Model-based design of an HVAC control strategy

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ABSTRACT

Thermal management systems are fundamental to provide comfort in all kinds of passenger vehicles. However, in the field of electric vehicles, the thermal management system can consume a significant amount of energy from the battery. For example, when heating in cold winter conditions or cooling in warm summer conditions (e.g. at an ambient temperature of -10 °C and +40 °C, respectively), it can consume up to 50% of the batterie’s capacity, which in turn reduces the maximum driving range of the vehicle by 50%. The growing number of contributions in scientific literature highlights the importance of this topic. Much of the current literature on thermal management pays particular attention to developing new heating- and cooling technologies or to improving the efficiency of existing components.

This paper proposes to use modelling and simulation to find an efficient operating strategy for a thermal management system of a passenger electric vehicle. The specific objective of this study is to reduce the amount of energy needed to heat up or cool down the passenger cabin. In turn, this leads to an increased maximum driving range of the electric vehicle.

This contribution begins with modelling and parameterizing the thermal management system of a reference electric vehicle. It will then go on to model-based system analysis, where the efficiency in different operating points will be evaluated. Finally, an optimized operating strategy for the components of the thermal management system will be elaborated for different ambient conditions.

The proposed approach develops an enhanced and efficient operating strategy of the thermal management system in a virtual environment. This offers a reduced development time when compared to real-life testing. Measurements are only needed for parameterizing the single components.

KEYWORDS

Modelling and simulation, thermal management system, operating strategy, efficiency.

INTRODUCTION

In recent years, electric mobility has become more and more popular. This is supported by the fact that all big companies in the automotive industry have at least one electric vehicle in their portfolio. One big problem of electric vehicles, which is currently not solved, is that all devices in an electric vehicle use energy from the battery, which leads to constraints in maximum driving range. Trying to overcome this problem, there have been many scientific publications during the last years which deal with driving range anxiety [1] or increasing efficiency of Heating, Ventilation and Air Conditioning (HVAC) systems [2 - 10], either on component level or on system level. The importance of proper thermal management is highlighted by the fact that heating in cold winter conditions or cooling in warm summer conditions (e.g. at an ambient temperature of -10 °C and +40 °C, respectively), can consume up to 50% of the batterie’s capacity, which in turn reduces the maximum driving range of the vehicle by 50%. In order to deal with this issue, protracted real life test can be used for designing and testing new HVAC systems and components. Another, more time-saving option would be to base the design of the HVAC system or its operating strategy on simulation models, like it was done in [11].

The work, described in this paper is part of the QUIET project [12] and targets at optimizing the efficiency of the HVAC system by increasing on the one hand the efficiency of the conventional (air-based) HVAC system and on the other hand by adapting novel technologies such as infrared heating panel. However, the paper focuses on the design and optimization of the HVAC operating strategy by using a model-based design approach.

MODELLING

In order to investigate the operating behaviour of the HVAC system in different application scenarios (i.e. heat pump operation at low ambient temperatures and cooling operation at high ambient temperatures), an entire Propane-based (R290) HVAC model has been implemented in Dymola/Modelica. The implemented model is depicted in Figure 1 and will be described more in detail later in this section.

