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# Operation stability analysis of district heating substation from the control perspective

Yaran Wang[a,b], Shijun You[a,b], Huan Zhang[a,b], Xuejing Zheng[a,*], Shen Wei[c], Qingwei Miao[a], Wandong Zheng[a]

[a] School of Environmental Science and Engineering, Tianjin University, Tianjin 300350, PR China
[b] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, MOE, Tianjin University, Tianjin 300350, PR China
[c] Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, UK

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ABSTRACT

Since the heating substation plays a key role in transferring the thermal energy from the primary network to the secondary network and controlling the heat output of district heating system to meet the thermal load, high operation performance of heating substation is essential for energy conservation, cost saving and emission reduction. The dynamic operation stability of heating substation is a very important dynamic characteristic of heating substation and largely affects the operation efficiency of district heating system. The operation instability of heating substation mainly manifest as flow rate and pressure oscillations, which will deteriorate the network hydraulic condition, break the network thermal balance, reduce the consumer comfort and increase the energy cost of the pumping system. Since heating substations will easily operate unstably under some conditions, this paper presents a theoretical method to analyze the stability and retune the feedback controller for operation stability of heating substation. Mathematical model of the plate heat exchanger was established and the feedback control theory was adopted to study the operation stability of heating substation. Based on the mathematical model and feedback control theory, a stability criterion was proposed for analyzing the operation stability of district heating substation effectively. The dynamic model of plate heat exchanger was validated with measured data. Simulation results show that controller tuned at certain operating condition can't ensure operation stability of heating substation, when operating condition varies in large range. The stability analysis method proposed in this paper can be applied to analyzing the operation stability and tuning the controller of heating substation to enhance the operation stability.



## 1. Introduction

In China, The total energy consumption of district heating systems in northern areas covers 24% of the total energy cost of building energy systems [1]. Therefore, improving the operation efficiency of district heating system is important to reducing energy cost and enhancing room comfort. In large scale district heating systems, the heating substations are the terminals, which control the heat outputs to the secondary networks. Efficient regulation of the district heating network relies on effective operation and control of the heating substation.

There have been numerous researches on improvement of heating substation efficiency by applying new control strategy. Gustafsson et al. [2] developed a new control approach for indirectly connected district heating substations based on a physical model, which maximizes the ΔT of the district heating network. They also verified the control method experimentally through implementation of the control method in a real district heating substation; the results confirms that it is possible to control the radiator system based on the primary supply temperature while maintaining comfort; however, conclusions regarding improvements in ΔT were hard to distinguish [3]. Since high return temperature will lead to large amount of overall distribution energy cost, the temperature difference faults can be detected and eliminated by using fault detection approaches. Gadd and Werner [4,5] presented a fault detection based method to achieve low return temperatures in district heating substations.

Modeling the heating substation is important to analyzing and evaluating the operation performance of heating substation. Brand et al. [6] developed a numerical model for heating substation, which

* Corresponding author.
*E-mail address:* zhengxuejing@tju.edu.cn (X. Zheng).

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**Nomenclature**

| | |
|---|---|
| $A$ | matrix of state space model |
| $b$ | width of the plate heat exchanger flow channel (m) |
| $B_1, B_2, B_3, B_4$ | matrices of linearized state space model |
| $C$ | matrix of linearized state space model |
| $c_p$ | specific heat capacity of water (W/kg·K) |
| $C_v$ | flow capacity of control valve |
| $C_{Nu}$ | the empirical parameter |
| $d$ | distance between neighboring plates (m) |
| $D$ | hydraulic diameter (m) |
| $G(s), G_{d,1}(s), G_{d,2}(s), G_{d,3}(s), G_{d,4}(s)$ | transfer function of linearized plate heat exchanger model |
| i | $\sqrt{-1}$ |
| $k$ | overall heat transfer coefficient (W/m$^2$·K) |
| $K$ | transfer function of controller |
| $k_c$ | controller gain |
| $k_v$ | valve gain |
| $l$ | length of flow channel |
| $L(\mathrm{i}\omega)$ | loop transfer function |
| $M$ | number of flow channels in each side |
| $N$ | number of the control volumes in a flow channel |
| $n_1, n_2$ | the empirical parameter |
| $Nu$ | the Nusselt number |
| $Pr$ | the Prantl number |
| $q$ | volume flow rate (m$^3$/s) |
| $R$ | the rangeability of the valve |
| $Re$ | the Reynolds number |
| $s$ | the Laplace variable |
| $t$ | time (s) |
| $T$ | temperature (°C) |
| $x$ | coordinate along the flow channel (m) |
| $z$ | controller zero |
| $\lambda$ | heat conductivity coefficient (W/m$^2$·K) |
| $\mu$ | the dynamic viscosity |
| $\rho$ | density of the water (kg/m$^3$) |
| $\tau$ | time delay of temperature sensor (s) |
| $\delta$ | small deviation & increment symbol of variable |
| $\omega$ | frequency (rad/s) |
| $\Delta x$ | length of a control volume (m) |

