MODELING OF THERMAL DISTRICT HEATING NETWORKS WITH COMMON SOURCES AND DECENTRALIZED HEAT PRODUCTION

Konstantin FILONENKO*, Krzysztof ARENDT, Christian VEJE

Center for Energy Informatics, University of Southern Denmark
Campusvej 55, DK-5230 Odense M, Denmark; [kfi, krza, veje]@mmmi.sdu.dk

Abstract

A detailed modelling approach is proposed for dynamic simulation of district heating systems consisting of borehole heat exchangers, non-insulated piping, decentralized heat pumps and heat consumers. The boreholes and pipes are considered as distributed heat sources and ground source heat pumps are controlled individually to satisfy individual consumer demands. The models based on the presented approaches are simulated in Dymola using open-source district heating libraries, IBPSA, IDEAS and Buildings. The parameters of the heat pump are estimated. System dynamics is simulated in changing weather conditions throughout the year.

Keywords

Low-temperature district heating, sustainable energy sources, ground source heat pump, 4th generation district heating, object-oriented modelling.

1 Introduction

The concept called Termonet [1] emerged in Denmark to describe small district-scale heating networks, which will allow inhabitants with no access to district heating to satisfy their energy demand and maintain an indoor thermal comfort. Heating is produced in Termonet by converting electric energy inside individual ground source heat pumps to energy of the hot water stored in stratified water tanks. Heat pumps are installed in each house and the energy supplied to their cold side is extracted from common vertically oriented borefield. By utilizing sustainable energy sources, Termonet joins the development of 4th and 5th Generation District Heating [2, 3], which requires accurate dynamic modelling with the purpose of predicting system dynamic behaviour and comparison to other thermal networks under changing weather, pricing and occupancy conditions.

Decentralization of energy resources in 4th Generation District Heating leads to various network topologies with emphasis on heat storage, generation and transport at various locations inside the thermal network. This causes some difficulty in thermal grid modelling due to the increased physical complexity. Modelica [4] provides an excellent trade-off between complexity, simulation time and reusability for industrial applications. This study will present the modelling of a complete Termonet system in Modelica-based simulation tool Dymola [5] using open source libraries involved in the international project IBPSA project 1 [6] and Modelica Standard Library [7]. The borehole parameters in the model are based on the

Thermal Response Test of the Danish test site (Grønnegade, 6623 Vorbasse) with three buildings and three borehole heat exchangers. The calibration of the Termonet heat pump is made by running a genetic algorithm optimization using the ModestPy framework in Python [8]. On the supply side, the uninsulated horizontal piping and vertical borehole field is modelled and coupled to the calibrated heat pump model. Yearly simulations are run to ensure the model is suitable for longer simulations and the dynamics of the system is briefly discussed.

2 Methodology

2.1 Mathematical Model and Parameters

Simulations are run on Dymola Modelica, which allows to graphically represent the dynamic models implemented as object-oriented code. In district simulation, the opensource libraries developed in various projects are particularly useful. In this way, minor components were taken from the IBPSA library and the major components are taken from Buildings and IDEAS libraries. The general mathematical model of the district heating network in Dymola with three vertical borehole heat exchangers and three houses is shown in Figure 1.

