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GENERAL GUIDELINES IN GEOTHERMAL DISTRICT HEATING DESIGN

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ABSTRACT

The design of a geothermal district heating system requires robust mathematical considerations. The models used for the general design are macroscopic physical models, in steady state and dynamic. The solution of the sets of equations found in these models gives the main operational and sizing parameters for the system. This work outlines the basic mathematics in this process.

1. INTRODUCTION

Geothermal district heating system connects buildings to geothermal hot water supply through a pipe network. The sole purpose of the district heating system is to supply adequate heating for the consumer to maintain comfortable indoor temperature in their buildings regardless the weather situation and also provide them with hot tap water. Centralized district heating system is often more economical and environment-friendly, compared to individual ones.

The main parameter for district heating system's performance is the weather. The influence of weather on the operation of district heating system is mainly through the outdoor temperature. In this work, outdoor temperature, alone is assumed to present the weather conditions.

In the geothermal district heating system, hot water is taken directly from the low-temperature geothermal wells. Another possibility is to heat-up the cold groundwater with high-temperature geothermal fluids, using heat exchangers. Hot district heating water is collected to storage tanks. From the storage tanks, the water is then transmitted to the consumers and used to heat buildings and consumed as a tap water. The network can include a return pipe, but it is common that cooled district heating water is drained from the network, after use. Hot water temperature is about 80°C and it cools down to about 40°C in the radiators. Heat duty, transferred to buildings, is controlled by mass flow of the supply water. Schematic of a geothermal district heating system is shown in Figure 1.

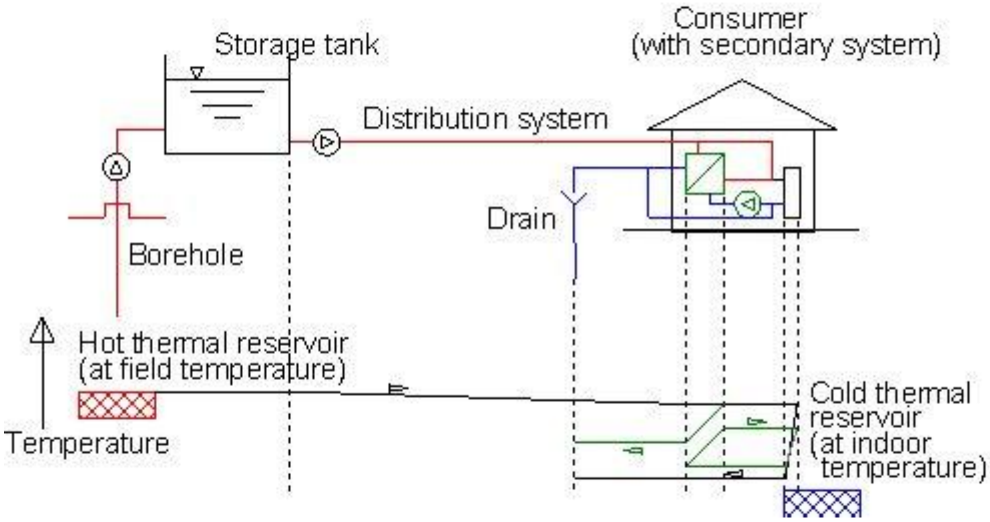

FIGURE 1: Schematic of a geothermal district heating system

1.1 Calculation models

Models of district heating systems can be classified as follows:

- 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 if 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. These models can be found in Valdimarsson (1993). In this section, models for a district heating network are described.

A macroscopic model describes the performance of entire district heating system from the viewpoint of supplier. A microscopic model describes the performance of district heating system from the viewpoint of consumer.

The district heating system is spread out over the city and its performance varies in the system. In a macroscopic model, the whole system is lumped into "equivalent consumer", entire distribution system and all of the consumers are considered as seen from the district heating water supply station. Models, treated in this work are macroscopic physical models.

1.2 Reference condition

The weather and load used for the design of the system is termed "Reference condition". The system calculation is then normalised to this reference condition, so that most of the calculations will be with dimensionless numbers.

