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Published in:
Science and Technology for the Built Environment

DOI:
10.1080/23744731.2020.1767442

Published: 20/10/2020

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Wang, H., Duanmu, L., Wu, X., Li, X., & Lahdelma, R. (2020). Operational strategies and pumping energy saving potential of the combined district heating system with peak shaving gas-fired boilers in heating substations. *Science and Technology for the Built Environment*, *26*(9), 1216-1230. https://doi.org/10.1080/23744731.2020.1767442

Science and Technology for the Built Environment

ISSN: 2374-4731 (Print) 2374-474X (Online) Journal homepage: https://www.tandfonline.com/loi/uhvc21

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Operational strategies and pumping energy saving potential of the combined district heating system with peak shaving gas-fired boilers in heating substations

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Abstract

Combined district heating (DH) systems have at least one base load heat plant and several peak shaving heat sources, which can be installed in primary network or in the heating substations. This paper studies the combined DH system with peak shaving gas-fired boilers in heating substations, where the peak boilers can be connected to the heat exchangers with series or parallel mode. We analyze the thermal balances for these two connection modes, and obtain the analytical operational regulation formulas for them. Then we study the operational methods for each connection mode considering the heat distribution control strategies in both primary and secondary networks. Adopted control strategies are: 1) variable temperature (VT) control, 2) variable flowrate (VF) control, and 3) variable temperature and flowrate (VT-VF) control. The combinations of these three strategies in primary and secondary networks are compared in terms of pumping energy consumption. The results indicate that operational strategies should be phased into different periods according to whether the peak heating is needed or not. In addition, the pumping energy consumption for parallel connection mode is less than that for series connection mode with the same operational strategy, and VF control strategy shows better energy saving potential.

Keywords: Combined district heating system, Operational strategies, Gas-fired boiler, Peak shaving, Pumping energy.

1. Introduction

District heating (DH) systems are very important city infrastructures for areas with cold climates in winter. In European countries DH systems usually supply heat for the space heating and domestic hot water (DHW) heating, but in China DH systems mainly cover the space heating demand, indicating that the DH system only operates in a heating season, which has different time periods for different cities. In this paper, we mainly focus on the DH system providing only space heating in the heating season. Another big difference is that in China the heating substations usually provide heat for a cluster of buildings or a community, and thus most of them are not the building level substations. Currently, DH is developing fast all over the world from the perspectives of technology evolution and DH demand. In Denmark, the 4th generation district heating (4GDH) (Lund et al., 2014) is proposed and under investigation. One of the most important characteristic of 4GDH is to make full use of multiple heat sources while highlighting the clean and renewable energy sources (RES). In China, the so called combined DH systems with multiple heat sources are also more and more prevailing due to the capabilities in increasing heating efficiency (Wang et al., 2010) and reliability as well as alleviating the environmental impact (Wang et al., 2013). In addition, combined DH systems also have the potential to save pumping energy for heat distribution with proper operating strategies in primary and secondary networks. It was reported that the heat distribution cost of the primary network can account for more than 60% of the total annual operating cost of a district heating network (DHN) with economic specific pressure drop under 100Pa/m in the pipes (Wang et al., 2017). This indicates that more attention should be paid to reduce the pumping energy consumption in order to increase the energy efficiency of the combined DH system.

There are different ways to save the pumping energy consumption for a DHN. Koiv et al. (2014) reported that an optimal dimensioning of the DHN is essential for the effective use of DH, and they proposed a new dimensioning method based on a probabilistic determination of the water flowrate in the DHN. In the method, heat loss and pumping electricity cost were calculated, and results showed that the cost of the DHN was reduced by 12% while the pumping cost was reduced by 35%. Nussbaumer and Thalmann (2016) carried out an economic analysis for DHN from 0.5MW to 4MW for Switzerland. They considered the geographical distribution of heat load and heat users, as well as connection modes, fuel prices and heat losses. Their results revealed that the minimization of heat distribution cost was clearly affected by the geographical distribution of heat load and consumers. However, in addition to the optimal network design, the energy saving potential of different operating strategies of the DHN still need to be improved. Ruesch et al. (2015) adopted the pump and hydraulic resistance model in Polysun software to simulate the electric energy consumption of the distributed circulation pumps based on simplified heat loads. They reported that the electric energy consumption was less than 1% of the transferred heat energy. A real low temperature DHN was adopted to validate the results, showing that the heat distribution electricity consumption was about 1.6% of the case study, due to the higher monitored pressure drop in the pipelines. This also indicates that the operating strategy of the DHN will have a dramatic impact on the pumping energy consumption of the DHN.

In China, the concept of distributed variable speed pump (DVSP) were extensively studied compared to the traditional central circulating pump (CCCP) DHN from the perspective of pumping energy saving. In a DVSP system, each heating substation has a variable speed pump, providing the required pressure drop and flowrate for the connected substation, and the central circulation pump only provides the lift needed for water circulation in the primary network. Yan et al. (2013), Sheng and Duanmu (2016) simulated the hydraulic performance of the DVSP DHN. They found that DVSP systems could save 30%~49% of the pumping energy consumption compared to the traditional CCCP systems. However, DVSP system can be planned easily in the newly built DHN, but not a good refurbishment for the existing DHN, due to the huge initial investment of the pumps and construction works to install them for all heating substations. Further, more pumping energy can be saved on top of the DVSP technology with effective operating regulation strategies without extra cost.

However, the study on the impact of operating strategies to the pumping energy consumption for the combined DH system with multiple heat sources is very limited. Zheng et al. (2018) built a hydraulic and heating model for indirect connection DHN based on combined heat and power (CHP) plant and studied the regulation methods in the primary network. They found that the 'variable temperature-variable flow control mode' is better than the 'variable temperature control mode' followed by the 'centralized control with flow varied by steps mode', but the regulation of the secondary network is not included in the analysis. Jie et al. (2015) tried to choose the optimal operating strategy for an existing traditional indirect connected DHN in terms of the pumping cost and heat loss. They calculated the heat distribution cost for four different operating strategies and found that controlling the flowrates in both primary and secondary networks can lead to minimum cost, but this operating strategy requires excellent controlling devices and a good hydraulic stability of DHN, which is not common in the secondary networks.

This study mainly focuses on the optimal control methods for combined DH system with peak shaving gas-fired boilers in heating substations, considering the regulating strategies in primary and secondary networks at the same time. This method can be applied in both newly built and existing DHN. The innovation compared to some previous studies is that it can not only reduce the pumping cost but also increase the heating capacity of the DHN; and the regulation strategies are evaluated for the combination of the primary and secondary networks, while the relative flow ratios are well considered to avoid hydraulic imbalances and save more pumping energy. The optimal regulating strategies can be obtained and used on top of e.g. 4GDH and DVSP systems to further reduce the pumping cost without extra cost.

The combined DH system in question also has the following characteristics: 1) the diameter of the primary network can be reduced because the primary network only provides the base load, and this can dramatically reduce the initial investment and thus the pumping cost of the primary network; 2) the reliability of the network can be increased, because the peak shaving heat sources are installed in heating substations and they can provide a centain level of backup heating capacity, even the heat supply from the primary network is not available in the most severe accidents, 3) it can extend the heating capacity of the existing DH system without changing the primary network. Of course, the use of gas-fired boilers will add extra investment and operating cost for the boilers and gas supply pipes, however the overall economy performance can be better with proper base load ratio compared to the traditional DH system with only base load heat plant or with multiple heat plants but operated independently (Zheng, 2007 and Wang, 2013). This paper will perform a comprehensive and systematic study on the pumping energy saving potential for this kind of combined DH system considering the matching of feasible operating strategies in both primary and secondary networks. In fact, for any kind of new DH technology improvement, including DSVP and 4GDH, it is very cost-effective to choose and implement most effective operating strategy on top of the technology improvement considering the pumping energy cost, in order to further increase the energy efficiency of the DH system and reduce the DH related CO_2 emissions.

This paper will define the connection modes and thermal balances for the combined DH system with peak shaving gas-fired boilers in heating substations. Then the combinations of operating strategies in primary and secondary networks will be analyzed and compared in detail according to the thermal balances of the combined DH system with different connection modes. In section 4, the pumping energy consumption for the regulating strategies with different connection modes will be calculated and compared using a case study in Harbin, China. Finally, the conclusions are drawn in section 5.

2. Connection modes and thermal balances of the proposed combined DH system

2.1 Base load ratio of the combined DH system

The design heat load of a combined DH system can be written as,

$$Q' = Q'_{load,b} + Q'_{load,p} \tag{1}$$

where Q' is the design heat load of the combined DH system; $Q'_{load,b}$ and $Q'_{load,p}$ are the design heat load of the base load heat plant and the peak shaving heat sources, i.e. gas-fired boilers in this study, W.

The base load ratio β of a combined DH system is defined as the ratio between the design heat load of the base load heat plant and the design heat load for the whole DH system.

$$\beta = \frac{Q'_{load,b}}{Q'} \tag{2}$$

In this paper, we mainly study the situation that the local base load ratio in each heating substation is equal to the based load ratio of the whole combined DH system.

$$\beta_i = \frac{q'_{load,b,i}}{q'_{load,i}} = \beta \tag{3}$$

where β_i is the base load ratio for the ith substation; $q'_{load,b,i}$ is the design heat load of the heat exchanger in the ith substation or the heat supply from the base load heat plant to the ith substation, W; $q'_{load,i}$ is the design heat load of the ith substation, W.

2.2 Connection modes between gas-fired boilers and heat exchangers

Figures 1 and 2 show that the proposed combined DH systems can be divided into series and parallel connection modes, depending on how the gas-fired boilers are connected to the heat exchangers in substations. For series connection mode, the return water of the secondary network firstly obtains the heat from the base load heat plant via the heat exchanger, and then a portion of the water ($\omega g_{2,i}$) flows into the gas-fired boilers to absorb more heat, while the rest of the water flows through the bypass pipe. These two water flows are mixed to reach the required supply water temperatures. As to the parallel connection mode shown in Fig. 2, the return water will be divided into two flows, one flow goes into the heat exchanger while the other enters the gas-fired boiler, and then the mixture of the two flows will be the supply water in the secondary network provided the temperature meets the operating regulation requirement.

In Figs. 1 and 2, $Q_{load,b}$, G_b are the heat load and flowrate of the base load heat plant; τ_s, τ_r are the supply and return water temperatures of the primary network; t_s, t_r are the supply and return water temperatures of the secondary network; G_2 is the flowrate in secondary network; $g_{2,i}$ is the flowrate in the ith heating substation; $t_{s,hr}$ is the supply water temperature of the heat exchanger; $t_{s,p}$ means the supply water temperature of the peak shaving gas-fired boiler and ω is defined as the peak shaving flow ratio (PSFR),

$$\omega = \frac{G_p}{G_2} \quad (4)$$

where G_p and G_2 are the flowrates of the circulation pump for peak shaving gas-fired boilers and for the secondary network, kg/s.

The peak shaving flow ratio under design condition is,

$$\omega' = \frac{G'_p}{G'_2} \quad (5)$$

where G'_p and G'_2 are the flowrates of the circulation pump for peak shaving gas-fired boiler and for the secondary network under design condition, kg/s. In this study, $\omega=\omega'$.

