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Research paper

# Operation optimization of existing district heating systems

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## HIGHLIGHTS

- The operating cost of existing district heating systems was studied.
- The optimization model used to minimize the operating cost of existing district heating systems was established.
- The operating progress of an existing indirect district heating system was optimized by using the optimization model.
- The operating strategy and heating parameters both influence the optimal results of the existing district heating system.

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## ABSTRACT

Reducing the operating cost of district heating (DH) systems can be regarded as an operation optimization of DH systems. It was proved that the pumping cost and heat loss cost (PHLC) determined the operating cost of an existing DH system. The minimum operating cost can be obtained by minimizing the PHLC. The optimization method was used. The optimization model used to minimize the PHLC of an existing DH system was established. Program was written to solve the optimization model by using MATLAB software. An existing indirect DH (IDH) system in Hohhot, Inner Mongolia, China was optimized by using the optimization model. Four strategies were used respectively. Results show that the minimum PHLC and related heating parameters can be obtained by using the optimization model.

When controlling the primary water mass flow rate (PMF) and the secondary water mass flow rate (SMF) simultaneously, the minimum PHLC is lower than that for other strategies. But this operating strategy requires the excellent hydraulic stability of DH systems. The limit of the frequency of pumps should also be taken into account when applying the optimization model to engineering practice.

## 1. Introduction

DH systems have been developed widely because it is considered an effective method to improve the energy efficiency of the space heating system in buildings. DH systems are very common in many countries, such as China, Russia, European countries and so on. In Sweden, energy used in the building sector accounts for 40% of the total energy. 55% of the heat demand of Swedish buildings is supplied by DH systems [1]. In towns in the north of China, the area of buildings connected to DH systems increased from 1.1 billion square meters in 1996 to 9.3 billion square meters in 2011 [2,3]. And therefore, the energy consumption caused by DH systems reached nearly 166 million tons of standard coal in 2011 [2,3]. Urban Persson et al. [4] studied the heat demand in 83 cities in France, Germany, Netherlands and Belgium. It was estimated that the average heat market share for DH systems within these 83 cities was 21% in 2006. Combined heat and power plant (CHP) and boilers can be used as heat sources of DH systems. DH systems are changing from fossil fuel-based energy systems to renewable energy systems, which means that fossil fuel (such as coal, oil, natural gas, etc.) is replaced by some non-fossil fuel in the process of heat production [5,6]. Solar, wind, geothermal energy, biomass, etc are used to supply heat for consumers of DH systems [7–14]. Moreover, using waste heat generated during industrial operation or electricity production increases energy efficiency and reduces the use of fossil fuels and other energy resources [15–17]. Therefore, DH systems play an important role in improving indoor thermal comfort and saving primary energy consumption. However, there still remain some problems which should be solved to make DH systems more efficient and more competitive. Heat produced in heat sources needs to be distributed to consumers through DH network. The heat medium can be hot water or steam. In this paper, we focus on DH systems using water as the

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**Nomenclature**

| | |
|---|---|
| $a_s$, $b_s$ | coefficients for calculating the heat transfer from one piece of radiator to rooms |
| $A_h$ | area of heat exchanger, $m^2$ |
| $b$ | distance between pipe centers, m |
| $c$ | specific heat of water, kJ/kg |
| $C_{hd}$ | operating cost of heat distribution, RMB |
| $C_{hs}$ | operating cost of heat sources, RMB |
| $C_l$ | heat loss cost, RMB |
| $C_p$ | pumping cost, RMB |
| $d_w$ | outer pipe diameter, m |
| $d_z$ | outer insulation diameter, m |
| $G_r$ | pump flow rate at rated speed, kg/s |
| $h$ | distance between pipe centers and ground surface, m |
| $H$ | corrected distance between pipe centers and ground surface, m |
| $K_h$ | heat transfer coefficient of heat exchanger ($W/m^2$ °C) |
| $l$ | pipe length, m |
| $m$ | total number of pipe sections with same diameter in the secondary heating network |
| $n$ | total number of pipe sections with same diameter in the primary heating network |
| $n_{pp}$ | total number of circulating pumps in the primary side |
| $n_s$ | pieces of radiators |
| $n_{sp}$ | total number of circulating pumps in the secondary side |
| $N_r$ | pump power at rated speed, kW |
| $Q_d$ | heat demand of consumers, kW |
| $Q_{lp}$ | heat loss of the primary heating network, kW |
| $Q_{ls}$ | heat loss of the secondary heating network, kW |
| $Q_s$ | heat supply, kW |
| $R_{b1}$, $R_{b2}$ | heat resistance for insulation materials of two parallel pipes (supply water pipes and return water pipes) buried in the ground, m °C/W |
| $R_c$ | additional heat resistance, m °C/W |
| $R_t$ | ground heat resistance, m °C/W |
| $t_g$ | ground surface temperature, °C |
| $\Delta t_m$ | logarithmic mean temperature difference, °C |
| $t_n$ | indoor temperature, °C |
| $t_{pr}$ | primary return water temperature, °C |
| $t_{ps}$ | primary supply water temperature, °C |
| $t_{sr}$ | secondary return water temperature, °C |
| $t_{ss}$ | secondary supply water temperature, °C |
| $U_e$ | electricity price, RMB/kWh |
| $U_h$ | heat price, RMB/kWh |
| $\lambda_b$ | heat conductivity for insulation materials of heating pipes, W/m °C |
| $\lambda_t$ | heat conductivity for the ground, W/m °C |
| $\tau$ | a period of time, s |
| $\eta_e$ | efficiency of pump electric motor, % |
| $\eta_f$ | efficiency of pump inverter, % |
| $\alpha$ | convective heat transfer coefficient between environment and ground surface, $W/m^2$ °C |
| $\beta$ | additional heat loss coefficient caused by accessories, compensators, valves, etc |

