

Using Air Walls for the Reduction of Open-Door Heat Losses in Buses

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ABSTRACT

A vital contribution for the development of an environmental friendly society is improved energy efficiency in public transport systems. Increased electrification of these systems is essential to achieve the high objectives stated. Since the operating range of an electrical vehicle is heavily influenced of the available energy, which primarily is used for propulsion and thermal passenger comfort, all heat losses in the vehicle systems must be minimized.

Especially for urban buses, the unwanted heat losses through open doors while passengers are boarding, have to be controlled. These energy fluxes are due to the large temperature gradients generated between in- and outdoor conditions and to install air-walls in the door opening areas have turned out to be a promising technical solution.

Based on air-wall technologies used for climate control in buildings, this paper presents an experimental investigation on the reduction of heat losses in the door opening of urban buses. Devices for creating the air-wall were located on top of the door opening of an articulated bus of Dresden public transport service DVB AG. Measurements of temperatures were conducted using distributed NTC-sensors.

An extensive measuring program was performed and it was found that the air walls had a significant influence on the energy exchange process. On a short door opening time the energy losses increased, while for longer door opening times major reduction on the energy losses were achieved.

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INTRODUCTION

The public transport plays in recent years an increasingly important role in the mobility activity. For example, based on the scientific forecast for the state of North Rhine-Westphalia, Germany, the specific weight of public transport in the passenger transportation will grow from 13 percent in 2010 to nearly 30 percent by 2050. [1] The electrification of a public transport is the key technology to achieve the predetermined, ambitious climate protection goals for society, to secure the mobility as a basic human need for all citizens and - because of the disproportionately expected rising cost of private car use - to ensure an affordable transportation possibility.

Effective energy and powertrain control is one of the important research directions in the area of hybrid and electric vehicles [2], [3], [4], [5], [6].

Effective thermal management of vehicle components and systems, such as a battery, vehicle interior, powertrain etc., is also an important matter for electric and hybrid vehicles, especially, during a cold weather [7], [8], [9], [10], [11], [12].

The bus auxiliary systems such as an air conditioning compressor, cooling fan(s), air compressor, steering pump, etc. use a significant part of the whole energy amount, which is needed by bus operation. Bus auxiliary systems might consume in summer more energy as vehicle traction units [13]. The heating, ventilation, air conditioning system of a bus uses a significant part of this power in order to ensure the required level of passengers' thermal comfort [14].

The air conditions in public transport are regulated by VDV-guideline 236, which covers inter alia streaming, moisture, fresh air flow rate, air purity, noise emission as well as air temperature. Thermal conditions are distinguished between cooling, ventilating and heating the passenger compartment and the driver's workplace. Regardless the driver's heat demand, in heating mode, the minimum mean cabin air temperature is set to a constant 18°C. [15] Thus, the temperature

difference between the warm cabin and the cold ambient and therefore the heat losses through cabin walls and open doors rises with lower ambient temperatures. [16] The minimal thermal requirements as well as the temperature difference [15] are shown in Figure 1.

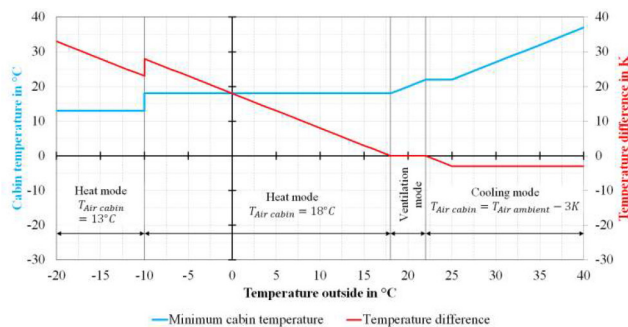


Figure 1. Temperature regulation of regular buses by VDV 236

To compensate the above mentioned heat losses and to meet the thermal requirements by VDV 236, the heat demand is typically supplied by a combination of free waste heat e.g. the combustion engine or the fuel cell and an additional heat source like heating oil fired extra heaters or electric heating exchangers [17], [18], [19], [20], [21], [22]. With progressive electrification and constant thermal requirements, the additional heat sources are taking over more heating activities. This is proven by the comparison of the heat oil consumption of comparable articulated hybrid and conventional diesel buses in Dresden shown in Figure 2.