The design peak shaving flow ratio for series and parallel connection modes should satisfy the following inequalities (Wang, 2013).

$$\frac{(1-\beta)(t'_s - t'_r)}{t'_{s,p} - t'_{s,hr}} \le \omega' \le 1, \text{ for series connection mode} \quad (6)$$

$$\frac{(1-\beta)(t'_s - t'_r)}{t'_{s,p} - t'_r} \le \omega' \le 1-\beta, \text{ for parallel connection mode} \quad (7)$$

2.3 Thermal balances and operating regulation formulas for the proposed combined DH system

2.3.1 Thermal balances under design condition

Under the design condition at the outdoor temperature t'_{out}, we can obtain the following thermal balances for the proposed combined DH system.

$$Q'_{load,b} = \beta Q' = Q'_{hr} = \sum_i q'_{hr,i} \quad (8)$$

$$Q'_{load,b} + Q'_{load,p} = Q'_{network} = Q'_{radiator} = Q'_{building} \quad (9)$$

where,

$$Q'_{load,b} = G'_1 c_{water} (\tau'_s - \tau'_r) \quad (10)$$

$$Q'_{load,p} = \begin{cases} \omega' \sum_i g'_{2,i} c_{water} (t'_{s,p} - t'_{s,hr}) & \text{Series connection} \\ \omega' \sum_i g'_{2,i} c_{water} (t'_{s,p} - t'_r) & \text{Parallel connection} \end{cases} \tag{11}$$

$$Q'_{building} = \sum qV(t_{in} - t'_{out}) = Q' \tag{12}$$

$$Q'_{radiator} = \sum aF \left(\frac{t'_s + t'_r}{2} - t_{in} \right)^{1+b} \tag{13}$$

$$Q'_{network} = G'_2 c_{water} (t'_s - t'_r) \tag{14}$$

where $Q'_{building}$, $Q'_{radiator}$, $Q'_{network}$ are the design heat load of the buildings, design heat releasing load of radiators and the design transported heat load in the network. G'_1 is the design flowrate in the primary network, τ'_s, τ'_r are the design supply and return water temperatures in the primary network, °C; t'_s and t'_r are the design supply and return water temperatures in the secondary network, °C; $g'_{2,i}$ is the design flowrate of the *i*th substation in secondary side, kg/s; q is the volumetric heating index of the buildings, W/m^3; V is the peripheral volume of the buildings, m^3; t'_{out} is the design outdoor temperature, °C; t_{in} is the design indoor temperature, °C; F is the radiation area of the radiators, m^2; a and b are the coefficient and index of the heat transfer equation for radiators.

Because $G'_2 = \sum g'_{2,i}$, we can obtain the following equation from Eq. (11) for both series and parallel connection,

$$Q'_{load,p} = (1 - \beta) G'_2 c_{water} (t'_s - t'_r) \tag{15}$$

The design heat load of the heat exchanger is,

$$Q'_{hr} = K' F_{hr} \Delta t' \tag{16}$$

where $\Delta t'$ is the design logarithmic mean temperature difference,

$$\Delta t' = \frac{(\tau'_s - t'_{s,hr}) - (\tau'_r - t'_r)}{\ln \dfrac{\tau'_s - t'_{s,hr}}{\tau'_r - t'_r}} \tag{17}$$

and G'_2 is the design flowrate in secondary side, kg/s; K' is the heat transfer coefficient of the heat exchanger under design condition, W/(m^2·°C); F_{hr} is the heat exchange area, m^2.

Further, the relative heat transfer coefficient of water-water heat exchanger $\overline{K}$ can be written as (He et al., 2009),

$$\overline{K} = \overline{G}_1^{0.5}\overline{G}_2^{0.5} \tag{18}$$

where $\overline{G}_1$ and $\overline{G}_2$ are the relative flowrate ratios in primary and secondary network.

For series connection, the relative heat transfer coefficient of the heat exchanger in the *i*th substation is,

$$\overline{K}_i = \overline{g}_{1,i}^{0.5}\overline{g}_{2,i}^{0.5} \tag{19}$$

where $\overline{g}_1$ and $\overline{g}_2$ are the relative flowrate ratios of primary and secondary side in the *i*th substation.

For parallel connection, relative heat transfer coefficient of the heat exchanger can be written as,

$$\overline{K} = \overline{G}_1^{0.5}\overline{G}_{hr}^{0.5} \tag{20}$$

where $\overline{G}_{hr}$ is the relative flowrate ratio in the secondary side of the heat exchanger, and it is,

$$\overline{G}_{hr} = \frac{G_{hr}}{G'_{hr}} = \frac{G_{hr}}{(1-\omega')G'_2} = \begin{cases} \dfrac{G_2}{(1-\omega')G'_2} = \dfrac{\overline{G}_2}{(1-\omega')} & \text{peak heating is not needed} \\ 1 & \text{peak heating is needed} \end{cases} \tag{21}$$

Hence, Eq.(18) can take form,

$$\overline{K} = \begin{cases} \dfrac{\overline{G}_1^{0.5}\overline{G}_2^{0.5}}{(1-\omega')^{0.5}} & \text{peak heating is not needed} \\ \overline{G}_1^{0.5} & \text{peak heating is needed} \end{cases} \tag{22}$$

The regulating formulas can be deduced analytically based on the above mentioned thermal balances under design or other working conditions of the proposed combined DH system.

2.3.2 Regulating formula during peak heating period

When the outdoor temperature drops below the critical peak heating temperature, base load plant is operated at full load, and peak-shaving gas-fired boilers will be activated to compensate the insufficient part of the heat. The relative heat load ratio in primary network is,

$$\bar{Q}_1 = \frac{Q_{load,b}}{Q'_{load,b}} = \frac{Q_{hr}}{Q'_{hr}} = 1 \tag{23}$$

therefore,

$$\bar{G}_1 \frac{\tau_s - \tau_r}{\tau'_s - \tau'_r} = \bar{K}\frac{\Delta t}{\Delta t'} = 1 \tag{24}$$

For the secondary network,

$$\frac{Q'_{load,b} + Q_{load,p}}{Q'} = \bar{Q} = \frac{Q_{network}}{Q'_{network}} = \frac{Q_{radiator}}{Q'_{radiator}} = \frac{Q_{building}}{Q'_{building}} \tag{25}$$

Namely,

$$\bar{G}_2 \frac{t_s - t_r}{t'_s - t'_r} = \frac{(t_s + t_r - 2t_{in})^{1+b}}{(t'_s + t'_r - 2t_{in})^{1+b}} = \frac{t_{in} - t_{out}}{t_{in} - t'_{out}} \tag{26}$$

Eqs. (24) and (26) are the analytical formulas for operating the primary and secondary DH network when peak heating is needed.

Before the peak heating starts, the relative heat load ratio of the primary and secondary networks are equal, but they are different after the peak heating is needed. Because when peak heating starts, the relative heat load ratio of the primary network $\bar{Q}_1$ =1, and it can not be increased anymore; however, as long as the t_{out} decreases further, the heat received from primary network can not be increased and thus not sufficient, then peak shaving gas-fired boilers will be activated to compensate the insufficient part of the district heat. Because the thermal balances are different for the two connection modes before and after the peak heating starts, the operating of the proposed combined DH system should be divided into two periods in terms of base load ratio β, and it is necessary to explore the proper regulation method in each time period.

2.3.3 Regulating formula when peak heating is not needed

Before peak heating period, the thermal balance of the combined DH system can be written as,

$$Q_{load,b} = Q_{hr} = \sum_i q_{hr,i} = Q_{network} = Q_{radiator} = Q_{building} \tag{27}$$

where $Q_{building}$, $Q_{radiator}$, $Q_{network}$ are the heat load of the buildings, heat releasing load of radiators and the transported heat load in the network under working condition at outdoor temperature t_{out}, W.

The relative heat load ratio takes form,

$$\overline{Q} = \frac{Q_{load,b}}{Q'} = \frac{Q_{hr}}{Q'} = \frac{Q_{network}}{Q'_{network}} = \frac{Q_{radiator}}{Q'_{radiator}} = \frac{Q_{building}}{Q'_{building}} \tag{28}$$

According to Eq.(4), $Q' = Q'_{load,b} / \beta = Q'_{hr} / \beta$,

$$\overline{Q} = \frac{\beta Q_{load,b}}{Q'_{load,b}} = \frac{\beta Q_{hr}}{Q'_{hr}} = \frac{Q_{network}}{Q'_{network}} = \frac{Q_{radiator}}{Q'_{radiator}} = \frac{Q_{building}}{Q'_{building}} \tag{29}$$

Namely,

$$\beta \overline{G}_1 \frac{\tau_s - \tau_r}{\tau'_s - \tau'_r} = \beta \overline{K} \frac{\Delta t}{\Delta t'} = \overline{G}_2 \frac{t_s - t_r}{t'_s - t'_r} = \frac{(t_s + t_r - 2t_{in})^{1+b}}{(t'_s + t'_r - 2t_{in})^{1+b}} = \frac{t_{in} - t_{out}}{t_{in} - t'_{out}} \tag{30}$$

where τ_s, τ_r are the supply and return water temperatures in the primary network under working condition at outdoor temperature t_{out}, °C; t_s and t_r are the supply and return water temperatures in the secondary network, °C; Δt is the logarithmic mean temperature difference of the heat exchanger at outdoor temperature t_{out}, °C. Eq. (30) is the analytical formula for operating the combined DH system before peak heating is needed.

3. Operating regulation strategies of the combined DH system with peak shaving gas-fired boilers in heating substations

This paper studies the operating methods for each connection mode considering the heat distribution control strategies in both primary and secondary networks. Adopted control strategies are: 1) variable temperature (VT) control, 2) variable flowrate (VF) control, and 3) variable temperature and flowrate (VT-VF) control. Combinations of those control methods are analyzed in order to examine the pumping energy saving potentials.

3.1 Regulation strategy 1 - VT before supply temperature reaches the design value and then VF in the primary network

We use base load ratio β=0.8 in the following analysis. Before the peak heating, VT control method is proposed in the primary network, the relative flowrate ratio ψ, which is a predefined value of $\bar{G}_1$ can be 0.5~0.8 (Lei, 2005). But in order to reduce the pumping energy consumption, we let ψ=0.5 in this study. Because of the small flowrate, the supply water temperature will increase more rapidly to provide the same amount of heat compared to that with larger ψ. This makes the supply water temperature in the primary network reach the design value before the peak heating starts. This relative heat load ratio is denoted $\bar{Q}_\psi$($<\beta$), and when $\bar{Q} > \bar{Q}_\psi$ the regulation method of the primary network will be changed to VF control with a constant supply water temperature $\tau_s=\tau'_s$. In the parallel connection mode, the design flow rate in the heat exchanger is $(1-\omega')G'_2$, which is smaller than G'_2 for the series connection mode. In order to reduce the pumping cost of the secondary network, $1-\omega'$ should be equal to β. Therefore, regulation strategy 1 can be divided into following phases according to the relationship between $\bar{Q}_\psi$ and β, as shown in Fig.3.

3.1.1 When the peak heating is not needed and $\bar{Q}_k \leq \bar{Q} < \bar{Q}_\psi$,

According to Fig. 3, when the peak heating is not needed and $\bar{Q}_k \leq \bar{Q} < \bar{Q}_\psi$, VT regulation at $\bar{G}_1=\psi=0.5$ is used in the primary network, and VT at $\bar{G}_2=1$ (series connection) or $\bar{G}_2=\beta=0.8$ (parallel connection) are used in the secondary network. During this period, outdoor temperature $t_{out,\psi}<t_{out}\leq 5$°C, where $t_{out,\psi}$ is the outdoor temperature when $\bar{Q}=\bar{Q}_\psi$.

