Towards Open-Source Modelica Models for Steam-Based District Heating Systems

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Abstract

This paper introduces new models of the Modelica Buildings Library for thermo-fluid simulation of steam-based district heating systems in support of design, operation, and energy analysis. Steam represents a prominent and indispensable form of energy, providing energy for 97% of district heating and upwards of 84% for some manufacturing industries in the United States. Our primary contribution is to enable modeling and simulation of complete steam heating districts that was not previously possible at large scales for industry practices. We implemented open-source models using the Modelica standard, with models ranging from base classes through complete systems. In this paper, we present the newly developed models, including their main assumptions and physical relations, and demonstrate their application for complete district heating systems featuring $N \in [10, 200]$ number of buildings. Compared to district models with the commonly-adopted IF97 water/steam model and equipment models from the Modelica Standard Library, the new implementation eliminates costly nonlinear systems of equations, significantly improving the scaling rate for large districts from $\mathcal{O}(N^{3.5})$ to $\mathcal{O}(N^{1.7})$. For an annual simulation with 180 buildings, this translates to a computing time reduction from 3.4 hours to 3.6 minutes. These results are critically important for thermo-fluid simulations of large steam heating systems.

Keywords District Heating · Steam · Equation Based Modeling · Modelica · Open Source · Numerical Simulation

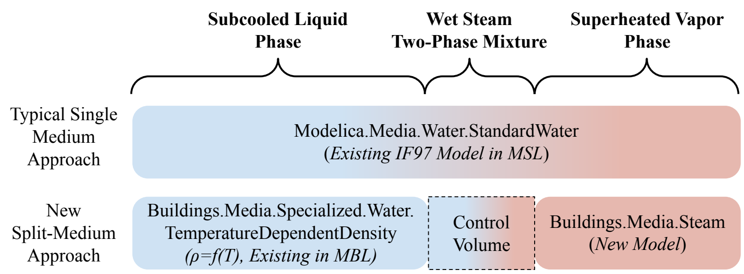


Figure 1: Water and steam modeling approaches. The liquid water model from the MBL calculates density ρ as a function of temperature T.

1 Introduction

For industrial and heating processes, steam provides an "indispensable means of delivering energy" due to its low toxicity, ease of transport, high efficiency, high heat capacity, and relatively low cost [1]. For these reasons, steam is commonly used in industrial and energy-intensive applications, representing 47% to 84% of the total energy used in some major manufacturing industries [2]. Further, steam is common in district heating (DH) applications, where waste heat can be recovered from energy-intensive processes (i.e., manufacturing or electric power generation) and used for space and domestic hot water heating applications. This waste heat recovery with DH provides multiple benefits, including decreased fuel consumption, energy costs, and operational costs, while also reducing the need for heating equipment and associated maintenance at individual buildings [3]. Indeed, steam is the most common heat transfer medium for DH in the United States, representing 97% of all installations [4].

Our application domain is thermo-fluid simulation of steam DH systems in support of design, operation, and energy analysis. Despite its prominence and energy efficiency benefits, existing tools fall short in supporting complete steam DH system simulations. This is particularly true when considering the usability standards and quick simulation timelines required for industry adoption. As such, past literature on steam DH modeling and simulation have predominantly focused on the central plant [5], distribution network [6], or interconnected buildings [7], but not complete systems [8]. In terms of modeling approaches, the International Association for the Properties of Water and Steam (IAPWS) 95[9] and IF97[10] formulations for water/steam thermodynamic properties are most commonly adopted. In the Modelica domain, ThermoSysPro [11] and ThermoPower [12] libraries are suitable for steam plants, while the Modelica Buildings Library (MBL) [13] and IDEAS library [14] are suitable for buildings connected to district networks, among other applications. However, complete steam DH system modeling tools and studies are generally lacking. To enable simulation of steam DH systems at large district scales (e.g., 100+ buildings), two principle challenges need to be addressed. First, complete district simulations contain *multiple parallel closed loops* in the thermo-fluid system that grow linearly with the number of buildings N. These thermo-fluid lops can create coupled systems of nonlinear equations, which require the application of iterative, nonlinear solvers that can be computationally costly. Second, steam heating systems involve phase changes that cross the two-phase wet steam region. With this, discontinuities in the thermodynamic functions at the phase change boundary can cause significant challenges (e.g., chattering [15]) and at times failure when simulating large-scale thermo-fluid systems.

