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Simulation of District Heating System in Tianjin, China

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ABSTRACT

Both geothermal heating and a fuel fired system using steady-state model and dynamic model were simulated based on heat load calculation, influence of radiator size on return temperature and mass flow was analyzed and radiator was selected, a sample district heating system network was set up, pressure and temperature drop of pipeline were calculated, and the system simulated. The results indicate that radiator size affect the indoor temperature significally, and, dynamic simulation model is an effective way to study the system performance, as the heating system can be controlled freely by controlling the maximum mass flow and radiator size.

1. INTRODUCTION

A district heating system is composed of many elements, building a chain from the heat source to the heated buildings. The sole purpose of a district heating system is to supply adequate heat to its consumers. Geothermal energy is abundant in Tianjin, it has been developed and used for district heating for its low temperature (70-90°C) in recent years. Compared to the conventional energy, geothermal energy is at a fixed temperature, which usually can't be controlled by the district heating system operator. Tianjin geothermal district heating system consists of two main subsystems, the geothermal pipeline system and the city distribution loop. The geothermal pipeline system transfers the geothermal fluid from wellheads to the pumping stations. In the pumping stations, the energy of the geothermal fluid is transferred to water which is circulated in the city distribution loop using heat exchangers.

2. BUILDING CALCULATION

2.1 Sample Building

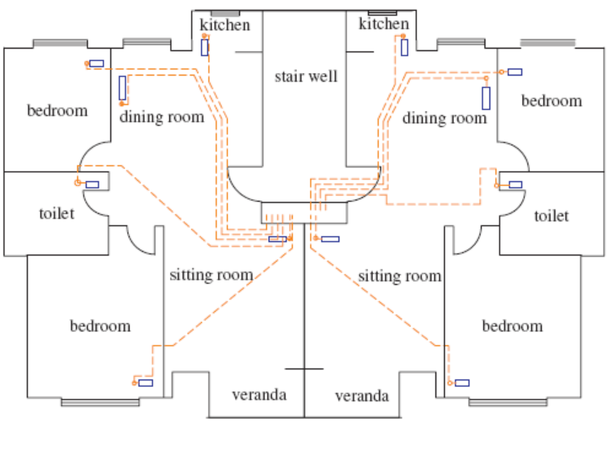

Figure 1: Layout of sample building in Tianjin.

Figure 1 shows a sample building in Tianjin (Xu and Fu, 2009), heat loss through building envelope and infiltration is 64.65 kW based on calculations of construction material properties (Emeish, 2001).

2.2 Building Heat Load Models

2.2.1 Meteorologic Data

Figure 2 shows the outdoor temperature duration curve. The data is recoded at a resolution of 1°C.

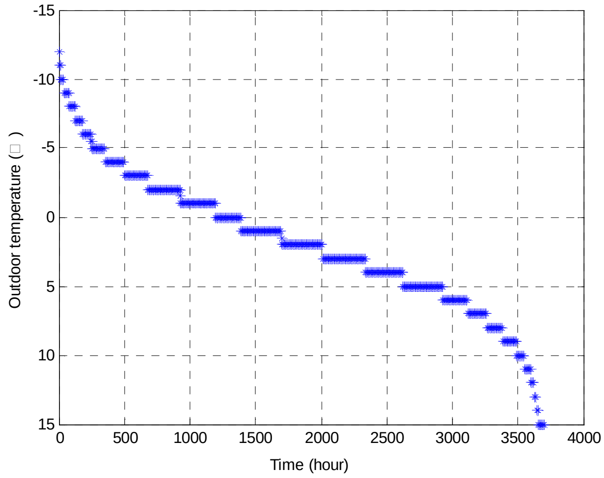

Figure 2: Duration curve of outdoor temperature.

2.2.2 Models

The models treated are macroscopic and physical (Larsen and Bolm, 2004). The district heaing network is lumped into one model block. These models for radiators, water heat duty, building heat loss, pipe heat loss, building heat storage, as well as steady-state approach and dynamic approach can be found in Valdimarsson (1993). Variables used in the model theory are defined in Nomenclature.

