A Modular Model of Reversible Heat Pumps and Chillers for System Applications

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Abstract

Vapour compression machines such as heat pumps and chillers are vital for achieving climate goals. Efficiency of both depend mostly on system integration. In order to simulate coupled energy systems, fast and stable simulation models are required. Hence, we implement an open-source model for reversible vapour compression machines. The black-box based refrigeration cycle is replaceable, additional inertia and losses are optional. Furthermore, we model relevant safety controls of vapour compression machines. To show validity of the presented approach, we first calibrate two different black-box models onto measured heat pump data. The table-based model fits both measured temperature and power with minimal calibration effort. Second, we show influences of different model options onto coupled building performance simulations. Computation time increases up to 50 % when enabling all model options. Simultaneously, seasonal efficiency decreases by up to 23 % when modeling all safety controls. *Keywords: Heat Pump, Chiller, Modular Model*

1   Introduction

Heating and cooling account for half of Europe's secondary energy demand (Heat Roadmap Europe 2017). While cooling is already mainly achieved using electrically driven chillers (e.g. air conditioners), heat pumps (HPs) are set to replace gas or oil fired boilers (IEA 2020). Thus, improving efficiency of both is a major goal of current research.

As both chiller and heat pump are based on the same vapour compression cycles, designation mainly depends on which side contains the usable heat flow. Using a four-way reversing valve, a heat pump may act as a chiller and vice versa. Hence, in the following we refer to both as vapour compression machines (VCM).

To increase efficiency of VCMs, improvements on component level and system integration level are possible. Generally, the efficiency depends on the applied temperature levels. These temperature levels on the other hand depend mainly on the system integration. Thus, we focus on the integration of VCM into an energy system.

To thoroughly assess efficiency on system level, seasonal coefficients of performance (SCOPs) are required (Huchtemann and Dirk Müller 2012). While Hardware-in-the-Loop experiments as in Mehrfeld, Nürenberg, Knorr, et al. (2020) or field tests are cost intensive, model-based simulation analysis offers a viable solution to not only assess the SCOP but also to find promising control and system designs that optimize efficiency.

A model is always created based on the aim of the simulation analysis (VDI 3633:2014-12 2014). Consequently, numerous approaches for the modeling of VCMs exist in literature. The following section will give a brief overview.

2   Related work

The main distinction in models is between two types: Modeling the refrigeration cycle with empirical data (black-box) and using physical-based equation (gray/white-box) (Jin 2002). Black-box models are usually robust and require less computation time compared to the latter. In most cases, empirical data is based on steady-state operating points. Outside the given performance maps, which are often small, extrapolations usually yield non-physical results (Cimmino and Wetter 2017). However, for certain investigation aims, partly higher accuracies are achieved compared to gray-box models (Carbonell Sánchez et al. 2012). Afjei and Dott (2011) assign investigation targets to the different model types. Gray-box models are, due to the high level of detail and the high flexibility, suitable for the investigation of new heat pump concepts. For dynamic simulations on the other hand, black-box models with dynamic effects are useful (Afjei and Dott 2011).

2.1   Gray-box models

Cimmino and Wetter (2017) introduce two gray-box models, `ScrollWaterToWater` and `ReciprocatingWaterToWater`. By assuming a simplified refrigeration circuit, the modeling of the expansion valve is not required. Both models are non-reversible. As refrigerant, R410A is used. HP internal safety control is taken into account using temperature protection. By calibrating the model with manufacturer data, the parameters are defined and made accessible via records (Cimmino and Wetter 2017). Dechesne et al. (2017) model an inverter-controlled air/water HP with consideration of the refrigeration circuit for the refrigerant R410A. The possible icing of the evaporator

is taken into account through various assumptions. However, a validation of these assumptions is not performed (Dechesne et al. 2017). The model of a heat pump with water as refrigerant is implemented by Chamoun, Rulliere, Haberschill, and Berail (2012) for industrial applications. In another contribution, they introduce a screw compressor model for HP applications (Chamoun, Rulliere, Haberschill, and Peureux 2013).

