Development of Models for Long-Term Simulations of District Heating Networks at High Temporal and Spatial Resolutions

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Abstract

In innovative district heating systems with integration of distributed renewable heat sources, dynamic processes in the pipe network, such as flow reversals and zero flow periods due to decentral feed-in, and their effects on efficiency, service life and control strategies are getting more important. To investigate the effects of these processes, a dynamic thermo-hydraulic model for district heating networks using Modelica is developed. The new model builds upon available model libraries and adds improvements and design principles, that enable fast and accurate simulations. A general model design is proposed so that users can set-up correct district heating network models fast and easy. The new model is successfully validated against other software and measured data for representative load situations (high, medium, low load and a temperature step). On a regular computer, within six hours annual simulations of a district heating network with 85 consumer units can be run at a high temporal resolution of three minutes for all pipe segments including house lead-in pipes.

Keywords: district heating network, dynamic thermo-hydraulic simulation, Modelica, model design

1. Introduction

A vital element of the energy transition towards renewables is the integration of renewable heat sources into new and existing district heating networks (DHN). In many cases these renewable heat sources are distributed over the network, e.g., solar thermal units and waste heat sources. Their decentral feed-in results in an increase of dynamic processes in the DHN, such as flow reversals, compared to conventional DHNs with centralized heat supply units (Paulick et al., 2018).

This new situation creates a need for dynamic thermo-hydraulic models of DHNs, so that the effects on the network such as flow reversals, cold and hot plugs or temperature changes and their impacts on efficiency, service life as well as control strategies can be investigated. These models should enable dynamic simulations, that meet the following requirements:

- Long simulated times, up to one year, to examine the performance and relevant effects with seasonally variable heat sources and sinks
- High temporal resolutions, < 1 hour, to capture the fluctuating nature of renewable supply units
- High spatial resolutions, which means including all individual pipe segments, to capture the state of all parts of the DHN

In this contribution, the development and validation of such a model is described.

2. Model Development

To set up the dynamic model, the acausal, object-oriented modelling language Modelica (Modelica Association, 2013) and the simulation tool Dymola (Dassault Systèmes, 2019) are chosen, as this environment provides great capabilities to model thermo-fluid systems and a variety of high quality open-source model libraries such as the Modelica Standard Library (Modelica Association, 2019) and IBPSA library (IBPSA, 2018). Furthermore, the object-oriented approach of Modelica, including the usage of inheritance, enables a modular model design with good reusability and compatibility of the different component models. For the development of the component models, suitable base models from the Modelica Standard Library are used, wherever possible.

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2.1 Pipe model

The pipe model is based on a validated plug-flow model (van der Heijde et al., 2017) which calculates delay, heat-loss and the effect of the pipe wall heat capacity and is capable to handle flow reversals. The model efficiently handles varying inlet temperatures and flow reversals by using the Modelica spatialDistribution() operator (an inbuilt operator to implement plug-flow calculations) to calculate fluid and temperature propagation. The heat losses are modelled separately, using a Lagrangian approach, where the outlet temperature T_{out} of each fluid parcel is calculated from its dwell time in the pipe $(t_{\text{out}} - t_{\text{in}})$, its inlet temperature T_{in}, the temperature of the surroundings T_{b}, the thermal resistance between the fluid and the surroundings R and the heat capacity of the fluid C according to equation 1. This approach neglects changes of the temperature of the surroundings, axial diffusive heat transfer and effects of pressure loss, wall friction and dissipation, which are valid simplifications in most of the operational range of DHNs (van der Heijde et al. 2017).

$$T_{\text{out}} = T_{\text{b}} + (T_{\text{in}} - T_{\text{b}})\, exp\left(-\frac{t_{\text{out}} - t_{\text{in}}}{RC}\right) \qquad \text{(eq. 1)}$$

However, the original model produces hot plugs after zero flow periods as an artifact due to a simplification of the heat loss calculation: The pipe model contains a plug-flow model and a volume model in series (see Fig. 1). The original model allocates the heat loss only in the flow model and does not calculate heat losses for the volume model. This solution results in hot plugs of uncooled water, that get flushed through the network once the mass flow is reestablished after a zero flow period. A demonstration of this behavior is shown in Fig. 2 and Fig. 3. This is an unwanted artifact of the model and results in computational costs because the solver drastically reduces its timestep to accurately calculate the propagation of these hot plugs. To avoid this, heat losses for the volume model are included as well, while keeping the total heat loss of the pipe equal. The exact allocation of heat losses is undertaken by dividing the total heat conductivity according to the shares of heat capacity of water and pipe wall so that the volume model cools down simultaneously to the water in the plug-flow model. This improvement is important in case zero flow situations may occur often, for example in and close to feed-in points of solar thermal fields.

