Advanced Control Strategies with Simulations for a Typical District Heating System to Approaching Energy Efficiency Buildings

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.72290

Abstract

District heating systems (DHSs) are very common and important in cold areas in the world not only because of the huge energy consumption including kinds of fuel, electricity and water but also due to thermal comfort of all customers. To increase the energy efficiency and improve heating quality within the operational period, suitable and optimal control strategy should be applied for the DHSs. Thus, in this chapter, a typical DHS is designed. Based on the DHS information, a dynamic model is developed by using thermodynamic principles and corrected according to the measured operational data from real systems. The DHS properties are simulated by utilizing the open-loop tests (OLTs) of the developed actual dynamic model. System performance of operation, energy consumption and zone air temperature are addressed for several control strategies. Based on the energy consumed and indoor air temperature response, average water temperature set point corrected by equivalent outside air temperature (Case 4) and indoor air temperature control directly (Case 5) are considered, which are the best cases of optimal operation in the DHS.

Keywords: district heating system, dynamic modeling, control strategy, simulation, estimation, energy efficiency

1. General information of typical district heating systems

1.1. Introduction of DHSs

Indoor environment of living and work in cold areas in the world must satisfy certain conditions in cold period. For instance, in some Nordic countries, if people feel cold with in zone air temperature, they could run the heating system to maintain the air temperature warmer due to the DHS operated yearly. Another example is that, in China, following the heating guide, if average outside air temperature lowers than 5°C within 3 days continuously, heating systems should be run from that time (adjusted a few days actually). The space heating systems have been developed from decentralized heating to district heating, which are sometime called as central heating systems, usually with huge served heating floor area.

When the DHSs are operated from the beginning to the end, the systems have been expectedly running in an optimal way to improve their performance, increase their energy efficiency, reduce the pollutant emissions and maintain accepted indoor air temperature as well. Consequently, energy efficiency of buildings has been approached. DHS performance is related to operational data collection, status estimation, alarm, data analysis, control settings and control strategies. Energy efficiency should consider the heat transfer from the heat source to the end users, which could be separated by efficiency of heat source, pipe network and substation, respectively. Although zone air temperature is normally kept in constant, but the set points could be reasonably changed such as to increase the human body adaptability with a little bit zone air temperature fluctuation.

From energy-saving point of view, how to reduce energy consumption including fuel, electricity and water is always a hot topic, a question and a great challenge. These reasons behind are that currently DHSs integrated not only have been become larger and larger but also require strong and various technologies to assist the activity. For example, Beijing Heating Group has the biggest DHSs in the world, around 2.55 Mm^2 in 2016–2017 heating period with powerful SCADA system to support the operation.

One way to increase system energy and served building efficiency is to investigate the system properties using collected operational data and apply the results to the real system operation. However, this is time-consuming and cannot test all kinds of situations, which are expected because of potential risks. Therefore, what the efficient way could be utilized has been considered by the researchers and HVAC engineers in this field. Currently, this methodology is entitled as dynamic simulation based on mathematical modeling, which basically could be used to obtain system characteristics, study control strategies and predict energy consumption and dynamic responses of system operation.

1.2. The advantages and disadvantages of dynamic modeling

System modeling has two types of methods: one is steady-state modeling, and the other is dynamic modeling [1, 2]. The thermal capacities of DHSs are not considered in steady-state modeling process, but those have been calculated in dynamic modeling. This is because thermal capacities have profound influence in actual system dynamic responses and process control. To investigate the system responses closely to the real world, the system modeling and simulations in this chapter always refer to the dynamics. The properties of modeling can be described as follows.

1.2.1. The advantages of modeling

(1) An ideal model of an overall DHS can be developed by the first law of thermodynamics and corrected by operational data, which has been changed to the actual model.

http://dx.doi.org/10.5772/intechopen.72290

(2) Quick dynamic responses and characteristics could be gathered in the simulation with acceptable accuracy by simulating the actual model.

(3) The results could be obtained in simulation environment without any risks.

(4) The boundary conditions could be changed very efficiently by inputting different parameters and could be utilized while they are modified.

(5) Both greater efficiency and time-saving of R&D could be achieved by programming with friendly user interface.

(6) Almost all consideration and simulation could be fulfilled by using dynamic modeling to attain optimal results.

(7) The system responses such as the performance of system, energy efficiency and zone air temperature could be observed and analyzed.

(8) By using simulation method, the optimal parameters of system operation could be found and applied for real system to improve energy efficiency of buildings as well as overall DHSs.

1.2.2. The disadvantages of modeling

(1) It is relatively difficult to develop an overall dynamic model of a DHS with correction.

(2) Programming based on mathematics, control theory, optimization method and computer skills is required for various dynamic simulations.

(3) Simulations for fast dynamic system, water mass flow rate and pressure, for instance, could consume more time to get results.

(4) Very powerful computers could be required for more accurate simulation with bigger and more complex DHS system.

1.3. Methods of dynamic modeling and simulation

1.3.1. Dynamic modeling method

Any closed system must obey certain laws including energy, momentum and mass conservation [3–5]. According to the properties of DHSs, the dynamic responses mainly depend on slow response system (temperature dynamics) rather than fast response system (mass and pressure dynamics). To this end, the dynamics of fast response systems could be replaced by using steady-state method without affecting the major dynamic properties of DHSs. Energy and mass conversion are applied for the development of an overall DHS that is addressed in the following section below.

1.3.2. Dynamic simulation method

Recently, simulation methods of DHSs have played more important rule than ever followed by the progress of science and technology. The computer, algorithm, programming and software become very powerful as simulation tools. Many businesses or academic software such as BLAST, EnergyPlus, DeST, DOE-2, RNSYS, PKPM-CHEC, eQuest, VisualDOE, ESP-r, Ecotect, IES, etc. [6] can be easily obtained from various channels. However, if considering inside of the software, most of them were developed based on steady-state approach. In research area, dynamics is normally applied to equipment or partial system simulations. Few researchers are working in the dynamic simulation field for developing entire DHS modeling and try to utilize the models for system-level improvement [7–12].