Under this regulation strategy, the supply and return water temperatures of the secondary network can be written as (Lei, 2005 and He et al., 2009),

$$t_s = t_{in} + 0.5(t'_s + t'_r - 2t_{in})\bar{Q}^{\frac{1}{1+b}} + 0.5(t'_s - t'_r)\frac{\bar{Q}}{\bar{G}_2} \quad (31)$$

$$t_r = t_{in} + 0.5(t'_s + t'_r - 2t_{in})\bar{Q}^{\frac{1}{1+b}} - 0.5(t'_s - t'_r)\frac{\bar{Q}}{\bar{G}_2} \quad (32)$$

The relative flow rate is,

$$\bar{G}_2 = \begin{cases} 1 & \text{series connection} \\ \beta & \text{Parallel connection} \end{cases} \quad (33)$$

Substitute Eq.(33) and $\bar{G}_1=0.5$ into Eqs.(18) and (20), we obtain,

$$\bar{K} = \begin{cases} \bar{G}_1^{0.5}\bar{G}_2^{0.5} = \psi^{0.5} & \text{series connection} \\ \bar{G}_1^{0.5}\bar{G}_{hr}^{0.5} = \dfrac{\bar{G}_1^{0.5}\bar{G}_2^{0.5}}{(1-\omega')^{0.5}} = \dfrac{(\psi\beta)^{0.5}}{(1-\omega')^{0.5}} & \text{parallel connection} \end{cases} \tag{34}$$

Substitute Eq.(34) into Eq.(30), we can obtain the supply and return water temperatures of the primary network,

$$\tau_s = \frac{1}{e^{U}-1}\left[e^{U}\frac{\bar{Q}}{\beta\psi}(\tau_s'-\tau_r') - (t_s - e^{U}t_r)\right] \tag{35}$$

$$\tau_r = \frac{1}{e^{U}-1}\left[\frac{\bar{Q}}{\beta\psi}(\tau_s'-\tau_r') - (t_s - e^{U}t_r)\right] \tag{36}$$

where, $\Delta t'$ is calculated by Eq.(17), and

$$U = \begin{cases} \dfrac{\psi^{-0.5}(\tau_s'-\tau_r') - \psi^{0.5}(t_s'-t_r')}{\Delta t'} & \text{series connection} \\ \dfrac{\left[\dfrac{\beta^{0.5}}{(1-\omega')^{0.5}\psi^{0.5}}(\tau_s'-\tau_r') - \dfrac{\beta^{0.5}\psi^{0.5}}{(1-\omega')^{0.5}}(t_s'-t_r')\right]}{\Delta t'} & \text{parallel connection} \end{cases}$$

3.1.2 When the peak heating is not needed and $\bar{Q}_{\psi} \le \bar{Q} < \beta$

When the peak heating is not needed and $\bar{Q}_{\psi} \le \bar{Q} < \beta$, VF regulation at $\tau_s=\tau'_s$ is used in the primary network, and VT at $\bar{G}_2=1$ (series connection) or $\bar{G}_2=\beta=0.8$ (parallel connection) are used in the secondary network. During this period, outdoor temperature $t_{out,p}<t_{out}\le t_{out,\psi}$, where $t_{out,p}$ is the critical peak heating temperature, which is the outdoor temperature when $\bar{Q}=\beta$.

Supply and return water temperatures of the secondary network are the same with Eqs. (31) and (32). But the relative flowrate ratio of the primary network is,

$$\bar{G}_1 = \left(\frac{\tau_s'-\tau_r'}{\tau_s'-\tau_r}\right)\frac{\bar{Q}}{\beta} \tag{37}$$

Substitute Eqs.(37) and (33) into Eqs. (18) and (20), we obtain,

$$\bar{K}=\begin{cases}\bar{G}_1^{0.5}\bar{G}_2^{0.5}=\left[\left(\frac{\tau'_s-\tau'_r}{\tau'_s-\tau_r}\right)\frac{\bar{Q}}{\beta}\right]^{0.5}=\left(\frac{\tau'_s-\tau'_r}{\tau'_s-\tau_r}\right)^{0.5}\left(\frac{\bar{Q}}{\beta}\right)^{0.5} & \text{series connection}\\ \bar{G}_1^{0.5}\bar{G}_2^{0.5}=\frac{\bar{G}_1^{0.5}\bar{G}_2^{0.5}}{(1-\omega')^{0.5}}=\left(\frac{\tau'_s-\tau'_r}{\tau'_s-\tau_r}\right)^{0.5}\left(\frac{\bar{Q}}{1-\omega'}\right)^{0.5} & \text{parallel connection}\end{cases} \tag{38}$$

Substitute Eq. (38) into Eq. (30), we can obtain two implicit equations for return water temperatures of the primary network,

$$\begin{cases}\left(\frac{\tau'_s-\tau'_r}{\tau'_s-\tau_r}\right)^{-0.5}\left(\frac{\bar{Q}}{\beta}\right)^{-0.5}(\tau'_s-\tau'_r)-\left(\frac{\tau'_s-\tau'_r}{\tau'_s-\tau_r}\right)^{0.5}(\bar{Q}\beta)^{0.5}(t'_s-t'_r)=\Delta t'\ln\left(\frac{\tau'_s-t_s}{\tau_r-t_r}\right) & \text{series connection}\\ \beta\left[(1-\omega')\bar{Q}\left(\frac{\tau'_s-\tau'_r}{\tau'_s-\tau_r}\right)\right]^{-0.5}(\tau'_s-\tau'_r)-\left(\frac{\bar{Q}}{1-\omega'}\right)^{0.5}\left(\frac{\tau'_s-\tau'_r}{\tau'_s-\tau_r}\right)^{0.5}(t'_s-t'_r)=\Delta t'\ln\left(\frac{\tau'_s-t_s}{\tau_r-t_r}\right) & \text{parallel connection}\end{cases} \tag{39}$$

we can solve Eq.(39) by trial algorithms for τ_r.

During this period, the supply water temperature of the primary network is naturally,

$$\tau_s=\tau'_s \tag{40}$$

3.1.3 When the peak heating is needed

When the peak heating is needed, $\beta\leq\bar{Q}\leq1$, then VF regulation at $\tau_s=\tau'_s$ is used in the primary network, and VT at $\bar{G}_2=1$ is used in the secondary network. During this period, outdoor temperature $t'_{out}<t_{out}\leq t_{out,p}$, where t'_{out} is the design outdoor temperature when $\bar{Q}$ =1.

Supply and return water temperatures of the secondary network are the same with Eqs. (31) and (32). The relative flowrate ratio of the primary network is,

$$\bar{G}_1=\frac{\tau'_s-\tau'_r}{\tau'_s-\tau_r} \tag{41}$$

Substitute Eqs.(41) and $\bar{G}_2$ =1 into Eqs.(18) and (20), for both series and parallel connection modes, we obtain,

$$\overline{K} = \overline{G}_1^{0.5}\overline{G}_2^{0.5} = \left(\frac{\tau_s' - \tau_r'}{\tau_s' - \tau_r}\right)^{0.5} \tag{42}$$

Substitute Eq.(42) into Eq. (24), we can obtain a implicit equation for return water temperatures of the primary network,

$$\left(\frac{\tau_s' - \tau_r'}{\tau_s' - \tau_r}\right)^{0.5}\left[(\tau_s' - \tau_r) - (t_{s,hr} - t_r)\right] = \ln\left(\frac{\tau_s' - t_{s,hr}}{\tau_r - t_r}\right)\Delta t' \tag{43}$$

we can solve Eq.(43) by trial algorithms for τ_r. During this period, the supply water temperature of the primary network is τ'_s.

For example, let ψ=0.5, β=0.8, τ'_s=130°C, τ'_r=70°C, t'_s=85°C, t'_r=60°C, t'_{out}=-26°C, b=0.3; then the supply and return water temperatures, relative flowrate ratios, and relative heat transfer coefficients of the heat exchanger can be calculated and shown in Figs. 4 and 5. It can be seen from Figs. 4 and 5, that the relative heat load ratio for phasing the regulation time $\overline{Q}_\psi$ (ψ=0.5) is 0.53 and 0.55 for series and parallel connection modes, respectively; and when $\overline{Q}_k<\overline{Q}<\beta$, the supply water temperature for series connection is a little higher than that for parallel connection mode. This is because that the supply temperature of the heat exchanger $t'_{s,hr}$ is higher (Wang, 2013) in the parallel connection mode, which makes the average logarithmic mean temperature difference also higher than that for series connection mode.

3.2 Regulation strategy 2 - VT before supply temperature reaches the design value and then VT-VF in the primary network

For regulation strategy 2, the control method in the primary network before supply temperature reaches the design value is the same as in the regulation strategy 1, but after that, VT-VF control method is used in regulation strategy 2. In addition, the value of $\overline{Q}_\psi$

is different compared to that in the regulation strategy 1, although ψ=0.5 is the same in both strategies. In all, the heating season can be divided into three phases as shown in Fig.6, where $\bar{Q}_{\psi}$ is the relative heat load ratio when the supply temperature reaches the design value at $\bar{G}_1$=ψ=0.5.

3.2.1 When the peak heating is not needed and $\bar{Q}_k \leq \bar{Q} < \bar{Q}_{\psi}$,

When the peak heating is not needed and $\bar{Q}_k \leq \bar{Q} < \bar{Q}_{\psi}$, the regulation is the same as in the regulation strategy 1. Therefore, supply and return water temperatures of the secondary network can be calculated by Eqs.(31) and (32), while Eqs.(35) and (36) are used for regulating the primary network.

3.2.2 When the peak heating is not needed and $\bar{Q}_{\psi} \leq \bar{Q} < \beta$

Under this condition, VT-VF regulation at τ_s-τ_r=τ'_s-τ'_r is used in the primary network, so the temperature difference is kept stable at the design temperature difference, but the supply and return water temperatures are always changing. VT regulation at $\bar{G}_2$=1 (series connection) or $\bar{G}_2$=β=0.8 (parallel connection) are used in the secondary network. The supply and return water temperatures of the secondary network can be calculated by Eqs. (31) and (32).

The relative flowrate ratio of the primary network is,

$$\bar{G}_1 = \frac{\bar{Q}}{\beta} \tag{44}$$

Substitute Eqs. (44) and (33) into Eqs. (18) and (20), we can obtain,

$$\bar{K}=\begin{cases}\bar{G}_1^{0.5}\bar{G}_2^{0.5}=\left(\dfrac{\bar{Q}}{\beta}\right)^{0.5} & \text{series connection}\\ \bar{G}_1^{0.5}\bar{G}_{hr}^{0.5}=\dfrac{\bar{G}_1^{0.5}\bar{G}_2^{0.5}}{(1-\omega')^{0.5}}=\left(\dfrac{\bar{Q}}{1-\omega'}\right)^{0.5} & \text{parallel connection}\end{cases} \tag{45}$$

Substitute Eq. (45) into Eq. (30), we can obtain,

$$\tau_s=\frac{1}{e^C-1}\left[e^C(\tau_s'-\tau_r')+e^C t_r-t_s\right] \tag{46}$$

$$\tau_r=\frac{1}{e^C-1}\left[(\tau_s'-\tau_r')+e^C t_r-t_s\right] \tag{47}$$

where,

$$C=\begin{cases}\dfrac{\beta^{0.5}\bar{Q}^{-0.5}(\tau_s'-\tau_r')-\left(\beta\bar{Q}\right)^{0.5}(t_s'-t_r')}{\Delta t'} & \text{series connection}\\ \dfrac{\beta\left[(1-\omega')\bar{Q}\right]^{-0.5}\left[(\tau_s'-\tau_r')-(t_s'-t_r')\right]}{\Delta t'} & \text{parallel connection}\end{cases}$$

3.2.3 When the peak heating is needed

During this period, VT-VF regulation at τ_s-τ_r=τ'_s-τ'_r is used in the primary network, and VT at $\bar{G}_2$=1 (both series and parallel connection) is used in the secondary network. Supply and return water temperatures of the secondary network are the same with Eqs.(31) and (32), but $\bar{G}_2$=1 .

The relative flowrate ratio of the primary network is,

$$\bar{G}_1=\frac{\tau_s'-\tau_r'}{\tau_s-\tau_r}=1 \tag{48}$$

The relative heat transfer coefficient $\bar{K}$=1, and according to Eq.(24),

$$\tau_s=\frac{1}{e^C-1}\left[e^C(\tau_s'-\tau_r')+e^C t_r-t_{s,hr}\right] \tag{49}$$

$$\tau_r=\frac{1}{e^C-1}\left[(\tau_s'-\tau_r')+e^C t_r-t_{s,hr}\right] \tag{50}$$

for both series and parallel connection modes,

$$C = \frac{(\tau_s' - \tau_r') - (t_{s,hr} - t_r)}{\Delta t'}$$

$\bar{Q}_\psi$ is calculated again under this regulation strategy and it is 0.4 at ψ=0.5. Then the regulation curves are shown in Figs. 7 and 8. It can be seen that, when $\bar{Q} < \bar{Q}_\psi$, both primary and secondary network use VT control method; when $\bar{Q}$=0.4, the temperature difference in the primary network reaches the design temperature difference of 60℃. When 0.4<$\bar{Q}$<β, the flowrate ratio of the primary network gradually increases from 0.5 to 1.0, but the temperature difference is kept stable at 60℃. When the peak heating is needed, VT-VF is still applied in primary network with a constant temperature difference, but the flowrate ratio is 1, and in the secondary network, VT is still used at $\bar{G}_2$=1.

