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DISTRICT HEATING MODELLING AND SIMULATION

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ABSTRACT

Low and moderate geothermal resources are found in most areas of the world. In order to decrease air pollution and save conventional energy, geothermal energy as a heat source for district heating system have been used widely in China in recent years due to its cleanness and lower operating cost. This paper describes the geothermal resource and district heating system in Tianjin. Heat load for one sample building was calculated. Based on it, both geothermal heating and a fuel fired system using steady-state model and dynamic model were simulated, 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 show that radiator size affect the indoor temperature significantly, 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 because of 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.

1.1 Geothermal Fields and Wells

In Tianjin, there are 11 geothermal anomalous areas （Fig.1）that have been found and comprehensively researched so far, the total areas of which are on the order of 2000 km^2. All of them are typical medium- to low-temperature geothermal resources, and there are currently 239 geothermal wells in Tianjin, including 10 injection wells. Tab.1 gives basic information on some typical geothermal wells.

1.2 Cliamte

Air temperature affects the indoor temperature through heat conduction in the external walls, windows and through free and forced infiltration[1]. In order to obtain good simulation results, climate data should be used. Fig. 2 shows the outdoor temperature during one year in Tianjin[2].

Fig. 1: *Geothermal anomalies in Tianjin*

Tab. 1: Basic information on geothermal wells

No.	Depth (m)	T (°C)	Mass flow (kg/s)	Reservoir
HX-05	915	56	27.78	Nm
HD-22	1066	49	27.22	Nm
DL-26	1372	51	22.78	Nm
DL-16	1312	70	41.67	O
HX-10	1543	57	22.78	O
DG-08	1878	69	25.00	Ng
TG-02	2222	78	36.39	Ng
DL-14	1727	96	57.50	Є
HX-11	2010	92	43.06	Є
HX-25	1608	89	31.11	Jxw
DL-22	2546	94	48.89	Jxw
HD-12	3165	88	43.06	Jxw

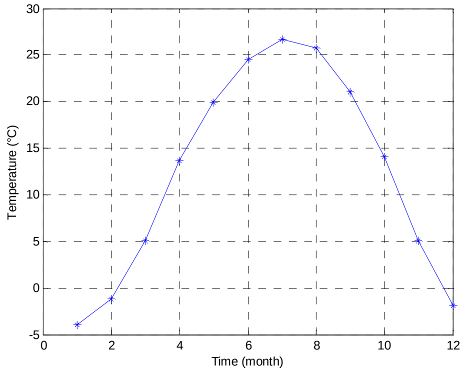

Fig 2: Monthly mean temperature in Tianjin

1.3 Sample building

Fig. 3: Sample building in Tianjin

Fig.3 shows a typical building in Tianjin, which has four flats of three types(A, B and C). Heat loss through building envelope and infiltration is 64.65 kW based on calculations of construction material properties[3][4][5].

2. BUILDING CALCULATION

2.1 Building heat load models

2.1.1 General

A district heating system consists of buildings, pipes, pump station and heat producing station. Heat can be produced from geothermal field or by combustion. In this chapter, district heating models are studied. Geothermal district heating systems are compared to existing fuel fired systems. The models which include steady-state model and dynamic model are programmed with Matlab.The signals used in district heating systems are summarized in Tab.2 [6][7].

Tab. 2: Main influencing signals

Input signals	Control signals	State signals	Output signals
Out door temperature	System water supply temperature	Indoor temperature Water quantity in storage	Water flow Return temperature System heat load

2.1.2 Weather Data

Fig. 4 shows the outdoor temperature duration curve (Y axis is inverted). It can be seen that outdoor temperature is below 15 °C for 3600 hours, or about 5 months. The data is recoded at a resolution of 1 °C.

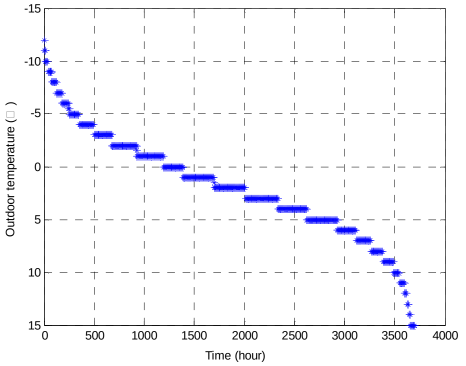

Fig. 4: Duration curve of outdoor temperature

2.1.3 Models

The models treated are macroscopic and physical. 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[8]. 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[9], the relative heat load of a radiator can be written as:

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

Where Q/Q_o =The ratio of the actual heat output from the radiator to the heat output at design conditions.

