THERMAL MANAGEMENT CONCEPT FOR NEXT GENERATION VEHICLES

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Abstract— **In this paper, a thermal management concept for future intercity and long-distance vehicles is described in which the waste heat from a fuel cell system was being used for heating the cabin inlet air. To this end, various waste heat utilization concepts are created with different location of heat-exchanges and PTC-heaters and then modeled in the simulation environment Modelica/Dymola. From the obtained simulation results, a suitable waste heat utilization concept is examined in the entire vehicle.**

Keywords— ***thermal management; waste heat recovery; fuel cell vehicles; electric vehicle; cooling circuit; simulation .***

I. INTRODUCTION

Electric vehicles have the great advantage of environmental sustainability because due to local emission freedom and independence from fossil fuels by using renewable energy. Pure battery electric vehicles have the disadvantage of a short range and long charging time. The required energy for the thermal management which is provided from the battery reduces the range, so this energy is no longer available for traction. Therefore, pure battery electric vehicles are most appropriate for urban traffic. For intercity and long-distance vehicles additional primary energy converter such as a hydrogen-powered fuel cell are provided. In addition to the electric energy the fuel cell system produce waste heat for heating the cabin air. Thus, the range can be increased and the attractiveness of e-mobility can increase.

II. METHODOLOGICAL APPROACH FOR THE DEVELOPMENT OF A THERMAL MANAGEMENT CONCEPT

This section discusses the thermal management concept development. Initially, the power demand on the transient and stationary cabin heating via a heating was simulated. Transient heating means that the cabin temperature is equal to the ambient temperature. Stationary heating describes heating for keeping the comfort temperature in the cabin.

Therefor the performance of the fuel cell system is estimated and created a concept of how the system is to be used. Finally, various cooling circuit concepts are created, the waste heat from the fuel cell can be used for cabin heating.

A. *Power requirements for transient and stationary cabin heating of an electric vehicle*

The thermal power demand of the cabin heating is dependent on the ambient temperature and condition of the heating process (transient and stationary). At -20 °C, the ambient temperature is well below the comfort temperature of 22 °C ([1], page 7). Table 1 shows the simulated power requirements for different ambient temperatures for stationary heating and transient heating of the cabin.

TABLE 1: HEATING REQUIREMENTS FOR THE TRANSIENT HEATING (LEFT) AND STATIONARY HEATING (RIGHT) OF THE CABIN

transient heating		
ambient temperature	mass flow	heating power
-20 °C	3,5 kg/min	4,6 kW
-10 °C	3,6 kg/min	2,7 kW
0 °C	2,9 kg/min	1,0 kW
stationary heating		
-20 °C	3,5 kg/min	3,8 kW
-10 °C	3,6 kg/min	1,9 kW
0 °C	2,9 kg/min	0,6 kW

B. *Deriving fuel cell power requirement*

The German Aerospace Center (DLR) is distributed in multiple locations throughout Germany. The Institute of Vehicle Concepts is located in Stuttgart. The location Lampoldshausen is very close with beeline about 63 km. Not only the proximity of the two locations, also the present of hydrogen infrastructure makes it possible to refuel a fuel cell vehicle at both places. The idea of the internal commuting co-management to replace it with a fuel cell vehicle is an important point for the vehicle concept.

The route from Stuttgart to Lampoldshausen on national roads was driven by using a test vehicle with equipped measuring instruments. The test drive was performed at an outside temperature of about 23 °C. This allows disabling the air conditioning. The air-conditioning, electrical air heater (PTC-heater[1]) and the cabin inlet air blowers were always turned off.

For the 91 km route an average speed of 46 km/h resulted in a journey time of about 2 hours. The electrical power from the vehicle battery to the traction was 5 kW in mean. The electrical discharge peak power of the vehicle battery during acceleration was 25 kW and the recuperation power was about 18 kW. The proportion of recuperated electrical energy is 14 %. The energy consumption of the complete route was 10 kWh, the specific energy consumption 11 kWh/100km.