2.2 Black-box models

In the following, two black-box models of the `IBPSA` library will be described (International Building Performance Simulation Association 2018). In each, the two variables electricity consumption P_{el} and used heat flow $\dot{Q}_{Con}$ are determined. Assuming a steady-state, adiabatic process, $\dot{Q}_{Eva}$ is then calculated:

$$0 = P_{el} + \dot{Q}_{Eva} - \dot{Q}_{Con} \tag{1}$$

The models `Carnot_TCon` and `Carnot_y` are based on the same principle, only the input variable changes. `Carnot_TCon` sets the output temperature of the condenser $T_{Con,out}$ via an ideal heater. Using the output $\dot{Q}_{Con}$ and the COP, P_{el} and $\dot{Q}_{Eva}$ are calculated. `Carnot_y` determines P_{el} by the product of $P_{el,Nom}$ and the input y which is the part load set point between zero and one. For both models, the COP is obtained using the Carnot efficiency at nominal and current conditions. These model approaches are valid for both chillers and heat pumps. For chillers, condenser and evaporator are switched (International Building Performance Simulation Association 2018).

For heat pumps, the `AixLib` library introduced an approach obtaining P_{el} and $\dot{Q}_{Con}$ through manufacturer data based on EN 14511 (EN 14511-1:2018-03 2018; D. Müller et al. 2016). Based on the same approach, the `IDEAS` library contains a heat pump model as well (Jorissen et al. 2018).

Besides these open-source models, researchers have presented their approach in various contributions. De Coninck et al. (2010) calculates P_{el} and $\dot{Q}_{Con}$ based on the ambient temperature T_{amb}, the condenser temperature T_{Con}, and manufacturer data. Wystrcil and Kalz (2012) use field test data to determine a four coefficient polynomial of the *COP* as a function of the temperatures $T_{Eva,in}$ and $T_{Con,out}$.

Until now, we focused our review on Modelica models. However, the modeling approaches in other simulation tools mostly do not differ. The assumption in Equation 1 is state of research for black-box approaches. Examples are given in (Afjei and Wetter 1997; EN 12900:2013-10 2013).

This review highlights the gap in the current state of the art, which can be summarized in two points.

1. Each contribution develops a new model. However, the black-box approaches only differ in how P_{el} and

$\dot{Q}_{Use}$ are calculated. To spend less time in model development and more time in simulation analysis, a uniform and modular approach is necessary.

2. Besides Cimmino and Wetter (2017), VCM internal safety controls are disregarded. However, such controls strongly influence the behaviour of the machine in the energy system and thus, it's SCOP (Mehrfeld, Nürenberg, Knorr, et al. 2020).

Following the identified gaps, we present a new modular model for reversible heat pumps and chillers. The vapour compression cycle is modeled as a black-box. Contrary, the interactions with the energy systems are gray-box based. The model is presented in the following section.

3 Modular modeling approach

The following section presents our modeling approach. The overall model is depicted in Figure 1. To ensure reuseability of the approach, we implement all presented models in the open-source library `AixLib` (D. Müller et al. 2016). We aggregate all relevant inputs and outputs using a pre-defined expandable bus connector. All bus variables are listed in Table 1. In general, `Set` indicates a control variable and `Mea` a physical variable. As core of each VCM, we start with the black-box approach of the vapour compression cycle.

Table 1. Pre-defined variables of the VCM bus.

Variable	Explanation
nSet	Relative compressor frequency
modeSet	Set to false to reverse the device
onOffMea	Boolean indicating if device is on
PelMea	Measured electrical power
CoPMea	Measured COP
iceFacMea	Icing factor f_{ice}, see subsection 3.1
TOdaMea	Outdoor air temperature
TEvaInMea	Evaporator inlet temperature
TEvaOutMea	Evaporator outlet temperature
TEvaAmbMea	Ambient temperature at evaporator
TConInMea	Condenser inlet temperature
TConOutMea	Condenser outlet temperature
TConAmbMea	Ambient temperature at condenser

3.1 Vapour compression cycle

In order to realize a reversible and modular VCM model, we introduce a partial model named `PartialPerformanceData`. Inputs to the model are all bus variables listed in Table 1. Outputs are the three main energy flows, $\dot{Q}_{Con,out}$, $\dot{Q}_{Eva,out}$ and $P_{el,out}$. Both HP and chiller models may extend this model and connect these inputs to the outputs based on a black-box approach.

