COMPARISON OF TWO SIMULATION TOOLS FOR DISTRICT HEATING APPLICATIONS

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Abstract

The emerging framework of 4th Generation District Heating involves technologies, which make dynamic simulations necessary for planning and management of district heating networks. The standard district heating software Termis (static or quasi-static simulations) is compared on a single-consumer test case to the Modelica-based object-oriented modelling framework Dymola (dynamic simulations). As a result, a new Modelica pipe component was developed and verified for the simple case study in Termis, which can be used for pipe dimensioning, production optimization and planning in Modelica-based tools. Study shows that the dynamic tool is directly applicable to the conventional district heating problems, which brings new possibilities for (a) dynamic analysis and assessment of novel technologies inside the future district heating network and (b) comparison of existing and novel district heating systems considering their real time status and performance.

Keywords

District heating simulation tools, pipe model, thermal networks, Termis, Dymola Modelica.

1 Introduction

The fast transition of the global energy system requires modelling and development of sustainable and highly efficient heating technologies. Especially with respect to their integration with sustainable energy sources and in ICT-based smart energy frameworks for demand/response balancing [1]. Making these new objectives a part of the integrated resource planning and dispatch, at the national or regional level, requires considering additional dynamic effects, which come with sustainable energy sources and novel energy production technologies [2].

Termis has good reputation as a simulation tool for hydronic network design [3] and is therefore adopted by many European district heating companies. It can handle both historical and real time data and be used for optimization of the thermal networks. This framework is however limited with respect to adding new physics, running dynamic simulations and coupling of different energy domains.

Modelica, on the other hand, is a tool well known for its specialization in dynamic simulation of multi-physical systems, co-simulation and equation-based drag-and-drop approach in modeling [4]. The active development of the Modelica-based tools for district heating applications, including free libraries, tools for optimization and model-predictive control [5], poses a question whether the associated framework can be used for planning and management of the energy systems with novel energy production and multi-physics interactions.

Before answering this question, it is important to establish a connection between the two tools and understand how they differ in solving the basic problems from the domain, where both tools are strictly applicable. In this study, we apply Termis and Modelica to static simulation of the simplest district heating system consisting of a single source (plant), a single transport unit (one supply and one return pipe) and a single sink (heat consumer). The comparison must check (a) that Modelica can reproduce the results obtained from Termis, (b) that the results obtained from Modelica are in accordance with the formulas reported in Termis help section (consistency analysis), (c) how the difference between the two models changes with changing model parameters (sensitivity analysis). Based on the above three steps, the verified Modelica model of the district heating pipe is developed and presented in the Methodology section.

2 Methodology

The general mathematical model of a single consumer is derived from conservation laws and its implementations in Termis and Modelica, is described. Parameters of the verification case study are given, which establishes the background for consistency and sensitivity analyses.

2.1 Mathematical Model and Parameters

The specific form of conservation laws referred to as a second form of energy balance [6] is often used in Modelica as a basis for dynamic pipe models [7, 8, 9],

$$\frac{\partial \rho\, u\, A}{\partial t}+\frac{\partial \rho\, v\, A\left(u+\frac{p}{\rho}\right)}{\partial x}-\frac{A\, v^2}{2}\left(\frac{\partial p}{\partial t}+\frac{\partial p v}{\partial t}\right)=Av\frac{\partial p}{\partial x}+\frac{2\rho f}{D}A|v|v^2+\frac{\partial}{\partial x}\left(k\, A\frac{\partial T}{\partial x}\right)+Q \tag{1}$$

where $A = \pi D^2/4$ is the cross-section area of the pipe with diameter D, $\dot{m}$ is the mass flow rate, ρ is the water density, c_p is heat capacity of water, c is the speed of sound, p is the pressure and T is the temperature. It is important to note, that the friction factor in Eq. (1), $f = 2\,\tau/(\rho\, v^2)$ with τ denoting the shear stress, is the Funning friction factor used in Termis and not the Darcy friction factor, $f_D = 8\,\tau/(\rho\, v^2)$.