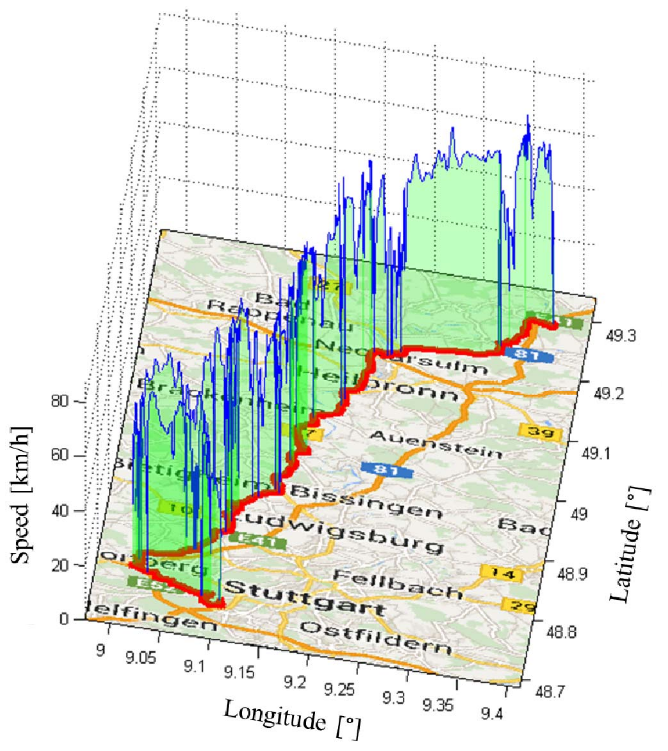

Figure 1: Speed profile of the rout from DLR-Stuttgart to DLR-Lampoldshausen over the street map from google.

The electrical output of the fuel cell system is derived from the average traction power of test drive, therefor resulting in an electrical power for the fuel cell system of 5 kW. The average electrical efficiency of the fuel cell by 48 % (see [2]) results a thermal power of 5.4 kW.

C. *Operating strategy of the fuel cell*

Since the rated power is to be moved during operation, the operating strategy of the fuel cell system focused on the ON/OFF control of the system. Only after reaching the energy breakeven point (BEP analogy) a waste heat using and system activating make sense. In order to avoid unnecessary heating energy for switching on the fuel cell system is only useful from the point of intersection where the usable waste heat from the fuel cell system is higher than the required energy for heating the fuel cell to operating temperature. As higher the ambient temperature, as lower the required thermal power for the stationary heating (see Table 1). This leads to a shift of the energy break-even point.

D. *Create high-temperature fuel cell system waste heat utilization concept*

The waste heat from the fuel cell system will be used for transient heating the vehicle cabin.

Therefor the waste heat from the fuel cell system has to be given to the cabin air by using the high-temperature cooling circuit (HT). In addition to the high-temperature cooling circuit and the cabin inlet air circuit (Air) is in the test vehicle the low-temperature cooling circuit (NT) for receiving the fuel cell waste heat available. This circuit can transfer the heat to the cabin air via a built-in liquid-to-air heat exchanger.

For the transfer of heat from the high-temperature cooling circuit into the cabin a concept has to be created with available of the following interfaces:

- High-temperature cooling circuit
- low-temperature cooling circuit
- cabin inlet air circuit

The following figure shows the different cooling circuits which can used for integration of a high temperature fuel cell in a vehicle. The developed waste heat utilization concept is indicated via the box **heating concept** with the interfaces (input / output).

[1] PTC-heater: Positive Temperature Coefficient heater

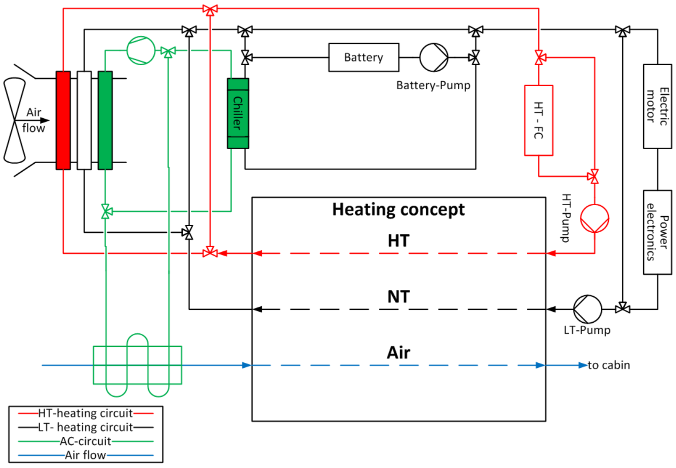

Figure 2: Available cooling circuit for integrating waste heat utilization concepts

