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# Simulation and optimization of the district heating network in Scharnhauser Park

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**Abstract**

A network simulation tool for district heating and cooling systems was developed in this work. It was designed for the hydraulic and thermal simulation of meshed pipes networks. It calculates the operating parameters of the system with hourly time steps and provides monthly and annual balances of heat load and supply. Entities like supply and return temperature, flow rate, heat losses and pump energy are calculated and compared for different operating scenarios.
To validate the model and to show district heating network optimization potentials, a case study for a biomass powered district heating network in Scharnhauser Park, Germany was carried out. A 6 MW biomass cogeneration plant was analysed in efficiency as a function of the investigated load situation. It could be shown that the different geographical distributions of consumers within the network change the network losses by up to 11%. Using variable pressure control of the network distribution pumps can reduce electrical energy consumption by 40%. The network model was also used to analyse different solar thermal energy supply systems, which currently only contribute 0.3% of the total heating energy demand.

## Keywords

District heating network, solar assisted, graph theory, operation optimization

## 1 Introduction

District heating and cooling networks gain in importance, as they facilitate large scale renewable energy integration and a more even matching between supply and demand. For the design and operational optimization of complex networks, simulation tools play an important role. During the last twenty years different approaches for modelling district heating (DH) networks have been applied and validated. A node method was developed at the Technical University of Denmark [1]. The aggregation methods presented in [2] and [3] have been separately developed in Denmark and Germany. The authors reduced the number of modelled pipes (up to 7% of the initial pipes) without significantly decreasing the accuracy of the model. Helge [4] validated the aggregated network model using measurement data from a Danish site. This method is especially used in mesh-free networks.

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Based on the graph theory, the programme SMILE [5] developed at the Technical University of Berlin calculates the flow rates and pressure losses in the network. It has been used for planning and control strategy optimization of a German DH system, but is currently not developed any further. A similar approach was successfully applied in the work of Wenstedt [6]. Several commercial tools like TERMIS [7], sisHYD [8] and Grades Heating [9] have been upgraded during the last years to simulate both steady and dynamic network behaviour.
This paper presents the programme spHeat developed within the European POLYCITY [10] project. The purpose of the work is to establish a tool for modelling DH networks, which can be coupled to building demand simulations and renewable power plants. The DH system in Scharnhauser Park presents the first case study for spHeat. The distribution of the volumetric streams is calculated based on a graph-theoretical approach similar to the methods in [5] and [6]. A simple algorithm is implemented in MATLAB [11] to dynamically determine the water temperature propagation.
The currently available network simulation tools are mainly used for the initial network design and mostly not flexible enough to be combined with renewable energy supply and building demand simulations. The purpose of this work was to develop a simulation tool, which can be easily integrated to district simulations including buildings and energy plants.

## 2 The DH network in Scharnhauser Park

The combined heat and power (CHP) plant of Scharnhauser Park provides 584 consumers with local heat. Hot water with temperatures between 70°C and 95°C is distributed to the consumers through a closed network with multiple-loop topology. The studied part of the network consists of connected underground pipes with the total length of approx. 13.5km. The consumer buildings (grey blocks in Figure 1) are indirectly supplied through heat exchangers and are equipped with local flow control systems. The commercial software sisHYD has been used by the operating company SWE (Stadtwerke Esslingen) to model and manage the heat distribution System in Scharnhauser Park.

## 3 The Network simulation

### 3.1 The programme structure

In order to limit the simulation time, the modeled network is restricted to 6 main meshes (supply and return sub-network 3 meshes each). The consumers are centralized to 7 load stations as shown in Figure 1. For high accuracy of the results, the consumer groups were properly chosen using appropriate tools in the geographic information software GeoMedia. The spHeat program consists of 5 sub-programs with appropriate input data like pipe length and diameter, supply temperature and heat load (see Figure 2). The volume flow control is implemented using a simple P-controller. Return temperatures between 50 and 65°C are considered as a set point for the control system.

The model is based on a quasi-dynamic approach, where the flow and pressure are calculated using a static flow model in spHydro. The temperature is calculated dynamically in spThermo depending on the flow velocity and several boundary conditions like ground and ambient temperatures. A backward-difference method is implemented to solve the differential equations of heat transfer along the pipes. The following assumptions are made during the calculation:

- High flow resistance in the node area is neglected
- The fluid pipe flow is one-dimensional
- Turbulent fluctuations are not considered
- The network is free of leakage
- The fluid characteristics like density and heat capacity are constant

### 3.2 The hydraulic calculation

The network description is based on the graph theory [12], [13]. The DH system in Figure 3 is considered as a collection of nodes connected by directed edges (pipes): the network graph. The studied graph consists of 11 nodes, 13 edges and 3 circuits (a path which ends at the node it begins). Each circuit contains at least one link: an edge that belongs only to this circuit.

