

HEAT BALANCE ANALYSIS FOR AN ELECTRIC CAR

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Abstract. The paper focuses on the analysis and simulation of thermal management systems in electric vehicles. In the computational section, heat exchange in the passenger cabin and the electric drive system was modeled using advanced engineering software Siemens Amesim. These models were employed to simulate the cabin's heat balance and to calculate heat losses in the drive system in order to determine the thermal load on the cooling and air conditioning systems. Based on the results, the impact of operating conditions on heat exchange with the environment was analyzed, and directions for further development of cooling systems in electric vehicles were proposed. A well-described Tesla Model SR 2021 RWD electric vehicle was analyzed. Calculations were performed for three variants, one with a stationary vehicle, the second with a variable ambient temperature, and the third with a variable vehicle speed. The calculations revealed a significant impact of ambient temperature on heat flows penetrating the car's structure, and in the case of increasing car speed, a significant demand for battery and engine cooling.

Keywords: electric vehicle, heat fluxes, heat balance, thermal management system.

1. Introduction

In the 21st century, growing environmental problems have led to the European Union and the rest of the world increasingly promoting environmental protection and introducing new restrictions on pollutant emissions. There is a strong focus on greenhouse gas emissions into the atmosphere by various sectors of the economy. Road transport accounted for 11.9% (Ritchie, 2020) of global greenhouse gas emissions in 2020, which is why manufacturers are obliged to sell vehicles with increasingly low-emission powertrains so that the average emissions of the model range sold are sufficiently low (Holenko et al., 2024). Thanks to zero emissions during use, cars with electric drive systems are an attractive solution for reducing the average emissions of all cars sold by a given brand. The work focused mainly on cooling systems in BEV vehicles (Battery Electric Vehicles). In these vehicles, the Thermal Management System (TMS) is responsible for controlling the temperature of components and managing the thermal energy generated by the main components of the electric vehicle, i.e., the battery, engine, and passenger compartment. The main task of this system is to ensure safety during use and to increase the reliability of the electric car's drive system. In addition, it ensures the proper performance of individual components. It consists of individual elements which,

either independently or in a combined system, control thermal conditions by heating and cooling individual components (Guo et al., 2024).

The Battery Thermal Management System (BTMS) is designed to ensure that the battery operates within the appropriate temperature range so that it can function safely and cell degradation is limited, while maintaining high efficiency when delivering energy to the motors (Guo et al., 2024). This subsystem is designed to prevent thermal instability (Thermal Runaway), especially when the outside temperature is high, and when the ambient temperature is low, it must adequately heat the battery so that it can be charged with high-intensity current, which directly reduces the charging time of the electric car. Furthermore, too low battery temperature limits the electric current that it can supply to the vehicle's electric motors. Liquid cooling, air cooling, Peltier modules, Phase-Changing Materials (PCM) or heat pipes are used to perform the above tasks (Gabbar et al., 2021). The development and improvement of battery cooling systems is crucial for increasing the efficiency and reliability of batteries, which ultimately translates into an easier and mass transition to electromobility. One of the most popular technologies used in batteries for EV cars are lithium-ion (Li-ion) batteries. Thanks to their high energy storage density, low self-discharge rates, high number of charging cycles, and low weight, they outperform other

