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DESIGN AND OPERATION OF GEOTHERMAL FLOOR HEATING SYSTEM IN TIANJIN, CHINA

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ABSTRACT

Geothermal energy is increasingly used as a heat source for district heating systems in China. It is clean and has a lower operating cost. A geothermal floor heating system has an advantage over other heating systems because it lowers the discharge water temperature, so it can fully use the geothermal energy. Floor heating systems using geothermal energy have become very popular in Tianjin, China. This paper describes the geothermal resource and floor heating systems, specifically for buildings and conditions in Tianjin. Heat loss of a simple and typical building is calculated using Chinese codes. Using these values, the heat load of floor heating systems is determined. The paper also presents the design methods for pipe loops. Steady-state models are simulated for the different types of systems in China and Iceland, obtaining the operational parameters relative to outdoor temperatures. Applying these parameters, it is beneficial to optimize system controls in order to adjust the geothermal floor heating system effectively and conserve the geothermal resource, as also described in the paper.

1. INTRODUCTION

1.1 Geothermal energy resources in Tianjin

Geothermal energy is abundant in Tianjin in China (Figure 1). There are 10 geothermal areas that have been found and comprehensively researched so far (Wang Kun, 2008). The temperature gradient of the Tianjin geothermal fields is 35-88°C/km. These fields have been developed and used for district heating in recent years because of their suitable temperature (70-90°C); district heating represents 63% of the total geothermal energy used. All of these fields are typical medium- to low-temperature geothermal resources. The sedimentary geothermal reservoirs are 500-2000 m deep and the temperature ranges from 30 to 78°C, with a maximum temperature of 98°C.

1.2 Geothermal district heating

Tianjin is one of the biggest cities located in northern China. The annual mean temperature of Tianjin is 12.3°C, and the average temperature is -0.9°C during the 122 day heating period. The energy

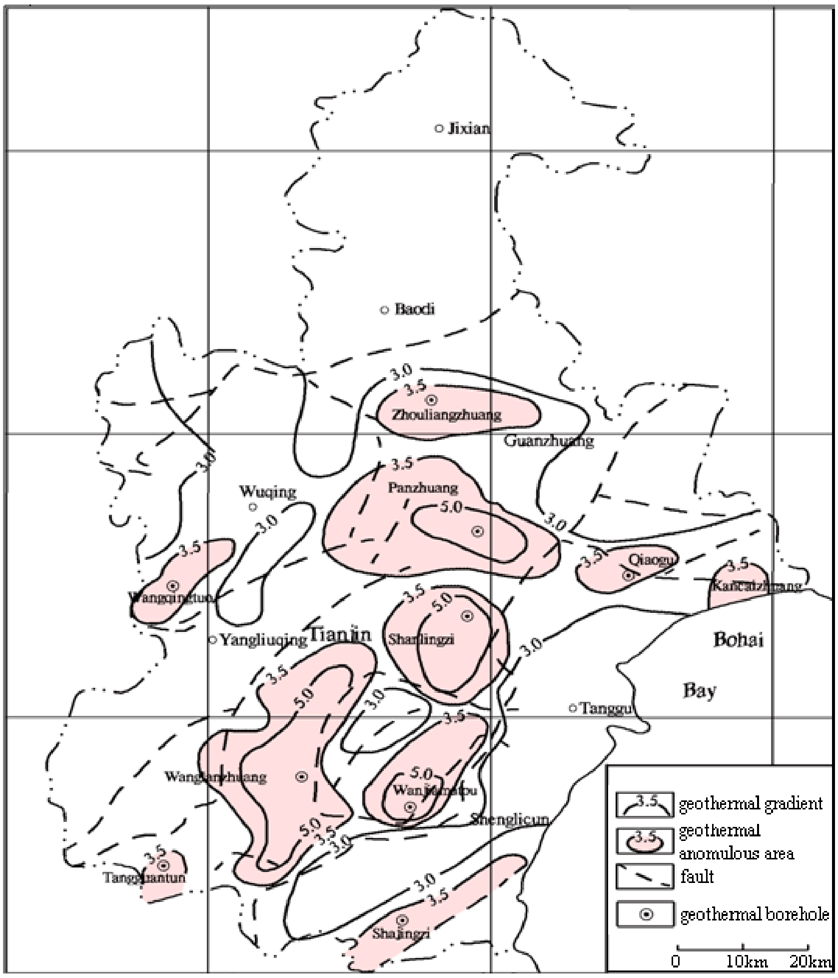

FIGURE 1: Distribution of geothermal fields in Tianjin

consumption of space heating covers 20% of the total energy use. Coal is the major energy resource used for heating in Tianjin; others used are natural gas, oil and geothermal energy. Geothermal energy is the encouraged resource for replacing fossil energy. Geothermal energy in Tianjin plays an important role in the supply of energy, the alleviation of environmental pollution and in general improving the quality of life. Geothermal energy has more advantages: compactness of its heat supply station, lower operating cost, and high efficiency in its comprehensive utilisation, with a quick capital cost return. In addition, geothermal water has stable heat output, which is beneficial for the effective control and regulation of the system.

In contrast to conventional heat sources, geothermal energy has a fixed temperature, which cannot be controlled by the district heating system operator. For geothermal water quality in Tianjin, a plate heat exchanger is often adopted to transfer the heat from the geothermal water to the circulation water. To fully use the geothermal energy, the waste geothermal water temperature is expected to be lower than 35°C. According to these factors, designers are required to choose suitable equipment that can be effectively used in lower temperature ranges. Floor heating is one of the best choices for such utilization.

1.3 Geothermal floor heating

Laying hot water pipe into the floor, walls and roof in order to heat a room is known as radiant heating. This method has a long history but is now used more widely. It has many advantages. Human perception of radiant-heat is more comfortable than that of convection heat. Because the body's blood circulation in the foot is worse than in the head, elevating the temperature felt by feet is conducive to blood circulation. Floor heating can save a lot of energy when compared to traditional convection heating. There are two main reasons. Firstly, the demand of supply water temperature is relative low; the suitable temperature range is wide, 30-60°C. So the use of low-temperature geothermal energy makes sense and can lower the discharge water temperature. Secondly, the whole floor is used as a heat delivery surface. It is possible to use such a low-temperature heat source though the surface temperature is low. The heat transfer will be sufficient as the heat transfer surface is much larger than that of a traditional radiator. So a small difference in supply and return water temperature can satisfy the heat load of buildings. In addition, floor heating saves room space to increase the area for indoor activities.

Although floor heating has the above advantages, there are also disadvantages: the pipe loops need higher security requirements, and the event of a leak or plug maintenance can prove to be inconvenient.

2. HEAT LOSS OF BUILDINGS

The heat load of a building should equal the heat loss under design parameter conditions. It mainly consists of the following components:

1. Heat loss through building surroundings;
2. Heat loss by infiltration;
3. Heat load due to inflow of cold air when opening doors.

Other components such as radiation from the sun, illumination, human body heat and devices are neglected, because these heat loads are much smaller than the three mentioned above and because they are temporary and unstable. The design criteria cover the worst case.