To address these challenges, we develop (1) a novel "split-medium" approach for water and steam thermodynamics and (2) computationally efficient component models for steam DH systems. The objectives of these developments are to eliminate nonlinear systems of equations by decoupling the mass and energy balance equations and to minimize numerical challenges at the phase-change transition. Shown in Figure 1, the "split-medium" approach divides the liquid and vapor phases between two separate medium models, rather than implementing a single medium model as typically done. This allows several models for water/steam thermodynamics to be coupled with a numerically-efficient liquid water model from the MBL. The liquid model used here calculates density as a function of temperature only (i.e., incompressible), thus decoupling density from pressure. Further, our new steam vapor model replaces key thermodynamic property functions (e.g., specific enthalpy and entropy) with accurate polynomial approximations in a reduced pressure-temperature range. While this reduced range (0.1-0.55 MPa, 0-160°C) does not apply to all steam systems, its intention is to address the numerical challenges caused by the IF97 formulation in the superheated vapor region. When suitable for the intended application, these secondary simplifications may further reduce computing time and numerical challenges. More information about our approach and evaluations of the accuracy and computing speed for thermodynamic property calculations, individual component model simulations, and complete DH simulations is available in Hinkelman et al. [8]. While our previous publication focused on several water/steam thermodynamic modeling approaches across multiple scales, this paper presents the new open-source models not previously available.