T_s =Water supply temperature (°C);

T_r =Water return temperature (°C);

T_i =Indoor temperature (°C);

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. In order to determin the radiator size, the following Equation is used.
The logarithmic mean temperature difference for radiator, ΔT_m (°C) is defined as:

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

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 = 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[8], 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 Equation 7 and 8, the transmission effectiveness, τ is obtained by:

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

Combining Equations 7 and 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 Equation 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:

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

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

2.2 Steady State Approach

In the steady-state model, buildings are assumed to be with no heat accumulation. Return temperature is calculated by combining Equations 4 and 6[10].

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

T_r is calculated with iteration from Equation 13. According to Valdimarsson[8], the fastest convergence is obtained, when T_r inside logarithm is calculated with:

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

Where z is:

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

When the outside temperature is given, T_i is assumed to be constant and supply temperature is available. Hence $T_{r,n+1}$ is obtained iteratively from Equation 14.
In the steady state-model, the heat loss from buildings is the same as the heat load supply, i.e.:

$$Q_{\sup p} = Q_{loss} \tag{15}$$

$$mC_p (T_s - T_r) = k_l (T_i - T_o) \tag{16}$$

Mass flow is obtained directly from Equation 16:

$$m = \frac{k_l (T_i - T_o)}{C_p (T_s - T_r)} \qquad (17)$$

Factor k_l can be calculated from the reference conditions

$$k_l = \frac{m_o C_p (T_{so} - T_{ro})}{T_{io} - T_{oo}} \qquad (18)$$

2.3 Dynamic approach

2.3.1 Return temperature calculation

In the steady-state model, Tr was found by combining Euqation 4 and 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 Equation 4 by an iteration loop:

$$T_{r,n+1} = (T_s - T_i).e^{-y} + T_i \qquad (19)$$

Where

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

2.3.2 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 Equation 20,

$$m = k_p (T_{i\_set} - T_i) + m_{ave} \qquad (20)$$

By differentiation of Equation 20

$$\frac{dm}{dt} = k_p . \frac{dT_i}{dt} \qquad (21)$$

T_i can be solved from 20:

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

Euqation 12 can be written as follows:

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

(23)

Combining Equation 21, 22 and 23, gives equation 24:

$$\frac{dm}{dt} = -\frac{k_p}{C} \left(C_p (T_s - T_r) + \frac{k_l}{k_p} \right) m - \frac{k_l k_p}{C} T_o + \frac{k_p k_l}{C} (T_{i-set} + \frac{m_{ave}}{k_p}) \qquad (24)$$

Equation 24 can also be written in a matrix form as:

$$\left[\frac{dm}{dt} \right] = \left[-\frac{k_p}{C} \left(C_p (T_s - T_r) + \frac{k_l}{k_p} \right) \right] m + \left[-\frac{k_l k_p}{C} \; \frac{k_l k_p}{C} \left(T_{i-set} + \frac{m_{ave}}{k_p} \right) \right] \begin{bmatrix} T_o \\ 1 \end{bmatrix} \qquad (25)$$

2.3.3 Heat exchangers

Heat exchangers transfer heat, Q from one flow stream to another, without mixing the fluids. There are elements with four connection points, as shown in Fig. 5:

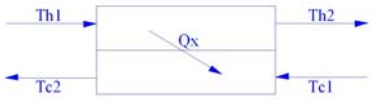

Fig. 5: schematic of a heat exchanger

Here: $$Q = m_h Cp(T_{h1} - T_{h2}) \qquad (26)$$

$$Q = m_c Cp(T_{c1} - T_{c2}) \qquad (27)$$

$$Q = UA\Delta T_m \qquad (28)$$

$$\Delta T_m = \frac{(T_{h1} - T_{c2}) - (T_{h2} - T_{c1})}{\ln \dfrac{T_{h1} - T_{c2}}{T_{h2} - T_{c1}}} \qquad (29)$$

In order to model the heat exchanger within the network, an equivalent model with two connection points has to be introduced. The equivalent heat transfer coefficient is associated with this simplification. This coefficient is non-linear and dependent on the fluid temperatures, so iteration is necessary for an exact thermal solution.

