BauSIM2022 in Weimar
20.-22. September 2022

DETAILED MODELLING OF LARGE DISTRICT HEATING AND COOLING NETWORK COUPLED TO GROUND HEAT EXCHANGER

Hauke Hirsch[1], Anne Paepcke[1]
[1] *Institut für Bauklimatik, Technische Universität Dresden, Deutschland,*
E-Mail: hauke.hirsch@tu-dresden.de

Abstract

Modelling of district heating and cooling (DHC) systems allows for optimized system design and operation. We present a novel thermo-hydraulic network model, which we apply to a large 5th generation DHC network, coupled to a horizontal ground heat exchanger. We use Co-Simulation with finite-volume models in order to account for heat gains of both, the ground heat exchanger as well as the uninsulated network piping system. We found that the network contributes about 50 % of the source heat demand during the heating period, whereby it strongly varies over the course of the year. The model's simulation performance is relatively high as we reduce the number of pipe ground models by identify pipes with similar ground temperatures.

Introduction

In recent years, novel district heating and cooling (DHC) concepts have been applied in practice, incorporating renewable heat sources such as geothermal energy. These systems, referred to as low temperature district heating and cooling networks or 5th generation DHC (5GDHC) [1], [2] feature operation temperatures in the range of -5 °C to 20 °C. Several 5GDHC systems have been installed in Europe, mainly in Switzerland and Germany already. An overview of existing systems can be found in Buffa et al. [2].

Simulation models constitute a valuable tool for design, planning and optimization of 5GDHC systems. A comprehensive literature review regarding modelling tools can be found in Allegrini et al. [3]. Also Schweiger et al. [4] compared several thermal network simulation tools and validated the pipe models with measured data from a laboratory setup. In recent years, the most widely used tool among researchers has been Modelica, using the pipe model from IBPSA Modelica Library [5]. The respective model is described by van der Heijde et al. [6] and widely used in multiple studies (see e.g. [7], [8]). However, Modelica models have shown poor simulation performance when applied to large-scale networks, making simulations time-consuming or practically impossible. Modellers therefore often simplify the network topology or the physical relations [9]. Additionally, heat exchange between uninsulated network pipes and the surrounding soil as well as between supply and return pipes is commonly modelled with over-simplified soil models, which cannot account for changing boundary conditions at the soil surface.

Therefore, we developed a novel thermo-hydraulic network model [10], which is part of open-source simulation software SIM-VICUS [11]. For heat exchange with the soil, we use two-dimensional hygro-thermal finite-volume models of the ground that can also capture ice-formation around the pipes [12].

In this paper, we present our model and simulation results of a 5GDHC network with a horizontal ground heat exchanger (HGHX), which has been installed recently in Germany. We briefly describe the thermo-hydraulic network model, the ground models for the pipe surrounding and the HGHX as well as the coupling method. Eventually, we evaluate heat gains from the network and the HGHX in detail and consider the impact of passive cooling.

Simulation Model

Thermo-Hydraulic Network Model

The thermo-hydraulic network model is part of open-source simulation software SIM-VICUS [11] and extensively described in [10]. In contrast to existing models, we take into account the current flow regime for calculations of pressure loss and convection inside the pipe, thereby also considering temperature-dependent fluid properties. Pipes are discretised in multiple fluid volumes along flow direction, whereby we solve the thermal balance equation for each single fluid volume. For numerical solution we use error-controlled, multi-order, adaptive time step solver CVODE.

We have implemented hydraulic controllers (P, PI-controller) for controlling the temperature difference at each sub-station. For modelling of heat pumps, we use bi-quadratic polynomials for the COP, which are based on evaporator and condenser temperatures. Heat demand profiles are obtained from building energy simulations of all buildings in the district, which have been carried out with SIM-VICUS as well.

Pipe Ground Model

As mentioned before, pipes in 5th generation DHC networks are usually not insulated and thus exchange heat with the surrounding soil. The network operation temperatures are expected to drop below 0 °C, so we can assume that this heat exchange strongly influences the surrounding soil temperature. We therefore set up a finite-volume model of the pipe surrounding, which accounts for boundary conditions at the soil surface as well as for heat exchange between supply and return pipe. For this purpose, we use hygro-thermal simulation software DELPHIN, which features coupled heat and moisture transport, as well as a physical freezing model based on the material pore size distribution [13], [14]. The hygro-thermal parameters for different soil types have been implemented as described in [15].