The sub-programme spStructure stores the network graph in a matrix data structure containing the incidence matrices $A = (a_{i,j})$ and $B = (b_{i,j})$:

$$A = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \end{pmatrix}$$

$$B = \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{pmatrix}$$

The *11-by-13* matrix *A* associates each edge with its pair of nodes. The *3-by-13* matrix *B* describes the orientation of the edges in each circuit. In analogy to the Kirchhoff's circuit laws for calculating the current and the voltage in electric circuits, the equations describe the flow rates and pressure losses in the network:

- The law of conservation of mass: the total amount of flow into one node is equal to the total amount of flow out of it:

$$A\vec{\dot{V}} = \vec{0} \qquad (1)$$

with the flow vector $\vec{\dot{V}} = \{\dot{V}_1, \dot{V}_2, ........., \dot{V}_{11}\}$

- The law of conservation of energy: the sum of all pressure differences along the edges of one circuit is equal 0:

$$B\vec{\Delta}p = \vec{0} \qquad (2)$$

with the pressure difference vector $\vec{\Delta}p = \{\Delta p_1, \Delta p_2, ........., \Delta p_{11}\}$

There are also three independent link edge flows belonging to three different circuits. All other volume flows can be calculated as a linear combination of them. Since the columns of *B* describe which link edge stream flows in which pipe, the relationship

$$\vec{\dot{V}} = B^T \vec{\dot{V}}_L \qquad (3)$$

can be obtained using the link flow vector $\vec{\dot{V}}_L = \{\dot{V}_1, \dot{V}_2, \dot{V}_3\}$. The equation (3) reduces the number of unknown entities to three. Each pipe is considered as a flow resistance whose pressure loss is proportional to the square of its flow rate [14]. That means in general:

$$\Delta p = R_r \dot{V}^2 \qquad (4)$$

$R_r$ depends on the pipe´s coefficient of friction, the fluid density and both length and diameter of the considered pipe. If this relationship is developed for all pipes, the equation of conservation of energy becomes:

$$B \cdot f(\vec{\dot{V}}) = \vec{0} \quad ; f : \Re^n \rightarrow \Re^n \qquad (5)$$

using the nonlinear vector function $f$ as in [15]. $\vec{\dot{V}}$ is substituted to obtain:

$$B \cdot f(B^T \cdot \vec{\dot{V}}_L) = F(\vec{\dot{V}}_L) = \vec{0} \qquad (6)$$

by applying the vector function

$$F = f * B^T \qquad (7)$$

The nonlinear equation system (6) is solved by means of a Newton algorithm [16], which can be summarized in the following steps:

- An initial value is set for $\vec{\dot{V}}_L$
- $F(\vec{\dot{V}}_L)$ is calculated using (7) and (4)
- The Jacobian matrix $JF$ of $F$ is calculated using $JF = B \cdot diag(f') \cdot B^T$ and $f_i' = \frac{\partial f_i}{\dot{V}_i}$
- The linear equation system $JF \cdot \Delta\vec{\dot{V}}_L = -F(\vec{\dot{V}}_L)$ is then solved by the application of a standard numerical algorithm like the Gauss elimination method or the method of square roots
- and $\vec{\dot{V}}_L = \vec{\dot{V}}_L + \Delta\vec{\dot{V}}_L$ can be calculated
- The last four procedures are repeated until $\left\|\Delta\vec{\dot{V}}_L\right\|$ becomes too small (within the range of $10^{-3}$litre per hour). The remaining flow rates can be subsequently calculated using (3) and verified using (1).

### 3.3 The thermal calculation

Once the flow rates are determined for all pipes, spThermo calculates the propagation of heated water in the network. First the propagation within one pipe is introduced in this chapter. Then the complete algorithm for the network will be presented.

Each pipe contains a finite number of elements with the section *A* and the length *dx* as indicated in Figure 4. $\dot{Q}_c$ and $d\dot{Q}_l$ present the convective heat flow and the radial heat loss flow for each pipe element respectively. We consider the following notation: *m* for the element mass, $c_p$ for the specific heat capacitance, *h* for the specific enthalpy, *k* for the radial heat transmission coefficient to earth, *T* for the water temperature and

$T_{earth}$ for the pipe surrounding temperature. The first law of thermodynamic is applied for one pipe element:

$$\frac{\partial(mh)}{\partial t} = \dot{Q}_c(x) - \dot{Q}_c(x+dx) - d\dot{Q}_l \qquad (8)$$

An approximation of $\dot{Q}_c(x+dx)$ with 1.st order Taylor series leads to:

$$\dot{Q}_c(x+dx) = \dot{Q}_c(x) + \frac{\partial \dot{Q}_c(x)}{\partial x} \cdot dx \qquad (9)$$

Included in equation (8), it results in:

$$\frac{\partial(mh)}{\partial t} = -\frac{\partial \dot{Q}_c(x)}{\partial x} \cdot dx - d\dot{Q}_l \qquad (10)$$

Assuming the following two equations:

$$\frac{\partial(\dot{Q}_c(x))}{\partial x} = \frac{\partial(\dot{m}_x h)}{\partial x} = \dot{m}_x c_p \frac{\partial T}{\partial x} \qquad (11)$$

and

$$d\dot{Q}_l = k \cdot dx \cdot (T - T_{earth}) \qquad (12)$$

(10) becomes:

$$m c_p \frac{\partial T}{\partial t} = -\dot{m}_x c_p \frac{\partial T}{\partial x} \cdot dx - k \cdot dx \cdot (T - T_{earth}) \qquad (13)$$

$$\frac{\partial T}{\partial t} = -\frac{\dot{m}_x}{\rho A} \cdot \frac{\partial T}{\partial x} - \frac{k}{\rho A c_p} \cdot (T - T_{earth}) \qquad (14)$$

This PDE describes the temperature propagation in one small element. The finite difference method discussed in [16] is then applied to approximate $\frac{\partial T}{\partial t}$ and $\frac{\partial T}{\partial x}$ and iteratively solve the PDE:

$$\frac{\partial T(x,t)}{\partial x} = \frac{T(x,t) - T(x-dx,t)}{dx} \qquad (15)$$

$$\frac{\partial T(x,t)}{\partial t} = \frac{T(x,t) - T(x,t-dt)}{dt} \qquad (16)$$

