energies

MDPI

Article

New Low-Temperature Central Heating System Integrated with Industrial Exhausted Heat Using Distributed Electric Compression Heat Pumps for Higher Energy Efficiency

Fangtian Sun [1,2,*], Yonghua Xie [1], Svend Svendsen [2] and Lin Fu [3]

1 Beijing Research Center of Sustainable Energy and Buildings, Beijing University of Civil Engineering and Architecture, Beijing 100044, China; 2108521318098@stu.bucea.edu.cn
2 Department of Civil Engineering, Technical University of Denmark, 2800 Lyngby, Denmark; ss@byg.dtu.dk
3 Department of Building Science, Tsinghua University, Beijing 100084, China; fulin@mail.tsinghua.edu.cn
* Correspondence: sun_fangtian@163.com; Tel.: +86-010-6832-2133; Fax: +86-010-8836-1680

Received: 23 October 2020; Accepted: 9 December 2020; Published: 14 December 2020

check for updates

Abstract: Industrial exhausted heat can be used as the heat source of central heating for higher energy efficiency. To recover more industrial exhausted heat, a new low-temperature central heating system integrated with industrial exhausted heat using distributed electric compression heat pumps is put forward and analyzed from the aspect of thermodynamics and economics. The roles played by the distributed electric compression heat pumps in improving both thermal performance and financial benefit of the central heating system integrated with industrial exhausted heat are greater than those by the centralized electric compression heat pumps. The proposed low-temperature central heating system has higher energy efficiency, better financial benefit, and longer economical distance of transmitting exhausted heat, and thus, its configuration is optimal. For the proposed low-temperature central heating system, the annual coefficient of performance, annual product exergy efficiency, heating cost, and payback period are about 22.2, 59.4%, 42.83 ¥/GJ, and 6.2 years, respectively, when the distance of transmitting exhausted heat and the price of exhausted heat are 15 km and 15 ¥/GJ, respectively. The economical distance of transmitting exhausted heat of the proposed low-temperature central heating system could approach 25.1 km.

Keywords: central heating; exhausted heat recovery; distributed compression heat pump; thermodynamic performance; system configuration; economical transportation distance

1. Introduction

The rapid development of China's urbanization results in the insufficiency of the heating capacity of existing central heating sources [1]. On the other hand, there are both a great deal of low-temperature exhausted heat available to be the centralized heat source of central heating systems [2], and an overcapacity in China's Northern power grids [3,4]. Recovering low-temperature exhausted heat for central heating by using electric compression heat pumps would help to cover the growing demand of heat load and contribute to increasing the energy efficiency of central heating systems.

Due to the restriction of environmental protection policies, most industry plants are located far away from urban districts. The space mismatch between exhausted heat sources and urban districts would have a greater influence on the thermal performance and the economic benefit of central heating systems based on industrial exhausted heat [5]. For conventional central heating systems based on industrial exhausted heat, industrial exhausted heat is currently recovered by means of a water-to-water heat exchanger [6], or upgraded by using the heat pump [7,8]. Due to the restriction of the shorter economical distance of transporting exhausted heat, the conventional central heating systems integrated with industrial exhausted heat could not recover and transport more exhausted heat to heat users located far away from industry plants [9,10]. Therefore, the longer exhausted heat transportation distance has been a key problem to be resolved for the development of low-temperature central heating systems integrated with industrial exhausted heat.

The longer economical distance of transporting exhausted heat helps to solve the above problem of space mismatch between industry plants and urban districts [11], and also contributes to constructing the heating network of central heating systems based on multi-source energy [5]. By using heat pumps, rising the supply water temperature or reducing the return water temperature of the primary network helps to increase the economical distance of transporting exhausted heat [12,13]. Oluleye et al. [14] present selection principles of heat pumps for higher energy efficiency. Lund et al. [15] point out that introducing the electric compression heat pump into the central heating system contributes to achieving a large socioeconomic potential. Exhausted heat is often upgraded to higher temperature by using centralized electric compression heat pumps [16,17]. Averfalk et al. [18] point out that recovering low-grade exhausted heat for central heating by using centralized electric compression heat pumps helps to improve the performance of cogeneration, and it also improves the flexibility of the heat and electricity supply of cogeneration [19]. The electric centrifugal compression heat pump [20] and the two-stage one [21,22] could upgrade the exhausted heat to 50 °C and 70 °C, respectively. The two-cycle parallel system with centrifugal compressors has a larger coefficient of performance (COP) when the temperature lift is kept at 30 °C [23]. When the temperature lift is 58–72 °C, the COP of the cascade compression heat pump could be improved to 3.1 by using R600 and R290 [24]. The centralized electric compression heat pump can upgrade exhausted heat to higher temperature, but its COP is much smaller. Thus, the application of centralized electric compression heat pumps in recovering low-temperature exhausted heat for central heating is still restricted to a certain extent.

Decreasing the return water temperature of the primary network also contributes to increasing the economical distance of transporting exhausted heat, and helps to recover exhausted heat efficiently [25]. Both the absorption heat exchanger [26] and the ejector heat exchanger [27] can greatly decrease the return water temperature of the primary network in substations, but they need higher-temperature supply water as the driving heat source, which is not lower than 120 °C. Therefore, the two kinds of heat exchanger cannot be applied in the low-temperature central heating systems integrated with industrial exhausted heat. Greatly reducing the return water temperature of the primary network is a key problem to be solved for the low-temperature central heating system integrated with industrial exhausted heat.

To solve the above problem, a new low-temperature central heating system integrated with industrial exhausted heat using distributed electric compression heat pumps (CH-DHP) is proposed.

2. System Description

For the proposed CH-DHP, electric compression heat pumps are distributed in the substations. In each substation, the distributed electric compression heat pump is coupled with a water-to-water heat exchanger to be a new hybrid heat exchanger unit. The new hybrid heat exchanger unit is illustrated in Figure 1.

As for the new hybrid heat exchanger unit, the supply water of the primary network is first cooled by the return water of the secondary network in the water-to-water heat exchanger, and then further cooled by low-temperature refrigerant in the evaporator of the electric compression heat pump. Return water of the secondary network is first divided into two parts at the inlet. One is heated by circulating water in the primary network in the heat exchanger, and the other is heated by high-temperature refrigerant in the condenser of the electric compression heat pump. The heated water in the secondary network is converged at the outlet and serves as supply water. By this means, the return water temperature of the primary network is greatly decreased. Thus, the temperature difference between the supply and return water of the primary network becomes larger.

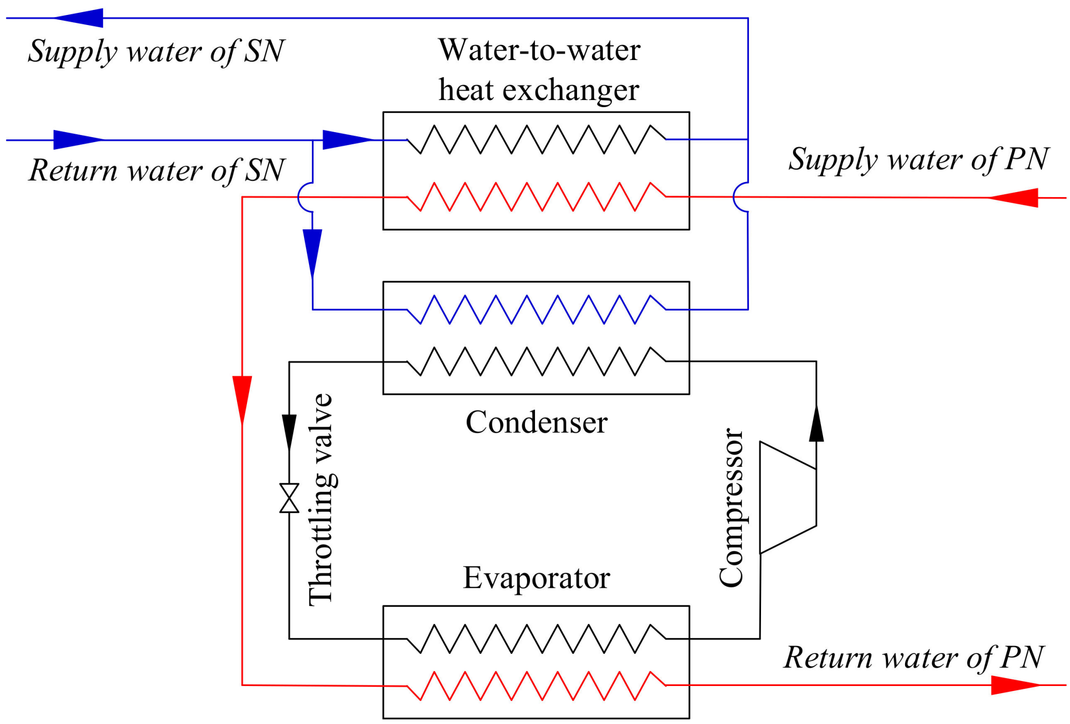

Figure 1. Sketch of new hybrid heat exchanger unit.