Another consequence of the original heat loss calculation is that the instantaneous heat loss of the pipe is not known, as just the heat loss of the fluid parcel leaving the pipe is calculated. While this is the same value at steady state conditions, in dynamic situations with varying mass flows or even zero flow periods the values may drastically differ (see Fig. 3, number 3). With the improved heat loss calculation above it is possible to estimate the instantaneous heat loss of the pipe from the temperature in its volume model. This new heat loss variable is added to the model, so that the instantaneous heat loss can be evaluated easily.

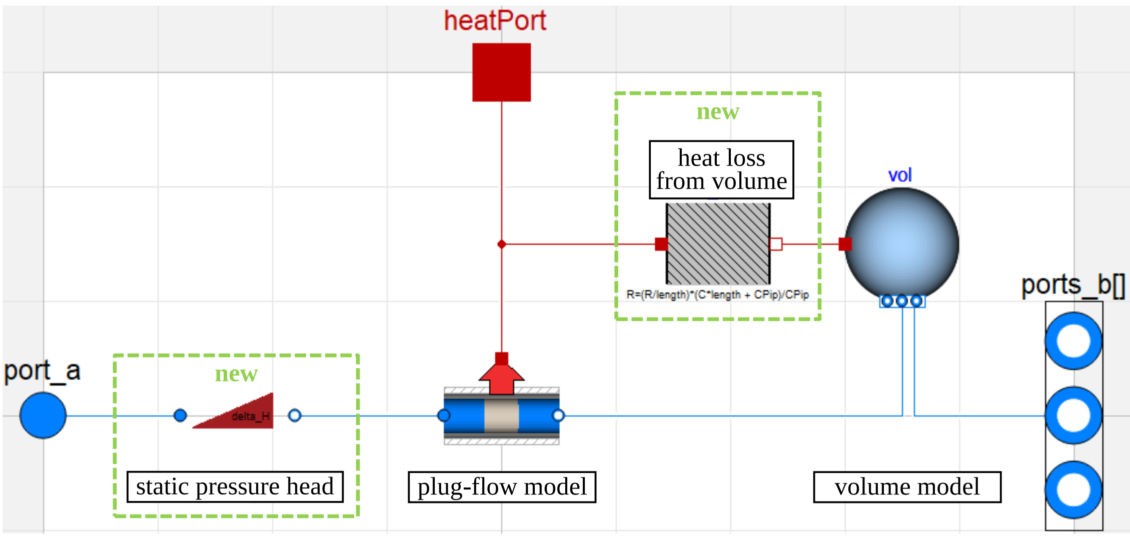

Fig. 1: Plug-flow pipe model consisting of a static pressure head model, a plug flow model, and a volume model with a heat loss component. Green boxes highlight improvements within this work compared to the original model (van der Heijde et al., 2017).

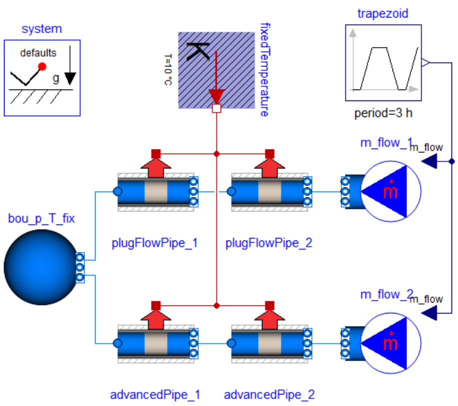

Fig. 2: Model to compare the original plug-flow pipe with the advanced version. Two serial pipes of each type experience a period of zero flow.

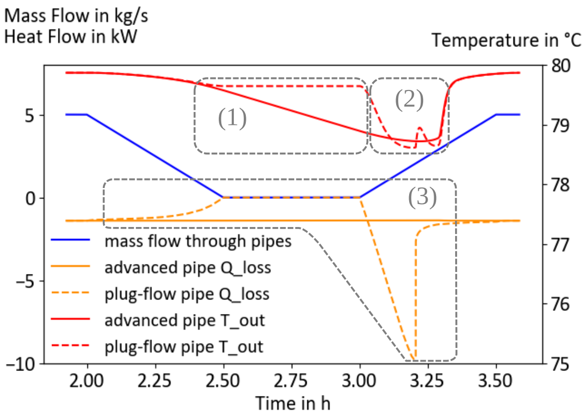

Fig. 3: Results that show the improvements of the advanced pipe model: realistic cooling during zero flow (1), no temperature peaks when pipes are flushed afterwards (2) and the heat loss variable that is independent from mass flow (3).