1) First concept proposal

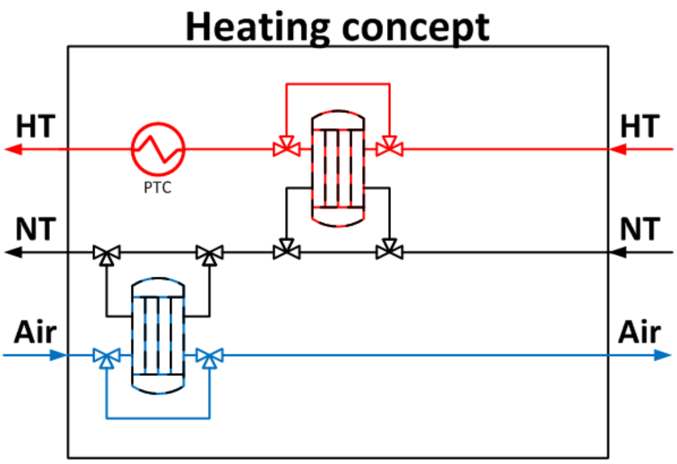

Figure 3: First concept proposal with PTC in HT-circuit

In the first concept proposal the waste heat of the high-temperature fuel cell system is dissipated into the high-temperature cooling circuit. Over a liquid-liquid heat exchanger, the heat is transported to the low-temperature cooling circuit and from there via a liquid-to-air heat exchanger to the cabin inlet air. The heating of the fuel cell stack happened via a PTC in the high-temperature cooling circuit. This allows direct heating of the fuel cell system up to operating temperature.

2) Second concept proposal

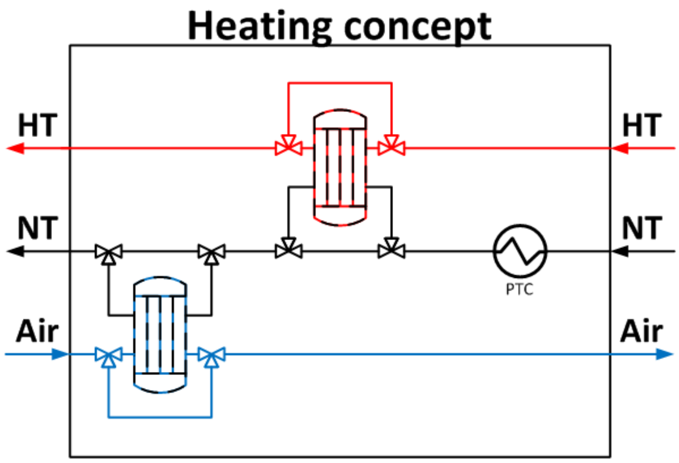

Figure 4: Second concept proposal with two PTCs one in HT-circuit and one in air circuit

The second concept proposal is similar to the first, there is an additional PTC air heater integrated into the cabin inlet air circuit. Through the use of an air-PTC the vehicle cabin can be directly heated. The high-temperature cooling circuit and low-temperature cooling circuit must initially not become heated up.