1) Radiators

Radiator is the heat exchanger that transfers heat from the heating system to the room air. According to Anon (1977), the relative heat load of a radiator can be written as:

$$\frac{Q}{Q_0} = \left(\frac{\Delta T_m}{\Delta T_{m0}}\right)^{(4/3)} = \left(\frac{T_s - T_r}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \cdot \frac{\ln\left(\frac{T_{s0} - T_{i0}}{T_{r0} - T_{i0}}\right)}{T_{s0} - T_{r0}}\right)^{(4/3)} \quad (1)$$

where Q/Q_0, T_s, T_r, T_i are the the ratio of the actual heat output from the radiator to the heat output at design conditions, water supply temperature, water return temperature, indoor temperature, respectively.

Supply water temperature is assumed to be around 80°C and return water temperature is 40°C for geothermal systems. For fuel fired system, similar calues are 90/70°C, with indoor temperatureat 20°C. The logarithmic mean temperature difference for a radiator, ΔT_m (°C) is defined as

$$\Delta T_m = \frac{(T_s - T_i) - (T_r - T_i)}{\ln \frac{T_s - T_i}{T_r - T_i}} \tag{2}$$

2) Water heat duty

The heat load, Q (W) due to hot water going through the radiator is:

$$Q = C_p m (T_s - T_r) \tag{3}$$

The relative heat load of water flow can be written as

$$\frac{Q}{Q_0} = \frac{m(T_s - T_r)}{m_0 (T_{s0} - T_{r0})} \tag{4}$$

3) Building heat loss

The heat loss of the building can be defined as:

$$Q_{loss} = k_l (T_i - T_o) \tag{5}$$

Where K_l is the building heat loss factor, which is a constant. Relative heat loss is obtained by:

$$\frac{Q_{loss}}{Q_{loss0}} = \frac{T_i - T_o}{T_{io} - T_{oo}} \tag{6}$$

4) Pipe heat loss

There is heat loss in the pipes from the pumping station to the buildings, which is calculated by using pipe transmission effectiveness parameter. According to Valdimarsson (1993), the transmission effectiveness τ is defined as follows:

$$\tau = \frac{T_s - T_g}{T_1 - T_g} = e^{\frac{U_p}{mC_p}} \tag{7}$$

The reference value of the τ can be concluded from the reference conditions:

$$\tau_o = \frac{T_{so} - T_g}{T_{1o} - T_g} = e^{\frac{U_p}{m_o C_p}} \tag{8}$$

Parameters U_p and C_p are assumed to be constant in the system. Combining Eq. (7) and Eq. (8), the transmission effectiveness, τ is obtained by:

$$\tau = \tau_o^{\frac{m_m}{m}} \tag{9}$$

Combining Eq. (7) and Eq. (9), the supply temperature to the building is calculated by:

$$T_s = T_g + (T_1 - T_g)\tau = T_g + (T_1 - T_g)\tau_o^{\frac{m_o}{m}} \tag{10}$$

The return water temperature at the pumping station is obtained from Eq. (11).

$$T_2 = T_g + (T_r - T_g)\tau = T_g + (T_r - T_g)\tau_o^{\frac{m_o}{m}} \tag{11}$$

5) Building energy storage

Buildings will not cooling immediately when the heating stopped because of their heat capacity. The building energy storage model is:

$$\frac{dT_i}{dt} = \frac{1}{C} Q_{net} = \frac{1}{C}(Q_{\sup p} - Q_{loss}) = \frac{1}{C}(mC_p(T_s - T_r) - k_l(T_i - T_o)) \tag{12}$$

In the steady-state model, all time derivatives Eq.12 to zero, so Eq. 12 is only used in dynamic model.

