ISSN 2004-2965 Energy Proceedings, Vol. 19, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 522

Quantifying Structural Thermal Storage Flexibility of District Heating System Considering Heat Transfer Processes and Migration Delay

Xing Gou [1], Qun Chen [1,2*], Ke-Lun He [1], Shun-Jiang Wang [3], Ji-Ming Dai [4]

1 Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing, 100084, China

2 State Key Laboratory of Control and Simulation of Power Systems and Generation Equipments, Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China

3 State Grid Liaoning Electric Power Supply CO. LTD, Shenyang, 110004, China

4 State Grid Fuxin Electric Power Supply Company, Fuxin, 123000, China

ABSTRACT

With the growing penetration of RES, more flexibility is required in power system. District heating system with large capacity is able to offer flexibility to power system. Based on the model of a district heating system built by heat current method, this work proposes a quantification method to evaluate the flexibility of district heating system, which is a hybrid algorithm utilizing simulations and dichotomy method. Quantitative indicators including average power shifting capability and available storage capacity are defined to describe the flexibility. The results of case study present the flexibility of system under a general working condition. Then, influence factors are discussed that with the increase of dispatch time and decrease of the time of heat migration delay, the storage capacity of heating network increases.

Keywords: thermal storage, energy flexibility, heat current model, system simulations

NONMENCLATURE

Abbreviations	
RES	Renewable energy source
CHP	Combined heat and power
Symbols	
Φ	Heat transfer rate
R	Thermal resistance
T	Temperature
$\boldsymbol{\varepsilon}$	Thermal potential
C	Heat capacity
Y	Thermal conductance
Q	Thermal power

1. INTRODUCTION

With the developing of renewable energy source (RES) worldwide, the penetration of RES in power system grows rapidly [1]. Due to the nature of fluctuation and intermittent of RES [2], it requires much flexibility from power system for RES consumption. However, the flexibility provided by power system is usually inadequate considering various practical situations [3]. For example, in northern China, centralized combined heat and power (CHP) generation unit supplies vast heat in the heating season, and the strong interdependency between its heat and power supply limits the flexible regulation of its electric generation, then restricts the consumption of RES [4].

Hence, improving power system flexibility benefits the utilization of RES. Several solutions include retrofit measures for CHP units [5], improving interconnection of power grid [3] and increasing controllable electric load such as electric vehicles [6]. Meanwhile, due to the large scale of heat load in winter, the heating system introduces significant possibility for providing the flexibility to power system through CHP units or other energy conversion devices connecting power system and

Corresponding author. Department of Engineering Mechanics, Tsinghua University, Beijing, 100084, China.
E-mail address: chenqun@tsinghua.edu.cn (Q. Chen).

heating system [7]. The heating system, which usually consists of district heating network and heat users such as residential buildings, often has a large capacity of heat storage and plays an important role to offer flexibility for heat supply [8].

Some researches focused on the heat storage characteristics of buildings. The building is referred to as structural thermal storage mainly due to the thermal mass of the building structure or hot water storage. Reynders et al. used the structural thermal storage for demand-side management, offering the flexibility to improve the balance between electricity demand and production [9]. Besides indoor air and building envelope, Li et al. also considered thermal mass of furniture in buildings and proposed a new method to calculate the equivalent thermal mass of actual furniture which has irregular shapes [10]. To quantify energy flexibility in buildings, Hurtado et al. utilized several parameters including comfort capacity which represents the maximum response time before reaching comfort limits to describe the flexibility action of buildings [11]. While these works only consider the heat storage inside the buildings, it is not enough when analyzing the flexibility problem of heat supply system since the heat demand at this moment is actually satisfied by the heat generation a few minutes or hours ago due to significant transmission delay of heating pipes.

Kouhia et al. utilized the same method with common analyses of the heat storage characteristics in buildings and regarded the water temperature in heating pipelines as the same value, which actually ignored the heat migration process in pipes and the energy storage characteristics since the inlet and outlet power of heating pipe should often be different because of migration delay [12]. Li et al. employed a node method to account for time delays and heat losses in pipelines which utilized the outlet temperature as a decision variable, while they used the average water temperature in heat supply pipeline to represent the charging/discharging energy of district heating network without considering the influences of varying temperature of return water, which is also not precise enough to describe the heat storage characteristics of district heating network [13]. What`s more, they usually did not consider the heat exchange station between primary heating network and secondary heating network, ignoring the practical heat transfer process.