1.4. Major focus on this chapter

In this chapter, a typical hot water DHS is considered and designed. Then, a dynamic mathematical model is developed based on the physical model and thermal dynamic principles. An actual model is developed by correcting an ideal model of the DHS. Following that, the characteristics of the DHS could be collected by using open-loop test (OLT) method. Finally, five types of control strategies are simulated and compared with the analysis of dynamic response, energy consumption and zone air temperature responses.

2. Design of a typical DHS

2.1. A typical DHS diagram

Due to the heated floor area of DHSs which become very larger, indirect DHSs are commonly formed in practice for major district heating field with substations. A typical DHS diagram is shown in **Figure 1**, and the meaning of symbols in it is given in the nomenclature.

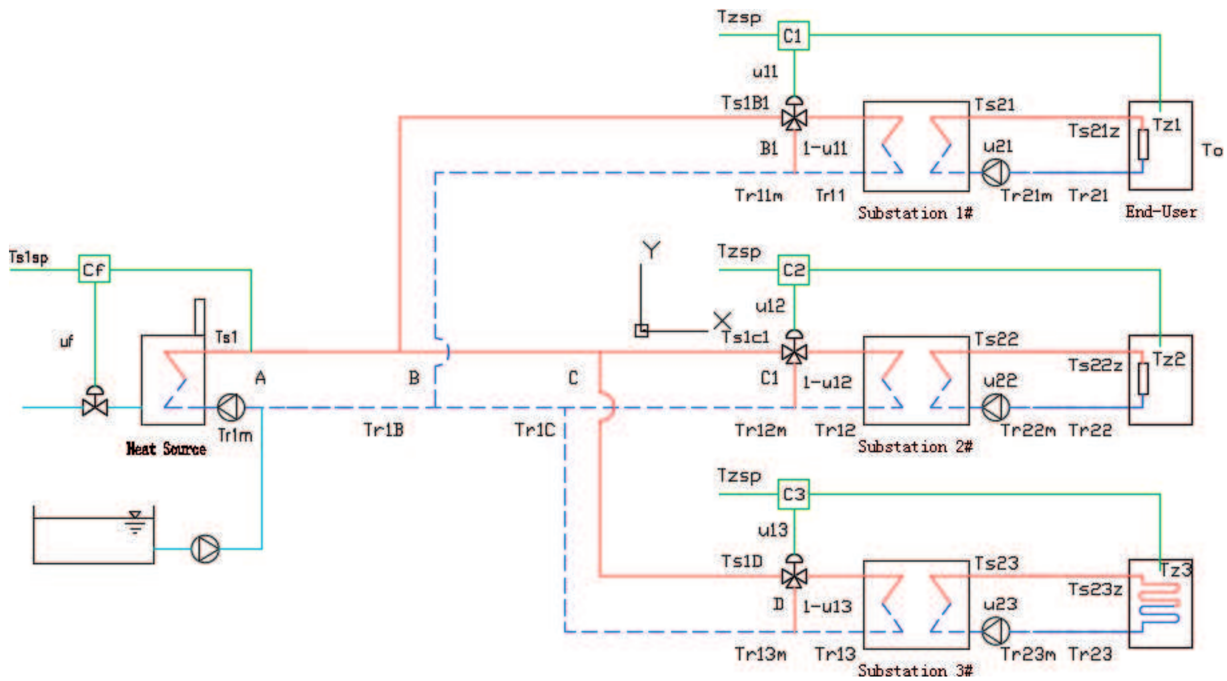

Figure 1. A typical DHS diagram with control principle.

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The hot water with high-level temperature (usually less than 150°C in design condition) is supplied from the boiler (sometimes from CHPs) in the heat source and transfers heat to the substations; then the heat is released to the secondary side in the substation, and the temperature of the return water in the primary side is decreased. The radiators at the end-users receive transferred heat from the substations and then are emitted to the indoor air for space heating. The supplied heat should be continuously gained to maintain suitable zone air temperature due to the heat balance between the indoor and the outdoor environments. The three-way control valves installed in the primary side of the substations are utilized to regulate the water mass flow into the heat exchangers and to balance the heat supplied to the secondary systems. Note that the makeup water systems in the secondary side are same as it is in the primary side (drawing ignored).

2.2. Subsystem of the DHS

From **Figure 1**, it is realized that the structure of the indirect DHS includes the following subsystem such as heat source, pipe network in the primary side, substation, pipe network in the secondary side, heat emit system from terminal, indoor air and outside environment.

3. Mathematical model development

3.1. Physical model

To obtain the mathematical model of the DHS, it is required to design the heating system illustrated in **Figure 1**. The design parameters are given in **Table 1**. The DHS is designed based on these parameters, which could be utilized to develop mathematical model and simulations.

3.2. Assumption of model development

The designed DHSs are a very complex system from mathematic modeling point of view because of the multiple connections among the subsystems. To simplify the dynamic model development process, several assumptions are listed below without affecting major properties of the DHSs [13]:

(1) Some parameters such as comprehensive heat transfer coefficient of buildings and heated floor area of buildings are integrated.

(2) The water leakage from the pipe network is assumed taking place in the primary pipe network of the substation and in the end-user of the secondary side, and it is divided into half in supply and half in return pipes, respectively.

(3) Transportation delay of pipe network is not considered in the system dynamics.

(4) Fast response system is expressed as steady-state condition.

(5) The solar radiation is considered from south side windows in the outside wall only.

(6) The water mass flow rate remains constant in the secondary system in each substation.

