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A novel model for steam transportation considering drainage loss in pipeline networks

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HIGHLIGHTS

- Drainage loss terms are involved in a proposed steam transportation model.
- The proposed model achieves accurate estimation of drainage/heat loss along pipes.
- The proposed model was validated via cases of one single pipe and pipe-network.
- Saturated steam model was also presented.

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ABSTRACT

High temperature steam is still used widely in many industries. And waste steam from some industries can still be used as supplement heat sources for district heating and cooling. Drainage recovery is very valuable during steam transportation and distribution in district heating or industry heating projects in order to save energy and water. However, drainage amount collected by steam traps along the pipes can hardly be estimated precisely. A novel model was proposed in this paper to improve the simulation of steam transportation in pipes with consideration of the amount of drainage loss. In the proposed model, drainage involved terms which emblem the continuous mass loss and energy loss during the steam transportation included in mass conservation equation and energy conservation equation respectively. The proposed model was compared with models from other literatures analytically. Furthermore, the simulation results of the proposed model were validated by two steam transportation cases from Baoshan Iron & Steel Co. Shanghai. In case 1, the simulation of steam transportation in a single long pipe showed that the proposed model could achieve more accurate results than previous models. The difference between the simulation results and measured data from on-site experiment was 2.34 K (0.44%) for outlet steam temperature and 0.038 kg/m^3 (0.56%) for outlet steam density. In case 2, the simulation of steam transportation and distribution in a steam network showed that maximum relative differences between results of proposed model and measured data from meters of a steel plant were no more than 5%.

1. Introduction

In the first generation of district heating (DH), the widely used heat medium in pipes from heat sources to users was high temperature steam from boilers. With more advanced technologies arising in DH, water instead of steam is used as the main heat medium in pipes [1]. DH is developed towards 4th generation in recent years [1]. The heat sources could be renewable resources and industry waste heat [2,3]. Nevertheless, high temperature steam is still used widely in many industries [4–6]. And waste steam from some industries can still be used as a supplement heat source for district heating and cooling [7,8]. In recent years, development of an eco-industrial park (EIP) has drawn attention as a promising approach seeking for the mutual benefit to the economy and environment [9]. In EIP, by the using of waste heat utilization networks, the total energy cost and the amount of waste heat discharged (including waste steam and water from the region) can be reduced [10]. Waste steam from one industry can be transported through networks to other industries in EIP [11].

The heating pipeline or networks are always necessary parts in a district heating system or industry heating system with hot

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Nomenclature

A	cross sectional area, m^2
d	internal pipe diameter, m
d_o	external pipe diameter, m
E	specific energy, J/m^3
f	friction factor
g	gravity acceleration, m/s^2
h	enthalpy, J/kg
h_c	enthalpy value of drainage, J/kg
h_m	convection heat transfer coefficient, W/(m^2 K)
h_a	convection heat transfer coefficient, W/(m^2 K)
K	heat transfer coefficient, W/(m^2 K)
m	mass, kg
m_c	specific mass loss of steam drainage, kg/(m^3 s)
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
q_m	specific main steam heat loss, W/m^3
q_c	specific heat loss to drainage, W/m^3
q_s	specific heat loss to temperature drop of the main steam, W/m^3
Re	Reynolds number
r_c	latent heat of vaporization, J/kg
S_u	source item
T	temperature, K
u	fluid specific internal energy, J/m^3
v	fluid velocity
Z	elevation from a reference level

Greek symbols

θ	pipe angle from the horizontal, rad
μ	viscosity, Pa s
ρ	density, kg/m^3
δ	thickness, m
ε	emissivity
σ	Stefan-Boltzmann constant, W/(m^2 K^4)
Φ	heat transfer rate, W/m
λ	roughness of pipe inner surface

Abbreviations

CV	control volume
E	position of east side
W	position of west side
P	position of local side
WW	position of west of west side

Superscripts

0	value of last time step or previous value
$*$	temporary value in iterations

Subscripts

c	condensation
j	position index of parameters
m	main steam
sat	saturated steam
q	heat loss

water or steam flow in pipes. Heat from sources needs to be transported to users in pipes in an economic and effective way. It is not an easy task, especially in a pipe network connected with multiple sources and multiple users. During the transportation process, the heat loss from steam or water to surroundings should be minimized to save energy. In recent years, methods used to estimate or simulate heat loss from hot water to surroundings through pipes were reported in many papers [12–19]. However, the process of heat loss from steam to surroundings is so different from that of water. Part of steam would change into condensation, and accordingly latent heat of condensation would take a main part of heat loss. Liu [20] put forward a thermal model for heat loss from steam to ground soil, air and pipe trenches and discussed some main factors that affect the heat resistance from steam to the surroundings. Zhang [21] developed a thermal-hydraulic model to simulate steam transportation in pipeline of Tianjin Airport Industry Park. The simulation results agreed well with the actual operating data. Alfonso et al. [22] presented a hydraulic model for the steam pipe network in Los Azufres geothermal field and validated the model with operation data. With PIPEPHASE software, Alfonso et al. [23] simulated the steam pipe network in Cerro Prieto geothermal field, which could be the largest geothermal field in Mexico with 162 producing wells and a large network connecting to 13 power-generating plants. The simulation results helped those operators to improve the retrofitting of pipes or proper opening of some valves in pipeline. Zhong et al. [24] developed a hydraulic calculation model to study the steam flow regime considering heat dissipation and condensation in pipes. An operation optimization method was proposed to help eliminate steam stagnation through optimizing the heat load distribution of each heating source. It was found that heat dissipation and condensation in pipes would influence the overall hydraulic calculation of steam. The drainage induced heat dissipation could account to 3–10% of the total heat supply. Luo et al. [25] demonstrated the method to set up the pipe network hydraulic-thermal synthetic mode by applying hydraulic and thermal models of single pipe. Liu et al. [26] established a simplified static model according to steam flow features in pipe networks. The solutions to the governing equations were obtained by using the standard fourth-order Runge-Kutta method. In these papers [20–26], the heat dissipation was affected by the flow rate of the main stream in pipes, thickness and material of pipe-wall and insulation layers as well as temperature difference between steam and ambient etc. However, heat loss of drainage (collected by steam traps along the pipes) was neglected.

In heating projects, steam transportation in pipes was deeply influenced by drainage induced mass and heat decrease. The values of pressure, flow rate and temperature of steam flow would be changed with the condensation and drainage. It is important to transport steam safely in a proper state. If the steam flows at a low velocity or is stagnated, there might be some serious accidents, such as CIWH (condensation induced water hammer) [27–29]. However, the model of steam transportation in pipes with condensation and drainage is still rarely developed. There have been two major types of approaches to develop steam transportation model. One of the approaches is one-phase flow model in which the main stream in pipe would be treated as vapor only without condensation. Most of the papers mentioned above applied this type of model [20–22,24–26]. It is quite reasonable to simplify the steam flow model as one-phase flow when vapor takes the main part in pipes. And in most scenarios, the simulation results of one-phase model seemed to be well matched with measured data from meters [23,30]. And some sophisticated gas network models could be used as well [31,32]. However, this kind of model cannot estimate the amount of drainage along pipes. Another approach is two-phase flow model where the main stream in pipe was treated as a mixture of water and steam [33–36]. In two-phase flow model,