The model geometry and boundary conditions are depicted in Figure 1. We take into account convection, solar irradiation and long-wave radiation at the soil surface. The supply pipe (light blue) and the return pipe (dark blue) are simplified through quadratic empty spaces and placed 1.5 m below the surface with a separation of 0.3 m. The edge length of the quadratic spaces is $x_{pipe} = \frac{\pi}{4} d_{pipe}$, with d_{pipe} being the pipe outer diameter.

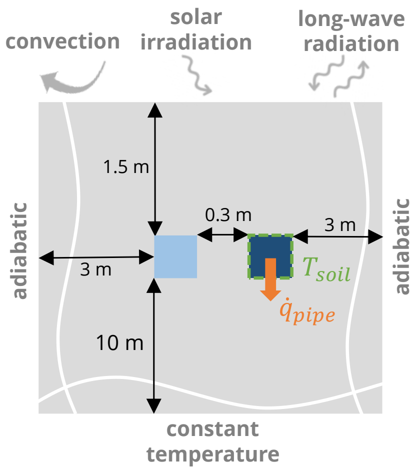

Figure 1: Ground model geometry and boundary conditions

Both lateral edges of the volume have sufficient distance from the pipes, so that the influence of the pipes can be neglected. Below the pipes, a constant temperature of 10 °C in a distance of 10 m is set. The geometry is simplified to a two-dimensional plane perpendicular to the pipes. We assume a constant moisture content for the entire plane, hence only heat conduction and ice formation perpendicular to the pipes are considered. The final discretised finite-volume model contains approximately 2000 elements.

Co-Simulation of Network and Pipe Ground Model

For coupling between the network pipe model and the ground model, we use the FMI interface, which is supported by both SIM-VICUS and DELPHIN. The DELPHIN ground model provides the averaged soil temperature T_{soil} at the pipe outer surface for the SIM-VICUS network models as input. As shown in Figure 2, our pipe model is discretised in multiple fluid

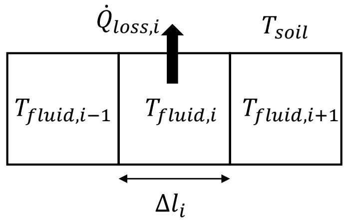

Figure 2: Scheme of discretized pipe

volumes. Accordingly, we calculate the pipe heat loss as

$$\dot{Q}_{loss} = \sum_i (T_{fluid,i} - T_{soil}) UA_{pipe,i} \quad \textbf{(1)}$$

with the pipe's UA-Value

$$UA_{pipe,i} = \frac{l_i}{\frac{1}{\pi h d} + \frac{1}{U_{pipe}}} \quad \textbf{(2)}$$

and the fluid temperature of each discretised volume $T_{fluid,i}$, the length of each discretised volume l_i, the pipe diameter d, the heat transfer coefficient between fluid and pipe wall h and the pipe's length-specific U-Value U_{pipe}.

The boundary condition for the ground model is then formulated as the area-specific heat flux

$$\dot{q}_{pipe} = \frac{\dot{Q}_{loss}}{\pi \, d_{pipe} \, l_{pipe}} \quad \textbf{(3)}$$

Considering the fact that the entire network model, as shown in Figure 4, has a total of 387 distinct pipes, using a unique pipe ground model for each pipe would result in very high computational effort. Hence, we coupled the same pipe ground model to pipes with similar fluid temperatures.

For this purpose, we developed the following algorithm:

1. We calculate the fluid temperature change between inlet and outlet for each pipe, assuming a mean temperature difference of 1 K between fluid and soil as well as a nominal mass flow $\dot{m}_{nom}$. Using equation (1) this can be written as

$$\Delta T_{pipe} = \frac{UA_{pipe}}{\dot{m}_{nom} c_p} \quad \textbf{(4)}$$

2. We follow the flow path from the source, i.e. the horizontal ground heat exchanger (HGHX) outlet, to each single building using a graph algorithm and sum up the cumulative temperature change along that path (between the HGHX outlet and

each single pipe outlet). This value, called the cumulative temperature change ΔT_{cum} is assigned to each pipe along that path. Subsequently, a pipe that is far away from the HGHX has a higher ΔT_{cum} and one which is closer to the HGHX has a lower ΔT_{cum}, even though both may have the same diameter.

