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ENERGY AND EXERGY ANALYSES OF TWO TYPICAL CENTRAL HEATING SYSTEMS: AN APPLICATION IN TIANJIN ECO-TECH AREA, CHINA

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ABSTRACT

In order to optimize the operation of the hot water and steam central heating systems in Tianjin Economic-Technological Development Area, China, the energy and exergy efficiencies and exergy losses of overall system have been analyzed by integrating the first and the second law of thermodynamics. The results indicate that the energy efficiencies of the hot water heating system and steam heating system are 57.10% and 89.98%, while the exergy efficiencies are only 13.89% and 41.02%. The heat losses of energy stations account for 56.98% and 89.75% and the exergy losses of energy stations account for 94.84% and 98.64% for the hot water central heating system and steam central heating system, showing that the energy station is the major part of energy and exergy destruction in the heating system. In order to improve the energy and exergy efficiencies, more attentions should be paid to improving the combustion efficiency of the boiler, and some measures should be taken to reduce energy and exergy losses, such as reducing the exhaust gas temperature, recycling condensed water and improving the hot water or steam temperatures. Besides, good thermal insulation materials should be used to reduce the heat losses of heating pipe networks.

Keywords: central heating system, energy and exergy analyses, system optimization

NONMENCLATURE

Symbols	
C_p	specific heat at constant pressure, kJ/(kg K)
e_{xf}^{0}	specific exergy of fuel, kJ/kg
ex_{el}	specific exergy of electric energy, kJ/kWh
e_{el}	specific energy of electric energy, kJ/kWh
e_x	specific exergy, kJ/kg
h	enthalpy, kJ/kg
m	the mass flow rate, kg/h
Q_n	net calorific value of fuel, kJ/kg
r	latent heat of vaporization of water, kJ/kg
s	entropy, kJ/(kg k)
W_p	energy supplied by boiler auxiliaries, kJ/h
Greek letters	
ω	weight fraction of water in fuel
Subscripts	
f	fuel
l	loss
p	pressure
s	steam
w	water

1. INTRODUCTION

The heating energy consumption in buildings was about 166 million tons of standard coal in the northern towns of China in 2011, accounting for 24.2% of the total building energy consumption [1]. Reducing the energy consumption for heating is an effective way to alleviate the pressure of energy resource shortage. However, the limited technical level and careless management make the energy utilization efficiency very low at present, and resulting in a great waste of energy each year. Compared to the developed countries, the unit energy consumption for heating in China was double or three times more than that in the same latitude countries [2]. According to "The 12th Five-Year Plan" of national energy conservation program, the energy consumption per ten thousand Yuan GDP (Gross Domestic Product) should be decreased to 869 kilogram of standard coal in 2015 [3]. Therefore, the investigation on energy usage of each link of heating system plays an important role in the improvement of the energy efficiency, energy saving and greenhouse gas emission.

Energy and exergy analysis have been widely used in the optimization and performance evaluation of energy systems. They are helpful for engineers to find out the sections needed to be optimized and guide the further

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improvement. Performance evaluation of the Gonen geothermal district heating system was investigated based on energy and exergy analysis. Exergy destructions in the overall system were quantified and illustrated by using exergy and energy flow diagrams. It was observed that the exergy destructions in the system particularly took place as the exergy of the fluid lost in the pumps, the heat exchanger losses, the exergy of the thermal reinjected water (geothermal fluid) and the natural direct discharge (hot water distribution losses) of the system [4, 5]. The actual operation performances of ground source heat pump system were investigated by using the energy and exergy analysis method. The exergy diagram was presented for the GSHP system. Energy and exergy analyses provided insight on system efficiency and sources of irreversibility [6-8].

In view of power plants, Xu et al. [9] present a theoretical framework for the energy and exergy analyses of the solar power tower system. Both the energy and exergy losses in each component and in overall system are evaluated to identify the causes and locations of the thermodynamic imperfection. And the measures which could increase energy and exergy efficiencies were analyzed. Regulagadda et al. [10] performed a thermodynamic analysis of a subcritical boiler–turbine generator for a coal-fired power plant. Both energy and exergy formulations were developed for the system. The exergy losses distribution indicated that boiler and turbine irreversibilities yield the highest exergy losses in the power plant. And a parametric study was conducted for the plant under various operating conditions in order to determine the parameters that maximize plant performance.

