Simulation of heat pump performances in buildings

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***Abstract*— According to various reports, a significant amount of energy use and carbon emissions can be attributed to the building sector. Apart from increasing the utilization of renewable sources, demand flexibility has also been noted as a key factor that can positively contribute to the reduction of the carbon footprint of buildings. A key driver of demand flexibility are novel approaches in the thermal domain. Here, heat pumps present a noteworthy untapped potential with projections of even higher impact in the future. However, current solutions for heat pump simulation lack interoperability and ease of deployment. Hence, this paper presents an improved, open approach to both heat pump modeling as well as building modeling, such that the complete loop from controls inputs to indoor ambient temperature can be simulated.**

I. Introduction

According to a report by the United Nation Environmental Program [1], 30% of final energy consumption and 28% emissions of carbon emissions can be attributed to buildings. When focusing specifically on residential properties, the report estimates that they are responsible for around 22% of final energy consumption as well as 17% of carbon emissions. With these numbers in mind, it is evident why a special focus within the combat against climate change should be placed on energy consumptions in buildings. Key mitigation factors in this regard have been noted to be the increase of renewable energy penetration and the utilization of demand-side flexibility. The main goal of these actions would be to allow for easier balancing of highly variable renewable energy production with the load.

Besides renewable energy sources, one of the key appliances that has been noted in relevant literature to have a high potential impact on the reduction of carbon emissions and improvement of overall building energy efficiency, are heat pumps. Although their initial popularity can be attributed to their perception as a means to an end for air-conditioning during hot summer months, novel solutions that also offer the ability for inversion seek to significantly improve efficiency for both cooling and heating applications. For example, resistive heating offers efficiency ratings close to 100%, meaning that all input electric energy is essentially converted to heat. With these figures being slightly lower for gas boilers and solid fuel furnaces, heat pumps can offer efficiency ratings in a range from 300% to sometimes over 600%. In other words, by spending a given amount of electric energy, heat pumps can transfer or remove 3 to 6 times as much heat, with the "missing" energy coming from the environment. However, proper use of heat pumps requires a noteworthy amount of additional work regarding planning, deployment and active optimal control to achieve these high efficiency ratings. A necessary prerequisite for these is having the ability to properly numerically model the corresponding processes.

In state-of-the-art solutions, heat pump systems and accompanying building models are often modeled on a case-by-case basis using specialized proprietary software solutions like TRNSYS, Matlab's Simulink, Modelica and others. This type of workflow is severely restrictive in terms of later deployment of the developed control and planning algorithms into actual production environments. Namely, the mentioned programs are often used for adequate sizing of the system and one-time performance simulations as opposed to active management of different process parameters. However, novel solutions offer open-source and easily deployable software frameworks for both thermodynamic system modeling as well as building thermal modeling. This paper presents a methodology based on two such frameworks that facilitates a joint simulation of heat pump-powered heating and cooling systems with a parametric model of the infrastructure that is heated or cooled.

II. Methodology

Due to the complexity of underlining physical processes that govern the operation of heating, ventilation and air-conditioning systems, traditional simplistic modelling and optimization approaches using (mixed-integer) linear programming, as is common practice in energy applications, is not applicable. Due to various nonlinearities and variable interdependence, heat pump modelling usually requires the application of numerical methods. A concrete approach depicted in this paper is based upon the TESPy (Thermal Engineering Systems in Python) [2] which is a part of a wider open energy modeling framework oemof [3]. In order to properly assess how heat pump operation influences environmental parameters like room temperature, the heat pump model will also be extended with a building model determined using a gray-box approach – combining exact physical models and machine learning to determine building properties that are otherwise hard to compute or measure.

Thermal system modelling using TESPy is performed by introducing different system components (heat exchangers like evaporators and condensers, compressors, valves, pumps, etc.) that are linked using connections. In essence, each component introduces a set of parameters and system equations (constraints) that govern the way fluids within the model behave. Fluid conditions are represented with a set of variables (mass flow rate, pressure, temperature and mass-specific enthalpy) with each set corresponding to a