3) Third Concept Proposal

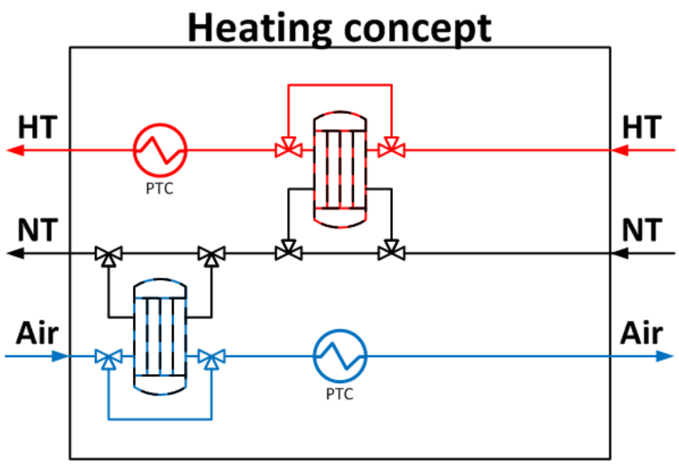

Figure 5: Third Concept Proposal with PTC in NT-circuit

The waste heat using from the fuel cell system is in the third concept proposal similar to the first concept proposal. The heating of the fuel cell stack is implemented using a PTC in this concept in the low-temperature cooling circuit. In the low-temperature cooling circuit a cooling medium must be used, which allows the start temperature of the fuel cell system.

4) Fourth Concept Proposal

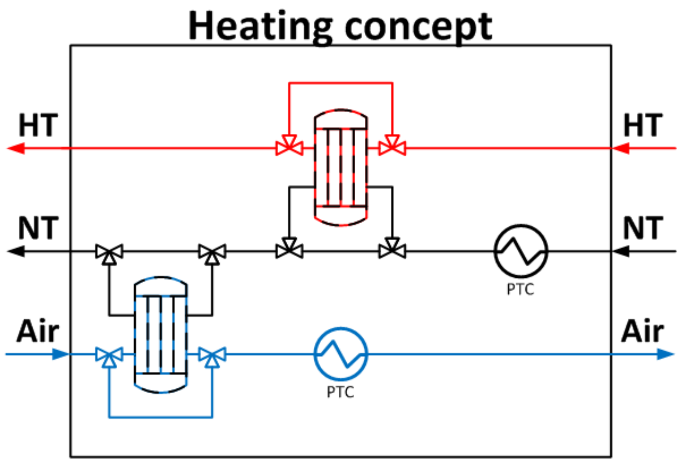

Figure 6: Fourth Concept Proposal with two PTCs one in NT-circuit and one in air circuit

The fourth concept proposal is similar to the third concept proposal, in addition to the PTC in the low-temperature cooling circuit an additional PTC air heater is integrated into the cabin inlet air circuit.

5) Fifth concept proposal

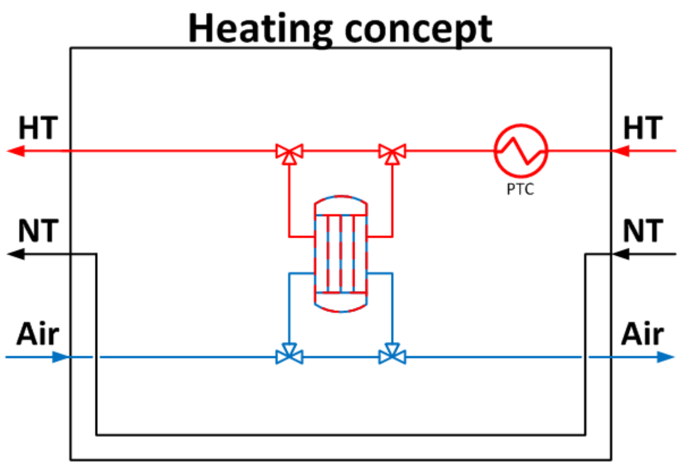

Figure 7: Fifth concept proposal with one heat exchanger and one PTC in HT-circuit

By the fifth concept proposal the waste heat from the fuel cell system in the high-temperature cooling circuit is fed directly to the cabin inlet air circuit. A double heat transfer from the low-temperature cooling circuit is saved. The waste heat can be efficiently supplied with this concept to the vehicle cabin. The waste heat from the low-temperature cooling circuit must be done separately and is not part of this study.

