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Selecting the optimum pressure drop per unit length of district heating piping network based on operating strategies

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HIGHLIGHTS

- Operating parameters are considered in the mathematical model on the optimum pressure drop per unit length.
- The annual cost of a district heating network can be reduced by selecting the optimum pressure drop per unit length.
- Four operating strategies and five design temperature regimes are analyzed in a case study.
- Pump overall efficiency greatly influences the minimum annual cost of a district heating network.
- Operating strategies obtained from various perspectives may be different.

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ABSTRACT

A mathematical model used to obtain the optimum pressure drop per unit length (PDPUL) and the minimum annual cost (MAC) of a district heating (DH) piping network based on operating strategies was established. A case study based on a DH system in Hebei Province, China, was carried out. Four operating strategies were used respectively. Sensitivity analysis method was used to investigate the impact of pump overall efficiency, electricity price, heat price and interest rate on the optimum PDPUL and the MAC of the DH piping network. Results showed that the optimum PDPUL and the MAC of the DH piping network could be obtained by using the mathematical model. The MAC of the DH piping network for variable mass flow rate (VMFR) operating strategies was lower than that for constant mass flow rate (CMFR) operating strategies. Also, the decrease of the design supply temperature in the primary side caused the reduction of the optimum PDPUL. But the MAC increased with the decrease of the design supply temperature in the primary side. Among all the parameters, the pump overall efficiency had the greatest impact on the optimum PDPUL and the MAC of the DH piping network.

1. Introduction

DH systems are usually used to supply heat for buildings to maintain a stable indoor temperature when outdoor temperature is lower than indoor temperature. DH systems can also be used to supply hot water for buildings. In addition, heat supply of DH systems may be used in some production process such as drying, cooking, cleaning, and melting [1]. DH systems mainly consist of heat sources, piping network and consumers. Heat is produced at heat sources, and then it is distributed to buildings through piping network. Water or steam can be used as the heat medium for DH systems. When fossil fuel boilers are used as heat sources, the combustion temperature of fossil fuels is much higher than the heat medium of DH systems. Therefore, plenty of useful exergy is lost according to the second law of thermodynamics. However, the energy efficiency and exergy efficiency could be improved substantially by using heat from combined heat and power (CHP) plants [1–6]. Nowadays, geothermal energy [1,7–13], solar energy [1,7,9,10], wind energy [1,8,9], biomass fuels [1,8–10,14–16], heat from waste incineration [1,7–9,14,15,17] and waste heat from industrial processes [1,8,9,14,18] can also be used during heat production in most current DH systems. Such measures cause remarkable reductions in fossil fuel consumption, greenhouse gas emission and operating cost.

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Nomenclature

Abbreviations

CHP	combined heat and power
CMFR	constant mass flow rate
DH	district heating
MAC	minimum annual cost
PDPUL	pressure drop per unit length
VMFR	variable mass flow rate

Parameters

a	constant term in linear regression equation
A	annual cost related to a DH piping network (¥/year)
b	regression coefficient in linear regression equation
C_m	cost of DH pipes per unit length (¥/m)
C_{pa}	equivalent annual pipe investment (¥/year)
C_p	pipe investment cost (¥)
d	pipe diameter (m)
G	mass flow rate (t/h)
H	pressure drop (Pa)
I	interest rate (%)
k	average heat transfer coefficient of pipes (W/ (m^2 °C))
l	length of pipes with the same diameter (m)
L	length of the main route in a DH piping network (m)
m	total operating hours of the whole heating season (h)
n	total number of pipe diameters
M	material properties of a DH piping network (m^2)
ΔP	differential pressure (Pa)
E	electrical power (kW)
R	pressure drop per unit length (Pa/m)
R^2	determination coefficient
t	temperature (°C)
U	price (¥/kW h for electricity price and ¥/MW h for heat price)
y	life time of a DH piping network (years)
φ	capital recovery factor
ρ	water density (kg/m^3)
η	pump overall efficiency (%)
α	coefficient (%)

Subscripts

a	average value in supply and return pipes
as	assumed value
d	design value
de	depreciation
dp	design value in the primary side
e	electricity
ev	environmental
h	heat
hl	heat loss
hs	heat source and substation
i	index for operating hours
j	index for pipe diameters
lr	local resistance
o	operating value
od	optimum design value
op	operating value in the primary side
os	operating value in the secondary side
pu	pump
rd	repairing and depreciation
re	repairing
rdp	design value in return pipes in the primary side
rds	design value in return pipes in the secondary side
rop	operating value in return pipes in the primary side
ros	operating value in return pipes in the secondary side
sdp	design value in supply pipes in the primary side
sds	design value in supply pipes in the secondary side
sop	operating value in supply pipes in the primary side
sos	operating value in supply pipes in the secondary side
sr	supply and return pipes
sro	operating value in supply and return pipes
t	total

However, efforts have still been made to reduce the energy consumption and operating cost through the optimization of DH systems. Persson and Werner [19] studied the heat distribution with regard to the future competitiveness of DH systems. In [20–23], it was suggested that the operating temperature of DH systems should be reduced so as to reduce the primary energy consumption and heat losses during heat distribution. Verda and Colella [24] believed that the primary energy consumption and total cost could be reduced when using heat storage tanks in CHP plants for DH systems. Tol and Svendsen [25] developed the optimization method to reduce heat losses from a DH piping network. They found that an appreciable reduction in heat losses could be achieved by selecting the optimum pipe diameters.

As for a DH system, the operating cost consists of the annual cost of the heat source and piping network. The annual heating load mainly determines the annual cost of the heat source. Therefore, the operating cost of a DH system is mainly influenced by the annual cost of the piping network when the annual heating load is determined. The PDPUL plays an important role in determining pipe diameters. When design values of heating load, supply temperature and return temperature are determined, the design mass flow rate is determined. Higher PDPUL results in higher flow velocity. It means that pipes with smaller diameters are used when higher PDPUL is selected. Therefore, the pumping cost increases, while the pipe investment cost and heat loss cost decreases. On the contrary, if lower PDPUL is selected, pipe diameters increase because of the reduction of flow velocity. As a result, the pumping cost decreases, while the pipe investment cost and heat loss cost increases. It can be seen that there must be an optimum PDPUL for a DH piping network. The MAC of a DH piping network can be obtained by selecting the optimum PDPUL.

Generally speaking, three methods can be used to select the PDPUL for a DH piping network. Firstly, the PDPUL can be selected based on empirical data. Wide ranges of PDPUL were used in different countries and various studies. In China, the PDPUL value of a DH pipe segment was recommended to be 30–70 Pa/m according to the design code [26]. In Denmark and some other European countries, the PDPUL of 100 Pa/m was usually used to design a DH piping network [27]. In [16], it was assumed that the maximum PDPUL value was 200 Pa/m. Yildirim et al. [28] pointed that DH system practice was to design it for the PDPUL of 50–200 Pa/m. In [29], the PDPUL value was recommended to be 150–200 Pa/m when designing a DH piping network. Secondly, comparison method was often used to select the PDPUL. Pirouti et al. [27] proposed an approach for minimization of the energy consumption and equivalent annual cost of a DH system in UK. Different design cases were obtained by using various PDPUL and temperature regimes. The annual pump electrical energy consumption, heat losses and equivalent annual cost of each design case were analyzed based on four operating strategies. It was found that operating strategies with VMFR and variable supply temperature were beneficial in all cases. They suggested increasing the temperature