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Systematic optimization for the utilization of low-temperature industrial excess heat for district heating

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ABSTRACT

Because of extensive heat shortage and serious air pollution, industrial excess heat (IEH) has attracted much attention in the district heating (DH) markets of Northern China, as it has great potential for recycling and satisfying the large demand. Most of the available IEH is released at low temperature by steel plants, chemical plants, etc., which are located far away from the heat users. The energy consumption and pipe investment for heat transportation should be optimized to improve the comprehensive efficiency. This study will use systematic models to make optimization to primary-network temperatures and corresponding connecting forms. Several suggestions will be proposed to help improving the energy efficiency. Furthermore, based on a real case study, two new schemes are proposed and compared with the existing scheme. The connecting form of the optimized scheme is different to conventional heat pump systems using sources such as sewage and ambient water. The rated COP is estimated to be 6.16, and the annual electricity consumption is 40.78 kWh/GJ. The system has significant advantages in terms of energy savings and reductions in pollution emissions in comparison to conventional source systems, implying that it can be worth exploiting IEH even at low temperatures and long distances.

1. Introduction

Owing to air pollution characterized by hazy weather, clean heating has been a prevailing developing trend in Chinese heating systems. In 2017, Premier Li Keqiang announced a boost to clean heating in North China as an important task of the energy revolution in the report on the work of the government [1]. The goals and possible approaches for clean heating have already been established in the 13th five-year plan for building energy saving and green building development, aiming to facilitate the substitution of high-emission heat sources, increase the portion of clean energy, reduce the heat consumption of buildings, and improve the efficiency of district heating (DH) networks [2].

Clean energy will be required for the substitution of existing coal boilers and to meet the rapid increase in heating demand owing to urbanization. According to the Annual report on the energy efficiency of Chinese building, the total floor area that was heated in North China was 12 billion m^2 in 2013, of which approximately 9 billion m^2 was serviced by DH networks. The total heating demand is expected to reach a floor area of 20 billion m^2 in 2030 as urbanization is still progressing. As the heat source, coal boilers accounted for the largest portion of DH floor area at approximately 48%, followed by combined heat and power (CHP) at 42%, natural gas boilers at 8%, and renewable energy at less than 2% [3]. It is a great challenge to substantially transform the energy structure and simultaneously meet the fast-increasing demands.

A source of massive clean energy is essential to achieve clean heating. On the one hand, renewable energy should be exploited. In some advanced DH networks in Nordic countries, heat input is mainly constituted by biomass, waste, and some heat pumps with low-temperature sources such as sewage and ambient water [4–6]. Some of these heat sources are available in some places of China; hence, some studies and implementations of related technologies have already been conducted [7–9]. On the other hand, industrial excess heat (IEH) should be fully reused. The quantity of available IEH is estimated to be approximately 3 exajoule (EJ) during the heating period (approximately four months), which can heat a floor area of approximately 6 billion m^2 according to the national average heat intensity, which was 0.52 gigajoule (GJ) per m^2 in 2015 [10,11]. IEH has great potential as a future clean heat source under the

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prevailing conditions in China.

If IEH were allocated by temperature, heat at a temperature above 50 °C can be theoretically recycled by DH streams with the help of heat exchangers. Studies and demonstrations in both China and Europe have shown significant energy-saving effects and economic benefits of utilizing excess heat above 50 °C [12–18]. Heat below 50 °C needs an increase in temperature by heat pumps [19–21] or must be connected to low-temperature heating networks [22]. The utilization of such heat requires more investment and energy consumption, but it is still worth studying because this heat accounts for a significant proportion of the recoverable IEH. According to Luo's investigation on North China, more than 60% of the excess heat in the iron & steel industry and cement industry is below 50 °C [23]. The utilization of IEH below 50 °C can save energy in both the industrial side and DH side. In addition, as heat below 50 °C is normally released by cooling towers, consuming a large amount of water, its utilization also contributes to water saving, especially in North China, where water resources are very deficient [24].

In contrast to sewage and ambient water, the feasibility of excess heat below 50 °C is affected by not only the temperature level, but also the distance of transportation. If industrial plants are ordinarily located far away from the areas where heat demands are centralized or connected to existing networks, the high energy consumption of the water pump and extra investment in the piping network cannot be neglected, which implies that sometimes it makes sense to sacrify the energy efficiency of heat pumps to achieve lower energy consumption for the whole system.