Including (15) and (16) into (14) enables the calculation of $T(x,t)$ based on both values $T(x-dx,t)$ and $T(x,t-dt)$ (compare Figure 4) . Solving the PDE (14) for an element series (i.e. one pipe) means the determination of the temperature profile along the pipe after $dt$ sec. For each time step $dt$ spThermo executes these three tasks:

- The discretization of the pipe length into finite elements with the length *dx* each.
- The approximation of $\frac{\partial T}{\partial t}$ and $\frac{\partial T}{\partial x}$ according to the equations (15) and (16) above
- The calculation of $T(x,t)$ for each pipe element using the previous temperature profile as initial condition and the pipe input temperature as boundary condition.

The pipe output temperature varies after each time step *dt*. In other words, new boundary conditions are available for the next pipe. This new condition (node temperature) results after the mixture of all streams flowing into this node [5]. For example if pipe 1 receives hot water from pipe 2 and 3, then:

$$T_1 = \frac{\sum \dot{m}_i T_{out,i}}{\sum \dot{m}_i} = \frac{\dot{m}_2 T_{out,2} + \dot{m}_3 T_{out,3}}{\dot{m}_2 + \dot{m}_3} \qquad (17)$$

To determine the network temperature profile at the end of the simulation time $t_s$, spThermo runs the following steps:

- Setting an initial temperature in the different nodes of the network

- The calculation of the temperature propagation in each pipe after *dt* sec using the finite difference method
- The calculation of the new node temperature using the rule of mixture (17)
- The repetition of the last two steps until the end of the simulation time $t_s$

### 3.4 First simulation results

Dynamic simulations were run with the introduced programme to predict the heat propagation in the DH network in Scharnhauser Park. The time needed for a 1-year simulation amounts to 15 minutes. To validate the model, three parameters were used: the return temperature, the flow rate and the heat loss percentage. Figure 5 and Figure 6 show a good agreement between calculated and measured data. The recorded supply temperature profile of Figure 6 was used as an input for this simulation. The calculated data show high fluctuations in both diagrams. They are mainly caused by sudden variations in the consumer load and high k-factor in the implemented P-controller of Figure 2. The low measured temperature values in Figure 6 are due to previous measurement error.

The calculated heat loss amounts to 8.5% and characterizes the energy transmitted through the pipe cover to the earth. It is smaller than the real value of about 13%. The difference between the calculated and the measured percentage may be explained as follow:
The modelled network has a total pipe length of 11.16 km. An approximation for the remaining (unconsidered) pipe length is calculated acc. to the equation below:

$$Q_{l,r} = \int_{1.Jan.}^{31.Dec.} \{k_a \cdot L_r \cdot (T_{pipe} - T_{earth})\}\, dt \qquad (18)$$

with:

$Q_{l,r}$ The heat losses in the remaining pipe length $L_r = 2.34\text{km}$
$k_a$ The average heat transmission coefficient of the pipes
$T_{pipe}$ The water temperature (in both supply and return pipes)

The heat loss amounts to 9.6% including these extra losses. Further incertitude is due to:

- The neglecting of water leakage (approx. 1m³/day)
- The reduction of the number of heat transfer stations from 584 to only 7 which decreases the calculated heat losses within the building installations.
- The heat transmission coefficient may be higher than its nominal value in the pipe connection areas.

## 4 The network optimization

### 4.1 The operating pressure control

The control variables of the district heating in Scharnhauser Park are the supply temperature and the pump pressure. The temperature set point of the heated water depends on the ambient temperature according to the following relationship for winter mode:

$$T_{supply} = -1.316 \cdot T_{amb} + 85.26\ [°C] \qquad (19)$$

For ambient temperatures above 4°C, the supply temperature is fixed to 80°C. The static pump control is based on a constant pressure difference value between supply and return subsystem, which considers the pressure losses along the pipes in the worst case (i.e. in the case of maximal flow rate). The advantage of a dynamic pressure control is to decrease the pressure between the supply and return pipes to the minimum necessary level for given operating conditions. Higher pressure values during the summer are avoided and the pump operating costs can be minimized.

Figure 7 shows the necessary pressure difference that should be applied by the plant pumps depending on the total volume flow, indicated in the x-axis. Applying the approximated red curve as a control function $\Delta p = f(\dot{V})$ instead of a fixed set value (1bar) decreases the electrical pump energy by about 40% from 35.6MWh to 21MWh yearly. A pump efficiency of 65% was assumed in this calculation.

### 4.2 The consumer distribution

The impact of load distribution on the system performance has been investigated with spHeat. The following questions are important especially during the network layout phase: Is there a relationship between the average consumer distance from power plant and the heat losses? Can we supply the same number of consumers with the same load profile and with lower pump energy?
In a first step the yearly heat consumption of the Scharnhauser Park was redistributed among the 7 consumers in order to get 3 different load repartitions (in addition to the existing one). Figure 8 gives the average consumer distance to power plant weighted by load for all 4 cases.

Second, dynamic simulations were run for each case. The total heating energy consumption was set to 24077 MWh/a and the measured supply temperatures of 2008 were used as input for the yearly simulation. In all cases a dynamic pressure control was applied. As shown in Figure 9, the yearly heat losses and the electric pump energy increase with increasing consumer distance from heat source. Although the curve in Figure 8 is quasi linear, the Scharnhauser Park has an approximately uniform behaviour in Figure 9. In fact, Figure 8 illustrates the straight line distance to the power plant, without taking into account the real pipe length needed by the heated water to reach the consumer. In a meshed network, this pipe length strongly depends on the water streams in the different pipes.