3. We divide the range between minimum and maximum obtained ΔT_{cum} by a prescribed integer N_{pgm}(e.g. $N_{pgm} = 10$), which is the number of different pipe ground models. Now we have N_{pgm} intervals of ΔT_{cum} and we can assign each pipe to one of the intervals, i.e. to one pipe ground model.

Co-Simulation with Ground Heat Exchanger Model

The network is coupled to a horizontal ground heat exchanger (HGHX), which we model with DELPHIN as well, applying identical boundary conditions at the soil surface and the bottom as described above. The geometry, as shown in Figure 3, is simplified to a two-dimensional plane, whereby we assume symmetry in the centre and therefore only model half of the HGHX. The final discretised finite-volume model for the HGHX contains approximately 4200 elements. Due to the size of the collector, we do not represent each single pipe in this plane. Instead, we implemented a volumetric heat source for each of the two layers. This heat source is applied to a volume V_{HGHX}, which comprises the HGHX area ($A_{SGHX} = 11.000\ \mathrm{m}^2$) multiplied by the pipe outer diameter ($d_{pipe} = 25\ \mathrm{mm}$). Within the thermo-hydraulic network model, the HGHX is represented through an array of N_p parallel pipes. The boundary condition for the ground model, provided by the thermo-hydraulic network model is then

$$\dot{q}_{HGHX} = \frac{N_p\ \dot{Q}_{loss}}{d_{pipe}\ A_{HGHX}} \quad (5)$$

where $\dot{Q}_{loss}$ is the heat loss of one single pipe.

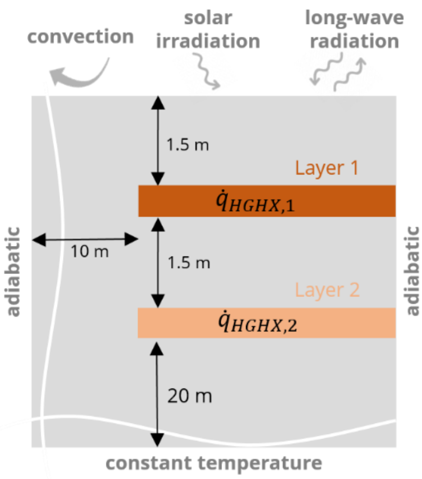

Figure 3: HGHX model geometry and boundary conditions

We use FMI simulation master MASTERSIM [16], [17] for model coupling. All simulations were carried out for a period of 5 consecutive years to ensure quasi steady-state of the ground models. The results were evaluated only for the 5th year.

Investigated DHC Network

The considered DHC network has recently been installed in the city of Bad Nauheim, Germany. It supplies heat to a new housing area, consisting of 180 houses (multi-family and single-family) with distributed heat pumps and a total heat demand of appr. 2400 MWh/a.

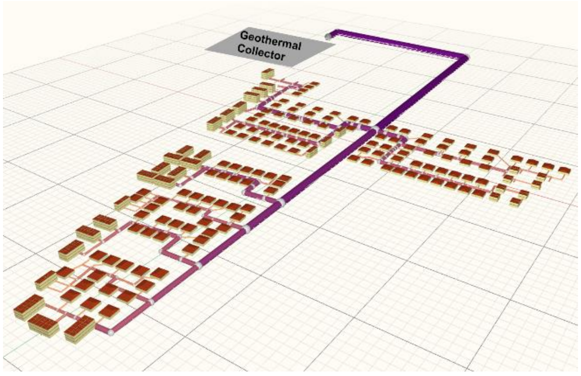

Figure 4: Simulation model of the DHC network in SIM-VICUS. The pipe diameters are scaled by factor 30 for enhanced visibility. Major grid size is 100 m.