2.3 Steady State Approach

In the steady-state model, buildings are assumed to be with no heat accumulation. Return temperature is calculated by combining Eq. 4 and 6 (Nappa, 2000)

$$\frac{Q}{Q_0} = \left(\frac{T_s - T_r}{T_{s0} - T_{r0}} \cdot \frac{In\left(\frac{T_{s0} - T_{i0}}{T_{r0} - T_{i0}}\right)}{In\left(\frac{T_s - T_i}{T_r - T_i}\right)} \right)^{4/3} = \frac{T_i - T_o}{T_{io} - T_{oo}} \tag{13}$$

T_r is calculated with iteration from Eq. (13).

$$T_{r,n+1} = (T_s - T_i).e^{-z} + T_i \tag{14}$$

$$z = \frac{T_s - T_{r,n}}{T_{so} - T_{ro}} \cdot \left(\frac{T_{io} - T_{oo}}{T_i - T_o} \right)^{3/4} .In\left(\frac{T_{so} - T_{io}}{T_{ro} - T_{io}} \right) \tag{15}$$

In the steady state-model, the heat loss from buildings is the same as the heat load supply, i.e.:

$$Q_{\sup p} = Q_{loss} \tag{16}$$

$$mC_p(T_s - T_r) = k_l(T_i - T_o) \tag{17}$$

Mass flow is obtained directly from Eq. (17):

$$m = \frac{k_l(T_i - T_o)}{C_p(T_s - T_r)} \tag{18}$$

Factor k_l can be calculated from the reference conditions

$$k_l = \frac{m_o C_p (T_{so} - T_{ro})}{T_{io} - T_{oo}} \tag{19}$$

2.4 Dynamic Approach

2.4.1 Return Temperature Calculation

In the steady-state model, T_r was found by combining Eq. (4) and Eq. (6). This is not a valid approach in dynamic simulations due to energy stored in the buildings. So T_r should be calculated from the Eq. (4) by an iteration loop:

$$T_{r,n+1} = (T_s - T_i).e^{-y} + T_i \quad (20)$$

Where

$$y = \left(\frac{T_s - T_{r,n}}{T_{so} - T_{ro}}\right)^{(-1/4)} \left(\frac{m}{m_o}\right)^{(-3/4)} In\left(\frac{T_{so} - T_{io}}{T_{ro} - T_{io}}\right) \quad (21)$$

2.4.2 Relation Between Mass Flow and Indoor Temperature

The flow controller in the system is unknown. There is no simple physical relation between water flow and indoor temperature, and different buildings have different regulations systems. Each consumer has his own preferences about the indoor temperature and how to change it. The relation between the indoor temperature and the water flow has to be presented as some average of all consumers in the system. Here P-control (proporational) is used.

The P-controller is presented by Eq. (20),

$$m = k_p(T_{i\_set} - T_i) + m_{ave} \quad (22)$$

By differentiation of Eq. (22)

$$\frac{dm}{dt} = k_p \cdot \frac{dT_i}{dt} \quad (23)$$

T_i can be solved from Eq. (20):

$$T_i = T_{i\_set} - \frac{m - m_{ave}}{k_p} \quad (24)$$

Eq. (12) can be written as follows:

$$\frac{dT_i}{dt} = -\frac{k_l}{C}T_i + \frac{C_p}{C}(T_s - T_r)m + \frac{k_l}{C}T_o \quad (25)$$

Combining Eq. (23), (24) and (25), gives Eq. (26):

$$\frac{dm}{dt} = -\frac{k_p}{C}\left(C_p(T_s - T_r) + \frac{k_l}{k_p}\right)m - \frac{k_l k_p}{C}T_o + \frac{k_p k_l}{C}(T_{i-set} + \frac{m_{ave}}{k_p}) \quad (26)$$

Eq. 24 can also be written in a matrix form as:

$$\left[\frac{dm}{dt}\right] = \left[-\frac{k_p}{C}\left(C_p(T_s - T_r) + \frac{k_l}{k_p}\right)\right]m + \left[-\frac{k_l k_p}{C} \; \frac{k_l k_p}{C}\left(T_{i-set} + \frac{m_{ave}}{k_p}\right)\right]\begin{bmatrix} T_o \\ 1 \end{bmatrix} \quad (27)$$

2.5 Reference Values and Constants

All reference values are marked with subscript *0*. Common reference values for geothermal district heating network are:

Supply water temperature T_{s0}=80°C;

Return water temperature T_{r0}=40°C;

Indoor temperature T_{i0}=40°C.