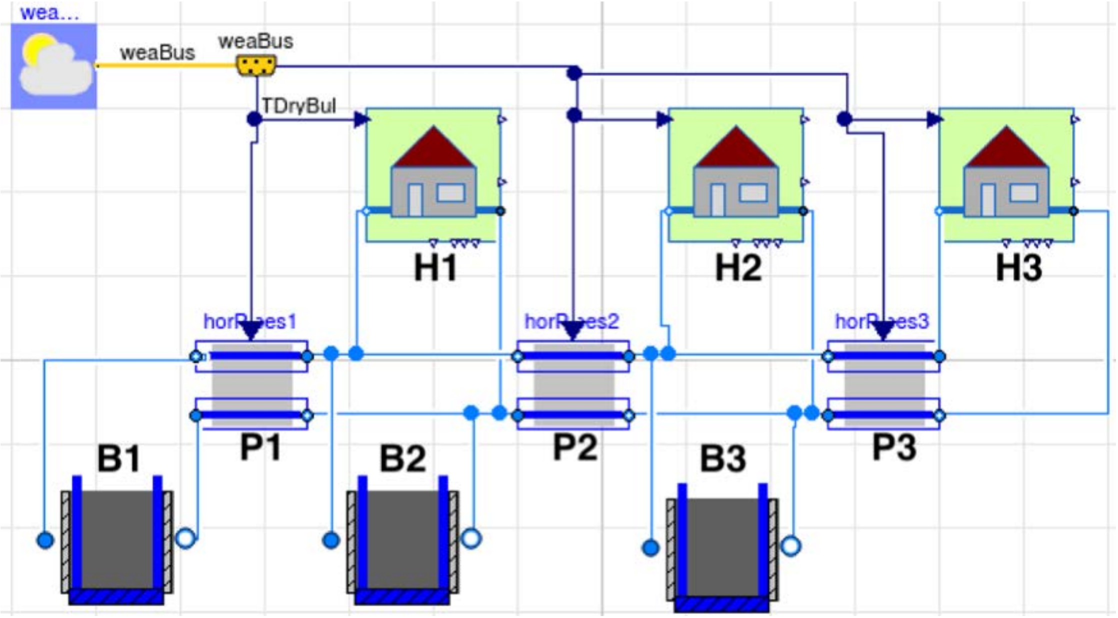

Figure 1: Dymola model of a thermal network Termonet with three houses and three boreholes

The blue component in the upper left corner is the multichannel source of the weather data stored in the external file, which is supplied to the information bus *weaBus*. The bus selects the specific time series (in this case, ambient temperature time series) from the data stream and supplies the data to different components in the model. The row of green components represents the reduced order models of identical residential houses H1, H2 and H3, each with three hydronic loops including a heat pump, stratified heat storage tank, radiator, as well as the building thermal mass and the thermal resistance of the outside wall. The next row in the figure consists of three identical components of the pipelines, which are implemented using the dynamic pipe model from Modelica Buildings Library coupled to the ambient temperature and the far-field ground temperature boundary conditions through the single storage element with appropriate resistances in between. The parameters of the borehole taken from the Thermal Response Test provided by the company Geodrilling (owner of Termonet in Vorbasse and some other places in Denmark) and the assumed parameters of the building are listed in Table 1. Parameters for the heat pump were estimated in the results section from the sensor measurements taken at the test site and the ambient temperature is modelled based on the yearly temperature profile measured by a dry-bulb thermometer in Copenhagen.

Table 1: Parameters used in the model

Parameter	**Value**
pipe length	50 m
pipe depth	1 m
seasonal depth	30 m
undisturbed temperature	7.7°C
distribution pipes	SDR17 PE100, 50x2
specific heat of soil	1500 J/K
external pipe diameter	0.05 m
pipe thickness	0.002 m
insulation thickness	0.03 m
insulation conductivity	0.032 J
borehole resistance	0.07 K/W
ground capacitance	810 J/K
ground density	2700 kg/m^2
borehole hight	90 m
borehole radius	0.089 m
tube diameter	0.032 m
tube conductivity	0.38 m
tube thickness	0.15 m

2.2 Parameter estimation algorithm

To make Modelica components useful for modelling a specific heat pump available on the site, it is necessary to calibrate and validate the heat pump model against test site measurements. The optimization method based on a genetic algorithm was used to fit the Termonet unit heat pump and check the validity of the resulting model. The used Python package [8], was developed specifically for building HVAC systems and has been tested before for ventilation system models. While testing it here on a hydronic heating, it is important to see how much indeterminacy the genetic algorithm can handle. The simplified version of the Termonet unit is constructed in Figure 2 from IDEAS library components (heat pump, storage tank with an immersion heater, radiator and two pumps) and Modelica Standard Library (indoor thermal mass, external resistance and tank wall resistances).

