Research Article

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Efficiency of electric vehicle interior heating systems at low ambient temperatures

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Abstract: The electric car market is becoming more and more extensive. According to ACEA, in 2019, 549,387 full electric passenger vehicles, hybrid plug-ins and hydrogen vehicles were registered in the European Union. Thus, it is an increase of 52.9 percent compared to 2018. Germany is the leader with 108 839 registrations of vehicles (+60.9% y/y). Great Britain achieved an increase of 21.5 percent y/y and the number of registrations at 72 834 pieces. The Netherlands came next (66 957 pcs, + 146.3% y/y), France (61 356 pcs, +34.6% y/y) and Sweden (40 406 pcs, + 39.4% y/y). Registration results in Europe shows that the popularity of electric vehicles is increasing. Along with the development of this type of vehicles, the technology used in their construction also changes. The biggest calls at the moment are batteries for these vehicles, as well as their ranges on a single charge. There are already vehicles with ranges of 500 km or even 600 km.

However, it turns out that these are not the only problems with electric vehicles. One of the drawbacks is the way they heat their passenger cabins. There is no typical heater in an electric vehicle as in the case of a vehicle with a conventional drive. For this purpose, e.g. an electric heater with a blower is used for this purpose. For this reason, the authors of the paper decided to determine the efficiency of the heating system in an electric vehicle at low ambient temperatures.

Own tests were carried out on the vehicle at temperatures of +5°C, -5°C and -10°C. Based on the research, the authors of the paper could draw conclusions on how to heat the interior in the electric vehicle under test, as well as check whether the efficiency of such a system for individual places in the car is sufficient to obtain the set temperature.

Keywords: Electric vehicles, heating, efficiency, environmental protection

1 Introduction

Electric vehicles have been considered as vehicles for everyday use for about decade ago. This is the result of an increasing number of vehicles in the world, and thus a significant increase in emission of harmful exhaust gas, which in the end has negative impact on the natural environment and human health. These aspects combined with shrinking resources of oil-derived fuels have contributed to the intensification of works on alternative drives and fuels in transport [1–8].

According to the IEA report, the number of electric vehicles (BEV), hydrogen vehicles (FCEV) and plug-in hybrid (PHEV) on global roads in 2017 reached 3.1 million (an increase of 54% y/y). In 2017, more than 1 million electric cars were sold in total (54% more than in 2016), half of which (580 thousand) in China. The second place was taken by the United States with a result of 280.000 vehicles [9]. On the roads of the Middle Kingdom, there were 1.23 million electric vehicles (40% of the global EV fleet), in Europe 0.82 million, in the US 0.76 million, while in the rest of the world – 0.3 million. In 2018, the largest EV share in the new vehicle market was recorded in Norway (39.2%), Iceland (11.7%) and Sweden (6.3%). China (2.2%), Germany (1.6%), USA (1.2%) and Japan (1.0%) [9–11].

Over the last year, the number of electric vehicles (BEVs) has increased significantly. According to [10–12] 7,992,535 electric vehicles were registered worldwide in 2019. However, the proportions have not changed and still show that the greatest number of such vehicles is in China. China has more than 3.8 million electric vehicles, which is even more than the entire world had two years ago.

There are 321,248 cars without a combustion drive in Norway, 300,633 in Germany, 264,905 in the United Kingdom and 218,043 in France. In Scandinavia the share of BEVs in overall sales of new vehicles exceeds 50% [10–12].

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With the increase in the share of BEVs in sales, a problem emerged with the heating of such cars. These vehicles are operated in different conditions, also in regions where temperatures periodically fall below -10°C .

A well-known and big challenge for electric vehicles is the heating system of their cabins. The use of electric heaters, for obvious reasons, reduces their range, but also their competitiveness against combustion vehicles, also in terms of ecology. The authors decided to pay attention to one selected aspect related to the heating system of these vehicles, namely the efficiency of the BEV interior heating system and the differences resulting from the heating solutions applied. This will allow for more reflection on the actual usefulness of these vehicles in colder regions of the world.