No.	Name	Unit	Data	Remark
1	Outside air temperature	°C	−20	
2	Supply water temperature in the primary system	°C	120	
3	Return water temperature in the primary system	°C	60	
4	Heat capacity in the heat source	MW	7	
5	Natural gas-fired boiler	%	92	
6	Water volume in the boiler body	T	3	
7	Supply water temperature in the secondary system	°C	75	Radiator
8	Return water temperature in the secondary system	°C	50	Radiator
9	Supply water temperature in the secondary system	°C	50	Floor heating
10	Return water temperature in the secondary system	°C	40	Floor heating
11	Indoor air temperature	°C	20	Radiator terminal
12	Indoor air temperature	°C	18	Floor heating terminal
13	Heated floor area in Substation #1	m^2	50,000	
14	Heating load index in Substation #1	W/m^2	55	
15	Water volume in the radiator of Substation #1	T	75	
16	Factor of the heat transfer coefficient test in Substation #1		0.35	
17	Heated floor area in Substation #2	m^2	35,000	
18	Heating load index in Substation #2	W/m^2	42	
19	Water volume in the radiator of Substation #2	T	38	
20	Factor of the heat transfer coefficient test in Substation #2		0.28	
21	Heated floor area in Substation #3	m^2	40,000	
22	Heating load index in Substation #3	W/m^2	35	
23	Water volume in the radiator of Substation #3	T	38	
24	Factor related to heat transfer coefficient simulation in Substation #3		0.04	
25	Heating load in Substation #1	MW	2.75	
26	Heating load in Substation #2	MW	1.47	
27	Heating load in Substation #3	MW	1.40	

Table 1. Design parameters of the DHS.

3.3. Dynamic modeling

By applying for the first law of thermodynamics and mass conservation principle, each subsystem dynamic model is shown and described briefly below:

3.3.1. Boiler model

$$C_b \frac{dT_{s1}}{dt} = u_f G_{fd} HV \eta_b - c_w (u_{11} G_{11d} + u_{12} G_{12d} + u_{13} G_{13d})(T_{s1} - T_{r1m}) \quad (1)$$

In Eq. (1), the net heat stored in the water of the boiler body is computed with the difference between the heat from the gas combustion and the heat transferred to the circulation water in the primary system. Note that the boiler efficiency is calculated according to measured operational data.

3.3.2. Substation model

$$C_{ex11}\frac{dT_{r11}}{dt} = c_w(u_{11}G_{11d} - 0.5G_{mk11})(T_{s1B1} - T_{r11}) - f_{ex1}U_{ex1}LMTD_1 \tag{2}$$

$$C_{ex12}\frac{dT_{r12}}{dt} = c_w(u_{12}G_{11d} - 0.5G_{mk12})(T_{s1c1} - T_{r12}) - f_{ex2}U_{ex2}LMTD_2 \tag{3}$$

$$C_{ex13}\frac{dT_{r13}}{dt} = c_w(u_{13}G_{13d} - 0.5G_{mk13})(T_{s1D} - T_{r13}) - f_{ex3}U_{ex3}LMTD_3 \tag{4}$$

The return water temperatures from each substation in the primary system are given in Eqs. (2)–(4). The net heat stored in the heat exchanger (primary side) is computed between the heat from the pipe network to the substation and the heat transferred in the substation:

$$C_{ex21}\frac{dT_{s21}}{dt} = f_{ex1}U_{ex1}LMTD_1 - c_w u_{21}G_{21d}(T_{s21} - T_{r21m}) \tag{5}$$

$$C_{ex22}\frac{dT_{s22}}{dt} = f_{ex2}U_{ex2}LMTD_2 - c_w u_{22}G_{22d}(T_{s22} - T_{r22m}) \tag{6}$$

$$C_{ex23}\frac{dT_{s23}}{dt} = f_{ex3}U_{ex3}LMTD_3 - c_w u_{23}G_{23d}(T_{s23} - T_{r23m}) \tag{7}$$

The supply water temperature from the substation in the secondary system is presented in Eqs. (5)–(7). The net heat stored in the heat exchanger in the secondary side is related to the heat transferred in the substation and the heat taken from the substation to the secondary system. Note that the logarithmic mean temperature difference (LMTD) is calculated in Eq. (8). Note that it refers to each substation from 1 to 3. Letter i denotes to 1–3, which is the number of substation:

$$LMTD_i = [(T_{s1in} - T_{s2zi}) - (T_{r1i} - T_{r2im})]\left[\ln\left(\frac{T_{s1in} - T_{s2zi}}{T_{r1i} - T_{r2im}}\right)\right]^{-1} \tag{8}$$

3.3.3. Radiator model

$$C_{ht1}\frac{dT_{r21}}{dt} = c_w(u_{21}G_{21d} - 0.5G_{mk21})(T_{s21z} - T_{r21}) - f_{ht1}U_{ht1}[0.5(T_{s21z} + T_{r21}) - T_{z1}]^{(1+k1)} \tag{9}$$

$$C_{ht2}\frac{dT_{r22}}{dt} = c_w(u_{22}G_{22d} - 0.5G_{mk22})(T_{s22z} - T_{r22}) - f_{ht2}U_{ht2}[0.5(T_{s22z} + T_{r22}) - T_{z2}]^{(1+k2)} \tag{10}$$

$$C_{rf}\frac{dT_{r23}}{dt} = c_w(u_{23}G_{23d} - 0.5G_{mk23})(T_{s23z} - T_{r23}) - f_{rf}U_{rf}[0.5(T_{s23z} + T_{r23}) - T_{z3}]^{(1+k3)} \tag{11}$$

The return water temperature from the end-user (radiator and radiant floor heating) is addressed in Eqs. (9)–(11). The net heat stored in the terminal equals to the heat difference between the heat gathered from the circulation water and emitted to the indoor air.

3.3.4. Indoor air model

$$C_{z1}\frac{dT_{z1}}{dt} = c_w(u_{21}G_{21d} - 0.5G_{mk21})(T_{s21z} - T_{r21}) + q_{sols}F_{s1} + q_{\text{int}}F_1 - U_{en1}(T_{z1} - T_o) \tag{12}$$

$$C_{z2}\frac{dT_{z2}}{dt} = c_w(u_{22}G_{22d} - 0.5G_{mk22})(T_{s22z} - T_{r22}) + q_{sols}F_{s2} + q_{\text{int}}F_2 - U_{en2}(T_{z2} - T_o) \tag{13}$$

$$(C_{z3} + C_c)\frac{dT_{z3}}{dt} = c_w(u_{23}G_{23d} - 0.5G_{mk23})(T_{s23z} - T_{r23}) + q_{sols}F_{s3} + q_{\text{int}}F_3 - U_{en3}(T_{z3} - T_o) \tag{14}$$

Zone air temperature dynamic responses can be represented in Eqs. (12)–(14). The net heat stored is related to the heat obtained from the circulation water in the secondary system, the solar radiation from south side windows, the internal heat gains and the heat transferred to the outside environment. Note that the thermal capacity in the terminal of floor heating is considered by accumulating the influence of the concrete structure.

