Energy Conversion and Management 157 (2018) 71–85

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

New model for onsite heat loss state estimation of general district heating network with hourly measurements

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A R T I C L E I N F O

Keywords:
District heating
Thermal simulation model
Heat loss
Onsite state estimation
Insulation deterioration

A B S T R A C T

With the development of advanced automation and information technologies, more intelligent meters and measurements are involved in the management of modern district heating systems. A huge amount of measured data can be exploited to technical improvements and environmental protections besides billing purpose. In this paper, a new model is proposed to estimate onsite heat losses of a general pipe network with hourly measurements of heat sources and substations. A detailed heat loss profile along each pipe can be obtained by the proposed model, which can significantly improve the accuracy of the location of damaged insulation. Furthermore, the thermal deterioration of buried pipes can also be evaluated conveniently. In the case study, a real district heating system which has 3 heat sources and 34 substations is analyzed to validate the proposed model. The onsite heat losses of all pipes for 24 h are calculated by the hourly measured data. The results indicate that the heat loss profile of a return pipe is lower and more fluctuating than that of corresponding supply one. The heat losses of selected pipes are nearly 3.51–8.32% more than the reference values, which indicate that selected pipes' insulations are of a little aging or corroded by surrounding soil.

1. Introduction

Under the tide of relieving environmental impacts and enhancing energy efficiency, District Heating and Cooling has gained more and more interests from city authorities and developers for its potential advantages of integrating local renewables and surplus energies. A variety of modern district heating (DH) systems have extensively been adopted in cities and areas worldwide in recent years [1,2]. Such as north China, most large cities have employed DH as their fundamental urban service to local residents [3,4]. The future DH, proposed by Lund et al. [5], will be upgraded towards the 4th Generation District Heating (4GDH), in which smart thermal grid will support more efficient and sustainable heating and cooling with significant improvements, such as lower supply water temperature [6], longer transportation distance [7] and more renewables [8] and surplus heats accessibility [9]. That would achieve remarkable effects on heat losses and carbon emission reduction.

To construct an intelligent DH system, advanced automation and information technologies, even smart thermal grid [5], are necessary to be integrated for more supply flexibility [10]. According to EU directive report, independent heat metering devices have been utilized to obtain the consumption of both heating and domestic hot water in multi-apartment buildings by the end of 2016 [11]. In Beijing, China, a huge DH system which can serve nearly 19,280 million m^2 of area has been deployed with automated reading meters in all heat sources and substations by the year of 2015 [12]. Owing to the heating market reform in China, more automated calorimeters are also equipped in many DH systems [13]. Moreover, supervisory control and data acquisition (SCADA) systems have already been installed in some advanced DH systems to guarantee proper daily operations as well. In our recent work [14], with the help of the advanced automation and information technologies, a new hydraulic regulation method was proposed to achieve on-site hydraulic balance for DH systems.

However, the measurement data are still used for billing purpose in most circumstances. The measurement data can be exploited for technical improvements and environmental protections. One of the important utilizations of the large amount of measured data is to be estimated the heat losses of hot water during transportation in DH pipeline. Extensive studies have already been concentrated on the evaluation of energy or exergy losses in DH network [15–18]. Çomaklı et al. [16] investigated the energy and exergy losses occurring in a DH system. It was found that hot water temperature was the most important factor affecting exergy losses. Poredos et al. [17] presented the basic principles to describe the exergy states of a DH system. It indicated that in the most disadvantage case, almost 30% of exergy was lost during the heat transportation and distribution. And the heat losses

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https://doi.org/10.1016/j.enconman.2017.11.062
Received 16 September 2017; Received in revised form 22 November 2017; Accepted 23 November 2017
0196-8904/

Nomenclature

A	associated matrix of pipe network
B	basic circuit matrix of pipe network
d	diameter (m)
e	water energy (J/kg)
f	friction factor
g	gravity acceleration (m/s^2)
H_p	head of pump (m H_2O)
h	enthalpy (J/kg)
h_i	heat transfer coefficient inside the pipe (W/m^2 K)
h_o	heat transfer coefficient outside the pipe (W/m^2 K)
k	thermal conductivity (W/m K)
L	length of the pipe (m)
P	pressure (Pa)
Pr	Prandtl number
Q_{loss}	overall heat loss (W)
q_v	specific heat loss in volume (W/m^3)
q_l	specific heat loss in length (W/m)
R_b	resistance of each branch (Pa)
Re	Reynolds number
r	radius (m)
T	temperature (K)
ΔT	temperature difference (K)
U	overall heat transfer coefficient (W/m^2 K)
v	velocity (m/s)
$\dot{V}$	volume flow rate (m^3/s)
Z_b	pipe centerline's depth below ground surface (m)