2.4 Reference values and constants

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

1) Supply water temperature $T_{s0} = 80$ °C;
2) Return water temperature $T_{r0} = 40$ °C;
3) Indoor temperature $T_{i0} = 20$ °C.

Common reference values used for a fuel fired network are:

1) Supply water temperature for network

$T_{s0} = 90$ °C

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

3) Indoor temperature $T_{i0} = 20$ °C

The reference outside temperature depends on the local climate. The reference value used for Tianjin is $T_{oo} = -9$ °C was used here both for the geothermal and the fuel fired systems. Ground temperature was assumed to be constant at 14.2 °C. The reference water mass flow of water here was assumed to be 5 kg/s. The specific heat capacity of water assumed to be constant, which is, $C_p = 4.186$ kJ/(kg°C). The P-control parameter $kp = 4.5$ kg/(s°C). Finally, the heat capacity of buildings is calculated as 6.25 × 10^6kJ/°C.

3. SIMULATION OF HEATING SYSTEM

The models described above were progarmmed with Matlab, and some Figures were plotted and analysed for the steady-state model and dynamic model, respectively.

3.1 Simulation results

3.1.1 Steady-state modelling

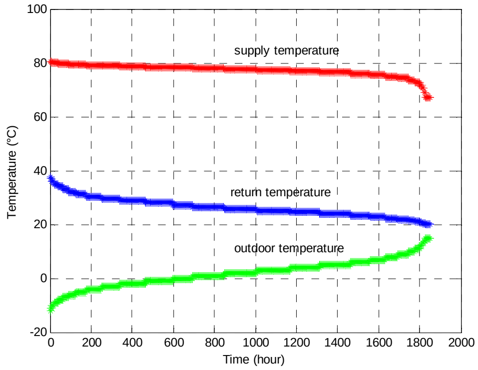

Fig. 6 Duration curve of temperature

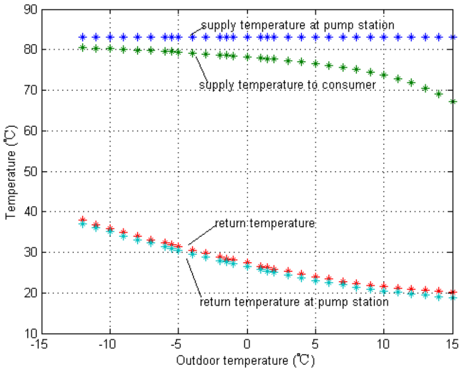

Fig. 7 Temperature in a geothermal heating system, heat loss in pipe included

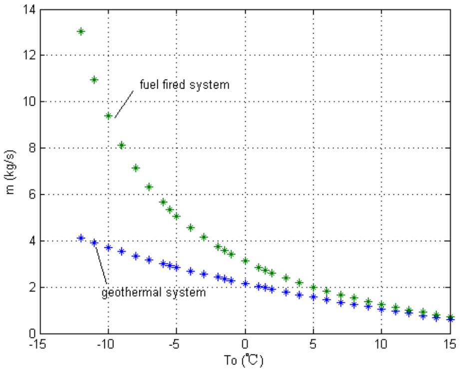

Fig. 8 Comparison of mass flow of geothermal system and fuel fired system

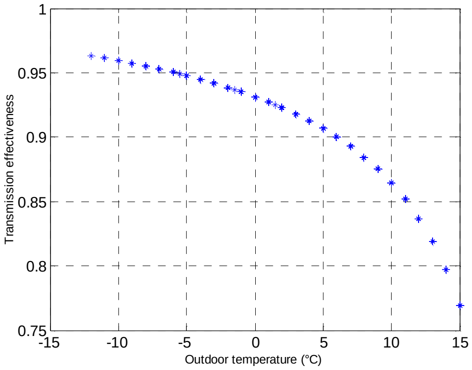

Fig. 9 Pipe transmission effectiveness with outdoor temperature

1) Fig. 6 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 equation 13, Q drop as T_o increase, thus logarithmic mean temperature difference drop, m decrease, which induce more temperature drop in the network, Ts drops a little bit, so T_r decrease, if Ts drops very much, then T_r will increase.