3.3 Regulation strategy 3 - VT before peak heating and VT with the design temperature difference when peak heating is needed in the primary network

In this regulation strategy, VT control method is used before peak heating, and VT regulation with design temperature difference of 60℃ is used when peak heating is needed. This strategy is similar with regulation 2, but there are only two phases according to the base load ratio, as shown in Fig. 9.

The regulation curves for this strategy are shown in Figs. 10 and 11. It can be concluded that, simple VT control method according to Eqs.(31) and (32) is not feasible for the proposed combined DH system, although the relative flowrate ratio $\bar{G}_1$ is always equal to 1. Simple VT before the peak heating can be applied, but when peak heating is needed, the base load heat plant reaches the design heating power, so the design temperature difference in the primary network will be stable, while the supply and return water temperatures can still increase and reach their design values at $\overline{Q}$=1. Specifically, the latter VT method is called VT at the fixed temperature difference.

4. Pumping energy consumption for the three regulation strategies

In this section, the pumping energy consumption of the primary and secondary circulation pumps as well as the peak shaving pumps for the above-mentioned three regulation strategies is analyzed and calculated.

The shaft power of a pump under the design condition can be written as (Amin and Ali, 2016),

$$P' = \frac{\rho_w g H' G'_v}{3600 \times \eta'_p} \tag{51}$$

where, H' is the lift of the pump under design condition, mH_2O; G'_v is the volume flow under design condition, m^3/h; η'_p is the efficiency of the pump under design condition; ρ_w is the density of the circulation water, kg/m^3; g is the gravity, g=9.8m/s^2.

In addition, the shaft power and lift of the pump will be affected by the fowrate or the relative flowrate ratio, and their relationships can be determined by (He et al., 2009),

$$P = P'\overline{G}^3, H = H'\overline{G}^2 \tag{52}$$

According to Eqs.(51) and (52), the flowrate and lift of the pump are necessary to calculate the pumping energy consumption of the pumps in different regulating phases. In addition, the operating time and efficiencies of the pumps are also needed. Operating time for each regulating phase can be obtained using the heat load duration curve, as shown in Fig. 12, by inversely mapping different relative heat load ratios to the duration time in days. In different regulating phases, the relative flowrate ratios can be determined according to the adopted regulation strategy discussed in section 3. The efficiencies of the pumps are assumed to be stable since the variable speed pumps are used in the analysis.

4.1 Pumping energy consumption for series connection mode

For regulation strategy 1, the circulation pumps in the secondary network and the peak shaving pumps are always working under the design conditions during the whole heating season. The relative flowrate ratio of the primary network is ψ=0.5, when $\bar{Q} \leq \bar{Q}_{\psi,s}$, but it is a variable according to Eqs.(37) and (41), when $\bar{Q}_{\psi,s} < \bar{Q} \leq 1$. Here '*s*' denotes the series connection. The total pumping energy consumption (kWh) under regulation strategy 1 with series connection mode can be deduced as following,

$$E_{R1,s} = 0.024 \left[P'_{1,s} \left(5 + \int_{5}^{N_{\psi,s}} \bar{G}_{1,s}^{3} dN + \int_{N_{\psi,s}}^{N_T} \psi^{3} dN \right) + N_T P'_{2,s} + N_p P'_{p,s} \right] \tag{53}$$

where, 0.024 is the unit conversion coefficient, other variables are in SI international unit; $N_{\psi,s}$ is the duration time at $\bar{Q} = \bar{Q}_{\psi,s}$; N_T is the whole heating season in days; N_p is the peak heating period in days. $P'_{1,s}$, $P'_{2,s}$ and $P'_{p,s}$ are the shaft power of the circulation pumps in primary, secondary networks and the peak shaving pumps under design condition.

For regulation strategy 2, the total pumping energy consumption can also be calculated by Eq.(53), and the relative flowrate ratio of the primary network is ψ=0.5 when $\bar{Q} \leq \bar{Q}_{\psi,s}$, but the value of $\bar{Q}_{\psi,s}$ is different from that in regulation strategy 1. When $\bar{Q}_{\psi,s} < \bar{Q} \leq 1$, the flowrate ratio is changing according to Eqs.(44) and (48).

For regulation strategy 3, all pumps are operating under the design conditions, therefore the pumping energy consumption can be written as,

$$E_{R3,s} = 0.024 \left[N_T (P'_{1,s} + P'_{2,s}) + N_p P'_{p,s} \right] \tag{54}$$

4.2 Pumping energy consumption for parallel connection mode

It is a bit more complicated to calculate the pumping energy consumption for parallel connection mode, because the relative flowrate ratio in secondary network is also a variable, i.e. $\bar{G}_2=\beta$ when peak heating is not needed and $\bar{G}_2=1$ otherwise.

For regulation strategy 1, when $\bar{Q}\leq\bar{Q}_{\psi,p}$, $\bar{G}_2=\beta$ and $\bar{G}_1=\psi=0.5$. Here 'p' denotes the parallel connection. When $\bar{Q}_{\psi,p}<\bar{Q}\leq\beta$, $\bar{G}_2=\beta$ but $\bar{G}_1$ is determined by Eq.(37). In the rest of the heating season, $\bar{G}_2=1$ and $\bar{G}_1$ is determined by Eq.(41). Therefore, the total pumping energy consumption (kWh) under regulation strategy 1 with parallel connection mode can be deduced as following,

$$E_{R1,p}=0.024\left[P'_{1,p}\left(5+\int_5^{N_{\psi,p}}\bar{G}_{1,p}^3dN+\int_{N_{\psi,p}}^{N_T}\psi^3dN\right)+(N_T-N_p)P_{2,p}+N_pP'_{2,p}+N_pP'_{p,p}\right] \quad (55)$$

where $N_{\psi,p}$ is the duration time at $\bar{Q}=\bar{Q}_{\psi,p}$; $P'_{1,p}$, $P'_{2,p}$ and $P'_{p,p}$ are the shaft power of the circulation pumps in primary, secondary networks and the peak shaving pumps under design condition.

For regulation strategy 2, the total pumping energy consumption can also be calculated by Eq.(55), and the relative flowrate ratio of the primary network is $\psi=0.5$ when $\bar{Q}\leq\bar{Q}_{\psi,p}$, but the value of $\bar{Q}_{\psi,p}$ is different from that in regulation strategy 1. When $\bar{Q}_{\psi,p}<\bar{Q}\leq1$, the flowrate ratio is changing according to Eqs.(44) and (48).

For regulation strategy 3, the circulation pump in the primary network and the peak shaving pumps are always working under design condition. But $\bar{G}_2=\beta$ when $\bar{Q}\leq\beta$, otherwise $\bar{G}_2=1$. Therefore, the pumping energy consumption can be written as,

$$E_{R3,p}=0.024\left[N_TP'_{1,p}+(N_T-N_p)P_{2,b}+N_pP'_{2,b}+N_pP'_{p,p}\right] \quad (56)$$

5. Results and discussion

The studied case is a combined DH system located in Harbin city, which belongs to the severe cold climate zone of China. The topology of the combined DH network is illustrated in Fig.13, in which the number of pipelines, nodes and heating substations are labeled. The heat load profiles of all heating substations are shown in Table 1. For this combined DH system, the peak shaving boilers are proposed to be installed in all heating substations, where the local base load ratio in each substation β_i is equal to β=0.8. Other design and operating parameters are listed in Table 2. Then the pumping energy consumption for the three regulation strategies with series and parallel connection modes are calculated and analyzed.

The design parameters of the circulation pumps for the primary and secondary networks and the peak shaving pumps are listed in Table 3. The pumping energy consumption are calculated and shown in Table 4 and Fig.14.

It can be seen from Table 4 and Fig. 14 that in the case study, the total pumping energy consumption in a heating season for series connection mode using regulation strategy 3 is 7.48M kWh, which is the largest among all scenarios. Thus it can be used as the basis for calculating the pumping energy saving ratios in the following analysis. The results show that combined DH system with parallel connection mode using regulation strategy 1 has the minimum pumping cost with an energy saving ratio of 48.8%. According to the mix of Chinese power generation sources (Wang et al., 2013), this is equivalent to a CO_2 emission reduction of 3639 tones per year. The pumping energy saving ratio for parallel connection mode using regulation strategy 2 is 46.2%, which is also promising with a CO2 reduction of 3445 tones per year. The energy saving ratios for series connection modes using the same regulation strategies are only 20~30%, equivalent to CO2 reduction potentials of about 1490~2237 tones per year. Therefore, the parallel connection mode will save more pumping energy compared to the series connection mode using the same regulation strategy. Because in parallel connection mode, the flowrate in the secondary network is only β (β<1) times compared to that in series connection mode before the peak heating period starts. Although the peak heating pumps will consume more power in parallel connection mode, as shown in Fig.14, the total pumping energy consumption is still reduced efficiently by 20~28% compared to the series connection mode.

In all, regulation strategy 1 - VT before supply temperature reaches the design value and then VF in the primary network is the most preferred control strategy for the proposed combined DH system in order to save pumping energy. However, regulation strategy 2 - VT before supply temperature reaches the design value and then VT-VF in the primary network is also very promising and the difference of pumping energy saving potential between these 2 strategies is only 2.6%. Therefore, both of the regulation strategies can be used in this kind of combined DH systems. Another important conclusion is that, in series connection mode, the smallest possible peak heating flow ratio according to Eq.(6) is recommended, in order to reduce the peak heating pumping cost and thus to reduce the total pumping cost, while the pumping cost in secondary network is stable. On the contrary, for parallel connection mode, the biggest possible peak heating flow ratio according to Eq.(7) should be adopted in order to reduce the pumping energy consumption in secondary network and the total pumping cost, because the increase in the peak heating pumping cost is much smaller than the saved pumping energy in secondary network.

6. Conclusion

The combined district heating system with peak shaving gas-fired boilers in heating substations has several advantageous compared to traditional district heating system with one heat plant or multiple isolated heat sources. It can increase the heating capacity and reliability as well as reduce the environmental impact. In this paper, we carried out a systematic research on the pumping energy saving potential for this kind of combined DH system considering the combinations of the feasible operating strategies in both primary and secondary networks. Firstly, we defined the connection modes between gas-fired boilers and heat exchangers in the heating substations, including series and parallel connections, and summarized their characteristics. For each connection mode, we established the thermal balances, based on which the feasible regulation strategies were proposed and the analytical operational regulation formulas were obtained. Adopted control strategies are: 1) variable temperature (VT) control, 2) variable flowrate (VF) control, and 3) variable temperature and flowrate (VT-VF) control. In the primary network all three strategies can be used, but in the secondary network, VT with different relative flow rate ratio before and after the peak heating is proposed in order to increase the hydraulic stability. Therefore, we defined three combinations of the control strategies in the primary network:

- Regulation strategy 1 - VT before supply temperature reaches the design value and then VF in the primary network;

- Regulation strategy 2 - VT before supply temperature reaches the design value and then VT-VF in the primary network;
- Regulation strategy 3 - VT before peak heating and VT with the design temperature difference when peak heating is needed in the primary network.

