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Cabin heating of electric buses

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The thermal balance of vehicle cabins when only an internal combustion engine was used was an insignificant element of the vehicle design. The excess thermal energy on board did not require energy saving. Only the cold start was slightly problematic. However, it could still use a combustion heater that quickly warmed up the cabin. In purely electric cars, each use of electricity stored in the battery shortens the vehicle's range. Three types of heating are used in this case: a) an electric air heater; b) an electric heater for the liquid cooling the drive components; c) a heat pump receiving heat from the drive components, also temporarily supported by an electric air or liquid heater. The use of a heat pump is the most promising and is also used in cheap city cars (e.g. Renault ZOE). The source of thermal energy for a heat pump is: a) vehicle drive engine(s); b) AC/DC converters – charger, DC/DC – charger, DC/AC – motor inverter; c) battery. In cheaper vehicles, air cooling is partially used; currently, a mixture of antifreeze fluids is used. The article presents a calculation example for a city bus cabin.

Key words: *electrical bus, bus cabin heating, bus road test, vehicle heating systems, heat pump*

1. Introduction

People's feelings of thermal comfort are entirely subjective. Firstly, it depends on temperature, humidity, lighting, noise, and air speed. Other influencing factors. Other influencing factors include individual characteristics such as emotional state, health, previous experiences, age, and gender.

The interest in vehicle air conditioning systems stems from the fact that people spend more and more time in vehicles. According to the source [1], this is 9 hours and 35 minutes per week in their cars. Unfortunately, no information on the average time a passenger spends on a city bus was found in the literature.

2. State of the art

There are many mathematical models for calculating thermal comfort in passenger car cabins. There are only a few publications on city buses [3, 11].

Pala and Oz in 2015 developed mathematical models of bus air conditioning by calibrating these models based on experimental data [5]. Velt and Daanen in 2017 dealt with electric buses in relation to their energy efficiency during operation of air conditioning systems. They assumed the maximization of driving range on one battery charge at a cabin temperature of 22.5°C to 20.9°C [8].

Scurtu and Jurco in 2019: modelled air flows in the bus cabin with the possibility of using air guides to improve thermal comfort [8]. More common are scientific articles on energy consumption in passenger cars [4, 6]. Pielecha [6] writes in 2020 that there are two control strategies for regenerative braking: charging priority and heating priority. Mamala [4] has written that limiting the speed in cities to 30 km/h reduces the number of accidents but increases the specific energy consumption. The minimum specific energy consumption is in the speed range from 30 to 45 km/h.

Vehicle structures allow engineers to create conditions that are beneficial for traveling people only to a certain extent. There are the following limitations:

- the vehicle structure must meet safety requirements – resistance to operational loads and crash tests, which limits the use of materials and the size of window openings
- the cabin must be ergonomic
- the vehicle must not exceed the recognized environmental preservation standard.

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In a city bus, the most difficult phenomena to model are the air exchange when opening multiple doors and changing the number of passengers and their position in the cabin. In this work, a very simplified heat exchange model based on basic criteria numbers from thermodynamics was adopted. The object of the research was an electric city bus, the technical data of which are presented in the publication [7].

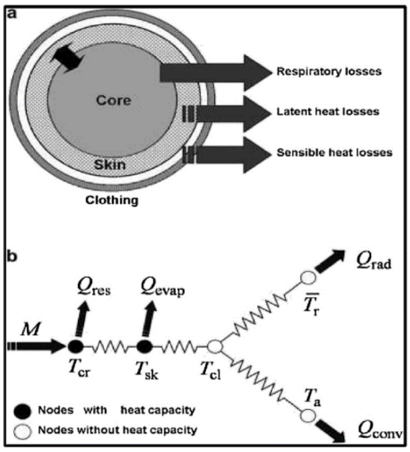

Fig. 1. Model of heat exchange between human body and environment [4]

People sitting in a bus are a source of heat. It is assumed that a sitting person emits a heat flux per unit area of about 58 W/m^2. A standing person emits 70 W/m^2. The model of heat exchange with the environment is presented in Fig. 1.

In passenger cars designed especially for short city trips, the fuzzy logic cabin heating strategy (FLC) can, according to the author [5], increase the range by up to 14%. FLC regulates the power of the layer heater, which is dependent on the battery state and current, as well as the coolant and cabin temperature. So there is a priority for charging and not heating. In buses, due to the variable number of passengers in the cabin, the thermal inertia changes. The advantage of the bus operation method is almost uninterrupted driving (no cooling cycles while standing for a long time) and the possibility of heating from the electrical network before starting the trip. Due to their utility features, city buses often have an air conditioning system placed on the roof, and numerous cabin ventilation ducts distribute heated or cooled air inside the cabin. Such a construction is shown in Fig. 2.