Common reference values used for a fuel fired network are:

Supply water temperature for network T_{s0}=90°C

Return water temperature for network T_{r0}=70°°C

Indoor temperature T_{i0}=20°C

The reference outdoor temperature T_{o0}=-9°C°C for Tianjin was used here (He and Sun, 1993). Ground temperature was assumed to be constant at 14.2°C. The reference mass flow of water is related to the size of network. Here it was selected to be 5 kg/s. The specific heat capacity of water is C_p=4.186 kJ/(kg°C). The P-control parameter k_p=4.5 kg/(s°C).

3. MODELING THE HEATING SYSTEM

3.1 Simulation Results

3.1.1 Steady-State Modelling

1. Figure 3 shows the duration curve of supply temperature, return temperature and outdoor temperature during heating period. It can be seen that T_s and T_r decrease as T_o increase, this is because heat load is a linear function of outdoor temperature according to Eq. (13), Q drop as T_o increase, thus ΔT_m drop, m decrease, which induce more temperature drop in the network, T_s drops a little bit, so T_r decrease, if T_s drops very much, then T_r will increase. The scatter line shows the corresponding operating data of T_s and T_r in a geothermal heating system during heating period, it can be seen that operating data and simulation results fits well.

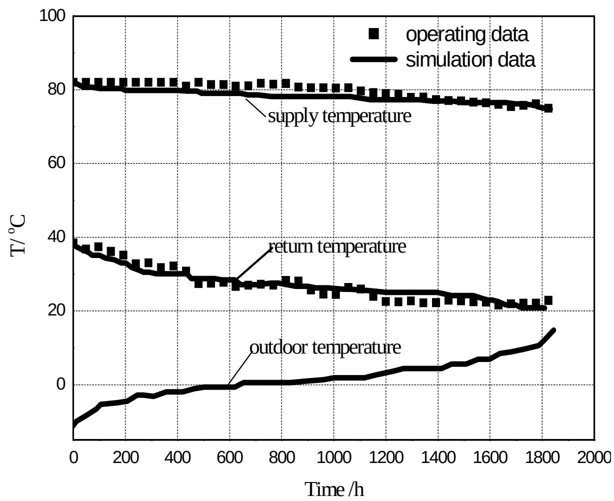

Figure 3: Duration curve of temperature.

2. Figure 4 shows the dependence of mass flow on outdoor temperature of two types of heating systems. T_s / T_r is 80/40°C in the geothermal heating system and 95/70°C in the fuel fired system. Temperature difference of the former is bigger than that of the latter, according to Eq. (3), mass flow of the geothermal system is less than that of the fuel-fired system. The simulation results can be validated by scatter lines which are the experimental data of mass flow in fuel fired and geothermal system, respectively.

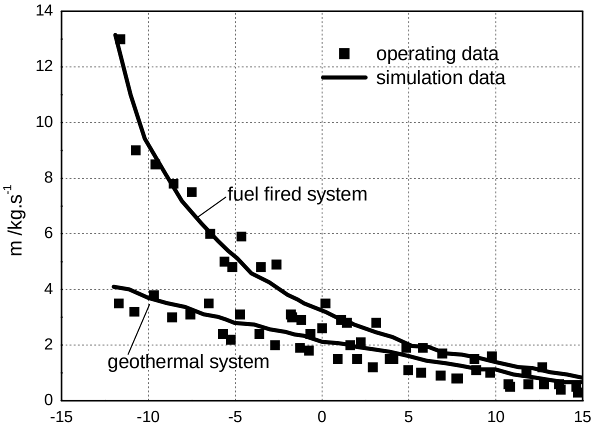

Figure 4: Comparison of mass flow of geothermal system and fuel fired system.