Then, the three strategies were compared in terms of pumping energy consumption in a combined DH system located in Harbin, China. The results show that the operational strategies should be phased into different periods according to when the supply water temperature reach the design value and whether the peak heating is needed or not. In the case study, the total pumping energy consumption for series connection mode using regulation strategy 3 is the largest among all scenarios and it was thus used as a base scenario for the comparison analysis. It was then found that the parallel connection mode can save more pumping energy compared to the series connection mode using the same regulation strategy. Because in parallel connection mode, the flowrate in the secondary network is only β (β<1) times of that in series connection mode before the peak heating period. Although the peak heating pumps will consume more power in parallel connection mode, the total pumping energy consumption is still reduced efficiently by 20~28% compared to the series connection mode. Moreover, minimum possible peak shaving flow ratio which is defined as the ratio between the flowrate of gas-fired boilers and the secondary network should be used for series connection mode, while maximum possible PSFR (peak shaving flow ratio) should be adopted for parallel connection mode, in order to reach the minimum of the pumping energy consumption. Although regulation strategy 1 shows a little better energy saving potential compared to regulation strategy 2, the difference is very small and both of them can be used in this kind of combined DH systems. In all, the parallel connection mode using regulation strategy 1 or 2 is recommended for the combined DH system with peak shaving gas-fired boilers in heating substations.

Acknowledgement

This work was supported by the China national key research and development program – China-Finland intergovernmental cooperation in science and technology innovation (Funding NO. 2016YFE0114500) and the Academy of Finland (grant number NO. 299186).

Nomenclature

a, coefficient of the heat transfer equation of radiators.

b, index of the heat transfer equation of radiators.

c_{water}, specific heat capacity of water; 4186.8J/(kg•℃).

F, radiation area of the radiators; m^2.

F_{hr}, heat exchange area; m^2.

G_b, flowrate of the base load heat plant; kg/s.

G_p, flowrate of the circulation pump for peak shaving gas-fired boiler ; kg/s.

G_1, flowrate in the primary network; kg/s.

G_2, flowrate of the circulation pump for secondary network; kg/s.

$g_{2,i}$, flowrate in the ith heating substation; kg/s.

$\bar{G}_1$, relative flowrate ratio in primary network.

$\bar{G}_2$, relative flowrate ratio in secondary network.

$\bar{g}_1$, relative flowrate ratio of primary side in the *i*th substation.

$\bar{g}_2$, relative flowrate ratio of secondary side in the *i*th substation.

$\bar{G}_{hr}$, relative flowrate ratio in the secondary side of the heat exchanger.

$\bar{K}$, relative heat transfer coefficient of water-water heat exchanger.

$\bar{K}_i$, relative heat transfer coefficient of the heat exchanger in the *i*th substation.

Q', design heat load of the whole combined DH system; W.

$Q_{load,b}$, heat load of the base load heat plant; W.

$q_{load,b,i}$, heat load supplied from the base load heat plant to the *i*th substation; W.

$q_{load,i}$, heat load of the *i*th substation; W.

$Q_{load,b}$, heat load of the base load heat plant; W.

$Q_{load,p}$, peak shaving heat load during the peak heating period; W.

Q_{hr}, heat load of all heat exchangers; W.

$Q_{network}$, heat load that users receive from the network; W.

$Q_{building}$, heat load of the buildings in the network; W.

$Q_{radiator}$, heat releasing load of radiators in the network; W.

q, volumetric heat index of the buildings; W/m^3.

$q_{hr,i}$, heat laod of heat exchanger in the *i*th substation; W.

$\bar{Q}_1$, relative heat load ratio in primary network.

$\bar{Q}_2$, relative heat load ratio in secondary network.

t_s, supply water temperature of the secondary network; ℃.

$t_{s,hr}$, supply water temperature of the heat exchanger; ℃.

t_r, return water temperatures of the secondary network; ℃.

$t_{s,p}$, supply water temperature of the peak shaving gas-fired boiler; ℃.

t_{out}, outdoor temperature; °C.

t_{in}, design indoor temperature; °C.

Δt, logarithmic mean temperature difference of the heat exchanger; °C.

V , peripheral volume of the buildings; m^3.

α, peak load ratio.

β, base load ratio of a combined DH system.

β_i, base load ratio for the *i*th substation.

ω, peak shaving flow ratio (PSFR).

τ_s,, supply water temperature of the primary network; ℃.

τ_r, return water temperature of the primary network; ℃.

Note: parameters with '" means design value.

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Fig. 1. Sketch of combined DH system with peak shaving gas-fired boilers in all heating substations with series connection.

1 - heat exchanger; 2 - circulation pump for secondary network; 3 - circulation pump for gas-fired boiler; 4 - gas-fired boiler; 5 - inverse valve; 6 - flow control valve

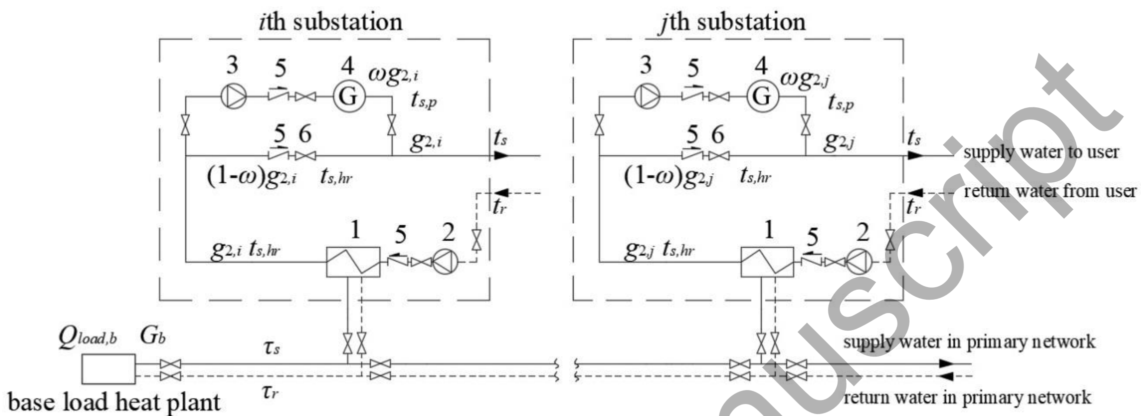


Fig. 2. Sketch of combined DH system with peak shaving gas-fired boilers in all heating substations with parallel connection.

1 - heat exchanger; 2 - circulation pump for secondary network; 3 - circulation pump for gas-fired boiler; 4 - gas-fired boiler; 5 - inverse valve

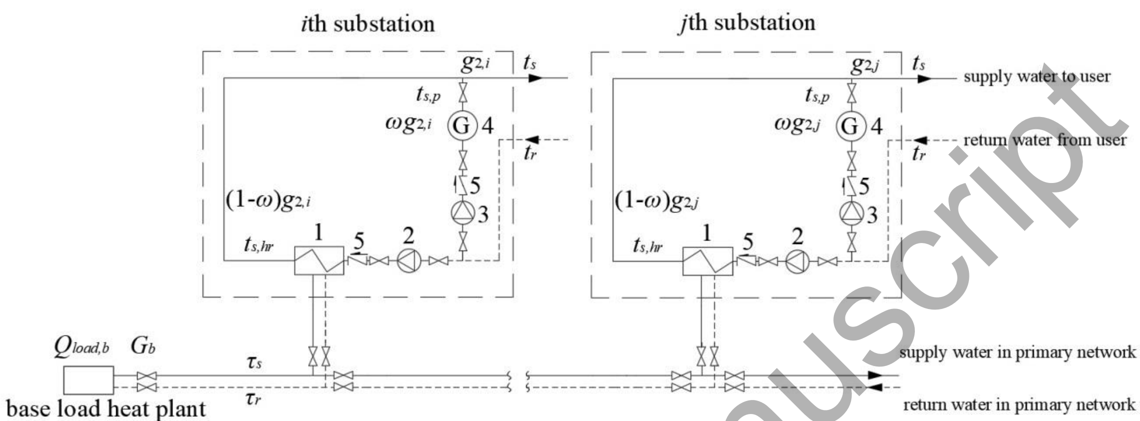


Fig. 3. Regulation phases for the proposed combined DH system with VT and VF control strategy in primary network and VT in secondary network.

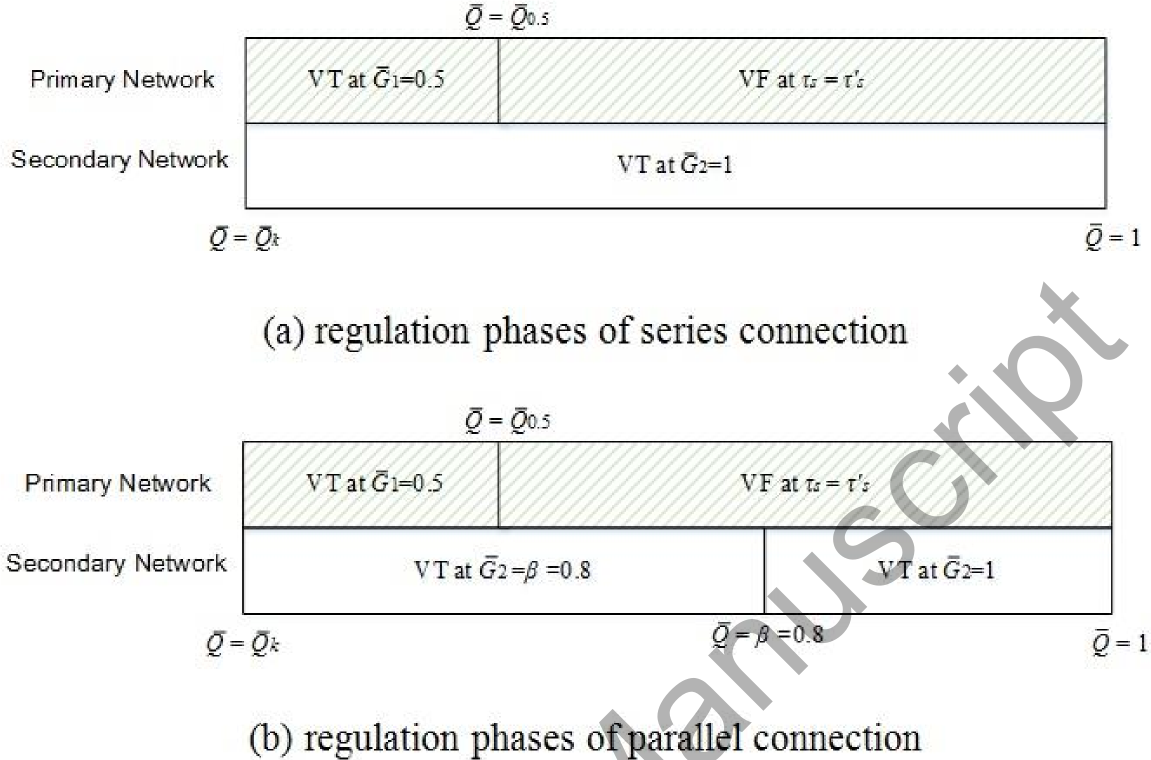


Fig. 4. Regulation curves of VT and VF control strategy in the primary network for proposed combined DH system with series connection mode of the peak shaving gas-fired boilers.