The topology is shown in Figure 4. The source heat is provided partly by a large horizontal ground heat exchanger (HGHX), which is buried in two layers (at 1.5 m and 3.0 m) with an area of 11.000 m² each. The remaining part of the source heat is covered by the uninsulated network pipes, which have a length of 6 km (12 km in total for supply and return). The network can also be used for passive cooling during the summer without operating the heat pump. The network design fluid temperatures are in a range between -5 °C ... 20 °C. At each network substation there is a valve ensuring a prescribed mass flux which corresponds to a temperature difference of 4 K at the heat pump. For further information, we refer to [1].

Results

Heat Gains from network and HGHX

In We carried out simulations with different number of pipe ground models N_{pgm}, in order to evaluate how this impacts the accuracy of the coupled model. In Figure 8 the heat gains from network pipes and HGHX are shown over the course of the 5th year (upper plot). Moreover, we plotted the respective heat gains relative to the source heat drawn from the ground by all heat pumps, i.e. the heat demand coverage (central plot) as well as the ground temperatures at all supply pipes, return pipes and both HGHX layers (lower plot). Here, supply pipes are in flow direction from HGHX to

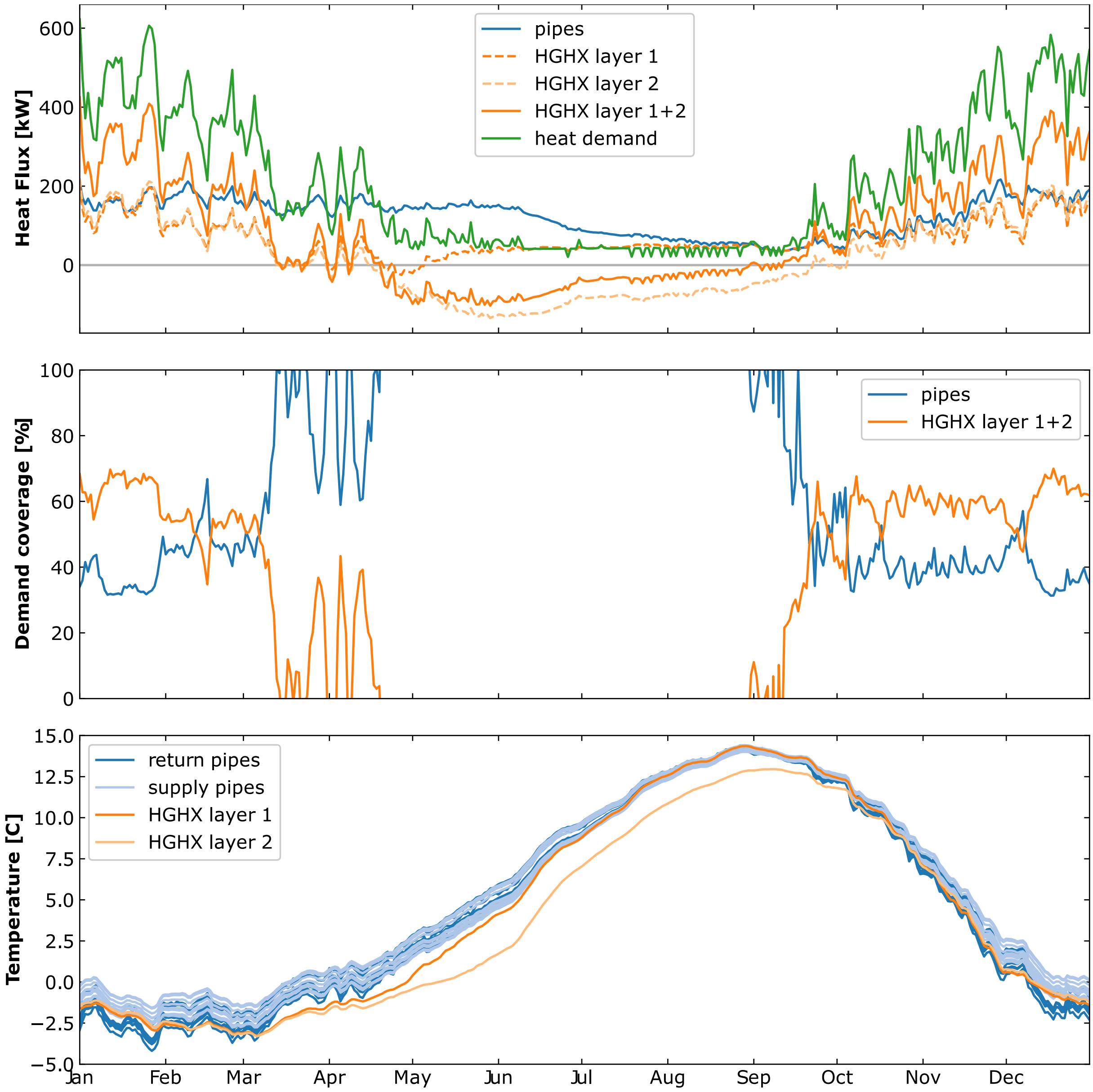

Figure 5: Upper plot: Heat gains from network pipes and HGHX layers. Center plot: Heat demand coverage from network pipes and both HGHX layer. Lower plot: Ground Temperatures at supply pipes (HGHX to buildings) and return pipes (buildings to HGHX) as well as at both HGHX layers. All values are daily averages.

buildings and return pipes are from buildings to HGHX.

