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Research Paper

Function method for dynamic temperature simulation of district heating network

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HIGHLIGHTS

- A new physical method for dynamic temperature simulation of DHN was proposed.
- Dynamic thermal conditions can be solved analytically and efficiently.
- Method was validated at large and quick temperature changes and different flows.
- Simulations of new method is agreed better with measurements than node method.
- Compared with node method, the calculation time of new method is reduced by 37%.

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ABSTRACT

A thermal dynamic characteristic of district heating network was analyzed with an emphasis on simulating dynamic temperature distribution. Therefore, a new physical method (namely function method) and corresponding computer codes for dynamic temperature simulation were proposed. The function method takes into account various factors, such as flow time, heat capacity of the pipe and heat loss, in one single step by using Fourier series expansion as the mathematical basis to obtain the analytical solution of transient energy equation. Further, two key parameters, delay time and relative attenuation degree, were described to represent the time delay and heat loss respectively and were used to obtain the temperature distribution of the network. Moreover, the function method is validated by applying it to a real district heating network at different temperature change stages. For comparison purpose, the node method was also used, and the simulated supply temperatures at substations were compared with measurements. Comparisons of both methods were also performed considering different fluid velocities at heat source using numerical results. The results showed that the function method could be recommended to simulate the dynamic temperature of district heating network accurately and quickly for efficient system performance.

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1. Introduction

District heating (DH) is represented by heat networks used to deliver heat from heat source (HS) to consumers to satisfy space heating [1]. Nowadays, heat produced by various sources in a DH system is widely used for energy efficiency and the heat production proportion of these sources vary over time depending on demand, price and availability, which results in heat redistribution. Additionally, renewable energy sources, such as wind, solar and geothermal energy, are gradually used to supply heat for consumers of DH system, which changes irregularly due to weather conditions [2–4]. Furthermore, heat load variation for consumers due to changes in weather condition and daily demand also intensifies the process of heat redistribution [5,6]. As a result of above-mentioned factors, operation conditions are never stable and static temperature simulation for a network [7] cannot satisfy dynamic operation conditions. Therefore, modeling a dynamic characteristic of a DH system becomes necessary for efficient system performance, such as determining optimal start-up time of heat plants or pumps to reduce pumping cost [8,9] and determining optimal supply temperature at HS to reduce heat loss cost [10,11].

In the published papers, there are mainly two models, statistical model and physical model, to simulate the dynamic temperature distribution of DH network. The statistical models, based on

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Nomenclature

A	amplitude (m)
c	specific heat of water (J/(kg °C))
c_p	specific heat of pipe wall (J/(kg °C))
C_{ext}	exterior perimeter of pipe wall (m)
C_{int}	internal perimeter of pipe wall (m)
F	cross-sectional area of flow channel (m^2)
F_p	cross-sectional area of pipe wall (m^2)
L	pipe length (m)
M	the maximum value of the second derivative of the function
N	the number of Fourier series expansion
n	number of collected data
n'	$n' = 0.5n$
$t(\tau, 0)$	pipe inlet temperature (°C)
$t(\tau, x)$	temperature distribution of water (°C)
$\bar{t}(\tau, x)$	average temperature of water (°C)
t_e	environment temperature(°C)
$t_p(\tau, x)$	temperature distribution of pipe wall(°C)
u	water velocity (m/s)
x	distance from the pipe inlet (m)
α	convective heat transfer coefficient between flow and pipe inner wall (W/(m^2 °C))
β	convective heat transfer coefficient between environment and pipe outer wall (W/(m °C))
η	delay time (h)
θ	initial phase (rad)
σ	error caused by substitution for inlet temperature
σ_E^2	mean squared error of temperature test data
φ	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 (h)

Subscripts

i	item of Fourier series expansion

standard transfer function models or neural networks, are generally simpler to update and easier to operate for state estimation of DH networks when compared to physical models but require availability of measurements for model estimation and validation for different operation strategies [12,13]. In addition, the estimation and tracking of time delays in the networks played an important role in statistical models and were reported to be the main source of problems, especially if temperatures were changed abruptly [14].

As for the physical models, a full physical modeling of the network is involved without introducing artificial changes to the structure of the network. The physical models mainly contain the element method firstly presented in [15], node method firstly presented in [15] and characteristic method [16]. Compared with node method, both the element method and characteristic method divide the pipe into many discrete "elements" or "nodes" and in each calculation step, every "element" or "node" is required to be calculated, which tend to be computationally intensive. Additionally, according to published literatures [14,15], the element method was found to be inferior to node method, both with respect to accuracy and stability. Node method is most widely used for modeling thermal dynamic characteristics of DH networks and the accuracy of node method has been validated in several real DH networks by comparing simulations and measurements of supply temperature at substations [5,6,17].

In node method, the temperature of outlet node needs three steps for establishing: firstly, estimating preliminarily the temperature of inlet node by taking flow time into account; secondly, taking into account the heat capacity of the pipe; finally, taking heat loss into account. It is not simple enough to obtain the outlet temperature based on the inlet temperature and will result in more time consumption for simulation. However, there have been few published literatures to optimize the node method or introduce a new method to reduce the time consumption for simulation with significant accuracy in recent years, which play an important role in online operating system and efficient system performance. Additionally, the accuracy validation of the dynamic methods mentioned above was not under condition of large and quick temperature changes occurring in the HS, which usually results in extreme deviations between measured and predicted temperatures. Furthermore, the validation methods were carried out at a fixed velocity only, not related to the validations at different fluid velocities. Therefore, the aim of this paper was to solve those problems and make sufficient contributions to the knowledge.

2. Dynamic model of heating network

In the process of heat transmission and distribution from HS to consumers, there are time delay and heat loss, which have a great influence on temperature prediction [18,19]. In addition, heating network consists of numerous pipes in which time delay and heat losses occur. Consequently, research on temperature prediction is mainly focused on time delay and heat loss of pipe [19].

2.1. Modeling assumptions

Generally, in order to investigate the main thermal dynamic characteristic of DH network, the following assumptions are used in physical models [20]:

1. The steady-state hydraulic condition is considered. Even though the volume flows vary over the simulation time, the pseudo-dynamic method is used, which means that the simulation time will be divided into many time steps and a new flow situation is determined by steady-state flow calculation at every time step.
2. The heat storage of insulation, mantle and ground outside the pipe is ignored. As for the insulation layer, the thermal conductivity should not be greater than 0.12 W/(m K), and the density should not be greater than 200 kg/m^3 [21]. As a result, the heat storage of insulation is small and the effect of fluctuation of ground temperature on water temperature is small, so they can be ignored.
3. The fluid is treated as an ideal one.
4. The impact of hydraulic dispersion, thermal diffusion and axial heat transmission are neglected.

These assumptions were used in most literatures about dynamic temperature simulation for their rationality [5,6,16,17].

2.2. Modeling of district heating network

The heat is transferred from the fluid to the pipe wall. Simultaneously, the heat is transferred from pipe wall to environment

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