3.3.5. Pipe segment in the primary and secondary systems

$$C_{segj}\frac{dT_{segoutj}}{dt} = c_w G_{seginj} T_{seginj} - c_w G_{segoutj} T_{segoutj} - Q_{mksegj} - Q_{hlsegj} \tag{15}$$

The schematic diagram of a pipe segment is shown in **Figure 2**. The makeup water and the heat loss from the pipe insulation are considered to gather the water temperature left from the pipe segment. The supply water temperature from the pipe segment is related to the heat loss from the pipe segment, while the return water temperature has been considered in the heat losses from pipe insulation and makeup water. In Eq. (15), the net heat stored in the pipe segment equals to the heat received from the entrance minus the heat outlet from the exit and the heat losses from both makeup water leakage and pipe segment. Note that supply pipe segments do not consider the water leakage by the assumption. Letter j represents each pipe segment.

In summary, 29 dynamic equations are used to address the overall DHS mathematical model. The developed model is utilized to obtain system properties, simulate various dynamic responses of control strategies and compare with system energy consumption.

Figure 2. Schematic diagram of a pipe segment.

4. Actual dynamic model corrected by using open-loop test

4.1. The purposes of OLT

The purposes of doing OLT based on the developed dynamic model are stated hereby. Firstly, the mathematical model should be checked out with ideal condition to ensure the accuracy. Then, by applying the experience and operational data, the ideal dynamic model could be corrected to seek the characteristics of the DHS and various simulations.

4.2. Ideal model of the DHS

The ideal conditions represent that outside and indoor air temperature and water mass flow rate in primary and secondary system are same as their design values. The affluent factors of both heat transfer area of each substation and terminal equal to 1. No solar radiation and internal heat gains exist in the ideal dynamic system. The heat losses from both water leakage and pipe network are ignored.

With these situations, the dynamic responses of the ideal model with the fuel control signal by 0.798 are shown in **Figure 3**. In addition to the zone air temperature in Substation #3, which is equal to 17.9°C due to the huge thermal capacity of the floor heating structure, the supply and return temperatures from the heat source and substations are identical to the design conditions. Steady-state time of the water temperatures and zone air temperatures except for the zone air temperature in Substation #3 (48 h) reaches 15 h similarly.

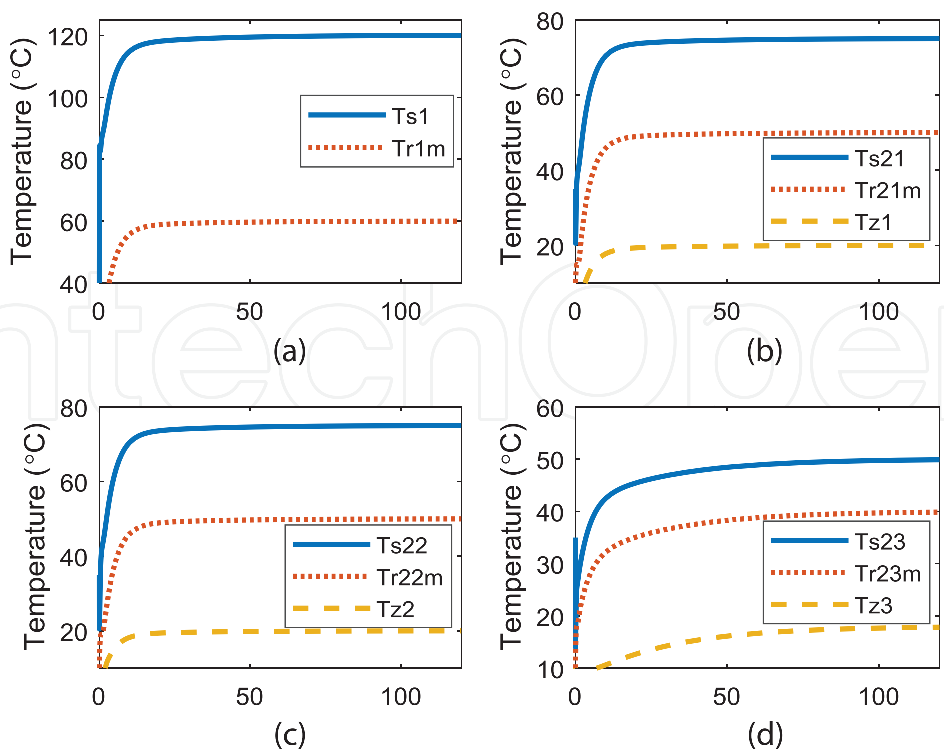

Figure 3. Dynamic responses of ideal model (a) Time(h), (b) Time(h), (c) Time(h), (d) Time(h).

4.3. Actual model of the DHS

In practice, the affluent factors of both heat transfer area of each substation and terminal are greater than 1 because of the safety consideration from designers. The circulation water flow rate could be adjusted rather than design values. With these situations, the ideal dynamic model should be modified to simulate the real DHS, which is entitled as actual dynamic model. Regarding the experience and operational data of typical DHSs in China, the affluent factors of each heat transfer area and terminal in Substations #1–#3 are provided as [1.4, 1.4, 1.4, 1.5, 1.35, 1.4], respectively.