Furthermore, the calculation of the static pressure head was added and the detailed pressure calculation from the Modelica Standard Library (Modelica Association, 2019) was made available as an option in case it is needed instead of the simplified approximation that is already included. For a good usability, two pipe models are wrapped into a double pipe model representing supply and return line and an easy parametrization via pipe types is implemented. Multiple pipe models can be connected at network nodes through their vectorized ports, so that the pipe model instances can form any network layout.

2.2 Functional units

The functional units of the district heating network (supply units, loads and bypasses) are modelled as fluid boundary conditions (either pressure or flow boundary conditions at setpoint temperatures) without detailed modelling of the actual components, such as heat exchangers, pumps, or storages (see Fig. 4). The setpoints for pressures, mass flows and temperatures are calculated in control blocks from input data and relevant states in the network, such as the temperature at the outlet of the supply line pipe entering the respective functional unit. This reflects the underlying assumption, that all units follow their setpoints accurately enough, so that deviations from the setpoint can be neglected. Furthermore, in the functional units, there is no fluid model connection between supply and return line so that the fluid flow equations for supply and return line are decoupled, which reduces the computational effort.

Load model icon   Load model diagram

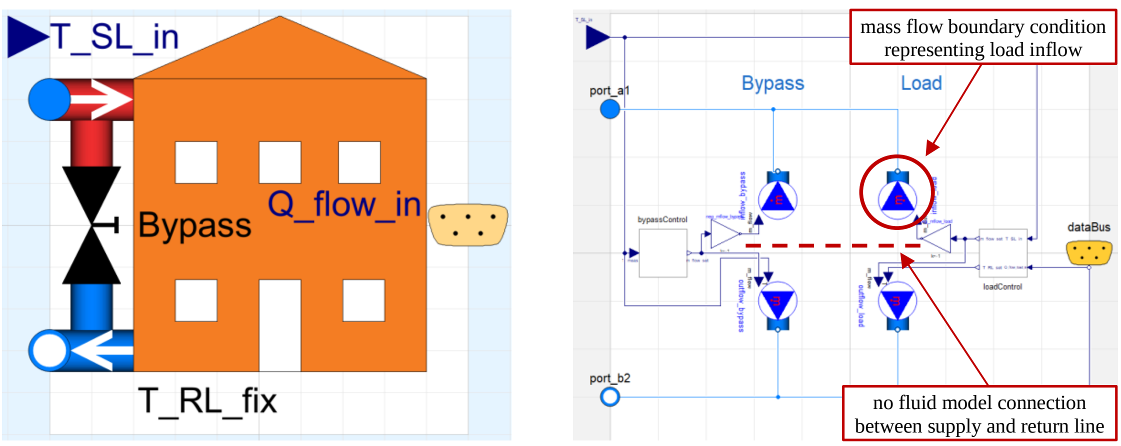

Fig. 4: The load model as an example for the model architecture of the functional units. The lefthand-side shows the model icon, which indicates the general model behavior and its connectors to other model instances, while the righthand side shows the model diagram with its inner structure. The inputs supply line temperature ("T_SL_in", top left) and load data ("dataBus" center right) are used to calculate the mass flows that occur. The fluid models are separated between supply and return line.

The mass flow calculations in the functional unit include time constants that restrict the dynamics of mass flow changes. This allows smooth simulations where the computation of highly dynamic effects (or artifacts) that are out of the relevant time scale are avoided.

2.3 General Model Design

The fluid in the network is modelled as constant property water, with the properties separately calculated for supply and return lines at the respective design temperatures. However, the models are still compatible to other variable property fluid models in case a user wishes to introduce them at the cost of higher computational effort.

The dynamic pressure effects in water occur on time scales below the focus of the model (< 1 s). Thus, the pressures in the network are calculated stationary assuming an incompressible medium and neglecting expansions of the hydraulic components. Therefore, the pressure control loop results in a large non-linear algebraic equation system, that must be solved iteratively for each timestep (so-called algebraic loop). This algebraic loop can be avoided by introducing a state variable within the loop (Jorissen et al., 2018). To do so, a PT1-block is included in the pressure control loop. Jorissen et al. point out, that this approach increases the computational effort for the integrator. However, in the use case of pressure control loops for large pipe networks in DHN, this additional effort is by far compensated by the advantage of avoiding the iterative solution of the non-linear algebraic system: For a case study of a radial DHN with about 400 pipe model instances, the introduction of the PT1-block reduces the CPU-time of a simulation by a factor >10.