Common reference values for geothermal district heating system at design conditions are:

- Supply water temperature $T_{s0} = 80°C$
- Return water temperature $T_{r0} = 40°C$
- Indoor temperature $T_{i0} = 20°C$

The reference outdoor temperature depends on climate. The reference value for Iceland is T_{o0} = -15°C. This value is typically close to the lowest temperature to expect. A good value can be found by looking at a “Typical year for energy calculations” and use the lowest value of outdoor temperature during this typical year.

Soil temperature at certain depth is assumed to be constant all the year around and soil temperature for Iceland is T_g = 4°C. This value is typically very close to the yearly average outdoor temperature.

Reference return temperature is a function of radiator system in the buildings. In district heating system, every consumer has a different types and sizes of radiator, so the reference return temperature is assumed as an average of the whole radiator system’s function.

1.3 Tap water

In the geothermal district heating network, part of geothermal water is used for supplying tap water, either consumed directly or used for heating of cold water in the heat exchangers. The consumption of the tap water does not depend on the outdoor temperature, but is a function of consumer’s average behaviour. The tap water consumption is expected to have a periodic daily variation, with very low consumption during the night. The common amount of tap water use in the Reykjavik district heating system is 10 - 15% of the yearly total mass flow. It is not unreasonable to estimate the tap water load similar to the calculated heating load at 13 – 15°C outdoor temperature. Of course the estimation of the tap water consumption has to be based on the actual consumer behaviour.

A word of warning: Experience has shown that the consumer tap water behaviour changes when geothermal district heating becomes available – *and the consumption increases drastically*. This is just showing what an improvement in quality of life is given by the geothermal district heating – the consumer enjoys tap water as much as he likes, without having to worry about cost or availability.

1.4 Transmission and network loss

The transmission effectiveness is the ratio between two temperature differences. The temperature difference between the supply temperature and the ground temperature, both at the feed point into the system and at the consumption point are used. The transmission effectiveness is defined by Equation 1.

$$\tau = \frac{T_s - T_g}{T_1 - T_g} \tag{1}$$

The transmission effectiveness at the reference condition is a measure of the distribution network quality, and is an important parameter in the subsequent modelling of the system. A good value of the reference condition transmission effectiveness τ_0 is 0.95 to 0.97 depending on insulation of the network pipes.

2. WEATHER DATA

Reliable weather data must be used for the calculations. A good source is EERE (2008), and from there data from Qingyuan and Huang. (2004) and ASHRAE (2001) has been obtained for this work.

The heat load is proportional to the temperature difference between the indoor air temperature and the outdoor temperature. Thus information on the relative heat load and heat load duration can be obtained from the outdoor temperature time series for a typical year (design year). The relative building heat load for a few cities is shown on Figure 2, and the duration of the relative heat load on Figure 3.

There is not much difference between Beijing, Tianjin and Xi'an. Inchon is slightly colder than the Chinese cities during the summer. The other cities are substantially colder.