The vapour compression cycle model, named `innerCycle`, then uses this partial model as a re-
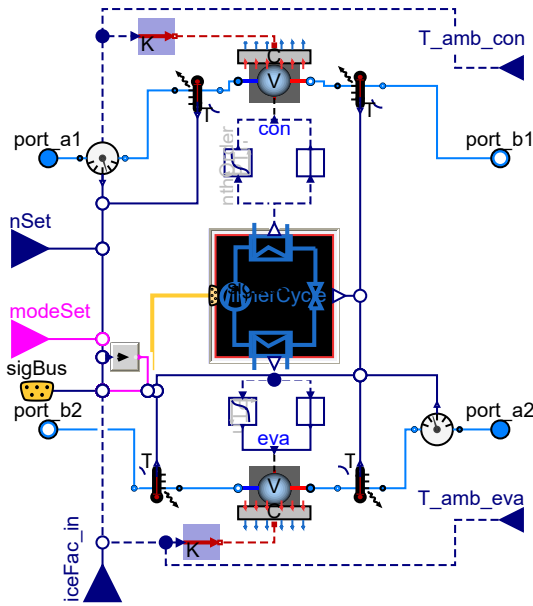
Figure 1. Partial model of a reversible thermal machine

placeable option. Based on the Boolean input `modeSet`, the cycle switches between data for cooling and heating. This approach is visualized in Figure 2. At the
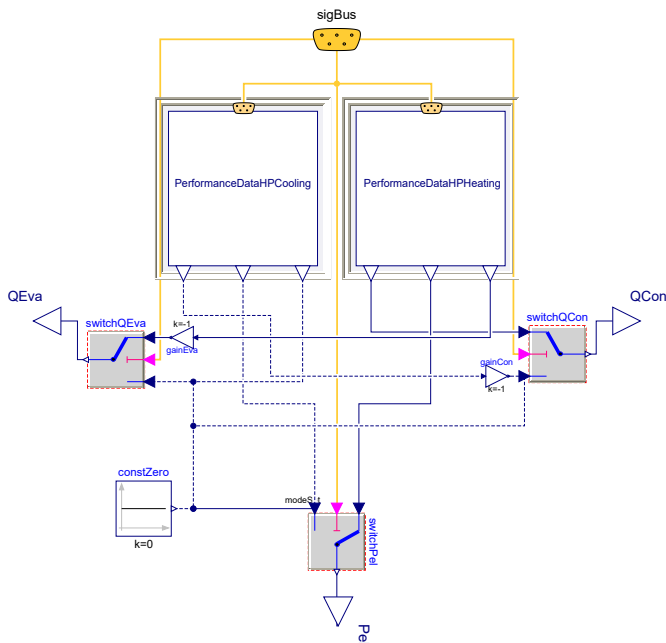

Figure 2. Black-box model of the reversible vapour compression cycle, exemplified for a HP

current state, we have introduced three performance data approaches.

1. *Functional approach*: Any modelica function using variables in Table 1 to calculate the outputs.

2. *2D-Data*: All VCMs on the market require data according to the EN 14511 (EN 14511-1:2018-03 2018). As table inputs, $T_{\text{Eva,in}}$ and $T_{\text{Con,out}}$ are re-

garded. For non fixed-speed devices, the compressor speed is necessary to model the part load behaviour. We account for part load by linearly multiplying model outputs with `nSet`. Note however, that table data was not necessarily obtained at full load. Hence, we introduce a third approach.

3. *3D-Data*: Also based on EN 14511-1:2018-03 (2018), we add compressor speed as a table dependency. While this solves the part load issue, only some manufacturer publish tables this detailed.

All the above-mentioned approaches include two further options. First, a scaling factor may be used to scale the VCM according to demand. Second, we model the VCM internal effect of possible evaporator frosting. As we chose a black-box approach for the vapour compression cycle, gray-box modeling of frost is challenging. Hence, we adapt a black-box approach as well. The icing factor f_{ice} accounts for losses in evaporator efficiency due to frosting effects. This factor has to be calculated using external models, e.g. according to the COP correction proposed by Afjei and Wetter (1997). For output of the inner cycle it follows:

$$\dot{Q}_{\text{Eva,out}} = f_{\text{ice}} \cdot \dot{Q}_{\text{Eva}} \tag{2}$$

$$P_{\text{el,out}} = P_{\text{el}} \tag{3}$$

$$\dot{Q}_{\text{Con,out}} = \dot{Q}_{\text{Eva,out}} + P_{\text{el,out}} \tag{4}$$

3.2 Inertia

As stated in the prior section, the `innerCycle` model is based on stationary data points. Hence, transient calculation of the performance in the vapour compression cycle does not take place. This is especially problematic during on-off switching of the device. When the compressor is switched on, it requires instantaneous electrical power. However, the refrigerant and components have mass and thermal inertias. As a result, the effective heat flow is delayed. Thus, we consider this inertia of the inner cycle by adding a `CriticalDamping` filter. This adds an PT delay of n-th order on the black-box outputs $\dot{Q}_{\text{Con}}$ and $\dot{Q}_{\text{Eva}}$. Again, usage and order of the filter are custom parameters.