Figure 9 demonstrates that the same heat energy can be delivered in a more efficient way. If the main consumers are closer to the power plant, the global temperature and flow rate levels of the network is lower. That leads to smaller heat and pressure losses along the pipes. However larger temperature differences between the consumer nodes are calculated for the close case. Far consumers (node 5 and node 8) would be supplied with slightly lower water temperatures (see Figure 10) especially in the winter season.

The average temperature decrease in the winter can be neglected compared to the savings made in the pump energy and heat distribution. With approximately 1°C lower supply temperature for far nodes, the total heat needed for the Scharnhauser Park can be delivered more efficiently (up to 11% lower heat losses).

## 5 The solar assisted network

This section presents the results of the solar assisted district heating network. The integration of 200m² preinstalled flat plate collectors into the pipes system of the Scharnhauser Park is investigated, and the heat balances are calculated for three different integration scenarios. In all cases a direct integration without heat storage unit is implemented: water from the network pipe flows in the collector heat exchanger circuit and is heated proportionally to solar radiation $I_{sol}$:

$$\Delta T_{pipe} = \frac{\eta_{col} \cdot A_{col} \cdot I_{sol}}{\dot{m}_{pipe} \cdot c_p} \qquad (20)$$

$\eta_{col}$ and $\dot{m}_{pipe}$ present the collector efficiency and the pipe´s mass flow rate respectively. $A_{col}$ is the total collector aperture. Finally the heated water is re-fed into the pipe. Depending on the connected network pipes, three different supply strategies are possible:

- The SS-assisted network (from a supply pipe into a supply pipe)
- The RR-assisted network (from a return pipe into a return pipe)
- The RS-assisted network (from a return pipe into a supply pipe)

## 5.1 The solar assisted supply subsystem (SS-assisted)

In this section, the solar collectors are integrated at different levels (pipes 1, 4, 8, 11 and 13) of the water supply pipes. The network pipes are numbered according to Table 1. Depending on the selected location of heat addition, the mean supply temperature in the appropriate consumer side increases. Solar heat supply is used in this case to increase the operational temperature of distant consumers with originally lower supply temperatures. Supplying pipe 4 or 8, respectively connected to consumers 5 and 8, is therefore most efficient (compare Figure 11).

Supplying for example pipe 8 with additional solar heat decreases the temperature difference range from around 1.5°C to 1°C over all consumers. A significant improvement is logically calculated in the summer. A DH network with solar assisted distant pipes and the main consumers concentrated around the heat source is a good alternative to the current system: higher efficiency and well-balanced temperature profile.

Another supply scenario consists of reducing the plant supply temperature and subsequently heating the water through the solar heat exchanger to maintain the initial operation temperature level. The energy savings for this case are presented in Figure 12 depending on the collector size. Using collectors with the aperture area of 200m² results in 0.2% solar fraction over the year with a specific solar gain of 248kWh/m²a. The high temperature level in the supply pipes limits the thermal collector efficiency and leads to relative low solar gain values.

However, the produced electric power of the modelled heat source (the biomass based ORC power plant) decreases with reduced heat production and increasing supply temperatures. The electric energy illustrated in Figure 12 has been calculated in relationship to the produced thermal power $P_{th}$[kW] and supply temperature $T$ [°C] using an empiric approximation based on measurement data fits:

$$P_e[kVA] = \frac{990.4}{0.977 \cdot \left(\frac{8147.6}{P_{th}}\right)^{\frac{18.7T + \frac{7724.5}{1578.8 - 16.8T}}{0.8 P_{th}}}} \qquad (21)$$

The heating energy savings are accompanied with lower electric energy values (Figure 12). Total savings about 2275€/a can be reached with 200m² collector surface (2385€/a saved through solar supply minus 110€/a electric energy sales). The electric consumption of the collector pump is not considered.

## 5.2 The solar assisted return subsystem: RR-assisted

Another strategy consists of supplying the district heating network with solar energy in the return pipe 1 (close to the heat source). Since the collector efficiency increases with lower inlet temperatures, higher solar heat gains are expected.
Using meteorology data of the year 2008 in Stuttgart Germany, a low yearly solar fraction of 0.32% has been calculated (421kWh/m²a). The resulting electric energy decrease amounts to around 6MWh over the year due to higher return temperatures. Without taking the collector pump consumption into account, the overall savings amount to 3567€/a.
Above the heat load 6MW two gas fired boilers with a maximum power of 18MW are in operation. If the solar collectors are only connected during peak load phases to reduce the boiler contribution, the produced electric energy is not affected: The ORC process would be running with maximal output power. In this case, the 200m² collector area provides only 91.5kWh/a thermal energy, because of low solar radiation during peak load phases (winter).

## 5.3 The solar assisted return-supply subsystem: RS-assisted

RS-assisted district heating networks have two advantages: the solar gain is higher than in the SS-case because of lower collector temperatures and the electric power plant efficiency is not affected since the return temperature doesn´t increase. However the additional supply costs are higher than in the other two cases (SS and RR), since the installed pump has to overcome the pressure difference between the return and supply networks. In our case matched-flow control was applied for the water being heated in order to reach exactly the temperature level in the supply pipes. The RS-assisted district heating network in Scharnhauser Park results in total savings about 2950€/a with 0.26% solar fraction (342 kWh/m²a).