3. Figure 5 shows the relationship between pipe transmission effectiveness and outdoor temperature. As discussed above, heat load Q decrease as T_o increase, then m decrease. T_i and T_g are constant, so heat loss in the pipe is roughly constant, thus the lower m, the lower T_s, according to Eq. (7), pipe transmission effectiveness decrease with T_o increase. Scatter line is obtained by the calculation according to Eq. (7), T_s and T_1 were given by operating data of a geothermal system.

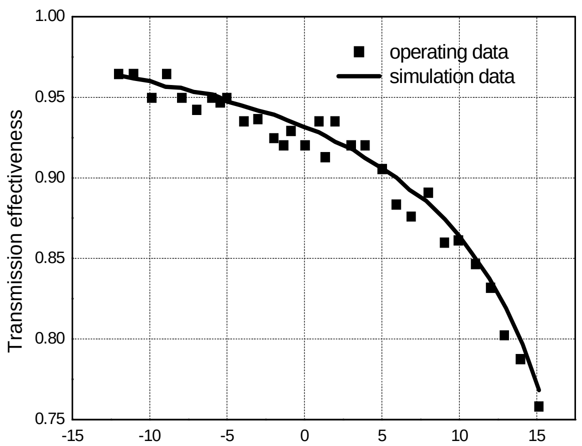

Figure 5: Pipeline transmission effectiveness with outdoor temperature.

<u>3.1.2 Dynamic Modeling</u>

In dynamic modeling, initial values for the mass flow m and for the indoor temperature T_i were guessed. The indoor temperature in the steady-state model is constant, but in the dynamic model it is calculated by the building cooling differential equation. Figure 6 to Figure 8 showed the results.

1) Figure 6 shows the curve of supply temperature, return temperature and outdoor temperature without mass flow limitation. Compared to Figure 3, temperature trend is the same, but T_s and T_i fluctuated much corresponding to the same T_o in dynamic model.

2) Figure 8 shows the comparison of different maximum mass flow for different radiator sizes. The maximum mass flow are 2.5 kg/s and 5 kg/s, and radiator size are 1, 2 and 3 times, respectively. From Figure 8, it can be seen that when the maximum mass flow is 2.5 kg/s, indoor temperature condition is bad despite increasing the radiator size, so this mass flow is too low. For the 5 kg/s maximum mass flow, 2 times radiator size is better than 1 time (baseline), therefore this is the preferable selection for the heating system.

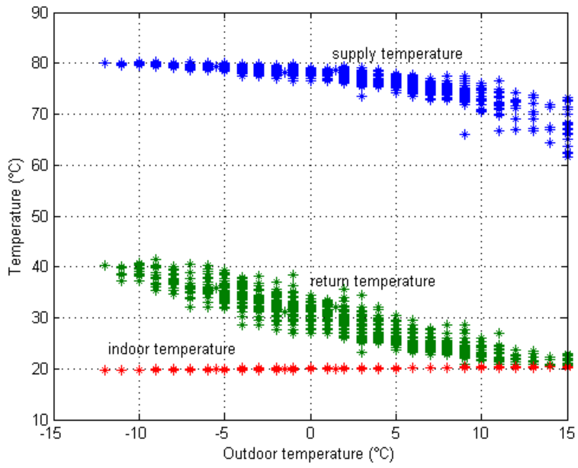

Figure 6: Temperature curve.