3.3 Heat exchangers

The heat flow rates calculated in the `InnerCyle` are directly fed into the secondary fluids. Current open-source models neglect heat losses with the ambient. However, the dynamics during heat up and cool down phases may be relevant for the system interaction. Thus, we extend the heat exchanger `HeaterCooler_u` from the `IBPSA`. We add a capacity between secondary fluid and ambient air, refer to Figure 3. Thus, the ambient temperature influences the secondary fluids. Heating the device up takes longer due to higher capacity. Similarly, the capacity may transfer heat to the secondary fluid during cool down, even though the device is turned off. As some black-box data implicitly accounts for such losses, not all use cases require this option. It's usage is thus optional.
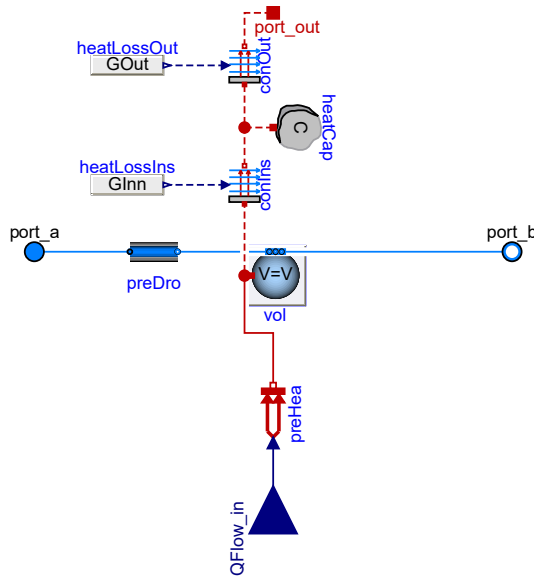
Figure 3. Model for evaporator and condenser

3.4 Safety controls

In section 2 we point out that current model approaches neglect interaction of system controls with the internal safety control of VCMs. As only the interaction with the system is relevant to us, we regard all safety controls which influence the long term performance of the system level as relevant. Furthermore, the order of safety controls is relevant in Modelica. We choose the following order, going from set point generators over logical controls to physical safety controls.

- **Thermal disinfection:** Frequent thermal disinfection of domestic hot water is required for HPs to ensure safety of users. Temperatures over 60 °C are necessary (Van Kenhove 2018).

- **Defrost:** For air-source VCMs, evaporators may need a defrosting control to ensure an operation without frost on the coils. For reversible VCMs, we model reverse cycle defrost. If the VCM is not reversible, defrost is modeled using auxiliary heaters.

- **On/off control:** Most VCMs require a minimal run time, a minimal off-time and forbid frequent on/off switching. All three requirements depend on `nSet` and `pre(nSet)`. Thus, they are included in one model. Switching single requirements on or off is achieved through booleans.

- **Operational envelope:** The compressor of VCMs can only operate in a given operational envelope. If outside of the envelope, pressure switches and thermal resistors shut the VCM off. In the model, we select `TConOutMea` and `TEvaInMea` as input for the model. As in Cimmino and Wetter (2017), a hysteresis prevents frequent switching.

- **Frost protection:** For water or brine sources, the fluid temperature may not fall below certain thresholds to prevent phase change. Hence, we add a safety control to ensure `TEvaOutMea` and `TConInMea` are greater than a given threshold.