The general model design includes a variety of further auxiliary models, that are bundled within a “DH environment” model, so that users can set-up a correct DHN model fast and easy. A diagram of a simple DHN model with all auxiliary models is shown in Fig. 5. The auxiliary models are:

- The <u>system</u> component builds upon the Modelica.Fluid.System model from the Modelica Standard Library (Modelica Association, 2019). It is used to set general parameters, that are important for the simulation. The original model is extended by parameters to set the time constant of the functional units, parameters to support the definition of nominal temperatures to be used in model instances wherever useful, parameters for pipe default settings and parameters for the network structure (e.g. number of network sections).
- <u>Data input</u> is managed via data readers (Modelica.Blocks.Sources.CombiTimeTable; Modelica Association, 2019) for temperature and load data. A <u>data bus</u> is used to automatically connect the numerous signals to the corresponding units. To ensure a correct signal propagation, the load units must be assigned with unique IDs and the input data table must be arranged accordingly.
- A <u>heat loss connector</u> is automatically connected to all pipe models on the one hand and the soil temperature signal on the other hand to ensure a correct heat loss calculation.
- The <u>pressure control loop</u> bundles and processes the pressure signals from the outlets of all pipes and the differential pressures at all loads so that the <u>pressure setpoints</u> can be followed using PI-controllers. The pressure control loop includes a PT1-block, to break the algebraic loop as described above.

Finally, the simulation timestep of the solver is limited to a maximum value to avoid propagating increasing numerical errors in series of pipe models that can be observed when the integrator timestep gets too large. These numerical errors especially occur within short pipe instances: Once the solver time step exceeds the dwell time within short pipe models (so that the plug-flow model is fully flushed within one time step), the temperature calculation becomes an error prone extrapolation. The numerical errors then propagate to the next pipe model, inducing sudden changes of temperature which then forces the solver to drastically reduce the simulation timestep until the temperature oscillation gets consumed by a load instance. The optimal value for the maximum simulation time step depends on the pipe lengths and the flow velocities (which themselves depend on load profiles, flow and return temperatures, and network design) within the network. Limiting the solver time step to a maximum value of 180 s has proven to be a decent choice for medium sized DHN with typical hourly load profiles for residential buildings.