2.1 Background of sample building

The sample building is a traditional apartment building in Tianjin. It has six stories and each story has two individual apartments, as shown in Figure 2. Each apartment's area is 63 m^2; the total building area is 2500 m^2. Table 1 gives surrounding areas for each room of one apartment.

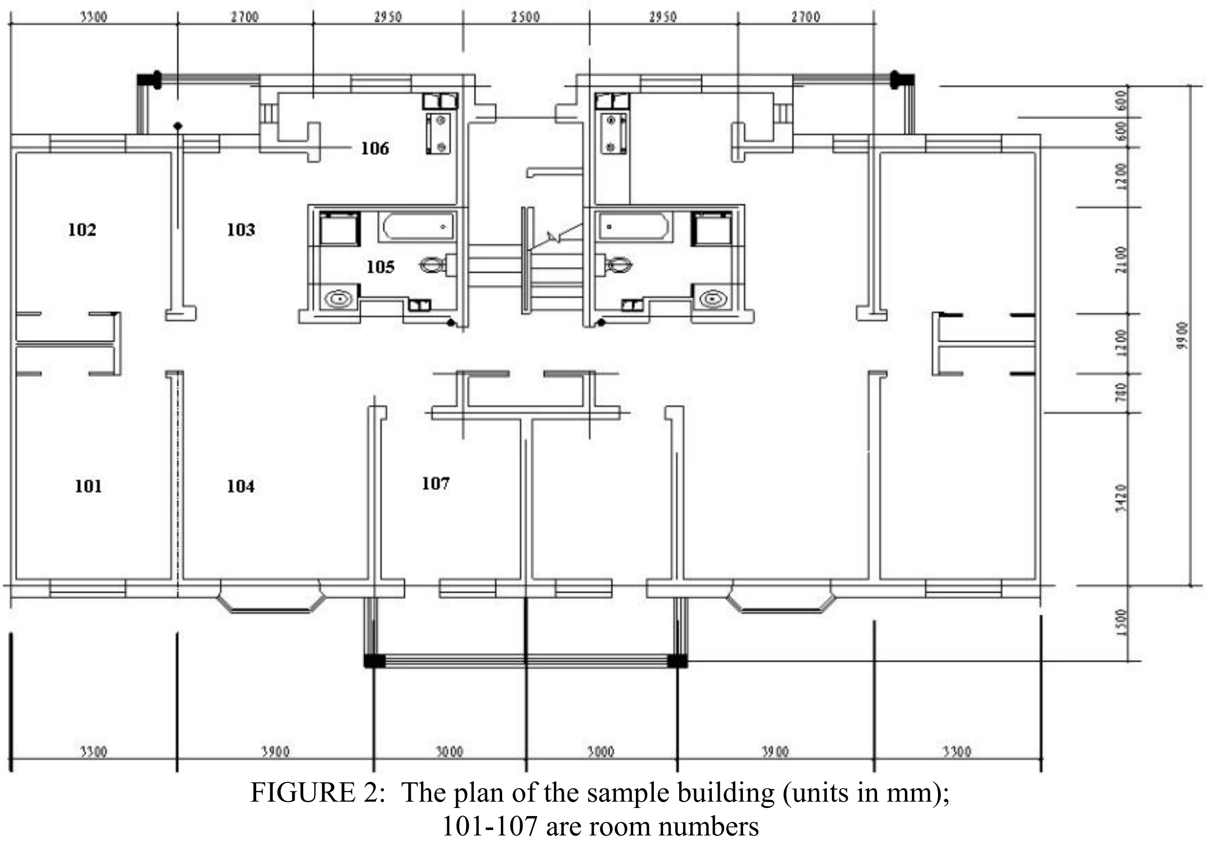

FIGURE 2: The plan of the sample building (units in mm);
101-107 are room numbers

TABLE 1: Surrounding areas of one apartment

Room no.	**Room type**	**Room area (m^2)**	**Surroundings**		
			Name	**Orientation**	**Area (m^2)**
101	Bedroom	14.14	Outer wall	Western	13.44
				Southern	6.54
			Outer window	Southern	2.7
102	Bedroom	11.38	Outer wall	Western	10.92
				Northern	6.99
			Outer window	Northern	2.25
103	Dining room	7.82	Outer wall	Northern	3.02
			Outer door	Northern	3.60
			Inner wall	-	1.68
104	Living room	11.60	Outer wall	Southern	6.60
			Outer door	Southern	4.32
105	Bathroom	2.67	Inner wall	-	2.67
106	Kitchen	5.85	Outer wall	Northern	6.46
			Outer window	Northern	1.80
			Inner wall	-	2.67
			Inner door	-	1.68
107	Bedroom	8.78	Outer wall	Southern	4.08
			Outer door	Southern	4.32

2.2 Heat losses through building surroundings

In winter the outer air temperature is lower than the indoor temperature, heat will transfer from indoors to outdoors through the walls and roof of the building. In addition to the temperature difference, the building direction, wind speed, building height and cool infiltration air also influence the heat load. So we can calculate the basic heat loss through the walls and then, based on the condition of the building, revise the heat values.

2.2.1 Basic heat loss through walls

The basic heat losses are determined by wall areas, material and temperature differences between the inner door and outer door, according to Equation 1:

$$Q_1 = \alpha F U (t_i - t_o) \tag{1}$$

where Q_1 = Basic heat load transfer through building walls (W);
α = Correction factor for temperature difference;
F = Area surrounding building (m^2);
U = Total heat transfer coefficient of building surrounding (W/(m^2 °C));
t_i = Calculated indoor temperature (°C);
t_o = Calculated outdoor temperature (°C).

As some rooms' surroundings are not totally exposed to outdoor air, a correctional factor of temperature difference should be incorporated. For outer walls, windows and doors α is equal to 1.0, but for inner walls that are adjacent to an unheated room, α=0.7.

U is the parameter describing heat transfer between the building and its environment due to conduction, convection and radiation. The reciprocal of U is heat resistance of surroundings R. R can be calculated by the following formula:

$$U = \frac{1}{R} = \left(\frac{1}{\alpha_i} + \sum_i \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_o} \right)^{-1} \tag{2}$$

where α_i = The convention heat transfer coefficient between indoor air and inner surface of walls (W/ (m^2 ·°C));

α_o = The convention heat transfer coefficient between outdoor air and outer surface of walls (W/(m^2 ·°C));

i = Layers of multiple building surroundings;

λ_i = The thermal conductivity of i layer surroundings (W/(m°C));

δ_i = Thickness of i layer surroundings (m).

Table 2 gives the walls and roof materials, thickness and thermal parameters. Based on these values, the heat transfer coefficients α_i and α_o and the total heat transfer coefficient, K are obtained; for the inner surface α_i is 8.72 W/(m^2 °C) and for the outer surface α_o is 23.26 W/(m^2 °C).