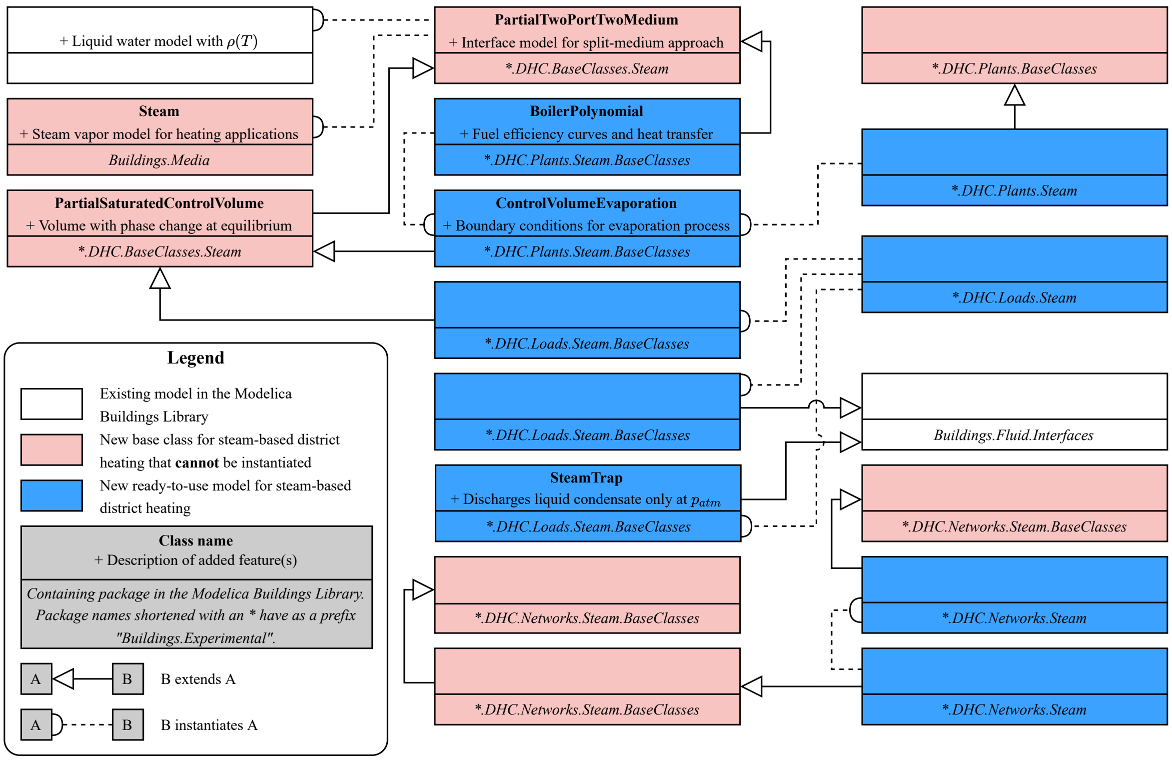


Figure 2: Class inheritance and instance diagram for the new steam district heating models in the MBL. Complete references to existing MBL models are not included due to space constraints. Note that the DHC package is located within the *Buildings.Experimental* package while it remains under development. This will later be moved to the *Buildings.Applications* package.

The new models introduced with this paper are open-source in the MBL, available at commit ee9000f [16]. In the following sections, we present the new models, starting with the package structure in section 2 before the content details in section 3. The example model and simulation results of complete steam DH systems featuring 10 to 200 buildings are in section 4. Lastly, conclusions are in section 5.

2 Package Structure

In Modelica, models are collected in packages, which are organized hierarchically. Consistent with the MBL design, a class hierarchy is used with the new steam DH models, as shown in Figure 2. This structure allows users to reuse base classes and replace models, using Modelica's redeclaration constructs. These base classes also define standardized interfaces. In Figure 2, white components are existing models, red components are new base classes, and blue components can be instantiated by users to construct complete system models. While some new models are integrated with existing packages of the MBL, most are included in the new *Experimental.DHC* package, which contains models from several ongoing projects to enable district heating and cooling (DHC) simulations from steam through combined heating and cooling (cold network). For more information on DHC types and generations see [17].

3 Model Contents

Due to space limitations, we only present some selected new models. In this section, base classes and models of key equipment are described, including the underlying physics and assumptions. Further modeling details, including subsystem and system examples, are available in the MBL documentation and Hinkelman et al. [8].

3.1 Base Classes

3.1.1 PartialTwoPortTwoMedium

This base class provides a basic interface for all models utilizing the split-medium design for phase-change processes. It allows separate medium model assignments at each fluid port. Medium packages are replaceable to allow liquid water and steam vapor models to be assigned depending on the phase-change process that occurs in the component, such as condensation for a heat emitting device or evaporation for a boiler. In addition, this base class sets the mass flow as positive from `port_a` to `port_b`, pressure drop `dp` between the ports, and defines several parameters common to all models (i.e., energy balance type).

3.1.2 PartialSaturatedControlVolume

This partial control volume represents evaporation or condensation phase change processes with the liquid and vapor states in equilibrium. Two principal assumptions are made: First, we assume that the water is always saturated, and fluid leaves the volume as either saturated vapor (quality $\chi = 1$) for evaporation or saturated liquid ($\chi = 0$) for condensation. Second, we assume that the liquid and vapor components are at equilibrium (i.e., a single pressure-temperature (p, T) state). With these assumptions, any superheating or subcooling can occur in up- or down-stream components, such as with heat exchangers or superheaters. Models that extend this base class must assign the boundary conditions at the ports, including the mass flow rate and specific enthalpy, as done with the components in sections 3.2.1 and 3.2.2.

The fundamental equations are as follows. The fluid mass m in the volume is calculated as

$$m = \rho_s V_s + \rho_w V_w, \tag{1}$$

where ρ is density, V is volume, and subscripts s and w represent the steam and liquid water components, respectively. The total internal energy U is

$$U = \rho_s V_s h_s + \rho_w V_w h_w - pV, \tag{2}$$

where h is specific enthalpy, p is pressure, and the total volume of fluid is $V = V_s + V_w$.