To make use of this equation for comparison with static Termis model, it can be simplified by assuming constant specific heat capacity of the fluid, so that $u + p/\rho = h = c_p T$, and constant cross section area of the pipe, $A = \pi D^2/4$. Neglecting the axial heat conduction, time-derivatives of density, mass flow rate and pressure, and applying conservation of mass gives [9],

$$A\,\rho\, c_p\frac{\partial T}{\partial t}+\dot{m}c_p\frac{\partial T}{\partial x}=Av\frac{\partial p}{\partial x}+\frac{2\rho f}{D}A|v|v^2+Q \tag{2}$$

Now, symbols $\rho, \dot{m}$ and v denote density, mass flow rate and velocity of the fluid averaged over the pipe length. Assuming a steady state and taking the heat transfer term in the form $Q = C_h(T - T_g)$, where C_h is the heat transfer coefficient and T_g is the temperature of the surrounding ground, Eq. (2) can be written as an ordinary differential equation previously applied in [9] to speed up the simulation of pipe dynamics in Modelica

$$\frac{\partial T}{\partial x} + \frac{C_h}{\dot{m}\, c_p} T = -\frac{A\, v}{\dot{m}\, c_p}\frac{\partial p}{\partial x} + \frac{C_h}{\dot{m}\, c_p} T_g + \frac{2\rho f}{D\, \dot{m}\, c_p} A|v|v^2 \tag{3}$$

The equation is integrated under the approximation that the right side is constant and assuming the average values for pressure gradient, velocity and ground temperature. The solution is then given in the form

$$T(x) = T_g + \frac{A}{c_h} v \frac{\partial p}{\partial x} + \frac{2\rho f |v| v^2}{D\, c_h} + \left(T(0) - T_g - \frac{A}{c_h} v \frac{\partial p}{\partial x} - \frac{2\rho f |v| v^2}{D\, c_h}\right) \exp\left(-\frac{C_h x}{\dot{m}\, c_p}\right) \tag{4}$$

which is convenient for comparison, because it corresponds to model described in the Termis user guide and can easily be implemented in Modelica. The pressure gradient in Eq. (4) can be estimated from the simplified form of the momentum balance

$$\frac{\partial q}{\partial t} = -\frac{A}{\rho}\frac{\partial p}{\partial x} - \frac{2\, f}{D} v \frac{\partial v}{\partial x} - gA\frac{\partial z}{\partial x} - \zeta A v \frac{\partial v}{\partial x}, \tag{5}$$

In the assumption of steady state, it results in

$$\frac{\partial p}{\partial x} = -\frac{\rho}{A}\frac{2\, f}{D}|v|\frac{\partial v}{\partial x} - \frac{\rho g}{A}\frac{\partial z}{\partial x} - \zeta\rho|v|\frac{\partial v}{\partial x} \tag{6}$$

The integration of Eq. (4) leads to the expression for the pressure drop in the pipe, which is equal to the sum of pressure loss due to wall friction, pressure loss due to gravity, and local friction losses (produced by fittings, elbows, etc.):

$$\Delta p = -\left(2\, f\, \rho \frac{L}{D}\right)|v|v + g(z_D - z_U) - \frac{1}{2}\zeta\rho|v|v, \tag{7}$$

The calculations based on this formula show that the pressure gradient along the supply and return pipes is sufficiently accurately represented by the first term on the right side of Equation (1), when calculated by Termis,

$$\frac{\partial p_s}{\partial x} = \left(2\, f_s\, \rho_s \frac{1}{D}\right)|v_s|v_s, \quad \frac{\partial p_r}{\partial x} = \left(2\, f_r\, \rho_r \frac{1}{D}\right)|v_r|v_r \tag{8}$$

The Funning friction factor in the above relations is found by solving the Colebrook-White equation for the supply and the return pipe separately:

$$\frac{1}{\sqrt{f_{s,r}}} = -4\log_{10}\left(\frac{k}{3.7\, D} + \frac{1.413}{Re_{s,r}\sqrt{f_{s,r}}}\right) \tag{9}$$

2.2 Termis model

The Termis model of the system is shown in Figure 1, illustrating a simple supply network consisting of a single plant (left), pipe (line) and consumer (right dot). The model was created using predefined district heating components in Termis and subsequently also simulated. In the case study simulation (Section 3.1), the model parameters were set equal to the values listed in Table 1. Subsequently, the inlet temperature of the model was varied from 30 °C to 120 °C and the pipe length was varied from 50 m to 250 m in the sensitivity study (Section 3.2). Finally, parameters from Table 1 and the Termis results from the case study were used to make consistency analysis in Dymola (Section 3.3).