While outside and indoor air temperature and water mass flow rate in primary and secondary system are identical to their design values, no solar radiation and internal gains exist, the water leakage and heat losses from pipe segments are considered, the control signal of fuel equals to 0.854 and the dynamic responses of the temperatures from actual model are shown in **Figure 4**. In this figure, the steady-state values of the supply and return water temperatures from the heat source and Substations #1–#3 are 97.5, 33.2, 57.6, 31.6, 58.6, 33.6, 38.4 and 28.1°C, while the zone air temperatures equal to 20.8, 19.6 and 18.8°C, respectively. From the values, the supply water temperature from the heat source is not necessary to satisfy its design value (120°C), while outside air temperature is −16.9°C. Meanwhile, the zone air temperatures are not same as the design values. The reason behind is that the affluent factors of the heat transfer area affect the operation very much in the DHS. It is also hinted that the zone air temperature should be controlled separately because they cannot approach its design value simultaneously.

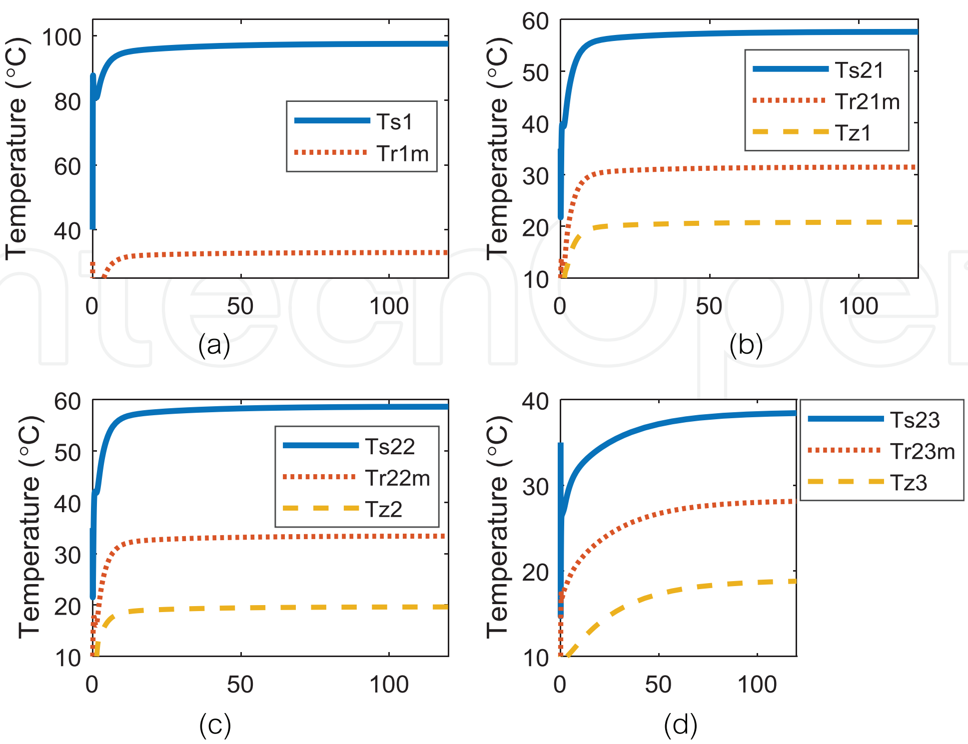

Figure 4. Dynamic responses of actual model (a) Time(h), (b) Time(h), (c) Time(h), (d) Time(h).

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5. Advanced control strategies and simulations

5.1. System disturbance

Usually, the disturbances taking place in DHSs include outdoor air temperature, solar radiation and internal heat gains, while outdoor air temperature plays the biggest rule in system operation. On the other hand, when the comprehensive heat transfer coefficient (U_{en} value) of the buildings is getting smaller and smaller, the additional heat gains (solar radiation and internal gains) should be considered in the simulation and in real system operation. In this chapter, outdoor air temperature, solar radiation and internal heat gains are drawn into actual model with the range from 8.2 to 13.1°C, from 0 to 45 W/m^2 and from 0.9 to 6.8 W/m^2, respectively, for all simulations of the cases.

5.2. Control signals

In many circumstances, DHSs are operated with experience; likely, the supply water temperature from the heat source has been controlled depending on the experience of operators. Nevertheless, the disturbances described above change based on time. It means that the heating supply from the heat source and the heat consumption (heating load) should be tracked and balanced. Thus, the DHS must be regulated accordingly. Otherwise, the zone air temperature could fluctuate in larger range, which influences thermal comfort of end-user. By simulating the dynamic responses of actual model with different conditions (change outdoor air temperature, indoor air temperature as similar as design value, design water mass flow rate in the pipe network, constant water leakage rate, considered pipe insulation heat loss, no solar radiation and internal gains), the simulated stable results from OLTs are listed in **Table 2** as set points for related parameters used in control strategies.

5.3. Control strategies

Five cases are selected for dynamic simulations (given in **Table 3**) to study the system responses, the energy consumption (heat consumed in the cases) and the thermal comfort of the end-user [14–17]. Note that typical PI algorithm is used to all controllers to gather output signals [18].

5.4. Case study based on dynamic simulation

5.4.1. Case 1

Many operators run DHSs according to their experience if they cannot realize the set points of supply water temperature from the boiler. In this case with 5 days consciously, the dynamic

T_o, °C	15	10	5	0	−5	−10	−16.9	−20
T_{s1}, °C	37.5	49.1	54.2	70.6	81.1	91.4	104.2	111.8
T_{w2arg1}, °C	24.5	28.5	29.2	35.3	38.4	41.3	44.5	46.9
T_{w2arg2}, °C	25.1	29.3	30.2	36.6	39.8	43.0	46.5	49.0
T_{w2arg3}, °C	20.4	22.7	21.8	26.5	28.3	29.9	31.6	33.2

Table 2. Set points used in control strategies.

responses of the DHS are presented in **Figure 5**. From this figure, the supply water temperature from the boiler changes depending on the outside air temperature (**Figure 5(a)**). The average water temperature responses of the secondary side in Substations #1 and #2 are almost similar and higher than that in Substation #3 due to the difference between the radiator and the floor heating terminals (**Figure 5(b)**). The difference of indoor air temperature dynamic responses shown in **Figure 5(c)** is mainly resulted from the structure of terminals. By