All controls aggregated, the resulting `SafetyController` is depicted in Figure 4. Each option may be disabled. To better analyze simulation results, integer outputs show users the number of times the control was used.
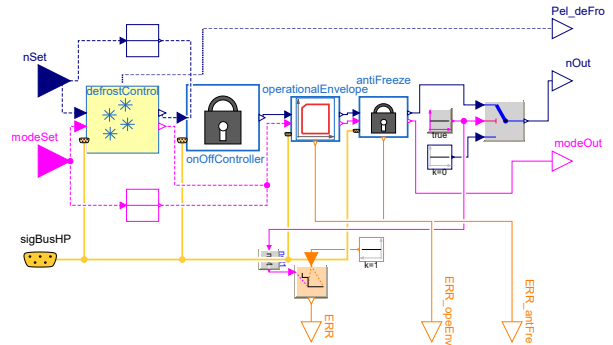

Figure 4. Implemented safety controller for the VCM

3.5 System integration

Lastly, we adapt a model of the overall VCM system by adding additional components used in VCM. These include secondary pumps, fans and an auxiliary heater. Again, all listed components are replaceable and optional. Not optional is the system controller. It includes the safety controls and the control to generate the signals `nSet` and `modeSet`.

This system model is currently implemented for a heat pump. An example is located in the package `AixLib.Systems.HeatPumpSystems`.

For reference, the models may be viewed and tested on the latest commit `38c19751b` in the repository `AixLib`[1].

4 Heat pump calibration

To show validity and modularity of our presented approach, we calibrate a brine/water HP with different black-box approaches. As calibration method, we select the approach presented in Mehrfeld, Nürenberg, and Dirk Müller (2021).

Experiments are performed at a Hardware-in-the-Loop test bench. Temperature inputs, outputs and consumed $\hat{P}_{el}$ are presented in Figure 5. Measured data is denoted using the hat operator, e.g. $\hat{T}$. The data between 6000 and 8000 s data is not used for calibration but for validation only. We calibrate the *NRMSE*, refer to Equation 5, of both P_{el} and $T_{Con,out}$ weighted equally.

$$NRMSE = \frac{1}{\hat{x}_{\max} - \hat{x}_{\min}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(x_i - \hat{x}_i)^2}{n}} \quad (5)$$

[1] https://github.com/RWTH-EBC/AixLib

Table 2. Data of the HP on the test bench according to EN 14511

	P_{el} in W		
$T_{Con,out}$ in °C	$T_{Eva,in}$ in °C	0	10
35		1300	1500
55		1900	2300
	$\dot{Q}_{Con}$ in W		
$T_{Con,out}$ in °C	$T_{Eva,in}$ in °C	0	10
35		6100	8400
55		5700	7600

As calibration parameters, we select only those which are most sensitive to our target values. These parameters are mass flow rate at condenser $\dot{m}_{Con}$, volume of condenser V_{Con} and frequency of the inertia filter $f_{inertia}$. First, we
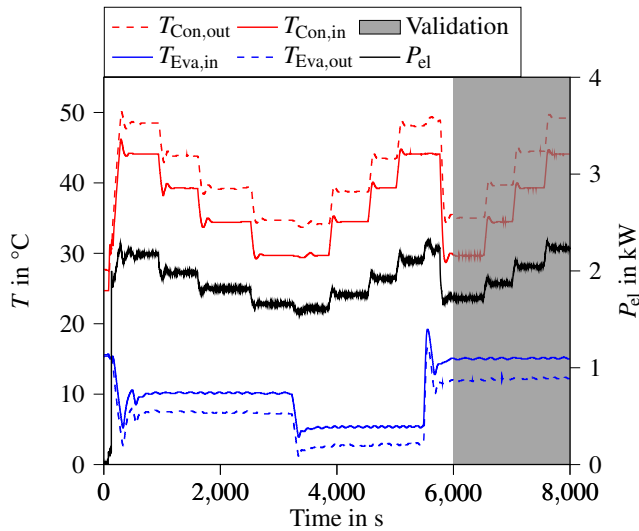
Figure 5. Experimental data for the calibration and validation

model the HP according to manufacturer data listed in standard EN 14511 (EN 14511-1:2018-03 2018). The data is stated in Table 2. Second, we use a Carnot approach with a constant quality grade. The consumed electrical power is constant at nominal conditions. This approach is equivalant to the Carnot approach in the `IBPSA` for on/off heat pumps. The equations are as follows:

$$P_{el} = P_{el,Nom} \tag{6}$$

$$\dot{Q}_{Con} = P_{el,Nom} \cdot \xi \cdot \frac{T_{Con,out}}{T_{Con,out} - T_{Eva,in}} \tag{7}$$

In this study, the quality grade ξ and nominal power $P_{el,Nom}$ are additional calibration parameters.

4.1 Results and Discussion

The resulting parameter values of both calibrations are listed in Table 3 together with applied boundaries. Ad-

ditionally, time series plots for both cases are displayed in Figure 6.