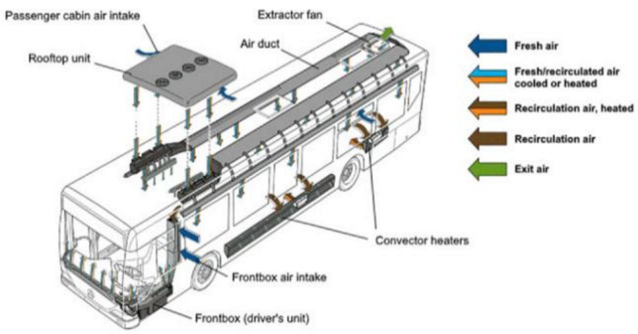

Fig. 2. Air conditioning system of a city bus [11]

This drawing shows traditional electric heaters (electric resistance) placed in the wall halfway along the body and under the rear seats. In the case of electric bus drive, electric heaters are used for limited operating time only at very low ambient temperatures.

2.1. Thermal comfort conditions in the vehicle

People's perception of heat or cold is subjective and include individual characteristics such as: emotional state, health, previous experiences, age, and gender.

For technical calculations, average temperatures around the passenger must be assumed. The air flow in the bus cabin, where there are many obstacles, is uneven. Hence, passengers standing in different places will experience thermal comfort differently.

The cabin is cooled more due to the opening of the doors and greater heat loss through the door windows. The purpose of the calculations is to determine the air inlet temperature to the cabin. A large part of the heating air circulates in recirculation, and a slightly smaller amount is taken from the environment and discharged to the environment. In the work [11], optimization calculations were performed for 7 passengers in different parts of the cabin. The heating air temperature calculated in computer simulations is 31ºC.

2.2. Calculations of the heat balance of the bus cabin

In the publication, the winter operating conditions of a heat pump heating system are discussed. The primary heat source is the waste heat of the bus drive system. The air is heated in the pump evaporator and distributed in the cabin through ventilation ducts. The evaporator draws heat mainly from the cooling systems: battery, inverter, traction motor.

To assess the heat demand, it is necessary to calculate the heat outflow to the environment during driving, the heat loss through air exchange when opening the doors at bus stops and the heat inflow from passengers.

3. Bus thermal balance

3.1. Load of the powertrain and heat sources

Heat flows away from the body to the environment through the walls and insulated roof, often made of composite, windows and chassis. There is practically no heat exchange through the rear wall of the body.

Sources of waste heat that can be used to heat the cabin. While driving, many machines and electrical devices require heat dissipation for their stable operation at proper working temperatures. These components are primarily:

- battery
- electric drive motor
- inverter.

The heat flux dissipated from these devices is a function of the power needed to drive the bus and power its accessories. This power is usually tested in real city driving conditions or simulated tests. Such tests for city transport are SORT (Standardized On Road Test) developed by the "Union Internationale des Transport Publics" [10].

The test speed profiles are shown in Fig. 3a and Fig. 3b.

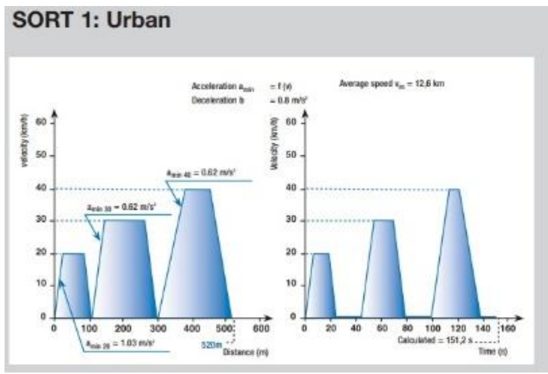

Fig. 3a. SORT urban test speed profile [7]

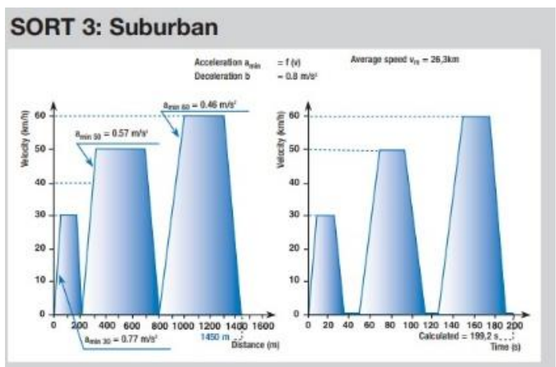

Fig. 3b. SORT suburban test speed profile [7]

However, the actual load of the drive system resulting from city driving usually has greater variability over time. Such actual loads recorded during the driving of a public transport bus in Lublin are shown in Fig. 4.