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technologies in this application. However, in order for the battery to retain its positive characteristics, it must be kept within at least the theoretical operating temperature range of between $-10\text{ }^{\circ}\text{C}$ and $50\text{ }^{\circ}\text{C}$ (Ziad et al., 2023). As a standard, car manufacturers further narrow this range so that the battery is at its most optimal point, where it achieves the highest performance and can be heavily loaded electrically while remaining safe. Furthermore, keeping the battery at the right temperature directly affects its lifespan. Using a cold battery (below $-10\text{ }^{\circ}\text{C}$) results in significantly deteriorated properties and adverse phenomena. In addition, a lithium-ion battery heated to high temperatures (above $50\text{ }^{\circ}\text{C}$) also exhibits poorer performance and dangerous internal processes. In EV cars, the thermal management system will aim to maintain the battery operating temperature between $15\text{ }^{\circ}\text{C}$ and $35\text{ }^{\circ}\text{C}$ (Yu et al., 2023) in order to ensure high efficiency and maximize safety by leaving a margin relative to the theoretical operating range of lithium-ion cells. Additionally, the difference between individual cells (Battery Cell) in the battery (Battery Pack) is a maximum of $5\text{ }^{\circ}\text{C}$, which further improves safety aspects. The thermal power that needs to be dissipated from an electric car battery depends on its size and type, and is usually in the range of 2.5 kW to 15 kW . Currently, electric cars use different types of lithium-ion batteries, which differ in the materials used to construct the anode in order to optimize them in terms of safety, service life, and efficiency. The Motor Thermal Management (MTM) system is used to maintain the engine within the appropriate temperature range. Advances in technology have led to significant increases in the power, torque, and rotational speeds achieved by electric engines, while maintaining compact dimensions. This has resulted in increased heat generation and necessitated the development of cooling systems to maintain efficiency and reliability. Electric engines are cooled using liquid cooling (usually glycol or transformer oil) and air cooling). Heat is generated both by magnetic starts and mechanical losses, which makes this issue quite complicated, as heat must be dissipated from various components inside the motor, and this complicates the heat exchange process. Electric motors used in electric cars are characterized by high power, high torque values, and high rotational speeds, which, combined with their compact size, results in high heat loss density and high temperatures. The power of electric motors most commonly used in modern cars ranges from 100 kW to 200 kW and includes various types of motors. They have different operating characteristics, but all types of electric motors will lose their performance and have a limited service life if they are not sufficiently cooled. In addition, low efficiency will result in high energy consumption, which will affect the short range of the electric car (Sun et al., 2023). The amount of energy that needs to be dissipated from an electric motor depends on its power and can range from $2.5\text{--}6\text{ kW}$, $6\text{--}10\text{ kW}$, and $10\text{--}15\text{ kW}$, which results

in different cooling system requirements depending on the specific vehicle. The typical operating temperature range for an electric motor is $-20\text{ }^{\circ}\text{C}$ to $60\text{ }^{\circ}\text{C}$. The Cabin Thermal Management (CTM) system, which usually consists of air conditioning, is a key element because it is responsible for maintaining the right temperature in the passenger compartment and even providing heating or cooling power for the entire TMS system. With the development of heat pump technology, which has higher efficiency, resulting in greater range for electric vehicles, classic (for electric vehicles) heaters based on PTC (Positive Temperature Coefficient) elements have begun to be replaced.

2. Heat balance of the passenger cabin

The summation of all the load types will be the instantaneous cabin overall heat load gain. The mathematical formulation of the model can thus be summarized as (Zearban et al., 2024; Tikadar et al., 2021; Grabowski et al., 2016):

$$Q_{Tot} = Q_{Met} + Q_{Dir} + Q_{Dif} + Q_{Ref} + Q_{Amb} + Q_{Exh} + Q_{Eng} + Q_{Ven} + Q_{AC}.$$

All of the above values are thermal energies per unit time. Q_{Tot} is the net overall thermal load encountered by the cabin. Q_{Met} is the metabolic load. Q_{Dir} , Q_{Dif} and Q_{Ref} are the direct, diffuse, and reflected radiation loads, respectively. Q_{Amb} is the ambient load. Q_{Exh} and Q_{Eng} are the exhaust and engine loads due to the high temperature of the exhaust gases and the engine. Finally, Q_{Ven} the term is the load generated due to ventilation, and Q_{AC} is the thermal load created by the AC cycle. The metabolic heat flow is constant and amounts to 116 W , based on the standard ISO 8996 (International Organization for Standardization, 2021). The heat flow from solar radiation was assumed based on data from a meteorological station in Warsaw (Poland). For simplicity, the total heat flux from solar radiation was assumed. The heat fluxes from solar radiation through the structural elements of the vehicle, i.e., transparent (windows) and opaque (roof, doors, etc.) partitions, were calculated. Heat gains from the exhaust system have been omitted because electric cars do not have this component, which is closely associated with combustion engines. The next stream that was omitted is the gains from the engine (Electric Vehicle database, 2021). It was assumed that the engine is temperature-stabilized by a cooling system, and the temperature range is similar to the temperatures in the cabin, which is separated from the drive components by fireproof partitions that provide good thermal insulation.