Under local climate conditions, direct solar assistance with 200m² collector aperture does not have a significant economic benefit in the case of Scharnhauser Park. A larger aperture surface has to be installed to increase the solar fraction. The RR-heat supply represents the most effective strategy among the studied cases. Using 1200m² collector surface increases the solar fraction to 1.75% (385 kWh/m²a) and saves around 20.000€/a.

# 6 Conclusions

In the paper a network model was introduced and used to simulate the DH system in Scharnhauser Park. Both hydraulic and thermal models are derived in a mathematical form that can be easily transformed into a computer code. The programme structure in MATLAB was described and the obtained results were compared to the measured data. Applying a dynamic pressure control in the simulation reduces the pump energy costs by 40%. The influence of consumer distribution on heat losses was also investigated. More than 10% savings in heat loss and pumping distribution energy can be obtained, if consumers with high demand are situated closer to the power plant. The solar thermal contribution is currently very low at 0.3% of the total heat demand. Different options to integrate solar thermal systems in the network were evaluated using the tool. With 421kWh/m²a specific solar gain the RR-assisted option is the most effective strategy to integrate the existing solar thermal collectors into the network.

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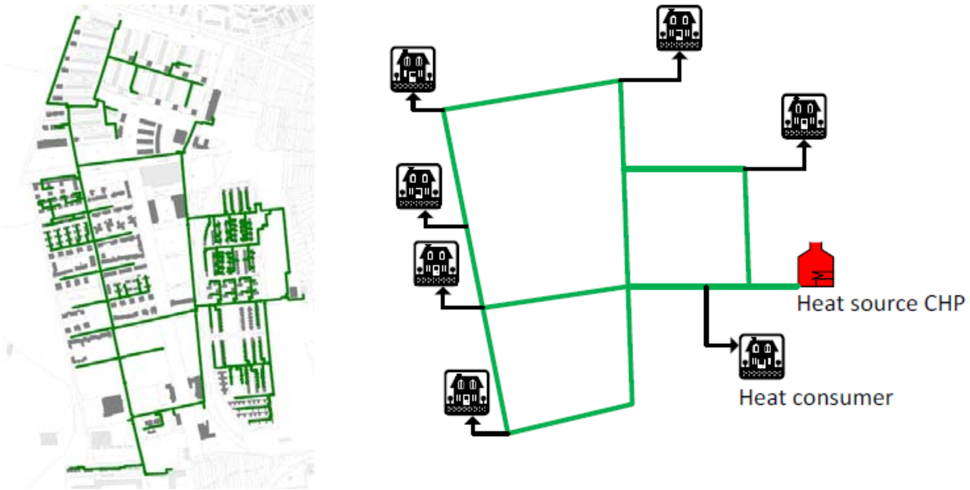
## Nomenclature

$T$: Temperature [K]
$\dot{V}$: Water flow [m³/s]
$\Delta p$: Pressure loss [Pa]
$A$: Element section [m²]
$dx$: Element length [m]
$dt$: Time interval [s]
$\dot{Q}_c$: Convective heat flow [W]
$d\dot{Q}_L$: Heat loss flow [W]
$m$: Element mass [kg]
$c_p$ : Specific heat capacitance [J/kgK]
$h$ : Specific enthalpy [J/kg]
$k$ : Linear heat transmission coefficient [W/mK]
$T_{earth}$: Ground temperature [K]
$T_{amb}$: Ambient temperature [°C]
$\rho$: Density [kg/m³]
$\dot{m}$ : Mass flow [kg/s]
$t_s$: Simulation time [s]
$I_{sol}$: Specific solar radiation [W/m$^2$]
$\eta_{col}$: Collector efficiency [%]
$A_{col}$: Collector area [m²]

Figure captions:



