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Optimization modeling of district heating networks and calculation by the Newton method

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HIGHLIGHTS

- The optimization model of the district heating system is set up.
- The Newton method is applied to solving the optimization model.
- The optimal results are obtained for two numerical examples.
- Effects of some parameters on the optimal results are discussed.

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ABSTRACT

The optimization model of the district heating system for an *N*-floor building is set up. The mass flow rate and thermal conductance distributions are optimized for prescribed total mass flow rate and prescribed total thermal conductance respectively by the Newton method. Two numerical examples are presented, and the effects of the parameters, such as the heat load, its distribution and the room temperature, on the optimal results are discussed. It is shown that for a three-floor building with two users on each floor, larger heat load requires larger mass flow rate on the corresponding floor when the total mass flow rate is prescribed. Putting the user of larger heat load nearest to the upstream flow reduces the total mass flow rate for fixed total heat load on the floor. For the three-floor building with one user on each floor, larger thermal conductance of the corresponding heat exchanger is required for the room with higher temperature when the total thermal conductance is prescribed. With fixed total heat load of two floors, distributing more heat load to the room with lower temperature reduces the total mass flow rate.

1. Introduction

The district heating systems have been widely used in industry and daily life because they can improve energy utilization, exergy efficiency, and the exploitation of renewable energy [1–7]. The optimization of district heating systems, such as improving the system performance, minimizing the investment and operational costs [8], etc., is drawing more and more attention of researchers, and many methods have been developed, such as the mathematical programming [9–13], the neural networks [14], the genetic algorithm [15], etc.

Many researches on the optimization of district heating systems with the mathematical programming method were presented [9–13]. For instance, Bojic et al. [9] used the mixed 0–1 linear programming method to solve the optimization problem of a district heating system. Dobersek et al. [10] optimized a tree path pipe network with the mathematical model consisting of nonlinear objective functions. Henning [11] proposed the MODEST (Model for Optimization of Dynamic Energy Systems with Time-Dependent Components and Boundary Conditions), an energy-system optimization model, to minimize the capital and operation costs of energy supply and demand-side management by linear programming method. However, the calculation of the mathematical programming method for complex district heating systems is very large.

Other optimization methods were also used in the optimization. For instance, Kecebas et al. [14] applied the artificial neural network to optimizing the geothermal district heating systems. Wright et al. [15] optimized the pay-off between the energy cost of a building and the occupant thermal discomfort with the multi-criterion genetic algorithm search method successfully. Adamo et al. [16] proposed a procedure to optimize district heating networks on the basis of the second law analysis, which was derived from the

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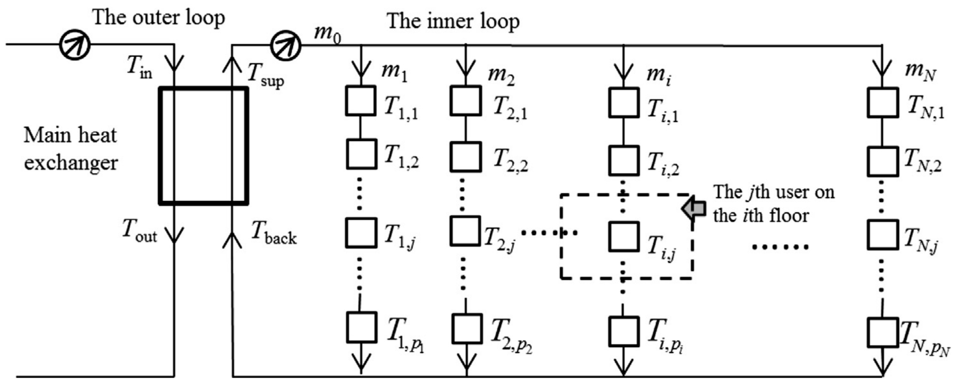

Fig. 1. Sketch of the district heating network.

exergonomic theory. However, these methods require large amounts of actual engineering data.

It is worth making further investigations on the methods of optimizing the district heating systems. When analyzing the thermal networks that are widely used in many engineering areas [17–23], Cheng et al. [22,23] found that the Newton method is effective for the calculation of thermal networks. Hence, we use this method to analyze and optimize the district heating system for an N-floor building in this paper. In addition, the effects of influencing parameters are discussed.