6) Sixth concept proposal

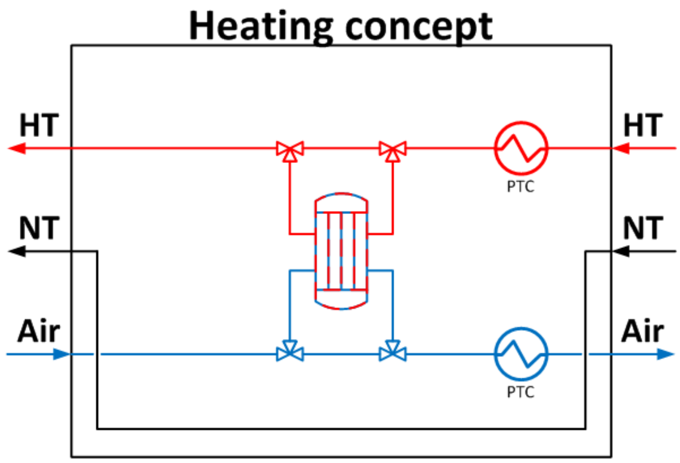

Figure 8: Sixth concept proposal with one heat exchanger and two PTCs, one HT-circuit and one in air circuit

The sixth concept proposal is similar to the fifth proposal and includes as in the previous approach proposed an additional PTC for heating the cabin inlet air.

III. SIMULATION

To evaluate the different waste heat utilization concepts for the fuel cell system on their advantages and disadvantages by the presented concepts in chapter 2 the concepts are modeled and simulated in the simulation environment Modelica/Dymola. Previously, the fuel cell system has to be modeled and analyzed for the heating-up behavior, conservation heating and cooling performance.

E. Heating-up of the fuel cell system to operating temperature

To turn on the fuel cell system is only after a minimum operating temperature of 150 °C (see manufacturer's data sheet [3]) possible. During operation it has to be cooled to keep the operating temperature. Figure 9 shows the thermal equivalent circuit model of the fuel cell system as modeled in the simulation. It is divided into four areas:

The green area shows the thermal radiation and convection between to the casing of the fuel cell system (gray) and the ambient temperature.

The gray area represents the casing of the fuel cell system. This is associated with the described area (green) as above and also with direct heat conduction to the fuel cell stack (yellow).

The heat capacity of the fuel cell stack is deposited here in yellow. This is one side connected to the casing (gray) and on the other side to the cooling medium (blue).

Blue is the interface to the cooling circuit through which the heat moves from the fuel cell into the fuel cell cooling system.

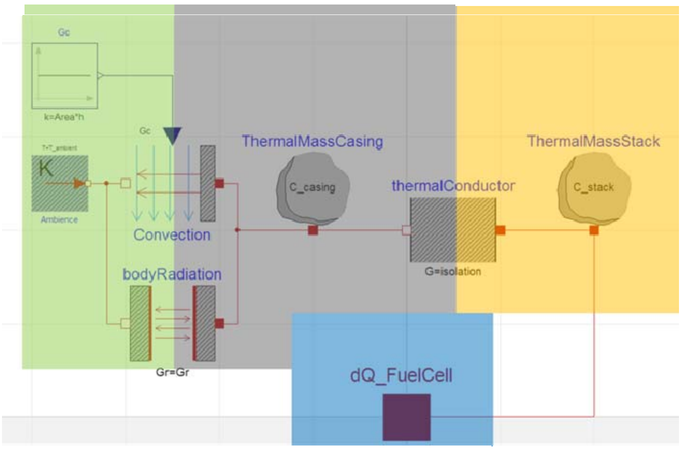

Figure 9: Thermal simulation model of the fuel cell system

The supplied heat power to the fuel cell stack is assumed in the simulation with a power of 2.5 kW. Figure 10 shows the simulated heating-up time and heating-up energy of the fuel cell stack for different ambient temperatures. On the left ordinate axis the energy for heating-up is applied in kWh, on the right ordinate the associated heat-up time in seconds. These two axes are plotted on the abscissa axis on the ambient temperature in degrees Celsius.