Case	Control strategy	Description	Used controller
1	Experienced T_{s1} control	Supply water temperature from the heat source controlled based on experience	C_f
2	Tuned T_{s1} control	Supply water temperature from the heat source controlled based on tuned set points	C_f
3	Tuned T_{s1} and T_{w2arg} control	Supply water temperature from the heat source and average water temperature in the secondary system of each substation controlled based on tuned set points	C_f, C_1, C_2, C_3
4	Tuned T_{s1} controlled based on T_o and T_{w2arg} controlled based on T_{oe}	Supply water temperature from the heat source controlled based on T_o and average water temperature in the secondary system of each substation controlled based on equivalent T_o (T_{oe})	C_f, C_1, C_2, C_3
5	Tuned T_{s1} controlled based on T_o and zone air temperature controlled based on T_z	Supply water temperature from the heat source controlled based on T_o and zone air temperature in each substation controlled based on T_z	C_f, C_1, C_2, C_3

Table 3. Control strategies used in the cases.

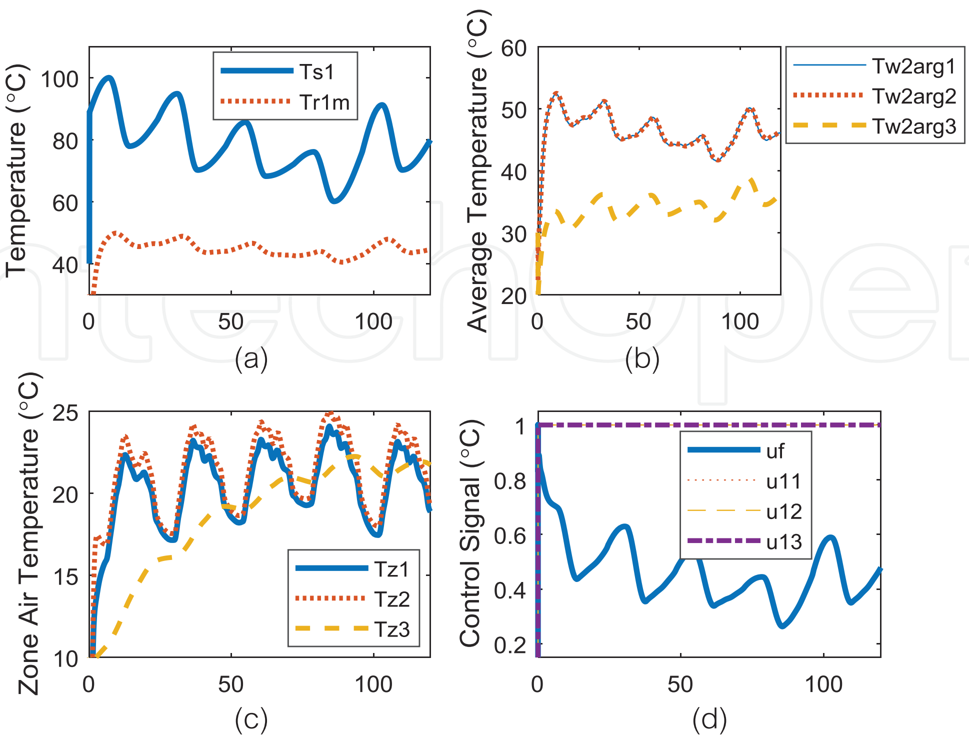

Figure 5. Dynamic responses in case 1 (a) Time(h), (b) Time(h), (c) Time(h), (d) Time(h).

considering the responses of the last 2 days rather than the influences of the initial parameter settings, the average and the range of the zone air temperatures in Substations #1–#3 are 20.2, 17.4–24.1, 20.9, 18.1–25.2, 21.1 and 20.7–22.2°C, respectively. The control signal of fuel in the heat source is changed based on the heating load (**Figure 5(d)**). The water mass flow rate in the pipe network is set to be the design values.

5.4.2. Case 2

From the simulation by using experience of the supply water temperature from the heat source, the average zone air temperatures excess their design values with bigger fluctuation. This situation should be improved by utilizing tuned supply water temperature set points (T_{s1sp}). With T_{s1sp} given in **Table 2**, the simulation results are shown in **Figure 6**. With the tuned setting value, the average zone air temperatures in Substations #1–#3 are given as 19.7, 20.2 and 20.1°C, meaning that average zone air temperatures are reduced comparing with those in Case 1.

5.4.3. Case 3

From Cases 1 and 2, the average and the fluctuation of zone air temperatures are still larger than the expected results. Because the heat properties of the substations are different, indoor air temperatures should be controlled separately to balance their heat supply and requirement. In this situation, the simulation is made and shown in **Figure 7** for zone air temperature responses only, and considering the time-consuming simulation, the time span is decreased to