With respect to transportation and industrial sectors, energy analysis and exergy utilization in the transportation sector of China were explored by considering the sectoral energy and exergy flows. It was found that highways transport was the biggest energy consumer, waterways transport was proved to be the most effective one. The calculated efficiencies over the studied period could be an important tool for policy makers and energy planners to gain insight into the performance of this sector [11, 12].

However, there is seldom report on the energy and exergy analyses of a central heating system from the heat source to pipeline network. The present work aims to provide detailed operation data to illuminate the system performance by using energy and exergy analysis method and provide a theory basis for energy conservation and transformation of the central heating system.

2. SYSTEM DESCRIPTION

2.1 Heating system

Tianjin is located in warm temperate zone and has four distinctive seasons. The two typical central heating systems studied in the paper are in Tianjin Economic-Technological Development Area, China. The first one, containing four chain steam boilers as presented in Fig.2 and one hot-water chain boiler as presented in Fig.1, was established in 2005 and had a total installed capacity of 105 MW. The second one, established in 2009, has two circulating fluidized bed boilers and one chain steam boiler with a total installed capacity of 130 MW.

By the end of 2014, these two systems had a total installed capacity of 235 MW, which can meet the demands for industrial production and heating in winter within 48 square kilometers.

In the present study, the heat balance tests were performed on a hot-water chain boiler (DZL29-1.6/130/70-AⅡ) and a steam circulating fluidized bed boiler (TG-75/5.29-M10). Besides, the hot water pipe network and the steam pipe network were also tested.

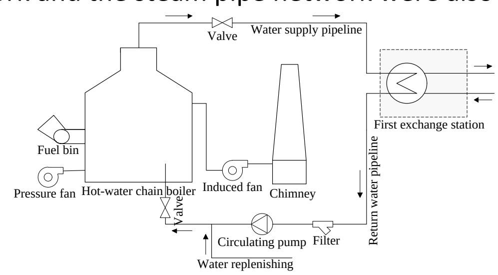

Fig.1. Schematic of a hot water central heating system.

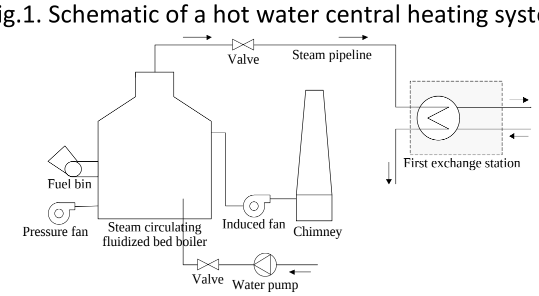

Fig.2. Schematic of a steam central heating system.

2.2 Measuring method and data

In order to ensure the accuracy of measurement, the testing process lasted for 4 hours. In the present work, the inlet/outlet temperatures of water or steam and pressures of the boilers, the water or steam flow rates, the electricity consumption of auxiliary equipment and pumps and fuel consumption were measured. The main operating parameters of the central heating system were summarized in Table 1.

Table 1 Operating parameters of the two typical central heating systems

Item	Unit	Hot water heating system	Steam heating system
Temperature of the inlet water of boiler	℃	60	105.7
Temperature of the outlet water/steam of boiler	℃	101	428
Temperature of the inlet water/steam of exchange station	℃	95	408
Temperature of the outlet water of exchange station	℃	64	80
Pressure of the outlet steam of boiler	MPa	—	3.42
Pressure of the inlet steam of exchange station	MPa	—	3.32
Mass flow rate	kg/h	490500	62100
Fuel consumption	kg/h	5550	11966
Net calorific value of coal	kJ/kg	19980	16550
Energy supplied by boiler auxiliaries	kJ/h	979200	1417400

3. THERMODYNAMIC ANALYSIS

3.1 Modeling

A typical hot water heating system consists of energy station, water supply network, first exchange station and return water network. Hot water in the heating system mainly passes by the four parts. Based on the energy flow direction, energy and exergy balancing gray box model of the hot water heating system is established, and the schematic diagram of the system is shown in Fig. 3.

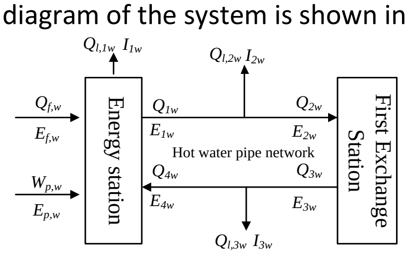

Fig.3 Schematic diagram of the hot water heating system

The steam heating system consists of energy station, steam network and first exchange station. In order to simplify the process, it can be considered that the energy loss of the condensed water is in the exchange station. The schematic diagram of the steam heating system is shown in Fig. 4.