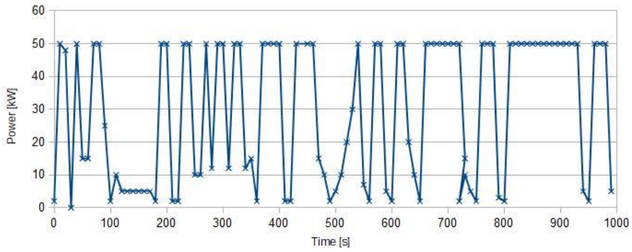

Fig. 4. Instantaneous power values at the battery terminals while driving a city bus

3.2. Battery cooling

The battery thermal balance is shown by equation (1)

$$C_{Li}\frac{dT_c}{dt}=Q_c+Q_s-Q_B \tag{1}$$

where: C_{li} – thermal capacity of the battery, T_c – battery temperature, Q_c – heat flux resulting from current flow, Q_s – entropy change, Q_B – heat exchange of the battery with the environment.

The generation of heat related to current flow depends on the internal resistance of the battery. Joule's law can be used to describe this phenomenon, written as equation (1)

$$Q_c = I^2R \tag{2}$$

where: I – current, R – internal resistance.

Heat generation is related to the change in entropy described by formula (3)

$$Q_s = -T_c\Delta S\frac{I}{F} \tag{3}$$

where: ΔS – entropy change in the battery, F – Faraday's constant.

Heat dissipation to the environment is described by formula (4)

$$Q_B=Ak(T_c-T_{amb}) \tag{4}$$

where: A – heat exchange surface, k – heat transfer coefficient through the battery casing, T_{amb} – battery coolant temperature or ambient temperature.

Due to the large variability of power at the battery terminals over time (Fig. 4), the share of heat accumulated in the battery mass after it has been heated up is negligible. All the heat generated results from the profile of electric power flow is proportional to the current flow at a constant voltage. The presented graphs (Fig. 4) show that the peak power drawn from the battery is 50 kW, but for longer periods, the power is much lower. Therefore, the heat flows discharged from the battery, inverter and traction motor can be used to heat the cabin in the quantities given in Table 1. For estimated calculations, the efficiency of heat sources was assumed.

To calculate the amount of heat generated in the battery more precisely, it is necessary to know the internal resistance of a single cell and the configuration of the cell connection, e.g. 0.6 mΩ/cell with a voltage of 3.7 V. With these data (velocity profile from Fig. 4), the course of the heat flux generated in the battery as a function of time was calculated using formula (2) – Fig. 5.

Table 1. Estimation of heat flows for cabin heating

Device	Average power supplied [kW]	Efficiency of the unit	Heat flow of the device cooling [kW]
battery	37	0.98	0.74
inverter	34	0.90	3.4
drive motor	30	0.85	4.5

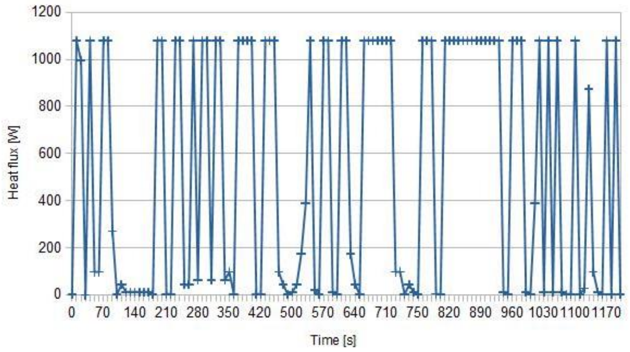

Fig. 5. Heat flux generated in the battery during bus travel according to the speed profile from Fig. 4

This flow flows to the battery cooling liquid in the radiator of the shape shown in Fig. 6.