2 Problem identification

Most electric vehicles (BEV) often have a smaller range than that declared by the manufacturer. To increase the range, it is necessary to use the available energy efficiently. Each trip has different energy loads in terms of drive and other energy consumers. Heating, ventilation and air conditioning system (HVAC) in certain conditions may be the biggest additional burden. In many cases, it appears that the range of an electric vehicle decreases when the HVAC system is activated [13, 14]. Depending on the weather conditions, up to 25% of the required energy is used by other receivers [15]. In order to increase the range, an attempt can be made to increase the efficiency of the heating and ventilation systems of the interior of the vehicle or to seek energy savings by diminishing the target interior or the assumed heating/cooling speed. Possible energy savings quickly lead to a conflict with passenger comfort. A five-zone model (Figure 1) is currently used for the calculation and simulation of HVAC systems.

This model takes into account the impact of the environment. Ambient temperature, insolation and the exchange of air masses from the air conditioning system are considered. This results in heat flows that ultimately affect the conditions in the interior (Figure 1), where “Ventilation” means the two-way heat flow of the air conditioning system. The general equation describing heat flow is calculated as the sum of heat exchange and diffuse and direct radiation:

$$\dot{Q}_{\text{body part}, i} = S \times U \times (T_{\text{out}} - T_{\text{in}}) + \epsilon \times \sigma \times S \times (T^4 - T_{\text{ambient}}^4) + \tau \times S \times \theta \times \dot{I}_{\text{sun}} \quad (1)$$

The heat flow depends on the ambient temperature (T_{out}), the temperature inside (T_{in}) and the heat transfer

Figure 1: Classification of the vehicle interior into five zones and representation of the influences and heat transfer mechanisms which are considered in the model [4]

surface (S), the total heat transfer coefficient (U), depends on several convection factors (h_i , h_o), material thickness (λ), as well as the thermal conductivity coefficient (κ). Solar radiation in this model reaches the interior of the car through absorption and permeability. The car glass practically does not absorb radiation energy; hence, the thermal energy is transferred directly to the car compartment [16].

Vehicle components such as bodywork, roof, chassis, side plates and windows describe the limits of the heating system in question. Most often in calculations, they are considered separately and are connected to the interior of the vehicle by means of appropriate heat flux. Models assume that all body surfaces are flat surfaces with simple geometry. The heat given away by the trunk and the front bulkhead is omitted. The volumes of air in the interior are connected to each other by convection itself, as are the body panels and thermal masses with adjacent air volumes. Bodywork parts are considered to be layered flat panels. All listed components are similarly modelled, except for car windows. They consist of only one layer. Figure 2 shows the heat transfer mechanisms, convection, radiation and

Figure 2: All chassis parts considered in the model and their coupling among each other. Representation of the occurring heat transfer mechanisms with passive heating or cooling [16]

permeability during passive heating or cooling, but without considering forced convection [16].

Elements with thermal capacity such as the parcel shelf, dashboard and interior are considered in the same way, with the exception of material parameters and environmental influences taken into account. Solar radiation affects the parcel shelf only through the rear window, and on the dashboard only through the windshield. The interior is illuminated by all windows. Each thermal mass is connected by heat convection to the volume in which it is located. This is described by the following formula [17]:

$$\dot{Q}_{\text{Convection}} = \alpha (N_u (R_e, Pr)) \times S \times \Delta T \quad (2)$$

In electric vehicles, the battery in the chassis of the reference vehicle constitutes an additional thermal mass of the known mass and affects the thermal condition of the car compartment, in particular by delaying the increase in the temperature of the legroom during the heating process [18]. In addition, the bodywork shape of the reference vehicle (hatchback) affects the heat input into the trunk, as the heat is also exchanged by side windows. In this case, the heat flux that flows through the side windows is divided into the main zone (V1) and the trunk zone (V5). In a conventional sedan, this heat flux fully reaches the main zone (V1). For convection volume coupling, there are six virtual contact surfaces (Figure 1). In the passive state, when heating and cooling the car compartment only by external conditions, the coupling is based solely on natural convection. The heat flow is calculated according to equation 2. In the case of active ventilation of the car compartment by the HVAC system, it is important to couple these six contact surfaces by forced mass airflows. The resulting heat flow depends on the supply temperature and the internal temperature. Choosing a ventilation mode determines how bulk flows will be blown through the car compartment. Since constant pressure is assumed in the car compartment of the car, the supply and outlet of air in each volume must be equal. The volume of heat flow depends on the temperature difference ΔT of adjacent volumes and can be described by the following formula:

