Simulation-Based Investigation and its Experimental Validation of the Thermal Behavior of a BEV Bus

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Abstract: Electrification of the public transport sector has a high potential to reduce emissions, especially in metropolitan areas. Due to its strictly scheduled routes and regular idle times, the public transport sector is ideal for the use of battery electric vehicles (BEV). The energy efficiency of a BEV can be increased by the implementation of a thermal management system that is able to decrease the overall energy demand of the system. The thermal management of an electric city bus controls the thermal behavior of the components of the powertrain, such as motor and inverters (drive and auxiliary), as well as the conditioning of the battery system. Moreover, the heating, ventilation, and air conditioning (HVAC) of the drivers' front box and the passenger room play an important role for the energy demand. In this research, the thermal behavior of the important components of an electric city bus is modelled in MATLAB/Simscape in co-simulation with Dymola under the influence of a driving cycle. The heating of the components, geometry and behavior of the cooling circuits as well as the different mechanisms of heat transfer are modelled close to the real system. Moreover, a test setup is developed for the validation of the simulation results. Results are presented, which show that the thermal behavior can be modelled with high accuracy in comparison to the real system. Moreover, potentials to reduce the overall energy demand by improving the thermal energy flows are identified.

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1 Introduction

Road transportation is responsible for nearly 75 % of the carbon dioxide (CO_2) emissions in the transportation sector [1]. Besides passenger cars or heavy-duty trucks, which are the largest groups, the public transport sector has an influence on the global emissions, which must not be neglected. Therefore, decarbonization of the public transport sector has the potential to reduce global greenhouse gas emissions and limit the effects of climate change. With its highly scheduled routes and plannable parking times at the depository, the operation profile of urban bus transport is beneficial for electromobility. Therefore, numbers of newly registered electric city buses increase in most German cities [2]. Energy efficiency is even more important for electric city buses than for conventionally powered buses with an internal combustion engine (ICE) with respect to the maximum range. Besides other aspects the thermal management, namely the integration of all thermal systems has a high influence on the energy efficiency of battery electric vehicles (BEV) [3]. The difference with regard to conventional vehicles, where cooling of the ICE is the main task of the thermal system, is the thermal management of the battery systems' temperature. Depending on the ambient conditions, the battery system must be cooled or heated [4]. Very low battery temperatures follow the decrease of the maximum discharge power to avoid increased degradation of the battery cells. Therefore, external heating is necessary at low ambient temperatures which causes an increase in the overall energy demand and a decrease in the maximum vehicle range [5]. On the other hand, lithium-ion batteries generate heat depending on the load cycle [6]. Therefore, the battery cell temperature must be limited to a temperature level of roughly $T_{Cell} = 298.15\ K \pm 10\ K$, especially at high ambient temperatures, which causes an additional energy demand due to a complex cooling demand [7][8][9]. Numerous articles give an overview on the effects of inconvenient temperatures on the battery cells as well as a review on different designs of thermal management systems, for example Ma et al. [10]. Different approaches describe a simulative approach for modelling thermal management of electric vehicles. Most of them focus on passenger cars, like Kiss et al. [11], Reiter et al. [12] or Shelly et al. [13]. Otherwise, the investigation focuses on specific parts of the overall thermal system, like the battery management system [14]. This research considers all thermal components of the electric city bus and their thermal integration. In previous research, the modelling of the thermal behavior of a battery electric city bus in MATLAB/Simscape and Dymola is described [15]; the results show high accuracy with respect to experimental results. Based on a powertrain system consisting of a Voith electrical drive system (VEDS), a Webasto CV Standard Battery system including battery management system (BMS) and an electrical Battery Thermal Management (eBTM) and an Eberspächer heating, ventilation and air conditioning system (HVAC) the simulative results have been experimentally validated. Nevertheless, the described simulation model has to be validated by further experimental results, especially regarding the thermal behavior of the battery system at inconvenient ambient conditions. This is the key aspect of the following research. Adjustments to the former investigations are explained, mentioning changes in the simulation model as well as modifications of the test setup for the experimental validation. Changes in the simulation model focus on the implementation of the eBTM and its activation and deactivation control mechanisms at cold or hot temperatures whereas the modification of the test setup deals with the pre-conditioning of the battery system to reach the necessary ambient conditions. The presented results show that the eBTM and the thermal behavior of the battery system under influence of external heating or cooling by the eBTM can be modelled accurately with the expanded simulation model. The summary gives an outlook on further research on this topic.