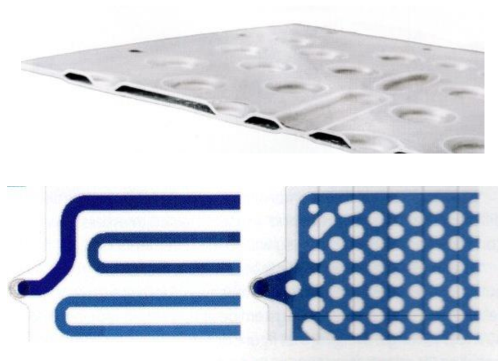

Fig. 6. Shapes of cooling plates and the course of channels made in them [11]

The fact that only one wall of the battery cell is in contact with the cooling plate means that this cooling is not very effective and some of the heat escapes to the environment and not to the cooling liquid. Only part of the heat generated during battery load can be used to heat the cabin.

3.3. Motor cooling

Motors in buses are cooled from the outside by a stream of air from a fan. This method is not effective and leads to high temperatures, especially of the rotor windings, as shown in Fig. 7.

In passenger cars, a liquid cooling circuit of the engine and inverter is used with channels in both the rotor and the stator. This method of heat collection is illustrated in Fig. 8.

A significant amount of heat then passes to the coolant. It can therefore be assumed that all of the heat losses of these components can be used to heat the cabin.

Fig. 7. Temperature inside the bus traction engine without an internal liquid cooling circuit [2]

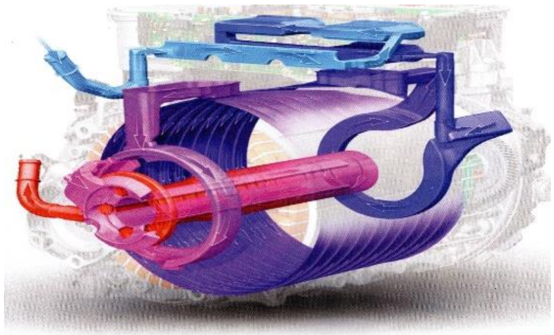

Fig. 8. Channels inside a passenger car traction engine [2]

3.4. Heat removal from the cabin

Heat flows out of the cabin in two ways

- by air exchange during cabin ventilation and opening doors at bus stops
- by heat exchange through the walls of the bus body.

Due to the adopted standards of air supplied to vehicle cabins for passengers in the amount of approximately 30 m^3 for one person during 1 hour, the ventilation air flow is proportional to the number of passengers.

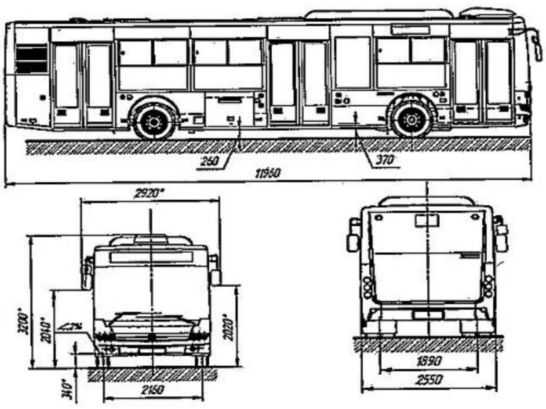

Fig. 9. City bus technical data of the sample bus network voltage 500 V; battery 119 cells of 4.2 V, R = 2.28 Ω; inverter; traction motor 170 kW (continuous power) [7]

Heat flow from the body to the environment takes place primarily through the side walls, front wall and roof. The chassis and rear wall can be omitted due to the low air flow velocity and small heat exchange surface. Heat flow calculations were performed on the example of a city bus (Fig. 9).

The air flows that remove heat from the external walls of the bus, including the side walls, roof and front wall, were taken into account, omitting the rear wall and chassis. The wall insulation is made of a 50 mm layer of polyvinyl chloride. Such insulation results in very low thermal transmittance of the walls, especially when compared to the transmittance of windows and doors (see Table 2). For this reason, manufacturers use multi-layered glass. Between the glass layers, there is a PVB (poly-vinyl-butyral) film with a thickness of 0.76 mm.

Table 2. Results of heat loss calculations through the bus walls under the following conditions: inside temperature 20°C, outside temperature 0°C, different driving speeds

The speed of air flowing over the side walls [km/h]	Insulated side walls and roof area of the body [m^2]	Area of glazed openings on the sides of the body [m^2]	Heat transfer coefficie nt through walls [W/m^2K]	Heat transfer coefficient through glass panes [W/m^2K]	Heat dissipation flow [W]
10	75.13	21.38	0.057	40.993	20190
20			0.057	41.018	20202
30			0.057	41.022	20204
40			0.057	41.024	20205

The model of heat exchange with the environment uses the Reynolds, Prandtl and Nusselt criteria numbers.

