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Modeling the dynamic characteristics of a district heating network

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ABSTRACT

The study of the dynamic characteristics of the district heating (DH) systems is a necessary prerequisite for the control strategy. Through the study of the primary system and secondary system in DH systems, dynamic models of the DH network are built in this paper. Two important parameters and their mathematical expressions representing the dynamic characteristics of the DH network are described. These parameters include the lag time and relative attenuation degree of DH systems. Test data about three heat exchange stations were used in the calculation of the lag time and relative attenuation degree in the process of solving the dynamic models. Peak-valley method was introduced to find the actual lag time, and the correspondence analysis method was used to obtain the actual relative attenuation degree. The comparison of actual data with calculating data of the two parameters verified the correctness of the dynamic models. The lag time is proved to be approximately equal to the flow time of the heat medium in the DH network, and some parameters influencing the relative attenuation degree are analyzed. This will help the technicians to regulate the DH systems in the process of operation and management using the two parameters.

1. Introduction

DH systems are an inseparable part of the infrastructure of agglomerations and cities in many countries, such as in China, Russia, Denmark, Finland, Sweden, Switzerland, and so on. DH heating covers often more than 50% of the heat supply [1,2]. It is also an important element of the economy. Heat coming from DH networks makes around 52% of the heat market [3].

A district heating system can be grouped into two types based on their structure [4]. One is called a direct district heating (DDH) system, which usually has a heated floor area ranging between 50,000 square meters and 250,000 square meters. If the heating area is larger than this range, an alternate heating system which is called an indirect district heating (IDH) system is recommended. Recently, several indirect district heating systems have already been built with more than 10,000,000square meters of heated floor area in China [5]. Heat is transported in the form of hot water or steam from the heat source to each terminal device in a heating system. The related technology of district cooling works in the same way, but instead of distributing hot water or steam, cold water is distributed.

The reason for such a wide use of the DH systems comes from their numerous advantages. These advantages include high efficiency of heat production, a large variety of fuels that can be used, relatively low influence on the environment, and so on. However, there still remains much room for the improvement of the technology to become even more efficient and environmentally friendly. Li Yingcai formulated the principles and design methods of a district heating system [6]. A steady-state design including heating load and circulating water flow rate calculation, distribution system, equipment selection, make-up water, and operating curves was focused on using different types of heating systems, such as DDH system and IDH district heating system. However, few factors such as an excess area factor of heat users and heat exchangers were not considered. Prabir Basu described the fuel and combustion calculations, the burner design, corrosion and erosion prevention, and the gas system design for a boiler used in a DH system [7]. The steady-state method was used in the calculations. Based on the heat balance principle, the heat released by fuel combustion should be absorbed by circulating water flow. However, for a variety of reasons, the released heat would not be utilized completely because several heat losses occur in the heat transfer processes. A heat balance between the thermal efficiency and heat losses was shown.

On the other hand, some authors questioned the accuracy of the steady-state used in the analysis of heating systems. And some

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Nomenclature

a	thermal diffusivity (m^2/s)
A	amplitude (°C)
c	specific heat of water (J/kg K)
c_p	specific heat of pipe wall (J/kg K)
d	pipe diameter (m)
D	pipe outer diameter (m)
F	cross-sectional area of flow channel (m^2)
F_p	cross-sectional area of pipe wall (m^2)
k	overall heat transfer coefficient (W/m^2 K)
L	pipe length (m)
L_1	internal perimeter of pipe (m)
L_2	external perimeter of pipe (m)
Nu	Nusselt number
Pr	Prandtl number
Q	water flow rate (m^3/s)
r	relative error
Re	Reynolds number
$t(\tau, x)$	water temperature distribution (°C)
t_e	ambient temperature (°C)
$t_{in}(\tau)$	inlet temperature (°C)
$t_p(\tau, x)$	temperature distribution of pipe wall (°C)
t_w	average water temperature(°C)
T	cycle time (s)
u	water velocity (m/s)
x	distance from the pipe inlet (m)
z	lag time with test data (h)
z_c	calculated lag time (h)
α	convective heat transfer coefficient between flow and pipe wall (W/m^2 K)
β	convective heat transfer coefficient between environment and outer surface of pipe (W/m^2 K)
ν	kinematic viscosity of water (m^2/s)
δ_p	pipe wall thickness (m)
λ_p	thermal conductivity of pipe wall (W/m K)
δ_{in}	insulation thickness (m)
λ_{in}	thermal conductivity of insulation (W/m K)
φ	initial phase (rad)
ζ	lag time (h)
η	relative attenuation degree
ω	angular frequency (rad/h)
ρ	density of water (kg/m^3)
ρ_p	density of pipe wall (kg/m^3)
τ	time (s)
Subscripts	
BW	referring to name of heat exchange station
XY	referring to name of heat exchange station
XM	referring to name of heat exchange station