This model allows both steady state and dynamic mass and energy balances. The dynamic mass balance is

$$\frac{dm}{dt} = \dot{m}_s + \dot{m}_w, \tag{3}$$

where $\dot{m}_s$ and $\dot{m}_w$ are the mass flow rates of steam and liquid water, respectively. The dynamic energy balance is

$$\frac{dU}{dt} = \dot{Q} + \dot{m}_s h_s + \dot{m}_w h_w, \tag{4}$$

where $\dot{Q}$ is the net heat flow rate into the volume.

It is important to note that the new *PartialSaturatedControlVolume* is similar to *Modelica.Fluid.Examples.DrumBoiler. BaseClasses.EquilibriumDrumBoiler* [18], except:

1. It is a reusable base class that can be applied for both evaporation and condensation processes;
2. Rather than a single medium model, the split-medium approach is implemented; and
3. The metal drum is excluded from the mass and energy balances.

3.2 Components

Two component models extend the *PartialSaturatedControlVolume* base class to add equations for evaporation and condensation. These two implementations are as follows.

3.2.1 ControlVolumeEvaporation

Extending the *PartialSaturatedControlVolume*, this instantiable model assigns mass flow rate and enthalpy at the ports as shown in Listing 1. With the control volume at a saturated state, leaving fluid is either saturated vapor (normal forward flow) or saturated liquid (reverse flow).

3.2.2 ControlVolumeCondensation

The condensation control volume involves the same mathematical formulation and assumptions as *ControlVolumeEvaporation* except that a condensation process occurs rather than an evaporation process. In the implementation (Listing 2), the differences are in the boundary condition assignments.

```
model ControlVolumeEvaporation
  extends PartialSaturatedControlVolume;
equation
  // boundary conditions
  port_a.m_flow = mWat_flow; // Assign ṁ_w to inlet port
  port_a.h_outflow = hWat; // Assign h_w to inlet port
  port_b.m_flow = mSte_flow; // Assign ṁ_s to outlet port
  port_b.h_outflow = hSte; // Assign h_s to outlet port
end ControlVolumeEvaporation;
```

Listing 1: *ControlVolumeEvaporation*.

```
model ControlVolumeCondensation
  extends PartialSaturatedControlVolume;
equation
  // boundary conditions
  port_a.m_flow = mSte_flow; // Assign ṁ_s to inlet port
  port_a.h_outflow = hSte; // Assign h_s to inlet port
  port_b.m_flow = mWat_flow; // Assign ṁ_w to outlet port
  port_b.h_outflow = hWat; // Assign h_w to outlet port
end ControlVolumeCondensation;
```

Listing 2: *ControlVolumeCondensation*.

3.3 Equipment

3.3.1 BoilerPolynomial

Figure 3 shows the schematic model view of the steam boiler that discharges saturated steam and has an efficiency curve defined by a polynomial. The rate of heat transferred to the water medium $\dot{Q}$ is

$$\dot{Q} = y\,\dot{Q}_0\,\frac{\eta}{\eta_0}, \tag{5}$$

where $y \in [0,1]$ is the load ratio, $\dot{Q}_0$ is the nominal heat capacity, η is the total efficiency at the current operating point, and η_0 is the total efficiency at $y = 1$ and boiler output temperature $T = T_0$, where T_0 is the nominal temperature. With efficiency $\eta = \dot{Q}/\dot{Q}_f$ and $\dot{Q}_f$ representing the rate of heat released by the fuel combustion, the three polynomial options to compute η are

$$\eta = a_1, \tag{6}$$

$$\eta = a_1 + a_2 y + a_3 y^2 + ... + a_n y^{n-1}, \quad \text{and} \tag{7}$$

$$\eta = a_1 + a_2 y + a_3 y^2 + (a_4 + a_5 y + a_6 y^2)T, \tag{8}$$

where a_1 through a_n are regression coefficients.