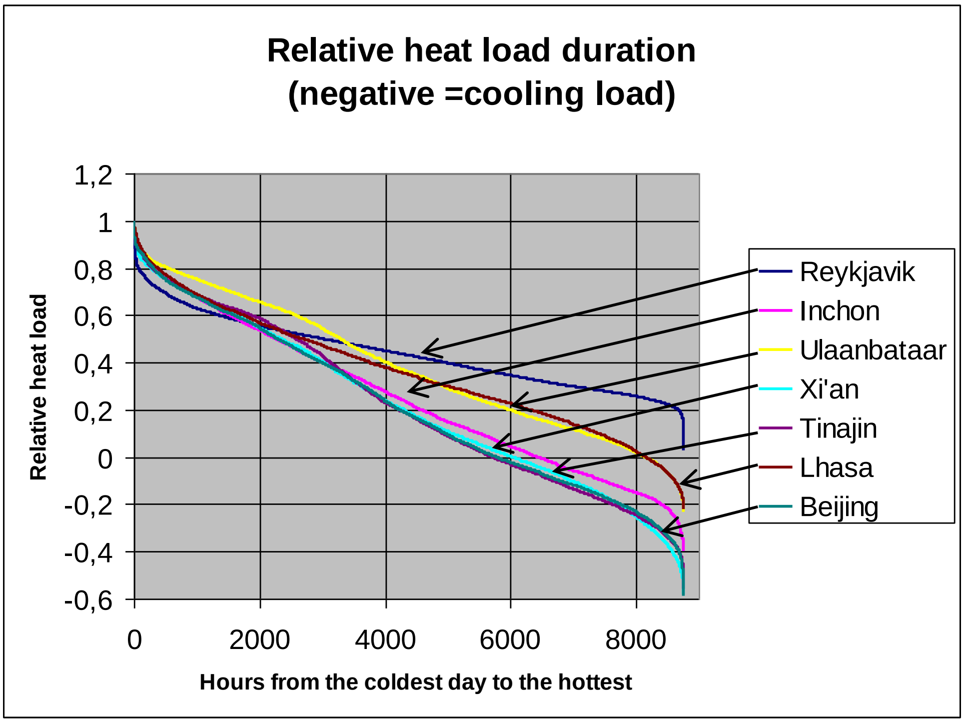

FIGURE 2: Building relative heat load duration (without tap water load)

The heating load is zero if the outdoor temperature is higher than the desired indoor temperature. The tap water load can be estimated to correspond to the heating load at 13-15°C outdoor temperature. If the same curves are plotted again, the picture becomes slightly different. This is shown on Figure 3.

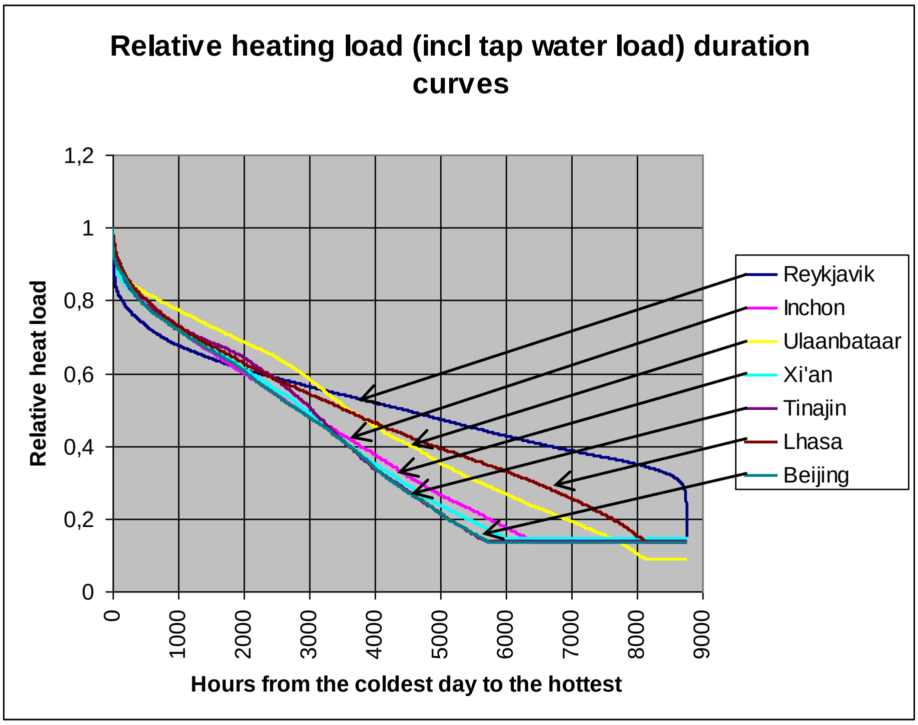

FIGURE 3: Building relative heating load duration (with tap water load)

The area under a duration curve is the energy needed during one year. If this total energy is divided by the maximum load, the utilisation time is obtained. The utilisation time tell for how long the system has to be run at maximum load to produce (consume) this energy. Utilisation factor is the ratio of the utilisation time to the length of the year.

If the duration curve is close to horizontal, the utilisation factor is high, and the city is a good candidate for a district heating system. If the curve is steep, the factor is lower and it will be more difficult to get reasonable economics for the district heating system. Reykjavik with its oceanic climate is therefore a better candidate than the Chinese cities with their more continental climate.