2 Simulation Model

The simulation model is based on MATLAB/Simulink in combination with the MATLAB/Simscape toolbox of physical systems and uses a Co-Simulation with Dymola in combination with elements of the TIL library to implement the HVAC system under usage of the Functional Mock-up Interface (FMI) exchange format. The detailed description of the simulation model of the system containing the VEDS, the Webasto battery system and the HVAC system can be seen in Schäfer et al. [15]. A schematic overview of the system and the simulation model including the interaction with the input signals can be seen in Figure 1.The model uses inputs as mentioned below and calculates the mechanical, electrical and thermodynamic values of the components.

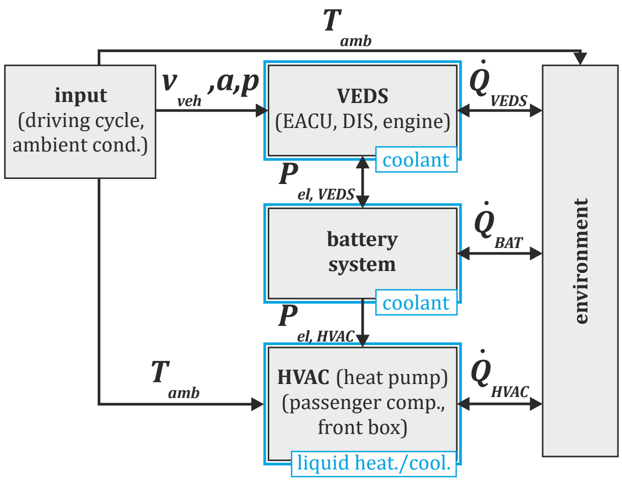

Figure 1: Schematic overview of the system and the simulation model in MATLAB/Simulink and MATLAB/Simscape in combination with Dymola/TIL library [15].

The simulation model contains a mechanical subsystem to calculate the tractive energy demand out of a longitudinal dynamics model. Adding the auxiliaries' power demand, the overall energy demand can be calculated. An electrical subsystem models the electrical behavior of the battery system, for example the calculation of the current state of charge (SoC) or the system voltage depending on SoC and cell temperature. A thermodynamic subsystem models the thermal behavior of each component and provides the components' temperatures as well as cooling or heating behavior of the coolant. The model is tested and validated adequately for medium ambient temperatures in which an external thermal management system for the battery system is not necessary. Further descriptions should explain the relevant modifications for modelling the thermal behavior and the impact on the overall energy demand of the eBTM.

2.1 Electrical Battery Thermal Management (eBTM)

The eBTM is a thermal management module provided by Webasto for conditioning the battery system by a liquid coolant circuit [16]. It consists of three circuits that are modelled in the simulation model as single subsystems connected to each other by exchange of the necessary physical variables. A schematic overview of the simulation model of the eBTM can be seen in Figure 2. The external coolant loop connects the coolant channels of the battery system with the eBTM and especially the heat exchangers of the refrigerant circuit. Moreover, a pump and a high voltage heater (HV heater) are implemented in the liquid circuit. The pump is activated when a cooling or a heating request is sent by the battery management system, the HV heater is only activated when a heating request is active. The HV heater provides a heating power of $P_{HVheater} = 10\ kW$. In the simulation model the external coolant loop is connected with the battery system by an input and an output connection. The physical values of liquid temperature, liquid pressure and volume flow are exchanged between the subsystems. On the other side, the external coolant loop is connected with the refrigerant loop and the heat exchangers. The refrigerant loop consists of two plate heat exchangers operating as evaporators, a climate compressor, one plate heat exchanger operating as condenser and a valve. In the simulation model the cooling power is controlled by defining the compressors' mass flow. The condenser of the refrigerant loop is connected with an internal coolant circuit that contains a second pump, an air-water heat exchanger and a fan.