*Subscripts*

| | |
|---|---|
| $i$ | number of pipe sections with same diameter in the primary heating network |
| $j$ | number of pipe sections with same diameter in the secondary heating network |
| $k$ | number of circulating pumps of the primary side |
| $q$ | number of circulating pumps of the secondary side |
| min | minimum value |
| max | maximum value |

heat medium. Pumps are required to provide power for the circulation of heat medium in this process. Therefore, the overall cost of heat distribution mainly includes the repayment of capital cost (such as pump investment cost, pipe investment cost, valve investment cost, substation investment cost, etc.), pumping cost, heat loss cost, maintenance cost, salaries, etc. When enough heat is supplied to consumers, how to reduce the total cost is a subject on optimization of DH systems. Some researches on this subject were conducted. Jonas Gustafsson [18] proved that it was possible to use the primary supply water temperature (PST) in the heating network of DH systems to control radiator systems while maintaining the comfort, with the purpose of increasing the temperature difference between PST and primary return water temperature (PRT). Increasing the temperature difference between PST and PRT can reduce the pump electrical energy consumption (PEEC) and improve the overall fuel efficiency. Also, in the CHP plant, more electricity can be produced with colder PRT caused by the increased temperature difference between PST and PRT. Similarly, in order to obtain the lowest PRT, P. Lauenburg et al. [19] used field experiments and computer simulations to develop a control algorithm of radiator systems in DH systems. Henrik Lund et al. [5] pointed out that low-temperature DH systems were beneficial to using low-temperature heat sources (e.g. waste) and improving the utilization efficiency of solar, geothermal energy, etc. Also, the heat loss could be reduced by using low-temperature DH systems. Aibin Yan et al. [20] developed a hydraulic model to simulate the hydraulic performance of a district heating network with distributed variable speed pumps. They found that such a system could save more energy than the DH system with conventional central circulating pumps. K.C.B. Steer et al. [21] studied the influences of the control period on the overall operating cost of DH systems. It was found that an appropriate control policy could save much energy. Tatu Laajalehto [22] proved that the pump power, heat loss and return water temperature could be reduced by utilizing a ring heating network and mass flow rate control, and therefore, significant energy efficiency improvements of DH systems could be achieved. Marouf Pirouti et al. [23] found that the annual energy consumption and equivalent annual cost when using variable flow rate and variable supply water temperature operating strategy was lower compared with other operating methods.

The energy consumption of heat sources is determined by heat supply, heat source forms, operating efficiency, etc. The heat supply is mainly determined by the heat demand of consumers. Therefore, as for an existing DH system, the energy consumption of heat sources changes little when the heat supply is constant. The energy consumption of heat distribution is mainly determined by PEEC and heat loss. According to the actual test and statistics in 2005–2006 heating season (from 15 November 2005 to 15 March 2006) in Beijing, the PEEC of direct DH systems is 1.3–2.0 kWh per square meter, while the PEEC of IDH systems is 2.6–3.2 kWh per square meter [24]. Also, it can be seen that much energy can be saved by reducing the PEEC. In this paper, we focus on PEEC and heat loss of IDH systems. The schematic diagram of an IDH system is shown in Fig. 1 [25]. In the primary side, hot water passes to DH substation through primary heating network, and then returns to heat sources. In the secondary side, water obtains heat from hot water in the primary side through heat exchangers, and then heat transfers from water to rooms