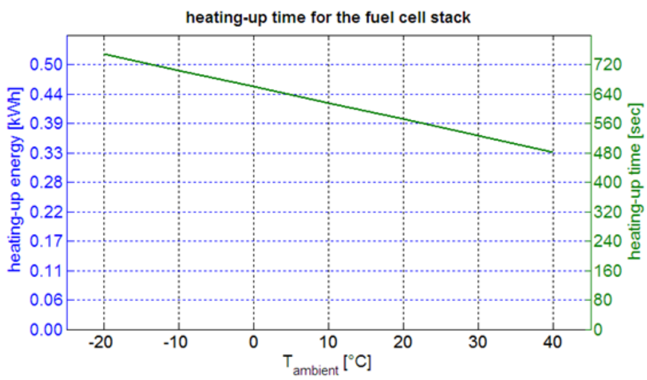

Figure 10: Required heating-up time and heating-up energy for the fuel cell stacks depending on different ambient temperature

For four scenarios [2]with different ambient temperatures, the Heating-up time and heating-up energy are listed in Table 2.

TABLE 2: THE HEATING ENERGY AND HEATING UP THE FUEL CELL SYSTEM IN DIFFERENT AMBIENT TEMPERATURES

Scenario	Ambient temperature [°C]	Energy required for complete heating [kWh]	Heating time [sec]
Winter	-20	0,52	749
Melting point of water	0	0,46	660
room temperature	20	0,4	571
Summer	40	0,33	152

F. *Influence of cooling curves to the operating temperature*

From the structure of the thermal simulation model of the fuel cell system it can be seen that the fuel cell stack has insulation. The thermal conductivity of the insulation layer is very low and favors the low heat loss from the fuel cell stack. The time-dependent temperature change is referred as cooling curve. Figure 11 shows the associated cooling curve for the four different ambient temperatures of the specified scenarios. After about 6 hours, the temperature is dropped to approximately 50 % of the temperature difference.

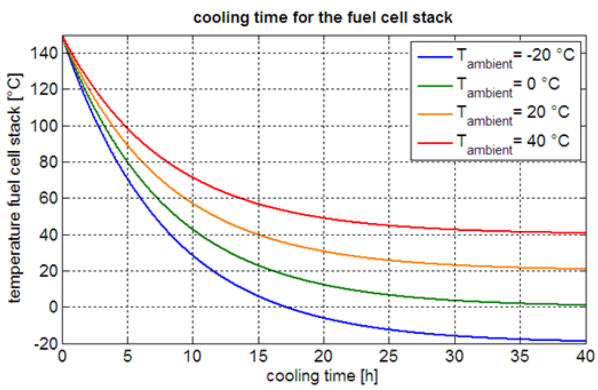

Figure 11: cooling curve of the fuel cell system at various ambient temperatures for the specified scenarios

G. *Conservation heating of the fuel cell system to operating temperature*

In order to maintain the operability of the fuel cell system the system can be hold at operating temperature. It is to be understood while conservation heating. The amount of heat dissipated to the surroundings must be supplied to the fuel cell system. Because of to the good insulation performance the necessary heating power is low. In Figure 12 the necessary heating power is applied on the ambient temperature.

[2] Here are two scenarios for use in a variety of extreme ambient temperatures that can occur in winter or summer. In addition, a scenario for the ambient temperature is still prevailing at about room temperature and a scenario with the ambient temperature at the melting point of water.

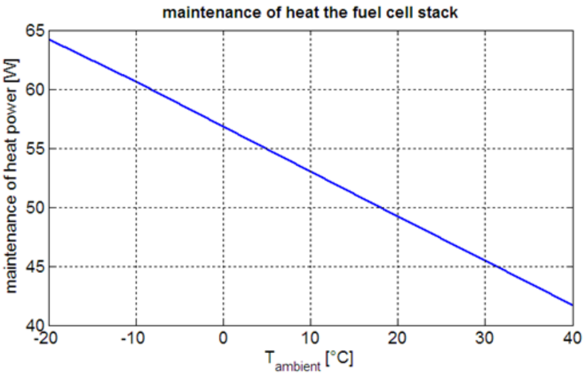

Figure 12: Performance requirements for conservation heating depending on the ambient temperatures

