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Thermal transient prediction of district heating pipeline: Optimal selection of the time and spatial steps for fast and accurate calculation

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HIGHLIGHTS

- New numerical model for thermal transient prediction of district heating network.
- Fast calculation procedure without iteration of the new model.
- Validation of the models with measured data of district heating network.
- Optimal selection of the time and spatial steps for the numerical models.
- Comparison of the characteristic line model with the implicit upwind model.

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ABSTRACT

Predicting the thermal transients of district heating (DH) network is the key to simulation analysis and operation optimization of DH system. Numerical methods can provide accurate prediction and sufficient information of thermal transients. But the high computation burden restricts the application of numerical methods, especially when applied to operation optimization of large DH networks. This dilemma can be relieved by suitably increasing the scales of time and spatial steps, but do not obviously affect the precision of the numerical models. However, there are few researches concerning such topics. In this paper, the optimal scales of time and spatial steps of a newly proposed implicit upwind model and the characteristic line model were studied for fast and accurate calculation. Results show that both models can ensure the prediction errors of the pipeline outlet temperature within ± 0.5 °C. For characteristic line model, the recommended time step and spatial step are 60 s and $170\ \text{m} < \Delta x < 520\ \text{m}$. And for implicit upwind method, the recommended time step and spatial step are 20 s and 30 m. Besides, the implicit upwind model is unconditionally stable and provides more information on temperature distribution along the pipeline, especially when small and fast propagation occurs.

1. Introduction

The thermal transient is the key characteristic of district heating (DH) network, which occurs during the dynamic operational regulation of DH network. As the weather condition varies, the heat demands of heating substations will change. The heat source supply temperature and substation flow rates are adjusted according to outdoor temperature to provide sufficient heat efficiently. The thermal transients may largely affect the operation performance of the DH system, especially for large scale DH network. Thermal transients of the DH network are embodied in the time delay of temperature propagation, heat losses and thermal capacity of the DH network. Time delays of supply temperature waves lead to overdue regulation of heating loads, which may cause low efficiency operation condition of the DH system. High heating temperature will result in large amount of heat losses to environment. Therefore, efficient operation of the DH system necessitates the prediction of thermal transients of the DH network [1].

The steady state thermal model of DH network has been widely used for simulation analysis [2,3] and operation optimization of DH network [4,5]. However, the steady state model fails to capture the thermal transients of DH network. One of the earlier researches on thermal transient model of DH network conducted by Kunz et al. [6] focused on

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Nomenclature

A_c	cross section area of the flow (m^2)	T	temperature (°C)
c_p	water specific heat capacity (J/(kg·K))	T_i^n	temperature of control volume i at time step n
M	number of control volumes	T_o	outdoor temperature (°C)
m	mass flow rate of the hot water (kg/s)	t	time (s)
m^n	mass flow rate at time step n (kg/s)	Δt	time step (s)
N	number of time steps	U	three dimensional velocity field (m/s)
R	total thermal resistance of the pipe (K·m/W)	x	position along the pipe (m)
S_T	source term	Δx	spatial step (m)
		λ	water thermal conductivity (W/(m·K))
		ρ	water density (kg/m^3)

lumped modeling of DH pipelines. In such model, each pipe is assumed as one lumped thermal capacity, the water temperature is assumed as the mean value of inlet and outlet temperatures. The shortage of such method is that the lumped model with only one thermal capacity is not able to capture the distributed parameter characteristics of the DH network. A further developed technique for modeling the thermal transients of DH network is the node method [7]. Because the velocities of DH pipelines vary continually, the time delays of temperature waves between two nodes also change all the time. The principle of the node method is that, it keeps trace of the time delay by calculating the time, a water mass takes traveling from one node to another. Based on the time series of the temperature histories of the pipeline inlet temperature, the outlet temperature can be evaluated according to the varying time delay, the heat loss and heat capacity of the pipe. In this way, the new temperature for all nodes in the network can be calculated in each time step. Gabrielaitienė et al. [8,9] applied the node method to a DH system to analyze the dynamic performance with an emphasis on temperature profile distortion. They also compared the node method with the commercial TERMIS software. Gabrielaitienė et al. [10] also studied the performance of a pseudo-transient approach implemented in the finite element code ANSYS and a node method at a low turbulent Reynolds number regime and small velocity fluctuations. Grosswindhager et al. [11] developed a mathematical physical model for dynamic simulation of flow and temperature in DH networks. In their approach, the thermal transient of pipeline is described by a delay differential equation derived from the partial differential equation of pipeline heat transfer, and the time delay is also calculated by tracking the flow mass as the node method. Recently, a similar technique was proposed in Duquette et al.'s study [12]. In their work, the time delay is also tracked in the similar way, but the temperature degradation at the outlet of pipe is calculated with the steady state method. They also compared the method with the Matlab Partial Differential Equation (PDE) Toolbox based model, and showed that the proposed approach require less computation time. The prominent advantage of the node method is its low time complexity, and therefore very applicable to online operation optimization [1]. Steer et al. [13] applied the node method to predictive control of DH network. They studied the frequency of adjustments to the supply temperature set-point in DH networks and its influence on the overall operating cost.