To clarify features of the CH-DHP, the low-temperature central heating system integrated with industrial exhausted heat using centralized electric compression heat pumps (CH-CHP) and the low-temperature central heating system integrated with industrial exhausted heat using heat exchangers (CH-WHE) are introduced and compared.

In general, a central heating system integrated with industrial exhausted heat consists of a heat source station, the primary network, substations, and the secondary network. For these three central heating schemes, thermal parameters of the secondary network are the same, and thus, the secondary network is not discussed in the following sections.

2.1. Operating Principle of CH-DHP

A sketch of the CH-DHP is presented in Figure 2.

As for the heat source station, exhausted heat is transferred from industrial exhausted water to the circulating water in the tertiary network by using an anti-corrosive heat exchanger, and it is then used to heat circulating water in the primary network by using a plate heat exchanger. By this means, industrial exhausted heat is recovered efficiently by using a conventional heat exchanger, and it is then transmitted to substations by way of the primary pipelines. In the substations, exhausted heat is transferred from the circulating water in the primary network to that in the secondary network by using new hybrid heat exchanger units, and the return water temperature of the primary network becomes much lower. The lower return water temperature of the primary network contributes to increasing the temperature difference between the supply and return water, and helps to recover more exhausted heat by using conventional heat exchangers in the heat source station.

With the increase in outdoor ambient temperature, heat load demand becomes small during a heating period. For the CH-DHP, the heating capacity of the new hybrid heat exchanger unit can be regulated to cover actual heat load demand by using the variable-frequency drive of the compressor.

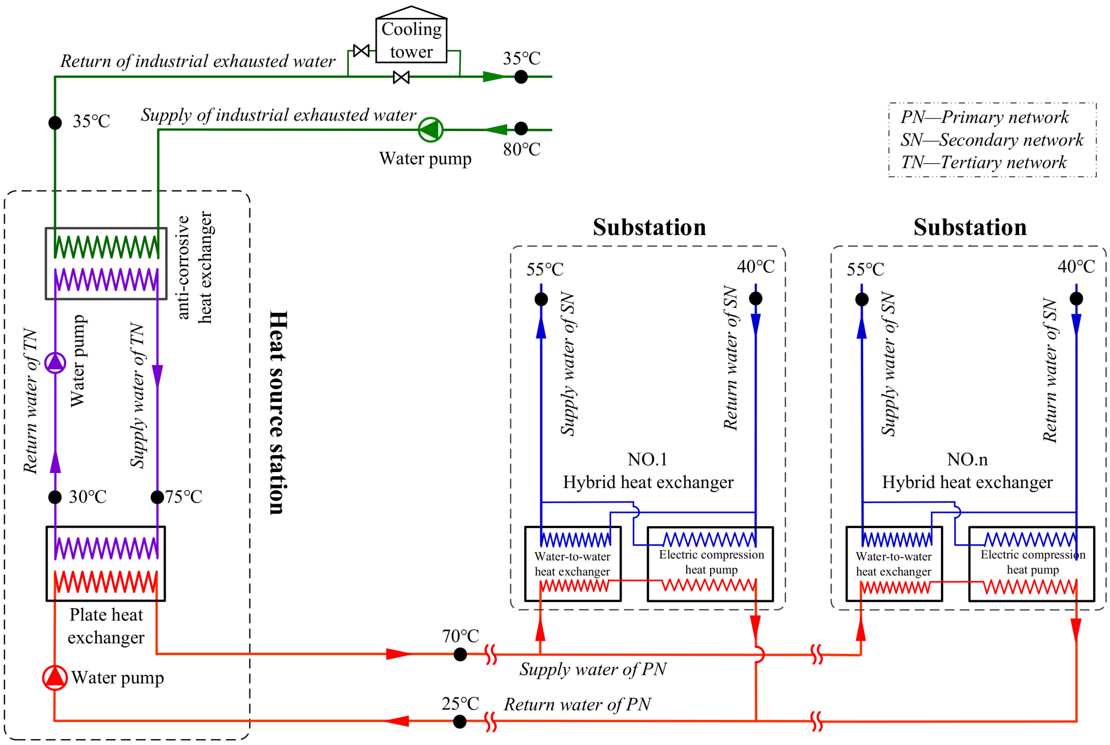

Figure 2. Sketch of central heating system integrated with industrial exhausted heat using distributed electric compression heat pumps (CH-DHP).

2.2. Operating Principle of CH-CHP

A sketch of the CH-CHP is illustrated in Figure 3.

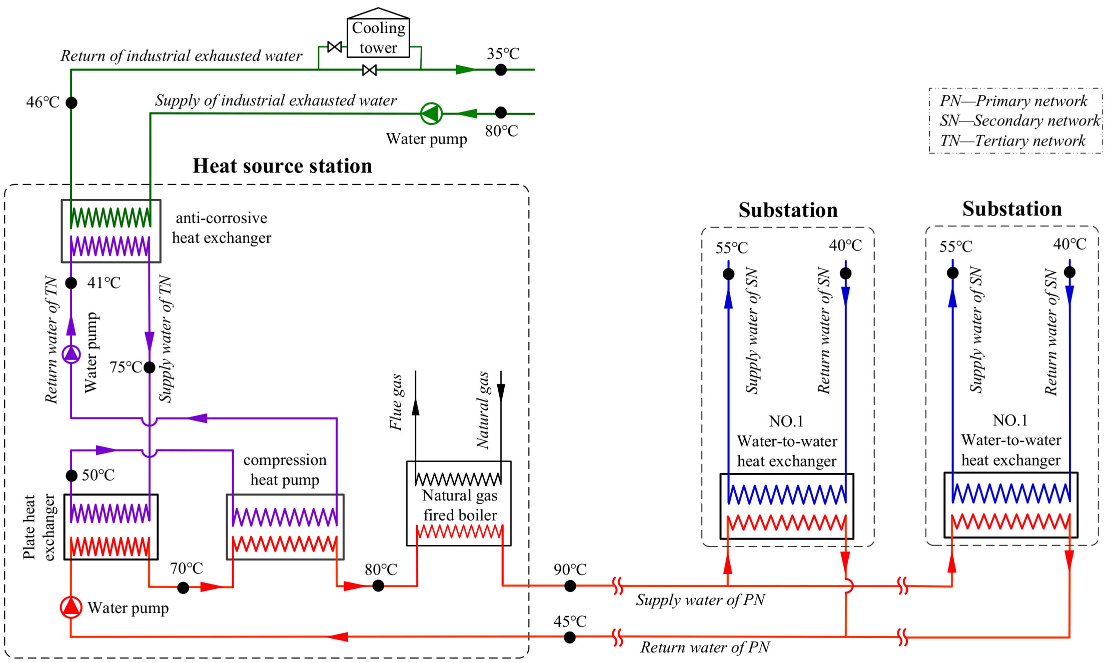

Figure 3. Sketch of central heating system integrated with industrial exhausted heat using centralized electric compression heat pumps (CH-CHP).