TABLE 1: Utilisation factors

City	**Reykjavik**	**Inchon**	**Ulaanbataar**	**Xi'an**	**Tianjin**	**Lhasa**	**Beijing**
Utilisation factor	0.51	0.38	0.44	0.38	0.38	0.45	0.37

3. STEADY STATE MATHEMATICAL MODEL OF A DISTRICT HEATING SYSTEM

The steady state model is a macroscopic physical model. There the state of the district heating system is determined for constant outdoor temperature. All consumers in the system are lumped into a single equivalent consumer, so the model diagram is exactly as shown on Figure 1.

- There are four heat transfer calculation blocks to be defined:
- The heat removed from the water
- The heat transferred from the radiator surface to the indoor air
- The heat lost from the building to the surroundings
- The pipe network heat loss model

All heat loads are normalised to the reference condition, and the calculation then based on the relative heat load or duty.

3.1 Water Heat Duty

The heat duty, which district heating water gives away, when going trough the radiators is:

$$Q = c_p m (T_s - T_r) \tag{2}$$

Relative heat duty of water flow can be written as:

$$\frac{Q}{Q_0} = \frac{m}{m_0} \frac{T_s - T_r}{T_{s0} - T_{r0}} \tag{3}$$

3.2 Radiator

Radiator is the heat exchanger that transfers heat from the district heating network to the indoor air. According to Anon. (1977) the relative heat duty of a radiator can be written as:

$$\frac{Q}{Q_0} = \left(\frac{\Delta T_m}{\Delta T_{m0}} \right)^{4/3} \tag{4}$$

Logarithmic temperature difference ΔT_m is defined as:

$$\Delta T_m = \frac{(T_s - T_i) - (T_r - T_i)}{\ln\left(\frac{T_s - T_i}{T_r - T_i} \right)} = \frac{(T_s - T_r)}{\ln\left(\frac{T_s - T_i}{T_r - T_i} \right)} \tag{5}$$

Inserting equation (5) to equation (4), it becomes:

$$\frac{Q}{Q_0} = \left(\frac{(T_s - T_r)}{\ln\left(\frac{T_s - T_i}{T_r - T_i} \right)} \cdot \frac{\ln\left(\frac{T_{s0} - T_{i0}}{T_{r0} - T_{i0}} \right)}{(T_{s0} - T_{r0})} \right)^{4/3} \tag{6}$$

3.3 Building Heat Loss

Heat loss from the buildings can be defined as:

$$Q_{loss} = k_l (T_i - T_o), \tag{1}$$

where building heat loss factor k_l is a constant. Relative heat loss is obtained:

$$\frac{Q_{loss}}{Q_{loss\,0}} = \frac{T_i - T_o}{T_{i0} - T_{o0}} \tag{2}$$

3.4 Pipe Heat Loss

Some heat is lost in the pipe connecting the pumping station and the buildings to be heated. The amount of the loss can be calculated by using district heating pipe transmission effectiveness parameter. According to Valdimarsson (1993) the transmission effectiveness τ is defined:

$$\tau = \frac{T_s - T_g}{T_1 - T_g} = e^{-\frac{U_p}{m c_p}} \tag{3}$$

The reference value of the τ can be calculated from the reference flow conditions:

$$\tau_0 = \frac{T_{s0} - T_g}{T_{10} - T_g} = e^{-\frac{U_p}{m_0 c_p}} \tag{4}$$

Parameters U_p and c_p is assumed to be constant all over the system. Combining equations (8) and (9) the transmission effectiveness can be obtained:

$$\tau = \tau_0^{\frac{m_0}{m}} \tag{5}$$

By combining the equations (8) and (10) the supply temperature to the house can then be calculated.

$$T_s = T_g + (T_1 - T_g)\tau = T_g + (T_1 - T_g)\tau_0^{\frac{m_0}{m}} \tag{6}$$

3.5 The solution

When the district heating systems are assumed to be in steady state, it is also assumed that no heat is accumulated in the buildings. Indoor temperature is assumed to be constant when flow controller is ideal, which means flow controller adjusts the flow such that exactly the heat lost from the building will be supplied to the building at the same time.

By assuming negligible heat capacity of the radiator itself, the relative heat flow from the radiator can be equated to the relative heat flow from the district heating water to the radiator. So, heat loss from the building and heat duty supply from the district heating water is equal all the time, assuming ideal controller.