The auto-dimension function was applied in conjunction with the Termis standard pipe table which holds information about pipe diameter and heat conductivity. The simulations resulted in the use of 3 different pipe types. Using 30 °C inlet temperature resulted in the use of a pipe with an internal diameter of 0.0544 m with a heat transfer coefficient of 0.21 W/(m·K). Increasing the inlet temperature to 60 °C resulted in the use of a pipe with an internal diameter of 0.0372 m and a heat transfer coefficient of 0.165 W/(m·K). Using 90°C and 120°C inlet temperatures resulted in the use of pipes with an internal diameter of 0.0273 m and a heat transfer coefficient of 0.16 W/(m·K). The model was simulated using a maximum pressure-loss gradient of 10 Pa/m and the model was simulated for the entire temperature range for each pipe length.

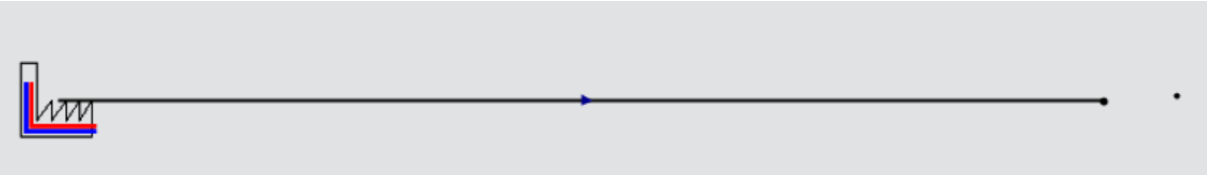

Figure 1: Termis model: a plant (left), pair of pipes (black line) and a consumer (right)

For the purpose of this paper, Termis was setup using some set control parameters. The plant uses the only consumer as a control point, whereas for larger and more complex networks the control point should be adjusted to the consumer furthest away to ensure all consumers receiving some set inlet temperature. The static return pressure to the plant was set to 3 bars and the pressure change at the consumer was set to 0.5 bar. The consumer was set up with a demand of 10 kW and a control return temperature of 300 K. The use of 300 K was based on having a constant return temperature for all the simulated temperatures, where the inlet of 30 °C was the lowest common denominator.

2.3 Modelica model

The Modelica model of the system is shown in Figure 2, where the left component represents the plant, right component represents the consumer, upper component is the supply pipe and the bottom component is the return pipe. The view of the package used for implementing this model is shown in Figure 3, where the connectors for different components are modelled in the subpackage **Interfaces**, the **Plant** and **Consumer** models are created within the **Sources** subpackage and a pipe model **StaticPipe** (common for both supply and return) is created within the subpackage **Distribution**. **Plant** and **Consumer** are the classes, which include the instances of the classes **Supply** and **Demand** in their implementation, which provides boundary conditions for production and consumption side. The four main components used in Figure 2 have the following functions (see also Table 1 for the present case study):

1. The **Plant** object sets the *Inlet Temperature* T_s of the water flowing into the supply pipe (80°C in Table 1), the *Static Supply Pressure* P_s in the water flowing from the plant to the supply pipe, the *Static Return Pressure* P_s flowing from the return pipe to the plant,
2. The **Consumer** component sets the return temperature *Temperature, Return* T_{cr} of the water inflowing to the return pipe to a fixed value (44.95°C in Table 1). It also calculates and sets the amount of mass flow rate in the system in the direction from the supply to the return pipe required to satisfy the prescribed demand given by *Power Control* Q (10 kW in Table 1). This component inherits from the **Demand** component, which uses the following formula for calculating the required mass flow rate:
$$\dot{m} = \frac{Q}{c_p(T_{rs} - T_{cr})} \tag{10}$$
where T_{rs} denotes the temperature of the fluid inflowing from the supply into consumer.

3. The **Pipe** component uses Eq. (4) together with Eqs. (6)-(9) to calculate the outlet temperature of the flow in the pipe based on its inlet temperature and average values of fluid properties (such as density, dynamic viscosity), pressure drop along the pipe and velocity, based on the calculated mass flow rate and parameters in Table 1.
4. The connector instances **FlowPort** within different elements of the network provide continuity of the system (mass balance) and insure the same temperature in the inlets and outlets of the neighbouring components.