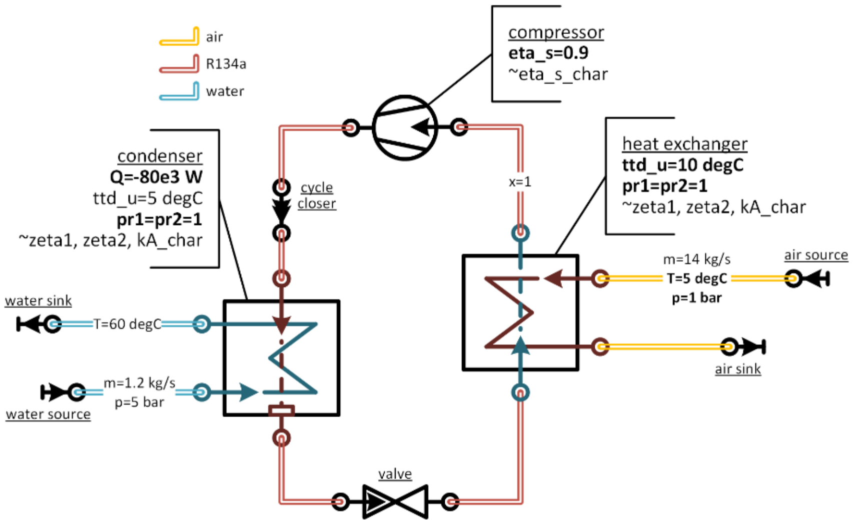

Figure 1 – Heat pump model using TESPy components

given connection that transfers the fluid in a given state from one to the next component.

The concrete heat pump model used in this study is presented in Figure 1. A heating cycle is implemented for an air-to-water heat pump system. Concretely, ambient air on the source side is blown over an evaporator (modelled as a heat exchanger component). Refrigerant R134a (1,1,1,2-Tetrafluoroethane) is circulated through the internal heat pump circuit and carries the heat absorbed from the ambient air in the process of evaporation into the compressor where, aided by input electric work, the refrigerant pressure is increased to facilitate condensation at a higher temperature. It then passes through a condenser component that releases the heat to the user loop in which water is circulated through a set of space heaters (e.g., radiators or underfloor heating loops). Figure 1 also denotes the chosen set of design parameters in bold (defining an operating point at which each component's unknown parameters are computed) and off-design parameters (denoted with a tilde sign) that are combined with varying meteorological conditions during the simulation to infer output performances.

The next step in the modelling process is to include the thermodynamic properties of the building that is supposed to be heated or cooled using the designed heat pump system. Several different approaches can be found in related literature that employ different techniques from white box modelling (using detailed mathematical relations of physical processes) to black box modelling (estimating system behavior without any knowledge of underlining processes). The model implemented within this methodology utilizes a gray box approach through the combination of the two aforementioned methodologies. Different base models can be selected for this approach, as classified by [4], with the TiTeThRia model (as a reference to the utilized parameters) being implemented here as described by [5]. Namely, with equivalencies between electric and thermal properties in mind, the building can be represented as an equivalent RC circuit depicted in Figure 2 where different components represent:

- R_{ih} – thermal resistance between the interior air and the heating system,
- R_{ie} – thermal resistance between the interior air and the building envelope,
- R_{ia} – thermal resistance between the interior air and the ambient air,
- R_{ea} – thermal resistance between the building envelope and the ambient air,
- C_{i} – heat capacity of the interior air,
- C_{h} – heat capacity of the heating system,
- C_{e} – heat capacity of the building envelope.

The ambient (outdoor) air temperature is maintained at a known value dictated by external meteorological conditions (as denoted by a DC voltage/temperature source) while the internal air temperature T_i, heating system temperature T_{h} and building envelope temperature T_{e} are state variables that can be computed by solving the following system of differential equations

$$\frac{\mathrm{d}T_{\mathrm{i}}}{\mathrm{d}t} = \frac{T_{\mathrm{e}} - T_{\mathrm{i}}}{R_{\mathrm{ie}}C_{\mathrm{i}}} + \frac{T_{\mathrm{h}} - T_{\mathrm{i}}}{R_{\mathrm{ih}}C_{\mathrm{i}}} + \frac{T_{\mathrm{a}} - T_{\mathrm{i}}}{R_{\mathrm{ia}}C_{\mathrm{i}}},$$

$$\frac{\mathrm{d}T_{\mathrm{e}}}{\mathrm{d}t} = \frac{T_{\mathrm{i}} - T_{\mathrm{e}}}{R_{\mathrm{ie}}C_{\mathrm{e}}} + \frac{T_{\mathrm{a}} - T_{\mathrm{e}}}{R_{\mathrm{ea}}C_{\mathrm{e}}},$$

$$\frac{\mathrm{d}T_{\mathrm{h}}}{\mathrm{d}t} = \frac{T_{\mathrm{i}} - T_{\mathrm{h}}}{R_{\mathrm{ih}}C_{\mathrm{i}}} + \frac{\dot{Q}T_{\mathrm{s}}}{C_{\mathrm{h}}}.$$