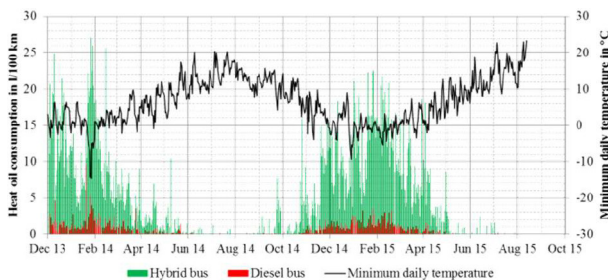


Figure 2. Daily average heat oil consumption of 10 diesel and 8 articulated serial hybrid buses on bus route 64 in Dresden [16]

As shown in [22], the total heat demand in a full electric zero-emission urban bus is covered without any free waste heat source. Therefore, the energy for the heating, ventilation and air conditioning operations comes directly from the traction battery. One way to lower the electric power demand of thermal comfort systems, in order to enhance the driving range of future plug-in hybrid and electric buses, is to reduce the heat losses.

A thermal environment in public buses differs from that in buildings where the geometrical orientation is always fixed, the occupancy rate is relatively low, doors are not opened frequently and glazed area is reduced or curtained. The high occupancy rate in public buses requires large quantities of fresh air. The geometrical orientation as well as glazed surface determines the solar load that can be reduced

by using special glazing or curtains. [23] Such units are used in box trailers of commercial vehicles to minimize cooling air losses during loading/unloading [24], [25].

The installation of air curtains and/or air walls in the door area of a bus is one of promising technical solutions to reduce heat/energy losses during vehicle stops (open doors' phase) [26], [27], [28], [29]. Figure 3 shows the example of an analysis of the effect of the door air curtain installed in bus. The air curtain blown from the upper portion of the door can significantly reduce the outflow of heat during heating - up to 15 percent, but has a little effect during cooling - approx. 1 percent. [27]

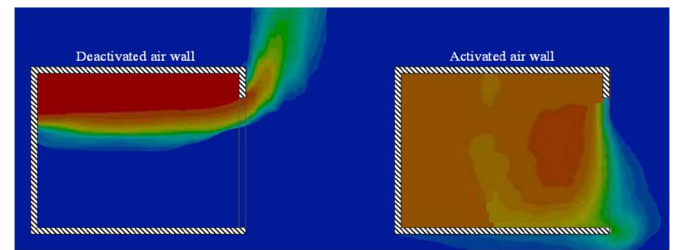


Figure 3. Effect of the air curtain, which is installed above the door in an urban bus following [27]

One of the key limiting factors that affect the distribution of air curtains in commercial vehicles is a limited space for its installation in/on the door aperture of buses and truck containers. The door opening system and passenger counting system are typically located in this place. In this regard, the air wall has the distinct advantage over the air curtain due to its modular design (the fan, the so-called air pressure linear module, which operates as a pressure reservoir, and the special nozzle can be mounted separately from each other and be connected with flexible air pipes). All above-mentioned components of air curtains are placed in a single housing, which considerably increases its dimensions. The modular design of the air wall also has a positive effect on the noise level during its operation, which is significantly lower compared with the air curtain. Another important advantage of the air wall compared to the air curtain is the lower energy consumption during operation. The air curtain reaches at the nozzle exit the discharge velocity 8-12 m/s. The flow pattern is highly turbulent and therefore mixes due to the high air amount with the ambient air. The fans, used in air curtains, are designed for the operation with high air volume at low pressure. As opposed, the air wall operates with the high pressure and high speed - with the pressure from 1000 Pa and the discharge velocity 15-30 m/s. The special nozzle with an internal wings and rectifiers forms the air and throws it with a narrow stream, a so-called free beam, far out. The nozzle gap is, depending on the configuration, only 10-18 mm. This results in a small air volume, but in a powerful air impulse, which separates the ambient air mass with the narrow flow image relatively laminar and without mixing. Only a small amount of heat energy is required to heat the narrow airflow -25% of the corresponding energy amount in case of air curtain. The electrical energy required for air stream forming in the air wall is about 40 percent lower in comparison with the air curtain system. [24]

Taking into account above-mentioned statements, authors proposed to investigate experimentally the possible usage of air walls to reduce corresponding heat losses through the opened doors in a hybrid urban bus.