2) Fig.7 shows the temperature in the different locations of the network. Similar to Fig. 6, T_s and T_r decreases as T_o increases. In addition, there is temperature drop between T1 and Ts, which is because there is heat loss in the pipe.

3) Fig. 8 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, respectively. Temperature difference of the former is bigger than that of the latter, according to equation 3, mass flow of the geothermal system is less than that of the fuel-fired system.

4) Fig. 9 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 equation 7, pipe transmission effectiveness decrease with T_o increase.

3.1.2 Dynamic modelling

In dynamic modelling, 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. Fig. 10 to Fig.13 show the results.

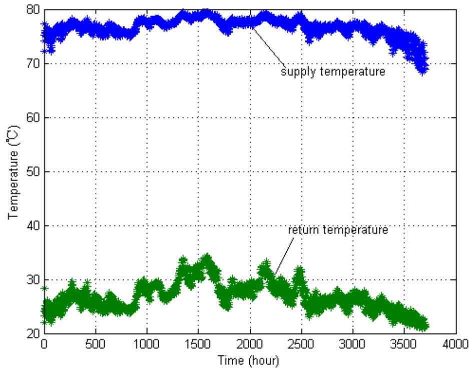

Fig. 10 Supply temperature and return temperature for the dynamic model

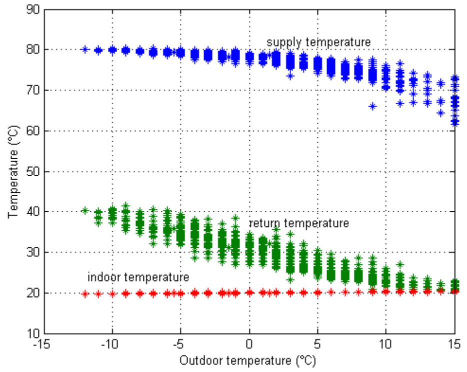

Fig. 11 Supply, return and indoor temperature as a function of outdoor temperature

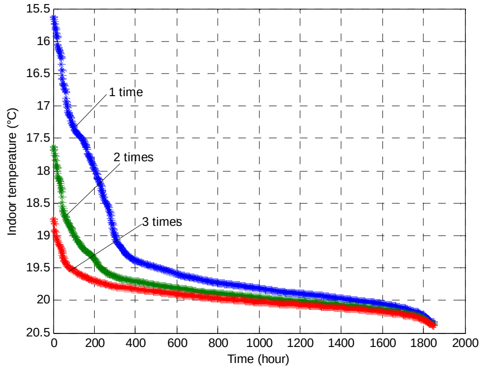

Fig. 12 Duration curve of indoor temperature for different maximum mass flow and radiator sizes

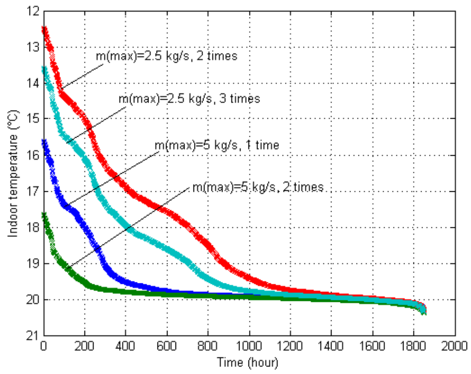

Fig. 13 Comparison of different maximum mass flow for different radiator sizes

1) Fig.10 shows the supply temperature and return temperature without mass flow limitation. The temperature difference between supply and return temperature is big in the geothermal system, the average temperature difference is about 48°C. Therefore, for the existing radiator, return temperature should be reduced as possible in order to maintain the desired indoor temperature.
2) Fig. 11 shows the curve of supply temperature, return temperature and outdoor temperature without mass flow limitation. Compared to Fig.6, temperature trend is the same, but T_s and T_i fluctuated much corresponding to the same T_o in dynamic model.
3) Fig. 12 shows the duration curve of indoor temperature for different radiator sizes. In Figure 12, k_p=25 (kg/s °C), $m_{\_max}$=5 kg/s, and for the original radiator size, there are 400 hours during the heating period that the indoor temperature is less than 19.5 °C. If radiator size is doubled, indoor temperature conditions become better. So when the maximum mass flow is limited, increasing the radiator size can reduce indoor temperature drop-in significantly. If the maximum mass flow is changed, the indoor temperature changed correspondingly, it is obvious that radiator size is an important parameter for the district heating system. Tab.3 shows the return temperature corresponding to the different radiator sizes, at design condition.
4) Fig.13 shows the comparison of different maximum mass flow for different radiator sizes. The maximum are 2.5 kg/s and 5 kg/s, and radiator size are 1 , 2 and 3 times, respectively. From Fig.14, 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.