Table 3. Applied calibration parameters and results

Parameter	Min	Max	Results	
			Table	Carnot
$\dot{m}_{Con}$ in kg s^{-1}	0.2	0.6	0.404	0.214
V_{Con} in L	1	50	4.47	1.59
$f_{inertia}$ in µHz	1	300	12	13.2
ξ in %	5	50	-	43.18
$P_{el,Nom}$ in kW	1.5	2.5	-	1.88
NRMSE Calibration			0.046	0.053
NRMSE Validation			0.041	0.055
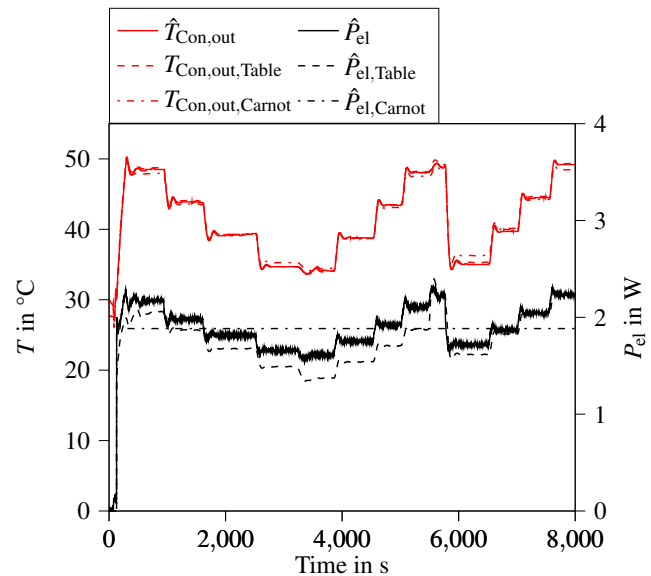
Figure 6. Time series plots for objectives of calibration.

First of all, both model approaches are able to reproduce the measured temperature. This is possible due to the dynamics introduced by the additional inertia and volume of the heat exchanger. For the validation part, source temperature increases and thus induces an extrapolation of the black-box approach. Hence, the error increases slightly.

However, the black-box is based on just four points (Table) or two parameters (Carnot). As interpolation typically yields sufficient accuracy, both approaches may be used for typical operation limits for brine/water HPs. Looking at the electrical power, both approaches differ. Obviously, the constant $P_{el,Nom}$ leads to error prone model outputs. Not as obvious, the measured data according to EN 14511-1:2018-03 (2018) also shows discrepancies. Most interestingly, the error is smaller during validation. As $T_{Con,out,Table}$ is higher than $\hat{T}_{Con,out}$ during validation, simulated $P_{el,Table}$ increases as well. Note that the results of the calibration depend on the weighting of objectives. With a higher weighting towards P_{el}, the fit would increase.

Concluding, both approaches may be used based on the aim of the simulation analysis. Minimal data input of just four data points or two calibrated parameters yield accurate representations when compared to experimental data.

5 Seasonal building performance simulations

The main goal of our contribution is to develop a modular model for the use in energy systems. Hence, our second use case concerns the integration of said model into a building energy system.

The building is based on the high-order approach in the `AixLib` (D. Müller et al. 2016). Demand of domestic hot water is neglected.

An air/water HP is simulated, hence the anti-freeze protection function is not applied. The simulation period is equal to one heating period, which is defined from 1st October to the 30th April. Besides computation time and the number of state events, the SCOP is calculated.

Model parameters are selected based on calibration results, scaled to the manufacturer data of an exemplary fixed-speed HP. Thermal disinfection is performed once a week by increasing the storage tank temperature above $60\,°C$ for a duration of $15\,min$. If the outdoor temperature falls below $5\,°C$, defrost cycles are modeled by a daily $10\,min$ reversal of the refrigeration circuit.

To demonstrate influences of introduced models, we analyze eight model configurations (MC). Together with relevant results, they are listed in Table 4. The simulation settings are stated in Table 5

Table 4. Definition and results of model configurations. Usage of option is indicated by (x).