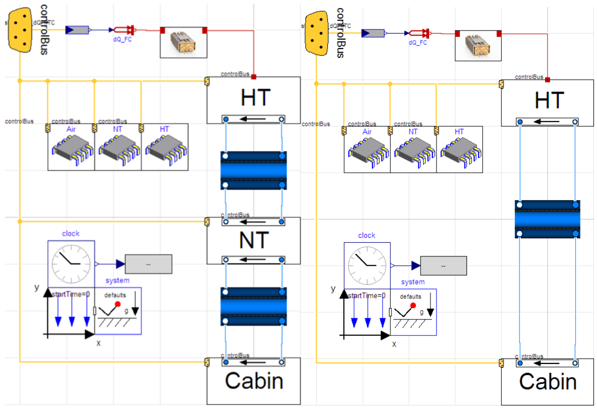

Figure 13: Simulation model for utilizing the waste heat from the fuel cell system

H. Thermal coupling between fuel cell cooling circuit and cabin

The waste heat from the fuel cell system can cover the entire heating demand of the cabin. The heat output of the fuel cell system is higher than the thermal energy required for the stationary or transient heating of the cabin. (see heating requirements in Section A with the thermal waste heat from Section B)

Which actual thermal power can be supplied from the fuel cell system of the vehicle cabin will be considered below. The cabin's supply air temperature is simulated in various high-temperature fuel cell system waste heat utilization concepts (see Section D) for stationary and transient heating of the fuel cell system at various ambient temperatures (scenario winter (-20 °C) and scenario melting point of water (0 °C)). It should be noted that the cabin inlet air mass flow not the temperature level of 70 °C exceeds [4].

I. Simulation of the cooling circuit concepts

For the simulation of the different cooling cycle approaches, two simulation models are needed. In Figure 13, both models are shown. On the upper part of the figure is the equivalent thermal model and high-temperature cooling circuit **HT** of the fuel cell system positioned. At the bottom of the figure is the model **Cabin**, which includes the cabin inlet air circuit.

On the left picture is the simulation model for heat transfer through the low-temperature circuit which is used for the concept proposals 1-6. The right side describes the concept proposals 5 and 6 with the direct coupling of the fuel cell waste heat from the high-temperature cooling circuit to the cabin inlet air circuit. The individual concept proposals are assigned through the parameterization of the PTC performance.

In the simulations, different PTCs were adopted with the following power:

- 5 kW for the air heater in the cabin
- 2.5 kW for heating the fuel cell system in the high-temperature cooling circuit[3]
- 2.5 kW for heating the fuel cell system in the low-temperature cooling circuit [4]

IV. Simulation Results and Evaluation of Different Cooling Circuit Concepts

The aim of the simulation is to choose a cooling circuit concept to heat the cabin to comfort temperature (see. [1]). The next step is to enable the use of the waste heat from the fuel cell system effectively.

For a suitable review in addition to the air temperature of the cabin inlet air circuit is also the temporal development of temperature is an important criterion. The same cabin inlet air mass flow was assumed in all simulations for a better comparison. The simulation getting for two different ambient temperatures (-20 °C and 0 °C) the following results:

TABLE 3: Simulation Results of Various Cooling Circuit Concepts

[3] There is a water heater with a 2.5 kW heating power used. In the first step, an efficiency of 100 % is assumed. The effect of lower heat output by lesser efficiency does not distort the evaluation of various high-temperature fuel cell system waste heat utilization concepts.

[4] To obtain a comparison of the heating-up of the fuel cell system is the heating power for the low-temperature cooling circuit the same as used for heating the high-temperature cooling circuit.

Concept proposal No.	Ambient temperature -20°C			Ambient temperature 0°C		
	T fresh cabin inlet air w/o. waste [°C]	T fresh cabin inlet air with. waste [°C]	Time to heat-up fuel cell to operating temperature [sec]	T fresh cabin inlet air w/o. waste [°C]	T fresh cabin inlet air with. waste [°C]C]	Zeit to heat-up fuel cell to operating temperature [sec]
1	-20	6	846	0	23	737
2	10	**35,8**	846	30	**53**	737
3	-20	6	1257	0	23	1097
4	10	**35,8**	1257	30	**52**	1097
5	-20	9,5	846	0	29	737
6	10	**39**	846	29	**60**	737

From the cabin supply air temperatures and the heat-up of the fuel cell system, the following findings can include:

- The use of a built-in air circulation PTC is necessary. First the one fresh cabin inlet air cannot be sufficiently heated. Second for the time without operation of the fuel cell system no heat output is achieved.
- The heating of the fuel cell system should be made directly via the high-temperature cooling circuit to prevent additional heat loss by preheating the low-temperature circuit.
- The waste heat from the fuel cell system is sufficient for the fresh air cabin heating, only with a proportionate recirculated air flow operation.