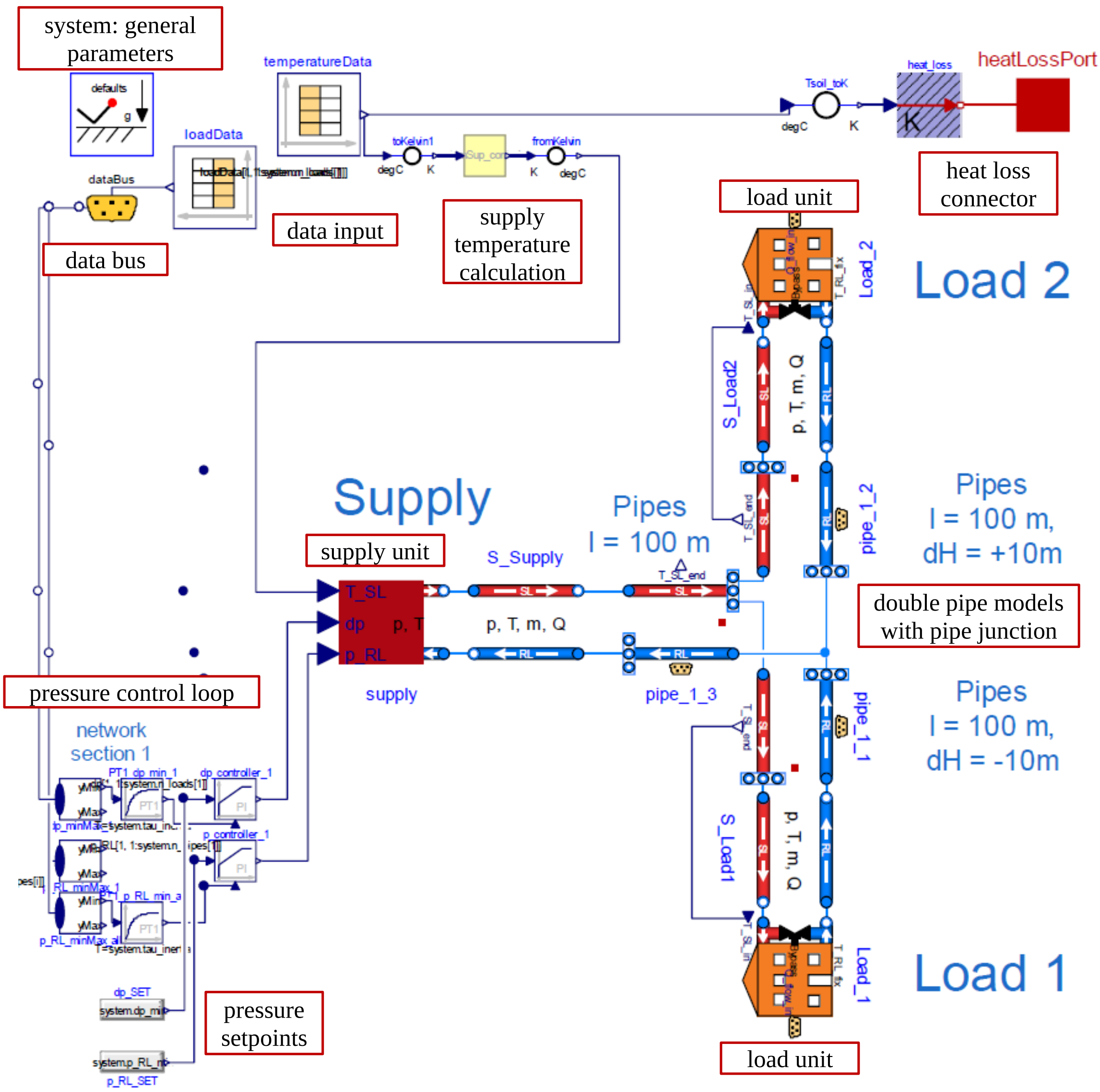

Fig. 5: Overview of the general model design showing a very simple DHN with one supply unit and two loads connected via pipe models with a pipe junction. The auxiliary models for general settings and parameters, data input and propagation, pressure control and heat loss calculation are arranged at the top and left side.

2.4 Development process and result

During the development process, the component's correct function and performance was permanently tested. Occurring issues were analyzed and solved, until through incremental improvements a proper performance of the full DHN model was reached. Finally, an annual simulation of a radial network with 85 loads at a high spatial resolution (no aggregation, including house lead-in pipes) can be run at a high temporal resolution (≤ 3 minutes) within six hours on a regular computer (Windows 10, 64 bit, CPU Intel i5-4300U @ 4x1.9 GHz, RAM 8 GB).

3. Model Validation

The first stage of the validation process was done by simulating a simple exemplary DHN in both, the commercial software STANET® (Ingenieurbüro Fischer-Uhrig, 2020) and using the new Modelica models. A variety of 100 randomly chosen static load situations was simulated. The results show, that for all important parameters (temperatures, differential pressures, heat losses and mass flows) the deviations are below 1 %. Thus, the new model proves highly accurate for stationary conditions.

The second stage of the validation process aims to validate the performance for dynamic situation. It is based on measured data (time resolution 15 min.) from a radial DHN with about 250 consumers. The accuracy of the measured data is limited, because at the consumer units, only momentary values are known, and these values are not exactly synchronous as they are transmitted via a serial bus system. Thus, the data was edited using the following procedure:

- Step 1, cross check of individual consumer data: At each consumer momentary mass flow, temperatures and heat meter values are known. Using the heat meter values, the mass flow data was upsampled to a 3-minute interval so that the mass flow timeseries is in line with the heat meter values. During this process, peaks were trimmed to a plausible duration and missing peaks were introduced.
- Step 2, using central measurement: At the central heat supply unit the total mean mass flow of the DHN is known accurately for each interval. However, the sum of all measured consumer mass flows is up to 10 % below this total mass flow. The reasons for this deviation may be inaccurate mass flow measurements and / or unmeasured mass flows in some parts of the network. As it was impossible to exactly identify the sources of deviation, the mass flow data at all consumers is increased by the deviation factor for each timestep.

This data editing procedure may in some cases confound the data due to incorrect adjustments. However, the raw data is inconsistent which would result in a failure of the validation process, while the edited data is a consistent, most applicable data set obtained by combining all available information. Yet, these limitations of the data quality restrict the achievable degree of agreement between measurements and simulation.

For the simulation, the edited timeseries of mass flow and return temperatures at the consumers and the supply temperature at the supply unit are used as an input. The simulation results are evaluated based on the resulting return temperatures and heat flows at the supply unit. The validation covers the full range of operating conditions throughout the year: periods of low, medium, and high load (each three days) and a period with a sudden rise of the supply temperature, as this is a highly dynamic situation in the measurement data. While these periods were simulated using the upsampled 3-minute timeseries and a maximum simulation timestep of 180 s, the evaluation of the agreement between simulation and data was done with 15-min mean values, as this is the data timestep at the central supply unit.