Therefore, this study will focus on utilization of the distant and low-temperature IEH, exploring the feasibility and economy to integrate into large DH networks. This study will use systematic models to optimize system schemes in terms of primary-network temperatures and corresponding connecting forms. By studying how the optimized results are influenced by variable factors such as the heat-source temperature, secondary-network temperature, heat-pump installation conditions, and hydraulic conditions of the primary network, qualitative suggestions will be made for guiding system design. Furthermore, for a typical case in North China involving the recycling of IEH from a chemical plant for DH, modified systematic schemes will be proposed for improving the existing system scheme. With an analysis of the economic and environmental benefits, the potential of low-temperature and distant IEH will be assessed to achieve clean heating.

2. Models

In this section, a model will be introduced to study the influence of the primary-network temperatures and connecting forms on the comprehensive electric consumption, which takes both the heat pumps and water pumps into consideration. Factors such as the heat-source temperature, secondary-network temperature, heat-pump installation conditions, and hydraulic conditions of the primary network are variable during the optimization of the network temperatures and connecting forms.

2.1. DH network structure

In China, most large-scale DH systems have primary networks and secondary networks. In a long-distance transmission network, the transmission pipeline and distribution network constitute the primary network. Heat exchangers or heat pumps in substations transfer heat from the primary network to secondary networks. The independent hydraulic condition in each secondary network makes the entire system easy to construct and safe to operate.

Primary networks usually have the connecting structure shown in Fig. 1. It can be broken down into four parts: the heat-source station that oversees heat exploitation, the distribution network for heat distribution according to the heat demand of each substation, the transmission pipeline that connects the heat-source station and distribution network, and the substations for releasing the heat from the primary network to secondary networks. As an increasing number of distant heat sources are being integrated into DH networks, long-distance transmission pipelines are not rare in China. For example, the networks of Taiyuan connect CHP stations 40 km away [25]. The network in Jinan at a distance of 60 km is already under construction.

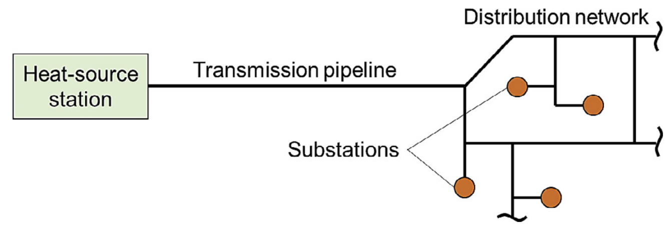

Fig. 1. Typical structure of a DH system.

2.2. Heat-transfer processes

In a heat-source station, low-temperature IEH is exploited for heating the DH stream from the return temperature to the supply temperature, while in each substation, the heat carried by the DH steam is released to secondary networks. In a simplified model, substations are considered similar in the water temperature demands of secondary networks, heating scheme, and construction conditions.

Irrespective of the supply temperature and return temperature of the primary network, heat-transfer processes can always be realized by using a combination of heat exchangers and heat pumps, as shown in Fig. 2. In the system design, the connecting diagram could be significantly different as the temperatures of supply and return water change. For example, it is assumed that the heat-source temperatures are 32/26 °C, the secondary-network temperatures are 40/35 °C, and the terminal temperature difference (TTD) of heat exchangers is 2 °C. Two connecting forms are commonly used in existing heat pump systems: when the primary supply water temperature is less than 30 °C, the heat-source station can exploit IEH with just heat exchangers while the substations need heat pumps; when the primary return water temperature is greater than 37 °C, the heat-source station needs heat pumps while the substations need just heat exchangers. In other conditions, the combined use of heat exchangers and heat pumps is employed.

Cascade heating can improve efficiency via series-connected heat pumps that have been allocated into several stages

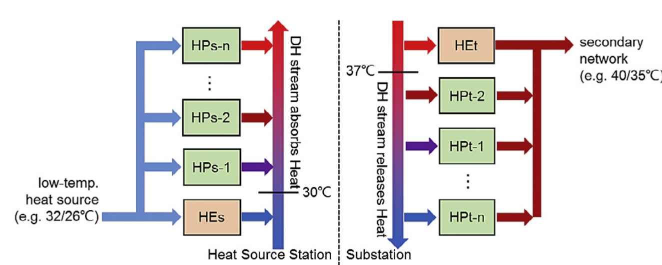

Fig. 2. Heat transfer diagram of a primary network. Note: HPs denote heat pumps in the source station, while HPts denote heat pumps in the terminal; HEs denote heat exchangers in the source station, while HEts denote heat exchangers in the terminal.