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Investigation of air exchange at the workplace of a bus driver

Abstract. The focus on thermal comfort of the driver and passengers is important not only for reasons of convenience, but also for safety reasons. This article examines the microclimate at the driver's workplace, which is formed on the basis of heat exchange between the exterior and interior of the cabin, as well as in the cabin itself. The influence of various factors and operating conditions on the microclimate in the bus interior is analysed. Attention is focused on local thermal comfort devices, since thermal comfort systems now work in an integrated manner, paying special attention to local thermal comfort. A ventilation system was modelled, which works to take fresh air into the cabin with forced removal to the outside. The air exchange at the workplace of a city bus driver with injection fans mounted in the roof of the bus, one of which works to draw fresh air into the cabin and the other to force it out, at air blowing speeds for four modes from 0.1 to 0.5 m/s, was modelled. The organisation of air exchange at the driver's workplace is proposed, which can be used in the design of thermal comfort for new models of vehicles, especially large-sized ones, such as buses

Keywords: microclimate, thermal comfort, ventilation systems

Introduction

The requirements for the microclimate of passenger transport have increased significantly. This is especially true for public transport and long-distance routes. Scientific studies by a number of researchers have shown the impact of inappropriate impact of the working environment on work fatigue and concentration, which is largely related to vehicle operation. Therefore, systems that provide an appropriate cabin climate are also important components of vehicle safety, especially during long trips when suitable climate is essential to maintain driver concentration. Not only does

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the driver's condition, degree of fatigue and reaction time depend on the cabin climate, but also the well-being of the passengers. The main reasons for this are due to the state of contamination of the cab and interior, the concentration of exhaust gases, noise, vibration, unfavourable microclimate, time spent, work intensity, etc.

Results

Analysis of comfort factors and standardsfor their assessment

Noise in the car cabin affects the driver's functional state: physiological functions are disturbed, fatigue appears due to increased energy consumption and nervous and mental stress. Permissible noise levels in vehicle cabs should be considered: for passenger taxis and buses – 50-60 dBA, for trucks and cars – 60-70 dBA. The permissible level of vibrations is in the frequency range of 1-80 Hz, beyond which discomfort is observed. Permissible levels of external noise for vehicles should not exceed 84 dBA for cars, 92 dBA for trucks and buses, and 86 dBA for motorcycles. Such studies were conducted in accordance with standardised methods for large vehicles, namely not only for city buses, but also for a two-section hybrid bus [1] and an electric bus [2]. The complexity of noise measurements is confirmed by measurements [3], where a complex consisting of 10 microphones placed at a height of 1.6 m from the floor surface along the aisle between the seats was used.

Whereas noise and vibration levels are defined and reasonable, the concept of microclimate assessment is rather subjective. The current standards that present methods for assessing thermal comfort in the vehicle interior can be found in EN ISO 14505 [4], which consists of three parts, and the American ASHRAE 55 [5]. The European standard EN ISO 7730 [6] is used to estimate thermal comfort in buildings and is based on the well-known Fanger theory [7] and the equivalent temperature model [8, 9].

More than 50 years ago, Fanger conducted a study in which subjects dressed in "standard" clothing performed "standard" activities. During the assessment, persons were exposed to different thermal conditions. According to their sensations, subjects rated the condition on the ASHRAE scale with 7 levels (-3: cold; -2: cool; -1: slightly cool; 0: neutral; 1: slightly warm; 2: warm; 3: hot). In his studies, subjects were offered to change their clothes, ambient temperature, to achieve a so-called neutral thermal state. Having analysed the system of thermoregulation and heat exchange of the human body, Fanger suggested the PMV index (Predicted Mean Vote [7]), according to the ASHRAE scale.