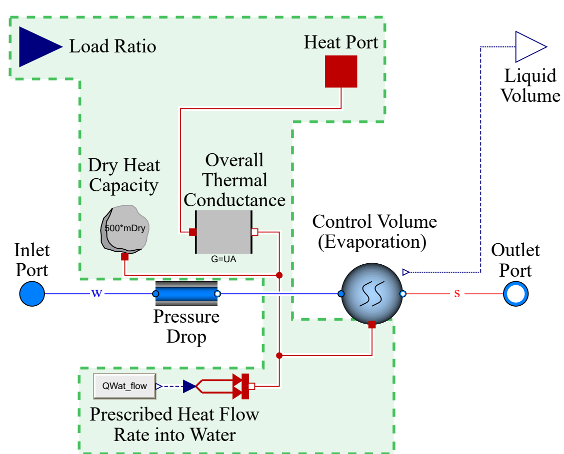
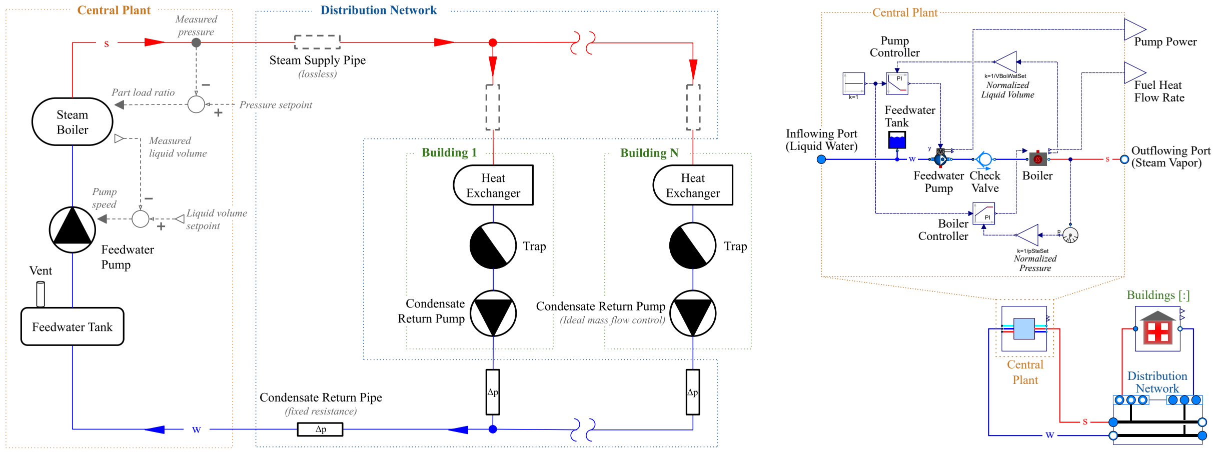


Figure 3: Modelica diagram for the steam boiler with an efficiency curve defined by a polynomial. Components in the green shaded region (including the heat port for the control volume, but not the volume itself) are conditionally removed if the boiler is configured with steady mass and energy balances.



(a) (b)

Figure 4: (a) Schematic diagram of the steam DH system with a central plant, distribution network, and N number of interconnected buildings and (b) Modelica diagrams of the complete DH system and central plant. The optional PRV in the building model is not included in this case study example.

The steam boiler model can have steady or dynamic mass and energy balances. If the boiler is configured in steady state, then several components (highlighted in green in Figure 3) are conditionally removed to maintain a consistent set of equations. This is unique to the saturated steam boiler because the thermodynamic state of steam is constrained at the outlet port at pressure $p = p_{sat}$ with $T = T_{sat}(p_{sat})$ and enthalpy $h = h_v(p_{sat})$, where subscript sat is the saturated state. Therefore, if the mass and energy balances are steady, then prescribing the heat flow into the fluid over-constrains the problem, and thus they are removed. Conversely, dynamic balances enable the heat flow rate into the control volume to be calculated based on the heat transfer from the fuel and through the boiler's enclosure with the external environment.

