2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER)

"Reducing the energy consumption for comfort and thermal conditioning in EVs"

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***Abstract*— One of the biggest barriers towards large scale adoption of electric and plug-in hybrid cars is still range limitation due to limited storage capacity of electric batteries. The air conditioning system for passenger comfort and the thermal conditioning system (battery and powertrain) are main auxiliary consumers in EVs with respect to energy consumption. Therefore, the Horizon 2020 project "OPTEMUS" proposes to tackle this bottleneck by leveraging low energy consumption and energy harvesting through a holistic vehicle-occupant-centred approach. This manuscript presents the approach of the project and first simulation results of the air conditioning system including a heat pump. This system is capable of using the ambient air or a preconditioned battery as heat source.**

***Keywords*—electric vehicle, passenger comfort, thermal conditioning, heat pump system, battery as heat source.**

I. INTRODUCTION

Currently electric vehicles are expected to be the most promising solution for (locally) emission-free future mobility. One of the biggest barriers towards large scale adoption of electric and plug-in hybrid cars is still range limitation due to limited storage capacity of electric batteries. Therefore, the energy efficiency of the powertrain and auxiliary consumers in EVs is crucial to reach a high driving range. The air conditioning system for passenger comfort and the thermal conditioning system are main auxiliary consumers in EVs with respect to energy consumption. Thus, increasing the efficiency of these systems can significantly increase the driving range of the vehicle.

The expected impact of the Horizon 2020 project "OPTEMUS" is the reduction of energy consumption under extreme ambient conditions for passenger comfort by at least 50 % and for component cooling or heating by at least 30 %. This will be accomplished by combining low energy consumption and energy harvesting via photovoltaic cells and regenerative shock absorbers. A comprehensive approach for the thermal- and energy management system shall be one of the major outputs of the project. A schematic overview of this approach, which shows the main technologies and their dependencies is shown in Fig. 1.

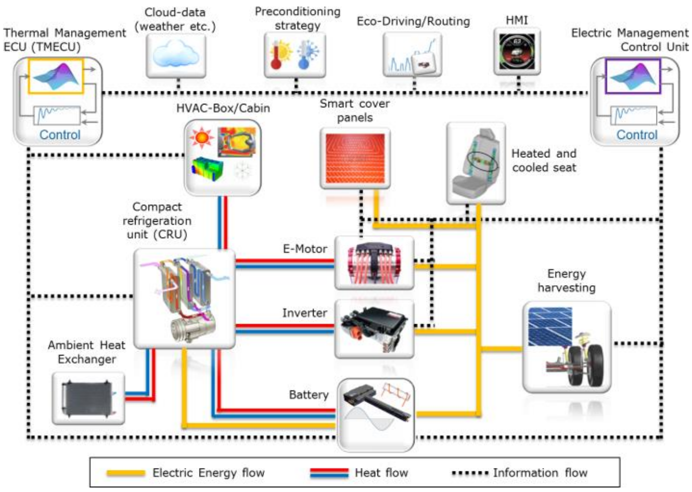

Fig. 1: Schematic overview of the main technologies and dependencies in the OPTEMUS project

The compact refrigeration unit (CRU), which basically "produces" warm and cold water in the vehicle, is supposed to redirect the heat flows in the vehicle according to the demands of the different systems/components (cabin, electric motor, inverter and battery). The use of the waste heat from components of the powertrain (e-Motor, inverter) or the battery for cabin heating could help to decrease the energy consumption in the vehicle [1]. Additionally, the use of a preconditioned battery as heat source could further improve the efficiency of the heat pump system [2]. The paper discusses simulation results, where the CRU operates in heat pump mode and uses the ambient air or a preconditioned battery as heat source in order to heat up the cabin of an A-segment vehicle.

II. Simulation Models And Boundary Conditions

In heat pump mode the CRU, which uses a natural refrigerant, transfers heat from a heat source to the passenger cabin, that is the heat sink. In the present paper the simulation results of the following two use cases are shown:

1) The ambient air as heat source
2) A preconditioned battery as heat source

These two cases have been modeled using the Software Dymola and the "AirConditioning Library" (Version 1.9) [3]. Figure 2 shows the simulation model of the first case, where the "cold coolant circuit" of the CRU is connected with the ambient heat exchanger (AHX) and the "warm coolant circuit" with the cabin. The CRU model itself consists of a compressor, two plate heat exchangers (refrigerant-coolant) and an expansion valve. Known geometries of heat exchangers for an A-segment vehicle and the performance curves of pumps were used for the parameterization of the component models. As coolant a 50 % glycol/water mixture was assumed. Also the simple cabin model was parameterized with known values for an A-segment vehicle. Via a PID-controller the compressor speed of the CRU was controlled to reach an air temperature entering the cabin of 50 °C.