Configuration	Heat losses	Additional inertias	Operational envelope	On/Off control	Thermal disinfection	Defrost	Computation time in h	state events in thousand	SCOP
1	o	o	o	o	o	o	5.2	46.1	2.44
2	x	x	o	o	o	o	6.9	45.7	2.21
3	x	o	x	x	o	o	6.5	64.8	2.14
4	o	x	x	x	o	o	7.2	61.8	2.36
5	x	x	x	x	o	o	7.4	64.7	2.15
6	x	x	x	x	x	o	7.5	65.3	2.14
7	x	x	x	x	o	x	7.8	65.6	1.88
8	x	x	x	x	x	x	7.8	66.0	1.88

5.1 Results and Discussion

Looking at Table 4, we want to analyze two influences in detail.

Table 5. Simulation settings for all studied configurations

Setting	Value
Start time	273 days
Stop time	485 days
Interval length	5 min
Solver	Dassl
Tolerance	0.0001
Store variables at events	true

First, the computation time in MC_2 increased by a factor of 1.33. As both heat losses and inertias are active in MC_2, the direct impact of both options is not distinguishable. By comparing MC_3 and MC_4 to MC_5, the impact can be assessed. Neglecting the system inertias in MC_3 leads to a 12.6 % reduction in computation time compared to MC_5. If the heat losses are not simulated, the computation time decreases by 3.6 % compared to MC_5. Despite increased number of state events, MC_3 is faster than MC_2. Overall, the `CriticalDamping` block of third order for mapping the inertia increases the computation time without having a noteworthy impact on the SCOP. This increase may be attributed in six additional continuous time states introduced by the model option. The usage of heat losses only introduce two new continuous time states. In general, the usage of inertias should always be weighted against the increased computation time.

Second, we analyze the influence of safety controls on the computation time and SCOP. Both the computation time and the number of state events increase between MC_1 and MC_3 to MC_8. The compliance with the operating envelope and on/off control evokes 15000-20000 state events depending on the MC, resulting in an increase of the computation time by at least 7.5 %. The operating envelope is not exceeded at any time. Therefore, this increase is due to compliance with the switching cycles. In MC_6, the influence of thermal disinfection is analyzed. Compared to MC_5, the SCOP is decreased by 0.5 %, and the computation time is increased by 1.2 %. The chosen period of $15\,min$ as well as the week-based circuit are possible reasons for the small influence. Overall, the defrost control has the greatest influence on the SCOP. As a result of reversing the refrigeration circuit, the SCOP decreases by 12.6 %. On the one hand, this is due to the fact that the table data already take defrosting losses into account. On the other hand, the duration and timing of the defrosting cycles in the use case are not based on validated assumptions. Following defrost control, the heat losses show the highest impact on the SCOP. Comparing MC_1 to MC_2, the SCOP decreases by 9.4 %. To show that this decrease is not induced by the additional inertias, we compare MC_4 to MC_5. Here, the decrease amounts for 8.9 %. This is explained by the fact that inertias change the dynamics of heat flow and not the quantity itself.

Generally, the obtained SCOP may seem small. However, we examined a supply temperature of 55 °C using a 2 K bandwidth hysteresis control. For these systems, the SCOPs are in similar ranges compared to SCOPs obtained in field tests (Huchtemann and Dirk Müller 2012).

6 Conclusion

A modular model for reversible heat pumps and chillers is presented. The vapour compression cycle is modeled as a replaceable black-box. Contrary, relevant interactions with the whole energy system are modeled as gray-box. Most notably, safety controls such as on/off controls and the operational envelope are regarded in the model. All models are optional, enabling users to choose modeling depth based on their simulation aim.

To demonstrate validity of our approach, we calibrate two different black-box approaches onto measured data. While both manage to reproduce supply temperatures, the Carnot based approach fails to match electricity demands.

Besides calibration, we show influences of different model options onto simulation speed and efficiency of heat pumps. The presented results indicate that safety controls should always be regarded neglected on system integration level.

While the presented approach is reversible, our background focuses mainly on the use of VCM as a heat pump in building energy systems. Calibration and validation of chiller applications may show limitations of the approach. Especially validation of experiments using a four-way reversing valve are of interest. As we neglect internal effects of the VCM, losses or dynamics during reverse cycle mode may lead to poor model accuracy.

Last but not least, we already implemented various black-box approaches in the `AixLib` (D. Müller et al. 2016). Researchers and practitioners are invited to contribute new black-box approaches to this open-source modeling library. Thus, the variety of simulation aims covered by the presented modeling approach may increase, yielding a more thorough understanding of heat pumps and chillers in system applications.

Acknowledgements

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