The energy demand for heating and cooling the cabin was determined based on heat balance calculations, which took into account various loss and gain flows. The calculations were performed using Simcenter Amesim (Advanced Modeling Environment for Simulation of

Engineering Systems), which is an advanced CAE tool for modeling and simulating multiphysics systems. It enables the design, analysis, and optimization of dynamic mechatronic systems, combining various fields of engineering. The program simulated heat exchange processes using a car cabin model (Fayazbakhsh & Bahrami, 2013; Kosobudzki & Grenzia, 2021).

3. Modeling vehicle operating conditions

Sample sets of atmospheric data (A) and vehicle speed were (v) used to model operating conditions in order to determine the impact of parameters such as ambient temperature (k), air humidity, radiation intensity, and driving conditions. Values were read after reaching a steady state.

The thermal load of the motor and battery was estimated using a simulation in Siemens Amesim. These two components were analyzed within a single model because they are closely related, forming the basis of the electric car's drive system. The model used for the simulation is shown below (Figure 1).

The main elements of the model are:

- car body,
- driver algorithm,
- drive system controller,
- motor with inverter,
- battery,
- battery and motor cooling systems.

Elements from a library dedicated to drive systems and other subsystems of various types of vehicles were used to construct this system. Due to the high availability of data for Tesla vehicles (Tesla model 3 2025), the parameters for the simulation were adopted to reflect the Tesla Model SR 2021 RWD car (Bin & Ziba, 2023; EVSpecifications, 2021). The calculations were performed

for three variants, the data for which are presented in Table 1. The first variant is a stationary car exposed to intense solar radiation. In the second variant, the ambient temperature was changed while maintaining the vehicle speed at a constant 50 km/h. In the third variant, the speed of the vehicle was changed. Efforts were made to keep the parameters inside the vehicle and the environmental conditions (to a limited extent) at the same level. The results of the calculations for variant I are shown in Figures 2–3. The results for variant II are shown in Figures 4–5, and variant III is shown in Figures 6–7.

Table 1. Summary of certain data used in the calculations

Specification	Value		
	I variant	II variant	III variant
Ambient temperature	from -35 °C to +35 °C	from -35 °C to +35 °C	20 °C
Comfort temperature	27 °C	27 °C	27 °C
Ambient relative humidity	50%	50%	50%
Vehicle speed	0 km/h	50 km/h	from 0 km/h to 140 km/h
Number of people in the vehicle	1	1	1
Ventilation flow	320 m ³ /h	320 m ³ /h	320 m ³ /h
Intensity of solar radiation	900 W/m ²	200 W/m ²	W/m ²