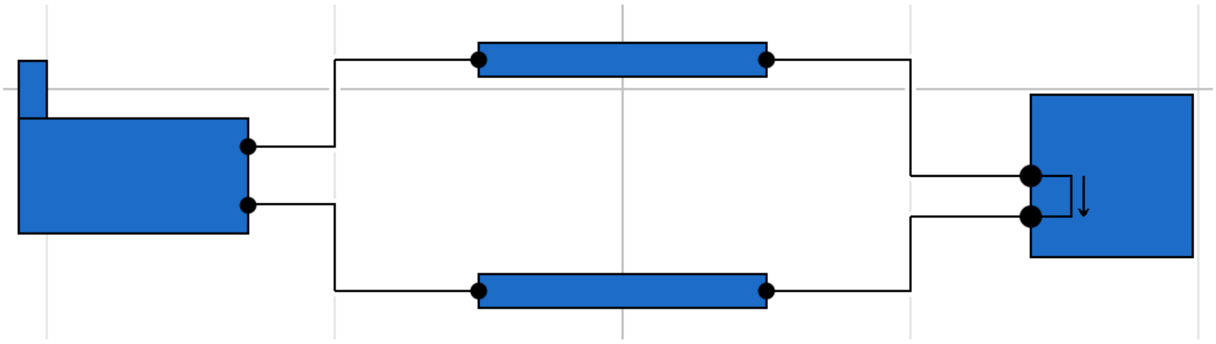

Figure 2: Visual representation of Dymola model with a plant, a pair of pipes and a consumer

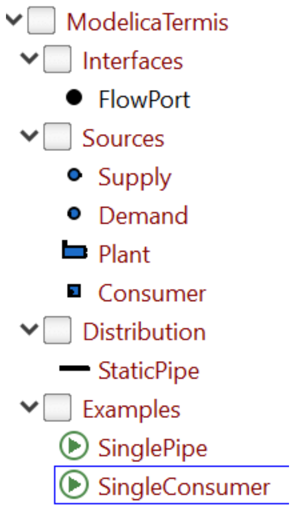

Figure 3: View of the Modelica library developed to verify Termis results

Table 1: Parameters used in the comparison case study

Parameter	Value	Symbol
(Plant) Inlet Temperature	80°C	T_s
(Plant) Static Return Pressure	3 bar	p_r
(Plant) Static Supply Pressure	3.5 bar	p_s
(Consumer) Power Control	10 kW	Q
(Consumer) Temperature, Return	44.95°C	T_{cr}
(Pipe) Diameter, Supply	37.2 mm	D
(Pipe) Roughness, Supply	0.0001 m	k
(Pipe) Length, Supply and Return	250 m	L
(Pipe) Heat Transfer Coeff., Supply	$0.165 \frac{W}{m \cdot K}$	c_h
(Pipe) Ground Temperature	10°C	T_g

3 Results

3.1 Comparison between Modelica and Termis

Table 2 shows the results of calculations of the single-consumer model implemented in Termis (Figure 1) and Modelica (Figure 2). The same **StaticPipe** component was used both as a supply and the return pipe in the Modelica model. The table shows that the temperature and pressure values for the supply pipe match in both calculations with small error. However, the calculations for the return pipe differ significantly with difference reaching 6 K. The reason for such discrepancy may be that the Modelica model approximates the pressure drop by the linear term of its Taylor expansion

$$\Delta p \approx \frac{\partial p}{\partial x} L \tag{11}$$

As discussed in the sensitivity analysis section below, the error between the inlet pressures to the return pipe in Termis and in Modelica exceeds 200%, which means that in this case the derivations presented in Methodology section must be reconsidered for the case of coordinate-dependent pressure gradient. This means that either more terms in the expansion must be taken into account in the derivations or the return pipe must be discretized with sufficient number of spacial elements.

Such conclusion seems probable, since such difference in temperature and pressure drop cannot be attributed to the difference in calculations of the other system variables listed in the result table. It was found that the change in friction loss parameters does not lead to any considerable change in the outlet temperature with maximum deviation from the average value on the order of 1-2 K. The introduction of the correction factor for the mass flow rate in Eq. (4) in the following form

$$CF = \frac{L\, c_h}{c_p\, A\, \rho \log\left((T_{cr}-T_g)/(T_{cr}-T_g)\right)} \tag{12}$$

makes the results for the temperature in the return pipe match. The same correction factor is used in the sensitivity study fulfilled in the next section to check whether this empirical approach is applicable to different boundary conditions in the system. Overall conclusion from this and other static simulations is that the developed Modelica model of the pipe accurately describes the temperature and pressure as long as the linear approximation for the pressure drop is accurate.