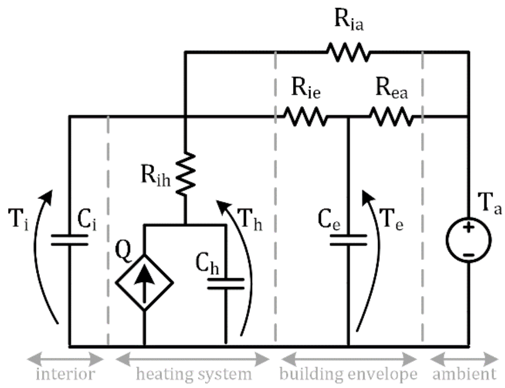

Figure 2 - Equivalent thermal RC circuit of the modelled building

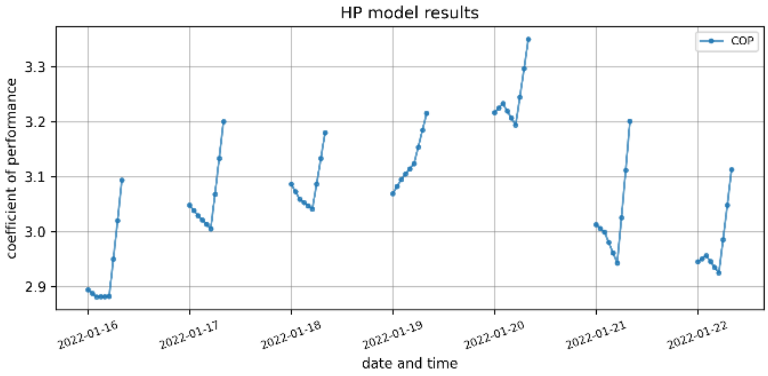

Figure 3 – COP of the simulated HP system

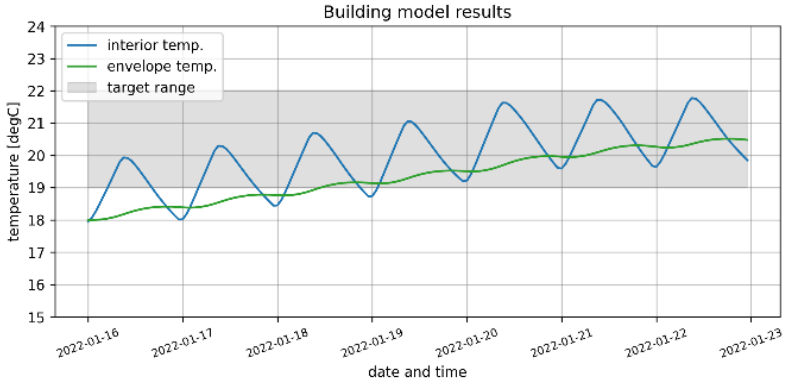

Figure 4 – Temperature trends of the model

Although each building has a different set of parameter values that depict its characteristics, with sufficient historical measurements, these can be estimated by minimizing residuals between the modelled and measured temperatures.

III. Results and Discussion

The performances of the proposed methodology are tested for the previously specified design conditions of the heat pump and a set of week-long hourly metrological observations in mid-January (ambient air temperature and pressure) obtained from typical meteorological year records for Belgrade, the capitol city of Serbia [6]. A simple control strategy has been devised that turns on the heat pump between 00:00 and 08:00 while the system remains turned off for the rest of the day, thus roughly aligning the heat pump activity timeframe to the period with lower price tariff that applies to residential users in Serbia.

Having in mind the natural daily variations of ambient temperature, the designed system shows a varying level of efficiency, depicted using a coefficient of performance defined as

$$\eta_{\mathrm{COP}} = \frac{\dot{Q}_{\mathrm{delivered}}}{P_{\mathrm{consumed}}}$$

where $\dot{Q}_{\mathrm{delivered}}$ is the (absolute) heat power that is being added to or removed from the user side while P_{consumed} is the total amount of electric power that needs to be consumed in order to achieve this. Figure 3 presents the η_{COP} of the designed system for the given control strategy and shows a variable coefficient of performance between around 2.8 and 3.4 in line with ambient temperature variations.

When instantiating the previously described building model with a set of parameters depicted in [5] and using the resulting heat transfer rate from the heat pump simulation to assess the state variables of the building model, the results from Figure 4 can be obtained. With the target range between 19 °C and 22 °C specifically denoted, it can be observed that the designed system has the ability to heat the space in question from the initial temperature of 18 °C to the acceptable range and maintain the temperature within the range, as well as to show the intra-day periodic nature of the temperature as the result of the selected simplistic control strategy.

IV. Conclusion and Future Work

In conclusion, this paper presents a methodology for simulating the behavior of heat pump systems in combination with parametric building models. As opposed to traditional methods, this work is based around open-source software for thermal models which can easily be utilized to support a wide variety of different system layouts. Furthermore, it is coupled with a parametric model of the building thermal properties in order to evaluate the effects that the heat pump output has on indoor air temperature. As such, this approach provides a necessary basis for future developments of more advanced control strategies in a way that is easier to deploy when compared to state-of-the-art solutions.

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