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Modeling and optimization for hydraulic performance design in multi-source district heating with fluctuating renewables

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ABSTRACT

Hydraulic performance of a district heating system is a significant aspect in designing. In the context of multiple heat sources and looped topology layout, severe non-linear hydraulic characteristics have markedly impacts on the hydraulic performance design of a district heating network. Design or select variable-speed circulating pumps with suitable capacities and hydraulic characteristics can be a rather difficult issue especially when there are fluctuating renewable heat sources. In this paper, an optimization model is proposed to achieve the lowest power consumption of all pumps and still fulfill the hydraulic head demands of all substations simultaneously. Based on the proposed model, a holistic design method is presented for optimal hydraulic design of the variable-speed pumps in each heat source. Then a case study is illustrated to validate the proposed method. With consideration of fluctuating heat load of a renewable heat source, the optimal rated capacities of all pumps and variable speed hydraulic characteristic curves are obtained in the designed heating schemes from 100% to 40% of full heat load. Moreover, when all pumps operating on their optimal regime, there always exists one substation branch whose excess head would reach the preset minimum value. The sensitivity analysis results show that the variation of total work of pumps can be from 0.16% to 7.56% when the heat load of the renewable heat source fluctuated 1.0% in different designed heating schemes.

1. Introduction

With rapid urbanization in recent decades, the environment protection and sustainable energy utilization issues get more and more attention in building sector [1]. In European Union, buildings account for 40% of the total energy consumption and 36% of the greenhouse gas emissions [2]. In China, the building sector represents more than 30% of the total energy consumption [3]. To tackle the challenge on climate change mitigation and security of energy supply, district heating (DH) is seen as one of the most efficient measures to provide energy to buildings with low carbon emissions [4]. During the DH modernization, Lund et al. [5] proposed the 4th generation district heating for future development including integration more renewable heat sources, a shift to lower supply temperature and utilization of waste heat from industries, etc. For instances, Lund et al. [6] analyses the role of district heating in future 100% renewable energy systems in the case of Denmark. Brand et al. [7] indicated that low supply temperature district heating system integrated with renewable sources could work properly without reducing the current high level of thermal comfort. Li et al. [8] proposed a heating scheme that surplus industry heat can be supplied to the nearby urban residents. Mathiesen et al. [9] present the development and design of Smart Energy Systems as an integrated part of achieving future 100% renewable energy and transport solutions. To utilize those fluctuating renewable energy efficiently, the district heating networks should be redesigned to adapt more penetrations of renewable energy. Buoro et al. [10] proposed a multi-objective optimization model for a cogeneration system integrated with central solar field and long-term heat storage. Balaman et al. [11] developed a comprehensive decision model for sustainable design of biomass based renewable energy supply chains and district heating systems with thermal energy storages. The model integrated the strategic decisions such as location and capacity selection for the energy plants, DH system, thermal storages, etc. Tereshchenko et al. [12] discussed the factors associated with the decisions on energy supply plants in district heating with considering three highly efficient energy conversion technologies. While integrating those fluctuating renewables to district heating systems, variety kinds of heat pumps, thermal storages and high thermal insulation measures, etc. are often utilized to improve those systems efficiently and environmentally as far as possible.

With the growth of the small-scale district heating networks successively to meshed DH network with multiple sources, there is increasing complexity for renewables to integrate into existing district

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Nomenclature

A	associated matrix of pipe network
B	basic circuit matrix of pipe network
C_p	heat capacity of the water (J/kg·°C)
d	inner diameter of pipe (m)
E	electricity consumption (W)
f	friction factor
g	gravity acceleration (m/s^2)
H	head of pump (m H_2O)
k_0, k_1, k_2	fitting coefficient
L	length of the pipe (m)
n	rotation speed (rpm)
P	pressure (Pa)
Q	volume flow rate (m^3/h)
q_{heat}	heat load or heat demand (W)
r_0, r_1, r_2	fitting coefficient
R	hydraulic resistor (Pa)
Re	Reynolds number
T	temperature (°C)
W	effective output work of pump (W)