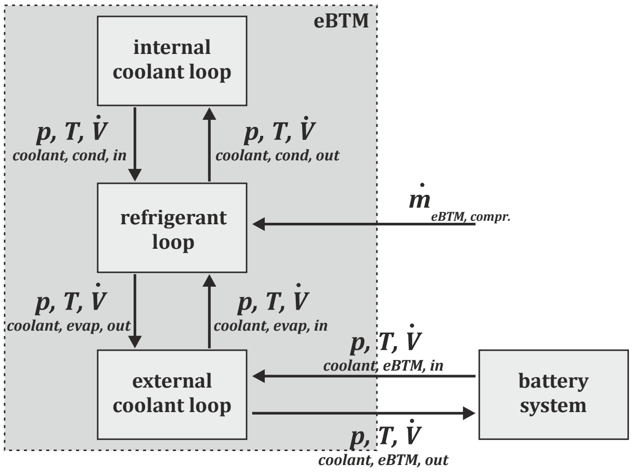

Figure 2: Schematic overview of the eBTM including the interfaces of the circuits in the simulation model.

Battery heating

Battery heating is realized by an HV heater implemented in the external coolant liquid cycle of the eBTM. In the simulation model, an external heat source is added to heat the coolant within the external coolant loop subsystem. The parameterization enables the accurate reproduction of the real system's thermal response. A subsystem named 'control eBTM' includes the logic to activate and deactivate heating based on simple MATLAB/Simulink paths. Heating is activated if the condition (lowest cell temperature $T_{Cell,min} < T_{Cell,min.limit,1}$, activation temperature heating) is active and deactivated if the condition (lowest cell temperature $T_{Cell,min} > T_{Cell,min.limit,2}$, deactivation temperature heating) is fulfilled. Moreover, the power demand of the HV heater is added to the overall power demand of the system and influences the battery capacity and the SoC.

Battery cooling

The cooling behavior of the eBTM is controlled by adjustment of the cooling power of the refrigerant compressor. Cooling is activated if the maximum cell temperature is above the limit ($T_{Cell,max} > T_{Cell,max.limit,1}$, activation temperature cooling). A defined target temperature for the coolant outlet temperature $T_{C,eBTM,out,SetPoint}$ is implemented and must be reached. In the simulation model the control behavior is reached by adjustment of the mass flow of the refrigerant compressor. The necessary mass flow is calculated in the 'control eBTM' subsystem and is proportional to a certain cooling power and a power demand of the refrigerant compressor $P_{compr.,eBTM}$. The cooling mode is deactivated if the maximum cell temperature decreases below a certain value ($T_{Cell,max} < T_{Cell,max.limit,2}$, deactivation temperature cooling). The control loop of the battery cooling can be seen in Figure 3.

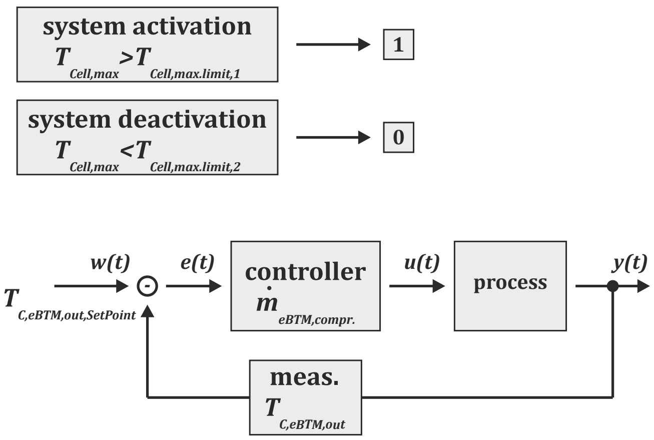

Figure 3: Structure of the control loop of the simulation model of eBTM cooling depending on activation due to high cell temperatures.

Both operating modes of the eBTM depend on basic criteria that must be fulfilled and are defined in the ‘control eBTM’ subsystem such as activation of the electric connection with the battery system and a minimum available energy in the battery system.

3 Model Validation

The experimental validation of the simulation model is done at the powertrain test rig of the Institute of Automotive and Powertrain Engineering at Helmut Schmidt University in Hamburg (HSU). A detailed description of the test rig and the test setup can be seen in Schäfer et al. [15]. The necessary modifications done in this research focus on the battery system. The battery system platforms’ dimensions are $V = 3.20\,m * 2.40\,m * 0.60\,m = 4.61\,m^3$. The platform is enclosed in a construction of sandwich profiles manufactured of 40 mm of Polyisocyanurat foam with a thermal conductivity of $\lambda = 0.55\,\frac{W}{m^2K}$. Figure 4 shows an overview of the test setup at the institutes’ power and inertia test rig (PAISI) on the left side as well as the enclosed battery system in detail on the right side. The eBTM, due to its interaction with the environment, and the vehicle interface box (VIB), which establishes the connection between the battery system and the power electronics of the VEDS, are located outside of the housing.