$$\dot{Q}_{\text{ventilation}} = \dot{m} \times c \times \Delta T \quad (3)$$

Upward flows over the dashboard and the parcel shelf cause circulation flows that lead to air exchange in the entire car compartment [16]. They are formed above the thermal mass because the components heat up faster than adjacent air volumes due to solar radiation. The airflow is directed from the windows to the overhead zone (V3), from there to the main zone (V1) and eventually back to the parcel shelf (V5) or the dashboard zone (V4). The vol-

ume of heat flows depends on the difference of temperatures between adjacent volumes and the resulting mass airflow over thermal masses. Another impact of the sun is also taken into account: solar radiation passes through the windscreen and is absorbed by the dashboard. However, thermal radiation of the heated dashboard does not pass back through the windscreen due to the length of the radiation wavelength. This effect is insignificant when solar radiation is not taken into account. All aforesaid heat flows are added to the resulting heat flow for each volume, which is generally calculated in the following manner [16]:

$$\dot{Q}_{V,i} = \dot{Q}_{\text{windows}} + \dot{Q}_{\text{body part}} + \dot{Q}_{\text{thermal masses}} + \dot{Q}_{\text{convection}} + \dot{Q}_{\text{ventilation}} \quad (4)$$

The above formula and the gas state equation can be applied to calculate the difference in temperatures:

$$\Delta T = \int_0^t \frac{\dot{Q}_{V,i}}{n \times c_p} dt = \int_0^t \frac{\dot{Q}_{V,i} \times R \times T}{p \times V \times c_p} dt \quad (5)$$

3 Own tests

The presented article discusses the mathematical relationships and mechanisms which determine the heating efficiency of individual zones of the vehicle cabin. Scientists conducting the research did not know the detailed thermodynamic properties of individual elements of the vehicle's equipment or the actual efficiency of heating devices, as these are only available to the manufacturer. Therefore, the only sensible way out of examining vehicles was to conduct empirical studies of the dependence of temperature in its four zones on time and on the temperature of the vehicle's surroundings. Therefore, in the results presented below, the most important were the values of temperatures in the assumed time thresholds and the verification of the overall ability of the vehicle to meet the required test assumptions.

Own tests were carried out in a low-temperature chamber, where a two-roller chassis dynamometer is also located, which forms the equipment of the Environmental Protection Centre of the Institute of Motor Transport.

Two-roll chassis dynamometer by Jaroš, type 2PT220EX with two rolls of 372 mm diameter each, with electric simulation of resistance to motion and mechanical simulation of vehicle inertia, located in the low temperatures chamber. Allows testing vehicles (at an ambient temperature down to -14°C) with the following parameters:

- maximum net power on wheel: up to 220 kW,
- maximum speed: up to 130/200 km/h,

- driving axle: load up to 2400 kg,
- drive on one or more than one axel, with the possibility of disconnecting the drive,
- maximum wheel track of driving axle: 2100 mm,
- maximum height of the vehicle: 2900 mm,
- maximum distance from the rear driving axle to the front of the vehicle: 5000 mm.

Figure 3: Two-roller chassis dynamometer in the low-temperature chamber in the Environmental Protection Centre of the Institute of Motor Transport

The tests did not cover all components of the dynamometer. However, thanks to its capabilities, it could be used as a stand to cool the BEV to the set temperature and further measurements of the vehicles. Then, after reaching the set temperature, the drive of the vehicle was switched on, the heating temperature was determined, and thereafter the temperature was recorded via thermocouples.

The studies took into consideration the impact of varied air supply settings in different test objects. For that reason, the automatic air conditioning – which was the equipment of each test object – was set to “auto”. The heating performance was then optimal according to the assumptions of the vehicle’s manufacturer. The air supply, in turn, was directed in such a way that there was no direct flow of the air on any of the thermocouples.

A total of four thermocouples were used for the study. Their attachment was at chest height. Located at a distance of approx. 10–15 cm from the backrest. The position of the driver’s seat was adapted to one driver to avoid different seat settings and as a result measurement errors. The thermocouples used for the study were characterized by the following parameters:

- Probe type: PT100
- Probe diameter: 5mm
- Probe length: 5cm

- Material: Stainless steel
- Cable length: 3m

Figure 4: Thermocouples used during own tests

4 Test objects

The heat pump in the vehicle uses ambient heat (air temperature). Using an air conditioning compressor, the cooling agent is compressed, whereby its temperature increases. The use of heat pumps in electric vehicles allows for saving up to 50% of the energy needed to heat the interior. In terms of the mentioned attempts to save electricity, it should therefore be a better solution than the standard system. Owing to free ambient heat, the electric heater is significantly relieved. Depending on the driving cycle, in winter conditions the range of the vehicle can be extended from 10 to 30%. There are currently no works undertaken on the use of such solutions in conventional combustion vehicles [19].

