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Research Paper

A thermal-electrical analogy transient model of district heating pipelines for integrated analysis of thermal and power systems

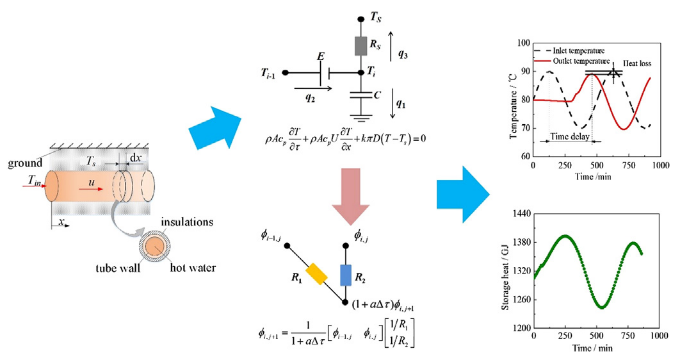
Ling Hao[a], Fei Xu[b], Qun Chen[b,c,*], Mingshan Wei[a], Lei Chen[b], Yong Min[b]

[a] School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China
[b] State Key Lab of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China
[c] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- Develop a thermal-electrical transient model for district heating pipelines.
- Derive the algebraic and matrix formulas to calculate the temperature variations.
- Heat transportation processes in pipes experience initial and normal states in sequence.
- Obtain the temperature variation curves under different inlet temperatures.
- Heat storage variation depends on the amplitudes and phases of inlet and outlet temperatures.

GRAPHICAL ABSTRACT



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ABSTRACT

District heating networks have an ability to store heat to improve the flexibility of power systems, but it lacks a compatible method to analyze thermal and power system together. Based on the thermal-electric analogy method and inspired by the electromagnetic transient analysis approaches, this paper develops a thermal-electrical analogy transient model for district heating pipelines (DHPs), which offers the matrix formulas to describe the variations of fluid temperature and stored heat with time in the pipelines, instead of the traditional partial differential equations. For a heating pipe with the length 20 km, applying the thermal-electrical analogy transient model gives the variations of the outlet temperatures and the stored heat of the pipe under step, periodic and sinusoidal inlet temperatures, where the outlet temperatures keep unchanged before 300 min due to time delay. From 300 to 380 min, the outlet temperature rises to approach the inlet temperatures, i.e. the thermal non-regular regime, but 1 °C lower due to heat loss. After 380 min, they vary in the same trend as the inlet temperatures, i.e. the thermal regular regime, but have 380 min delay. Besides, the heat stored in the pipe and its variation frequency depend on the amplitude and phase differences of inlet and outlet temperatures.

1. Introduction

Utilization of renewable energy sources and development of energy conservation techniques play important roles in addressing the energy crisis, where accommodation of renewable energy sources requires a higher flexibility of electrical power systems due to their characteristics of fluctuation and intermittence [1,2]. However, as a typical energy conservation technique, combined heat and power (CHP) plants [3,4]

* Corresponding author at: State Key Lab of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China.
E-mail address: chenqun@tsinghua.edu.cn (Q. Chen).

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Nomenclature

A	area of the cross section, m^2
C	thermal capacity, $J{\cdot}K^{-1}$
c_p	specific heat capacity, $J{\cdot}kg^{-1}{\cdot}K^{-1}$
D	pipe diameter, m
E	storage heat, J
k	heat transfer coefficient, $W{\cdot}m^{-2}{\cdot}K^{-1}$
R	thermal resistance, $K{\cdot}W^{-1}$
R_s	resistance between node and soil temperature in the basic thermal circuit
R_{se}	resistance between node and soil temperature in the equivalent thermal circuit
T	temperature, K
T_s	soil temperature, K
U	horizontal velocity of water, $m{\cdot}s^{-1}$
V	water velocity vector, $m{\cdot}s^{-1}$
x	longitudinal position, m
ρ	volume density, $kg{\cdot}m^{-3}$
λ	thermal conductivity, $W{\cdot}m^{-1}{\cdot}K^{-1}$
τ	time, s
τ_0	thermal regular regime point, s
ϕ	excess temperature, K

Subscript

in	inlet of the pipe
out	outlet of the pipe
i	space node
j	time node
m	total number of the space nodes
n	total number of the time nodes

reduce the flexibility of electrical power systems due to the "heat-led" operation mode [5]. This conflict have caused a severe problem of renewable energy curtailment [6,7]. For instance, at winter nights of cold areas, in order to satisfy the heat load, the power generation of CHP plants is higher, which satisfies a larger proportion of power load. That is, the power system has insufficient space for accommodation of renewable energy. According to the statistics, the curtailed wind power in China is 497 TW h in 2016 and accounts for about 21% of the total yearly wind power generation [8].