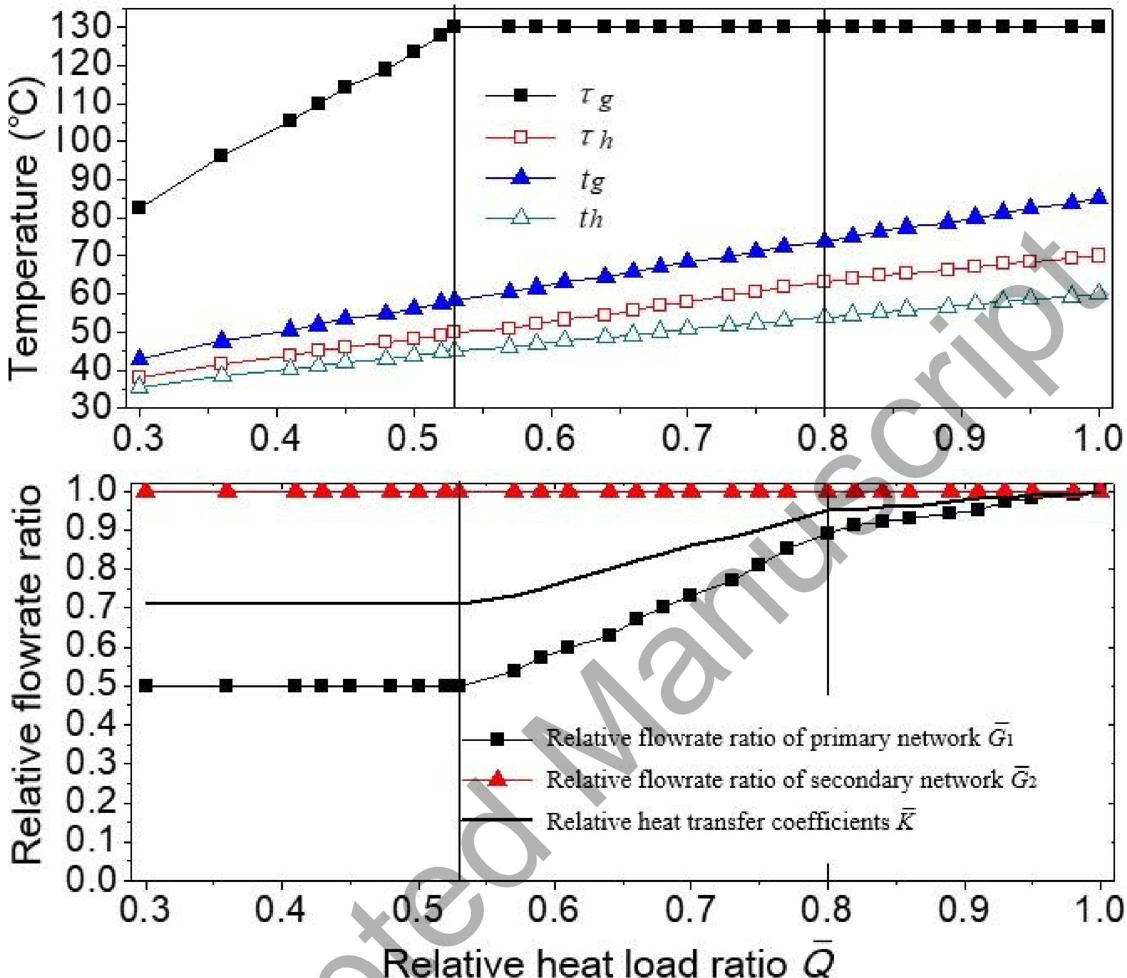


Fig. 5. Regulation curves of VT and VF control strategy in the primary network for proposed combined DH system with parallel connection mode of the peak shaving gas-fired boilers.

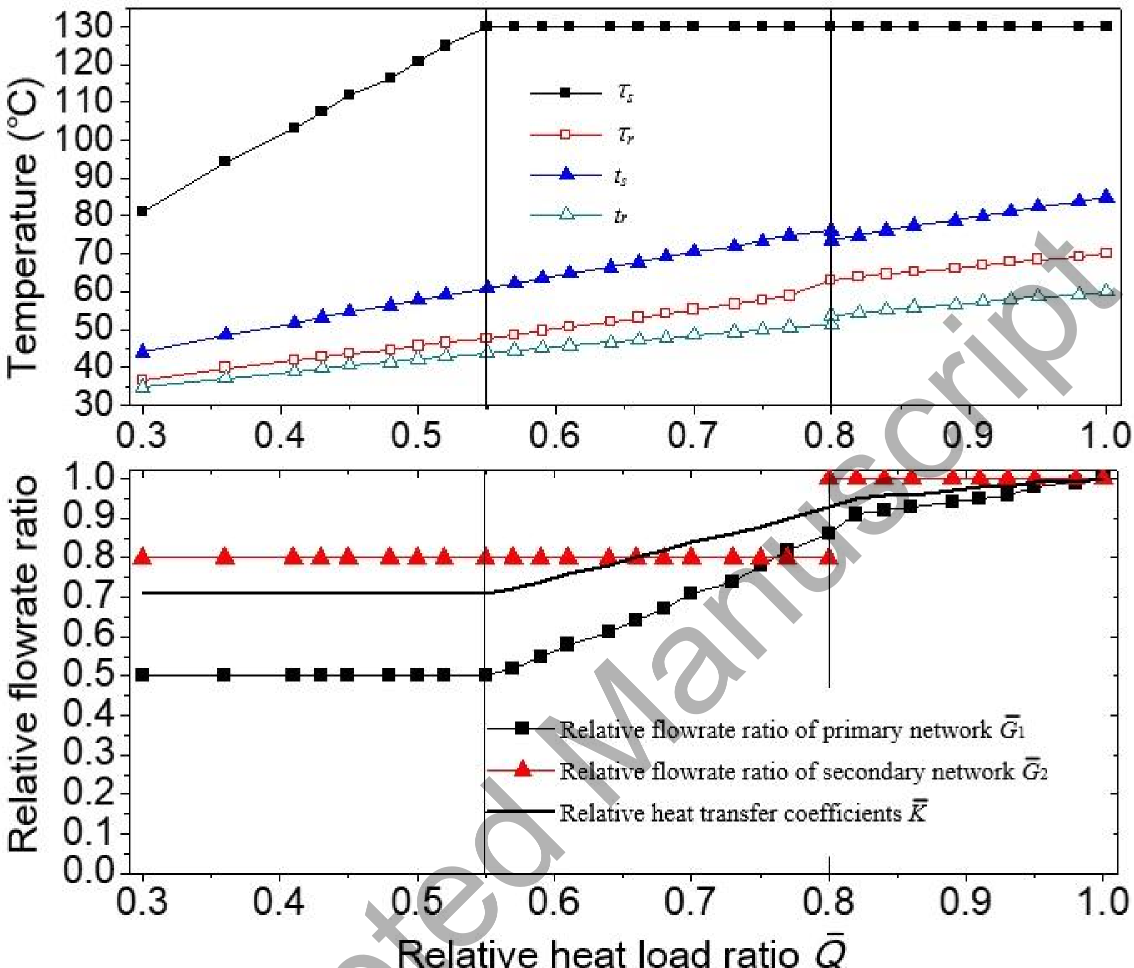
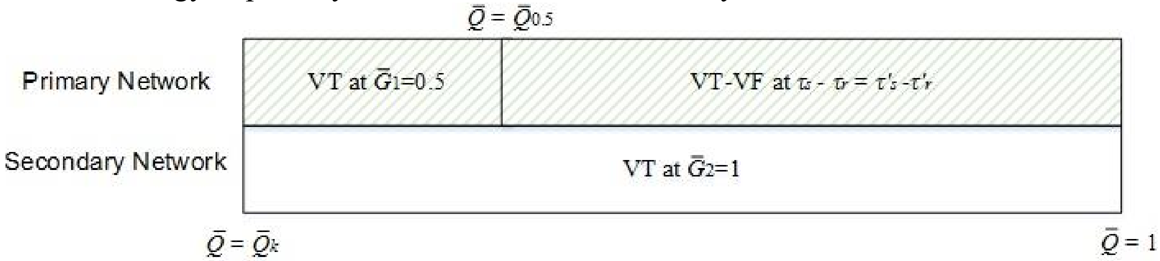
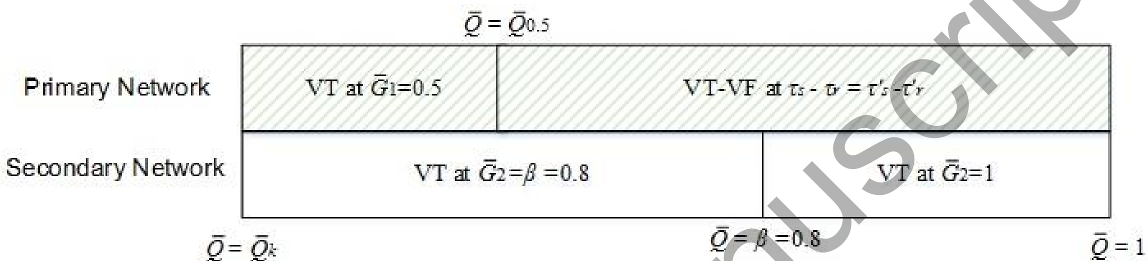


Fig. 6. Regulation phases for the proposed combined DH system with VT and VT-VF control strategy in primary network and VT in secondary network.



(a) regulation phases of series connection



(b) regulation phases of parallel connection

Fig. 7. Regulation curves of VT and VT-VF control strategy in the primary network for proposed combined DH system with series connection mode of the peak shaving gas-fired boilers.

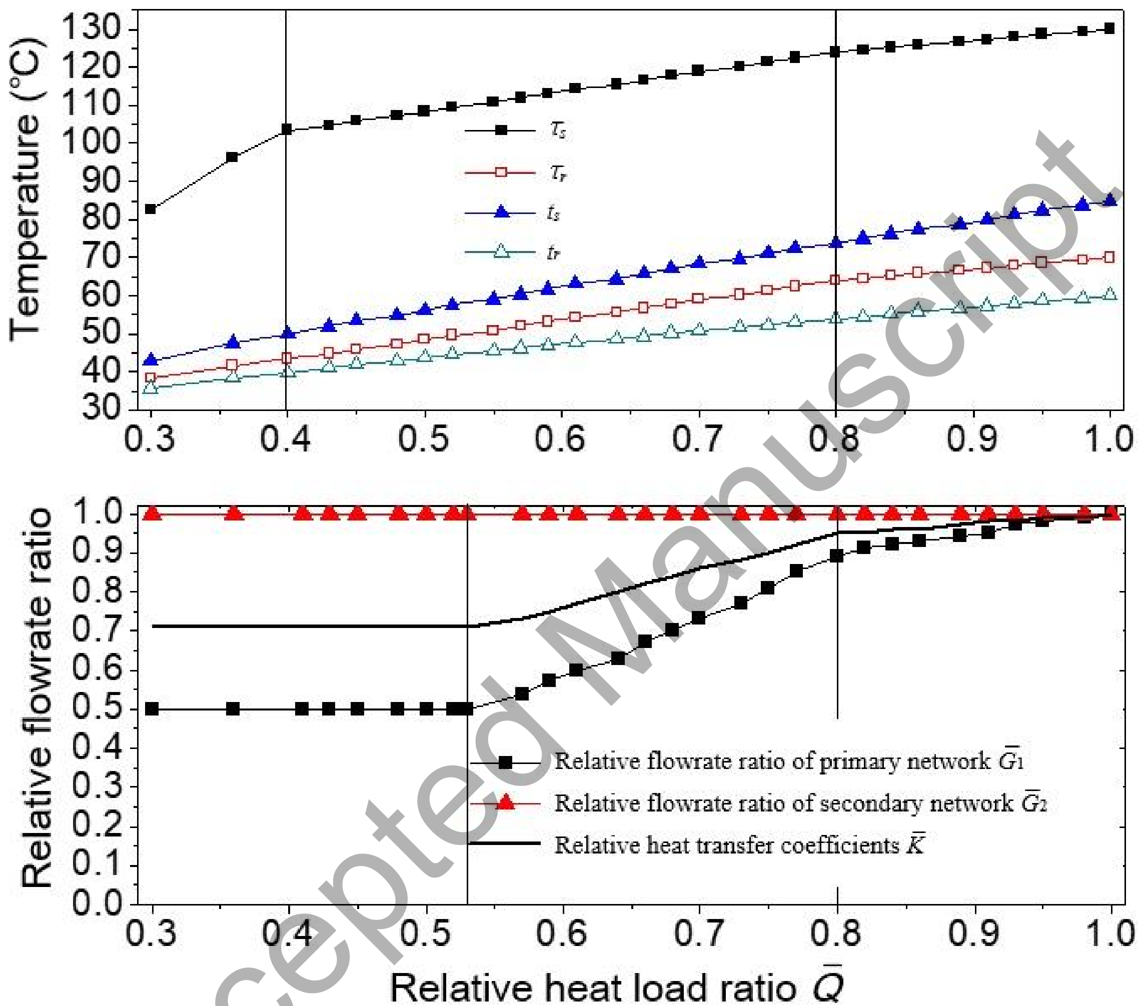


Fig. 8. Regulation curves of VT and VT-VF control strategy in the primary network for proposed combined DH system with parallel connection mode of the peak shaving gas-fired boilers.