Due to these assumptions, the previous equations can be solved together, giving the requested system parameters at this outdoor temperature.

The results of such a calculation are shown on Figure 4. There a given 80/40/-15 district heating system has been calculated, and the results given as a function of the outdoor temperature.

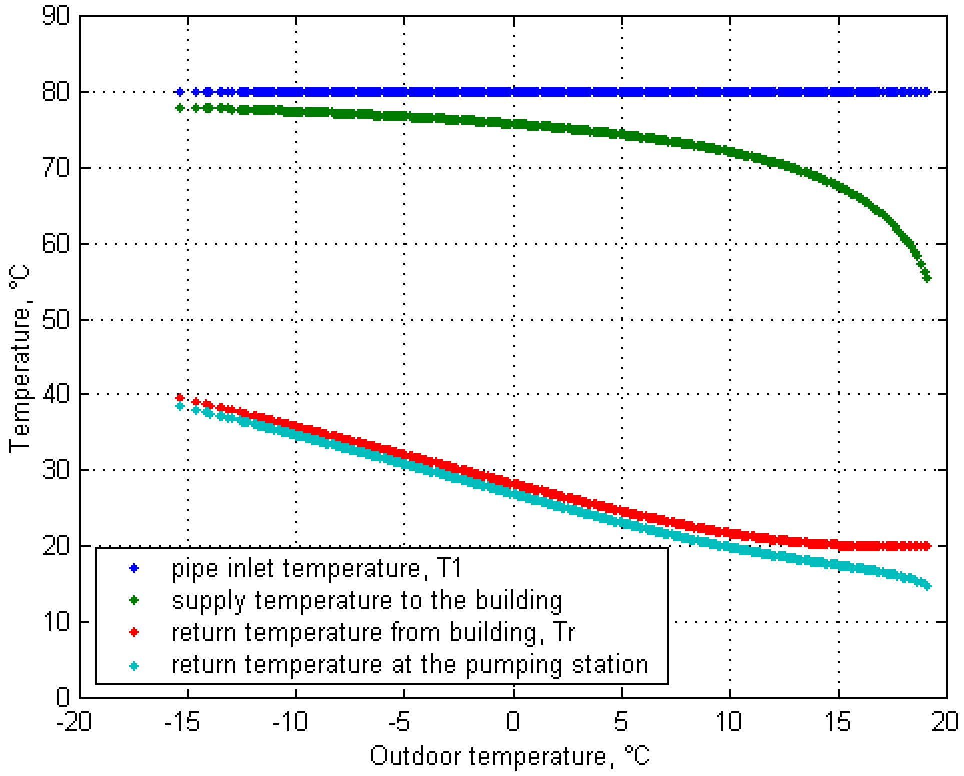

FIGURE 4: Temperatures in a the district heating network, pipe heat loss and tap water load included.

4. DYNAMIC MATHEMATICAL MODEL OF A DISTRICT HEATING SYSTEM

The steady state calculation assumes all heated parts of the building to be at uniform indoor temperature at all times, and thus the building can be modelled as a heat capacity element. This is of course not valid, and therefore a dynamic calculation is required, where the energy stored in the building is considered.

$$\frac{dT_i}{dt} = \frac{1}{C} Q_{net} = \frac{1}{C} \left(Q_{supp} - Q_{loss} \right) = \frac{1}{C} \left(m \cdot c_p \cdot \left(T_s - T_r \right) - k_l \cdot \left(T_i - T_o \right) \right) \tag{12}$$

All time derivatives are set equal to zero in steady state model and this equation is not used, but in dynamic modelling the equation plays the big part.

The indoor temperature is then not a constant any more, but varies with time. The flow controller tries to adjust the flow to the building in order to keep the indoor temperature at the value which the consumer has requested.

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 regulation 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. It can be done with some statistical methods.

In this report, steady state controller is assumed and used in the calculation, with limitation of mass flow to base temperature. Then the controller is ideal until some maximum flow (minimum steady state outdoor temperature) is reached. If the requested flow is higher, the controller limits the flow at this defined maximum value. Ideal means that the controller gives *exactly* the flow required to hold the indoor temperature constant at the requested value.