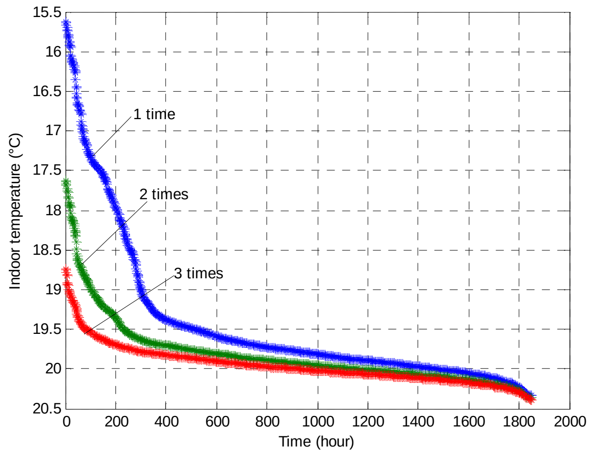

Figure 7: Indoor temperature for corresponding radiator size.

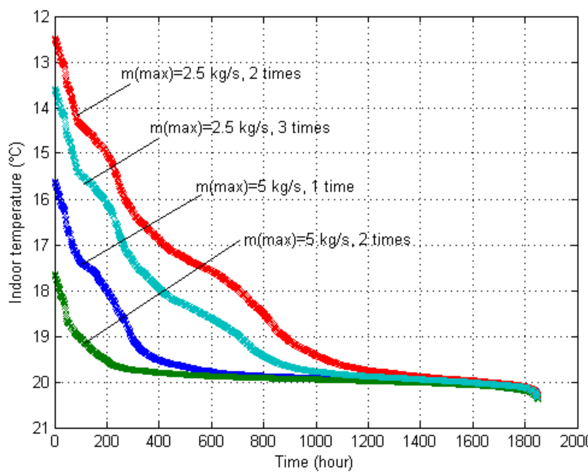

Figure 8: Comparison of mass flow for different radiator sizes.

3.2 Radiator Selection

Based on the heat output of radiators, suitable radiator sizes are given in Table 1 and Table 2.

Table 1: Influence of radiator size

Radiator size	T_r (°C)	m (kg.s^{-1})
2 times	59.8	8.2
3 times	52.5	6.6
4 times	47.0	5.8

Table 2: Radiator selection

Type	heat load (kW)	Output (W)	type
A	10.87	2805	22-60-C
B	11.75	3087	33-60-E
C	9.91	2524	22-60-C

4. NETWORK CALCULATION

As stated before, microscopic models can be used to describe the spatially distributed district heating system behavior. A simple district heating system, containing typical elements of such a system is shown in Figure 9. Numbers 1-10 are node numbers. Between the node numbers are mass flow in corresponding pipes. More detailed model of network can be found from Stevanovic (2007).

1) Conservation of mass
2) Conservation of momentum
3) Conservation of energy

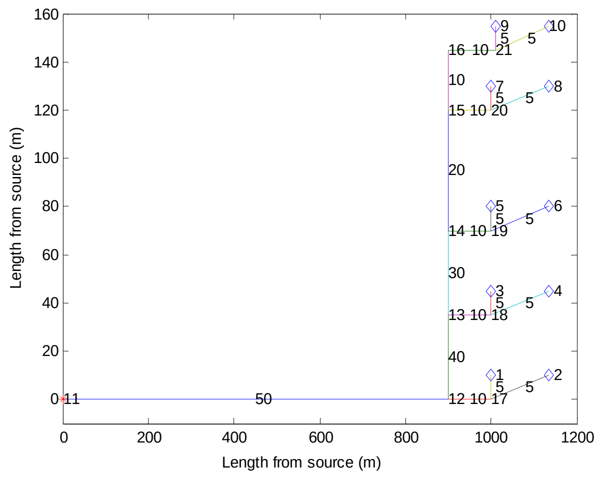

Figure 9: Scheme of sample district heating system network.

4.1 Cost Functions

The most common cost function is the monetary function, where investment and operating cost for the system are added. The investment cost is increasing with increasing pipe diameter, but the operating cost falls with increasing diameter. Pipe price calculation is shown in Tab.3. The district heating practice is to design for about 1 bar/km pressure loss.