The results are shown in Fig. 6 to Fig. 9 for the different periods. Each figure shows the timeseries of heat flow, supply and return temperature at the supply unit from measurement and simulation (top-left) and scatter plots to compare measured and simulated values for mass flow (top-right), return temperature (bottom-left) and heat flow (bottom-right). The comparison of simulation and measurement shows:

- The general course of the timeseries is met very well by the simulation: Peaks and valleys of the heat load are simulated accurately, and subsequent changes of the return temperature agree very well in magnitude and shape. This indicates, that the edited measured timeseries form a consistent data set and that the model correctly captures the DHN's structure and physics.
- The relative mean deviations of mass and heat flow are small (< 2 %) for all load situations, apart from the low load period (see next bullet point).
- The deviations are highest for the low-load period: The simulation yields systematically larger return temperatures (+1.6 K) and thus lower heat powers (-11 %) than measured. A plausible explanation for this systematic deviation lies in the data quality and editing: During the low load period, the heat load is domestic hot water use. This leads to strongly varying return temperatures at the consumers: While actual tapping events or the charging of a discharged storage produce large heat flow peaks with low return temperatures, the compensation of heat losses from storages (if existing) and circulation pipes leads to small, constant heat flows with a high return temperature. These fluctuations of the return temperature are not sufficiently tracked by the measured data and cannot be reconstructed properly from the available data. The results indicate that the data editing procedure tends to overestimate the return temperature which leads to underestimated heat loads. Thus, the deviation is rather a consequence of data quality than of shortcomings of the simulation model.
- Finally, the temperature step situation (Fig. 9) deserves special attention: Here, first the supply

temperature slowly drops and then rises by 15 K within 30 minutes, which is a highly dynamic situation for a DHN. The results show that the simulation accurately reproduces the heat flow peak once the flow temperature rises and captures the course of the drop and subsequent delayed rise of the return temperature.

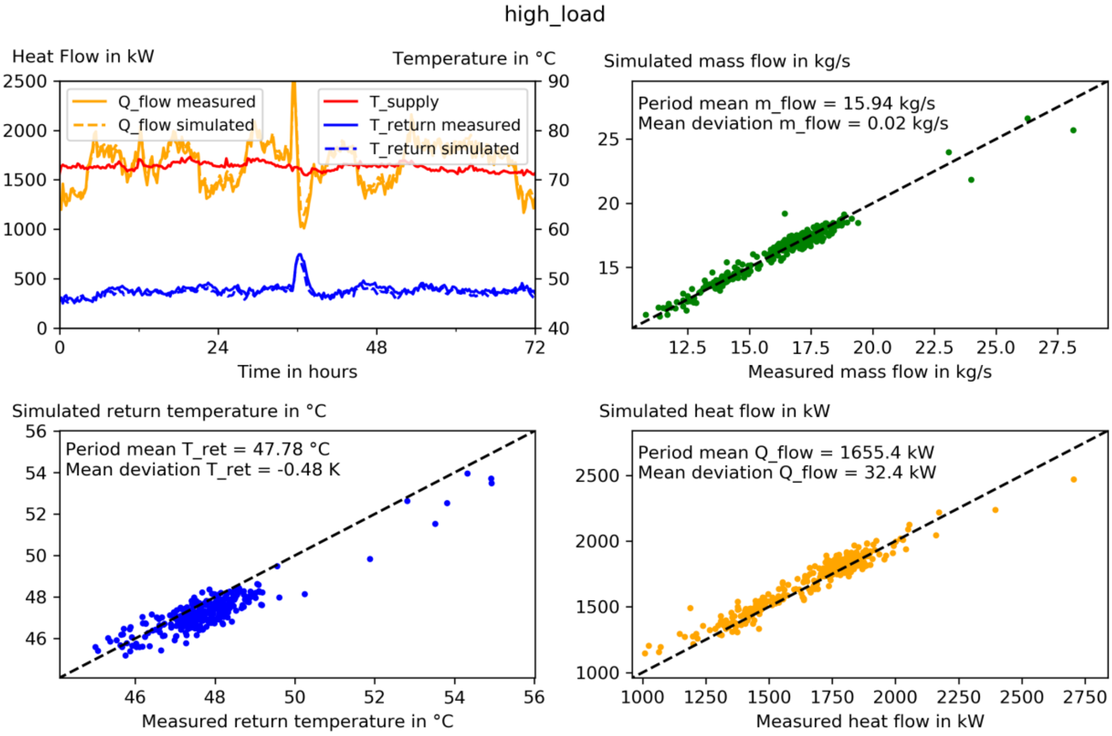

Fig. 6: Validation results for a high load period.