Table captions




(a) the real network (b): the reduced network

**Figure 1: The district heating network in Scharnhauser Park**

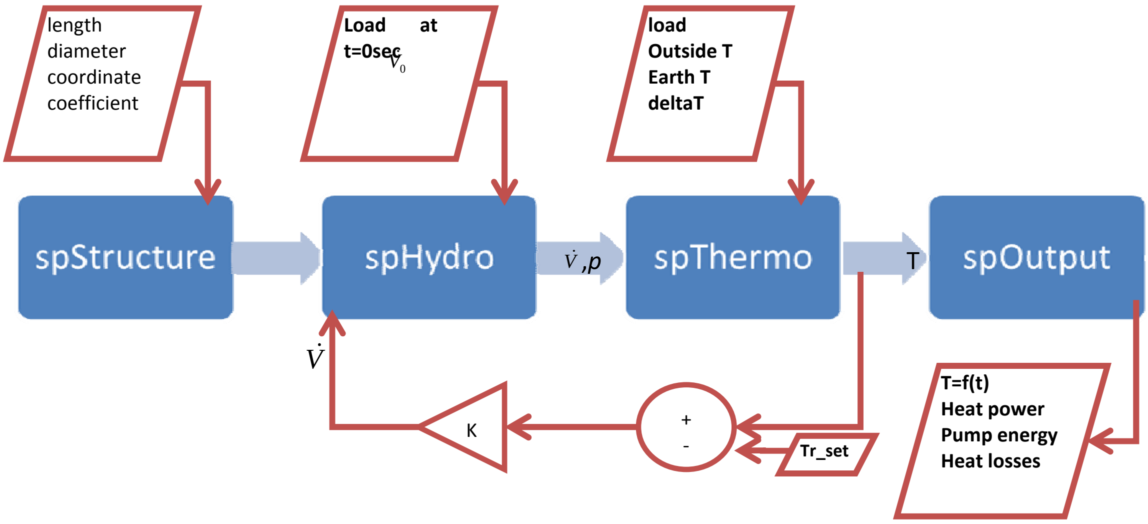



**Figure 2: The spHeat programme structure**

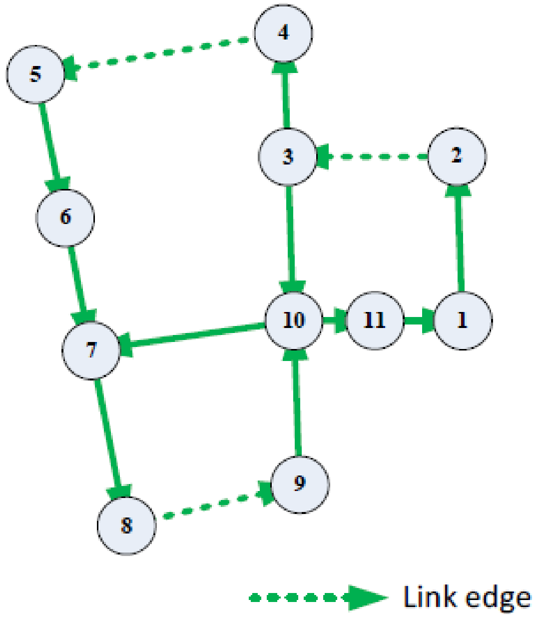



**Figure 3: The network graph**

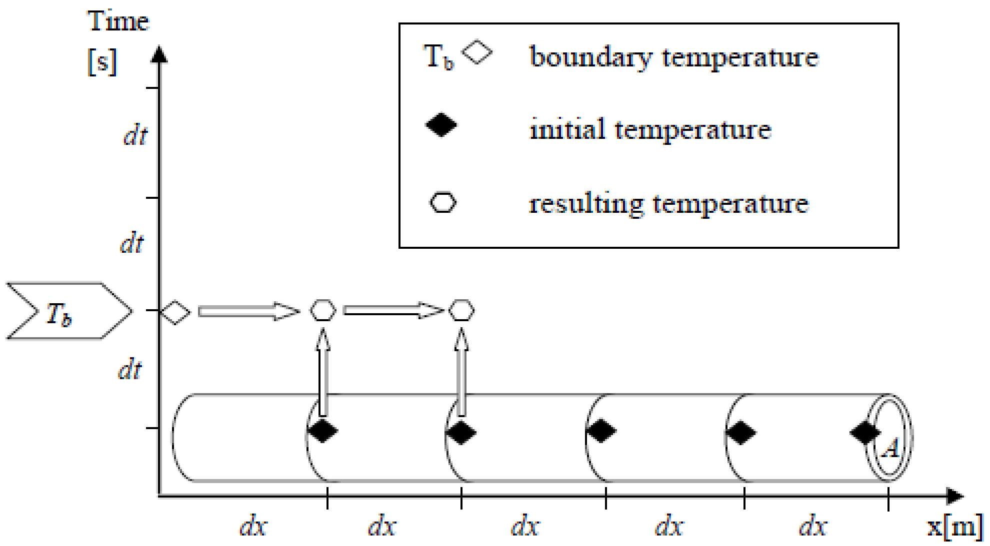



**Figure 4: The thermal calculation**

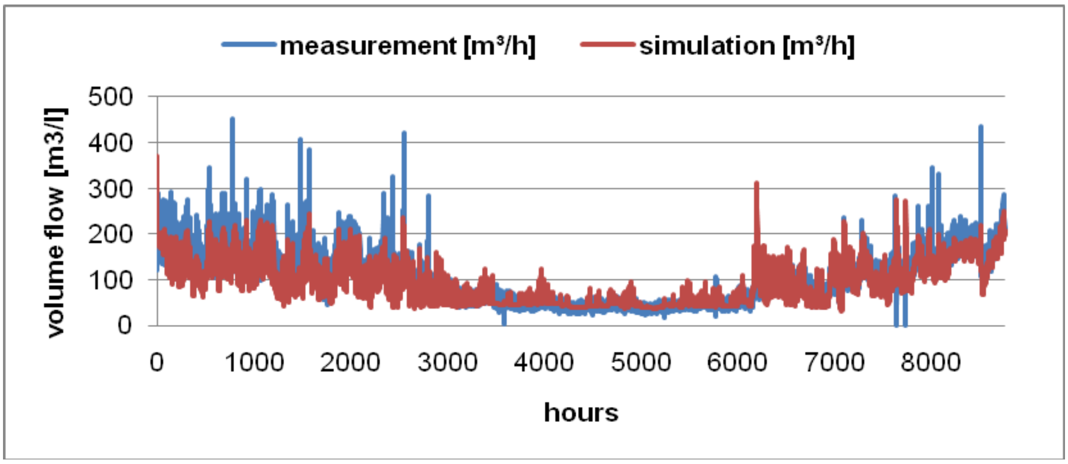
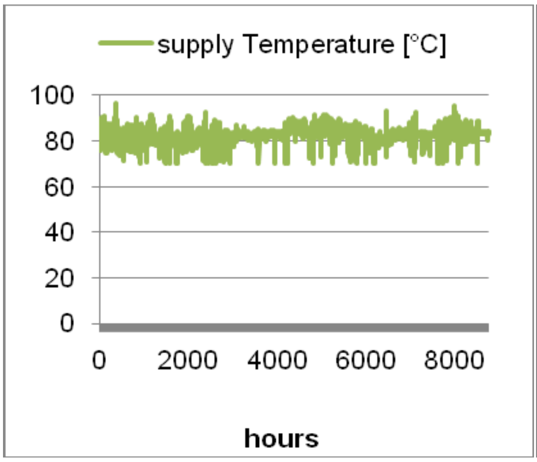