As for the heat source station, exhausted heat is first transferred from industrial exhausted water to circulating water in the tertiary network via an anti-corrosive heat exchanger, and then it is transferred to that in the primary network by using a conventional plate heat exchanger and a centralized electric compression heat pump. In this way, exhausted heat is recovered by using both the conventional heat exchanger and the centralized electric compression heat pump. By using the centralized electric compression heat pump, exhausted heat can be upgraded to higher temperature. A higher return water temperature of the primary network would result in a higher return temperature of industrial exhausted water, and thus, the exhausted heat recovered decreases. To cover heat load demand, a natural gas-fired boiler is introduced to provide more heat load. The exhausted heat is transported to substations through the primary pipelines. In the substations, exhausted heat is transferred from circulating water in the primary network to that in the secondary network by a water-to-water heat exchanger. In the substations, the return water temperature of the primary network is much higher than that of the secondary network. This is one of the significant differences between the CH-CHP and CH-DHP.

For the CH-CHP, the conventional plate heat exchanger, the centralized electric compression heat pump, and the natural gas-fired boiler are used to regulate the heating capacity of the central heating system to cover the growing demand of heat load as the outdoor ambient temperature rises.

In comparison to the CH-DHP, the CH-CHP features a higher return water temperature of the primary network and lower utilization rate of industrial exhausted heat.

2.3. Operating Principle of CH-WHE

A sketch of the CH-WHE is illustrated in Figure 4.

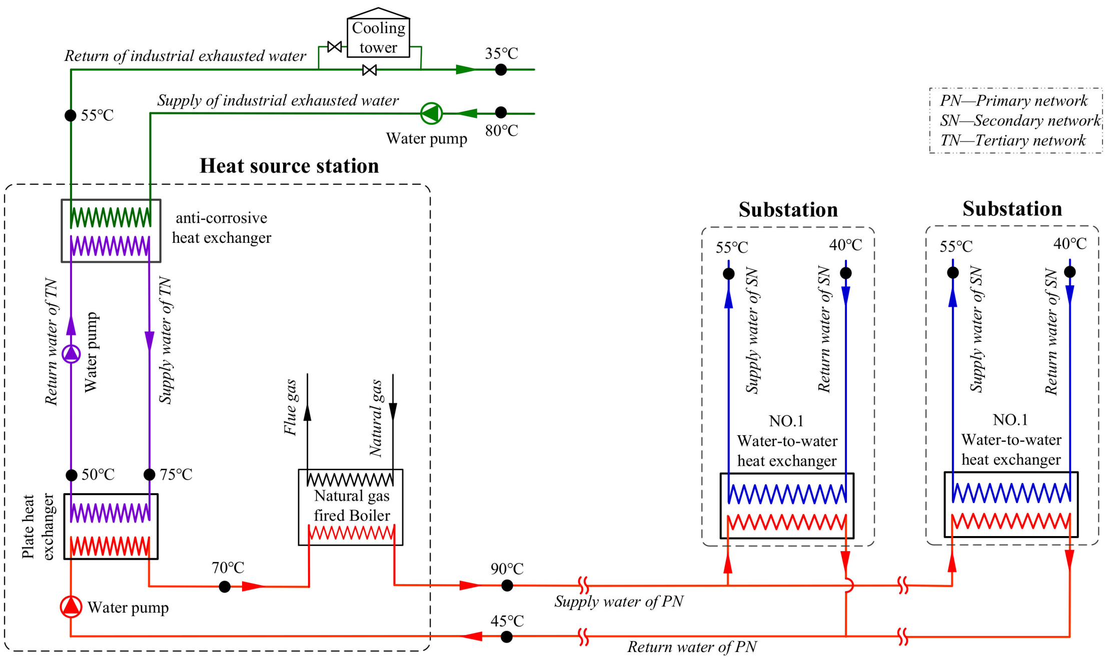

Figure 4. Sketch of conventional central heating system integrated with industrial exhausted heat using heat exchanger (CH-WHE).

The difference in system composition between the CH-CHP and CH-WHE is mainly located at the heating station. In comparison to the CH-CHP, the CH-WHE does not comprise a centralized electric compression heat pump in the heat source station, and its return temperature of industrial exhausted water from the anti-corrosive heat exchanger increases. Thus, the utilization rate of industrial exhausted heat in the CH-WHE is much smaller than that in the CH-CHP.

Comparing with both the CH-CHP and CH-WHE, the CH-DHP is featured by a lower return water temperature of the primary network, higher utilization rate of exhausted heat, and zero consumption of natural gas.

3. Thermodynamic Model

3.1. Main Equipment

(1) Electric compression heat pump Models of the compressor [28,29] are referred:

$$Q_{chp,con}(t_{ot}) = m_{hw}\left[h_{hw,out}(t_{ot}) - h_{hw,in}(t_{ot})\right] \tag{1}$$

$$m_{hw}\left[h_{hw,out}(t_{ot}) - h_{hw,in}(t_{ot})\right] = m_{chp,r}\left[h_{chp,con,r,in}(t_{ot}) - h_{chp,con,r,out}(t_{ot})\right] \tag{2}$$

$$Q_{chp,eva}(t_{ot}) = m_{cw}[h_{cw,in}(t_{ot}) - h_{cw,out}(t_{ot})] \tag{3}$$

$$m_{cw}[h_{cw,in}(t_{ot}) - h_{cw,out}(t_{ot})] = m_{chp,r}\left[h_{chp,eva,r,out}(t_{ot}) - h_{chp,eva,r,in}(t_{ot})\right] \tag{4}$$

$$W_{chp,com}(t_{ot}) = m_{chp,r}\left[h_{chp,con,r,in}(t_{ot}) - h_{chp,eva,r,out}(t_{ot})\right]/\eta_{me} \tag{5}$$

$$Q_{chp}(t_{ot}) = Q_{chp,eva}(t_{ot}) + W_{chp,com}(t_{ot}) \tag{6}$$

$$COP_{chp}(t_{ot}) = Q_{chp,eva}(t_{ot})/W_{chp,com}(t_{ot}) \tag{7}$$

(2) Hybrid heat exchanger unit

$$Q_{hhe}(t_{ot}) = m_{hw}\left[h_{hw,in}(t_{ot}) - h_{hw,out}(t_{ot})\right] + W_{hhe,com}(t_{ot}) \tag{8}$$

$$m_{hw}\left[h_{hw,in}(t_{ot}) - h_{hw,out}(t_{ot})\right] + W_{hhe,com}(t_{ot}) = m_{cw}[h_{cw,out}(t_{ot}) - h_{cw,in}(t_{ot})] \tag{9}$$

$$Q_{hhe,whe}(t_{ot}) = m_{hw}\left[h_{hw,in}(t_{ot}) - h_{whe,hw,out}(t_{ot})\right] \tag{10}$$

$$m_{hw}\left[h_{hw,in}(t_{ot}) - h_{whe,hw,out}(t_{ot})\right] = m_{cw,whe}\left[h_{whe,cw,out}(t_{ot}) - h_{cw,in}(t_{ot})\right] \tag{11}$$

$$Q_{hhe,con}(t_{ot}) = m_{hhe,con,cw}\left[h_{hhe,con,cw,out}(t_{ot}) - h_{cw,in}(t_{ot})\right] \tag{12}$$

$$m_{cw,con}\left[h_{hhe,con,cw,out}(t_{ot}) - h_{cw,in}(t_{ot})\right] = m_{hhe,r}\left[h_{hhe,con,r,in}(t_{ot}) - h_{hhe,con,r,out}(t_{ot})\right] \tag{13}$$

$$Q_{hhe,eva}(t_{ot}) = m_{hw}\left[h_{hhe,whe,hw,out}(t_{ot}) - h_{hw,out}(t_{ot})\right] \tag{14}$$