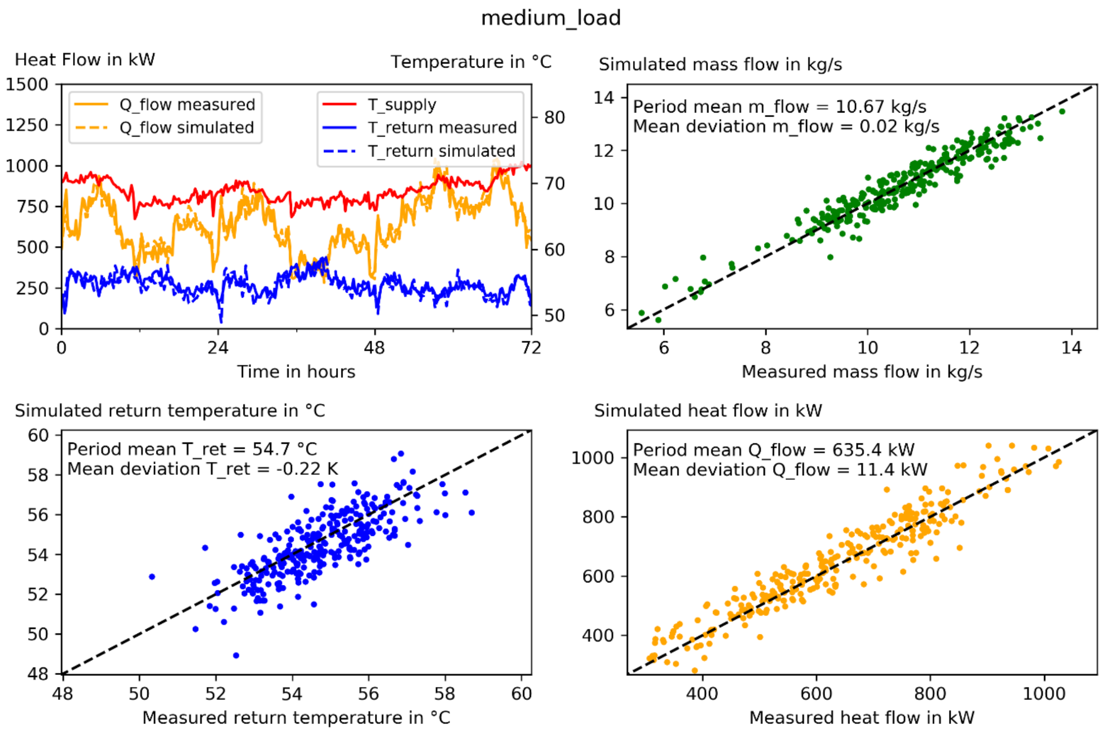

Fig. 7: Validation results for a medium load period.

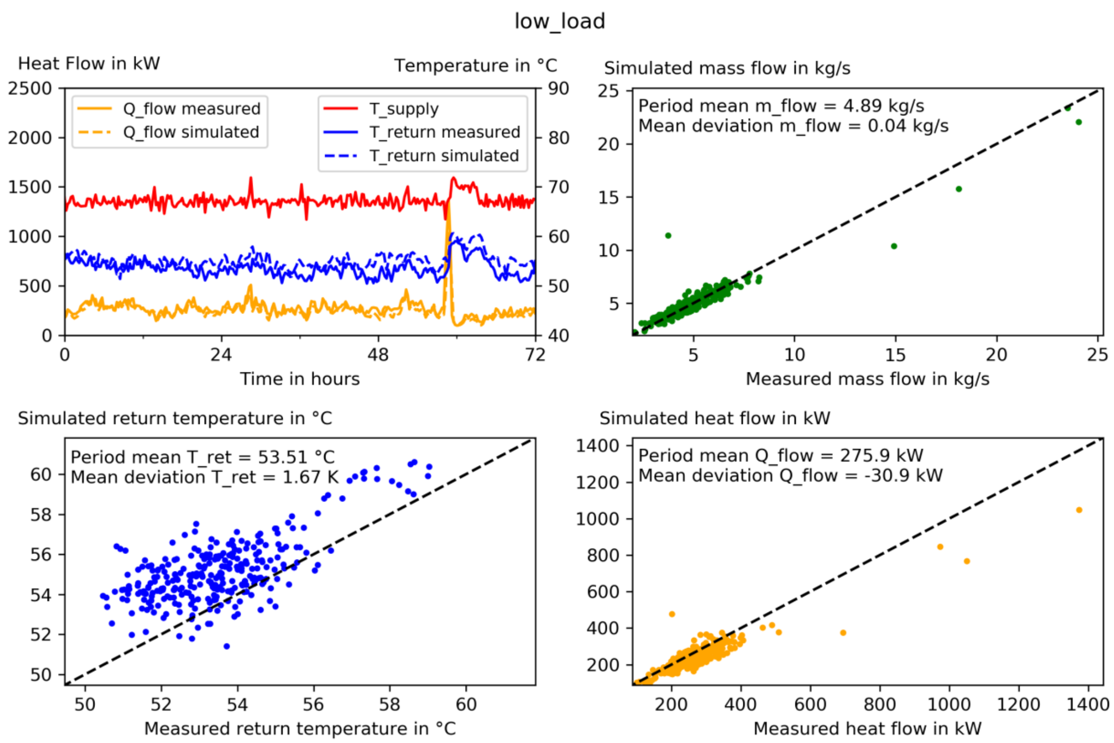

Fig. 8: Validation results for a low load period.