Recently, Chen et al. [14,15] proposed a heat current model and deduced the formula of thermal resistance of heat exchanger, which describes nonlinear heat transfer constraints accurately. On the basis, He et al. [16] expanded the application of heat current model to heat migration processes in pipelines and the dynamic heat transfer processes in building envelopes, which gives the convenience for analyzing flexible operation of heating system including district heating network and residential buildings.

Based on heat current method, this work constructs a model of district heating network, and proposes a model to quantify the flexibility of heating system with district heating network and residential buildings. The quantification method is a hybrid algorithm utilizing simulations and dichotomy method. Quantitative indicators including average power shifting capability and available storage capacity are defined to describe the flexibility of heating system. Then, case study is conducted to evaluate the flexibility of district heating system under a general working condition. Specially, focusing on district heating network gives a comprehensive evaluation of its heat storage characteristics. Finally, several influence factors are analyzed, discussing their relevance to variations of system flexibility.

2. THE MODEL OF THE DISTRICT HEATING SYSTEM

2.1 Physical model of a district heating system

Fig.1 gives the sketch of a district heating system. CHP plant supplies heat for the whole district heating system. After the heat migration in primary heating network, the heated water enters the heat exchange station and then heats the water in secondary heating network. The water in secondary heating network goes to the radiator of heat customer directly, supplying heat to satisfy the heat load. We consider that there is migration delay in primary heating network due to its long distance, while ignoring the migration delay in secondary heating network since it is often inside the building with relative short distance. There are often multiple heat customers in a district heating system. Thus, there are the same number of sets of secondary heating network correspondingly, as well as the heat exchange stations. The heat customer absorbs heat from radiators and releases heat to the cold environment through building envelope.

$$\boldsymbol{\Phi} = \boldsymbol{R}_h^{-1}\left(\Delta\boldsymbol{T} + \boldsymbol{R}_{h,\mathrm{CS}}\boldsymbol{\Phi}_{\mathrm{CS}} - \boldsymbol{\varepsilon}_{h,delay}\right) \tag{1}$$