3.3.2 ValveSelfActing

In DH systems, plants generate high pressure steam, which often needs to be reduced before being used on the building side due to functional and safety requirements. A common way of reducing the steam pressure is by isenthalpically throttling the steam passageway through a pressure reducing valve (PRV). These are self-acting control valves that automatically adjust the diameter of the valve orifice to reduce the unregulated inlet pressure to a constant, reduced outlet pressure. In the model, we assume a valve with ideal pressure reduction that discharges steam at a user-defined low pressure of p_{b0}. This allows the pressure drop in the valve model to be independent of mass flow rate, which improves simulation efficiency.

3.3.3 SteamTrap

A required component of steam heating systems, steam traps effectively ensure that only liquid condensate leaves components (e.g., steam heat exchanger), while any flashed steam is returned to a liquid state before discharge. This prevents the loss of steam while protecting pipes for water from damage by hot and high pressure steam vapor. In this model, we assume steady state mass and energy balances. The steam trap represents an isenthalpic thermodynamic process that transforms liquid water from an upstream high pressure (state 1) to atmospheric pressure (state 2a), followed by an isobaric condensation process to return flashed steam to a saturated liquid (state 2). The heat loss in the trap $\dot{Q}_l$ is

$$\dot{Q}_l = \dot{m}(h_{2a} - h_2), \tag{9}$$

where $\dot{m}$ is the steady state mass flow rate, and h_{2a} and h_2 are the specific enthalpies at states 2a and 2, respectively.

4 Example

We now present an example that demonstrates how the new steam DH models can be assembled into a complete system with N buildings. The new implementation involving models presented in this paper is referred as "New", while a physically-comparable system involving existing models from the Modelica Standard Library is referred to as "MSL". The MSL case includes the *EquilibriumDrumBoiler* and two-phase *Modelica.Media.Water.StandardWater* based on the

Table 1: Linear and nonlinear systems of equations after Dymola's built-in model manipulation.

N	*Linear Systems*		*Nonlinear Systems*	
	MSL	*New*	*MSL*	*New*
1	$\{2, 2\}$	$\{2\}$	$\{2, 4\}$	$\{3\}$
2	$\{2, 2, 2\}$	$\{2\}$	$\{3, 4\}$	$\{3\}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
n	$\{2, 2, ..., 2_{(n+1)}\}$	$\{2\}$	$\{n + 1, 4\}$	$\{3\}$

IF97 formulation. In [8], we demonstrated that compared to the MSL case, the New models produce similar accuracy and a significantly improved computing speed for DH systems with variable heating load profiles at the buildings. The simulation objective in this paper's example is to evaluate the accuracy and computing speed of the MSL and New example models when the buildings contain constant heating load profiles. Further, the model versions of this paper are the open-source releases [16], which were previously not available. Simulations ran in Dymola 2021 with the DASSL solver (simulation tolerance of 10^{-6}) on a Windows 10 workstation with a Intel® Xeon® 3.60GHz CPU and 32.0GB of RAM.

4.1 System Description

Figure 4 depicts (a) the schematic diagram and (b) Modelica diagrams for the top-level system and central plant, composed of models from section 3. This DH system is broken into three subsystems: a central plant, the distribution network, and buildings. At the plant, the feedwater pump and boiler both have dynamic energy and mass balances, and PI controllers are used to maintain the water level and pressure setpoints. While there are several mechanical and control designs seen in central plants [19], this configuration was selected because it is a simple yet common design found in practice. Saturated steam is discharged from the boiler at $300\,\mathrm{kPa}$. The boiler model has a constant efficiency of $\eta = 0.9$. For this example, we assume that heat losses across the boiler's enclosure with the ambient environment are included in η. In the distribution network, this example includes pressure drop in the condensate return pipes, but does not include mass nor heat losses in either supply or return pipes.