Greek symbols

ρ	density (kg/m^3)
ε	roughness of inner surface of pipe (m)
η_P	efficiency of pump (%)
ϕ_{sen}	sensitivity factor (%)

Superscripts

d	designed value
f	feed water or supply water
r	return water
rate, 0	rated value

Subscripts

b	pipe branch
k	index of a pipe branch
m	index of a substation
p	pump
s	index of a source
a	available head
e	excess head
v	valve

Abbreviations

CCCP	conventional central circulating pump
CHP	combined heat and power plant
DH	district heating

heating systems efficiently. To analysis hydraulic performance of complex heating networks, many effective efforts have been made in the studies of previous literatures. Vesterlund et al. [13] proposed a method for modeling complex district heating systems with multi-source meshed DH networks. This method made it possible to analyze how loops and bottlenecks affect the behavior of the network, and the thermal energy distribution path in it. On the basis of the proposed method, the same authors simulated a complex meshed DH network of the town of Kiruna (Sweden) [14]. And in the later work, the simulation process was also coupled with a hybrid MILP algorithm for the optimization of the operation cost in a multi-source meshed DH network [15]. Stevanovic et al. [16] presented a square roots method for numerical simulation and analyses of the steady state hydraulics of looped pipeline networks. Wojdyga et al. [17] investigated the hydraulic performance of a district heating system with two combined heat and power plants. It indicated that multi-source heating system could be significantly improved with well hydraulic design. Guelpa et al. [18] proposed a reduced model based on proper orthogonal decomposition and radial basis functions to optimize the energy consumption of pumps with much less computational time. In these previous works, one of the obvious improvements of the hydraulic models can be the technique to solve hydraulic equations based on looped topology of network structure. Recently, Wang et al. [19] proposed a hydraulic performance optimization problem of meshed DH network with multiple heat sources. In this work, the General Reduced Gradient (GRG) algorithm was adopted to minimize the total pump power by optimizing the pump frequencies and substation valve openings of the DH network.

Successful implementation of a DH system requires deliberated design, good maintenance and economical operation with respect to the high investment and the long service period. Great interests in optimal planning, designing and operation on DH systems show in recent decades. A number of optimization works have also been carried out to achieve the optimal aims. Bordin et al. [20] presented an optimization model to support the district heating system planning, which considered the selection of new users to be connected to an existing thermal network with more revenues and less infrastructure and operational costs. Pirouti et al. [21] proposed a new approach for minimization of the capital costs and energy consumption in a district heating network while considering different supply and return temperatures and target pressure losses. By increasing temperature difference between the supply and return pipes, the annual total energy consumption and the equivalent annual cost were reduced. Li and Svendsen [22] proposed an optimization method to determine the configuration of a district heating network, which considered multiple factors such as consumer heating load, the distance as well as the network heat loss. Fang and Lahdelma [23] developed a method for optimizing the heat production simultaneously at multiple heat plants at different locations to achieve minimization of the combined production and distribution costs. Wang et al. [24] developed an optimization method for planning and operating a CHP-DH system with solar thermal plants and thermal energy storages to minimize the overall costs of the net acquisition for heat and power in deregulated power market. Morvaj et al. [25] presented a mixed integer linear programming (MILP) model to investigate the optimal design and operation of distributed energy systems as well as optimal heating network layouts in order to achieve minimization of total cost and carbon emissions. Distributed energy systems coupled with district heating networks are promising concepts for realizing less carbon-intensive urban energy systems. Our recent work [26] proposed a new hydraulic regulation method for a district heating system with distributed variable speed pumps. With the help of the advanced automation and information technologies, on-site hydraulic balance for the district heating systems can be achieved in several rounds of regulations. Sameti and Haghighat [27] made a sufficient review on optimization approaches which are dealing with different types of optimization problems, constraints and techniques as well as the optimization tools used in district heating and cooling systems.

A multi-source district heating system is always a strongly hydraulic coupled water circulating network. Some sophisticated simulation models and software tools can be helpful to analyze the hydraulic and thermal performance of the existing system or design a new one. In the studies of most literatures, the methodology to analyze hydraulic characteristic of a district heating network is based on the Kirchhoff's current and voltage law as well as the graph theory [28,29]. Besides