$$m_{hw}\left[h_{hhe,whe,hw,out}(t_{ot}) - h_{hw,out}(t_{ot})\right] = m_{hhe,r}\left[h_{hhe,eva,r,out}(t_{ot}) - h_{hhe,con,r,out}(t_{ot})\right] \tag{15}$$

$$W_{hhe,com}(t_{ot}) = m_{hhe,r}\left[h_{hhe,con,r,in}(t_{ot}) - h_{hhe,eva,r,out}(t_{ot})\right]/\eta_{me} \tag{16}$$

$$COP_{chp,hhe}(t_{ot}) = Q_{hhe,\ eva}(t_{ot})/W_{hhe,com}(t_{ot}) \tag{17}$$

$$Q_{hhe}(t_{ot}) = Q_{hhe,whe}(t_{ot}) + Q_{hhe,con}(t_{ot}) \tag{18}$$

$$Q_{hhe}(t_{ot}) = Q_{hhe,whe}(t_{ot}) + Q_{hhe,eva}(t_{ot}) + W_{hhe,com}(t_{ot}) \tag{19}$$

(3) Water-to-water heat exchanger A model of the heat exchanger [30] is referred:

$$Q_{whe}(t_{ot}) = m_{hw}\left[h_{hw,in}(t_{ot}) - h_{hw,out}(t_{ot})\right] \tag{20}$$

$$m_{hw}\left[h_{hw,in}(t_{ot}) - h_{hw,out}(t_{ot})\right] = m_{cw}[h_{cw,out}(t_{ot}) - h_{cw,in}(t_{ot})] \tag{21}$$

(4) Circulating water pump

$$W_{wp} = \sum_{j=1}^{n}\left(m_j \cdot g \cdot \Delta H_j/\eta_{wp}\right) \tag{22}$$

$$\zeta = \sum_{j=1}^{n} \zeta_{cf,j} + \sum_{j=1}^{n} \zeta_{cl,j} \tag{23}$$

$$\Delta H = \zeta \left(\frac{m}{\rho} \right)^2 \tag{24}$$

(5) Natural gas fired boiler

$$Q_{gfb}(t_{ot}) = \eta_{gfb} B_{gfb} h_{lhv} \tag{25}$$

$$Q_{gfb}(t_{ot}) = m_{hw} \left[h_{hw,gfb,out}(t_{ot}) - h_{hw,gfb,in}(t_{ot}) \right] \tag{26}$$

3.2. Exergy Calculation

The formula of specific exergy is expressed as [31]:

$$e = (h - h_0) - T_0(s - s_0) \tag{27}$$

The formula of chemical specific exergy is expressed as follows [32]:

$$e_{y,ch} = \sum y_j e_j^0 + RT_0 \sum y_j ln y_j \tag{28}$$

$$\sum m_{in} + \sum m_{out} = 0 \tag{29}$$

$$\sum Q_{in} + \sum (m_{in} \cdot h_{in}) - \sum (m_{out} \cdot h_{out}) = 0 \tag{30}$$

$$\sum \left[Q_{c0} \left(1 - \frac{T_0}{T} \right) \right] + \sum Ex_w + \sum (m_{in} e_{in}) - \sum m_{out} e_{out} = \sum I \tag{31}$$

3.3. Central Heating System

For the central heating system, the energy conversation equation is written as:

$$\left[Q_{whe}(t_{ot}) + Q_{chp}(t_{ot}) + W_{wp} + \sum_{j=1}^{n} W_{hhe,com,j}(t_{ot}) \right] \cdot (1 - \eta_{lo}) = \sum_{j=1}^{n} Q_{hhe,j}(t_{ot}) \tag{32}$$

During a heating period, the total heat output of the central heating system is calculated as:

$$\Omega = \int \left[Q_{whe}(t_{ot}) + Q_{chp}(t_{ot}) + W_{wp} + W_{hhe}(t_{ot}) \right] \cdot (1 - \eta_{lo}) d\tau \tag{33}$$

During a heating period, the total electricity consumption of the central heating system is calculated as:

$$\Phi = \int \left[W_{chp}(t_{ot}) + W_{hhe}(t_{ot}) + W_{wp} \right] d\tau \tag{34}$$

3.4. Evaluation Indicators

During a heating period, the COP of the three schemes varies greatly with outdoor ambient temperature. To clearly clarify the performance of the central heating system, the annual coefficient of performance (*ACOP*) is presented, and it is defined to be the ratio of annual heat provision to annual electricity consumption, as follows:

$$ACOP = \frac{\int Q_{hhe}(t_{ot}) d\tau}{\int \left[W_{chp}(t_{ot}) + W_{wp}(t_{ot}) + W_{eng}(t_{ot}) \right] d\tau} \tag{35}$$

The annual electricity consumption consists of that of the compressor and water pumps, and the electricity converted from annual natural gas consumption according to the thermal efficiency of current gas-fired power plants of 40%.

To assess exergy performance of these three central heating schemes during a heating period, the annual product exergy efficiency (*APEE*) is presented, and it is defined to be ratio of annual exergy output to annual exergy input, as follows:

$$APEE = \frac{\int Ex_{op}(t_{ot})d\tau}{\int Ex_{ip}(t_{ot})d\tau} \tag{36}$$

The annual exergy output is the exergy difference between supply water and return water of the secondary network. For a central heating system, the annual input exergy comprises electricity, input exergy of exhausted heat, and chemical exergy of natural gas.

4. Case Study

A case of the low-temperature central heating system integrated with industrial exhausted heat is located in Northern China, and the industrial exhausted water is slag water from the steel plant.

4.1. Description of the Case

To analyze the three low-temperature central heating systems integrated with industrial exhausted heat, some information is given as follows:

(1) For the given steel plant, the mass flow rate and supply temperature of exhausted water are 265.54 kg/s and 80 °C, and the requirement of the return temperature of waste water is 35 °C.
(2) Heat load is calculated according to both the Design Manual of Central heating [33] and the ratio of heat loss to heating load of 5% [34].
(3) Outdoor/indoor design temperatures are −21.1 °C/20 °C for space heating, and the annual heating period is 169 days.
(4) Supply and return water temperatures of the secondary network are 55 °C and 40 °C, respectively.
(5) Mass flow rates of the primary, secondary, and tertiary networks are constant during a heating period.
(6) For electric compression heat pumps with R134a, both mechanical efficiency of the compressor and efficiency of the motor are 90% [35,36].
(7) Benchmark state parameters are 5 °C and 101.325 kPa for calculating exergy efficiency.
(8) Interest rate is 4.8% for calculating economic benefit.
(9) Annual heating price is 30 ¥/m^2, and the prices of waste heat, electricity, and natural gas are 15 ¥/GJ, 0.7795 ¥/kWh, and 2.36 ¥/Nm^3 (1 € = 7.8063 ¥ and 1 $ = 6.5848 ¥), respectively.

Main thermal parameters of the three central heating systems are listed in Table 1.

Table 1 shows that both heat load and temperature difference between supply and return water of the primary network are the same for the three central heating schemes. The potential of recovering exhausted heat in the CH-DHP is greatest, and that in the CH-WHE is smallest among the three central heating schemes. Thus, the role played by the distributed electric compression heat pump in recovering exhausted heat is greater than that by the centralized one. Besides, the *COP* of the distributed electric compression heat pump is much higher than that of the centralized one.

Table 1. Main thermal parameters of the three central heating systems.