TABLE 2: Building walls and roof parameters

Surrounding type	Material of layers	Thickness (mm)	Thermal conductivity (W/(m°C))
Outer wall	1:3 cement mortar	12	0.93
	Insulation mortar	60	0.29
	Moisture proof mortar	17	0.93
	Brick	370	0.81
	1:2.5 cement mortar	6	0.93
Inner wall	1:2.5 cement mortar	6	0.93
	Moisture proof mortar	17	0.93
	Brick	240	0.81
	1:2.5 cement mortar	6	0.93
Roof	Insulation	100	0.04
	Moisture proof	20	0.1

So the total heat transfer coefficient of building surroundings can be calculated from Formula 2. For example, the total heat transfer coefficient of outer wall U_{ow} is calculated as follows:

$$U_{ow} = \frac{1}{R_{ow}} = \frac{1}{\frac{1}{23.26} + \frac{0.37}{0.81} + \frac{0.06}{0.29} + \frac{0.033}{0.93} + \frac{1}{8.72}} = 1.184\, W/m^2 {}^\circ C$$

And in the same way, the inner wall's U_{iw} is 1.79 W/(m^2 °C); and U_f of the roof is 0.35 W/(m^2 °C)). The total heat transfer coefficient of doors and windows is shown in Table 3.

According to design codes, the outer door calculation temperature t_o is the mean temperature of a day that only allows 5 days to be colder during one year, based on a statistical average that covers many years. In Tianjin this temperature is -9°C.

TABLE 3: *U* values of doors and windows

Surrounding type	Style and material	*K* (W/(m^2 °C))
Outer windows	Double glazing, plastic-steel	2.8
Apartment door	Insulation, steel	2.33
Roof windows	Double glazing, PVC	2.58
Inner door	Single layer, wood	2.91

The indoor calculated temperature t_i is within the range at which people feel comfortable; during winter time this is 16-24°C. And it is relative to the type of building and room purpose. For this paper, the indoor temperatures were determined as shown in Table 4 (Lu Yaoqing, 2002).

TABLE 4: Calculated indoor temperature of rooms

Use of room	Bedroom	Dining room	Living room	Kitchen	Bathroom
t_i (°C)	18	18	18	13	18

According to Formula 1, the basic heat loss of the surroundings can be calculated. For example, the basic heat loss of the southern wall of room 101 is:

$$Q_1 = 1.0 \times 6.64 \times 1.18 \times (18 - (-9)) = 211.6\,W$$

2.2.2 Heat loss by infiltration

Infiltration is the leakage of outside air into the house through cracks around the windows and doors. The amount of the infiltration depends mainly on the tightness of windows and doors and on the outside wind velocity or the pressure difference between the outside and inside. Two methods can be used to estimate the volume of infiltrating air into the heating area: the crack length method and the air change method.

1) Crack length method
The basis of this method is the perimeter of windows and doors, according to the following equation:

$$V = \sum lLn \tag{3}$$

where V = Volume flow of infiltrating air (m^3/h);
l = The total length of the crack (m);
L = Infiltration air volume through windows and doors per metre (m^3/ (m·h));
n = Correction factor of infiltration for different directions.

2) Air change method
Using the air change method to determine V (m^3/h) gives:

$$V = nV_h \tag{4}$$

where n = Air change times per hour, usually 0.5-1.0 times/hour;
V_h = Room volume (m^3).

This method is based on the air volume in a space being replaced by outside air so many times per hour. This method is used here for calculating the infiltration. The Chinese heating codes recommend 0.5-1.0 air changes per hour for residential buildings. One air change per hour is used in this paper and can be calculated in W according to:

$$Q_2 = 0.278 c_{pa} V \rho_a (t_i - t_o) \tag{5}$$

where Q_2 = Heat loss by infiltration (W);
C_{pa} = Specific heat of air, 1.0056 kJ/kg;
V = Volume flow of infiltrating air (m^3/h);
ρ_a = Air density at the temperature T_o, 1.32 kg/m^3.

From Equation 5, for the southern outer windows of room 101, the infiltration heat loss is:

$$n = 0.5$$
$$V = 0.5 \times (4.8 - 0.18) \times (3.3 - 0.24) \times 2.3 = 16.26\ m^3$$
$$Q_2 = 0.278 \times 1.0056 \times 0.5 \times 16.26 \times 1.32 \times (18 + 9) = 161.1\ W$$

2.2.3 Heat load due to inflow of cold air when opening doors and windows

The heat load due to an inrush of air is the heat lost when cold air flows in and replaces warmer air as doors or windows are temporarily opened. The method for calculating this loss is to use the basic heat loss from windows and doors using a multiplication factor, as shown in Formula 6:

$$Q_3 = 65\% N Q_{1d} \tag{6}$$

where Q_3 = Heat loss due to inrushing air (W);
N = Number of stories;
$Q_{1\cdot d}$ = The basic heat lost through a closed outer door (W).

The basic heat loss of the apartment outer door is:

$$Q_{1d} = 2 \times 2.3 \times (10 + 9) = 87.4\ W$$

The additional heat load of inrushing air from outer doors is calculated as:

$$Q_3 = 87.4 \times 6 \times 0.65 = 340.8\ W$$

2.2.4 Additional heat loss through building walls and roof

Additional heat loss is determined by its percentage of the basic heat loss. There are three types of additional heat loss:

1) Orientation (β_o)
Additional percentages differ according to the wall orientation (Table 5):

TABLE 5: Additional orientation percentages

Orientation	Percentage (%)
Northern, Northeastern, Northwestern	0 – 10
Eastern, Western	-5
Southeastern, Southwestern	-10 – -15
Southern	-15 – -30

2) Wind (β_w)
Buildings on the highlands, the shore, in the wilderness or especially high constructions need to consider the influence of wind. Vertical building walls will have 5% additional wind percentage.

3) Height (β_h)
When the height of a room is more than 4 m, with every increase in height of 1 m, the total heat loss should be increased by 2% of the basic heat loss. In this case, the height of all rooms is less than 4 m, so it is not necessary to revise this heat loss.

Then the total heat loss Q_l of every room can be obtained as:

$$Q_l = Q_1(1 + \beta_o + \beta_w + \beta_h) + Q_2 + Q_3$$

The results can be seen in Appendix I.

3. HEAT LOOPS DESIGN OF FLOOR HEATING SYSTEM

3.1 Heat load of floor heating system

In order to calculate the heat load of the system, we should calculate the heat loss of buildings. In a radiator system, the heat loss is equal to the system's heat load. But in floor heating systems there are two different aspects:

1) The heat loss of ground which is heated by pipe loops should not be reckoned in the heat load.
2) The heat load of a floor heating system is 90-95% of the building heat loss. Then the floor heating additional factor β_f is -10 – -5%.

For heat metering residences, in view of intermittent heating and heat transfer between residential units, an additional heat load should be added to the total heat load. When the heated pipe loop is used, only part of a room is heated while the other part of the room is not; the total heat load is converted using the multiplying factor in Table 6. If the depth of a room is larger than 6 m, it should be divided into individual rooms to calculate the heat load and design pipe loop.

