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Research Paper

Diameter optimization of district heating and cooling piping network based on hourly load

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HIGHLIGHTS

- A mathematical model of annual equivalent cost of DHC piping network is established based on hourly load.
- An improved genetic algorithm is proposed bases on genetic operators: crossover, mutation and recombination.
- Optimal diameters of the DHC piping network are obtained.
- The change of electricity price has little effect on the optimal pipe diameter combination.

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ABSTRACT

In order to reduce the annual equivalent cost of a district heating and cooling (DHC) piping network, the optimal diameter combination of DHC piping network need to be determined. In this study, a mathematical model of annual equivalent cost of the DHC piping network was established based on the hourly load of substations. The model was solved by integer-coded genetic algorithm based on improved genetic operators: crossover, mutation and recombination. Two DHC piping networks, one with conventional central circulating pump (CCCP) system, and the other with distributed variable speed pumps (DVSP) system, were investigated in relation to the changes of electricity price. It was found that electricity price had little effect on the optimal pipe diameter combination and the annual equivalent cost of the DHC using a DVSP system is 20.8–27.7% lower than that of a CCCP system.

1. Introduction

According to the building climatic regionalization of China, Yangtze River Basin and its surrounding areas in central China are located in the hot summer and cold winter climate zone. In the past ten years, district heating and cooling (DHC) systems have been incorporated into the development of newly-built large public and residential buildings to deal with these conditions. The number of DHC system has been increasing every year [1] e.g. Gulou Software Park DHC project in Nanjing [2], Expo Park DHC project in Shanghai [3], financial harbor and science and technology city DHC projects in Wuhan [4] and the Binjiang New City Project B DHC system in Changsha which provided the case study for this paper.

Compared to conventional central air-conditioning systems, DHC system has many advantages, such as high-capacity per unit, high energy efficiency, reduced installed capacity of energy station, intensive use of chillers and machinery space, reduced operational cost and maintenance personnel, and landscape improvement [5–7]. Generally speaking, DHC system performs better than the conventional central air-conditioning system in regards to energy-saving and environmental benefit [8]. However, there are some issues in the technology, design, construction and its operational characteristics of DHC system. Therefore, in order to improve the economic benefits and energy saving characteristics of a DHC system, it is necessary to optimize design and operational characteristics.

The optimization of a DHC system design mainly includes energy station scheme design, energy station location, layout of distribution networks, pipe diameter, power system, insulation thickness, supply and return water temperatures, operation strategy of heat pump units, etc. [2,9–13]. Among these factors, the costs associated with piping network represent a significant share

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Nomenclature

Cn	investment cost of piping work
Cr	operation cost
Xt	effect coefficient of investment
α	annual depreciation and maintenance factor
d_i	diameter of the pipeline i
η_p	circulating pump mechanical efficiency
Gc_i	cold water flow of primary pump on the i hour
Gh_i	heat water flow of primary pump on the i hour
Hc_i	pump head of primary pump on the i hour in summer
Hh_i	pump head of primary pump on the i hour in winter
$Gc(i,j)$	cold water flow of the pipeline j on the i hour
$Hc(i,j)$	head loss of the pipeline j on the i hour in summer
$Gnc(i,j)$	cold water flow of the substation branch j on the i hour
$Hnc(i,j)$	head loss of the substation branch j on the i hour in summer
$Gh(i,j)$	heat water flow of the pipeline j on the i hour
$Hh(i,j)$	head loss of the pipeline j on the i hour in winter
$Gnh(i,j)$	heat water flow of the substation branch j on the i hour
$Hnh(i,j)$	head loss of the substation branch j on the i hour in winter
Dc	cooling days
Dh	heating days
ρ_c	density of cold water
ρ_h	density of heat water
L_i	length of the pipeline i
Ce	commercial electricity price
P	bank rate

Abbreviation

DHC	district heating and cooling
CCCP	conventional central circulating pump
DVSP	distributed variable speed pumps

of the total investment cost of a DHC system. Therefore, optimization of the pipe diameter is of vital importance for the efficient operation and economics of the entire system [14].