The building model represents the district-side thermo-fluid system with a heating load $\dot{Q}_b$ prescribed using tabulated data at the energy transfer station (i.e., the complete building-side piping is not modeled). We assume heat losses at the buildings are included in this tabulated data. A condensate return pump prescribes the mass flow rate of steam/condensate at the building as $\dot{m}_b = \dot{Q}_b/(h_1 - h_2)$, where h_1 and h_2 are the measured inflowing and outflowing specific enthalpy values, respectively. For this example, we assume constant heating loads of $\dot{Q}_b = 19.3$ kW, with the nominal heat flow rate of the plant's boiler being $\dot{Q}_0 = N\,\dot{Q}_b$. The DH system is simulated for 15 days with $N = [10, 20, 30, ..., 200]$ buildings. Simulations are repeated 5 times for each set of MSL and New cases, for a total of 200 simulation runs. Average computing times across the 5 repeated simulations are reported.

4.2 Results

As shown in Table 1, the linear and nonlinear systems of equations differ between the MSL and New MBL cases. The number of linear systems of equations increases linearly with N for the MSL case, while it is constant in the New case. More importantly, the dimension of the nonlinear system of equations increases linearly with N for the MSL case, while it is constant for the New case. We achieve this constant result because density and pressure are decoupled with the split-medium approach and the numerically-efficient water models of the MBL. This allows the Modelica tools to decouple the energy from the mass balance equations, eliminating algebraic loops that require iterative, nonlinear solvers.

However more important are the scaling results. Figure 5 shows the log-log plot of the computing time versus the number of buildings. For large N, the computing time is expected to scale as $t_{cpu} = k\,N^p$, where k is some constant and p is the order of the scaling. In a log-log plot, this curve becomes $\log(t_{CPU}) = \log(k) + p\,\log N$. Making a data fit for $N \geq 110$, which is where we see the expected linear behavior reproduced in the data, we obtain for MSL $p = 3.5$ and for New $p = 1.7$. Thus, while the MSL implementation scales as $\mathcal{O}(N^{3.5})$, the New implementation scales as $\mathcal{O}(N^{1.7})$. For an example of an annual simulation with 180 buildings, this result correlates to a computing time improvement from 3.4 hours with the MSL case to 3.6 minutes with the New case.

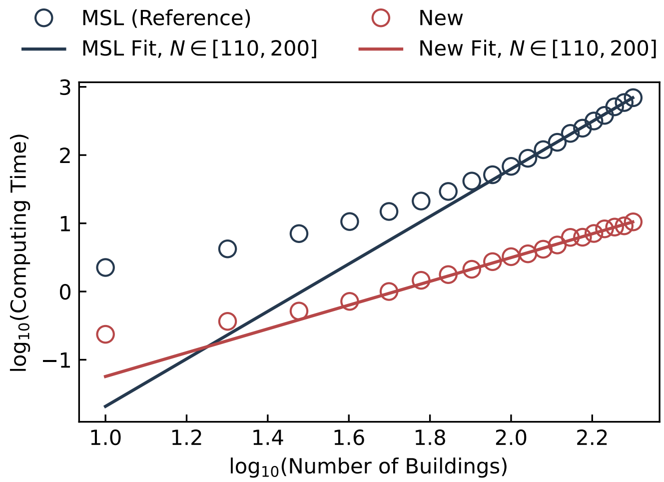


Figure 5: Computing time in seconds with respect to the number of buildings N and linear fits indicating scaling rates, on a log-log scale (base 10).

5 Conclusion

We present new modeling capabilities of the open-source MBL to enable fast and accurate simulation of complete steam-based DH systems. These models include base classes, components, equipment, and complete system examples to aid user adoption for their own project purposes. Compared to a typical steam heating implementation featuring the two-phase IF97 steam/water model and existing open-source components of the MSL, our new implementation eliminates costly nonlinear systems of equations by decoupling pressure and density calculations. This decoupling is critical for large-scale steam DH simulations, as the simulation time of the implementation that uses models from the MSL scales as $\mathcal{O}(N^{3.5})$, while our implementation scales as $\mathcal{O}(N^{1.7})$. This significantly increases the size of systems that can be simulated in practical applications.

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