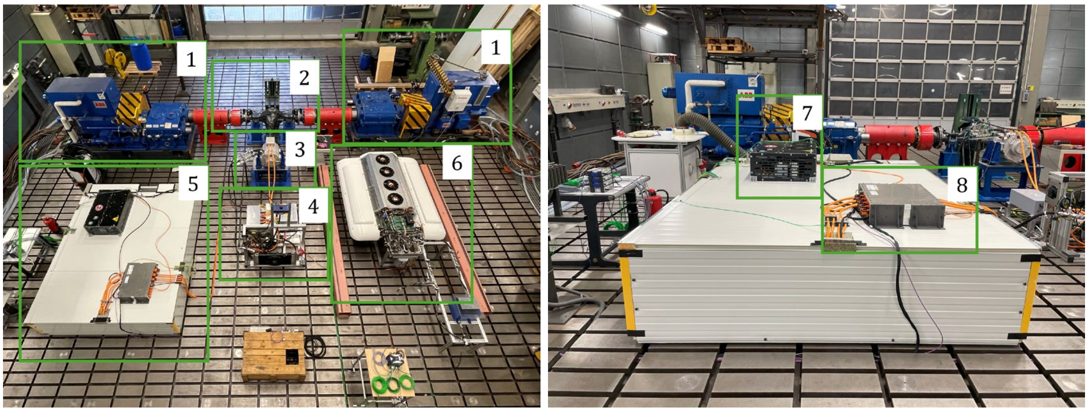

Figure 4: Modified test setup for the experimental validation of the modelled system on the PAISI of the Institute of Automotive and Powertrain Engineering (left).
Components: (1) electric machines, (2) axle, (3) electric motor, (4) power electronics, (5) battery system, (6) HVAC system.
Detailed view on the thermal isolated battery system (right).
Components: (7) eBTM, (8) VIB.

The setup enables the preconditioning of the battery system at different ambient temperatures. The preconditioning is done before the test starts. During this time period the eBTM is deactivated by interrupting the power supply. Otherwise, the eBTM would be activated too early and prevent preconditioning. Two different procedures have to be established in order to cool down or heat up the ambient temperature within the housing. The different approaches can be seen in Figure 5.

Preconditioning: Cooling

In order to reduce the temperature of the battery system the cold-water circuit of the HVAC system of the test setup is used. It is connected detachable to the cooling circuit of the battery system by a lockable T-connection. Once the target temperature is reached, the connection is closed and the system's initial state is restored. The coolant temperature reaches values of $T_{HW,HP,out} = 277.15\ K$.

Preconditioning: Heating

To increase the ambient temperature of the battery system in the housing a heat blower is installed that supplies hot air. A target inlet temperature of $T_{amb,BAT,in} = 318.15\ K$ is adjusted and verified by a temperature sensor. Under this condition, a constant ambient air temperature inside the housing is reached and monitored by two additional temperature sensors at two different places in order to identify a homogenous temperature distribution. The increased ambient temperature follows an increase in the battery cell temperature. Once a certain value is reached the test can be started. The blower stays operational in order to maintain the ambient temperature at a constant level.

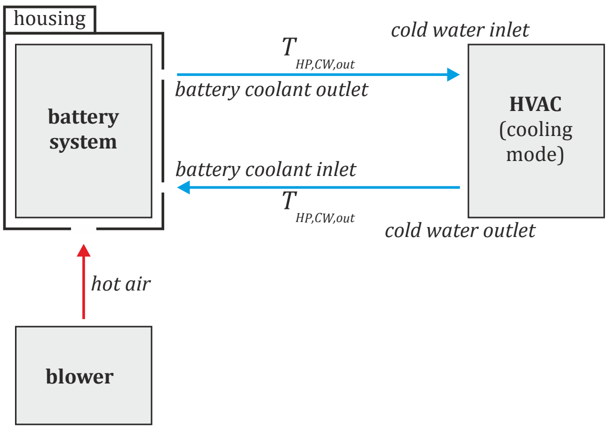

Figure 5: Implementation of the preconditioning at the test setup (heating and cooling of the battery system).

4 Simulation results

The high accuracy of the mechanical, electrical and thermal subsystem under neutral ambient conditions ($T_{amb} = \sim 293.15\ K$) is already described in detail in Schäfer et al [15]. The following evaluation is focused on the thermal effects affecting the battery system at low or high ambient temperatures with focus on the additional energy demand due to the activation of the battery thermal management system.