Superscripts

f	feed water or supply water
r	return water

Subscripts

c	calculated value
k	index of a pipe branch
m	measured value
n	index of a substation
s	index of a source

Abbreviations

4GDH	4th generation district heating
CV	control volume
DH	district heating

Greek symbols

ρ	density (kg/m^3)
ε	roughness of inner surface (m)

can be as much as 8–10% on average. Vesterlund et al. [18] calculated the annul heat losses in a DH network in Sweden based on the data from Geographic Information System (GIS). The results showed that the heat losses can reach 12% of the gross heat for a typical Swedish DH system. The heat losses can even reach up to 30% of the total heat in some DH networks [19]. From the conclusions of these studies, it is clear that the heat losses of pipes can significantly affect the thermal performance of a DH system, which should be considered deliberately.

On the one hand, to evaluate the thermal performance of a DH system comprehensively, efficient simulation models are always indispensable. Based on the pipe hot water temperature and flow regime, the ground soil temperature and thermal parameters of insulation layers, the heat transfer flux and water temperature propagation can be calculated by several simulation models. Larsen et al. [20] presented an aggregated model for dynamic properties of DH networks including water flow and heat propagation from production plants to consumers. By applying the simplified model to a real case study, a network with over 1000 pipes can be reduced to less than 10 pipes. Furthermore, Larsen et al. [21] also compared two aggregated models, the Danish model and the German model, for simulation and operation optimization of DH networks. Rosa et al. [22] gave the detailed calculations with 2D-model of DH pipes based on the Finite-Element Method. The model considered the influences of several pipe configurations, soil temperature and temperature-dependent conductivity coefficient of insulation foam. Moreover, Danielewicz et al. [23] proposed heat loss calculation for pre-insulated DH twin-pipes based on a 3D-model. It was shown that the factors such as geometry characteristics, temperature and moisture of the ground soil as well as operation parameters would have significant impacts on the pipe heat losses. Perpar et al. [24] determined the effect of the soil thermal conductivity coefficient on the heat loss from pre-insulated pipes during operation. These models mainly focused on the static heat transfer process with constant flow and parameter sensitivity between pipe and surroundings.

As far as a pipe network with variable flow is concerned, the problem of temperature wave propagations from heat sources to consumers may be better considered by transient models. Gabrielaitiene et al. [25] proposed a node method investigating the temperature dynamics of a DH system. The same authors [26] also compared the performances of pseudo-transient approach and the node method. Both of them had limitations in predicting the temperature response time and the peak values of the temperature wave, which is further hampered while the fluid is represented as an ideal one. Furthermore, the same authors [27] also investigated the dynamic performance of DH systems on temperature profile distortion by the node method. Stevanovic et al. [28] presented a new thermal transient prediction model to simulate the temperature front propagations in DH systems. The model based on one-dimensional partial differential equation (1D-PDE) pipe flow model and high-order numerical solution was validated by measured data in a real pipe network. Zheng et al. [29] gave a function method based on Fourier series expansion that can simulate dynamic temperature distribution of a DH network on the assumption of steady-state hydraulic condition. Recently, Heijde et al. [30] proposed a dynamic equation-based model based on plug flow approach. On the platform of Modelica, the time delay and the thermal inertia of pipe wall were considered in the proposed model. However, those transient models have the disadvantage of too much computational burden. To improve computational performance, Duquette et al. [31] constructed a pipe model which combined a steady state heat transfer model and a variable transport delay one (SS-VTD model). Results showed that when compared with the transient model at the same fixed time step, the computational intensity of the SS-VTD model is approximately 4000 times less. Sartor et al. [32] developed a quasi-steady state thermal simulation model to estimate the energy savings for a combined heat and power (CHP) biomass plant. Wang et al. [33] proposed a thermo-hydraulic coupled model for steam transportation considering drainage loss in pipeline networks. Keçebas et al. [34] presented a steady state thermal model to investigate the thermo-economic pipe insulation thickness optimization for five different pipe sizes and four different fuel types. To reduce the computational burden in those models [31–34], the temperature of ground soil or air is usually simplified as a presumed constant value. As the thermo-hydraulic simulation of a DH network with looped topology and multiple heat sources is rather difficult than that of a tree-like network, recent studies have also focused on the modelling of the complex DH networks [35–37].