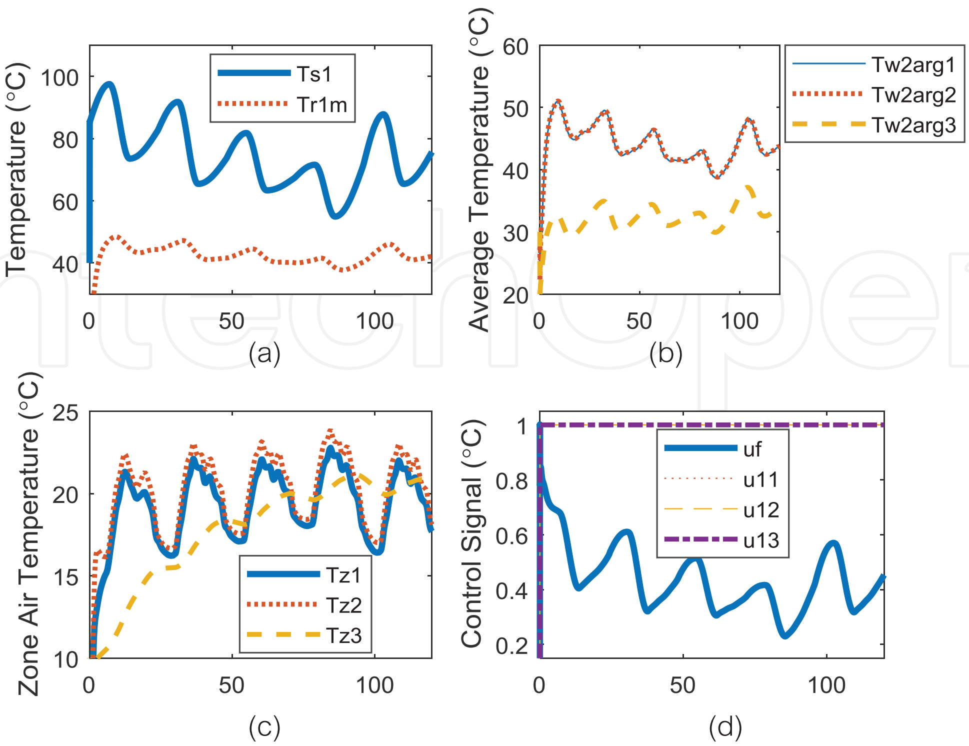

Figure 6. Dynamic responses in case 2 (a) Time(h), (b) Time(h), (c) Time(h), (d) Time(h).

2 days continuously. The results illustrate that the fluctuation of zone air temperatures is reduced significantly, but average zone air temperatures are still high compared with their design values.

5.4.4. Case 4

The meaning behind average zone air temperatures excessed the deign values is that the disturbances are never considered in the control algorithm. Consequently, a concept of an

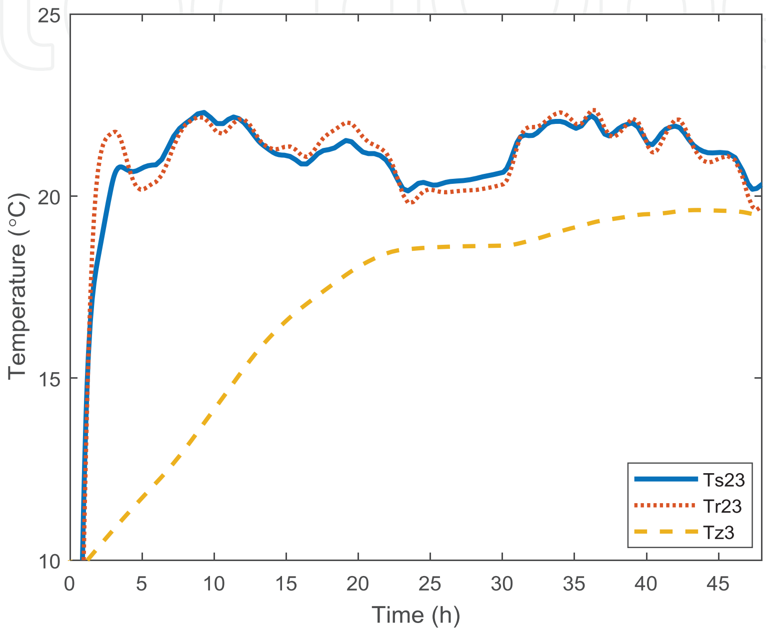

Figure 7. Dynamic responses in case 3.

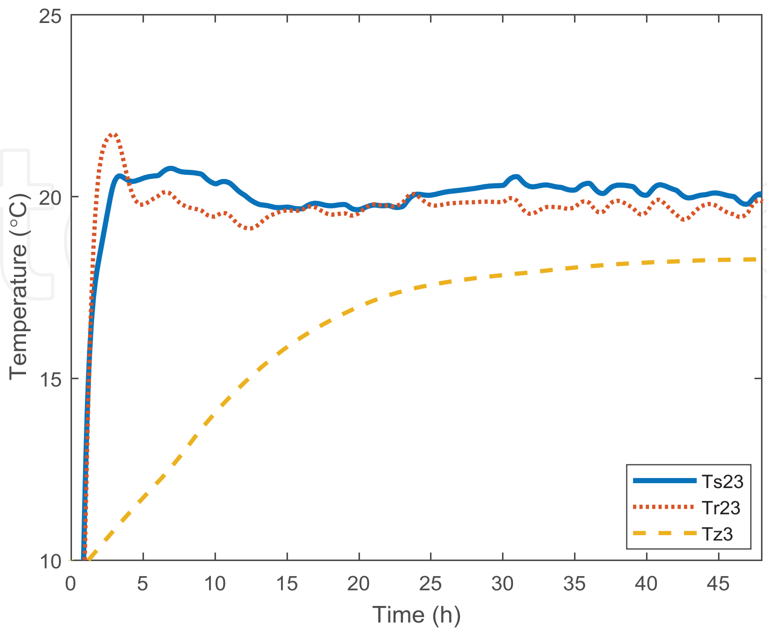

Figure 8. Dynamic responses in case 4.

equivalent outside air temperature is introduced to reset the original average water temperature set points and improve the stability and decrease zone air temperature swing. The equivalent outside air temperature is calculated in Eq. (16). This case is simulated and addressed in **Figure 8**. Compared with **Figure 7**, the purpose of decreasing zone air temperature fluctuation is realized perfectly:

$$T_{oei} = T_o + \left(q_{sols}F_{si} + q_{\text{int}}F_i\right)U_{eni}^{-1} \tag{16}$$

5.4.5. Case 5

As known that, average water temperature in a terminal is related to the zone air temperature indirectly, and the return water temperature from the terminal is delayed due to the thermal capacity of the terminal. If the zone air temperature is measured and applied for the control strategy, it would be better to elevate the thermal comfort of indoor environment. To this end, the simulation is made and shown in **Figure 9**. The dynamic responses of zone air temperatures in Substations #1–#2 are improved very much. Because of the huge thermal capacity of the radiant floor heating structure, the zone air temperature in Substation #3 although approaches 18°C still needs more advanced control strategy such as predictive control or two-temperature control to improve the dynamic response of zone air temperature.