For the second use case the model of the ambient heat exchanger was replaced by a (thermal) battery model, that represents the thermal mass of the battery as well as the coolant side pressure drop. A battery weight of 175 kg with an average heat capacity of 0.7 kJ/kgK was assumed. The boundary conditions for the two use cases for the simulated heat up (fresh air mode) of the cabin at -10 °C ambient temperature are shown in Table 1.

Table 1: Boundary Conditions For The Conducted Simulations

Ambient Temperature [°C]	-10
Relative Humidity [%]	90
Air Flow Heater [kg/h]	250
Air Flow AHX [kg/h]	2000
Volume Flow Heater @+70 °C [l/min]	10
Volume Flow AHX @-20 °C [l/min]	4
Volume Flow Battery @+20 °C [l/min]	7

The COP for the heat pump has been calculated according to Eq. 1, where the heating capacity was determined by Eq. 2.

$$COP_{heat\_pump} = \frac{\dot{Q}_{heater}}{P_{el\_comp}} \quad \text{Eq-1}$$

$$\dot{Q}_{heater} = \dot{m}_c \, c_p \left(T_{heater\_in} - T_{heater\_out}\right) \quad \text{Eq-2}$$

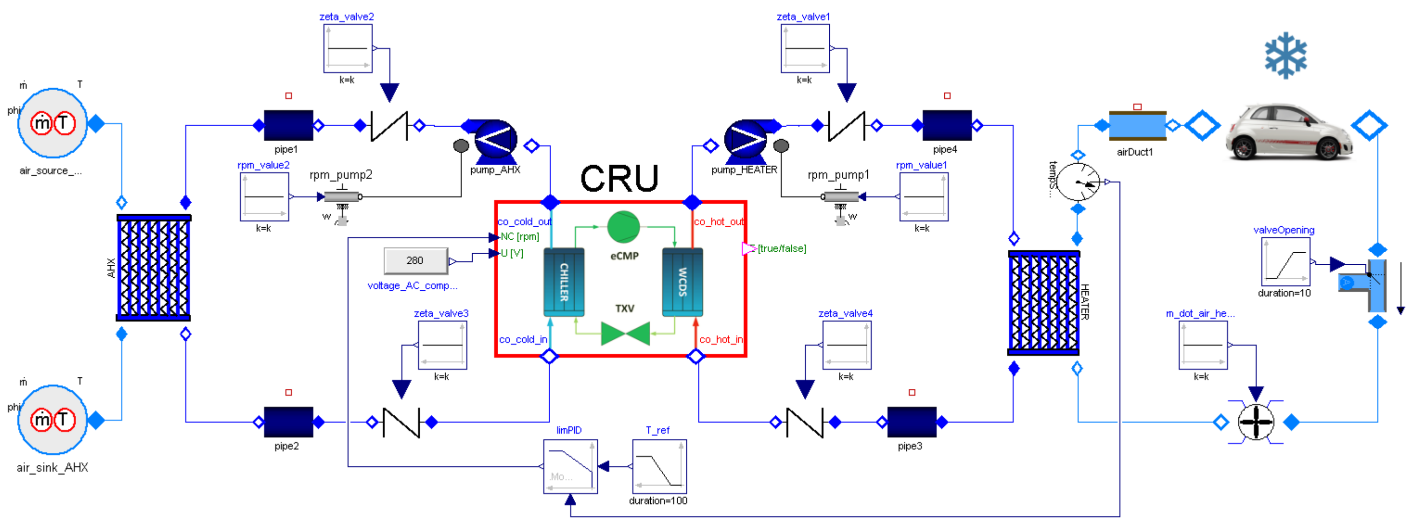

Fig. 2: Simulation model of the compact refrigeration unit and the connected coolant circuits, using the ambient air as heat source

The electric energy of the compressor was calculated by the integration of the compressor power (Eq. 3).

$$E_{el\_comp} = \int P_{el\_comp}\, dt \qquad \text{Eq-3}$$

III. Simulation Results

Fig. 3 shows a comparison of the air temperature entering the cabin and the average cabin temperature for the two simulated cases with the ambient air and the battery as heat source. It can be seen that an almost similar heat up behavior could be achieved, which enables a fair comparison of both cases. The cabin temperature reaches almost 20 °C at the end of the simulated 20 min.