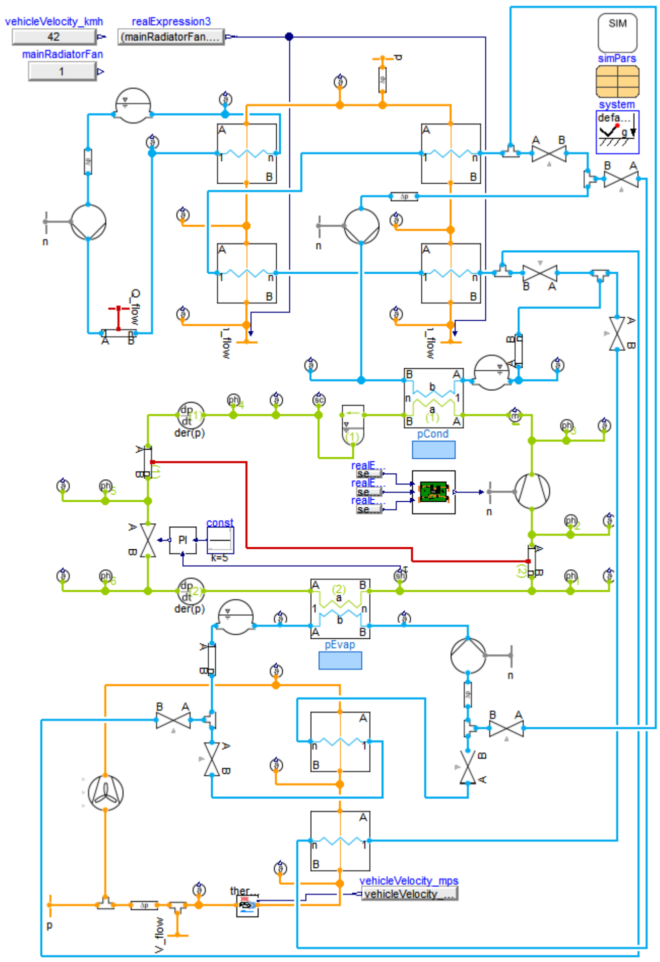

Figure 1: total HVAC model

In the first step, each single component has been parameterised separately. Therefore, measurement data has been used. The boundary conditions, such as pressure and temperature, in different operating points have been defined based on the measurements. Then, characteristic quantities that are relevant for the respective component (i.e. mass flow, heat transfer, outlet temperature, outlet pressure) have been analysed during simulation. Based on the comparison between measured and simulated values, the quality of the chosen model parameters can be determined. The parameter tuning process is a very extended process with a lot of iterations when varying the model parameters. Therefore, an automated adaptive tree search algorithm which has been implemented by the AIT for parameter tuning tasks has been used.

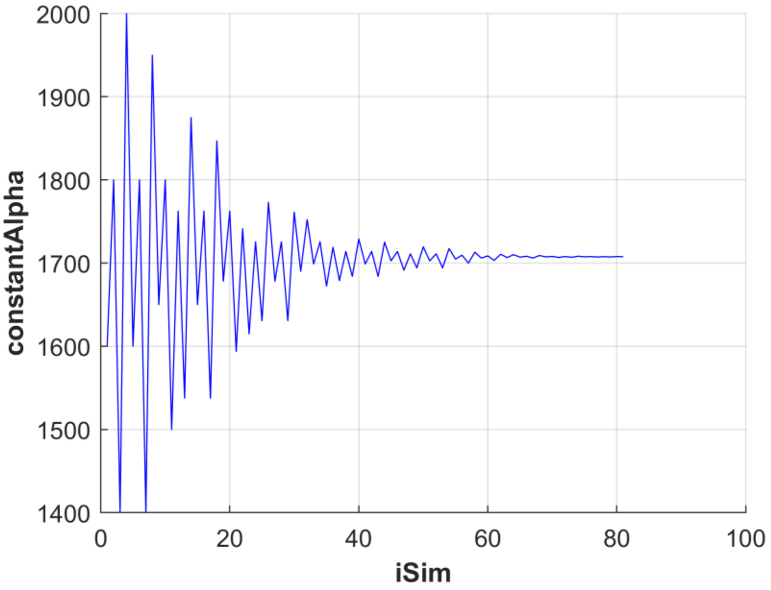

Figure 2: condenser heat transfer optimisation – constant heat transfer coefficient

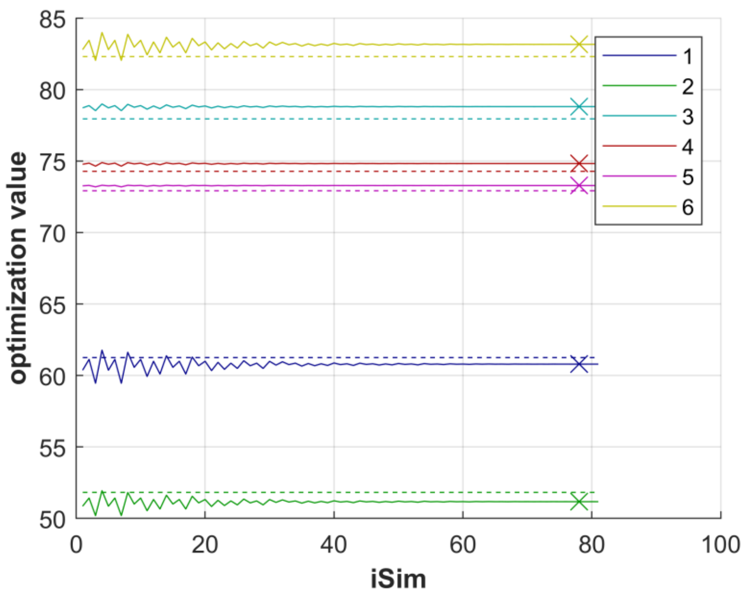

Figure 3: condenser heat transfer optimisation – comparison of target values and simulation

Figure 2 and Figure 3 show one representative result of the parameter tuning algorithm. For the condenser model, the constant heat transfer coefficient has been varied to find a parameter value, which minimises the error between measurement and simulation in different operating points at the same time. Figure 2 represents the variation of the heat transfer coefficient parameter while Figure 3 depicts the simulated (solid) and measured values (dotted) for the heat transfer of the condenser in six different operating points. The same procedure has been applied to find the parameters of all the other components in the HVAC system.