Table 2: Results of the verification simulation

Parameter	Result Termis	Result Modelica	Error in %
Pressure Before Consumer, Pa	352771	352768	0.00085
Pressure After Consumer, Pa	302771	300906	0.62
Pressure Gradient Supply, Pa	3.2439	3.2072	1.1
Pressure Gradient Return, Pa	3.5979	3.5393	1.6
Supply Pipe Outlet, °C	72.55	72.39	0.22
Return Pipe Outlet, °C	34.72	40.93	15.2
Supply Pipe Mass Flow, $\frac{kg}{s}$	0.08672	0.08557	1.3

Return Pipe Mass Flow, $\frac{kg}{s}$	-0.08672	-0.08557	1.3
Supply Pipe Velocity, $\frac{m}{s}$	0.08209	0.08074	1.6
Return Pipe Velocity, $\frac{m}{s}$	-0.08009	- 0.07916	1.2
Volumetric Flow Supply, $\frac{m^3}{s}$	8.922E-05	8.776e-05	1.6
Volumetric Flow Return, $\frac{m^3}{s}$	-8.7044E-05	-8.604e-05	1.2

3.2 Sensitivity analysis with Modelica

Figure 3 shows the sensitivity study of the supply pipe outlet as a function of the pipe length where different curves correspond to different temperatures of the plant outlet (quantity called *Inlet Temperature* T_s in Table 1). The solid (broken) curves show results from Dymola (Termis).

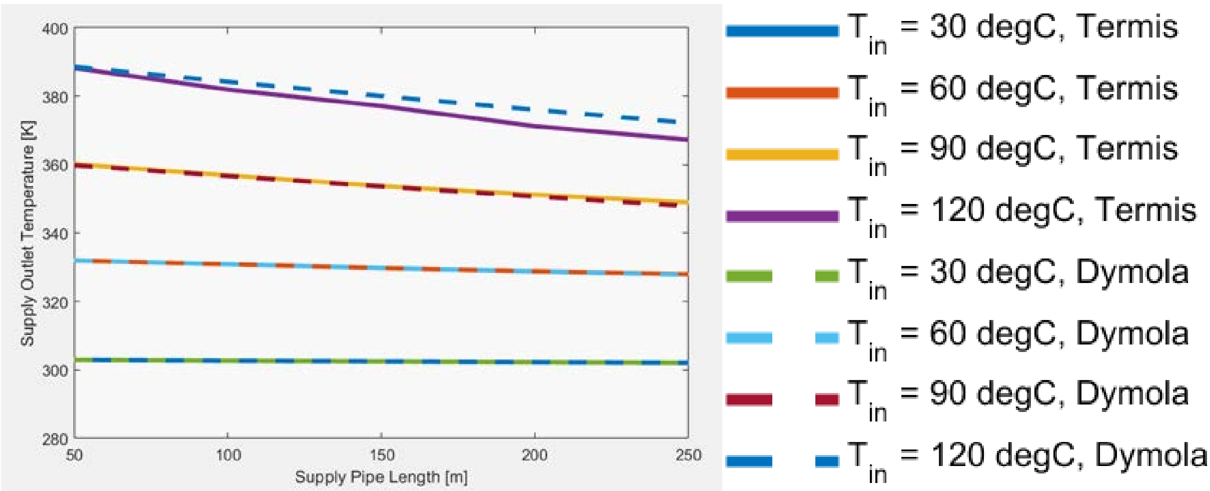

Figure 3: Supply pipe temperatures calculated in Termis (solid lines) and Modelica (broken lines) for several supply temperature values

From the figure, the outlet temperature dependency on inlet temperature can be seen in the range from 30 °C to 120 °C. The gradient of the line representing temperature loss as a function of length decreases at smaller inlet temperatures i.e. using higher inlet temperature increases the temperature difference and hence the heat loss. This is also coherent with the supply pipe length, as the length increases the surface area of the pipe resulting in higher heat loss. It should be noted that the error between the two models also increases with increasing temperature. This could be explained by the fact that at 3.5 bar the boiling point for water is 139°C, which may cause an error both in Modelica and in Termis results. As the figure shows, the accuracy decreases with both increasing length of the pipeline and increasing supply temperature.

3.3 Consistency analysis

To check whether the formulas used in Modelica give the same result as Termis, the consistency analysis is made as follows. Some of the Termis model outputs calculated using Table 1 are substituted into the Modelica model as parameters to find the remaining outputs.