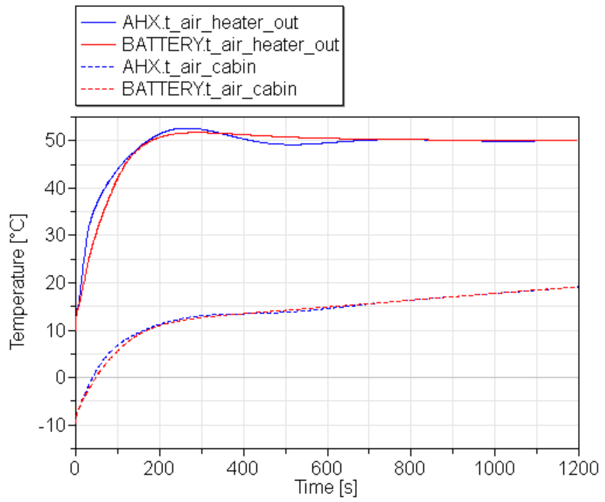

Fig. 3: Comparison of air temperatures entering the cabin and average cabin temperature for the two simulated cases

Fig. 4 shows a comparison of the suction and discharge pressures for both cases.

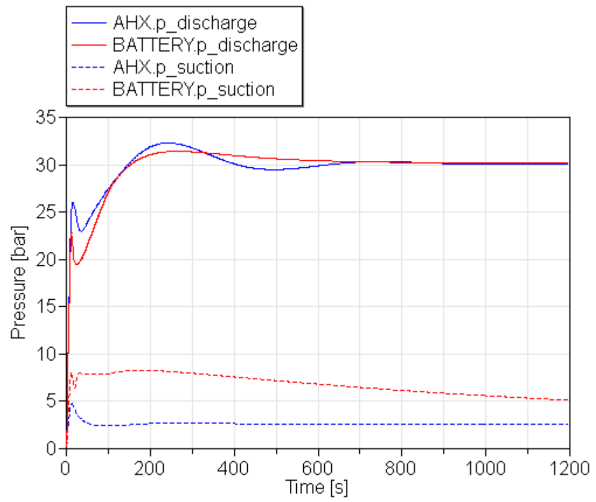

Fig. 4: Comparison of suction and discharge pressures for the two simulated cases

It can be seen that the suction pressure is significantly higher when the (warm) battery is used as heat source compared to the case with ambient air (8.4 compared to 2.8 bar after 200 s). This leads to a much lower (average) compressor speed (Fig. 5) where the battery is used as heat source (approximately 2600 rpm), compared to the case where the ambient air is used as heat source (approximately 7000 rpm in average and for the heat up at the beginning the max. speed of 8580 is needed).

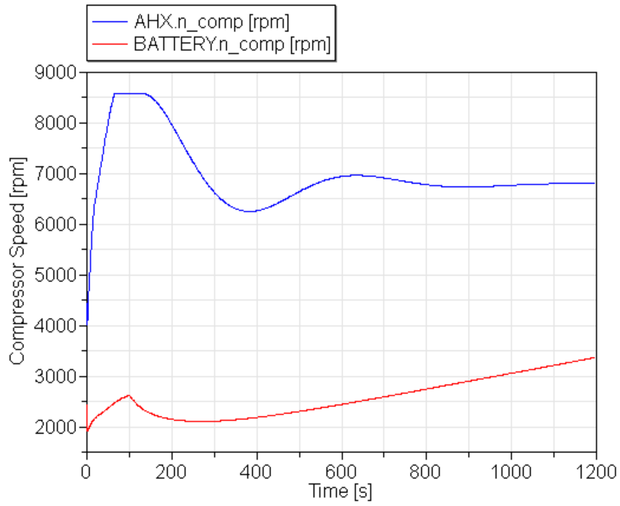

Fig. 5: Comparison of compressor speed for the two simulated cases

Further, also due to the lower (advantageous) pressure ratio the compressor power in the case where the battery is used as heat source is significantly lower and the resulting COP higher (Fig. 6). An average COP of 2.1 can be reached with the battery as heat source (average compressor power 2.0 kW) compared to 1.1 with the ambient air as heat source (average compressor power 3.8 kW).

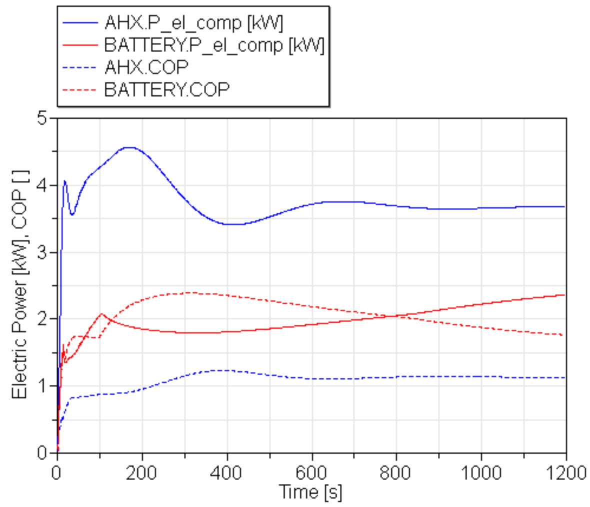

Fig. 6: Comparison of compressor power and resulting COP for the two simulated cases

When the battery is used as heat source, the COP decreases with the battery temperature. Fig. 7 shows the decrease of the battery temperature, starting at 35 °C (preconditioned). During the 20 min heat pump operation the temperature decreases to roughly 13 °C.