4.2 dh/L Calculations

The hydraulic drop, dh/L is a common design parameter. If the hydraulic drop is high, then the investment in the pipe is well utilized, but the operating cost is high. On the other hand, if the hydraulic drop is low, the investment is badly utilized, but the pumping cost is low. The heat loss in a district heating pipe is higher for badly utilized pipes. The hydraulic drop is thus a good indicator of optimality, but not a real cost function.

4.3 Nodal Pressure

The pressure at the nodes is determined by the element pressure loss. If a target pressure loss per unit length is defined, a target nodal pressure is also defined. The voltage law of Kirchhoff places restrictions on this, because the pressure loss along any closed path has to sum up to zero, and makes it therefore impossible to obtain target pressure loss in all the elements.

In this paper, we focus on a network with a total pipe length of 4.6 km and serving 10 buildings. So-called h/L diagrams are presented here to show the network performance. On these diagrams, the nodal head is plotted as a function of the distance from the inlet point. The h/L diagram for the existing network is shown on Figure 10. A similar graph for the nodal temperature is shown on Figure 11. The network shown is the supply network with a total pipe length of 4.6 km. These figures show that both the head loss and the temperature drop are acceptable for the selected pipes in the network，and the pipe calculation was shown in Tab.3.

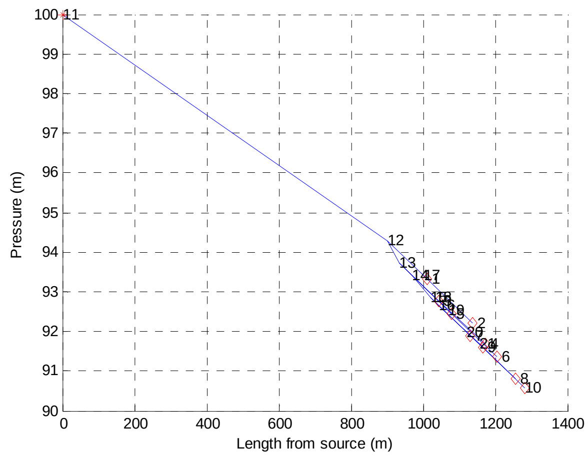

Figure 10: Pressure drop in network.

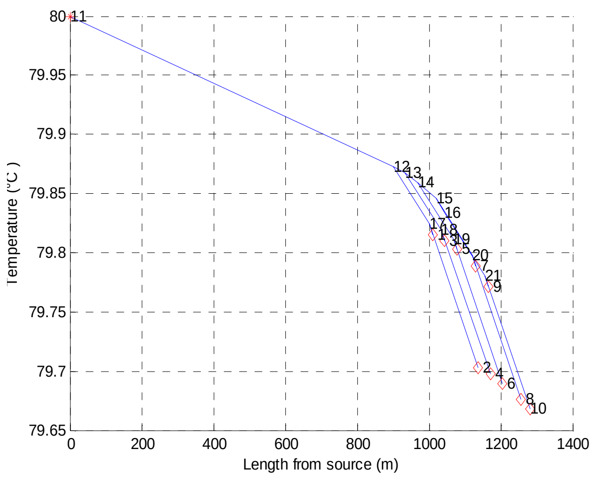

Figure 11: Temperature drop in network.