PROBLEM STATEMENT

Aiming for a simple way to comprehend an air wall's action mode in an urban bus in winter, the following chapter describes the theoretical principles behind the developed measurement system, the constraints and data evaluation algorithms.

Constraints

This investigation combines a four-door articulated bus with two electric driven overhead mounted air walls in a roofed outdoor low air flow area of the DVB ground in Dresden Gruna. This ensures minimal environmental influences e.g. by solar radiation or wind. The tests were carried out in the 9th calendar week of the year 2016. Meanwhile, the ambient temperature θ_{Amb} varied from -2.6°C to 8.1°C and the average air speed varied from 8 km/h to 24 km/h. To enhance the repeatability, the passenger exchange is not taken into consideration during all tests.

Theoretical Principles

Following the heat losses tests in buildings in winter period by [30], during the door opening time at a bus stop, warm air leaks through the upper door area while cold air flows inside the cabin from below. This enthalpy exchange leads to lower cabin air temperatures. Thus, the first law of thermodynamics can describe the thermal behavior of the air inside the bus interior during opening the doors as a transient open system:

$$\frac{dU_{Air,cab}(t)}{dt} = \sum_i \frac{dQ_{Air,i}(t)}{dt} + \sum_j \frac{dH_{Air,j}(t)}{dt}. \quad (1)$$

This differential thermal balance describes the variation of air internal energy $\frac{dU_{Air,cab}(t)}{dt}$ depending on summation of all i heat flows $\frac{dQ_{Air,i}(t)}{dt}$ and all j enthalpy flows $\frac{dH_{Air,j}(t)}{dt}$. The heat flows consist of transfer heat losses through cabin walls and heat flow brought by fan heaters. Their orientations depend on the direction of decreasing temperature gradient. The above-mentioned enthalpy flows are related to the direction of the air mass flow through open doors $\dot{m}_{Air,Door}(x, t)$ (Figure 4, a).

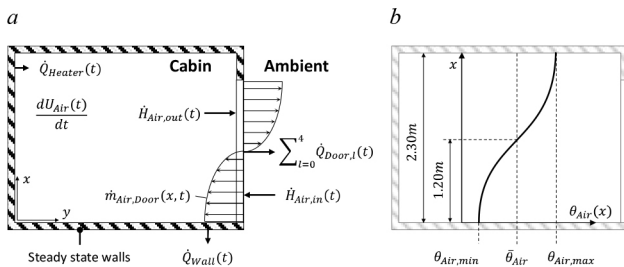


Figure 4. Thermal system description of the bus cabin a - bus as a transient open system; b - vertical temperature distribution

In combination with an assumed to be constant air heat capacity $C_{Air,cab} = m_{Air,cab} \cdot c_{Air}$ this leads to the extension of equation (1):

$$C_{Air,cab} \cdot \dot{\theta}_{Air,cab}(t) = \dot{Q}_{Heater}(t) - \dot{Q}_{Wall}(t) + \dots + \dot{H}_{Air,in}(t) - \dot{H}_{Air,out}(t). \quad (2)$$

Here, $\dot{Q}_{Heater}(t)$ summarizes the heat flow to the cabin air by up to $k = 5$ active sidewall fan heaters to heat up the cabin air:

$$\dot{Q}_{Heater}(t) = \sum_{k=1}^5 \dot{Q}_{Heater,k}(t). \quad (3)$$

With switched-off sidewall fan heaters whilst open doors period $\dot{Q}_{Heater}(t) = 0$, the variation of cabin air temperature $\frac{d\theta_{Air}(t)}{dt}$ describes the sought heat losses:

$$C_{Air,cab} \cdot \dot{\theta}_{Air,cab}(t) = -\dot{Q}_{Wall}(t) + \dots + \dot{H}_{Air,in}(t) - \dot{H}_{Air,out}(t). \quad (4)$$