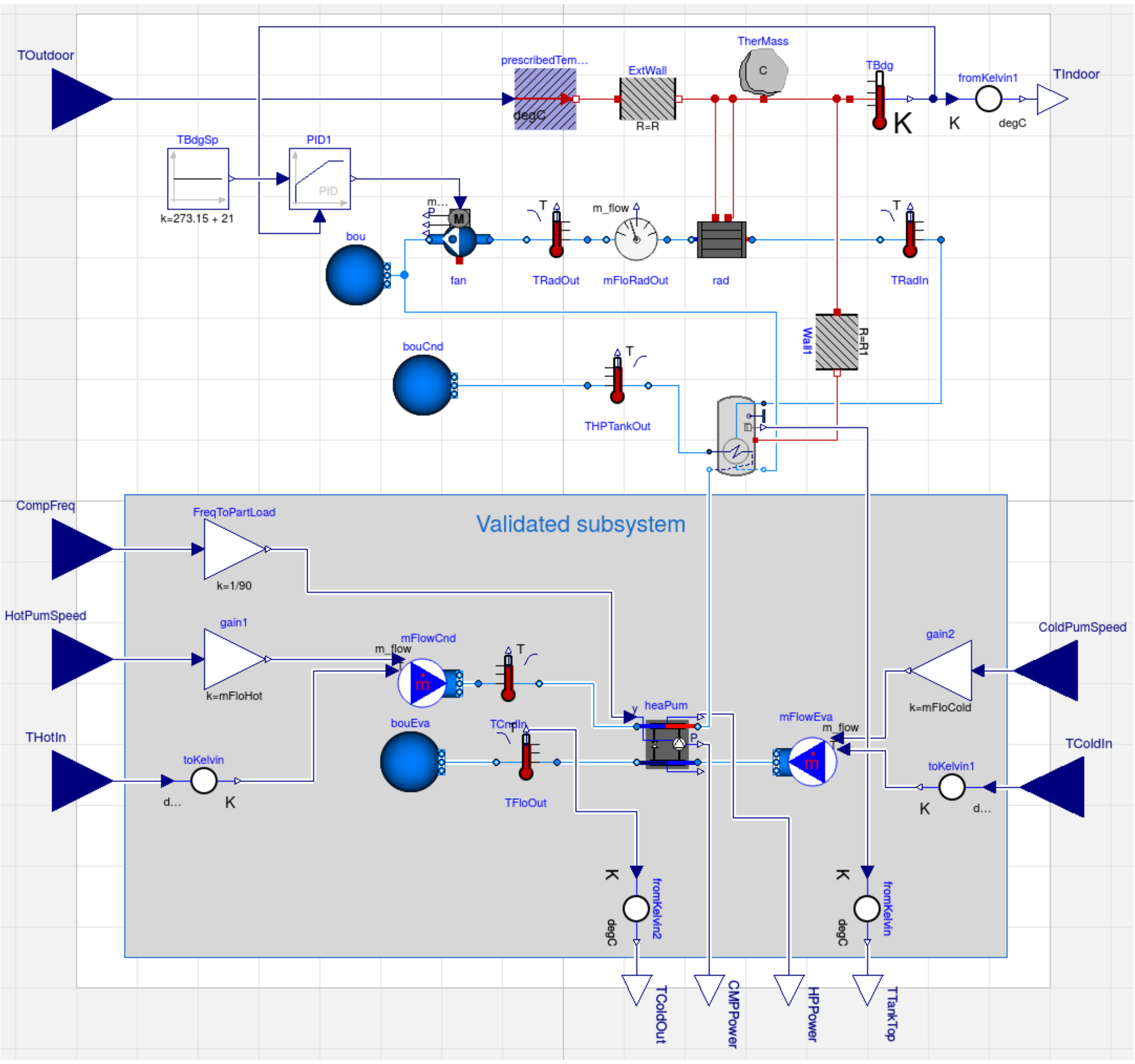

Figure 2: The model used for Termonet heat pump calibration

The following set of measured system inputs and outputs were used for calibration of the Termonet unit:

- Inputs: inlet fluid temperatures at the source and load sides of the heat pump, *TColdIn* and *THotIn*, compressor frequency *CompFreq* and speeds of the pumps operating at the source and load sides, *ColdPumSpeed* and *HotPumSpeed*,
- Outputs: water temperatures in the top layer of the tank and evaporator outlet, TTankTop and *TColdOut*, heating and compressor powers, *HPPower* and *CMPPower*.