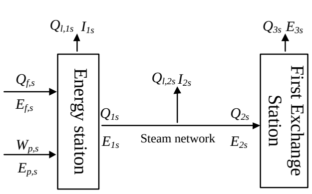

Fig.4 Schematic diagram of the steam heating system

3.2 Energy balance

3.2.1 Hot water heating system

According to Fig. 3, energy balance equation of the hot water heating system can be expressed as follow

$$W_{p,w} + Q_{f,w} = Q_{2w} - Q_{3w} + \sum Q_{l,w} \tag{2}$$

where $W_{p,w}$ is the energy supplied by boiler auxiliaries, $Q_{f,w}$ is the heat input of fuel, Q_{2w} is the inlet thermal energy of the exchange station, Q_{3w} is the outlet thermal energy of the exchange station and $\sum Q_{l,w}$ is the total heat losses of the system.

3.2.2 Steam heating system

According to Fig. 4, energy balance equation of the steam heating system can be indicated as follow

$$W_{p,s} + Q_{f,s} = Q_{2s} - Q_{3s} + \sum Q_{l,s} \tag{3}$$

where $W_{p,s}$ is the energy supplied by boiler auxiliaries, $Q_{f,s}$ is the h eat input of fuel, Q_{2s} is the thermal energy of inlet steam of the exchange station, Q_{3s} is the condensed water energy, and $\sum Q_{l,s}$ is the total heat losses of the system.

3.3 Exergy balance

The supply exergy of heating system consists of fuel exergy and electrical exergy of energy station auxiliaries. The available exergy of the system is the actually received heat exergy of first exchange station.

3.3.1 Exergy of fuel

Fuel exergy belongs to chemical exergy, according to calorific value of the fuel, solid fuel exergy can be calculated as

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

where e_{xf}^{0} is specific exergy of fuel, Q_n is the net calorific value of fuel, r is latent heat of vaporization of water, and ω is the weight fraction of water in fuel.

Generally, specific exergy of fuel can be approximately estimated as

$$e_{xf}^{0} = Q_n \tag{5}$$

3.3.2 Exergy of electricity

The electrical exergy equals to energy value because it can be directly converted into mechanical work. The electrical exergy can be expressed as

$$ex_{el} = e_{el} \tag{6}$$

where ex_{el} is the specific exergy of electric energy and e_{el} is the specific energy of electric energy.

3.3.3 Enthalpy-exergy of hot water

The specific exergy and exergy rate equations for the central heating system fluid flow can be defined as

$$e_x = h - h_0 - T_0(s - s_0) \tag{7}$$

where e_x is the specific exergy of hot water or steam, h is enthalpy, s is entropy, and subscript zero indicates properties at the state of P_0 and T_0.

Then the total exergy rate associated with hot water or steam is presented as

$$E_x = m[h - h_0 - T_0(s - s_0)] \tag{8}$$

where m is the mass flow rate of hot water or steam.

As for central heating system, the medium such as hot water or steam can be considered as steady flow. The enthalpy-exergy of per unit mass of hot water or steam varying with absolute temperature can be defined as

$$e_r = C_p[(T - T_0) - TIn\frac{T}{T_0}] \tag{9}$$

where C_p is the specific heat at constant pressure.

3.3.4 Exergy balance of hot water heating system

Exergy balance can be expressed as

$$E_{f,w} + E_{p,w} = E_{2w} - E_{3w} + \sum I_{l,w} \tag{10}$$

where $E_{f,w}$ is the exergy input of fuel, $E_{p,w}$ is the electrical exergy, E_{2w} is inlet hot water exergy of the exchange station, E_{3w} is outlet hot water exergy of the exchange station, and $\sum I_{l,w}$ is the total exergy losses in the system.

3.3.5 Exergy balance of steam heating system

Exergy balance of steam heating system can be expressed as

$$E_{f,s} + E_{p,s} = E_{2s} - E_{3s} + \sum I_{l,s} \tag{11}$$

where $E_{f,s}$ is the exergy input, $E_{p,s}$ is the electrical exergy, E_{2s} is inlet steam exergy of the exchange station, E_{3s} is condensed water exergy, and $\sum I_{l,s}$ is the total exergy losses in the system.