TABLE 6: Factors for local floor heating

Ratio of heating area to building area	>0.80	0.55	0.40	0.25	<0.20
Calculated factor	1	0.72	0.54	0.38	0.30

3.2 Floor heating pipe loops design

3.2.1 Heat release of pipe loops

Heat release of pipe loops involves the effective heat transfer to the room and the heat loss transfer to a lower layer (including the heat loss transfer from the ground floor to the soil); the following factors should be considered:

1) The effective heat release Q_e of every vertical neighbouring room, except the top floor room, is the difference between the heat load of room Q and heat transfer from the upper layer Q_u.
2) The heat supply of the heating system Q is the total value of the effective heat release Q_e and heat loss transfer to the lower layer Q_d.

The heated pipe loops heat the floor surface which then transfers heat to the inner air by radiation and convection. So the heat load is also obtained by:

$$q = q_r + q_c \tag{7}$$

where q = Heat load per building area (W/m^2);
q_r = Radiation heat transfer per building area (W/m^2);
q_c = Convection heat transfer per building area (W/m^2).

The radiation heat is calculated as follows:

$$q_r = 5\times10^{-8}\left[(t_{avre}+273)^4-(t_{aust}+273)^4\right] \tag{8}$$

where t_{avre} = Average temperature of heated floor surface (°C);
t_{aust} = Weighted average temperature of unheated surfaces in the room (°C).

The weighted average temperature is approximately the inner air temperature. And then convection heat transfer is defined as (ASHRAE, 2000):

$$q_c = m(t_{avre} - t_i)^n \tag{9}$$

where m = Constant, when heat transfers to the upper layer, m=2.13; when heat transfers to the lower layer, m=0.14;
n = Index, when heat transfers to the upper layer, n=1.31; when heat transfers to the lower layer, n=1.25.

For Formulae 8 and 9, the average temperature of the heated floor surface t_{avre} is needed when calculating q_r and q_c. The average temperature of the heated floor surface is relative to the effective heat release Q_e, inner calculated temperature t_i and effective heat release area of the floor A_e. A_e is the product of the floor area and correction coefficient, considering the influence of furniture and other coverings on the floor. There is an empirical formula for t_{avre}:

$$t_{avre} = t_i + 9.82\left(\frac{Q_e}{100A_h}\right)^{0.969} \tag{10}$$

By analysing the heat release from pipe loops, the effective heat release Q_e, heat loss transfer to the lower layer Q_d and average temperature of heated floor surface t_{avre} are obtained. Q_e is the sum of radiation heat Q_r and the convection heat transfers to the upper layer Q_u. Heat loss transfer to the lower layer Q_d is equal to the convection heat transfers to the lower layer. Apart from heat release, the average temperature of the heated floor surface t_{avre} is relative to human body comfort. It is limited to a certain range, shown in Table 7.

TABLE 7: Value range of t_{avre}

Environmental condition	Suitable range (°C)	Max. limit (°C)
Area of long-time stay for personnel	24-26	28
Area of short-time stay for personnel	28-30	32
Area of no stay for personnel	35-40	42

3.2.2 Pipe loops parameters design

There are several parameters of pipe loops that must be determined in a floor heating project. First, the supply and return water temperature of the floor heating system should be calculated according to the heat load of the system. Usually the supply water temperature is between 35 and 60°C, and cannot rise above 60°C. The temperature difference of supply and return water is less than or equal to 10°C. Secondly, the distance between pipes and the length of the pipe loops are the most important values when designing the floor heating system. These parameters determine effective heat release, the indoor calculated temperature, supply water temperature, return water temperature and the heat conductivity of the floor, (Formulae 11-14) (Yang and Tao, 1998):

$$Q = \lambda Sl(t_{pl} - t_{avre}) \tag{11}$$

where Q = Heat release of the pipe loops or heat load of room (W);
λ = Total heat conductivity of the coverings (W/(m°C));
S = Shape factor;
l = Pipe loops length (m);
t_{pl} = Mean temperature of circulation water (°C).

$$\lambda = \frac{\delta}{\sum \frac{\delta_i}{\lambda_i}} \tag{12}$$

where δ = Total floor covering thickness (m);
δ_i = Different layer thickness of the floor covering (m);
λ_i = Different layer heat conductivity of the floor covering (W/(m°C)).

$$S = \frac{2\pi}{\ln\left[\frac{2M}{\pi d}\,\mathrm{sh}\,(2\pi\frac{H}{M})\right]} \tag{13}$$

where M = Tube spacing (m);
d = Diameter of pipe loops (m);
H = Buried depth of pipe loops (m).

$$t_{pl} = (t_s + t_r)/2 \tag{14}$$

where t_s = Supply water temperature (°C);
t_r = Return water temperature (°C).

Figure 3 shows the structural profile of floor heating. The surface layer is wood, the thickness is 10 mm and heat conductivity is 0.22W/(m°C). The thickness of the cement mortar levelling layer is 20 mm; the heat conductivity is 0.93 W/(m°C). The thickness of the fine aggregate concrete is 40 mm; and the heat conductivity is 1.51 W/(m·°C). Hence, the total heat conductivity is:

$$\lambda = \frac{70}{\frac{10}{0.22} + \frac{20}{0.93} + \frac{40}{1.51}} = 0.96\, W/m°C$$

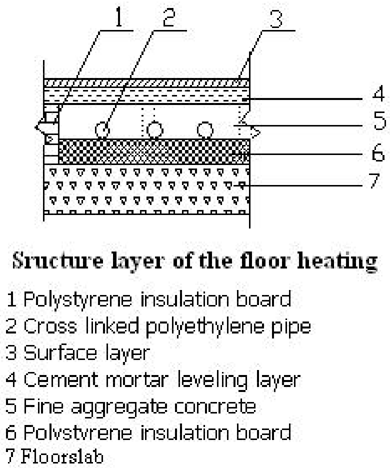

FIGURE 3: Structural profile of floor heating

When t_s=40°C and t_r =30°C, then t_{pl} is 35°C. For example, take a closer look at room 101: the heat loss of the room is 985W (see Appendix I). The heat load of the room is 90% of the heat loss. Then the heat load of room is 887W and per building area it is 62.7 W/m^2. From Formula 10, when Q_e/A_h is known, the value of t_{avre} is calculated as 25.3°C. If the floor heating system structure is determined, M is 300 mm, d=20 mm, H=50 mm. Shape factor and the pipe loops length can be obtained:

$$S = \frac{2\pi}{\ln\left[\frac{2\times 300}{\pi \times 20} sh(2\pi\frac{50}{300})\right]} = 2.53$$

Through Formula 13, the length of pipe loops is determined as S=35.7 m. Results for other rooms are found in Appendix I.

For a practical design, calculation tables are widely used. They show the effective heat release of pipe loops relative to different inner calculated temperatures, the mean temperature of the circulation water and tube spacing. The designer needs to calculate the heat release and find the relevant values in the calculation tables. Then the parameters of the floor heating system can be obtained.