5.5. Comparison with energy consumption

Due to relevant smaller parts of electricity and water consumption in DHSs, the heat consuming is considered only for energy comparison. The simulated results in the fuel control signal responses are presented in **Figure 10**. From this figure, the fuel consumption in Case 2 has the lowest value but with larger zone air temperature fluctuation. By observation with all cases,

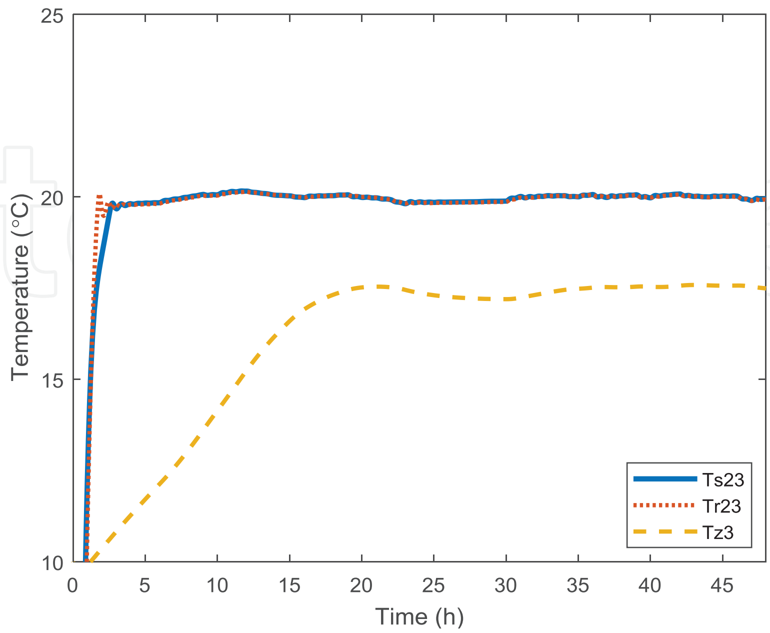

Figure 9. Dynamic responses in case 5.

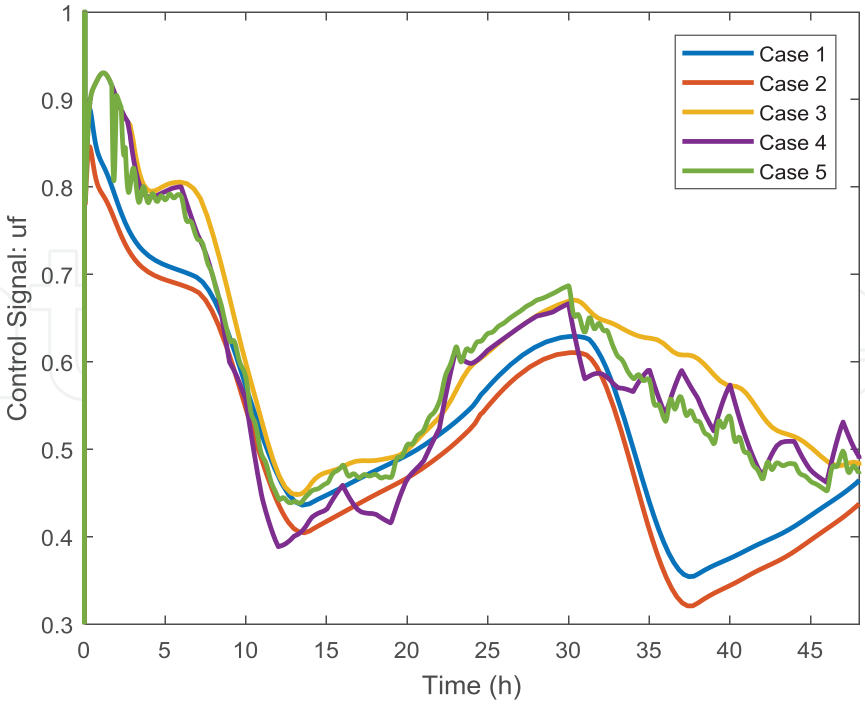

Figure 10. Comparison with fuel consumption.

Case 5 is the best control strategy based on both dynamic responses of zone air temperature and the fuel consumption. Without measuring zone air temperature for compensation, Case 4 is the best one for optimal operation of the DHS.

6. Conclusions

6.1 The first law of thermodynamics and mass conservation principle can be utilized to develop dynamic mathematical models of DHSs.

6.2 The developed ideal dynamic model must be corrected to obtain actual model, which can be applied for various simulations, analysis and compression.

6.3 DHSs must be controlled due to the disturbances from outside air temperature, solar radiation and internal heat gains to reduce the influence of zone air temperature.

6.4 By dealing with the disturbances in Cases 4 and 5, the thermal comfort level has been improved significantly because of the compensation of disturbances.

6.5 Instead of the limitation of measuring zone air temperature in buildings, the equivalent outside air temperature method could be utilized to compensate the disturbances.

6.6 The best thermal comfort can be approached with the lowest energy consumption (Case 5) by utilizing zone air temperature control strategy directly to regulate average water temperature in the secondary system.

http://dx.doi.org/10.5772/intechopen.72290

Nomenclature

c	specific heat (J/kg°C)
C	thermal capacity (J/°C) or controller
f	factor
F	heated floor area (m^2)
G	water mass flow rate (kg/s)
HV	heating valve of fuel (J/kg)
LMTD	logarithmic mean temperature difference (°C)
q	heating load per m^2 (W/m^2)
Q	heating load (W)
t	time (s)
T	temperature (°C)
u	control signal
U	heat transfer rate (W/°C)
Subscripts	
1, 2	number of substation or primary/secondary system
3	number of substation
arg	average
b	boiler
d	design
en	enclosure of building
ex	heat exchanger
f	fuel
hl	heat loss from pipe segment
ht	heater-radiator
i	1–3
in	inlet
int	internal
j	refer to pipe segment j

k	factor related to heater transfer coefficient test
m	mix
mk	makeup water
o	outside air
oe	equivalent outside air
out	outlet
r	return
rf	radiant floor
s	supply
seg	segment of pipe network
sol	solar radiation
sp	set point
w	water
z	zone air
Alphabet	
η	efficiency

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