During the winter period, from October to March, 53 % of the source heat is provided by the HGHX, while during the period of highest heat demand, in January, it rises up to 65 %. The ground temperatures clearly drop below 0 °C, implying ice formation at both the HGHX and the network pipes. This is also confirmed by the temperature field around network pipes at end of February (see Figure 6).

As it can be seen from the course of the temperatures over the year, after the winter period, the ground around the HGHX is significantly cooler than that around the network pipes and the regeneration takes longer. This is due to the fact that the HGHX pipes are tightly packed leading to a uniform temperature distribution in the respective layers. Accordingly, it takes until June for the ice in the second (lower) layer to vanish completely.

During summer, the heat gains of the second layer become negative, while the network pipes provide more heat than what is demanded from the heat pumps. Hence, heat is carried from the network pipes towards the HGHX.

While this effected was not intended during project design, it is a potential benefit of the system, as it contributes to the regeneration of the HGHX during the summer.

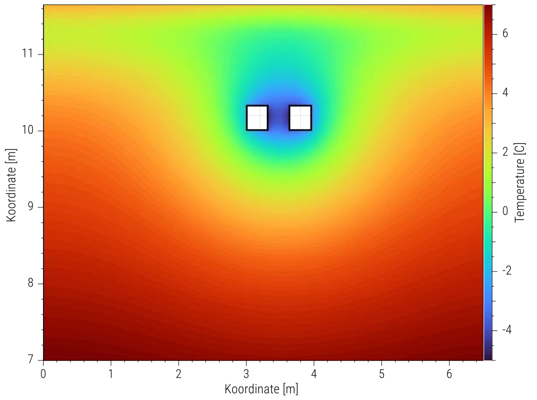

Figure 6: Temperature in ground around pipes at network main supply line at end of February. The pipe diameter is 40 cm.

Impact of passive cooling

In the current scenario only heating demand has been considered, neglecting passive cooling of the buildings. In a next step, we have included passive cooling, using according cooling demand profiles from building energy simulations. Figure 7 shows the respective HGHX ground temperatures in comparison with the default scenario without passive cooling. It should be noted that the amount of required cooling energy is only 10 % of the heating energy, as the district consists solely of residential buildings.

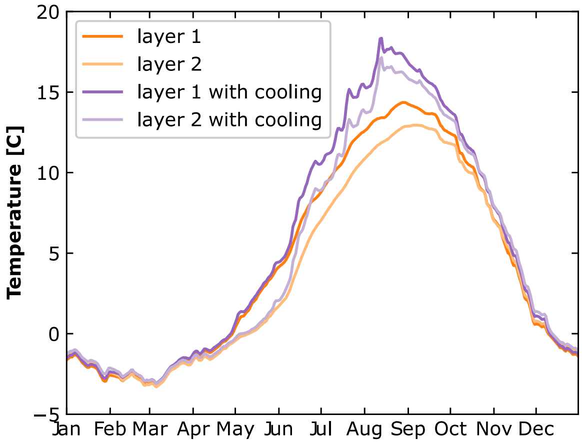

Figure 7: Daily averaged ground temperatures at HGHX layers with and without passive cooling.