The following seven parameters where chosen to be estimated:

- Indoor thermal mass, *C*,
- Nominal COP of the heat pump, COP_{nom},
- Outside wall resistance, R,
- Storage tank wall resistance, R_1,
- Nominal condenser temperature, $T_{con,nom}$,
- Mass flow rate on the hot (load) side of the heat pump, $\dot{m}_H$,
- The volume of the storage tank, *V*.

The results of the parameter estimation are presented in the next section and the heat pump parameters are used in the Termonet model, when simulating its dynamics.

3 Results

3.1 Heat pump parameter estimation

Optimization with genetic algorithm results in the 7 calibrated values for the estimated parameters listed in Table 2.

Table 2: Estimated values of the heat pump parameters

Heat pump parameter	Estimated Value
C, [J/(m K)]	1911792
COP_{nom}, [1]	2.5
R, [K/W]	0.1
R_1, [K/W]	0.076709
$T_{con,nom}$, [K]	313.15
$\dot{m}_H$, [kg/s]	0.5
V, [m3]	1.807541

The evolution of the parameter in the genetic algorithm is illustrated in Figure 3, where the colour of each point shows an error of the objective function and its height gives a parameter value.

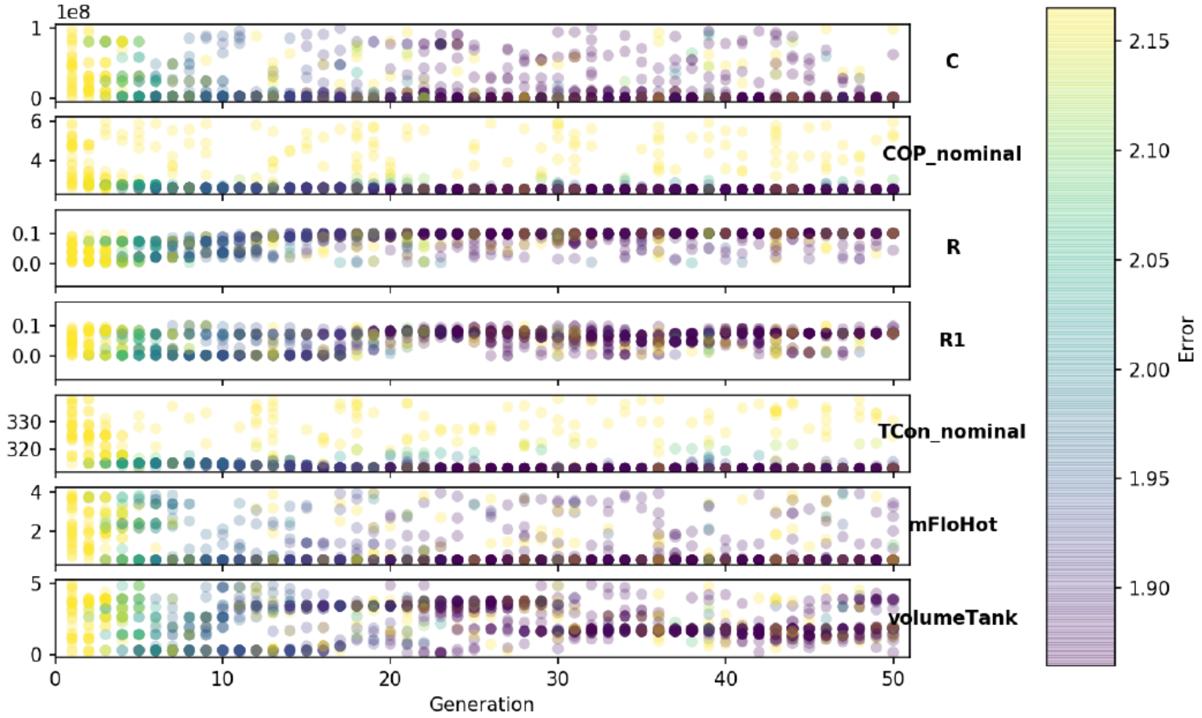

Figure 3: Visualization of heat pump parameter calibration using ModestPy

The calibrated parameters were inserted into the model shown in Figure 2 and the model was simulated over a two-week period following the training period. The results are compared to the corresponding test site values measured over the same period of time in Figure 4.