Table 3. Results of heat loss calculations through the bus walls under the following conditions: inside temperature 20°C, variable outside temperature, driving speed 20 km/h

Outside temperature [C]	Heat dissipation flow [W]
–5	25,252
0	20,202
5	15,151
10	10,101

The heat flux needed to heat the cabin at a temperature lower than –5°Cwould be even greater. In the literature [3], the heating power at –10°Cis mentioned as 40 kW.

3.5. Linde cycle

The Linde heating cycle is shown in Fig. 10. An 8°C temperature difference was assumed between the temperature of the fluid used in the evaporator to cool the drive components and the temperature of the refrigerant (R1234YF).

It is implemented by a heat pump operating in the temperature range resulting from the external and internal conditions of the vehicle. In the considered example, the evaporation temperature is –13ºC and condensation 20ºC. The Linde cycle shown in the graph indicates the required compressor compression at the level of 3.35. The heat that can be used is delta s·T = (1830 – 1100)·295 = 730 J/kgK·295 K = 215,350 kJ/kg. To obtain a heat flux of 25,252 W. The flow rate of the refrigerant in the system should be 25,252/215,350 = 0.117 kg/s.

The five main parameters collected from literature papers that are interesting to study their variation effect on the heat pump performance of battery electric bus are: the compressor speed, the mass flow rate of the air entering the condenser, the mass flow rate of the air entering the evaporator, the recirculation rate, and the flow effective area of the expansion valve.

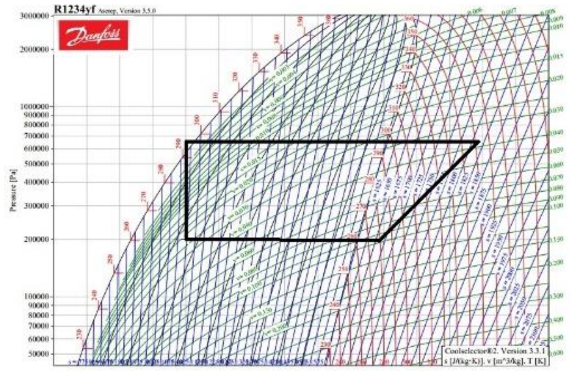

Fig. 10. Linde cycle

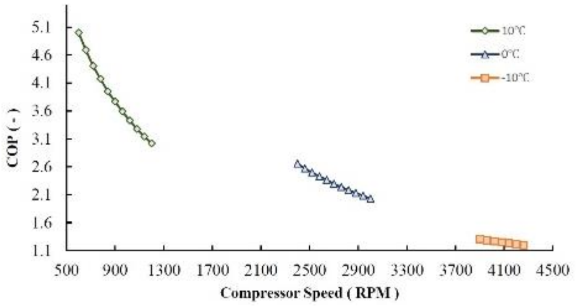

Fig. 11. Change of COP coefficient as a response to the change of external conditions [5]

If the outside temperature decreases, the compressor must increase its performance. Such changes result in a decrease in the COP coefficient, as shown in Fig. 11.

To ensure low energy consumption, an electric bus must be equipped with a complex air conditioning and heating system. Its structure is shown in Fig. 12.

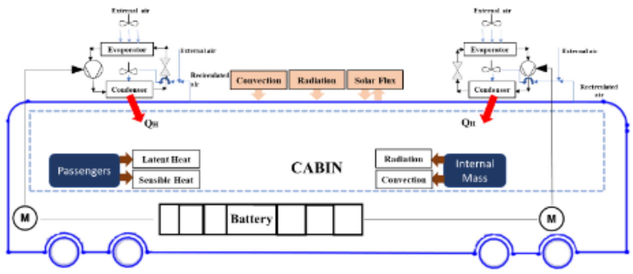

Fig. 12. HVAC – cabin configuration [5]

4. Conclusions

The most important thing is to limit heat conduction through the windows. Waste heat of machines and drive devices is sufficient to heat the cabin when using a heat pump to the temperature –5°C. Increasing the amount of energy for cabin heating is possible by replacing the air cooling of the traction motor with liquid cooling. The heat pump operates with a COP coefficient of 2.1. The compressor in the system should have an adjustable speed. The goal of calculating the heating circuit with a heat pump for the bus cabin in the form of circuit operating parameters was achieved.

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