Subsystem	Equipment	Items	CH-DHP	CH-CHP	CH-WHE
Heating station	Slag slushing water	Mass flow rate (kg/s)	265.54	265.54	265.54
	Anticorrosive plate heat exchanger	Heating capacity (W)	47,625,500	37,474,300	27,746,420
	Plate heat exchanger	Heating capacity (W)	47,625,500	27,746,420	27,746,420
	Compression heat pump	Heating capacity (W)	——	11,873,340	——
		COP (W/W)	——	4.50	——
	Natural gas-fired boiler	Heating capacity (W)	——	10,380,250	22,253,580
Primary heating network	Circulating water	Mass flow rate (kg/s)	253.20	265.54	265.54
Heating substation	Compression heat pumps	Heating capacity (W)	21,428,000	——	——
		COP (W/W)	7.50	——	——
	Water-to-water heat exchangers	Heating capacity (W)	28,572,000	50,000,000	50,000,000
Secondary heating network	Circulating water	Mass flow rate (kg/s)	796.49	796.49	796.49

4.2. Thermodynamic Performance

A longer exhausted heat transportation distance would affect the *ACOP*s and *APEE*s of the three central heating schemes. The impacts of exhausted heat transportation distance on the *ACOP*s of three central heating schemes are illustrated in Figure 5.

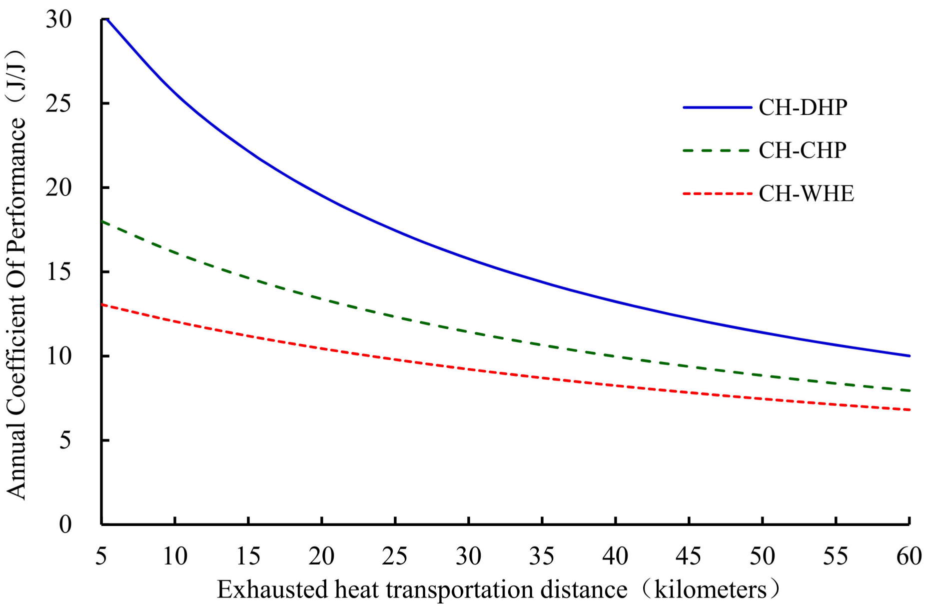

Figure 5. Impact of exhausted heat transportation distance on annual coefficients of performance (*ACOP*s).

Figure 5 shows that the *ACOP*s of the three central heating schemes decrease rapidly with the distance of transporting exhausted heat. It is because the power of water pumps becomes large with the increase in distance of transporting exhausted heat, but heat output is constant. Among the three central heating schemes, the *ACOP* of the CH-DHP is largest, and that of the CH-WHE is smallest. The *ACOP* of the CH-DHP is much larger than that of the CH-CHP. It indicates that the role played by the distributed electric compression heat pumps in improving the *ACOP* of the low-temperature central heating system integrated with industrial exhausted heat is greater than that by the centralized electric compression heat pump. Thus, from the aspect of the *ACOP*, the CH-DHP is a favorable choice for the low-temperature central heating systems integrated with industrial exhausted heat.

Annual electricity consumption distributions of the three central heating schemes are illustrated in Figure 6.

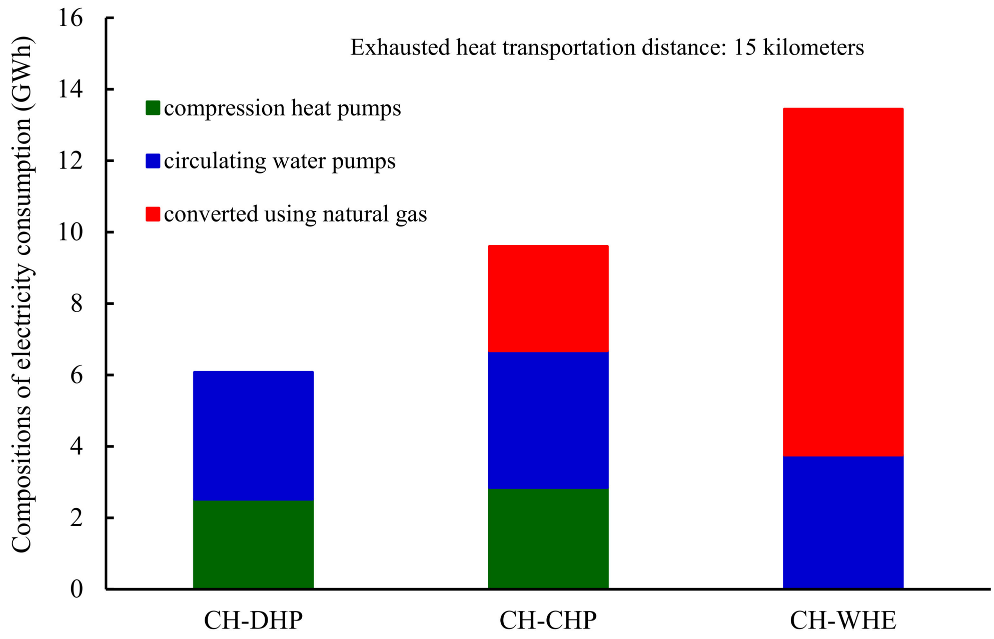

Figure 6. Distributions of annual electricity consumption of central heating scheme.

Figure 6 indicates that when the distance of transmitting exhausted heat is 15 km, the annual electricity consumption of the CH-DHP is smallest, and that of the CH-WHE is largest among the three central heating schemes. The annual electricity consumption of electric compression heat pumps in the CH-DHP is lower than that in the CH-CHP, and the annual electricity consumption of water pumps in the CH-DHP is also lower than that in the CH-CHP. As for the CH-DHP, the annual electricity consumption of water pumps accounts for about 58.5% of total electricity consumption. Besides, there is a certain amount of electricity converted using annual natural gas consumption in the CH-CHP and CH-WHE. In comparison to the CH-CHP, the CH-WHE consumes more natural gas, which could convert more electricity, and it has no electricity consumption of electric compression heat pumps. Thus, recovering exhausted heat by using electric compression heat pumps contributes to reducing annual natural gas consumption, and helps to improve the *ACOP* of the low-temperature central heating system integrated with industrial exhausted heat.

The impacts of exhausted heat transportation distance on the *APEE* are shown in Figure 7.

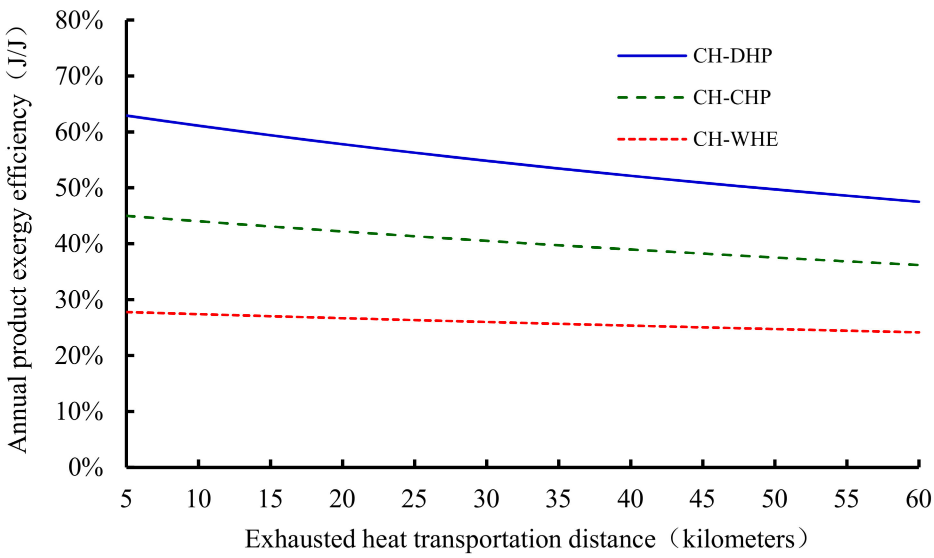

Figure 7. Impacts of exhausted heat transportation distance on annual product exergy efficiency (*APEE*).