3.3 Pipe connection and hydraulic calculation

A floor heating system is divided into subsystems by household. For each household, it is necessary to set up manifolds to connect heated pipe loops, and each main room has a pipe loop. The total length of every loop should be less than 120 m and the pressure of each loop should be less than 30 kPa. In front of the supply manifold, it is wise to install valves and a filter; behind the return manifold, valves need to be installed as well. Both manifolds must have air bleeders. To protect the pipe and extend its useful time, the working pressure of the heat medium in a central heating system is less than 0.8 MPa. To make sure that air bubbles are carried out with circulation water, the velocity of the water in the heated pipe cannot be lower than 0.25 m/s; usually 0.25-0.5 m/s is recommended. If the pipe length is too long or the flow speed is too fast, the pressure drop may be larger than the supply water pressure and head of the pump. Therefore, it is necessary to calculate the resistance of the floor heating system in the design. It can be calculated by the following formulae:

$$\Delta P = \Delta P_y + \Delta P_j = R_p l + \Delta P_j \tag{15}$$

where ΔP = Total pressure drop of pipe loop (Pa);
ΔP_y = Pressure drop along one-way pipe (Pa);
ΔP_j = Local pressure drop (Pa);
R_p = Specific frictional resistance (Pa/m).

R_p can be calculated by:

$$R_p = \frac{\lambda_p}{d} \cdot \frac{\rho v^2}{2} \tag{16}$$

where λ_p = Friction factor;
ρ = Density of water (kg/m^3);
v = Velocity of water (m/s).

$$\mathrm{Re} = \frac{vd}{\gamma} \tag{17}$$

where Re = Reynolds number;
γ = viscosity of water (m^2/s).

$$\lambda_p = \frac{0.3164}{\mathrm{Re}^{0.25}} \tag{18}$$

$$G = \frac{0.86Q}{t_s - t_r} \tag{19}$$

where G = Flow rate of water (kg/h)

4. GEOTHERMAL FLOOR-HEATING SYSTEM DESIGN

A typical geothermal floor heating system in Tianjin is shown in Figure 4. For corrosive geothermal water, the heating system needs a plate heat exchanger to separate geothermal water and circulation water. In China, residences are usually high density apartment buildings. The district heating zone is relatively small and the heat load is very concentrated. So the supply water pipe can be shorter than what is normally the case in Iceland. The supply water temperature and flow rate are adjusted well in

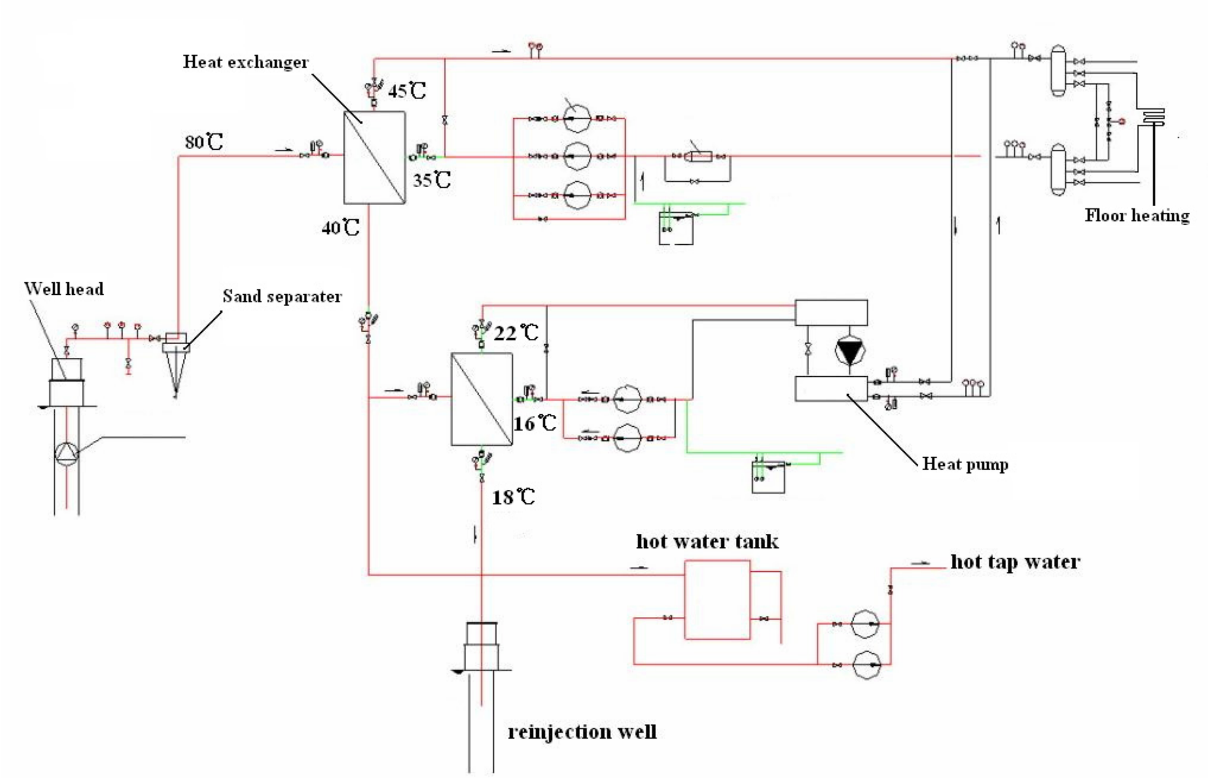

FIGURE 4: A typical geothermal floor heating system in Tianjin

the central pump station. If consumers do not change the degree of heat they want, the condition doesn't need to be regulated at the inlet to the user which makes the entrance devices of household heating simple and less costly. But in this system, it is not easy to adjust the operating conditions to satisfy the heat demand of every user.

In Iceland, the district heating system is designed for distribution. The long main pipe supplies hot water to individual consumers. The supply water temperature has a constant value of 80°C. For a floor heating system, this supply water temperature is too high for comfort of a room. So before the supply manifold, a mixing control valve and a by-pass pipe are used for constant control of the flow temperature. The return flow temperature in the floor heating circuit is kept constant according to the adjusted set value by mixing the heated water from the heat generator and the by-pass. Each household needs to install a circulation pump to let hot water flow. And a safety temperature limiter is installed on the entry of the return pipe (Figure 5). This control unit enables flexible control of the indoor temperature and, by adding some additional elements the user can easily and automatically control heat release according to atmospheric conditions.

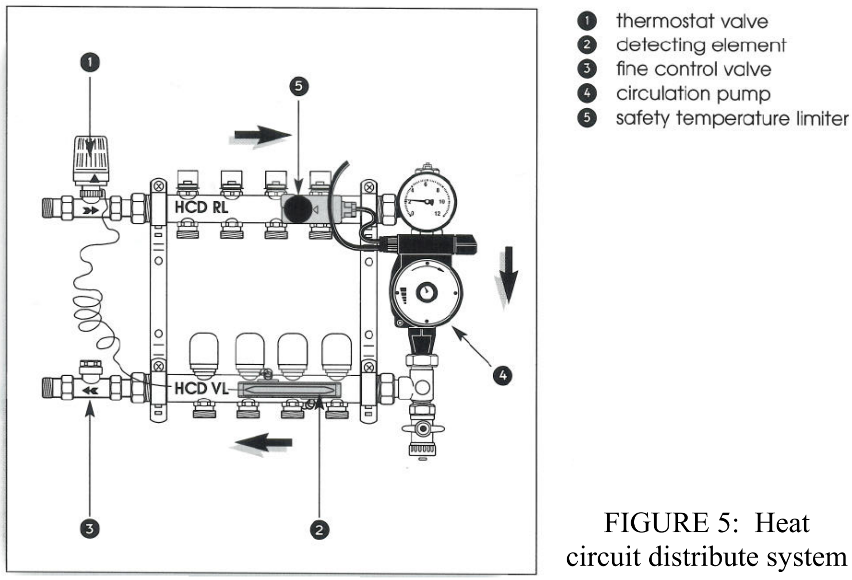

FIGURE 5: Heat circuit distribute system

5. OPERATION OF GEOTHERMAL FLOOR HEATING

5.1 Model of floor heating system

The operation of a floor heating system is optimal when its operation parameters vary in order to counterbalance changes in outdoor temperature and heat demands. The model of a heating system plays an important role in this operation. Models of district heating systems can be classified as follows (Lei Haiyan, 2004):

- By type: microscopic or macroscopic;
- By method: dynamic or steady-state;
- By approach: physical or black box;
- By usage: design or operation.