In the next step, the single models have been connected step-by-step to get the final HVAC model, which is depicted in Figure 1. The model is structured in three different parts: refrigerant cycle (green), water cycles (blue) and air cycles (orange). The refrigerant cycle considers the compressor, condenser, separator, internal heat exchanger, expansion valve and evaporator. The water cycles (for cooling power electronics and for HVAC system) consist of the water side of the condenser, evaporator and front heat exchanger, a PTC heater, pumps and valves. By switching the water cycle valves the refrigerant cycle can be either used in cooling or in heat pump mode. The air cycle considers the front heat exchanger (the heat exchanger is divided into four parts, where one quarter is used for the power electronics and three quarters are used for the HVAC system), the cabin heat exchangers (heater core and low temperature radiator), the front vehicle fan and cabin fan and a cabin volume.

VALIDATION

Finally, the total cycle has been validated as a whole system. Therefore, again, the measurement data has been compared to the simulation results. The Validation has been performed for one operating point in cooling mode (at 40 °C ambient temperature) and for one operating point in heat pump mode (at -10 °C ambient temperature), respectively. The compressor speed was controlled to fit the measured high pressure after the compressor, while the expansion valve was controlled to guarantee 5 K superheating after the evaporator. The validation of the HVAC model based on the pressure-enthalpy (p,h) diagrams can be seen in Figure 4 for the cooling (blue) and heating (red) mode. In the figure, the grey line is the saturation line of propane, the dashed lines represent the measurements and the solid lines represent the respective simulation results. The results show a very good coherence between the measurement and simulation.

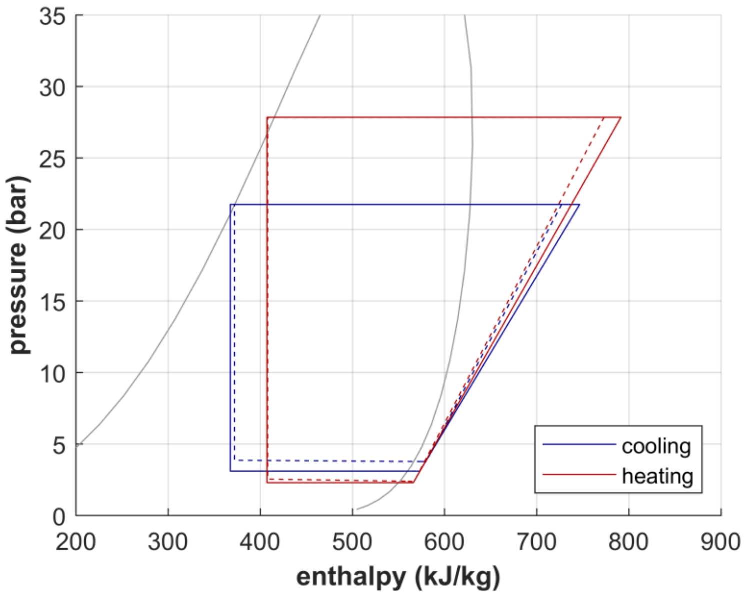

Figure 4: p,h diagram for model validation in cooling and heating mode

SIMULATION AND EVALUATION

The validated model has been used to investigate the system behaviour of the HVAC system in different operating points. Figure 5 depicts the p,h diagrams for different setpoints of high pressure, which lead to different values of cooling power and energy consumption. In the figure, the investigated cooling power at the given environmental conditions (40 °C ambient temperature, 0.54 m³/s volume flow at the main radiator, 0.07 m³/s volume flow at the cabin fan speed) ranges from 2307 W to 3505 W.