EV drive system

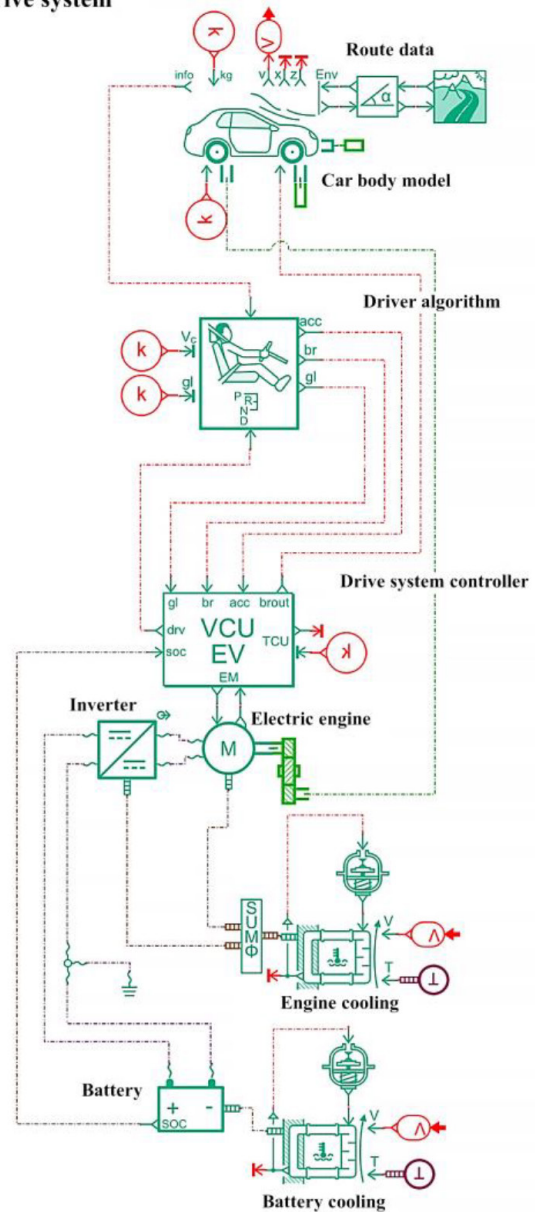


Figure 1. Drive system model in Simcenter Amesim

In variant I, with the car stationary and the ambient temperature changing, only the air conditioning system was observed to be operating. At low temperatures, the

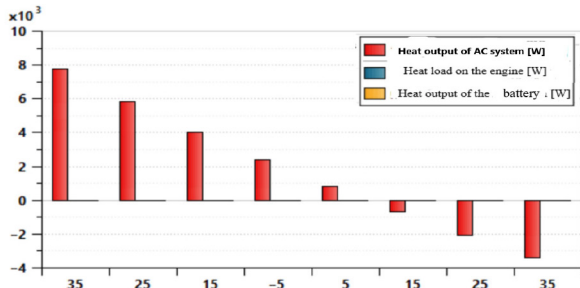


Figure 2. Heat flows from AC for variant I at different ambient temperatures

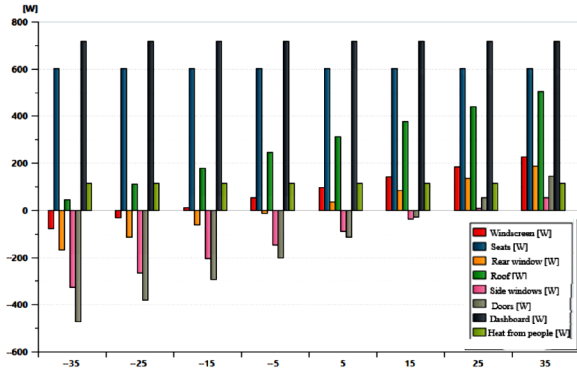


Figure 3. Heat flows for variant I at different ambient temperatures

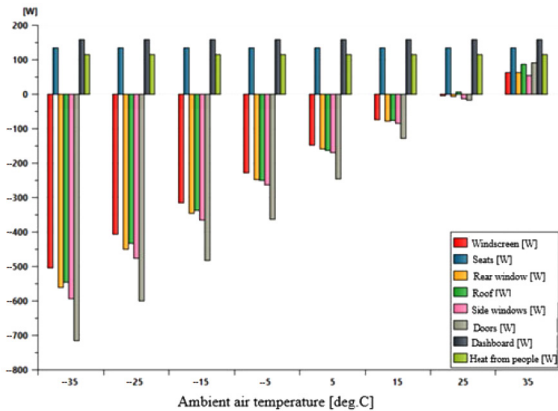


Figure 4. Heat flows for variant II at different ambient temperatures

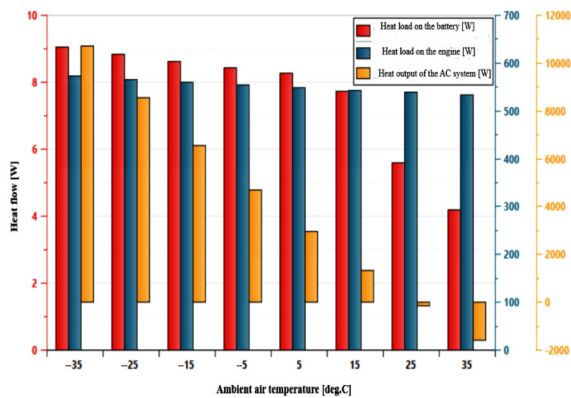


Figure 5. Heat flows from batteries, engine, and AC for variant II at different ambient temperatures

car is heated with a heating power of 7.8 kW at an ambient temperature of $-35\text{ }^{\circ}\text{C}$, reaching 0 kW at a temperature of approx. $27\text{ }^{\circ}\text{C}$, with maximum cooling of 3.5 kW at a temperature of $35\text{ }^{\circ}\text{C}$. In the case of heat gains, there are constant values from people, seats, and the dashboard, while heat losses to the environment from body components decrease as the ambient temperature increases.