Figure 7 shows that a longer exhausted heat transportation distance results in low *APEE*s of the three central heating schemes. Among the three central heating schemes, the *APEE*s of the CH-DHP is largest, and that of the CH-WHE is smallest. With the exhausted heat transportation distance becoming longer, *APEE* differences among the CH-DHP, CH-CHP, and CH-WHE become smaller. In comparison to the CH-CHP, the CH-DHP has a much higher *APEE*. Thus, the role played by the distributed electric compression heat pumps in improving the *APEE* of the low-temperature central heating systems integrated with industrial exhausted heat is greater than that by the centralized electric compression heat pump. From the aspect of the *APEE*, the CH-DHP is preferred to the low-temperature central heating systems integrated with industrial exhausted heat.

When the distance of transmitting exhausted heat is 15 km, compositions of annual energy consumption of the three central heating schemes are illustrated in Figure 8.

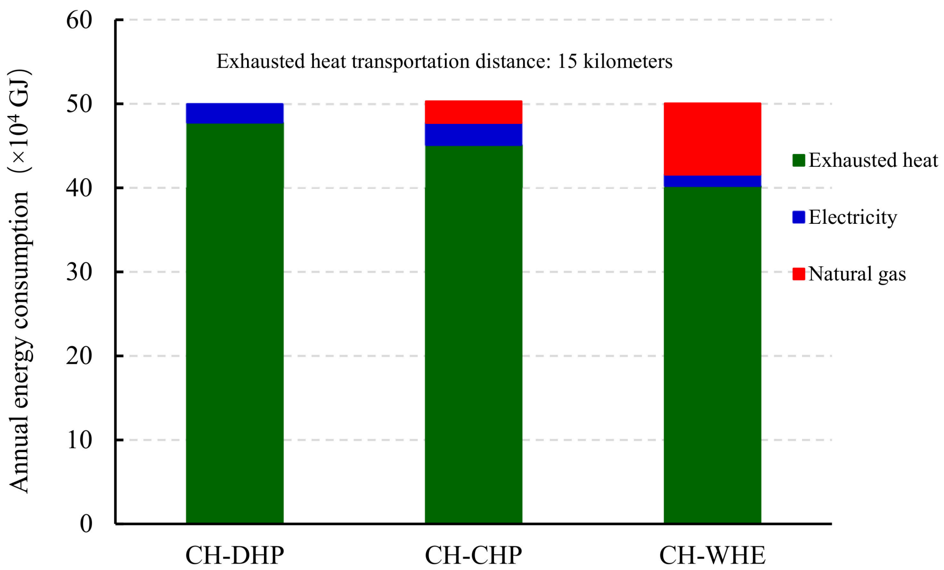

Figure 8. Composition of annual energy consumption.

Figure 8 shows that the amount of exhausted heat utilized by the CH-DHP is about 1.06 times of that by the CH-CHP, and about 1.19 times of that by the CH-WHE. During a heating period, the annual electricity consumption of the CH-DHP is lower than that of the CH-CHP, but higher than that of the CH-WHE. During a heating period, the annual natural gas consumption of the CH-WHE is about 3.31 times of that of the CH-CHP, and that of the CH-DHP is zero. During a heating period, the CH-DHP can recover exhausted heat of slag water by about 4.78×10^5 GJ. In comparison to the other two central heating schemes, the CH-DHP has a greater potential of energy-saving by recovering more exhausted heat. Thus, the role played by the distributed electric compression heat pumps in improving the thermodynamic performance of the low-temperature central heating systems integrated with industrial exhausted heat is greater than that by the centralized electric compression heat pump.

In summary, the CH-DHP has higher thermodynamic performance, and a greater potential of energy-saving, and thus, its configuration is optimal.

4.3. Economic Benefit

Equipment costs are determined by China's current prices, and costs of both installation and maintenance are calculated by the guidance of China's Public Project Investment Estimation [37]. When the exhausted heat transportation distance is 15 km, capital investment distributions of the three central heating systems are shown in Table 2.

Table 2. Capital investment distributions of the three central heating systems.

Subsystem	Item	CH-DHP	CH-CHP	CH-WHE
Heating station	Equipment cost (¥)	9,679,140	17,179,150	13,679,160
	Construction cost (¥)	1,451,870	2,576,880	2,051,880
	Installment cost (¥)	1,935,830	3,435,830	2,735,830
	Other cost (¥)	3,037,440	4,183,370	3,658,370
Primary heating network (15 km)	Pipe and equipment cost (¥)	14,630,100	15,428,720	15,411,370
	Construction cost (¥)	20,830,960	21,075,590	21,075,590
	Installment cost (¥)	7,092,210	7,300,860	7,297,390
	Other cost (¥)	3,546,110	3,650,430	3,648,700
Heating substation	Equipment cost (¥)	12,379,910	5,000,000	5,000,000
	Construction cost (¥)	1,856,990	750,000	750,000
	Installment cost (¥)	2,475,980	1,000,000	1,000,000
	Other cost (¥)	1,856,990	750,000	750,000
Total capital investment		80,773,530	82,330,830	77,058,290

Remarks: 1 € = 7.8063 ¥ and 1 $ = 6.5848 ¥.

Table 2 shows that the capital investment of the CH-DHP is about 0.98 times that of the CH-CHP, and about 1.05 times that of the CH-WHE. The ratio of the primary network's capital investment to total capital investment is about 57.1% for the CH-DHP, about 57.6% for the CH-CHP, and about 61.6% for the CH-WHE. Thus, the capital investment of the primary network is the major composition of total capital investment for the low-temperature central heating system integrated with industrial exhausted heat. A longer exhausted heat transportation distance would result in higher capital investment, and it would have a great influence on financial benefit of the three central heating systems.

In general, heating cost comprises energy cost and nonenergy cost. The nonenergy cost is made up of maintenance cost, labor cost, and the amortization cost of investment capital, and the energy cost consists of waste heat cost, electricity cost, and natural gas cost. According to the life cycle of equipment, the formula of amortization cost is expressed as:

$$AC = IC \cdot \left[\frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right] \tag{37}$$

where AC, IC, and n are amortization cost, investment cost, and the life cycle of equipment. The value of n is 40 for the heating network, and 15 for the other equipment.

For the three central heating schemes, compositions of heating cost are depicted in Figure 9.

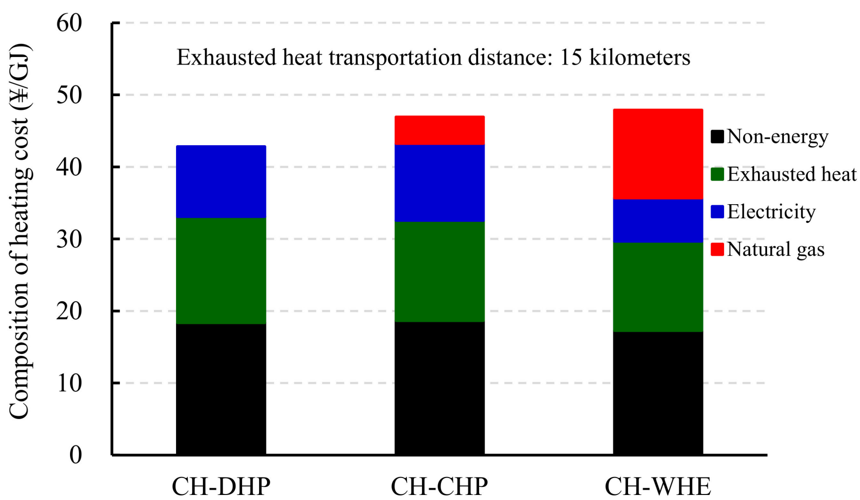

Figure 9. Compositions of heating cost.