The concepts "microscopic" and "macroscopic" refer to whether the state of the district heating system is to be studied in detail both in time and space, or if the district heating system is lumped into a few model blocks, ignoring spatial variance of the system state. Dynamic models depend on previous state history, whereas steady-state models are time independent and assume steady-state conditions. In this section, models for a district heating network are described. The models treated are macroscopic and physical.

A geothermal district heating system consists of buildings, heating equipment, pipes, a pump station and a heat producing station. Heat can be extracted from a geothermal field and transferred to the consumer. But for different control objectives, simulation modules, input signals and output signals should be carefully chosen. In this section, both the floor heating systems in Tianjin and Iceland are simulated. Table 8 shows the main model factors.

TABLE 8: Main model factors

System	Input signal	Simulation modules	Control signal	Output signals
Tianjin	Outdoor temperature	Floor heating Heat exchanger	Circulation flow rate	Return water temperature Geothermal flow rate
Iceland	Outdoor temperature	Floor heating Mixing controller	Supply water temperature	Return water temperature Geothermal flow rate

5.2 Simulation of a floor heating system in Tianjin

5.2.1 Floor heating loops

From Formula 11, the relative heat load of the floor heating circuit can be written as:

$$\frac{Q}{Q_0} = \frac{f(t_{aver}, t_i)}{f(t_{aver0}, t_i)} \tag{20}$$

where Q = Actual heat output from floor heating loops (W);
Q_0 = Heat output of floor heating circuit at design conditions (W);
t_{aver0} = Average temperature of heated floor surface at design conditions (°C).

The design criterion means that all results are at the indoor and outdoor calculated temperatures. In this case, the calculated indoor temperature is 18°C; the calculated outdoor temperature is -9°C. According to Formula 10, the average temperature of the heated floor surface at design conditions t_{aver0}

is equal to 24.7°C. Combining Formulae 8 and 9, heat output refers to the average temperature of the heated floor surface and the indoor temperature.

5.2.2 Water heat load

The relative heat load due to hot water going through the floor heating loops is:

$$\frac{Q}{Q_0} = \frac{m_c(t_s - t_r)}{m_{c0}(t_{s0} - t_{r0})} \tag{21}$$

where m_c = Actual flow rate of circulation water (kg/s);
m_{c0} = Flow rate of circulation water at design conditions (kg/s);
t_{s0} = Supply water temperature at design conditions (°C);
t_{r0} = Return water temperature at design conditions (°C).

Designers can set the supply and return water temperatures at design conditions based on the heating system. For the geothermal heating system in Tianjin, t_{s0} can be set as 40°C and t_{r0} as 30°C. For fuel fired systems, the values are 60/50°C.

5.2.3 Heat exchanger

Heat exchangers transfer heat, from one flow stream to another, without mixing the fluids. They are, thus, elements with four connection points, as shown in the schematic (Figure 6). Here, the relative heat transfer is:

$$\frac{Q}{Q_0} = \frac{m_h(T_{h1} - T_{h2})}{m_c(T_{c2} - T_{c1})} = \frac{U_h \Delta T_m}{U_{h0} \Delta T_{m0}} \tag{22}$$

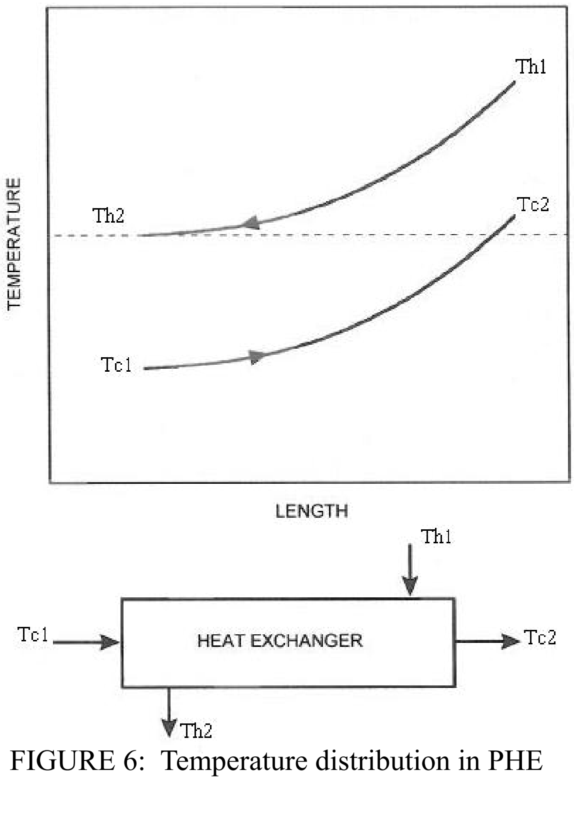

FIGURE 6: Temperature distribution in PHE

where m_h = Geothermal water flow rate (kg/s);
m_c = Circulation water flow rate (kg/s);
T_{h1}, T_{h2} = Geothermal water inlet and outlet temperatures (°C);
T_{c1}, T_{c2} = Circulation water inlet and outlet temperatures (°C);
U_h = Total heat transfer coefficient (W/(m^2°C));
ΔT_m = Logarithmic mean temperature difference (°C).

In a geothermal heating system, plate heat exchangers (PHEs) are commonly used. The heat transfer coefficient is mainly influenced by plate heat conductivity and fouling resistance. When temperature and flow rate are changed, U_h changes a little.

The logarithmic mean temperature difference for a heat exchanger is defined as:

$$\Delta T_m = \frac{(T_{h1} - T_{c2}) - (T_{h2} - T_{c1})}{\ln \dfrac{T_{h1} - T_{c2}}{T_{h2} - T_{c1}}} \tag{23}$$

For a floor heating system, the temperature difference between the inlet and outlet temperatures of the circulation water is only 10°C. But the temperature difference of the geothermal water is relatively high, up to 40-50°C. So the flow rate of the circulation water is 4-5 times that of the geothermal water flow rate. This is harmful to the operation of the plate heat exchanger, because the velocity and pressure drop are too different on the two sides of the plate. In practice, a by-pass pipe is used on the circulation water side to reduce the circulation water flow rate (see Figure 4). The ratio of the water flow rate through the plate exchanger to the circulation water flow rate is $\overline{m}_{pc}$. Then T_{c2} is given by:

$$T_{c2} = \frac{t_s - (1 - \overline{m}_{pc})t_r}{\overline{m}_{pc}} \tag{24}$$

The design temperatures of geothermal water inlet and outlet temperatures T_{h10} and T_{h20} are 80/35°C. If $\overline{m}_{pc}$=0.5, T_{c20} will be 50°C. T_{c10} is equal to t_{r0}. From Formula 22, the ΔT_{m0} is calculated as 13.95°C.