Since computing the variable time delays for all nodes at each time step is time consuming, the constant time delays have been considered in Sandou et al.'s study [14]. This hypothesis allows to model thermal propagation as a simple nonlinear dynamic system, which can be quickly solved. With this hypothesis they derived a highly tractable simplified model for dealing with online optimization of complex DH network. This hypothesis has also been adopted by Dobos et al. [15,16] to realize nonlinear predictive control of DH network. However, simplifying the varying transport delay as constant will cause prediction errors, since the flow rates are varying and the time delay are changing.

Although the node method provides an efficient approach for modeling the thermal transients, there are still two main shortcomings. The first is that, the node method does not solve the temperature wave propagation along the pipe, and the temperature wave diffusion and smearing could be expected [17]. The second is that, the node method only calculates the node temperatures, but does not calculate the temperature distribution along the pipeline [7–9,17]. This will be restricted when applying the node method to meshed DH networks or DH networks with multiple heat sources. Since in meshed DH networks or DH networks with multiple heat sources, the directions of water flow rates in certain pipes may change, due to the network hydraulic condition variations [18,19].

The numerical method can provide sufficient information required by different purposes of simulation analysis or operation optimization. One of the most effective numerical methods for thermal transient prediction of DH network was presented by Stevanovic et al. [17,20]. The flow rates of DH pipelines are calculated by an efficient numerical method [21], and the energy equation is solved with the characteristic line method with the application of the third order Lagrange interpolation polynomial. The predicted temperature front propagations show a good agreement with test data. Numerical method was also adopted by a commercial computer software TERMIS [22,23], but no open documents on the numerical solving technique are available in the open literature. Numerical models have been applied to several DH systems for operational optimization; first results show the saving of the total fuel energy consumption of 2% at least [24].

Numerical approaches can provide accurate prediction and sufficient information of thermal transients. But the disadvantage of numerical methods is that, they are time consuming, especially when they are applied to online operational optimization of large scale DH networks. Nevertheless, this dilemma can be relieved by optimally choosing the time and spatial steps in numerical calculations for both fast and accurate simulation. This requires plenty of numerical experiments and comprehensive analysis of the numerical and test results.

However, there are few researches concerning such topics. In this paper, a new numerical model, the implicit upwind model is presented for thermal transient prediction of DH network. And a high-efficiency calculation procedure, which does not need the numerical iteration, is developed for the implicit upwind model to improve the calculation speed. The presented implicit upwind model and the characteristic line model are both validated with measured data of an existing DH network in Shijiazhuang, China. The optimal scales of time and spatial steps for the two efficient numerical methods are analyzed via comparison of the numerical results with measured data.

2. Methods

2.1. Thermal transient modeling

The hot water inside the DH pipeline can be regarded as incompressible fluid, of which the energy conservation equation can be written as the following form [25]:

$$\frac{\partial T}{\partial t} + \nabla\cdot(\boldsymbol{U}T) = \nabla\cdot\left(\frac{\lambda}{\rho c_p}\nabla T\right) + \frac{S_T}{\rho} \quad (1)$$

where T is the three dimensional temperature field in the pipe, $\boldsymbol{U}$ is the three dimensional velocity field in the pipe, S_T is the source term, λ is