3.2 Radiator selection

Based on the heat output of radiators, suitable radiator sizes are given in Tab.3 and Tab.4.

Tab. 3 Influence of radiator size on return temperature and mass flow

Radiator size times	T^r (°C)	m (kg/s)
2	59.8	8.2
3	52.5	6.6
4	47.0	5.8

Tab. 4 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

As stated before, microscopic models can be used to describe the spatially distributed district heating system behavior. The goal of developing such models is to be able to calculate the water flow, pressure and temperature in all pipes of the system as a function of time. Network theory provides convenient ways of determining the flow in a given network. The thermal state of network can then be calculated from the flow solution. According to Valdimarsson[8], for modeling of district heating network these basic laws have to be fulfilled:

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

A simple district heating system, containing typical elements of such a system is shown in Fig.15. Numbers 1-10 are node numbers. Between the node number are mass flow in corresponding pipes. More detailed model of network can be found from Frederiksen[6].

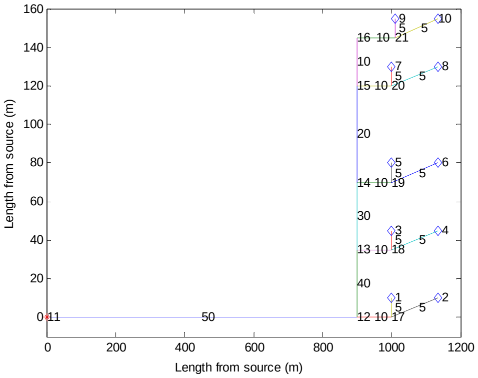

Fig 14: Scheme of sample district heating system network

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 (at least the pumping cost). Pipe price calculation is shown in Table 22. The district heating practice is to design for about 1 bar/km pressure loss.

4.2 dh/L calculations

The pressure loss per unitary length, dh/L is a common design parameter. If the pressure loss is high, then the investment in the pipe is well utilized, but the operating cost is high. On the other hand, if the pressure loss 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 pressure loss per unit length 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.

If the nodal pressure is considered an independent variable, the pressure loss per unit length can be calculated for all 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 19. A similar graph for the nodal temperature is shown on Figure 20. The network shown is the supply network with a total pipe length of 4.6 km. The return network has similar topology, but the opposite flow direction, and is not treated in this paper. These figures show that both the head loss and the temperature drop are acceptable for the selected pipes in the network.