3.4 *Energy and exergy efficiencies*

3.4.1 Energy efficiencies

Basically, the energy efficiency of the heating system can be defined as the ratio of total efficiently utilizable heat to total actual heat consumption. The energy efficiencies of the hot water and the steam heating system can be expressed as follows

$$\eta_w = \frac{Q_{2w} - Q_{3w}}{W_{p,w} + Q_{f,w}} \tag{12}$$

$$\eta_s = \frac{Q_{2s} - Q_{3s}}{W_{p,s} + Q_{f,s}} \tag{13}.$$

3.4.2 Exergy efficiencies

The exergy efficiency can be defined as the ratio between total exergy output and total exergy input which consists of fuel exergy, electrical exergy of auxiliary equipment and pumps. According to the analysis model and exergy balance equations, the exergy efficiencies of the heating system can be obtained by Eq. (14) and Eq. (15):

$$\eta_{e,w} = \frac{E_{2w} - E_{3w}}{E_{f,w} + E_{p,w}} \tag{14}$$

$$\eta_{e,s} = \frac{E_{2s} - E_{3s}}{E_{f,s} + E_{p,s}} \tag{15}.$$

When the systems run stably, the water or steam flow rate in each part of the central heating systems in Fig. 3 and Fig. 4 can be considered equal. And the exergy losses and the exergy efficiency can be described in Table 2.

Table 2 The exergy losses and exergy efficiency equations for the heating systems

Heating system	Parts	Exergy losses	Exergy efficiency
Hot water heating system	Heat source plant	$I_{1w}=E_{f,w}+Q_{p,w}+E_{4w}-E_{1}$	$\eta_{1w}=\frac{E_{1w}-E_{4w}}{E_{f,w}+Q_{p,w}}$
	Water supply pipeline	$I_{2w}=E_{1w}-E_{2w}$	$\eta_{2w}=\frac{E_{2w}}{E_{1w}}$
	Return water pipeline	$I_{3w}=E_{3w}-E_{4w}$	$\eta_{3w}=\frac{E_{4w}}{E_{3w}}$
	System	$\Sigma I_{l,w}=I_{1w}+I_{2w}+I_{3}$	$\eta_{e,w}=\frac{E_{2w}-E_{3w}}{E_{f,w}+Q_{p,w}}$
Steam heating system	Heat source plant	$I_{1s}=E_{f,s}+Q_{p,s}-E_{1s}$	$\eta_{1s}=\frac{E_{1s}}{E_{f,s}+Q_{p,s}}$
	Steam pipeline	$I_{2s}=E_{1s}-E_{2s}$	$\eta_{2s}=\frac{E_{2s}}{E_{1s}}$
	System	$\Sigma I_{l,s}=I_{1s}+I_{2s}$	$\eta_{e,s}=\frac{E_{2s}-E_{3s}}{E_{f,s}+Q_{p,s}}$

4. RESULTS AND DISCUSSION

A typical hot water central heating system and a steam central heating system have been analyzed. In the calculation, the dead state is in equilibrium with -7℃and 101.3 kPa. The thermodynamic properties are calculated and summarized in Table 3.

Table 3 The node parameters of the hot water and steam central heating systems

Heating system	State point	T (℃)	P (MPa)	M (kg/h)	H (kJ/kg)	s (kJ/kg·K)	e_x (kJ/kg)	Ex (×10⁶kJ/h)
Hot water heating system	Outlet water of plant	101	0.61	490500	423.66	1.32	68.96	33.83
	Inlet water of exchange station	95	0.60	490500	398.38	1.25	62.30	30.56
	Outlet water of exchange station	64	0.59	490500	268.31	0.88	30.65	15.03
	Inlet water of plant	60	0.57	490500	251.55	0.83	27.19	13.34
Steam heating system	Outlet steam of plant	428	3.42	62100	3287.10	6.95	1433.81	89.04
	Inlet steam of exchange station	408	3.32	62100	3242.90	6.90	1402.91	87.12
	Outlet water of exchange station	80	0.60	62100	335.03	1.07	46.70	2.90
	Inlet water of plant	105.7	0.61	62100	442.54	1.37	74.36	4.62

4.1 *Energy balance*

The energy balances of the two typical heating systems were presented in Table 4. It can be concluded that the most heat losses come from the energy station and does not from the transport links. The transport efficiencies of supply and return networks of the hot water heating system are 94.03% and 93.75%, which are higher than 90% that regulated by “Energy Efficiency Test Standard for Residential Buildings, China” (JGJ/T132－2009) [13].