To test the advantages of this solution, the authors of the paper decided to use two vehicles for research. They were BEVs (one smaller and one larger). BEVs were equipped with a heat pump. This way it was possible to check the differences in how they worked. However, the

Table 1: Chosen technical parameters of the tested cars

	Car 1 BEV	Car 2 BEV
Type of power		
Length/width	4087/1945 mm	4762/1884 mm
Type of heating	Heat pump	Heat pump
Battery capacity	40 kWh	80 kWh
Engine displacement	–	–

Heat pump

- 1 External condenser / evaporator
- 2 Electrical compressor
- 3 Accumulator
- 4 Inner condenser
- 5 Cockpit evaporator
- 6 Orifice tubes
- 7 Automatic air conditioning ECU
- 8 Heat pump ECU
- 9 Air conditioning fan
- 10, 11 Electrovalves

Air conditioning mode

Heating mode

Figure 5: Operation chart of a heat pump in an electric car [20]

tests did not take place only at positive ambient temperatures. They were performed at temperatures of approx. -10°C , approx. -5°C and approx. $+5^{\circ}\text{C}$. This allowed for checking the efficiency of the heating system of the compartment in the electric vehicle.

5 Test results

The tests were performed in a direct manner, i.e.:

- measurements were made using the same measurement method,
- measurements were made using the same measuring tool,
- measurements were made by the same observatory (measuring specialist),
- measurements were made in the same place,
- measurements were made in the same ambient conditions (pressure, humidity, light),
- measurements were repeated at short intervals [21–23]

During direct tests, a systematic error has a device error value ($p=\pm 0,15^{\circ}\text{C}$).

The first series of tests was carried out at ambient temperature of -10°C . The interior of the vehicle had the same temperature as the surroundings before the start of the tests. The interior temperature setting was 27°C . According to the averaged series of measurements, the maximum value achieved by vehicle 1 (Figure 6) was 21.16°C and for

Figure 6: The process of heating the interior in car 1 for air-conditioning setting of $+27^{\circ}\text{C}$ and ambient temperature of -10°C

Figure 7: The process of heating the interior in car 2 for air-conditioning setting of $+27^{\circ}\text{C}$ and ambient temperature of -10°C

vehicle 2 (Figure 7) 27.97°C . Though vehicle 1 did not reach the set temperature during the test (1200 seconds), a linear temperature increase is noticeable in both cases. Vehicle 2 was equipped with a more efficient heating system of a greater power.

In the test at an ambient temperature of -10°C and an air-conditioning setting of 19°C , it turned out that both vehicles did not reach the set temperature. In the case of vehicle 1 (Figure 8), it was 11.98°C and for vehicle 2 (Figure 9)

Figure 8: The process of heating the interior in car 1 for air-conditioning setting of $+19^{\circ}\text{C}$ and ambient temperature of -10°C

Figure 9: The process of heating the interior in car 2 for air-conditioning setting of $+19^{\circ}\text{C}$ and ambient temperature of -10°C

Figure 10: The process of heating the interior in car 1 for air-conditioning setting of $+27^{\circ}\text{C}$ and ambient temperature of -5°C

it was 17.63°C . The difference is significant for vehicle 1. Ambient temperature of -10°C proved to be significant in interior heating efficiency for a less efficient heat pump system.

The next measuring series took place at ambient temperature of -5°C . Vehicle 1 (Figure 10) with air-conditioning setting at 27°C achieved a maximum of 22.27°C . In turn, vehicle 2 (Figure 11) met its target and even exceeded it by warming up the driver's wheel space to 28.02°C . Better results were achieved for ambient temperature of -5°C and

Figure 11: The process of heating the interior in car 2 for air-conditioning setting of $+27^{\circ}\text{C}$ and ambient temperature of -5°C

Figure 12: The process of heating the interior in car 1 for air-conditioning setting of $+19^{\circ}\text{C}$ and ambient temperature of -5°C

Figure 13: The process of heating the interior in car 2 for air-conditioning setting of $+19^{\circ}\text{C}$ and ambient temperature of -5°C

air-conditioning setting at 19°C . In the case of vehicle 1 (Figure 12), the temperature assumption was almost met. The maximum reading was 18.12°C . In the case of vehicle 2 (Figure 13), it was 17.56°C .