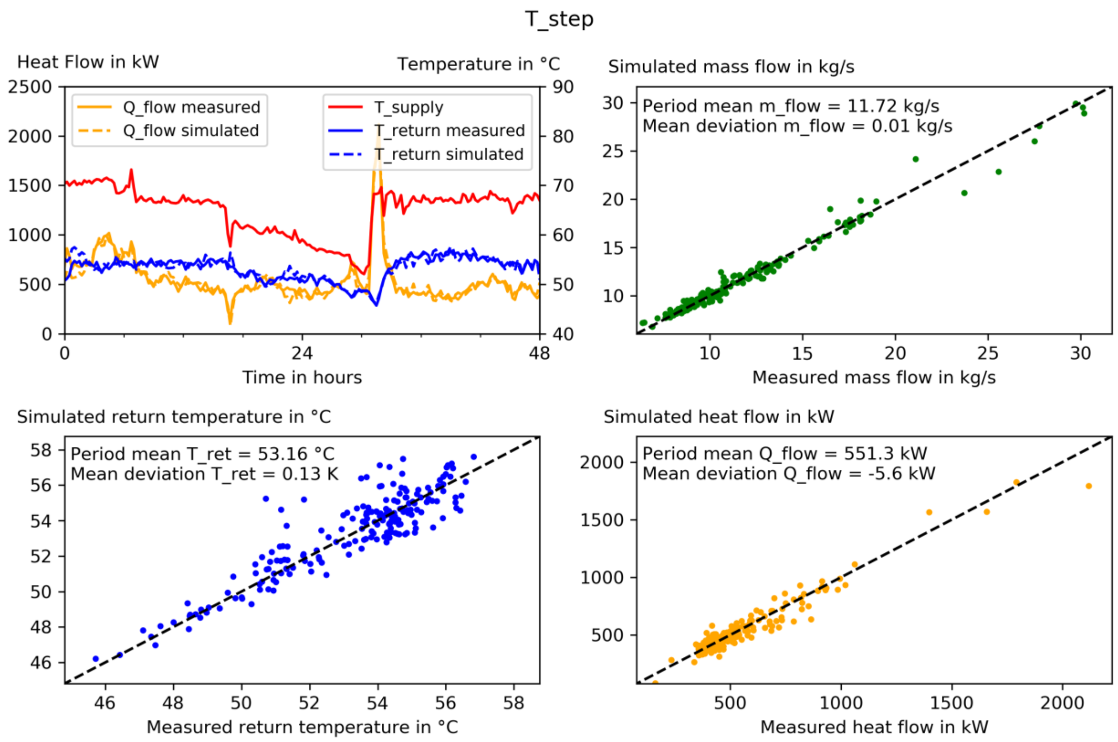

Fig. 9: Validation results for a period with a sudden flow temperature step.

In summary, the new model is successfully validated for static and dynamic situations comparing it to other simulation software and measured data from a real DHN.

4. Conclusion

A dynamic thermo-hydraulic model for the simulation of DHNs focusing on the dynamic processes within the pipe network (such as temperature wave formation and propagation) is successfully developed in the object-oriented modelling language Modelica. The model partly builds upon previously published open-source models with improvements concerning realistic behavior, usability of the models and computational performance. In particular, enhancements to the plug-flow pipe model by Jorissen et al., 2018 are proposed which yield realistic behavior and more stable simulations for situations with zero flow periods. Furthermore, design principles are proposed for the functional units, such as avoiding physical modelling of the inner hydraulic components and separation of fluid models for flow and return side to reduce the computational effort, and for the general model design with a set of auxiliary model components which facilitate the set-up of complete models of DHNs.

The model simulates a medium sized DHN (85 loads) at high temporal resolutions (3 min) for long simulated times (1 year) in about six hours on a regular computer. The new model is successfully validated for static states, compared to the commercial network simulation software STANET®. To also validate the model for dynamic conditions, measured data from a medium sized DHN for different load situations and a situation with a very sudden change of the flow temperature were processed and fed into the model. The simulation results show good agreement with the measured data. Thus, the newly developed model has proven its high performance and accuracy for dynamic simulations of DHNs.

5. Acknowledgments

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