5.2.4 Building heat loss

When the building heat loss factor k_l is constant, relative heat loss of the building can be defined as:

$$\frac{Q_{loss}}{Q_{loss0}} = \frac{(t_i - t_o)}{(t_{i0} - t_{o0})} \tag{25}$$

5.2.5 Simulation of floor heating systems

In the steady-state model, buildings can be assumed to have no heat accumulation. Heat output is equal to heat transfer and heat loss. Figure 7 shows the influence of the supply water temperature on the heat exchanger area and pipe loops length. The values are given for constant heat load. The inlet geothermal water is 80°C. The temperature difference of the outlet geothermal water and return water is 5°C. This is the reference condition when supply water temperature is 40°C. From the figure, we can see that if the supply temperature becomes higher than 50°C, the heat exchanger area increases too much. When the supply temperature becomes less than 35°C, the pipe loops length for the floor heating increases fast. The pipe length needed when the supply water temperature is 35°C is nearly double from the required length at 40°C. In a fuel fired system, the supply water temperature is 60°C; the pipe length is 34% of that in a geothermal heating system with a 40°C supply temperature. In that case, however, the heat exchanger area is nearly doubled. Considering the total cost of the heat exchanger and pipe loops and the lower temperature (40°C) of discharged geothermal water, the 40°C value for the supply water is reasonable.

For constant circulation water flow rate, as is typical in Tianjin, the operating parameter changes are shown in Figures 8 and 9. The design conditions are the same as above. From Formulae 20, 21 and 25, the figures give the relationships between the outdoor temperature and the supply/return water temperature under a design heat load of 60 W/m^2. Supply and return water temperatures decrease with an increase in outdoor temperature, and the difference between them is reduced, too.

From Section 5.2.3, the outlet of geothermal water and its flow rate are calculated under different heat loads. When outdoor temperature is high, the system heat load is lower, geothermal discharge water temperature and flow rates decrease. When the heat load is reduced, according to the analyses above,

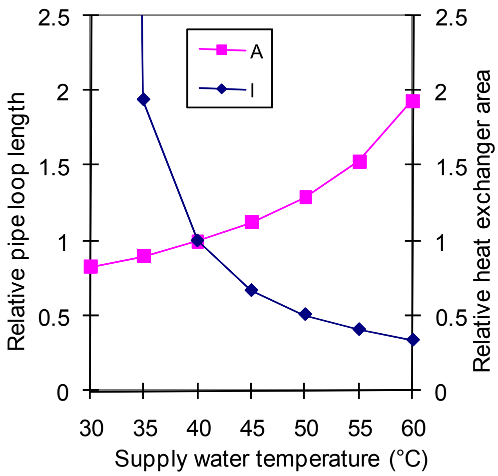

FIGURE 7: Relations for t_s, vs. heat exchanger area (A) and pipe loop length

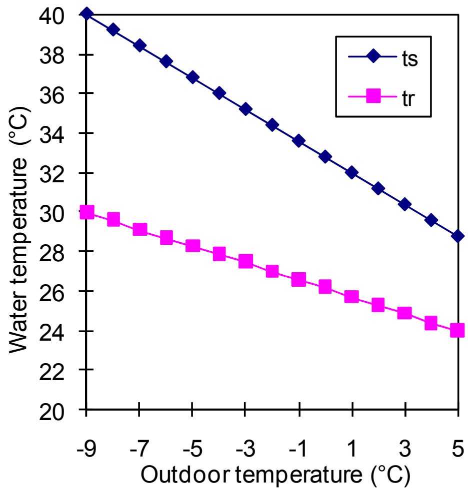

FIGURE 8: Relations for outdoor temperature vs. t_s and t_r

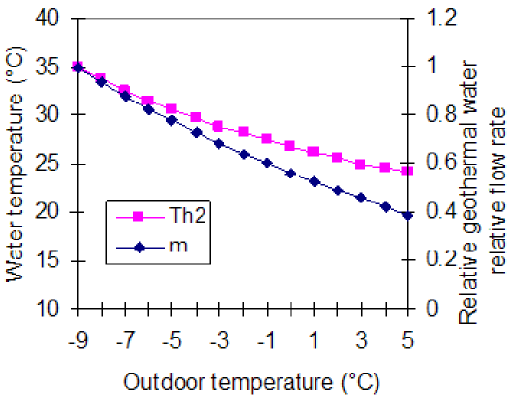

FIGURE 9: Relations for outdoor temperature vs. T_{h2} and m

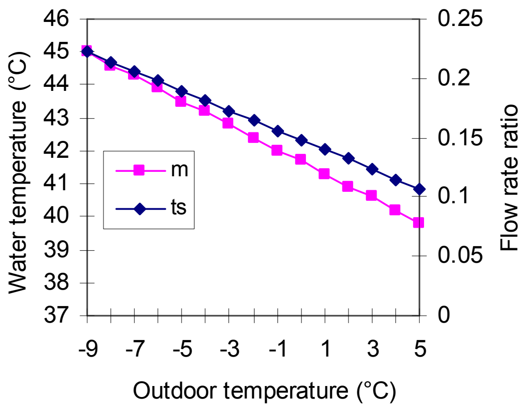

FIGURE 10: Relations for outdoor temperature, vs. t_s and hot water flow rate

operators can adjust the flow rate and discharge temperature of the geothermal water. Lowering the flow rate preserves the geothermal resource, and the geothermal energy is optimally utilized when the discharge water temperature is low, too.

5.2 Simulation of a floor heating system in Iceland

As seen in Section 4, a floor heating system in Iceland changes the supply water temperature; it can be concluded that:

$$t_s = \frac{t_g - (1 - \overline{m}_{gc})t_r}{\overline{m}_{gc}} \tag{26}$$

where t_g = Geothermal water temperature (°C):
$\overline{m}_{gc}$ = Flow rate ratio of geothermal water and circulation water;

The return water temperature is fixed at 35°C, controlled by a thermostat to change the mixture flow rate. The design supply and return temperatures are 45/35°C. Figure 10 shows the relationship of the heat load between the supply water temperature and the flow rate ratio. The supply water temperature and flow rate decrease with a decrease in the heat load. The flow rate is linearly changed. So it is easy to control during operation.