Due to decreasing air temperature gradient between cabin and ambient $T_{cab}(t) > T_{amb}(t)$ and balanced air mass flow equilibrium through all l open doors:

$$\iint \dot{m}_{Air,Door,l}(x, t) dx dt = 0, \quad (5)$$

The enthalpy exchange can be summarized as to the heat flows out of the cabin:

$$\dot{H}_{Air,in}(t) - \dot{H}_{Air,out}(t) = -\sum_{l=1}^4 \dot{Q}_{Door,l}(t). \quad (6)$$

This leads to the system equation for the bus cabin whilst open doors as a transient open system:

$$C_{Air,cab} \cdot \dot{\theta}_{Air,cab}(t) = -\dot{Q}_{Wall}(t) - \sum_{l=1}^4 \dot{Q}_{Door,l}(t). \quad (7)$$

In order to describe the benefit of air wall usage the heat flow difference $\dot{Q}_{diff}$ (see (15)) between the considered test configurations (Figure 6, b) is calculated. This leads to the elimination of $\dot{Q}_{Wall}(t)$. To improve clarity the heat flows were summarized to $\dot{Q}_{Door}(t)$.

$$C_{Air,cab} \cdot \dot{\theta}_{Air,cab}(t) = -\dot{Q}_{Door}(t) \quad (8)$$

Test Procedure

Following the empirically determined vertical temperature distribution as simplified shown in Figure 4, b, seven NTC-temperature sensors measure the air temperature along the length of

the bus interior at a height of 1.20m above the bus floor. To calculate the mean cabin temperature the sensors are located in the middle of each door area and in the space between doors (Figure 5).

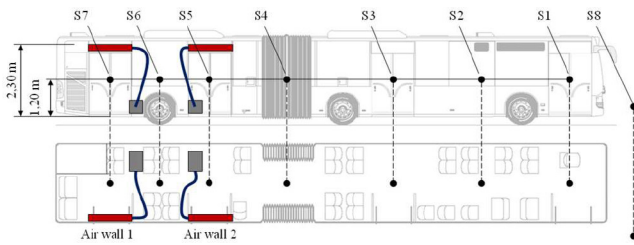


Figure 5. The test equipment arrangement in a bus interiorS... S8 - NTC-air temperature sensors;

The mean temperature of the inner air volume $T_{Mcab}(t)$ is calculated as the arithmetic mean of the horizontal allocated sensors values:

$$T_{Mcab}(t) = \frac{\sum_{m=1}^7 T_{S,m}(t)}{7} \quad (9)$$

With an 8th sensor placed outside to measure the ambient temperature $T_{amb}(t)$, this sensor arrangement reproduces the thermal behaviour of the bus interior at different thermal conditions in a proper way.

To find the most efficient air wall setup, following air wall parameters are considered in the tests: air flow direction $\alpha = (85^\circ, 90^\circ, 95^\circ)$, discharge velocity $v = (0 \frac{m}{s}, 4 \frac{m}{s}, 6 \frac{m}{s}, 8 \frac{m}{s}, 11 \frac{m}{s})$ and air temperature difference between cabin and ambient before the doors were opened $\Delta T(t_0) = (10K, 15K, 20K)$. Figure 6, a, visualizes the parameters at the air wall nozzle installation.