*Subscripts*

| | |
|---|---|
| $h$ | high temperature side |
| $in$ | inlet |
| $l$ | low temperature side |
| $out$ | outlet |

takes into consideration the effect of service pipes. With this model, they studied the effects of service pipe on waiting time for DHW, heat loss, and overall cost. Brand et al. [7] also used the commercial software IDA-ICE and Termis to model and analyze various solutions for controlling the redirected bypass flow and evaluated their performance and the effect on the DH network in heating substation. Kuosa [8] developed a numerical model for a district heating system with ring network, with which the variations of flow rates, pressure losses and overall heat transfer coefficients of plate heat exchanger in heating substation were simulated and analyzed on selected days. Dobos and Abonyi [9] developed the nonlinear dynamic model of the district heating network including the heat exchanger in heating substations, heat production units and pipelines to study the nonlinear model predictive control of district heating network.

Since plate heat exchanger is the core component of heating substation, mathematical modeling and control performance analysis of plate heat exchanger is important to improve the operation efficiency of district heating substation. Feedback control analysis and design of plate heat exchangers have been paid attentions. Al-Dawery [10] established a first order model with time delay to suggest the transient responses of a plate heat exchanger, and a fuzzy logic controller of the plate heat exchanger was designed to achieve less settling time and oscillatory behavior. Michel and Kugi [11] developed a control strategy without knowledge of the heat transfer of plate heat exchanger based on controlling the total thermal energy stored in the heat exchanger and a Kalman Filter to estimate the states.

However there were few studies concerning the dynamic operation stability of heating substation, which is a very important dynamic characteristic for heating substation and largely affects the operation efficiency of district heating system. The operation instability of heating substation mainly manifest as flow rate and pressure oscillations, which will deteriorate the network hydraulic condition, break the network thermal balance, reduce the consumer comfort and increase the energy cost of the pumping system. Since heating substations will easily operate unstably under some conditions, this paper presents a theoretical method to analyze the stability and retune the feedback controller for operation stability of heating substation. The theoretical method presented in this paper mainly utilized the techniques developed in feedback control theory [12]. The feedback control theory has been effectively applied to analyze the operation stability and elimination of oscillations in a central heating system using pump control [13]. Tahersima et al. utilized the feedback control theory to study the stability performance and developed a gain scheduling controller of radiator heating system in a room [14]. In our previous work, the control oriented approaches were adopted to establish an accurate low order model of room heating system and propose a two-degrees-of-freedom $H_\infty$ loop-shaping controller [15]. Research on the operation stability of district heating system focuses on dynamic variation and fluctuation of flow rates, pressures and temperatures in the district heating network, which is very important and applicable in improving the operating efficiency of the district heating network. In this paper, the operation stability of district heating substation was studied from the control perspective. An analytical tool was developed to analyzing the operation stability of district heating substation.

## 2. Control levels of district heating system

Fig. 1 shows the schematic of district heating system. The hot water is generated from the heat source and delivered to the heating substations by the primary circulation pump along the primary pipelines. The heating substations are usually located near the center of load regions. The main components of a heating substation are the plate heat exchanger, primary control valve, secondary circulation pump and the control system.

In order to provide sufficient thermal energy effectively, the district heating system is usually regulated under three control levels. The first level is named the centralized control; this level functions at the heat sources, which controls the primary supply temperature and the pump speed to meet the total heating load variations of the network. The second level is called the local control; this level functions at each heating substation, which controls the secondary supply temperature and secondary pump speed to satisfy the variable heating load of the heat consumers. The secondary supply temperature is controlled by adjusting the control valve of the plate heat exchanger at the primary side. The third level is personal control; this level functions at each radiator, which controls the flow rate of radiator according to the room temperature difference between the desired and value to maintain the room air