6. CONCLUSIONS

This paper describes geothermal floor district heating in Tianjin. Calculations, based on Chinese codes, were done on a sample building. The design conventions in China and Iceland were compared and a steady-state model was used to simulate the design values and operating parameters. According to the above, the following conclusions could be obtained:

- Heat loss of the building mainly consists of heat loss through building surroundings, heat loss by infiltration, and heat load of inrushing air due to the opening of doors.
- Floor heating is a comfortable and conservative energy system. The heat load of a floor heating system is 90-95% of the building heat loss.
- In China, the geothermal floor heating is designed mainly to be operated and adjusted in a pump station. It makes user equipment simple and cheap. On the other hand, this system is difficult to adjust by the individual user.
- In Iceland, the system is designed to be controlled and adjusted by the consumer; the equipment in each room is relatively uncomplicated and inexpensive.

A steady-state model was used to obtain characteristic curves for the district heating systems. Comparison was made between fuel fired systems and geothermal floor heating systems:

- In a fuel fired system, the pipe length is 34% of that in a geothermal heating system but the heat exchanger area is nearly doubled in size.
- When designing a floor heating system, the total cost of a heat exchanger and pipe loops should be considered with regard to a lower discharge temperature of geothermal water. In addition, the operation costs of the geothermal district heating system, using this low-temperature resource, must be taken into account when feasibility is evaluated.
- According to the simulation values in Tianjin, when a system's heat load is lower, discharge temperatures and flow rates of the geothermal water are reduced. Lower flow rates at low heat load helps preserving the geothermal resource and in addition the geothermal energy is fully utilized as the temperature of the discharge water is low.

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APPENDIX I: Calculations of heat loss and pipe loops design

TABLE 1: Heat loss values for the building

Room no.	Surroundings			*U* (W/ m²·°C)	t_i (°C)	t_o (°C)	Δt (°C)	α	Q_1 (W)	Addition heat loss			Q_2 (W)	Q_l (W)
	Name	Orientation	Area (m²)							β_o (%)	γ (%)	γ Q_1 (W)		
101	Wall	Western	13.44	1.18	18	-9	27	1.0	428.2	-5	0.95	406.8	227.6	985
	Window	Southern	2.70	2.80	18	-9	27	1.0	204.1	-15	0.85	173.5		
	Wall	Southern	6.54	1.18	18	-9	27	1.0	208.4	-15	0.85	177.1		
102	Wall	Western	10.92	1.18	18	-9	27	1.0	347.9	-5	0.95	330.5	183.3	943
	Window	Northern	2.25	2.80	18	-9	27	1.0	170.1	5	1.05	178.6		
	Wall	Northern	6.99	1.18	18	-9	27	1.0	238.9	5	1.05	250.9		
103	Door	Northern	3.60	3.26	18	-9	27	1.0	316.9	5	1.05	332.7	121.2	584
	Wall	-	1.68	2.91	18	13	5	1.0	24.4	0	1	24.4		
	Wall	Northern	3.02	1.76	18	-9	27	0.7	100.6	5	1.05	105.6		
104	Wall	Southern	6.60	1.18	18	-9	27	1.0	210.3	-15	0.85	178.7	187.4	644
	Window	Southern	4.32	2.80	18	-9	27	1.0	326.6	-15	0.85	277.6		
105	Wall	Northern	8.26	2.37	18	13	5	1.0	97.9	0	1	97.9	0	98
106	Wall	-	8.26	2.37	13	18	-5	1.0	-97.9	0	1	-97.9	76.8	247
	Window	Northern	1.80	2.80	13	-9	22	1.0	110.9	5	1.05	116.4		
	Wall	Northern	6.46	1.18	13	-9	22	1.0	167.7	5	1.05	176.1		
	Door	-	1.68	2.91	13	18	-5	1.0	-24.4	0	1	-24.4		
107	Wall	Southern	4.08	1.18	18	-9	27	1.0	130	-15	0.85	110.5	141.3	575
	Door	Southern	4.32	3.26	18	-9	27	1.0	380.2	-15	0.85	323.2		
111	Window	Southern	2.70	2.80	18	-9	27	1.0	204.1	-15	0.85	173.5	227.6	578
	Wall	Southern	6.54	1.18	18	-9	27	1.0	208.3	-15	0.85	177.1		
112	Window	Northern	2.25	2.80	18	-9	27	1.0	170.1	5	1.05	178.6	183.3	613
	Wall	Northern	6.99	1.18	18	-9	27	1.0	238.9	5	1.05	250.9		
113	Door	Northern	3.60	3.26	18	-9	27	1.0	316.9	5	1.05	332.7	121.2	584
	Wall	-	1.68	2.91	18	13	5	1.0	24.4	0	1	24.4		
	Wall	Northern	3.02	1.76	18	-9	27	0.7	100.6	5	1.05	105.6		
114	Wall	Southern	6.60	1.18	18	-9	27	1.0	210.3	-15	0.85	178.7	187.4	644
	Window	Southern	4.32	2.80	18	-9	27	1.0	326.6	-15	0.85	277.6		
115	Wall	Northern	8.26	2.37	18	13	5	1.0	97.9	0	1	97.9	0	98
116	Wall	-	8.26	2.37	13	18	-5	1.0	-97.9	0	1	-97.9	76.8	247
	Wall	Northern	6.46	1.18	13	-9	22	1.0	167.7	5	1.05	176.1		
	Window	Northern	1.80	2.80	13	-9	22	1.0	110.9	5	1.05	116.4		
	Door	-	1.68	2.91	13	18	-5	1.0	-24.4	0	1	-24.4		
117	Wall	Southern	4.08	1.18	18	-9	27	1.0	130	-15	0.85	110.5	141.3	575
	Wall	Southern	4.32	3.26	15	-26	41	1.0	577.41	-15	0.85	323.2		

TABLE 2: Pipe loops design values for the building

Room no.	**Heat load**	**Area of room**	**Heat load per area**	**Floor surface temp.**	**Mean water temp.**	**Temperat. difference**	**Tube spacing**	**Shape factor**	**Length of loops**
	Q **(W)**	A **(m^2)**	q **(W/m^2)**	t_{avre} **(°C)**	t_{pl} **(°C)**	$t_{pl}- t_{avre}$ **(°C)**	M **(mm)**	S	l **(m)**
101	887	14.14	62.7	24.8	35	10.2	300	2.53	33.8
102	849	11.38	74.6	25.9	35	9.1	150	2.25	45.6
103	526	7.82	67.2	25.2	35	9.8	200	2.13	23.9
104	580	11.60	50	23.5	35	11.5	300	2.53	20.8
105	89	2.67	33	21.7	35	13.3	100	1.74	4
106	222	5.85	38	22.4	35	12.6	300	2.53	7.3
107	518	8.78	58.9	24.3	35	10.7	300	2.53	19.9
111	808	14.14	57.2	24.2	35	10.8	300	2.53	30.8
112	838	11.38	73.6	25.8	35	9.2	150	2.25	44.5
113	526	7.82	67.2	25.2	35	9.8	200	2.13	23.9
114	580	11.60	50	23.5	35	11.5	300	2.53	20.8
115	89	2.67	33	21.7	35	13.3	100	1.74	4
116	222	5.85	38	22.4	35	12.6	300	2.53	7.3
117	518	8.78	58.9	24.3	35	10.7	300	2.53	19.9