The last of the series of measurements assumed a test at an ambient temperature of $+5^{\circ}\text{C}$. In those conditions and with an air conditioning setting of 27°C , it turned out that both cars achieved the goal without major problems. For vehicle 1 (Figure 14) it was 27.71°C and for vehicle 2 (Figure 15)

Figure 14: The process of heating the interior in car 1 for air-conditioning setting of $+27^{\circ}\text{C}$ and ambient temperature of $+5^{\circ}\text{C}$

Figure 15: The process of heating the interior in car 2 for air-conditioning setting of $+27^{\circ}\text{C}$ and ambient temperature of $+5^{\circ}\text{C}$

Figure 16: The process of heating the interior in car 1 for air-conditioning setting of $+19^{\circ}\text{C}$ and ambient temperature of $+5^{\circ}\text{C}$

as much as 33.75°C . However, with the air conditioning setting at 19°C , vehicle 1 (Figure 16) almost reached its set point – 18.18°C , whereas vehicle 2 (Figure 17) exceeded it, reaching 21.88°C .

Figure 17: The process of heating the interior in car 2 for air-conditioning setting of $+19^{\circ}\text{C}$ and ambient temperature of $+5^{\circ}\text{C}$

6 Discussion

The empirical research conducted by the authors of the paper focused primarily on the heating time of the interior of electric vehicles at low ambient temperatures. This type of research is extremely important because it shows the problem of using electric cars in a climate where there are large temperature differences, including cold winters. The research clearly showed that among the examined objects, only one had no major problem with heating the interior. The second test object either barely reached or did not reach the set temperatures inside. It is worth paying attention to the differences in the heating time of the research object that meets the requirements for the second research object. The best example is a test at an ambient temperature of $+5^{\circ}\text{C}$. In this case, vehicle 1 reached the set temperature (comparison for the sensor at the driver's seat) 366 seconds after the start of the measurement, and in the second only after 1104 seconds. Thus, it is 286.1% more than in the case of the reference car.

Vehicle 1 reached the set temperatures in four tests, only one of which was the setting of $+19^{\circ}\text{C}$ inside. Vehicle 2 has only reached the set temperature on one probe. The results are presented in Table 2.

Table 2: Percentage difference between expected and achieved temperature

	Settings	Car 1	Car 2
Probe 1 (−10°C)	+27°C	103,59%	78,37%
Probe 2 (−10°C)	+19°C	92,78%	63,05%
Probe 3 (−5°C)	+27°C	103,77%	82,48%
Probe 4 (−5°C)	+19°C	92,67%	95,37%
Probe 5 (+5°C)	+27°C	125,00%	102,63%
Probe 6 (+5°C)	+19°C	115,16%	95,68%

7 Conclusions

Heating electric vehicles poses a problem, especially at negative ambient temperatures. The following conclusions can be drawn from the studies:

- the power of the heat pump is of great importance. The higher it is, the easier it is to reach the set temperature,
- vehicle 1 with a lesser pump and engine power had significant problems in achieving the set temperatures at negative ambient temperatures,
- low ambient temperatures pose a problem for electric vehicles (especially smaller ones) as regards their heating systems. It is necessary to use more efficient systems that must not be too energy-consuming, as this will affect the range of the electric vehicle,
- in both vehicles, “stronger” heating of the driver can be observed compared to the other areas of the vehicle tested, which may be due to the greater driver’s comfort intentionally set by the automotive manufacturers – setting a higher portion of air injection in the direction of the driver,
- both vehicles had virtually no problems heating the interior to the set temperatures at a positive ambient temperature.

The studies carried out are a prelude to broader research. In this measuring part, the vehicle did not move on the rollers of the chassis dynamometer, in the low-temperature chamber. Therefore, the results do not take into account the increase of temperature in the passenger compartment resulting from the battery pack heating up during the load on the traction motor. The authors are conducting further research elaborating on the issue of “heating the interior of an electric vehicle” in different weather conditions and vehicle dynamics.

Summarizing, with reference to the aforementioned search for saving electric energy of a vehicle, one of the candidates for savings is the heating system. It turns out

that there is not much to save from because heating is not efficient enough anyway.

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