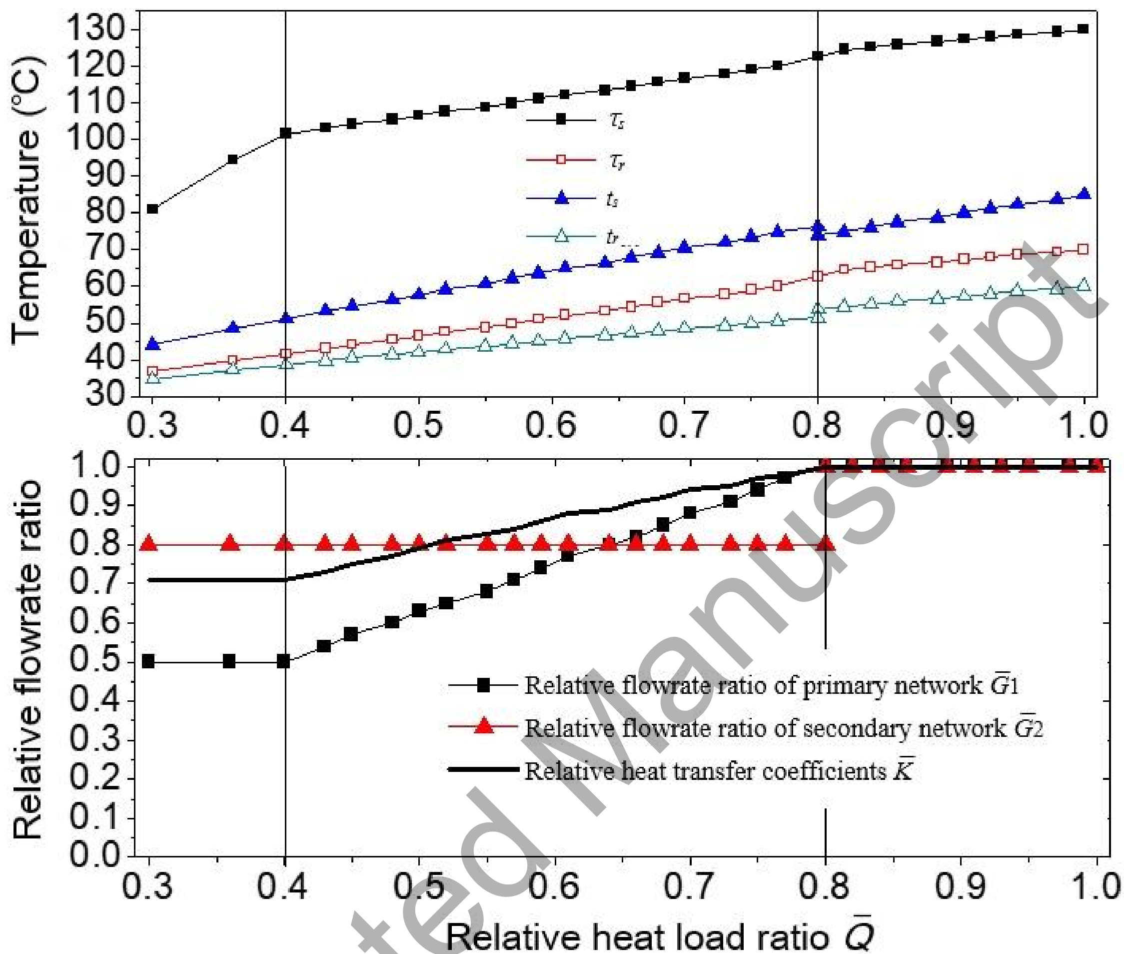


Fig. 9. Regulation phases for the proposed combined DH system with VT and VT at the design temperature difference in primary network and VT in secondary network.

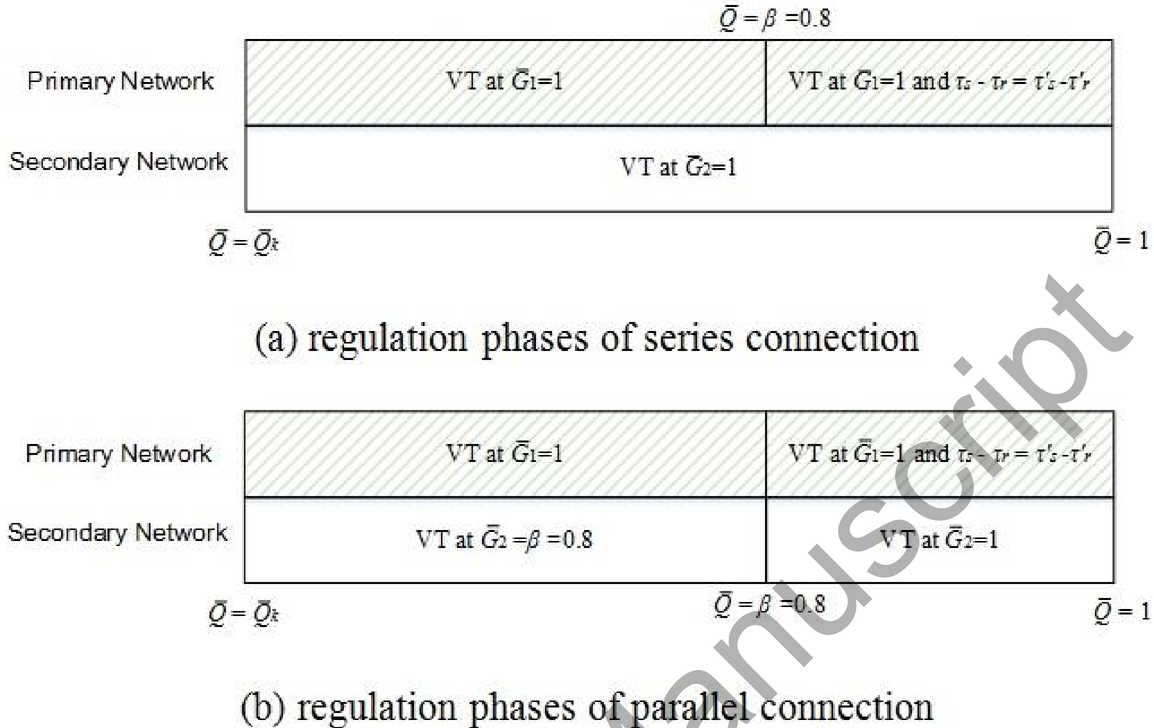


Fig. 10. Regulation curves of VT and VT at the design temperature difference in primary network for proposed combined DH system with series connection mode of the peak shaving gas-fired boilers.

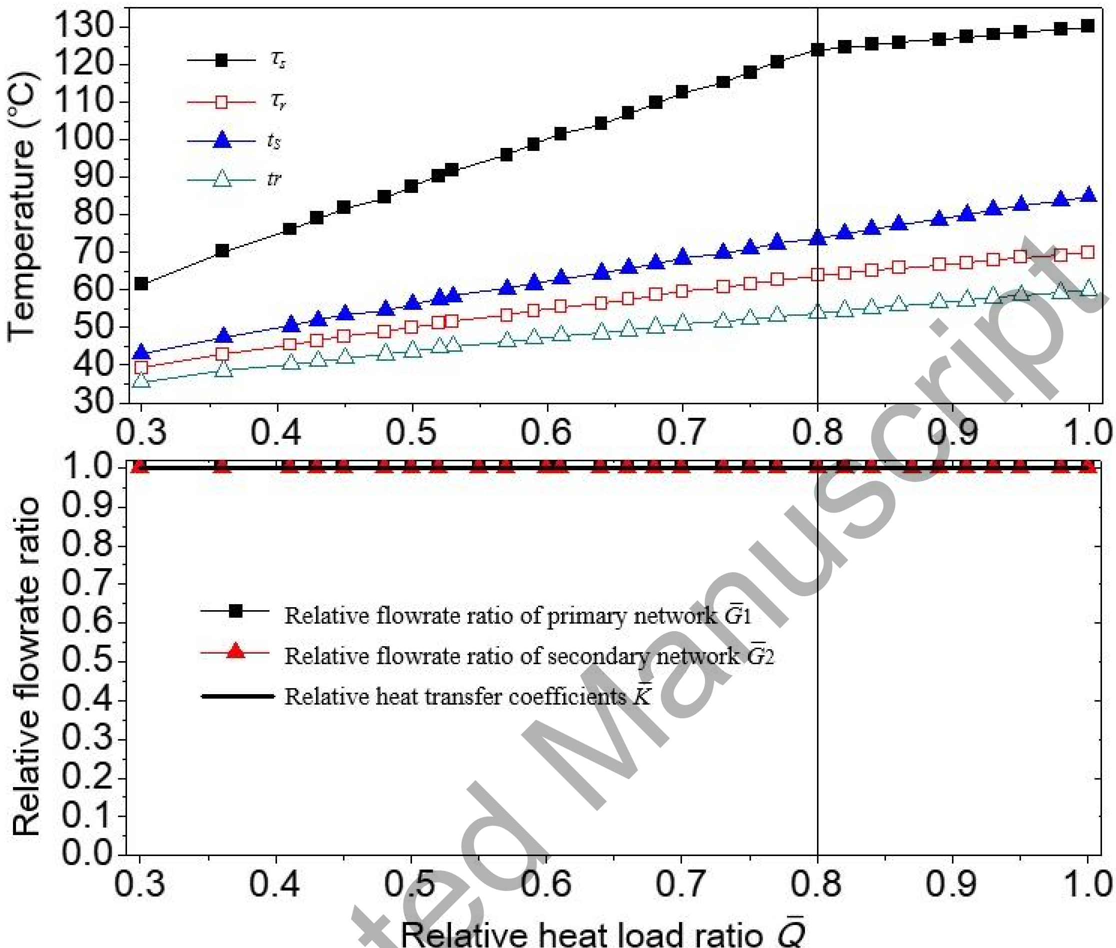


Fig. 11. Regulation curves of VT and VT at the design temperature difference in primary network for proposed combined DH system with parallel connection mode of the peak shaving gas-fired boilers.

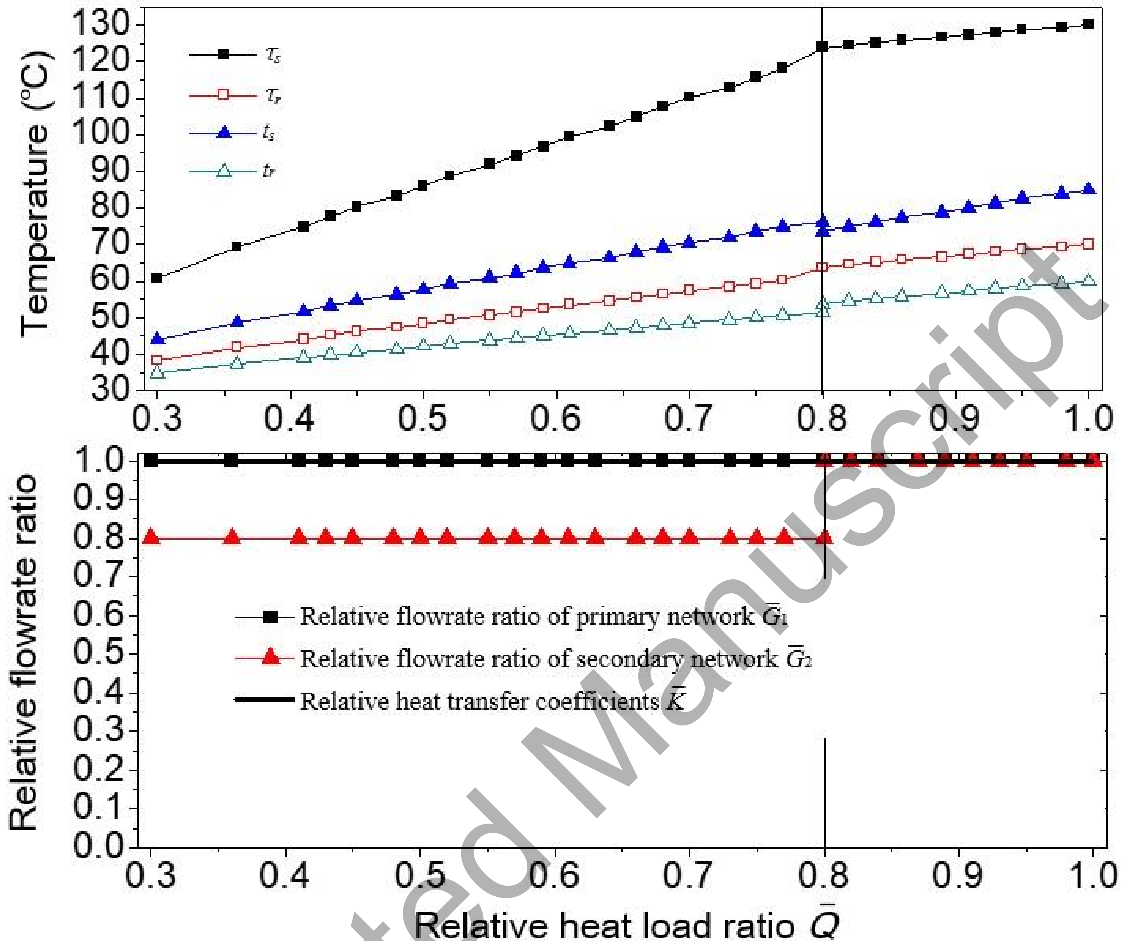


Fig. 12. Heat load duration curve for the studied case.