The ground temperature in both layers clearly rises during summer due to the heat injection. The difference to the default scenario in August is about 5 K. However, in December, the difference remains to be only 0.5 K and almost vanishes until the end of the heating season. Hence, the heat pumps benefit during winter only slightly from heat injection during summer.

Simulation performance

We carried out simulations with different number of pipe ground models N_{pgm}, in order to evaluate how this impacts the accuracy of the coupled model. In Figure 8, the daily-averaged network return temperature at the central pump is shown for different numbers of pipe ground models N_{pgm}. As reference, we use a simulation with 50 models. The evaluated cases with 1 or 10 different models are both relatively close to the reference case. However, the case with only 1 pipe ground model shows some deviation during summer, so we decided to use 10 different models, i.e. $N_{pgm} = 10$.

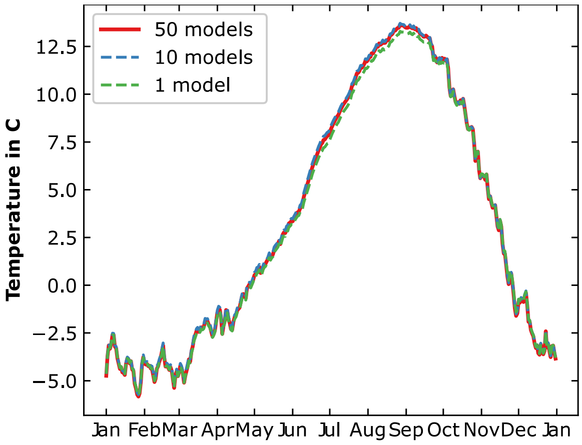

Figure 8: Daily averaged network return temperature at pumping station for different numbers of pipe ground models.

Table 1 shows the required CPU time for one year of simulation and different numbers of pipe ground models respectively. We use a Laptop with an i7-11800H and a CPU rate of 2.3 GHz for all simulations. The performance is clearly dominated by the thermo-hydraulic network simulation, which requires between 97 % of the CPU time ($N_{pgm} = 3$) and 68 % of the CPU time ($N_{pgm} = 50$). Considering the fact that the network model solves 1531 ODEs, which are in part tightly coupled due to hydraulic controllers for temperature difference control, the obtained performance is moderate when compared to similar models in Modelica/DYMOLA.

Table 1: Performance of coupled simulation for 1 year real time

N_{pgm}	**CPU time only network [h]**	**CPU time total [h]**
50	6.36	9.33
10	6.37	6.83
3	6.42	6.60

Conclusion

This article presented a model of a large-scale DHC network coupled with a horizontal ground heat exchanger (HGHX). The approach focuses on detailed modelling of heat exchange with the ground using dedicated finite-volume models for both the pipe surrounding and the HGHX. For modelling of the network, we use open source simulation software SIM-VICUS, which we couple to ground models in DELPHIN using the FMI 2.0 interface. We showed that with 10 different pipe ground models, the heat exchange between all network pipes and the ground can be described sufficiently, even though the network is relatively large and uninsulated.

The heat gains from the network contribute to the total heat gains by about 50 % during heating season and 35 % during peak heat demand in January. Subsequently, in January the ground heat exchanger covers the substantial part, which leads to lower ground temperatures compared to the pipe surrounding. Moreover, we found that passive cooling rises ground temperatures during summer substantially but has only minor impact on temperatures during heating season. The simulation time for the coupled model is about 6.8 h for one year of real time, being strongly dominated by the thermo-hydraulic network model.

Acknowledgement

The authors thankfully acknowledge the founding by the German Ministry of Economic Affairs and Energy (BMWi) for the research projects KNW-Opt under the project number 03EN3020D and ErdEisII under the project number 03ET1634C. Further, we would like to thank everyone who contributed to the development of SIM-VICUS, in particular Dr. Andreas Nicolai.

References

[1] R. Zeh *et al.*, ‘Large-Scale Geothermal Collector Systems for 5th Generation District Heating and Cooling Networks’, *Sustainability*, vol. 13, p. 6035, May 2021, doi: 10.3390/su13116035.