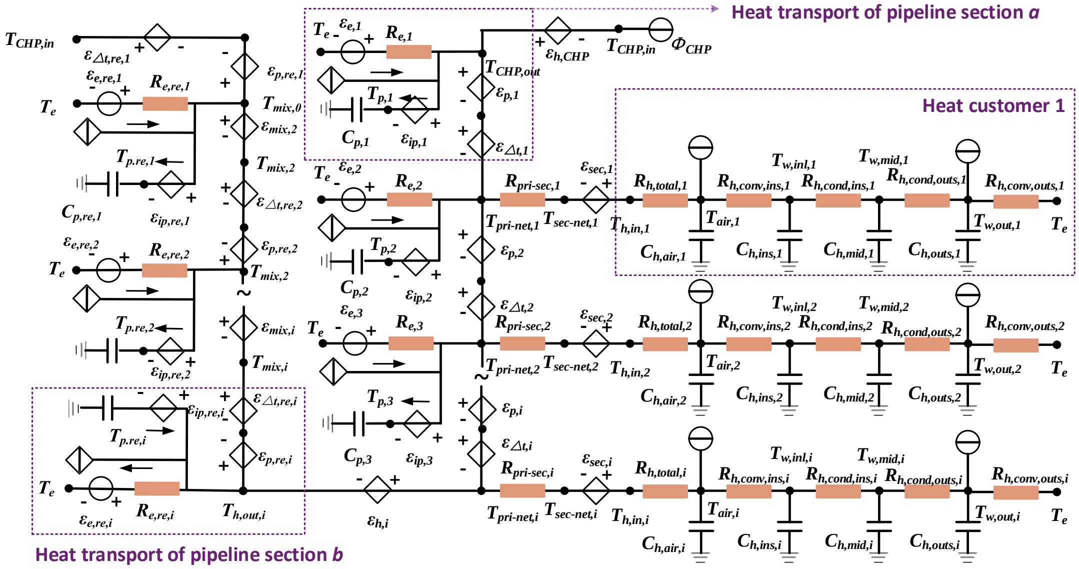

Fig. 2. The heat current model of district heating system

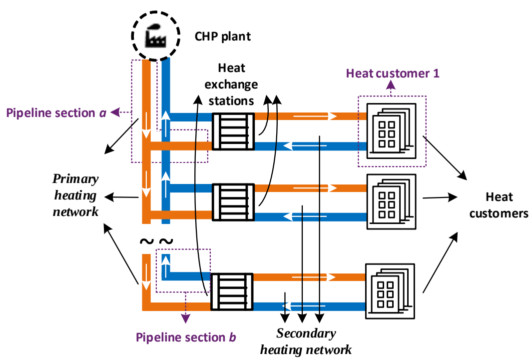

Fig. 1. Physical model of a district heating system

2.2 *Mathematic model of a district heating system*

According to the heat current method [16], the heat current model of district heating system is built, which is shown in Fig.2. The uppermost block represents the heat transport of pipeline section *a*, which is actually the first section of primary heating network when supplying heat in Fig.1. Similarly, the block at the bottom left represents the heat transport of pipeline section *b*, which is actually the farthest section of return water in Fig.1. The right block represents the heat transfer processes of Heat customer 1 in Fig.1 including the radiator and building envelopes. The model of the rest of district heating system can also be found in Fig.2. The reason we adopt the heat current model is that the model describes the heat transfer processes and heat migration processes accurately. What`s more, the analogy to electric conduction makes it easy to utilize electric simulation software which is mature and convenient.

Applying Kirchhoff's current and voltage laws gives the algebraic matrix equation of district heating network:

where $\boldsymbol{\Phi}$ and $\boldsymbol{R}_h$ are the heat transport rate vector and the thermal resistance matrix of heat transport processes in district heating system, respectively. $\Delta\boldsymbol{T}_i$ is the vector of temperature difference, $\boldsymbol{R}_{h,\mathrm{CS}}$ and $\boldsymbol{\Phi}_{h,\mathrm{CS}}$ are the matrix of thermal resistance and the heat generation vector of CHP plant, respectively. $\boldsymbol{\varepsilon}_{h,delay}$ is the thermal potential vector which reflects heat migration delay characteristics of heating network. The details of these matrices and vectors and the descriptions of Fig.2 could be found in [16].

Similarly, Applying Kirchhoff's laws for heat customers gives the matrix equation as

$$\boldsymbol{C}_{h,w,i}\frac{\mathrm{d}\boldsymbol{T}_{cus,i}}{\mathrm{d}t} = \boldsymbol{\Phi}_{cus,i} + \boldsymbol{Y}_{w,i}\begin{pmatrix}\boldsymbol{T}_{cus,i}\\ \boldsymbol{T}_e\end{pmatrix} \tag{2}$$

where $\boldsymbol{C}_{h,w,i}$ is the thermal capacitance vector of building envelope. $\boldsymbol{Y}_{w,i}$ is the thermal conductance matrix. $\boldsymbol{T}_{cus,i}$ is the temperature vector of heat customer, including indoor air temperature and wall temperature. $\boldsymbol{\Phi}_{cus,i}$ is the heat flow vector caused by heat sources, while this work does not consider any heat source inside the buildings. The details of these matrices and vectors could also be found in [16].

3. QUANTIFICATION OF SYSTEM FLEXIBILITY

To mitigate the operation pressure of power system, properly exploit the flexibility of district heating system. In a period of time $t_{dispatch}$, CHP plant may need to generate more electricity or less electricity to accommodate the uncertainty and fluctuation of RES. Thus, CHP plant will also generate more heat or less heat in that period correspondingly. We consider the condition that CHP plant generate more heat than normal level, and the analyses of less heat condition is similar.

When CHP plant generates more heat, the system operation constraints need to be satisfied:

$$T_{CHP,out} \le T_{CHP,out,\max} \quad (3)$$

$$T_{air,\min} \le T_{air} \le T_{air,\max} \quad (4)$$

where $T_{CHP,out}$ and $T_{CHP,out,\max}$ are the actual and maximum outlet temperature of CHP plant, respectively. T_{air} is the indoor temperature of heat customer. For comfort demand, the indoor temperature T_{air} must between the highest temperature $T_{air,\max}$ and lowest temperature $T_{air,\min}$.