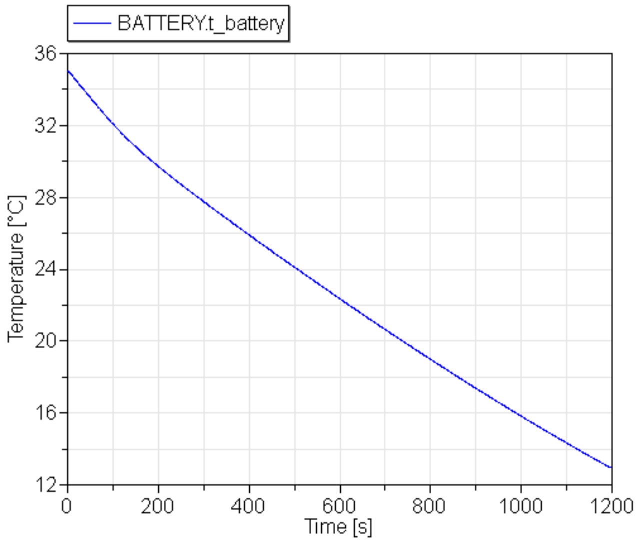

Fig. 7: Decrease of battery temperature during heat pump operation

A comparison of the used energy for the heat up of the cabin to 20 °C (Fig. 8) shows a decrease from 1.26 kWh using the ambient air as heat source to 0.66 kWh (-48 %) using the (preconditioned) battery as heat source.

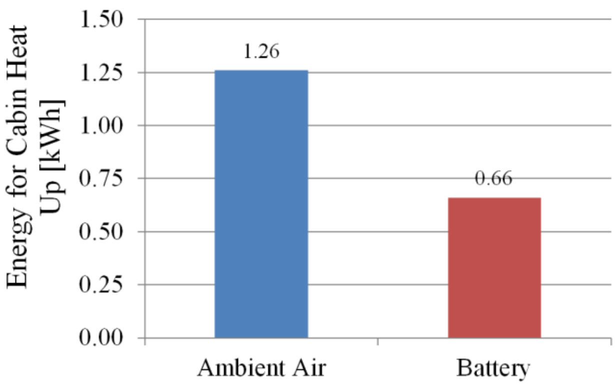

Fig. 8: Comparison of used electric energy for reaching a cabin temperature of 20 °C for the two simulated cases

IV. CONCLUSION

The paper was aimed at comparing two different heat pump operation modes using a compact refrigeration unit, which redirects the heat flows in the electric vehicle. In the first simulated use case the ambient air was used as heat source via an ambient heat exchanger. In the second use case a preconditioned battery acted as heat source.

The simulation results for a cabin heat up to 20 °C in roughly 20 min showed relevant advantages in terms of energy consumption for the second use case (battery as heat source). The higher suction pressure (8.3 compared to 2.7 bar after 200 s) compared to the case with the ambient air as heat source enables the use of lower compressor speeds (2600 compared to 7000 rpm). Additionally, also due to a lower pressure ratio of the electric compressor the operation point of the heat pump system is much more efficient. This leads to a significantly lower average compressor power (approximately 2.0 instead of 3.8 kW) and a decrease of energy consumption from 1.26 to 0.66 kWh (-48 %). The battery temperature decreases during these 20 min from 35 °C (preconditioned) to 13 °C, which is still acceptable in terms of battery thermal management.

ACKNOWLEDGMENT

The work reported in this paper was partially funded by the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 653288, by the COMET K2 - Competence Centres for Excellent Technologies Programme of the Austrian Federal Ministry for Transport, Innovation and Technology (bmvit), the Austrian Federal Ministry of Science, Research and Economy (bmwfw), the Austrian Research Promotion Agency (FFG), the Province of Styria and the Styrian Business Promotion Agency (SFG).

European Commission | Horizon 2020 European Union funding for Research & Innovation

The simulation model of the CRU and the data about the other thermal system components have been provided by DENSO AUTOMOTIVE Deutschland GmbH and DENSO THERMAL SYSTEMS S.p.A., respectively.

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DOI: 10.1109/EVER.2017.7935949