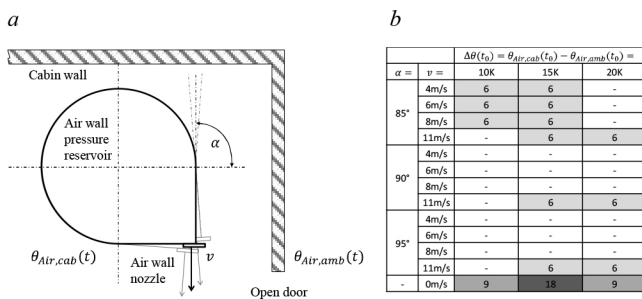


Figure 6. Considered air wall parameters a - regarded air wall parameters at the overhead mounted air walls; b - number of tests for each considered configuration

With variation of these parameters, 15 different configurations were tested. Each configuration was tested in a three times repeated sequence of two measurements with activated air wall and one reference measurement with deactivated air wall. The analysis of first six configurations with highest air flow velocity of air walls shows a significant higher benefit on the heat losses with an inward directed air wall nozzle than other configurations. Thus, configurations with $\alpha=85^\circ$ were examined more detailed. The distribution of all configurations is shown in Figure 6, b. Overall, a total amount of 108 testing procedures were performed.

Analysis of the Test Data

The test data of the temperature progression inside and outside the bus for one test day is the basis for the analysis of heat losses through the opened doors. This analysis aims to compare heat losses through the opened doors for various test configurations described in the previous chapter. Figure 7 shows following steps of the corresponding test data analysis.

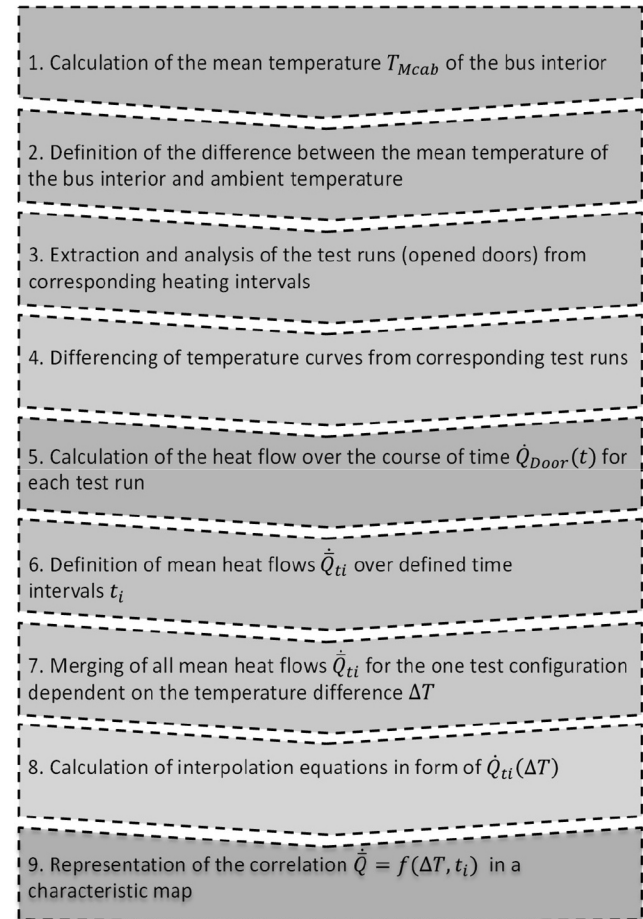


Figure 7. Analysis steps to compare heat losses through the opened doors for various test configurations

The temperature progression of each test run with opened doors is separated from the temperature progression of one test day (steps 1 - 3). The heat flow progression $\dot{Q}_{Door}(t)$ out of the bus is calculated for each test run (steps 4 - 5). Mean heat flows $\bar{Q}_{ti}$ are calculated with the heat flow data over defined time intervals t_i (step 6). By bringing the mean heat flows and the temperature differences together plots can be built, showing the results for all test runs of one test configuration (step 7). With this data the correlation between the heat flow, temperature difference and time intervals $\bar{Q} = f(\Delta T, t_i)$ can be found for each test configuration creating an interpolation equation $\bar{Q}_{ti}(\Delta T)$ for each time interval t_i (step 8). Visualization of the received correlations allows the interpretation and comparison of different test configurations (step 9).

Steps 1-6 are done for each test run. Steps 7-9 use the results of steps 1 - 6 to capture the relationships between the test configurations. Further, each step is described more detailed.