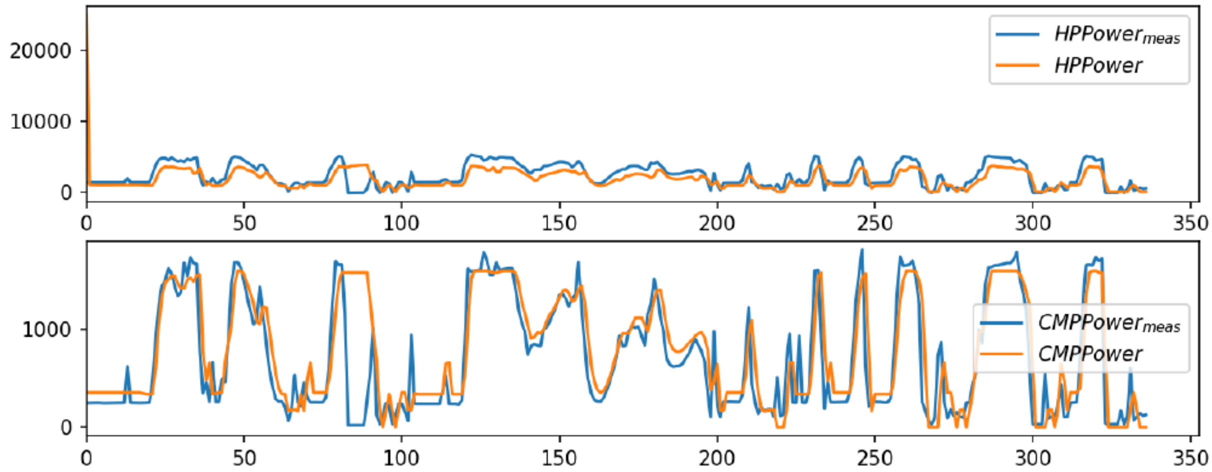

Figure 4: Validation of the calibrated model versus time [hours]: measured (blue) and calculated (orange) values of the heating power (top), compressor power (bottom)

The dynamics of the calibrated system (orange curve) is in a fair agreement with the measured data (blue curve). Simulated heating and electric powers accurately reproduce the measured profile apart from local variations. The results show that the genetic algorithm can handle large indeterminacy in the demand side properties and make estimation with relatively small error, althogh there is no guarantee that the values themselves are accurate, when compared to the real situation. A better accuracy of the parameter values, as well as the combination of the model with production optimization and control algorithms would require more detailed information about consumption and thermal comfort. The domestic hot water production, occupancy dynamics and floor heating system has to be explicitly modelled in order to introduce and fit more parameters nessesary in such detailed approach. This will require new measurements on these subsystems not presently available from the test site.

3.2 System dynamics

The temperature dynamics within the heating system of houses H1, H2 and H3 relies on the two PID controllers driving pumps in the three hydronic loops shown in Figure 2. The controller PID1 drives the upper pump, which runs the fluid through the radiator and the heat exchanger in the stratified water tank imposing the constant temperature set point of 50℃ in the upper layer of the tank. The controller PID2 drives the two other pumps, one delivering the water heated by the heat pump condenser to the lower layer of the water tank and second drawing the water from the district heating network and supplying it to the heat pump evaporator.