Research on pipe diameter optimization has used approaches including Tabu search algorithm [15], simulated annealing algorithm [16], genetic algorithm [17], ant colony algorithm [18] and particle swarm algorithm [19]. Most of this research has been concerned with urban water distribution network [15,16,19], natural gas network [17] and sanitary sewer network [18]. There are few papers focusing mainly on optimization of pipe diameter of DHC network for energy saving and efficient operation of DHC systems [20–22].

DHC pipe sizes have been designed to meet the maximum target pressure loss requirement in traditional design methods, without considering the energy efficiency and economic considerations [22]. Shu [20] proposed a segment optimization model of DHC piping network ignoring the hydraulic balance problem of parallel pipes. The results show that the optimal diameters of main pipelines were determined to satisfy the need of engineering practice. Li et al. [21] built a least-annualized-cost for optimal mathematical model comprising all constrict conditions to obtain the optimal combinations of discrete pipe diameters. Compared with the traditional design method, the annual equivalent cost of the network is reduced by 8.54%. In the above papers [20–22], pipe diameter optimization research focused on the maximum load of each substation node, and did not consider the fluctuation of the substation load.

The use of distributed variable speed pumps (DVSP) in DHC systems has been receiving increasing attention in recent years. For example, Yan et al. [23] analyzed the electricity consumption of DVSP in comparison to conventional central circulating pump (CCCP) system for a district heating piping network. Electricity consumption was reduced by 71% using DVSP system when the flow rate varied in all of the branches simultaneously. However, the annual equivalent cost was not considered in this research.

In addition, electricity price is one of the factors that affects the operational cost of piping network. Innovation in electricity price and corresponding policies are needed to meet the needs of the local economic development. While the influence of electricity price on pipe diameter was ignored in Refs. [21–23].

Consequently, the purpose of our study is to focus on the effect of electricity price and power system on the optimal pipe diameter based on hourly load.

The hourly heating and cooling load for each pipeline in a piping network of DHC was determined on a typical day based on hourly heating and cooling load of substations. The resistance loss of the pipeline was calculated when the flow, diameter and length of the pipeline are known. For the CCCP system, the annual operational cost of pump was determined based on the flow and the head of the pump. While for the DVSP system whose branches have no balance valves and control valves, the energy consumption of the DVSP system is the energy consumption which is consumed to overcome the resistance of every pipeline [23]. That is, the annual operational cost of the DVSP system is determined based on the flow and the resistance loss of every pipeline. The combination of pipe diameter of the piping network was encoded to become a genetic individual based on integer-code. This genetic individual was then optimized by genetic operators such as crossover, mutation and recombination. The optimal pipe diameter was obtained by the proposed optimization scheme. Finally, the results of optimization were applied to investigate whether electricity price and power system affect the optimal pipe diameter.

2. Mathematic model

The economic evaluation includes the two inter-dependent factors of investment cost and operational cost [24]. With the reduction of pipe diameter, the initial investment cost of the pipes would be concomitantly reduced, while the operational cost of pumps would be increased due to the enlargement of the resistance loss of the piping network. On the contrary, with the increase of pipe diameter, the initial investment cost would be increased, while the operational cost would be reduced. Therefore, in order to minimize the overall economic cost, the optimal diameter should be determined.

The annual equivalent cost (defined as: the sum of annualized investment cost, depreciation and maintenance cost, heat loss cost and operational cost of circulating pumps) was used as the index to estimate the optimized diameter combination of a DHC piping network [3,20,21]. As the heat loss cost accounts for only ~3% of the total annual equivalent cost [20], it was excluded from this study.

The annual equivalent cost may be expressed as shown in Eq. (1).

$$\mathrm{Min}(Z) = X_t \cdot C_n + C_r + \alpha \cdot C_n \quad (1)$$

where X_t is the effect coefficient of the investment, α is the factor of annual depreciation and maintenance (assumed to be 8%).

C_n is the investment cost, representing by Eq. (2) as follows.

$$C_n = \sum_{i=1}^{n} f(d_i) \cdot L_i \quad (2)$$