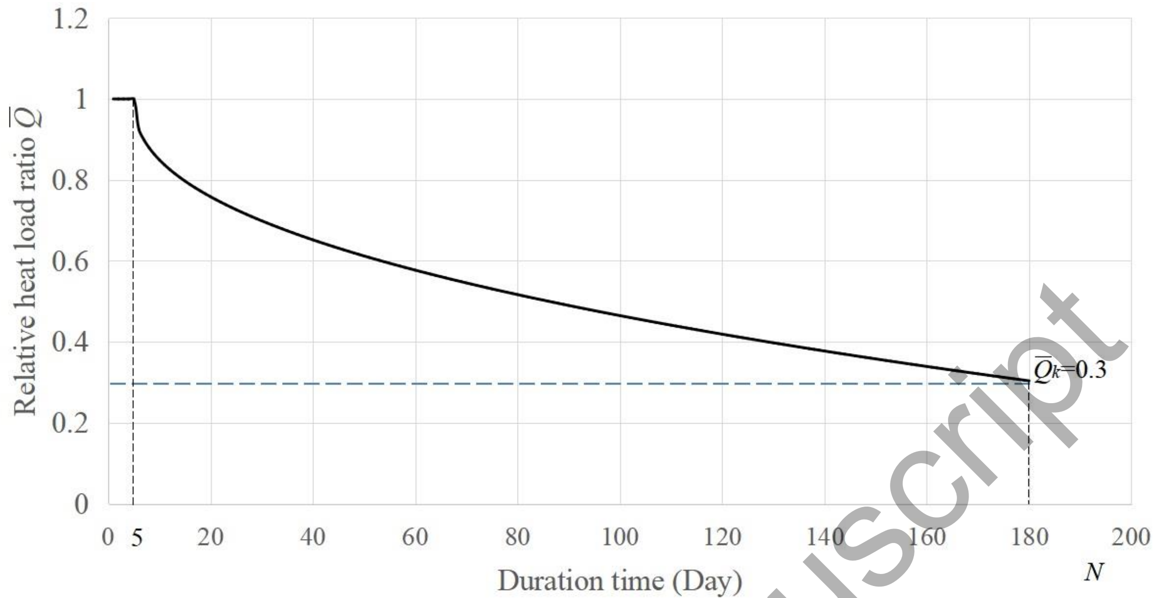


Fig. 13. Topology of the combined DH network in the case study.

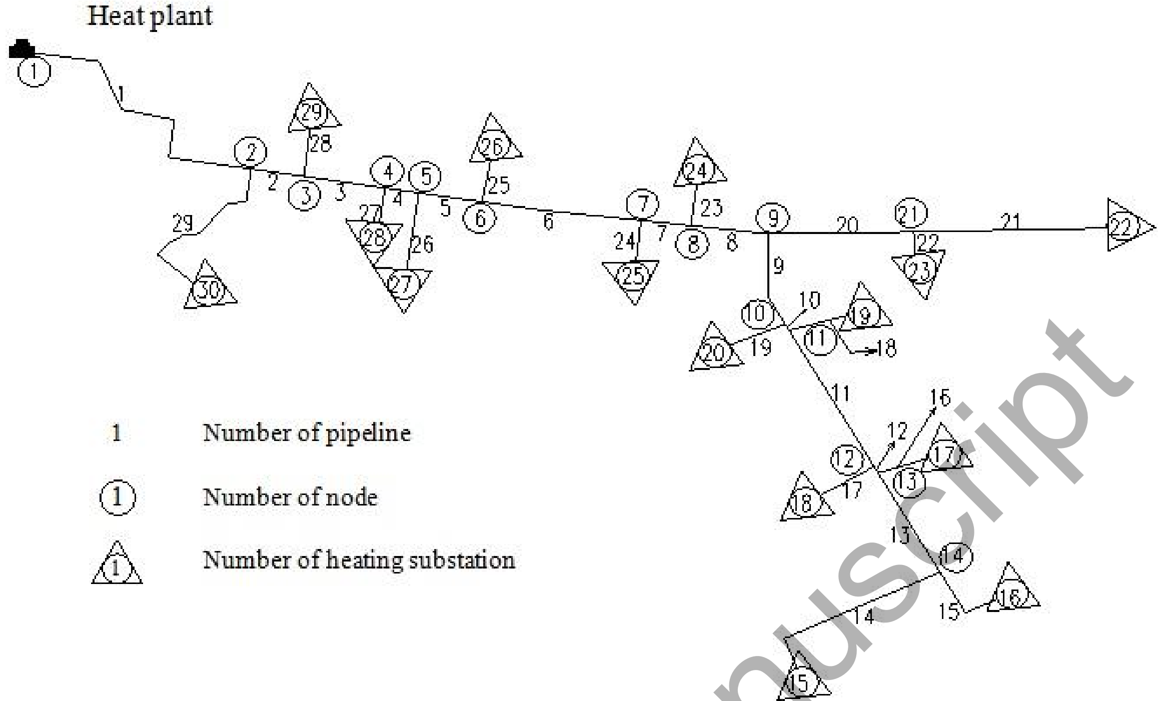


Fig. 14. Comparison of pumping Energy consumption under different regulation strategies and connection modes for the studied combined DH system.

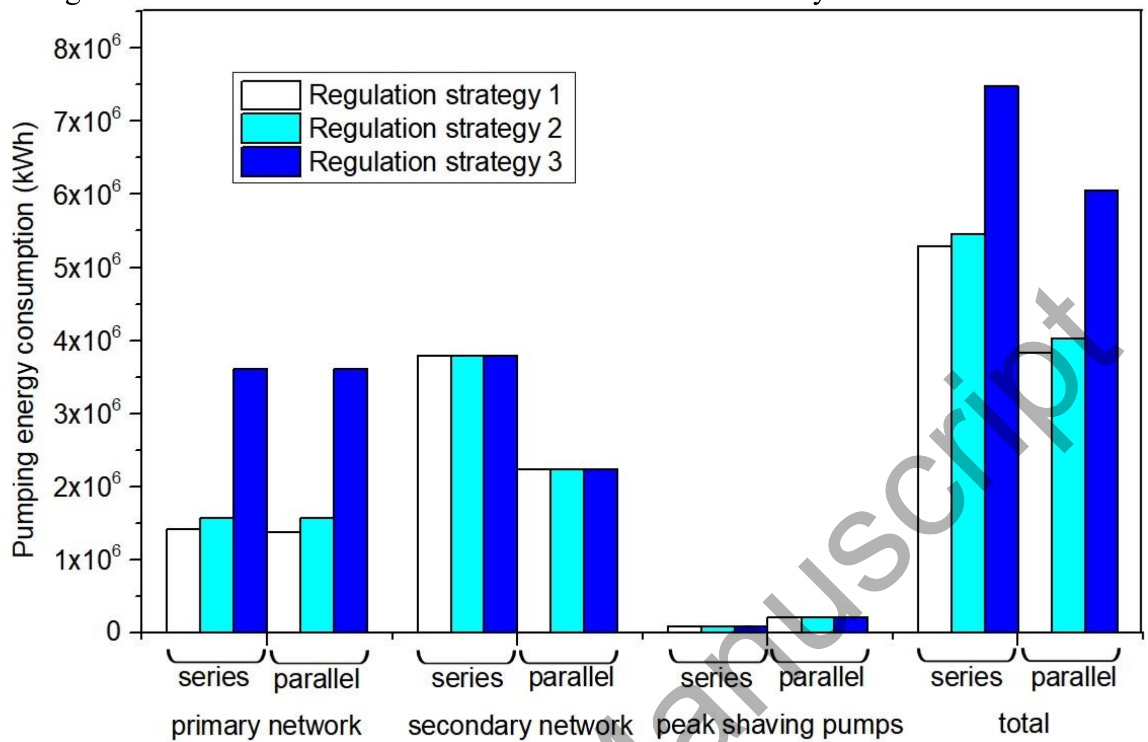


Table 1. Heating area and heat loads of substations.

Substation NO.	**Heating area (m^2)**	**Heat load (MW)**	**Substation NO.**	**Heating area (m^2)**	**Heat load (MW)**
15	270,000	17.55	24	110,000	7.15
16	270,000	17.55	25	160,000	10.4
17	250,000	16.25	26	120,000	7.80
18	300,000	19.50	27	150,000	9.75
19	203,000	13.20	28	152,000	9.88
20	300,000	19.50	29	120,000	7.80
22	130,000	8.45	30	150,000	9.75
23	210,000	13.65	Total	2,895,000	188.18

Table 2. Relevant parameters of the combined DH system.

Item	**Value**	**Unit**
Total heating area	2,895,000	m^2
Number of heating substations	15	
Design heat load	188.18	MW
Design outdoor temperature (t'_{out})[a]	−26	°C
Design indoor temperature (t_{in})[a]	18	°C
Design supply and return water temperature of primary network (τ'_s/τ'_r)	130/70	°C
Design supply and return water temperature of secondary network (t'_s/t'_r)	85/60	°C
Design water pressure in primary network	16	Bar
Average outdoor temperature during heating season	−9.5	°C
Heating period	180	d
Specific pressure loss of main pipelines	30~70	Pa/m

[a] Referred to in the handbook of regular-use data in HVAC of China, 2002 (China Architecture & Building Press, 2002).

Table 3. Design parameters of water circulation pumps for the three regulation alternatives of series and parallel connection.

Connection mode	**Design parameters of circulation water pumps in primary network**	**Design parameters of circulation water pumps in secondary network**	**Design parameters of peak shaving pumps**
series	G'_1=2157t/h H'_1=110mH_2O η'_1=77%	G'_2=6470t/h H'_2=40mH_2O η'_2=80%	G'_p=2161 t/h H'_p=10mH_2O η'_p=77%
parallel		G'_2=5176t/h H'_2=40mH_2O η'_2=80%	G'_p=1294t/h H'_p=40mH_2O η'_p=77%

Table 4. Pumping energy consumption of the combined DH system with different regulation strategies and connection modes (kWh).

Connection mode	**Regulation strategy**	**Pumping energy consumption in primary network**	**Pumping energy consumption in secondary network**	**Pumping energy consumption of peak shaving pumps**	**Total Pumping energy consumption**	**Energy saving ratio(%)**
Series	1	1418200	3786300	89100	5293600	29.2%
	2	1576300	3786300	89100	5451700	27.1%
	3	3606200	3786300	89100	7481600	0
Parallel	1	1382200	2234500	213500	3830200	48.8%
	2	1576300	2234500	213500	4024300	46.2%
	3	3606200	2234500	213500	6054200	19.1%