[2] S. Buffa, M. Cozzini, M. D’Antoni, M. Baratieri, and R. Fedrizzi, ‘5th generation district heating and cooling systems: A review of existing cases in Europe’, *Renew. Sustain. Energy Rev.*, vol. 104, pp. 504–522, Apr. 2019, doi: 10.1016/j.rser.2018.12.059.

[3] J. Allegrini, K. Orehounig, G. Mavromatidis, F. Ruesch, V. Dorer, and R. Evins, ‘A review of modelling approaches and tools for the simulation of district-scale energy systems’, *Renew. Sustain. Energy Rev.*, vol. 52, pp. 1391–1404, Dec. 2015, doi: 10.1016/j.rser.2015.07.123.

[4] G. Schweiger *et al.*, ‘District energy systems: Modelling paradigms and general-purpose tools’, *Energy*, vol. 164, pp. 1326–1340, Dec. 2018, doi: 10.1016/j.energy.2018.08.193.

[5] M. Wetter *et al.*, ‘IBPSA Project 1: BIM/GIS and Modelica framework for building and community energy system design and operation – ongoing developments, lessons learned and challenges’, *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 323, p. 012114, Sep. 2019, doi: 10.1088/1755-1315/323/1/012114.

[6] B. van der Heijde *et al.*, ‘Dynamic equation-based thermo-hydraulic pipe model for district heating and cooling systems’, *Energy Convers. Manag.*, vol. 151, pp. 158–169, Nov. 2017, doi: 10.1016/j.enconman.2017.08.072.

[7] T. Blacha, M. Mans, P. Remmen, and D. Müller, ‘Dynamic Simulation Of Bidirectional Low-Temperature Networks - A Case Study To Facilitate The Integration Of Renewable Energies’, Rome, Italy, 2019, pp. 3491–3498. doi: 10.26868/25222708.2019.210670.

[8] D. Saelens *et al.*, ‘Towards a DESTEST: a District Energy Simulation Test Developed in IBPSA Project 1’, Rome, Italy, 2019, pp. 3569–3577. doi: 10.26868/25222708.2019.210806.

[9] B. Falay, G. Schweiger, K. O’Donovan, and I. Leusbrock, ‘Enabling large-scale dynamic simulations and reducing model complexity of district heating and cooling systems by aggregation’, *Energy*, vol. 209, p. 118410, Oct. 2020, doi: 10.1016/j.energy.2020.118410.

[10] H. Hirsch and A. Nicolai, ‘An efficient numerical solution method for detailed modelling of large 5th generation district heating and cooling networks’, *Energy*, 2022. THIS PAPER IS IN REVIEW, A DOI WILL BE PROVIDED SOON.

[11] ‘SIM-VICUS - NEXT LEVEL BUILDING SIMULATION’, *SIM-VICUS*, Jan. 31, 2022. https://www.sim-vicus.de/ (accessed Jan. 31, 2022).

[12] H. Hirsch, H. Petzold, and J. Grunewald, ‘Efficiency and area demand of multi-layer ground heat exchanger using phase change of water’, *MATEC Web Conf.*, vol. 282, p. 02027, Jan. 2019, doi: 10.1051/matecconf/201928202027.

[13] L. Sontag, A. Nicolai, and J. Grunewald, ‘Influence of Ice Formation on Thermal Conductivity and Liquid Water Conductivity in Hygrothermal Transport Models’, Proceedings of the 10th Nordic Symposium on Building Physics. 2014.

[14] J. Grunewald, ‘Diffusiver und konvektiver Stoff- und Energietransport in kapillarporösen Baustoffen’, Phd Thesis, Dresden, 1997.

[15] J. Grunewald, H. Hirsch, and H. Petzold, ‘Implementation of a method for converting soil properties into building physical material properties’, *E3S Web Conf.*, vol. 172, p. 14001, 2020, doi: 10.1051/e3sconf/202017214001.

[16] A. Nicolai, *MasterSim*. 2022. Accessed: Feb. 10, 2022. Available: https://github.com/ghorwin/MasterSim

[17] A. Nicolai, A. Paepcke, and H. Hirsch, ‘Robust and accurate co-simulation master algorithms applied to FMI slaves with discontinuous signals using FMI 2.0 features’, 2019, pp. 769–776. doi: 10.3384/ecp19157769.