Table 3: Pipe calculation

Pipe	L (m)	m (kg.s-1)	Cost (EUR.m-1)	P (m)	T (°C)	Heat loss (W)	Price (EUR)
DN200	900	50	69.31	93.32	79.80	20924.59	62375.24
DN150	35	40	52.53	92.22	79.68	31.61	1838.69
DN150	35	30	52.53	92.77	79.79	31.86	1838.69
DN125	50	20	43.39	91.67	79.67	63.72	2169.30
DN100	25	10	37.29	92.44	79.78	14.62	932.18
DN100	100	10	37.29	91.35	79.66	234.02	3728.71
DN100	100	10	37.29	91.89	79.77	234.01	3728.71
DN100	100	10	37.29	90.80	79.65	233.99	3728.71
DN100	100	10	37.29	91.59	79.75	233.95	3728.71
DN100	110	10	29.66	90.58	79.64	283.03	3262.50
DN80	10	5	29.66	94.27	79.86	2.30	296.59
DN80	136	5	29.66	93.73	79.86	424.78	4033.63
DN80	10	5	29.66	93.40	79.85	2.30	296.59
DN80	136	5	29.66	92.85	79.83	424.76	4033.63
DN80	10	5	29.66	92.63	79.82	2.30	296.59
DN80	136	5	29.66	93.40	79.81	424.72	4033.63
DN80	10	5	29.66	92.85	79.80	2.30	296.59
DN80	136	5	29.66	92.53	79.79	424.65	4033.63
DN80	10	5	29.66	91.98	79.78	2.30	296.59
DN80	126	5	29.66	91.67	79.76	364.42	3737.04

5. CONCLUSIONS

This paper describes geothermal district hetaing in Tianjin. Calculation based on two kinds of methods for a sample building were done, two knids of simulation models were used and the results were analysed. In addition, a district heating network was set up, optimised, and the economical benefits were analysed. According to above, the following conclusions could be obtained.A steady state model was set up, optimised, and the economical benefits were analysed. According to above, the following conclusions could be obtained.

This paper describes geothermal district hetaing in Tianjin. Two types of simulation models were used and the results were analysed. A district heating network was set up and the economical benefits were analyzed. According to above, the following conclusions could be obtained.

1) A steady state model was set up to model district heating system, the results was validated by the operating data of one geothermal heating system, the two fit well.

2) A dynamic model was used to study heating system when maximum water flow is limited. For the sample building, 2.5 kg/s maximum mass flow is too small to maintain 20°C indoor temperature despite radiator size increased to double or triple. However, 5 kg/s maximum with double radiator size is preferable for indoor conditions.

3) Radiator size is an important parameter which affects the indoor temperature significally, increasing the radiator size to double or triple could improve the indoor temperature remarkably if maximum mass flow can not be changed.

4) District heating system can be controlled freely by dynamic model according to changing maximum mass flow and radiator size.

5) District heating network was set up, pressure and temperature drop of pipeline as well as pipe prices were calculated. The maximum pressure drop and temperature drop were 73 KPa/km and 0.3°C/km, respectively, which satisfy the simulation results.

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NOMENCLATURE

A	Heat transfer area, m^2;
C	Heat capacity of building, kJ/°C;
c_p	Water heat capacity, kJ/kg °C;
g	Acceleration due to gravity, m/s^2;
V	Volume flow of infiltrate air, m^3/h;
Q	Heat load, W;
Q_0	Heat load at reference conditions, W;
Q_{supp}	Heat supply, W;
Q_{loss}	Heat loss, W;
T_w	Wall surface temperature, °C;
T_i	Indoor temperature, °C;
T_o	Outdoor design temperature, °C;
T_1	Pipe inlet temperature, °C;
T_2	Return temperature at pumping station, °C;
T_{i_set}	Desired temperature in dynamic model, °C;
T_{i0}	Reference indoor temperature, °C;
T_{o0}	Reference outdoor temperature, °C;
T_{s0}	Reference supply temperature, °C;
T_{r0}	Reference return temperature, °C;
T_s	Water supply temperature, °C;
T_r	Water return temperature, °C;
T_g	Ground temperature, °C;
$\triangle T_m$	Logarithmic mean temperature difference, °C;
$\triangle T_{m0}$	Logarithmic mean temperature difference at reference conditions, °C;
y ,z	Variable;
k_l	Building heat loss factor, kW/°C;
k_p	P-control parameter, kg/s °C;
m	Water mass flow, kg/s;
m_o	Reference mass flow, kg/s;
m_{ave}	Average mass flow, kg/s;
τ	Pipe transmission effectiveness;
τ_0	Pipe transmission effectiveness at reference conditions.