**Figure 5: The flow rate in the district heating network**



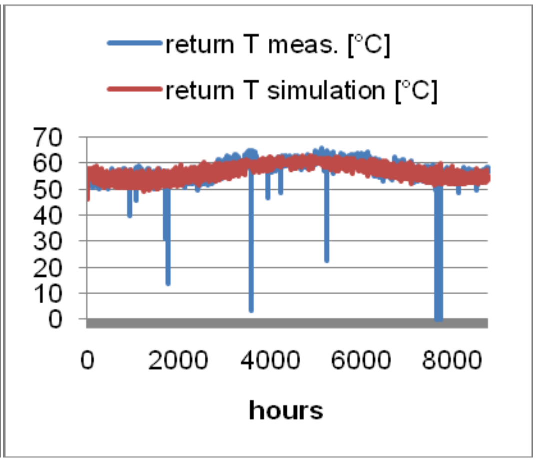




**Figure 6: The supply and return temperature of the district heating network**

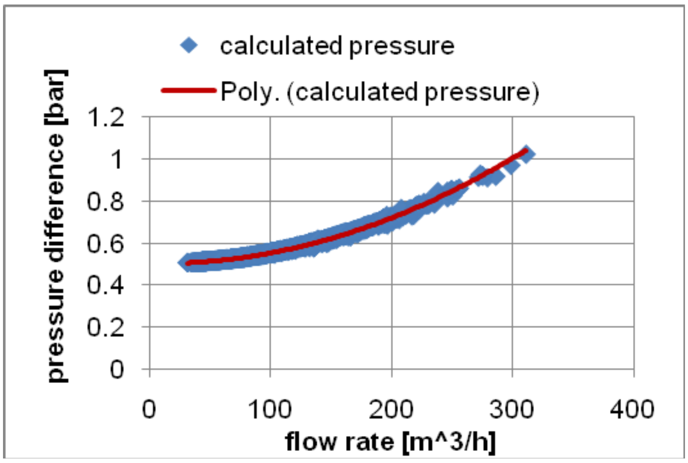



**Figure 7: Fitting curve for dynamic pressure control**


**Figure 8: The average consumer distance**

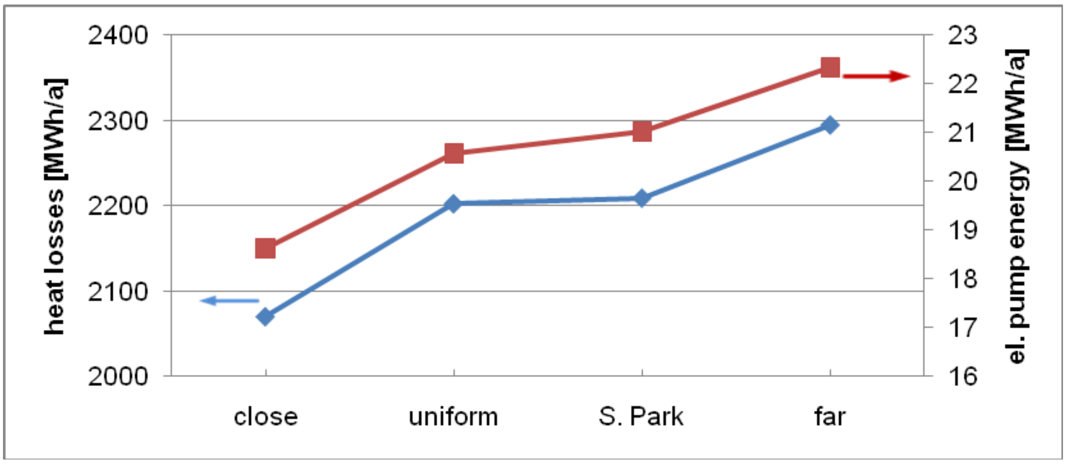



**Figure 9: Heat losses and electric pump energy**

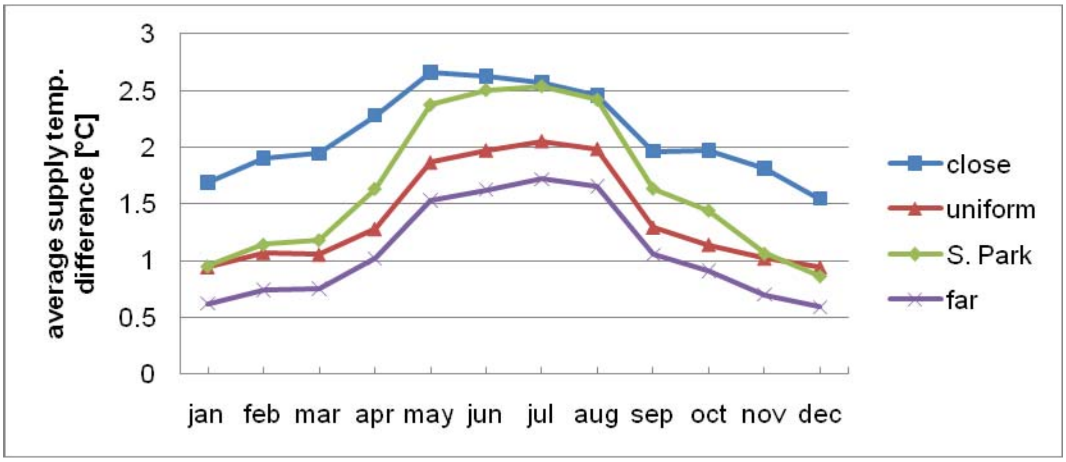