4.1 Low ambient temperatures

The simulation of the battery system at low ambient temperatures uses the initial temperature values of the system validation for battery cell temperature as well as the coolant temperature in the battery system that are reached under influence of the described cooling procedure. The 'control eBTM' subsystem acts similar to the real system and reacts to the heating request of the BMS because of the low battery cell temperature. Figure 6 shows the key figures of the thermal behavior of the battery system based on the defined driving cycle $v_{veh}(t)$ in comparison of simulation values and measurement data of the experimental validation. The external high voltage heater is activated due to the low initial battery cell temperature with a delay caused by the timespan to start and connect the system. The energy demand is $P_{HVheater} \approx 10\ kW$. When reaching the defined cell temperature, it is deactivated and the energy demand is zero again.

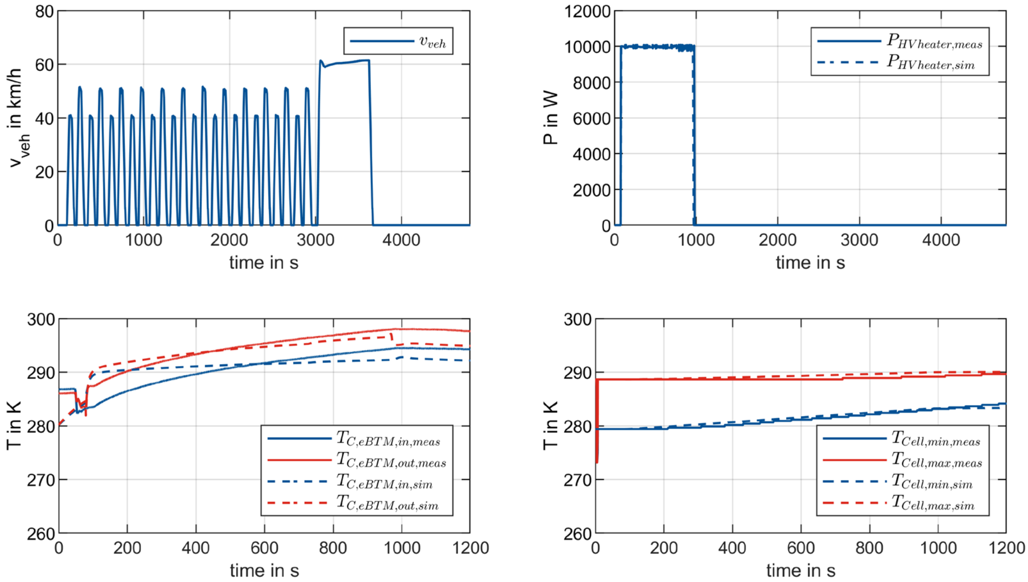

Figure 6: Simulation results in comparison to measurement data of the experimental validation at low ambient temperatures. Driving cycle $v_{veh}(t)$, power demand of HV heater $P_{HVheater}(t)$, battery coolant temperatures $T_{C,eBTM}(t)$ and battery cell temperatures $T_{Cell}(t)$ during heating period.

The comparison of the simulation results and the experimental values show a high accuracy regarding the thermal key figures. Considering the additional energy demand of the HV heater $W_{el,HVheater}$ (calculation in (4.1) and (4.2)) a deviation between the measured and the simulative results of $< 2\ \%$ can be seen.

$$W_{el,HVheater,sim} = \int P_{HVheater,sim} = 2.46\ kWh \tag{4.1}$$

$$W_{el,HVheater,meas} = \int P_{HVheater,meas} = 2.50\ kWh \tag{4.2}$$

Moreover, the temperature curve of the coolant temperature shows a similar heating trend, where it should be noted that the gradient of the simulative coolant temperature increase at the beginning is higher than the measured result. A need for further refinement in the parameterization of the heat transfer between the HV heater and the coolant has been identified. Nevertheless, the increase in battery cell temperature can be represented with high accuracy.

4.2 High ambient temperatures

For simulating the thermal behavior under high ambient conditions, the initial state is defined by the high-temperature measurement obtained from the specified heating procedure. The BMS sends a cooling request that activates the eBTM in cooling mode. The eBTM control acts to reach a defined target liquid temperature at its outlet of $T_{C,eBTM,out} = 298.15\ K$ in order to limit the battery cell temperature. Undercooling is not targeted to avoid efficiency losses of the battery system or even its damage. The control structure is discrete and results in a stepped power demand of the refrigerant compressor of the eBTM which is shown in Figure 7. Moreover, an oscillating coolant temperature $T_{C,eBTM}$ can be seen because of the dynamic cooling behavior of the eBTM.