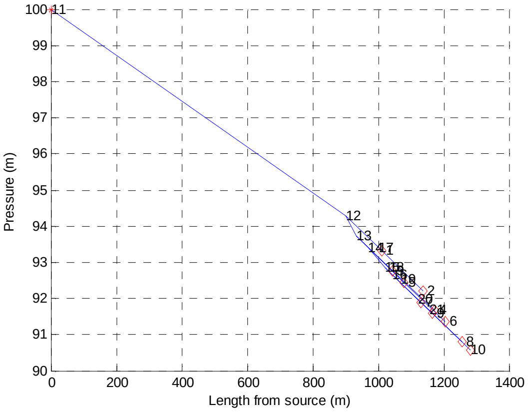

Fig. 15: Pressure drop in network

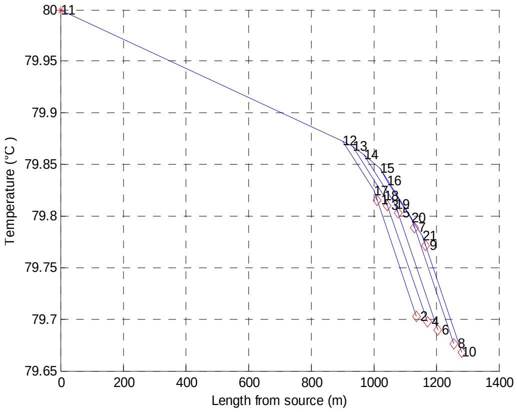

Fig. 16: Temperature drop in network

Tab.5: Pipe calculation

Name	node	node	L (m)	M (kg/s)	Std. D (m)	Cost (EUR/	P (m)	T (°C)	Total (W)	Total EUR
DN200	11	12	900	50	0.2101	69.31	93.32	79.8	20924.59	62375.2
DN150	12	13	35	40	0.1603	52.53	92.22	79.6	31.61	1838.69
DN150	13	14	35	30	0.1603	52.53	92.77	79.7	31.86	1838.69
DN125	14	15	50	20	0.1325	43.39	91.67	79.6	63.72	2169.30
DN100	15	16	25	10	0.1071	37.29	92.44	79.7	14.62	932.18
DN100	12	17	100	10	0.1071	37.29	91.35	79.6	234.02	3728.71
DN100	13	18	100	10	0.1071	37.29	91.89	79.7	234.01	3728.71
DN100	14	19	100	10	0.1071	37.29	90.80	79.6	233.99	3728.71
DN100	15	20	100	10	0.1071	37.29	91.59	79.7	233.95	3728.71
DN100	16	21	110	10	0.1071	29.66	90.58	79.6	283.03	3262.50
DN80	17	1	10	5	0.0825	29.66	94.27	79.8	2.30	296.59
DN80	17	2	136	5	0.0825	29.66	93.73	79.8	424.78	4033.63
DN80	18	3	10	5	0.0825	29.66	93.40	79.8	2.30	296.59
DN80	18	4	136	5	0.0825	29.66	92.85	79.8	424.76	4033.63
DN80	19	5	10	5	0.0825	29.66	92.63	79.8	2.30	296.59
DN80	19	6	136	5	0.0825	29.66	93.40	79.8	424.72	4033.63
DN80	20	7	10	5	0.0825	29.66	92.85	79.8	2.30	296.59
DN80	20	8	136	5	0.0825	29.66	92.53	79.7	424.65	4033.63
DN80	21	9	10	5	0.0825	29.66	91.98	79.7	2.30	296.59
DN80	21	10	126	5	0.0825	29.66	91.67	79.7	364.42	3737.04
Total price										108685.

4. 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.

A steady state model was used to obtain the district heating system characteristic curves.

A dynamic model was used to study the system when maximum water flow is limited. For the sample building in this report, 2.5 kg/s maximum mass flow is too small to maintain the indoor temperature at around 20 °C despite increasing the radiator size to double or triple, so it is not advisable way. However, 5 kg/s maximum with a double radiator size is preferable for the district heating system.

Radiator size is an important parameter that affect the indoor temperature significally, increasing the radiator sizeto 2 or 3 times can improve the indoor temperature remarkably if maximum mass flow can not be changed.

Dynamic simulation model is a powerful tool to study the system performance, as the heating system can be controlled freely by controlling the maximum mass flow and radiator size.

District heating network was set up, and pressure drop, and temperature drop of pipeline with pipe prices calculated. The maximum pressure drop and temperature drop were 0.73 bar/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);

U =Heat transfer coefficient (W/m^2 °C);

Cp =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_o =Heat load at reference conditions (W);

$Q_{\sup p}$ =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_{io} =Reference indoor temperature (°C);

T_{oo} =Reference outdoor temperature (°C);

T_{so} =Reference supply temperature (°C);

T_{ro} =Reference return temperature (°C);

T_s =Water supply temperature (°C);

T_r =Water return temperature (°C);

T_{c1} =Cold fluid inlet temperature (°C);

T_{c2} =Cold fluid outlet temperature (°C);

T_g =Ground temperature (°C);

T_{h1} =Hot fluid inlet temperature (°C);

T_{h2} =Hot fluid outlet temperature (°C);

ΔT_m =Logarithmic mean temperature difference (°C);

ΔT_{mo}= Referencelogarithmic mean temperature (°C);

y =Variable;

z =Variable;

kl =Building heat loss factor (kW/°C);

kp =P-control parameter (kg/s °C);

m =Water mass flow (kg/s);

mo =Reference mass flow (kg/s);

m_{ave} =Average mass flow (kg/s);

τ =Pipe transmission effectiveness;

τ_o =Reference Pipe transmission effectiveness;

U_{eq} =Heat exchanger transfer matrix (W/°C).