researchers focused on dynamic analysis and control methods used in hot water heating systems, which are the closest to the DH system in terms of operating characteristics. Staffan Andersson gave the mathematical model of the heating network its regenerative characteristic [8]. The water flow rate and return water temperature in the heat exchange station was considered to be known. It was assumed that the water reached all the heat exchange station at the same time. The next time the water assembled together at the heat source, completing the mixture process. Through the research of regenerative properties of the DH network, a suitable operation strategy for the network was proposed. But the heat loss was ignored in the model, and the heat production at the heat source was considered equal to the heat storage in the DH network and the heat dissipation capacity of the heat users. Pfeiffer R used a simplified model to describe the regenerative capacity of the DH network [9]. He pointed out that the heat storage was equal to the product of the amount of water and the temperature difference between supply and return water. But the return water temperature at the heat exchange station during operation remained unchanged.

Focusing on the dynamic characteristics of the heating system, some researchers were also concerned with the intrinsic relationship between the meteorological parameters and the dynamic characteristics. Sven Werner tested some DH systems in Sweden, analyzing the main factors impacting the heating load, such as outdoor temperature, natural wind, and solar radiation [10]. Fernando Simon Westphal Lamberts used different meteorological cycles and data to study the impact of weather parameters on the load and energy consumption [11]. He thought that the selection methodology of meteorological data influenced the results significantly, and the error can be 18%. Krzysztof Wojdyga corrected the outdoor temperature using the other methodology parameters. He studied the impact of solar radiation and wind speed on the heating consumption in Warsaw [12]. He found that when the wind speed was not more than 2 m/s, it did not affect the basic building load.

In this paper, we focus on the dynamic characteristic of the DH network. We presented the relationship between the thermal inertia of the pipe network and other parameters, such as its structure, water supply temperature, return water temperature, circulating water flow rate, operation mode, and so on. In order to make sure that the research results were consistent with the experimental dynamic characteristics of DH systems, we used water as the heat medium.

2. Methodology

In the DH network, the heat is distributed from the heat source to the heat users, using the pipeline system [13]. In an IDH system, hot water passes through a primary pipe network to each heat exchange station and returns back to the heat source directly. The secondary loop system in each heat exchange station obtains heat from the primary system. The schematic diagram of an IDH system is shown in Fig. 1. As there is the heat lag only in the process of heat transmission and distribution, the primary piping network and the secondary loop system are the key when studying the network model [14–16].

2.1. Dynamic model of the DH network

2.1.1. Physical model

In order to establish the dynamic mathematical model of the DH network to find the main factors in nature, we simplified the pipe used in DH systems [17,18]. The schematic diagram of the pipe is shown in Fig. 2. The assumptions are as follows:

(1) The hot water flows from the inlet to the outlet of the pipe, and the flow rate is kept constant.
(2) Only a single pipe is considered, without regard to the case of branching and merging.
(3) The pipe is made of homogeneous material. The distribution of the pipe wall temperature is uniform along the radial direction, ignoring the axial heat transfer of the pipe wall. There is only heat exchange between the water and the pipe wall, which causes axial temperature changes.