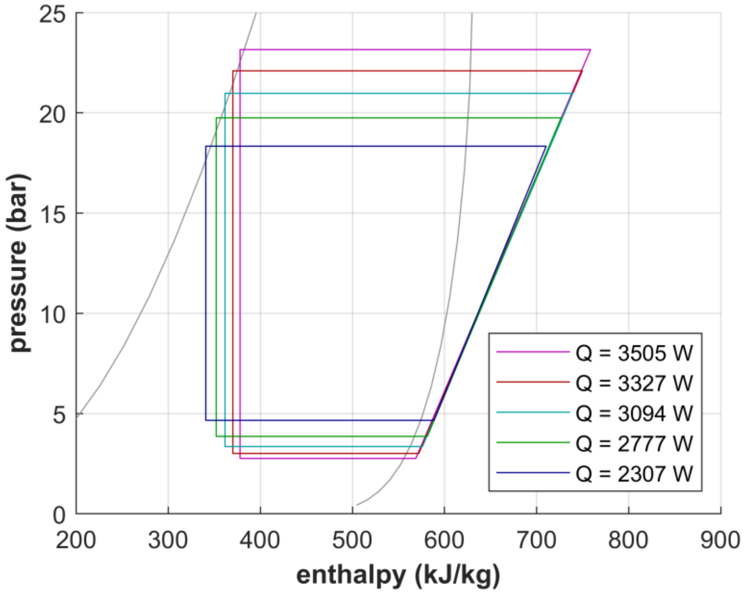

Figure 5: p,h diagram for cooling mode at different high pressures

Another possible application of the developed HVAC model is to analyse the power and the energy efficiency ratio (EER) in specific operating points in order to determine the most efficient high pressure for given ambient conditions. Exemplarily, the same environmental conditions (ambient temperature and volume flows) like in the previously described scenario have been used. Then, the compressor speed has been slowly increased from 40 Hz to 130 Hz. The rate of change of the compressor speed was increased slow enough to consider the system as steady state during the entire simulation. Figure 6 shows the efficiency and the cooling power of the simulated scenario over the high system pressure after the compressor. This diagram can be used, for instance, to determine the most efficient high pressure and hence to control the compressor speed with regard to a specific required cooling power. The same procedure can be done for further ambient conditions and for other components to derive an optimized operating strategy of the HVAC system.

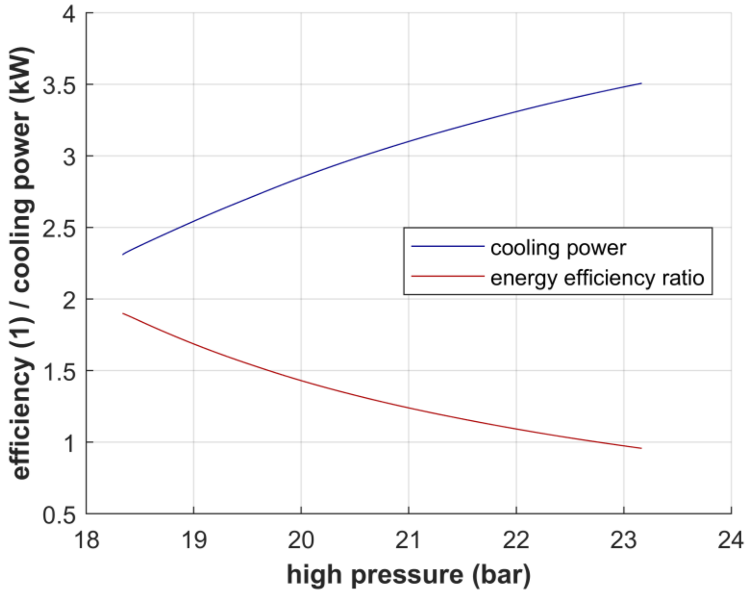

Figure 6: cooling power and energy efficiency ratio vs high pressure

CONCLUSION AND OUTLOOK

This paper has provided a workflow for creating a simulation model of an entire HVAC system of an electric vehicle. The model has been parameterized based on measurement data on component level. An optimization routine helped to reduce the necessary amount of time to adapt the model parameters to fit the measurements. The parameterized models have been used to implement an entire HVAC system model, which was validated using measurement data. The validation showed that the model is capable of reproducing the operating behaviour of the HVAC components. Finally, the system model has been used to analyse the efficiency of the HVAC system in different operating points.

In the further course of the QUIET project, the developed HVAC model will be used for determining and validating an optimal vehicle energy management strategy using model reduction and optimization methods [13]. The model can be further used for assessing the cooling and heating performance in different application scenarios which cannot be measured directly. Additionally, the model will be used to develop and test the hardware control algorithm for the HVAC components. The control algorithm will be implemented in the programming language Python. Via Socket interfaces, the algorithms in Python can communicate with the Modelica model to set the control variables of the different sub components (e.g. compressor speed, expansion valve opening, speed of the water pumps, fan speeds, etc.). Hence, the software interface can be used to investigate the validity of the control algorithms in a virtual environment (Software-in-the-Loop). With this approach, the basic functionality of the control algorithms can be tested in advance, even before the whole HVAC system has been set up in hardware. This will enable an improved development speed of the HVAC control system.

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