Table 4 Energy balance of the two typical central heating systems

Heating system	Component	Heat losses (×10⁶ kJ/h)	Heat efficiency (%)	Percent ratio (%)
Hot water heating system	Energy station	27.31	75.55	56.98
	Supplying Network	12.40	94.03	25.87
	Returning Network	8.22	93.75	17.15
	Total	47.94	57.10	100.00
Steam heating system	Energy station	24.03	88.03	89.75
	Steam Network	2.75	98.66	10.25
	Total	26.78	89.98	100.00

Note: This article considers the first network only, the second network and the pipe leakage are not considered.

The hot water heating system of first heat source plant was established in 2005, the supply and return pipes were buried under the ground with insulating material of rock wool with a thickness of 60 mm. Through on-spot inspection, it was found that parts of the waterproof layers had been dilapidated which caused the adsorption of water.

The second heat source plant was established and put into operation in 2011, the insulating material of the steam pipeline was calcium silicate tile covered with a glass steel protective layer with thickness of 3 mm, which had a smaller thermal conductivity and a better thermal insulation.

In the present work, heat balance tests of a hot-water boiler and a steam boiler are conducted and the results are shown in Table5.

Table 5 Summary of the boilers test results

Item	Hot-water boiler	Steam boiler	The national standard value of China
Boiler output	23.39 MW	62.10 t/h	—
Load rate	80.66%	82.80%	—
Positive balance efficiency	75.93%	88.26%	—
Counter-balance efficiency	80.14%	90.18%	—
Average thermal efficiency	78.04%	89.22%	76%(hot water boiler) 79%(steam boiler)
Excess air coefficient	1.61	1.49	<1.75(layer combustion) <1.50(fluidized bed)
Exhaust gas temperature	152℃	135℃	<180℃
Carbon-content of cinder	17.61%	3.41%	<13%
Temperature of the outer surface（Side）	64.20℃	40.50℃	—
Temperature of the outer surface（Top）	60.30℃	51.20℃	—

From Table 5, the thermal efficiency of hot water chain boiler is lower than that of the steam circulating fluidized bed boiler. Both boilers have good operation performance with the efficiencies of 78.04% and 89.22%, which are higher than the third grade standard value of “Economical Operation of Industrial Boilers” GB/T 17954-2007 [14].

4.2 *Exergy* balance

The thermal efficiency was non-intuitive or even misleading sometimes [15]. Energy losses could be large quantity while it was insignificant on thermodynamics because of its low quality. Exergy analysis, however, provided measures of approach ideality.

Exergy losses, exergy losses rate and exergy efficiencies of the two typical heating systems are summarized in Table 6.

Table 6 Exergy balance of the two typical central heating systems

Heating system	Component	Exergy losses ($\times 10^6$ kJ/h)	Exergy efficiency (%)	Exergy loss rate (%)
Hot water heating system	Energy station	91.25	18.34	94.84
	Supplying Network	3.27	90.34	3.40
	Returning Network	1.70	88.71	1.76
	Total	96.21	13.89	—
Steam heating system	Energy station	139.12	43.37	98.64
	Steam Network	1.92	97.85	1.36
	Total	141.04	41.02	—

The calculated exergy efficiencies of the two heating systems are 13.89% and 41.02%, which are much lower than the energy efficiencies. This means the energy is not used in a reasonable way and some effective measures should be introduced to optimize the system performance. Furthermore, the exergy efficiencies of networks are much higher than that of energy stations and systems.

The exergy losses of the energy stations account for 94.84% and 98.64% of the total exergy losses in the two systems, much higher than the heat losses ratios, which are the main irreversible processes in the system.

5. CONCLUSIONS

The energy utilization conditions of the heating systems have been investigated and evaluated by means of energy and exergy analysis. The main conclusions can be drawn as follows:

1) The energy efficiencies of the typical hot water and steam heating systems are 57.10% and 89.98%, respectively, while the exergy efficiencies are 13.89% and 41.02%, respectively.

2) The energy station contributes to the most heat losses and irreversibility in the heating system.

3) More attentions should be paid to the energy station, pipeline networks and steam condensate recovery to improve the energy and exergy efficiencies.

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