During $t_{dispatch}$, the total extra heat generated by CHP plant is

$$C_{sys} = \int_0^{t_{dispatch}} \left(Q_{CHP} - Q_{ref}\right) dt \quad (5)$$

where Q_{CHP} and Q_{ref} are the actual and planned thermal power generated by CHP during that time, respectively. When reaching the upper limit of system operation, C_{sys} is actually the maximum energy that the district heating system could absorb during the time, which is called available storage capacity. It is noted that the available storage capacity C_{sys} is related to the dispatch time $t_{dispatch}$.

Thus, during $t_{dispatch}$, the average extra heat generated by CHP plant is

$$Q_{sys} = \frac{\int_0^{t_{dispatch}} \left(Q_{CHP} - Q_{ref}\right) dt}{t_{dispatch}} \quad (6)$$

Q_{sys} is the average power shifting capability of district heating system, which is actually the maximum average charging power to district heating system from power system in $t_{dispatch}$. It is meaningful to give definitions of district heating system flexibility during a time period, since the only limitation of instantaneous charging power is the constraint of the maximum outlet temperature of CHP plant, and the district heating system could accommodate the huge instantaneous charging power because the sustain time could be extremely short.

To obtain the average power shifting capability Q_{sys} and the available storage capacity C_{sys}, direct calculation to determine the constraints violation is not enough since there is delay of heat migration process and heat capacity in district heating system. It is an optimization problem to search the maximum flexibility under certain operation constraints. Time domain simulation is necessary to check if the system operation constraints is violated from the time that CHP plant begins to generate more heat. Based on the heat current method, an electrical software named Digital Dynamic Real Time Simulator (DDRTS) is applied for simulation of district heating system, which has electromagnetic transient and electromechanical transient simulators. Among the simulation results, we utilize dichotomy algorithm to optimize the problem to obtain the maximum storage capacity of district heating system, since the algorithm has simple structure and is convenient to solve our problem.

4. RESULTS AND DISCUSSION

In the district heating system, there are 3 heat customers. The outlet temperature of CHP plant is 100℃ in normal situation, and the maximum outlet temperature of CHP plant $T_{CHP,out,max}$ is 130℃. The highest temperature of indoor air $T_{air,max}$ is 22 ℃. The environment temperature is 3 ℃. In primary heating network, the mass flow rate of each branch is 4286 t h-1. In secondary network, the mass flow rate of each loop is 1714 t h-1. The specific heat capacity and the density of water are 4200 J kg-1 K-1 and 960 kg m-3, respectively. Meanwhile, the total heat transfer coefficient between water in primary heating network and environment is 3 W K^{-1} m^{-2} considering the heat loss in long primary heating network. There is a time delay of 0.5h of every section of pipelines between two heat exchange station in primary heating network. The heat transfer coefficient of each heat exchange station is 5000 W K^{-1} m^{-2}. And the heat transfer areas are 1392, 1414 and 1456 m^2, respectively. Regards to each heat customer, the total heat transfer coefficient and the total heat transfer area of radiator are 5 W K^{-1} m^{-2} and 1977220 m^2, respectively. The heat capacity of indoor air and building envelope of each heat customer are 3.5 and 6.3 MWh K^{-1}, respectively. The convective heat transfer coefficient at the inside and outside of the building envelope are 9 and 20 W K^{-1} m^{-2}. The thermal conductivity of building envelope is 0.77 W K^{-1} m^{-1}.

4.1 Flexibility quantification under general operation mode

The outlet temperature of CHP plant is 100℃ under normal situation. To satisfy the regulation demand of power grid temporarily, CHP plant need to increase the power generation for 0.5h. Due to the operation constraints, the outlet temperature of CHP plant could not increase without limitation. It is necessary to determine the maximum outlet temperature of CHP plant during that period, which also reflects the storage capacity of district heating system.