Figure 9 indicates that the heating cost of the CH-DHP is lowest, and that of the CH-WHE is highest among the three central heating schemes. With regard to the exhausted heat transportation distance of 15 km, the heating cost of the CH-DHP is about 4.12 ¥/GJ less than that of the CH-CHP, and about 5.08 ¥/GJ less than that of the CH-WHE. The percentage of energy cost in heating cost is about 57.1% for the CH-DHP, about 60.2% for the CH-CHP, and about 63.9% for the CH-WHE.

Payback period is generally used to assess the economic benefit of central heating systems, and its calculating formula is expressed as:

$$PP = \frac{IC}{AP} \tag{38}$$

where *PP*, *IC*, and *AP* are payback period, investment capital, and annual profit.

Impacts of exhausted heat transportation distance on payback period are illustrated in Figure 10.

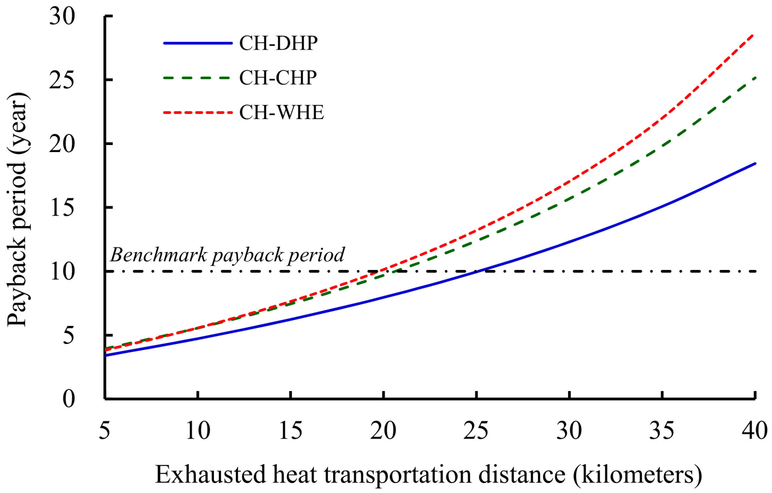

Figure 10. Impacts of exhausted heat transportation distance on payback period.

Figure 10 illustrates that with the increase in exhausted heat transportation distance, the payback periods of the three central heating schemes become long, and payback period differences among the CH-DHP, CH-CHP, and CH-WHE become big. Besides, with regard to the same exhausted heat transportation distance, the payback period of the CH-DHP is always shortest among the three central heating schemes. In accordance with the benchmark payback period of central heating systems, the economical distances of transporting the exhausted heat of the CH-DHP, CH-CHP, and CH-WHE are about 25.1, 20.7, and 19.5 km, respectively. Thus, the economical distance of transporting the exhausted heat of the CH-DHP is much longer than that of the other two central heating schemes.

Comparing with the other two central heating schemes, the CH-DHP has a lower heating cost, shorter payback period, and longer economical distance of transporting exhausted heat. Thus, the role played by the distributed electric compression heat pump in improving the financial benefit of the low-temperature central heating system integrated with industrial exhausted heat is greater than that by the centralized electric compression heat pump. From the aspect of economic benefit, the configuration of the CH-DHP is preferred.

5. Conclusions

The proposed low-temperature central heating systems integrated with industrial exhausted heat using distributed electric compression heat pumps is studied from the aspect of thermal performance and economic benefit, and conclusions are listed as follows:

(1) In comparison to the other two central heating schemes, the proposed low-temperature central heating system integrated with industrial exhausted heat using distributed electric compression

heat pumps has higher thermal performance and better economic benefit, and its system configuration is optimal.

(2) Compared with the low-temperature central heating system integrated with industrial exhausted heat using centralized electric compression heat pumps, the proposed one using distributed electric compression heat pumps could improve the *ACOP* by about 5.12, and *APEE* by 14.9% when the exhausted heat transportation distance is 25 km.

(3) The roles played by the distributed electric compression heat pumps in improving the thermal performance and economic effect of the low-temperature central heating system integrated with industrial exhausted heat are greater than those by the centralized electric compression heat pumps.

(4) When the exhausted heat transportation distance is 25 km, the proposed low-temperature central heating system integrated with the industrial exhausted heat using distributed electric compression heat pumps can reduce the heating cost by about 4.40 ¥/GJ, and decrease the payback period by about 2.4 years in comparison to that using centralized electric compression heat pumps.

(5) The proposed low-temperature central heating system integrated with industrial exhausted heat using distributed electric compression heat pumps has a longer economical distance of transmitting exhausted heat, which is about 25.1 km, and it would be a better choice for recovering industrial exhausted heat in Northern China.

Author Contributions: Conceptualization, F.S. and L.F.; methodology, F.S.; software, Y.X.; validation, S.S. and Y.X.; formal analysis, F.S.; investigation, Y.X.; resources, F.S.; data curation, Y.X.; writing—original draft preparation, Y.X.; writing—review and editing, F.S.; visualization, Y.X.; supervision, F.S.; project administration, Beijing University of Civil Engineering and Architecture; funding acquisition, Technology Program of Beijing Education Committee. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Technology Program of Beijing Education Committee, grant number Z18030 and China Scholarship Council, grant number 201909960004.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CH-DHP	central heating system integrated with industrial exhausted heat using distributed electric compression heat pumps
CH-CHP	central heating system integrated with industrial exhausted heat using centralized electric compression heat pumps
CH-WHE	conventional central heating system integrated with industrial exhausted heat using heat exchanger
PN	primary network
SN	secondary network
Q	heating capacity, W
m	mass flow rate, kg/s
h	specific enthalpy, J/kg
W	power, W
COP	coefficient of performance, W/W
T/t	temperature, K/°C
j,n	number
η	efficiency, %
$\triangle H$	pressure head, mH_2O
g	gravitational acceleration, m/s^2
ζ	resistance coefficient
ρ	density, kg/m^3
B	natural gas consumption, kg/s
e	specific exergy, J/kg
s	entropy, J/K
y	element

Ex	exergy flux, J
I	anergy flux, J
Ω	total heat output, J
τ	time, s
Φ	annual electricity consumption, J
ACOP	annual coefficient of performance
APEE	annual product exergy efficiency
AC	amortization cost, ¥
IC	investment cost, ¥
i	annual interest rate, %
PP	payback period, year
AP	annual profit, ¥
Sub- and Super-Scripts	
chp	compression heat pump
con	condenser
ot	outdoor air temperature
hw	hot water
out	outlet
in	inlet
r	refrigerant
eva	evaporator
cw	cold water
com	compressor
me	mechanical efficiency
hhe	hybrid heat exchanger
whe	water-water heat exchanger
wp	water pump
cf	coefficient of friction resistance
cl	coefficient of local resistance
gfb	gas fired boiler
lhv	lower heating value
0	referred state point
ch	chemical exergy
co	studied object
w	work
lo	loss
op	output
ip	input
eng	electricity converted using natural gas