2. Models for the optimization designs

The district heating network is composed of the inner and outer loops. As shown in Fig. 1, the hot water supplied by the outer loop pump heats the water of the inner loop through the main heat exchanger (HE). The heated water in the inner loop is delivered into the users, and supplies heat to the users' rooms through the HEs in the branch loops. Finally, the cooled water out of each floor through the branch loops flows back into the main HE. For the district heating network in Fig. 1, there are p_i users on the ith floor. The temperature and the heat loads of the rooms (users) are prescribed. For the jth user on the ith floor, assume that its temperature is $T_{i,j}$ and heat load is $Q_{i,j}$. The inlet and outlet temperatures of the outer loop are T_{in} and T_{out} respectively. For the inner loop, the water temperature out of the main HE is T_{sup}, and the temperature of the water back into the main HE is T_{back}. The specific heat capacity of water c_p is treated as a constant.

In order to minimize the total cost of the district heating system, the initial cost of the HEs and the pump operating cost to supply water are the two main factors to be reduced. Hence, the district heating system is analyzed from two viewpoints. When the total pump power is prescribed, the total mass flow rate is then fixed, and the mass flow rate distribution is to be optimized to find the minimum total thermal conductance. When the construction cost is fixed, the total thermal conductance is prescribed, and the thermal conductance distribution is to be optimized to get the minimum total mass flow rate.

2.1. Analyses of the mass flow rate distribution for prescribed total mass flow rate

When the total mass flow rate is prescribed, the minimum total thermal conductance is the optimization objective because smaller thermal conductance is related to smaller cost of the system [17]. Assume that the mass flow rate of the ith floor is m_i, and the prescribed total mass flow rate is m_0. There is

$$\sum_{i=1}^{N} m_i = m_0. \tag{1}$$

The water flow pattern of the jth HE on the ith floor is shown in Fig. 2. For the jth room HE on the ith floor, its logarithmic mean temperature difference can be calculated by

$$\Delta T_{i,j,\mathrm{m}} = \left[\left(T_{i,j,\mathrm{in}} - T_{i,j}\right) - \left(T_{i,j,\mathrm{out}} - T_{i,j}\right)\right] / \ln\left[\left(T_{i,j,\mathrm{in}} - T_{i,j}\right) / \left(T_{i,j,\mathrm{out}} - T_{i,j}\right)\right], \tag{2}$$

where $T_{i,j,\mathrm{in}}$ and $T_{i,j,\mathrm{out}}$ are its inlet and outlet temperatures. Assume the inlet temperature of the jth HE on the ith floor is just the outlet temperature of the $(j-1)$th HE on the ith floor, that is, $T_{i,j,\mathrm{in}} = T_{i,j-1,\mathrm{out}}$. The energy conservation gives

$$T_{i,j,\mathrm{in}} - T_{i,j,\mathrm{out}} = Q_{i,j}/m_i c_p, \tag{3}$$

$$T_{i,j,\mathrm{in}} = T_{\mathrm{sup}} - \sum_{j=1}^{j-1} Q_{i,j}/m_i c_p, \tag{4}$$

$$T_{i,j,\mathrm{out}} = T_{\mathrm{sup}} - \sum_{j=1}^{j} Q_{i,j}/m_i c_p. \tag{5}$$

Assume that the heat transfer coefficient of all the HEs is h and is constant. Combining Eqs. (2)–(5) gives the thermal conductance $hA_{i,j}$ of the HE for the jth user on the ith floor,

$$\begin{aligned} hA_{i,j} &= \frac{Q_{i,j}}{\Delta T_{i,j,\mathrm{m}}} = \frac{Q_{i,j}}{T_{i,j,\mathrm{in}} - T_{i,j,\mathrm{out}}} \ln \frac{T_{i,j,\mathrm{in}} - T_{i,j}}{T_{i,j,\mathrm{out}} - T_{i,j}} \\ &= m_i c_p \ln \frac{T_{\mathrm{sup}} - \sum_{j=1}^{j-1} Q_{i,j}/m_i c_p - T_{i,j}}{T_{\mathrm{sup}} - \sum_{j=1}^{j} Q_{i,j}/m_i c_p - T_{i,j}}. \end{aligned} \tag{6}$$

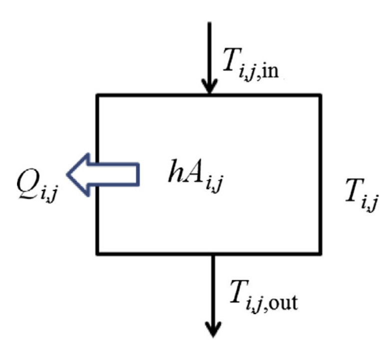

Fig. 2. Sketch of the flow pattern in the jth heat exchanger on the ith floor.