In variant II, with a constant vehicle speed of 50 km/h and an ambient temperature ranging from $-35\text{ }^{\circ}\text{C}$ to $35\text{ }^{\circ}\text{C}$, a constant decrease in AC heating power from 9 kW to 1.7 kW cooling power was determined. The heat from the engine remains at a similar level of 540–580 W. The heat flow from the battery is at a low level of 4–8 W.

In variant III, when changing the speed of the car from 0 km/h to 140 km/h, at a constant ambient temperature of $20\text{ }^{\circ}\text{C}$, a significant increase in heat flow from the battery from 0 W to 450 W can be observed, as well as an increase in heat flow from the engine to 4.1 kW.

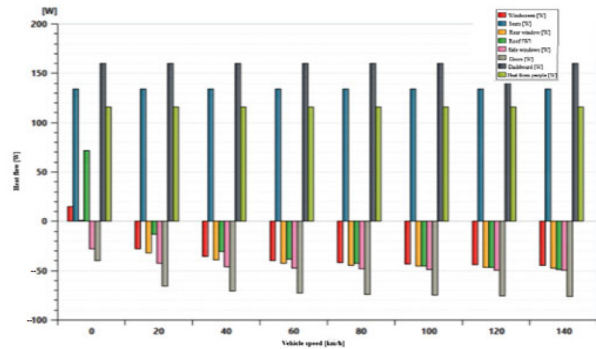


Figure 6. Heat flows for variant III at different car speeds

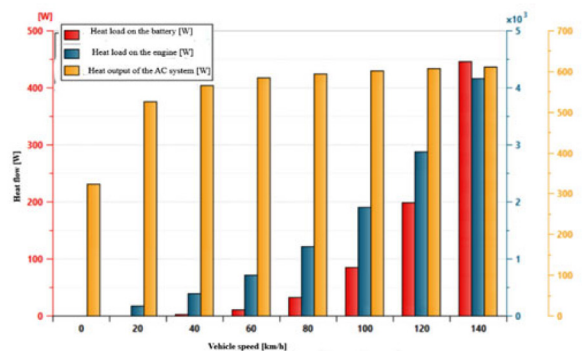


Figure 7. Heat flows from batteries, engine, and AC for variant III at different car speeds

4. Conclusions

Simulations and analyses have demonstrated the need for adequate heat management in electric cars. The thermal load on the passenger compartment is mainly influenced by solar radiation and ambient temperature, although vehicle speed further amplifies the impact of these factors. At low temperatures, a stationary car is heated with a heating power of 7.8 kW at an ambient

temperature of $-35\text{ }^{\circ}\text{C}$, reaching 0 kW at a temperature of approx. $27\text{ }^{\circ}\text{C}$, with maximum cooling of 3.5 kW at a temperature of $35\text{ }^{\circ}\text{C}$. On the other hand, a car traveling at a speed of 50 km/h at maximum temperature requires less cooling power, 0.8 kW, and increasing the speed has little effect on the cooling power of the air conditioning. Heat flows from the battery and engine increase significantly to 400–500 W as the speed of the car increases. Heat losses in the engine and battery depend primarily on the speed of the vehicle and, to a lesser extent, on the outside temperature. The heat balance of the driver's cab indicates slight changes in heat flows from people, seats, and the dashboard. The effect of speed on heat flows from the environment also appears to be minor, while a change in ambient temperature can alter them by an order of magnitude; for a temperature of $-35\text{ }^{\circ}\text{C}$, these values range from 500 to 700 W, and at a temperature of approx. $27\text{ }^{\circ}\text{C}$, they decrease to zero. The results show that it is possible to use an integrated cooling and air conditioning system that allows heat exchange between components and can reduce energy consumption, which is why the use of such solutions in the latest electric car models is justified.

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