These remaining values are compared in Table 4, where the second column is taken directly from Termis and the third column is produced by Modelica model. Specific studies concerning different formulas can be mentioned:

- the accuracy of Eqs. (7) is checked by calculating the pressure gradient in the supply and return pipes,
- the corresponding values for the temperatures are calculated from Eq. (4),
- the parameters, including the density and the dynamic viscosity, was calculated based on the average of the fluid temperatures at the ends of the pipes: $T_{av,s} = (T_s + T_{cs})/2$ (supply) and $T_{av,r} = (T_r + T_{cr})/2$ (return).

The used formulas for the water properties were taken from Termis users guide and are based on empirical constants $\alpha = -3.016, \beta = -0.0139, \alpha_D = -0.000547, k_0 = 2.1\text{e}9,\ T_0 = 325\ K, \rho_0 = 988\frac{kg}{m^3}, p_0 = 101.3\ \text{kPa}$:

$$\mu = \exp(\alpha + \beta\ T_{av}) \tag{13}$$

$$\rho = \rho_0 \exp\big((p_{av} - p_0)/k_0\big) \exp(\alpha_D(T_{av} - T_0)) \tag{14}$$

The mass flow rates and pressure gradients calculated from Eq. (8) differ from the Termis results with less than a 2% error. Although pressure gradient value calculated using Eq. (8) matches the value of the pressure gradient calculated in Termis, the return pressure gradient does not match the value of the pressure difference between the inlet and the outlet divided by length of the pipe, Eq. (11). It is seen, however, by looking at both the supply and return results for the outlet pipe temperatures, that the difference in the pressure drop definition does not influence the accuracy noticeably. It is however possible, that such influence would be seen, if the temperature drop was calculated using a more general law than Eq. (7). It is therefore necessary to reformulate the model in future simulations. Meanwhile, we have used the Correction factor to make a sensitivity analysis in previous section.

Table 3: Results of the consistency analysis

Parameter	Result Termis	Result consistency	Error in %
Pressure Before Consumer, Pa	352771	352756	0.0043
Pressure After Consumer, Pa	302771	300903	0.62
Pressure Gradient Supply, Pa	3.2439	3.3034	1.8
Gradient Supply from Eq. (11)	-	3.2528	0.27
Pressure Gradient Return, Pa	3.5979	3.6119	0.39
Gradient Supply from Eq. (11)	-	11.08436	67.5
Supply Pipe Outlet, degC	72.55	72.6829	0.18
Supply Outlet from Eq. (11)	-	72.6830	0.18
Return Pipe Outlet, degC	34.72	40.9376	15.2
Return Outlet using Eq. (11)	-	40.7367	14.8

4 Conclusion

At present stage, Modelica cannot directly compete with static district heating simulation tool, if the average in-company or governmental user is concerned. For Modelica to be directly applicable to the tasks such as network monitoring, financial and stability analysis, the physical approximations made in Termis should be accurately modelled and validated. This leads to a necessity of developing a new library for dynamic simulations verified against the existing static simulation tools. This task was partially accomplished in this paper by implementing the Modelica model of the static pipe in the approximation of linear dependence of the pressure drop on pipe length. The specific case study has shown that the Modelica model gives accurate results in the case of the supply pipe and identified problems in reproducing the correct outlet temperature from the return pipe. To further explore potential limitations, sensitivity and consistency analysis in Modelica were conducted, which used Termis as reference. The sensitivity analysis has shown, that the model should be reconsidered for the network with supply temperatures above 100°C to improve accuracy near the region of phase change from water to steam. The consistency analysis identified the problems for the model to handle a large pressure drop, which is especially important for systems with long pipelines with complicated topology. The study has shown, however, that apart from large pressure drops and temperatures, the model is able to accurately predict the values of temperature and pressure in the system based on the data provided for specific parts of the network with the same level of confidence as Termis.

Summarizing, it was shown that Modelica can reproduce the results obtained from Termis, that results obtained from Modelica are in accordance with the formulas reported in Termis help section (consistency analysis) and considered how the difference between the two models changes with changing model parameters. Further application of the developed package will explore advantages of Modelica for coupling between energy sectors, optimizing the combined network performance with respect to the financial and flexibility objectives and can be used with generic optimization tools for parameter estimation and planning of the district heating networks.

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