References

1. Building Energy Research Center of Tsinghua University. *Annual Report of China Building Energy Conservation 2019*; China's Architecture and Building Press: Beijing, China, 2019. (In Chinese)
2. National Bureau of Statistics of China. 2018. Available online: http://data.stats.gov.cn/easyquery.htm?cn=C01 (accessed on 1 February 2019). (In Chinese)
3. Xiandong, T.; Xinyang, H.; Yi, F.; Lijie, G.; Baoguo, S. Review of 2014 China's Power Supply and Demand, and 2015 Forecast. *Electric Power* **2015**, *48*, 1–5. (In Chinese)
4. Lin, J.; Kahrl, F.; Liu, X. A regional analysis of excess capacity in China's power systems. *Resour. Conserv. Recy.* **2018**, *129*, 93–101. [CrossRef]
5. Togawa, T.; Fujita, T.; Dong, L.; Fujii, M.; Ooba, M. Feasibility assessment of the use of power plant-sourced waste heat for plant factory heating considering spatial configuration. *J. Clean. Prod.* **2014**, *81*, 60–69. [CrossRef]
6. Ma, H.; Du, N.; Zhang, Z.; Lyu, F.; Deng, N.; Li, C.; Yu, S. Assessment of the optimum operation conditions on a heat pipe heat exchanger for waste heat recovery in steel industry. *Renew. Sustain. Energy Rev.* **2017**, *79*, 50–60. [CrossRef]

7. Zhang, J.; Zhang, H.H.; He, Y.L.; Tao, W.Q. A comprehensive review on advances and applications of industrial heat pumps based on the practices in China. *Appl. Energy* **2016**, *178*, 800–825. [CrossRef]
8. Wang, M.; Deng, C.; Wang, Y.; Feng, X. Exergoeconomic performance comparison, selection and integration of industrial heat pumps for low grade waste heat recovery. *Energy Convers. Manag.* **2020**, *207*, 112532. [CrossRef]
9. Karner, K.; McKenna, R.; Klobasa, M.; Kienberger, T. Industrial excess heat recovery in industry-city networks: A technical, environmental and economic assessment of heat flexibility. *J. Clean. Prod.* **2018**, *193*, 771–783. [CrossRef]
10. Xu, Z.Y.; Wang, R.Z.; Yang, C. Perspectives for low-temperature waste heat recovery. *Energy* **2019**, *17*, 1037–1043. [CrossRef]
11. Sun, F.; Zhao, J.; Fu, L.; Sun, J.; Zhang, S. New district heating system based on natural gas-fired boilers with absorption heat exchangers. *Energy* **2017**, *138*, 405–418. [CrossRef]
12. Fang, H.; Xia, J.; Jiang, Y. Key issues and solutions in a district heating system using low-grade industrial waste heat. *Energy* **2015**, *86*, 589–602. [CrossRef]
13. Li, Y.; Xia, J.; Fang, H.; Su, Y.; Jiang, Y. Case study on industrial surplus heat of steel plants for district heating in Northern China. *Energy* **2016**, *102*, 397–405. [CrossRef]
14. Oluleye, G.; Smith, R.; Jobson, M. Modeling and screening heat pump options for the exploitation of low grade waste heat in process sites. *Appl. Energy* **2016**, *169*, 267–286. [CrossRef]
15. Lund, R.; Ilic, D.D.; Trygg, L. Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark. *J. Clean. Prod.* **2016**, *139*, 219–229. [CrossRef]
16. Yang, X.; Svendsen, S. Ultra-low temperature district heating system with central heat pump and local boosters for low-heat-density area: Analyses on a real case in Denmark. *Energy* **2018**, *159*, 243–251. [CrossRef]
17. Kosmadakis, G. Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries. *Appl. Therm. Eng.* **2019**, *156*, 287–298. [CrossRef]
18. Averfalk, H.; Ingvarsson, P.; Persson, U.; Gong, M.; Werner, S. Large heat pumps in Swedish district heating systems. *Renew. Sustain. Energy Rev.* **2017**, *79*, 1275–1284. [CrossRef]
19. Yang, Y.; Wu, K.; Long, H.; Gao, J.; Yan, X.; Kato, T.; Suzuoki, Y. Integrated electricity and heating demand-side management for wind power integration in China. *Energy* **2014**, *78*, 235–246. [CrossRef]
20. Hu, B.; Liu, H.; Wang, R.Z.; Li, H.; Zhang, Z.; Wang, S. A high-efficient centrifugal heat pump with waste heat recovery recovery for district heating. *Appl. Therm. Eng.* **2017**, *125*, 359–365. [CrossRef]
21. Kwon, O.; Cha, D.; Park, C. Performance evaluation of a two-stage compression heat pump system for district heating using waste energy. *Energy* **2013**, *57*, 375–381. [CrossRef]
22. Cao, X.Q.; Yang, W.W.; Zhou, F.; He, Y.L. Performance analysis of different high-temperature heat pump systems for low-grade waste heat recovery. *Appl. Therm. Eng.* **2014**, *71*, 291–300. [CrossRef]
23. Hu, B.; Xu, S.; Wang, R.Z.; Liu, H.; Han, L.; Zhang, Z.; Li, H. Investigation on advanced heat pump systems with improved energy efficiency. *Energy Convers. Manag.* **2019**, *192*, 161–170. [CrossRef]
24. Bamigbetan, O.; Eikevik, T.M.; Nekså, P.; Bantle, M.; Schlemminger, C. The development of a hydrocarbon high temperature heat pump for waste heat recovery. *Energy* **2019**, *173*, 1141–1153. [CrossRef]
25. Fangtian, S.; Haoyuan, Y.; Lin, F.; Junwei, G. Operation characteristics and application of low temperature industrial waste heating system based on compression heat exchanger. *Acta Energy Sol. Sin.* **2018**, *39*, 1495–1501. (In Chinese)
26. Sun, J.; Fu, L.; Zhang, S. Experimental study of heat exchanger basing on absorption cycle for CHP system. *Appl. Therm. Eng.* **2016**, *102*, 1280–1286. [CrossRef]
27. Sun, F.; Chen, X.; Fu, L.; Zhang, S. Configuration Optimization of an Enhanced Ejector Heat Exchanger Based on an Ejector Refrigerator and a Plate Heat Exchanger. *Energy* **2018**, *164*, 408–417. [CrossRef]
28. Liu, J.; Li, Q.; Wang, F.; Zhou, L. A new model of screw compressor for refrigeration system simulation. *Int. J. Refrig.* **2012**, *35*, 861–870. [CrossRef]
29. Yu, F.W.; Chan, K.T. Improved energy performance of air cooled centrifugal chillers with variable chilled water flow. *Energy Convers. Manag.* **2008**, *49*, 1595–1611. [CrossRef]
30. Browne, M.W.; Bansal, P.K. An elemental NTU-ε model for vapour-compression liquid chillers. *Int. J. Refrig.* **2001**, *24*, 612–627. [CrossRef]
31. Cengel, Y.A.; Boles, M.A. *Thermodynamics: An Engineering Approach*, 8th ed.; McGraw-Hill Eduation Publisher: Boston, MA, USA, 2015.
32. Weicheng, W.; Runtian, M. *Energy Efficient Utilization of Technology*; Chemical Industry Press: Beijing, China, 1984. (In Chinese)

33. Xiaoqing, L. *Practical Heating and Air Conditioning Design Manual*, 2nd ed.; China's Architecture and Building Press: Beijing, China, 2008. (In Chinese)
34. Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD). *Industry standard of the People's Republic of China: Design code for city heating network (CJJ 34-2010)*; China's Architecture and Building Press: Beijing, China, 2010. (In Chinese)
35. Ahamed, J.U.; Saidur, R.; Masjuki, H.H. A review on exergy analysis of vapor compression refrigeration system. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1593–1600. [CrossRef]
36. Tian, Y.; Yuan, H.; Wang, C.; Wu, H.; Xing, Z. Numerical investigation on mass and heat transfer in an ammonia oil-free twin-screw compressor with liquid injection. *Int. J. Therm. Sci.* **2017**, *120*, 175–184. [CrossRef]
37. Standard Fixed Institute of MOHURD. *Indicators of Investment in Public Works Estimates*; China's Planning Press: Beijing, China, 2007. (In Chinese)