After calculation, the maximum of average outlet temperature of CHP plant during that dispatch time 0.5h is 121.5 ℃. Since the time delay of every section of pipelines is 0.5h, which means the return water does not change during the dispatch time, the total extra heat generation is 162.0 MWh, which is the available storage capacity of district heating system C_{sys} actually. Thus, the average power shifting capability Q_{sys} is 324.1 MW. Fig.3 gives the indoor air temperatures of 3 heat customers in district heating system. It is shown that the indoor air temperature of heat customer 1 reaches 22℃ at around 1h after CHP plant begins to generate more heat, which suggests that 121.5 ℃ is the maximum average outlet temperature of CHP plant. It is also clear in Fig.3 that there is a half hour interval between two maximum indoor air temperatures of heat customers due to heat migration delay. Because of heat loss in primary heating network, the maximum of indoor temperature of heat customer 3 is the smallest among 3 maximum temperatures, which does not reach 22℃.

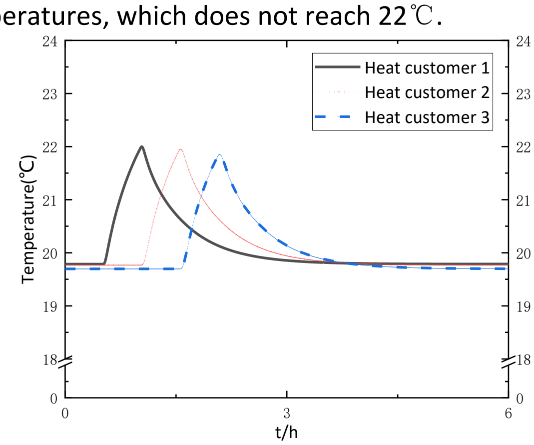

Fig. 3. Indoor air temperatures of heat customers

Fig.4 gives the energy storage situation of district heating system. The upper half of Fig.4 gives extra heat power generated by CHP plant and total heat consumption power including heat load and heat loss of primary heating network. The heat power from CHP plant maintains at 749.93 MW for 0.5h, then the dispatch time is over and the heat power recovers to normal level. However, at around 1h, the return water heated heat customer 1 flows back to CHP plant while the outlet temperature of CHP plant maintains at normal level 100℃, thus the heat power generated by CHP plant decrease for 0.5h. On the other side, with the heat migration in primary heating network, the extra heated water arrives at heat customers and the total consumption increases after 0.5h from CHP plant beginning to generate more heat. It is obvious that the subtraction of two lines gives the net charging power to heating network. Integrating the net charging power to heating network gives the actual energy stored in heating network, which is shown in lower half of Fig.4. The energy stored in heating network reaches the maximum 162.0 MWh at 0.5 h, then the stored heat releases slowly accompanying heat migration and heat transfer process. The storage capacity of heating network is a crucial indicator since the heating network connects the heat source and heat customers. The heating network is like a battery between source and load, and investigating its storage characteristics is beneficial for system regulation.

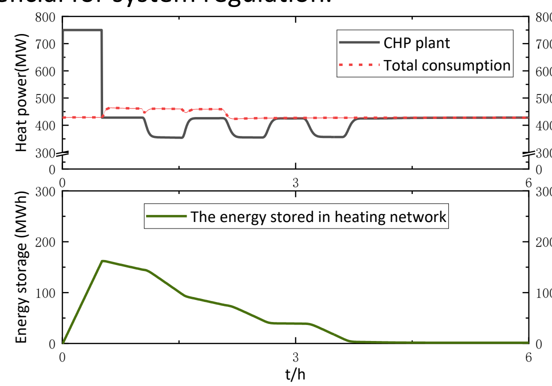

Fig. 4. Energy storage situation of district heating system

4.2 *Influence analysis*

Even from the same operation state of district heating system and under the same operation constraints, the storage capacity of heating network is not the same under different regulation mode. If the dispatch time, which is the period of time raising outlet temperature of CHP plant, is different, the flexibility of district heating system varies. Table.1 gives storage characteristics varying with dispatch time. With the increase of dispatch time, the maximum outlet temperature of CHP plant decreases and the storage capacity of heating network increases. It is obvious that the dispatch time is longer, the storage capacity is larger since the more place in heating network is utilized to store energy.