By introducing external physical quantities that affect heat transfer phenomena (air temperature, average radiation temperature, water vapour partial pressure and relative air velocity) and specific variables (thermal resistance of clothing, activity level, and average skin temperature) into the interrelationship of human body thermal equilibrium, the relationship between the generated and dissipated heat flux of the body is obtained. When there is an equilibrium heat balance, the heat produced by the human body is dissipated without increasing the activity of the body's thermoregulatory system [8-10]. PMV values vary from -3 to 3 on the ASHRAE scale (Fig. 1). It quantifies the average attitude of a group of subjects to comfort. This parameter is related to the PPD (Predicted Percentage of Dissatisfied) index, which represents the percentage of those who experience thermal discomfort. The value of 10% of the PPD index corresponds to the range from -0.5 to +0.5 for PMV on the Fanger scale. Even with PMV = 0, about 5% of the respondents feel uncomfortable.

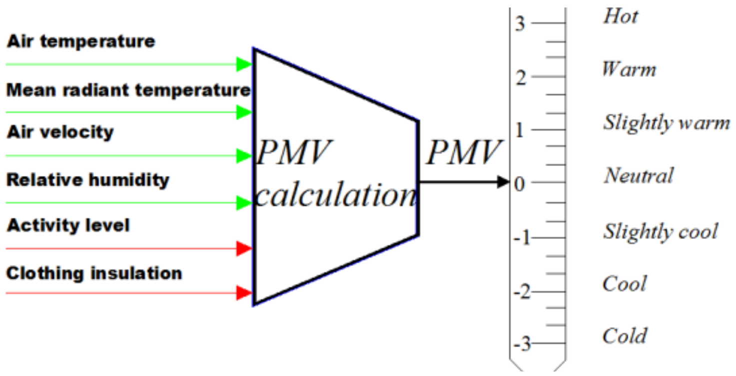


Figure 1. Fanger scale

Source: [7]

The expressions for calculating PMV are presented in [7]:

$$(PMV = (0.303e^{0.303} + 0.028)\{(M - V) - 3.05\,[5.733 - 0.007(M - V) - p_a] - 0.42[(M - V) - 58.15] - 0.0173M(5.87 - p_a) - - 0.0014M(34 - t_a) - 3.96 \times 10^{-8} f_{cl}\,[(t_{cl} + 273)^4 - - (`t_r + 273)^4] - f_{cl}\,h_c\,(t_{cl} - t_a)\},$$

where:

$$t_{el} = 35.7 - 0.0275(M - W) - I_{el}\{(M - W) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) - 58.15] - 0.0173M(5.87 - p_a) - - 0.0014M(34\ t_a)\}).$$

The indicator is determined from the following expression:

$$PPD = 100\text{-}95exp[-(0.03353PMV^4 + 0.2179PMV^2)],$$

were: M – metabolic heat intensity [W/m^2]; W – activity level [W/m^2]; t_{cl} – the temperature at the level of the garment [°C]; p_a – water vapour pressure [Pa]; t_a – air temperature [°C]; $I_{(cl)}$ is the thermal insulation of clothing [Clo]; $f_{(cl)}$ is the clothing factor [-]; $t_{(mr)}$ is the average radiation temperature [°C]; *hc* – convective heat transfer [W/m²°C].

Both ASHRAE 55 and EN ISO 7730 provide methods for evaluating the thermal environment of buildings to obtain a certain level of global comfort for occupants at a certain level of activity and clothing. ASHRAE 55 applies either the PMV-PPD method or the Standard Effective Temperature Comfort Zone (SET) method to air-conditioned spaces. It also provides an adaptive approach for determining acceptable thermal conditions in naturally ventilated rooms [4], while EN ISO 7730 proposes the PMV-PPD approach.