Recently, researchers developed several large-scale energy storage techniques [9], virtual power plants [10] and demand-side management methods [11] to improve the flexibility of power systems [2]. Besides, considering that the huge amount of water in district heating networks (DHNs) has an ability to store heat to improve the adjustability of CHP plants and that there is no extra initial investment for utilization of the existing DHNs [12–14], some researchers paid attention to the application of the passive heat storage capacity of DHNs. In this case, the temperature variation and the time delay will occur between heat sources and end users [15]. Hence, it is necessary to develop a thermal transient mathematical model of DHNs to analyze their dynamic characteristics and passive thermal storage capacity [16,17].

From perspective of the thermal and hydraulic analyses, several scholars presented steady-state and transient models of DHNs to obtain the pressure or temperature variations with the space or the time. Ravina [18] built a steady-state thermal model of DHNs, but it is not applicable for analyzing temperature variation with time. Stevanovic [19] put forward an efficient steady-state hydraulic model for the loop networks but without solving the momentum equations in all nodes. Guelpa [20] proposed a thermo-fluid dynamic model for the loop networks by solving steady-state momentum equations and thermal transient equations with fast computation speed. Other traditional thermal analysis methods solve the differential energy conservation equations of thermal systems by numerical methods [21–26] to investigate the heat transport and storage performance of DHNs.

The results showed that above models were of good accuracy compared to measured data [20–26]. Nevertheless, these DHNs models are not very compatible with the existing power operation and dispatching systems, which caused problems in utilizing the passive thermal storage of DHNs to provide flexibility for electrical systems. The reason is that, in electrical power analyses, the transient models only consists of algebraic or matrix equations without any intermediate variables, while the traditional thermal analyses methods aim at solving a series of partial differential equations with amount of iterations and intermediate parameters. Hence, these methods are difficult to analyze the heat transport and storage performance of DHNs together with the electric power systems [27].

From perspective of electrical power system analyses, many researchers developed several simple models of DHNs to consider DHNs together with the power systems. Awad et al. [28] regarded the heating pipes as single nodes with no volume in the integrated power and thermal systems, where the temperature variation with space was not considered. More detailed studies exploited the steady-state models of DHNs, where the steady-state outlet temperature is an exponentially equation of the ratio of the tube length and mass flow rate [29,30]. In order to establish a transient model of DHNs, Li et al. [14] developed a linear model considering the transmission delay of fluid flowing from the inlet to the outlet.

This paper proposes a transient thermal-electrical analogy model, including a basic thermal circuit and an equivalent thermal circuit, of district heating pipelines under the electrical framework, which is suitable for analyzing district heating pipelines together with electric power systems. Based on the thermal energy conservation equation, applying the thermal-electrical analogy method establishes the basic thermal circuit to reflect the heat transportation and storage mechanism in the heating pipes. Furthermore, introduction of the electromagnetic transient analysis approaches in power systems [31,32] simplifies the basic thermal circuits to the equivalent thermal circuits and gives an algebraic formula of outlet temperature varying with time. In addition, comparison of the outlet temperatures calculated by the newly proposed model and the finite volume method (FVM) validates the accuracy of the transient thermal-electrical analogy model. Finally, investigation of the dynamic heat transportation and storage characteristics of heat pipelines under three different variation curves of inlet temperatures shows the applications of the transient thermal-electrical analogy model.

2. Materials and method

2.1. Physical model of directly buried heating pipelines

This paper takes the directly buried heating pipelines as an example, which are surrounded by insulating materials and buried in soils. Fig. 1 shows the geometrical structures of a typical directly buried heating pipeline. For the heat transportation process in the pipeline, applying the energy conservation laws offers

$$\rho c_p \frac{\partial T}{\partial \tau} + \rho c_p U \cdot \nabla T = \nabla \cdot (\lambda \nabla T), \tag{1}$$

where ρ, c_p and λ represents the density, the constant pressure specific heat capacity, and the thermal conductivity of water, respectively. T represents the temperature, U represents the water velocity vector, and τ is the time. As shown in Eq. (1), the increase of the enthalpy equals to the net inflow heat flux due to fluid motion and heat conduction.

If the water temperatures are assumed uniform at the same cross