The coupling of the heat transfer from the fuel cell system into the cabin concept proposal 6 is the best. For this purpose, excess heat from the fuel cell system has to be removed via a cooling fan.

V. COMPLETE VEHICLE SIMULATION MODEL

In order to evaluate the cooling circuit which is identified for the waste heat recovery in the overall vehicle, an overall vehicle simulation model has been developed in Modelia/Dymola (see Figure 14). The simulation model is modular and it is made up of submodules of the drive train, fluid circuits and the cabin.

For the modeling of the drive train, the **AlternativeVehicles** library is used [5]. Figure 14 shows the drive train model of a fuel cell electric vehicle which consists of the chassis model for the longitudinal dynamics, the electric motor model, the model for the power electronics, a battery and fuel cell model.

The chassis model is used to determine the electric motor speed as well as the torque. Depending on these parameters, the electric power of the electric machine is determined using an efficiency map. For the modelling of the power electronics, an efficiency map is used to. The use of map-based models is suitable for complex vehicle simulation model and enables fast simulation and good results.

The components battery and fuel cell are generation electrical power for the drive train depending on the vehicle operating strategy. As shown in Figure 14, a DC / DC converter is implemented between the fuel cell and the battery, since both components have different voltage levels.

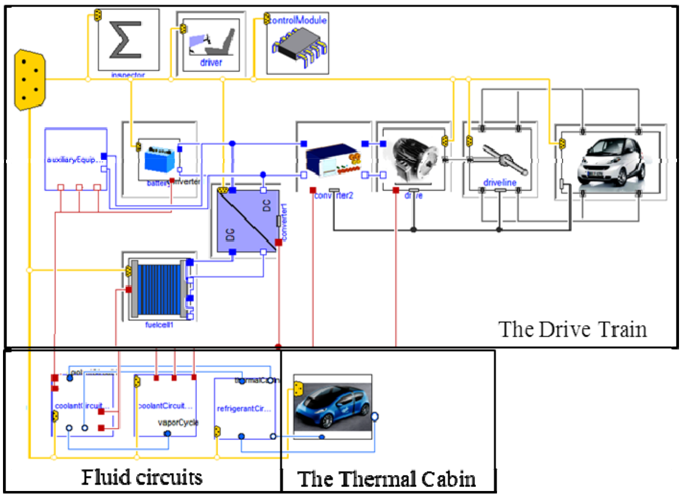

Figure 14: Complete vehicle Simulation model with thermal cabin and fluid circuits

The fluid circuits consist of a low temperature (LT) and high temperature (HT) cooling circuit. The LT cooling circuit ensures the temperature regulation of the battery, the power electronics and the electric machine. The HT coolant circuit presents the concept for the recovery of the fuel cell waste heat for the cabin heating. The cabin model represents the air in the passenger compartment which is enclosed by the body walls and windows. The model is developed and parameterized in accordance with the technical data of the project "Specific requirements for heating air system of electric motor-driven vehicles" carried out by the climate working group of the Research Association for Automotive Technology (FAT) [4].

VI. CONCLUSION AND SUMMERY

A fuel cell range extender has been added into an electric vehicle to release the traction battery. The fuel cell is not only a source of electric energy for range extension, rather a thermal source to heat the cabin as well.

Different cooling circuit concepts have been created, on one hand permit the heating of the fuel cell stacks and, secondly conduct the waste heat with the vehicle cabin. Those concepts were modeled in Modelica/Dymola. The results were evaluated for functionality and to select a concept which will further considered. The chosen high-temperature fuel cell system waste heat utilization concept shows the best behavior of fasten heating for the fuel cell and the highest cabin air inlet temperature level. Cause of using only one heat exchanger and an additional PTC in the air inlet circuit.

The next steps are to verify the simulation models with measured data of the system components. Next follows a full vehicle simulation and the final vehicle integration of the concept in the real vehicle

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