The yearly temperature variations in the radiator and water tank in each of the three houses are presented in Figure 5. The heating system follows the weather profile typical for northern countries: the heating is energy intensive in winter, larger part of spring and most of autumn. This corresponds to large temperature variations in the water tank, which provides balance between the heat consumer (radiator) compensating energy losses from the building's envelope and the heat source (heat pump) converting low-quality thermal energy of the ground into heating power provided to the tank. The enlarged image of two-day temperature dynamics is shown in the two insets: the left inset corresponds to March 29 and March 31 of 2017, the right inset corresponds to September 18 and September 19 of 2017. Two major things to notice is the large time scale of temperature variations (curve peak has width around two days) and the time shift of the H1 curve compared to H2 and H3 curves (on the order of

3-10 hours). This implies that some of the parameters related to the building envelope and the heating system do not correspond to real situation at the test site, since some of them were not measured, but guessed. However, the analysis on the system level can still be valid, since the scaling of individual components within the reasonable range should not add different physical effects.

Temperature dynamics of the radiators and storage tanks in Figure 5 is determined by the periodic increase of PID2-driven heat pump speed triggered by cooling of the upper tank layer below the set point of 50°C. At this event, the tank temperature peaks shown in the insets are attained because of heat pumping from the district heating network, at which point, the radiator temperature starts increasing at the expense of the tank energy. As it proceeds increasing, the tank temperature drops rapidly, which explains the small width of the peaks. As the hotter water from the tank is run through the radiator loop, the control signal reduces and the speed of temperature change in the radiator gets smaller and starts decreasing after the controller is switch off (right inset).