Table. 1. Storage characteristics varying with dispatch time

Dispatch time	0.5 h	1 h	1.5 h	2 h
Maximum outlet temperature of CHP plant (℃)	121.5	115.4	113.8	113.2
Storage capacity of heating network (MWh)	162.0	219.9	260.0	295.9

What's more, the heat migration delay influences storage capacity of heating network significantly. The heat migration delay varies as a result of variation of water mass flow rates. Table.2 shows the storage characteristics varying with delay time. It is obvious that with the delay time decreasing, the storage capacity of heating network increase because the delay time is shorter, the mass flow rates are larger, thus the heat carrying ability is larger in heating network.

Table. 2. Storage characteristics varying with delay time

Delay time	0.83 h	0.63 h	0.5 h	0.42 h
Storage capacity of heating network (MWh)	89.2	119.0	162.0	211.3

5. CONCLUSIONS

Based on the model of a district heating system built by heat current method, which consists of district heating network and residential buildings, this work proposes a quantification method to evaluate the flexibility of district heating system. The hybrid algorithm for quantification utilizes simulations and dichotomy method. Quantitative indicators including average power shifting capability and available storage capacity are also defined to describe the flexibility of heating system. Then, under a general working condition, the flexibility of district heating system is quantified. Finally, several influence factors are analyzed, and the results show that with the increase of dispatch time and decrease of the time of heat migration delay, the storage capacity of heating network increases.

ACKNOWLEDGEMENT

The present work is supported by the Science and Technology Foundation of SGCC (5400-202028125A-0-0-00).

REFERENCE

[1] Chu S, Majumdar A. Opportunities and challenges for a sustainable energy future. Nature 2012;488(7411):294-303.

[2] Lund H. Renewable energy strategies for sustainable development. Energy 2007;32(6):912-919.

[3] Shu Y, Zhang Z, Guo J, Zhang Z. Study on key factors and solution of renewable energy accommodation. Proc CSEE 2017;37(1):1-8.

[4] Nuytten T, Claessens B, Paredis K, Bael, J. V, Six D. Flexibility of a combined heat and power system with thermal energy storage for district heating. Appl Energy 2013;104:583-91.

[5] Ivanova P, Sauhats A, Linkevics O, Balodis M. Combined heat and power plants towards efficient and flexible operation. In: 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC); 2016. p. 1–6.

[6] Kempton W, Tomic J. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. J Power Sources 2005;144(1):280-94.

[7] Ma H, Chen Q, Hu B, Sun Q, Li T, Wang S. A compact model to coordinate flexibility and efficiency for decomposed scheduling of integrated energy system. Appl Energy 2021;285:116474.

[8] Guelpa E, Verda V. Thermal energy storage in district heating and cooling systems: A review. Appl Energy 2019;252:113474.

[9] Reynders G, Nuytten T, Saelens D. Potential of structural thermal mass for demand-side management in dwellings. Build Environ 2013;64:187–99.

[10] Li W, Xu P, Wang H, Lu X. A new method for calculating the thermal effects of irregular internal mass in buildings under demand response. ENERG BUILDINGS 2016;130:761-772.

[11] L.A. H, J.D. R, P.H. N, I.G. K, M.E. W. Quantifying demand flexibility based on structural thermal storage and comfort management of non-residential buildings: A comparison between hot and cold climate zones. Appl Energy 2017;195:1047-1054.

[12] Kouhia M, Laukkanen T, Holmberg H, Ahtila P. District heat network as a short-term energy storage. Energy 2019;177:293-303.

[13] Li Z, Wu W, Shahidehpour M, Wang J, Zhang B. Combined Heat and Power Dispatch Considering Pipeline Energy Storage of District Heating Network. IEEE T SUSTAIN ENERG 2015, 7(1):12-22.

[14] Chen Q. Entransy dissipation-based thermal resistance method for heat exchanger performance design and optimization. INT J HEAT MASS TRAN 2013; 60: 156-162.

[15] Chen Q, Hao J, Zhao T. An alternative energy flow model for analysis and optimization of heat transfer systems. INT J HEAT MASS TRAN 2017; 108: 712-720.

[16] He K, Chen Q, Ma H, Zhao T, Hao J. An isomorphic multi-energy flow modeling for integrated power and thermal system considering nonlinear heat transfer constraint. Energy 2020;211:119003.