**Figure 10: The supply temperature difference between consumers**

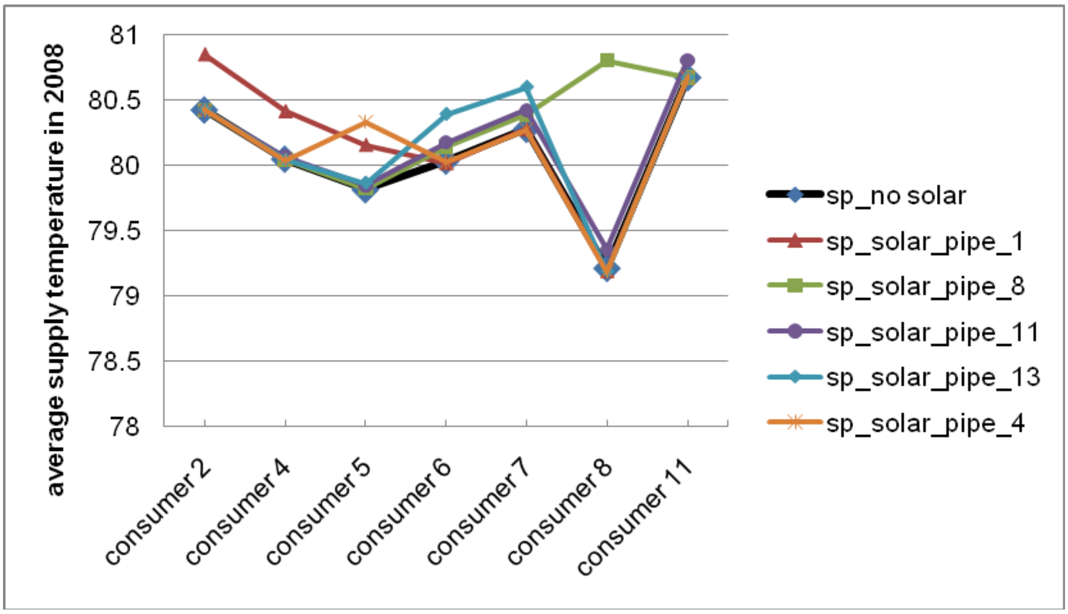



**Figure 11: The average consumer supply temperature in 2008**

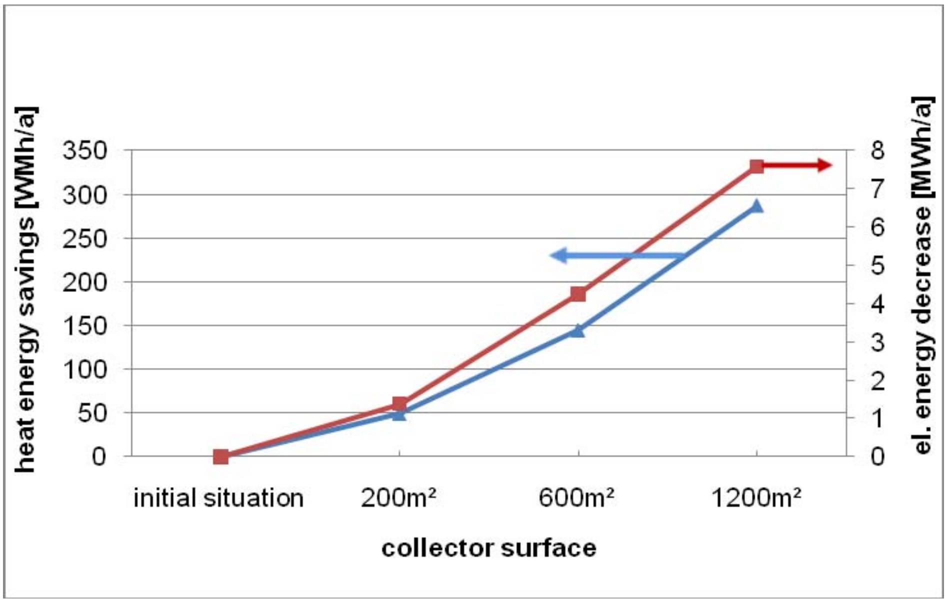



**Figure 12: The energy balances of the solar-assisted system**

**Table 1: The network pipes**

| Pipe N° | between node | and node |
|---|---|---|
| 1 | 1 | 2 |
| 2 | 2 | 3 |
| 3 | 3 | 4 |
| 4 | 4 | 5 |
| 5 | 5 | 6 |
| 6 | 6 | 7 |
| 7 | 7 | 8 |
| 8 | 8 | 9 |
| 9 | 9 | 10 |
| 10 | 10 | 11 |

| | | |
|---|---|---|
| 11 | 11 | 1 |
| 12 | 3 | 10 |
| 13 | 10 | 7 |