Building heat loss factor *U* and building heat capacity (energy storage) *C* is very important in the dynamic calculation. Especially dynamic calculation of indoor temperature is quite sensitive to building energy storage and building time constant. The ratio of the heat capacity to the heat loss factor has the dimension of time, and is called the building time constant. A building with good insulation on the outside of the walls can have time constant as high as 40 hours.

4.1 Base temperature

The outdoor temperature at which the steady state load leads to the maximum flow is called base temperature. Practically this is the lowest outdoor temperature at which the district heating system can keep all buildings at the desired indoor temperature. If the outdoor temperature goes below the base temperature, the indoor temperature will fall. A period with the outdoor temperature lower than the base temperature is called cold spell.

The base temperature is higher than the lowest temperature to expect. Why? The base temperature has to be selected in such a way, that the duration of the cold spell is not long enough for the building to react and the indoor temperature to fall to unacceptably low values.

This is an important factor for the economics of the system. This way of designing the system allows the designer to limit the investment without hurting the service level to the consumers. A rule of thumb states that the calculated indoor temperature of the equivalent consumer should be allowed to fall by 4°C once every 30-50 years. This calculated drop in the indoor temperature will not be noticed by the consumer due to the secondary heat sources (people, television, electrical appliances etc….). By using this criteria the investment cost in wells and distribution network can be reduced very substantially, without hurting the service level.

4.2 Simulation

Equation 12 is integrated for the time to be simulated. After a base temperature has been selected, it is sufficient to integrate a suitable time interval around the cold spells.

The results of such a simulation for weather data for Reykjavik for the period 1949 to 1990 is shown on Figure 5. The selected base temperature is -9°C. Outdoor temperatures higher than the base temperature are not shown, they simply do not matter. The upper curve shows the simulated indoor temperature for the equivalent consumer.

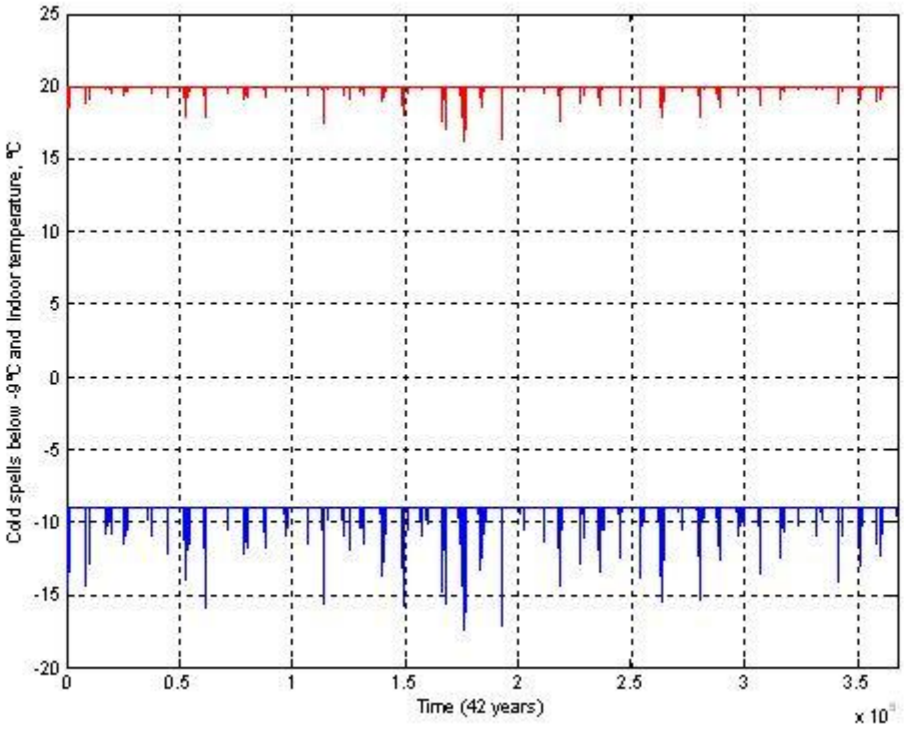

FIGURE 5: Cold spells below -9°C and simulated indoor temperature, Reykjavik 1949 - 1990

A close-up of the worst cold spell and a preceding less critical cold spell is shown on Figure 6. The time resolution is 3 hours.