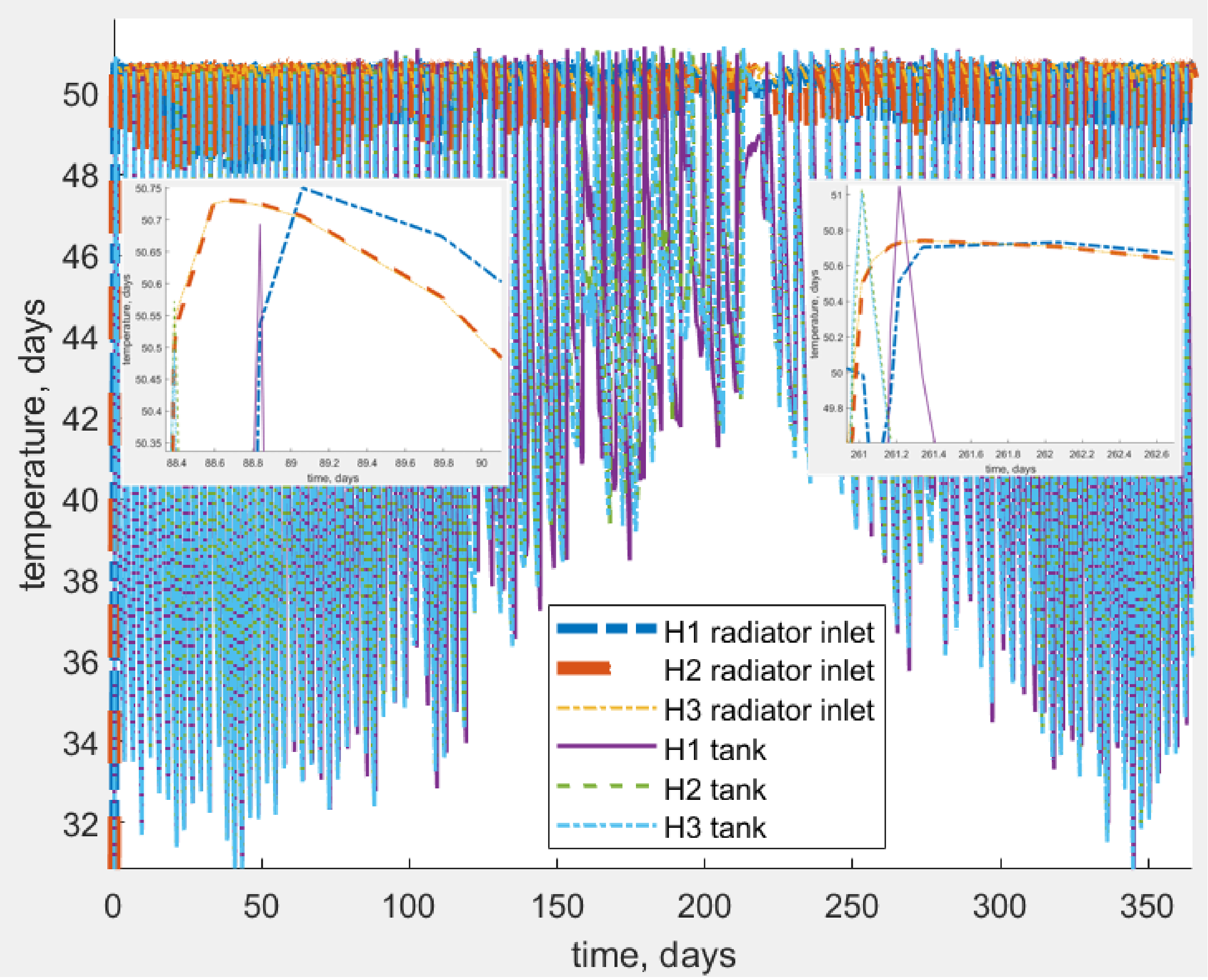

Figure 5: Yearly variations of radiator and water tank inlet temperatures for each building

The variation of different temperatures in the network corresponding to considered variation in radiator and water tank temperatures can be closer followed in Figure 6, where the single “period” of the heating process is shown. Figure 6(a) shows the PID2 signals generated in each of the three houses during a single-day period (April 12 in 2017), where the delay observed for the first house's radiator is particularly obvious (blue curve). In the end of previous day (April 11), the upper layer of the storage tank cools down below 50℃ (after 101.9 days in Figure 6(b)), which causes the PID2 signal in H2 and H3 to ramp up. Consequently, the heat pump draws more energy from the borehole decreasing the return temperatures to all three boreholes until the temperature of the tank reaches the set point again (at 102.2 days in Figure 6(b)). After this, the PID2 ramps down and the dynamics in the rest of the period is determined by PID1 and the immersion heater (not shown). The PID2 in H1, however, does not ramp up until 102.5, after which point, the tank temperature in H1 reduces below the set point. This delay can be explained from observing the H1 heat pump and B1 borehole temperature variation in the same period. The inlet temperature of the first house H1 transported to the cold side of the heat pump (blue curve in Figure 6(c)) is primarily determined by the first borehole outlet B1 (blue curve in Figure 6(d)) modified by thermal losses from the first pipeline P1 and is very weakly influenced by the other two pipelines P2 and P3. As can be seen the B1 maintains the largest temperature difference between the supply and the return, in the beginning of the day. This difference is enough to maintain appropriate temperature in the water tank and in radiator of H1 until later in the day. The other boreholes, however, are not able to do so, because the reduction in stored heat in all three houses and the pipelines P2 and P3 influence them directly without the transport delay in the pipes and the heat is drawn from these boreholes earlier to compensate for the heat loss. The delay time between activation of the first and second radiator consists in this case around 14.5 hours.