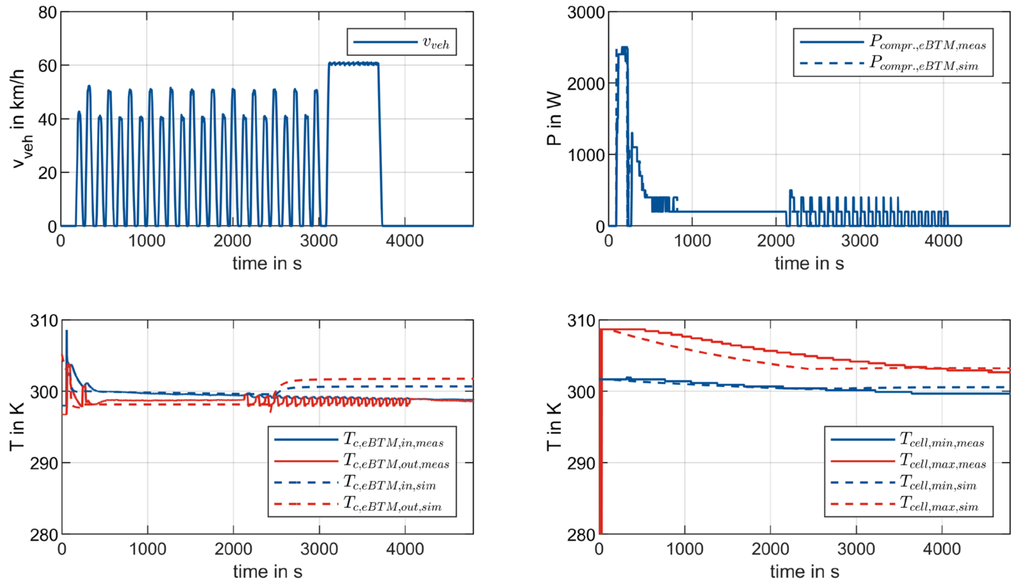

Figure 7: Simulation results in comparison to measurement data of the experimental validation at high ambient temperatures. Driving cycle $v_{veh}(t)$, power demand of eBTM compressor $P_{compr.,eBTM}(t)$, battery coolant temperatures $T_{C,eBTM}(t)$ and battery cell temperatures $T_{Cell}(t)$.

The comparison of the temperature values shows a high accuracy in the trend of the temperature decrease. The decrease of the simulated battery cell temperature shows a premature behavior that must be investigated. That follows a premature deactivation of the cooling system by reaching the target temperature of the battery cells. The additional energy demand $W_{el,compr.,eBTM}$ is calculated in (4.3) and (4.4) and therefore varies by values of roughly 10 %.

$$W_{el,compr.,eBTM,sim} = \int P_{compr.,eBTM,sim} = 0.27\ kWh \tag{4.3}$$

$$W_{el,compr.,eBTM,meas} = \int P_{compr.,eBTM,meas} = 0.30\ kWh \tag{4.4}$$

5 Summary / Conclusion

The results show that the thermal behavior of the components of a battery electric city bus, especially the calculation of the thermal key values of the battery system and its thermal management, can be modelled in MATLAB/Simscape. In addition to the results presented in the previous work by Schäfer et al. [15], the thermal behavior of the battery system at inconvenient ambient temperatures is validated by experiments on the test rig under usage of a modified test setup. In previous research, potentials have been identified to decrease the overall energy demand by combining the thermal liquid circuits and using synergy effects. The next step is the implementation of a thermal management module developed by Eberspächer to exploit the potentials and the implementation of this thermal management system in the simulation model including the experimental validation. Exemplary potentials to reduce the overall energy demand are the utilization of the engines' waste heat or the conditioning of the battery system under usage of the hot and cold liquid circuit of the HVAC. Factors such as passenger comfort and energy efficiency must be brought to harmony. The simulation model should identify an optimized operating strategy using the available heat flows to minimize the energy demand. The superior goal of the research is to increase the efficiency of the system and the busses range by decreasing the overall energy demand under influence of a certain driving cycle and certain ambient conditions.

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