, and can even have great differences. Taking energy as the benchmark, there is a lack of comparability among the evaluation indicators. The balance analysis method can evaluate the qualitative difference of energy, reveal the location or link of the greatest loss, can fully reflect the internal and external loss of the equipment, and achieve the best use of energy to avoid qualitative waste. The thermodynamic analysis method is more in line with the actual situation in evaluating the energy utilization of the system.

It can be concluded that the thermal efficiency of the first heat source plant of the central heating system is 32.56%, and the exergy efficiency is only 7.77%. The thermal efficiency of the second heat source plant is 57.03%, and the exergy efficiency is 13.88 %. Therefore, the energy utilization efficiency of the second heat source plant is relatively good. At the same time, the central heating system has a mediocre energy utilization effect but a poor energy quality utilization effect. Therefore, the system has a more significant potential for energy saving and exergy saving. From the distribution of energy loss and exergy loss, the proportions of heat loss in the boiler room are 43.50% and 57.10%, respectively, but the proportions of exergy loss reach 90.05% and 94.85%, respectively. Therefore, exergy loss is relatively low. Therefore, a large boiler room has great potential for energy saving and exergy saving. The boiler should be operated in strict accordance with the rated working conditions to ensure high combustion efficiency. Reduce smoke loss and incomplete combustion loss, appropriately increase the temperature of the heat source water outlet and adopt an automatic control system to adapt to load changes and ensure that it is in an optimized state down-run operation is the basic way of boiler energy saving. At the same time, the pump and fan are equipped with variable frequency speed regulation devices to change the air volume and circulating water volume and reduce power consumption. The proportions of heat loss in the heat transmission network are 56.50% and 42.90%, respectively. The heat loss is relatively large, but the proportions of exergy loss are only 9.95% and 5.15%, respectively. Therefore, thermal insulation materials with good thermal insulation effect should be selected, and the operation of the pipe network should be reasonably adjusted to increase the load rate of the pipe network, reduce the loss along the pipe network, and improve the efficiency of the pipe network.

Conclusion

The thesis should strengthen the regulation and management of the central heating system to keep the heat source plant operating at full load throughout the day. Strictly control the heat loss in the water supply and return pipe network to ensure that the thermal efficiency meets the requirements of energy conservation regulations. At the same time, the overall central heating system should be optimized to minimize the heat loss and exergy loss in each link, so as to reduce the energy loss and exergy loss of the entire heating system, so that the system can maximize its potential. If investment and operating costs are to be considered, thermal economic analysis of the central heating system is also required.

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