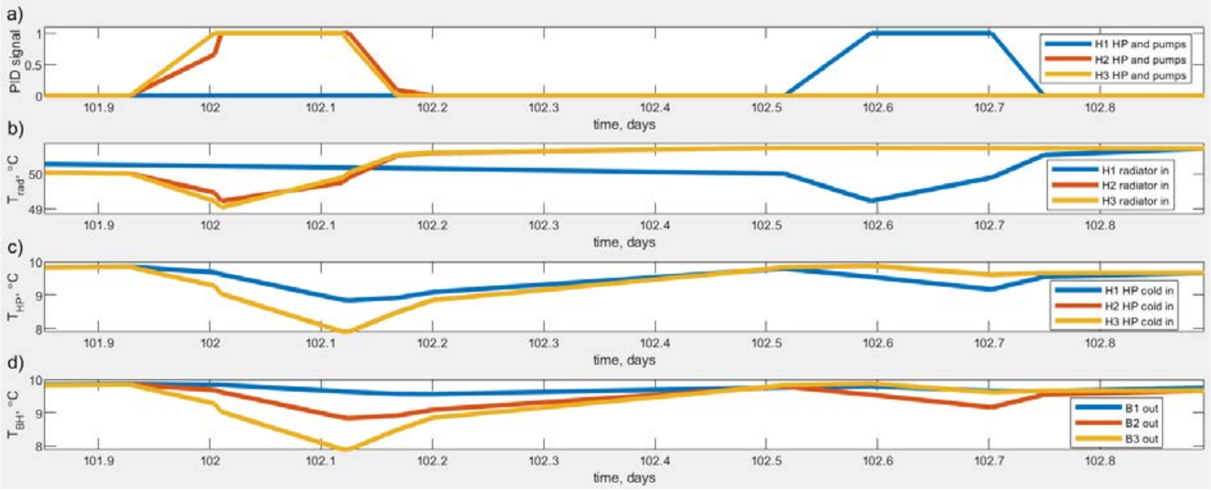

Figure 6: (a) PID2 signal and corresponding dynamics of (b) radiators, (c) heat pumps and (d) boreholes in Termonet

4 Conclusion

A detailed model of Termonet district heating network consisting of three borehole heat exchangers, non-insulated piping, decentralized heat pumps and heat consumers. The parameters of the heat pump are estimated using the open source Python package ModestPy and the genetic algorithm. System dynamics is simulated in changing weather conditions throughout the year. The simulation shows that the parameter values do not correspond to the real situation in the test site, because the observed period of temperature oscillations are around 1-2 days, which is not usual for poorly insulated residential buildings with moderate thermal mass. However, dynamics validated for 2-week period and simulated for the period of 1 year can be explained from the system topology and is rather intuitive. The choice of system topology itself leads to the situation, where the borehole located farthest from the buildings provide the largest temperature difference in the network, while other boreholes give minor contribution and therefore can be considered less efficient than the case with the centralized borefield modelled previously. However, to make more reliable conclusion on such efficiency, the appropriate key performance indicators should be defined for the network and the more accurate parameter estimation should be conducted.

In summary, we have demonstrated, that Termonet can be dynamically simulated based on the opensource libraries Building, IDEAS and IBPSA under development in IBPSA project 1. The corresponding production and consumption dynamics can be analysed in detail in a topology of choice thanks to drag-and-drop modelling capabilities. As an outlook, the refined version of the model will be developed to be used in optimization and more accurate parameter estimation will be conducted to extend analysis for other types of residential buildings and heating networks.

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References

[1] GeoDrilling, *Termonet concept* (in Danish), 2017. http://termonet.dk/koncept/

[2] Henrik Lund, Poul Alberg Østergaard, Miguel Chang, Sven Werner, Svend Svendsen, Peter Sorknæs, Jan Eric Thorsen, Frede Hvelplund, Bent Ole Gram Mortensen, Brian Vad Mathiesen, Carsten Bojesen, Neven Duic, Xiliang Zhang, Bernd Möller, *The status of 4th generation district heating: Research and results*, *Energy 164*, pp. 147-159, 2018.

[3] Simone Buffa, Marco Cozzini, Matteo D'Antoni, Marco Baratieri, Roberto Fedrizzi, *5th generation district heating and cooling systems: A review of existing cases in Europe*, *Renewable and Sustainable Energy Reviews* 104, 2019.

[4] Modelica Association github page, https://en.wikipedia.org/wiki/Modelica

[5] Dassault Systems, Dymola – Dynamic Modeling Laboratory,

https://www.3ds.com/products-services/catia/products/dymola/

[6] IBPSA Project 1, BIM/GIS and Modelica Framework for building and community energy system design and operation, https://ibpsa.github.io/project1/

[7] Modelica Association, Modelica Standard Library,

https://www.modelica.org/ModelicaLibrariesOverview

[8] Krzysztof Arendt, ModestPy - FMI-compliant Model Estimation in Python, https://github.com/sdu-cfei/modest-py