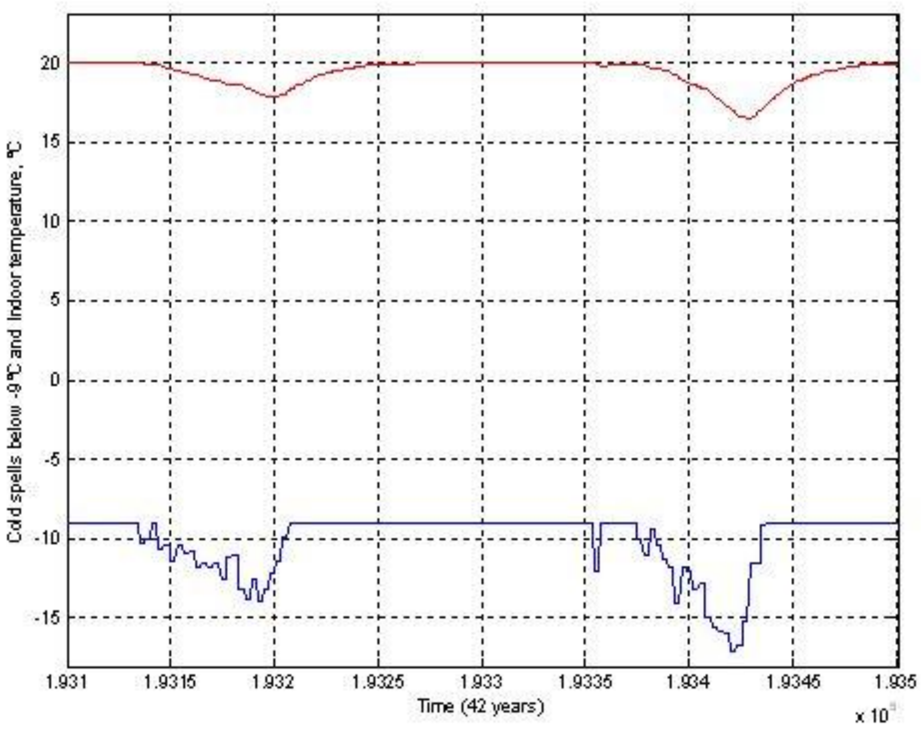

FIGURE 6: Close-up of two cold spells below -9°C and simulated indoor temperature

5. CONCLUSION

The design of a geothermal district heating system requires that the flow and temperature can be calculated in the system for all operational conditions. The steady state modelling is a tool to obtain this information for normal operations and situations where the weather fluctuations are not fast.

Maximum load information has to be obtained from dynamic modelling, where the short duration of the maximum load condition is taken into account, as well as the high thermal mass of the consumer buildings.

6. NOMENCLATURE

C	heat capacity of house, J/°C
c_p	water heat capacity, J/(kg °C)
k_l	building heat loss factor, W/ °C
m	water mass flow, kg/s
m_0	reference water mass flow, kg/s
m_{avg}	average mass flow
Q	heat duty, W
Q_0	heat duty at reference conditions, W
Q_{loss}	heat loss, W
Q_{net}	net heat, W
Q_{supp}	heat supply, W
T_1	pipe inlet temperature (pumping station), °C
T_2	return temperature at pumping station, °C
T_g	ground temperature, °C
T_i	indoor temperature, °C
T_{i0}	reference indoor temperature, °C
T_o	outdoor temperature, °C
T_{o0}	reference outdoor temperature, °C
T_r	return water temperature (primary network), °C
T_{r0}	reference return water temperature (primary network), °C
T_s	water supply temperature (primary network), °C
T_{s0}	reference water supply (primary network), °C
U_p	pipe heat loss factor, W/ °C
τ	pipe transmission effectiveness
τ_0	pipe transmission effectiveness at reference conditions
ΔT_m	logarithmic mean temperature difference, °C
ΔT_{m0}	logarithmic mean temperature difference at reference conditions, °C

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