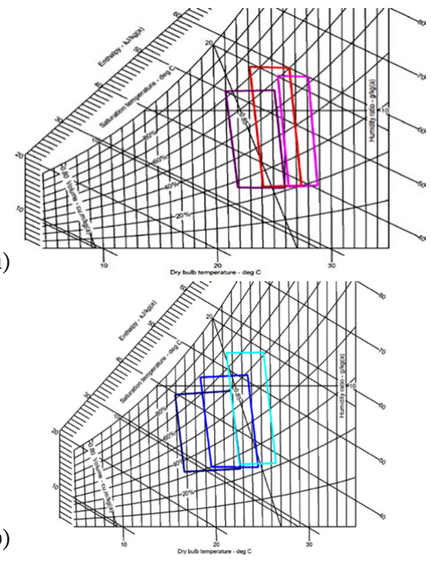
The EN ISO 14505 standard "Assessment of the thermal environment in vehicles" has three parts called: 1. Principles and methods for the assessment of thermal load; 2. Determination of equivalent temperature; 3. Assessment of thermal comfort using human occupants. In the first part of the standard there is a reference to EN ISO 7730, which suggests the use of PMV and PPD. Unfortunately, these two indices are generated, in particular, for homogeneous environments inside buildings. The second part of the standard proposes the Teq index, an equivalent temperature index. This is a local and global index proposed by Nilsson in his doctoral thesis [8, 9].

The equivalent temperature is calculated using is estimated using the same method as the operating temperature for ambient air velocities less than 0.1 m/s. It is the average air temperature and the average radiation temperature. Convective heat transfer is to be taken into consideration. For values of ambient air velocity exceeding 0.1 m/s, the equivalent temperature is expressed as a function of air temperature, average radiation temperature, air velocity and thermal resistance of clothing [11, 12]. Several equivalent temperatures can be distinguished here: directional equivalent temperature mentioned two indices are generated, in general, for homogeneous environments inside buildings.

Part 2 of the standard provides for the Teq index, whicn is equivalent temperature index. This index is both local – refers to heat transfer in the half-space in front of an infinitesimal plane and is described as a normal vector to the measurement plane at each point, determined by the magnitude and direction; omnidirectional equivalent temperature, which is around a part of the body or the whole body, measured, as a rule, with an ellipsoidal sensor; whole-body equivalent temperature, which refers to the entire human body and is a_ standardised value, as well as local equivalent. All of these equivalent temperatures can be determined using one or more hot film or ellipsoidal sensors or a heat dummy as described in EN ISO 14505/2. The equivalent temperature method using directional sensors or a heat manikin to assess thermal sensations in a vehicle has the main disadvantage that thermal sensations, primarily due to localised heat sensitivity, are assessed using clothing-independent thermal comfort charts.

The third part of EN ISO 14505 specifies a direct method for assessing thermal comfort in vehicles, the main indicator of which is the Thermal Sensation Vote (TSV) of the people surveyed. The method measures and registers people's reactions to their thermal sensations (www.researchgate.net) in the environment quantitatively, using the same scale of values as PMV. TSV takes into account both psychological and physiological factors. Research using this method requires standardized questionnaires for a controlled and representative sample. By averaging the results, an assessment is made of the specific situation under study.

In general, ISO 14505 seems to be more sensitive to warm environment that ISO 14505 is only suitable for thermally neutral situations where latent heat of evaporation is a very small part of the total heat transfer of the human body. Furthermore, when it comes to thermal comfort in the vehicle cabin, other design parameters can affect passenger experience in unpredictable ways. One of these parameters are the parameters of thermal sensation and are less sensitive to the conditions of the cold environment compared to other approaches for non-isothermal environments, such as the Berkeley model [13]. This may mean from car seats, for example, the thermal conductivity of the seat upholstery [14-16]. The effect of changes in metabolic rate and activity on the thermal comfort zone of passengers in summer and winter, calculated using Fanger models, is shown in Figures 2a and 2b, respectively [13]. The metabolic rate expresses the rate of the transformation of chemical energy into mechanical and thermal work as a result of metabolic processes in the body, usually expressed per unit area of the total body surface. In ASHRAE 55, this indicator is expressed in metric units. Metabolic rate depends on activity and fitness level.



a)

b)

Figure 2. The effect of changes in metabolic rate and activity on the thermal comfort zone

Notes: a) in summer, b) in winter

Source: [13]

When the air temperature is low, convective heat loss increases as air movement is associated with increased activity. Because of this, the thermal load on the body's evaporative cooling system is reduced, and this leads to a wider range of activity before discomfort is felt. Thus, the maximum range of activity within which a person feels comfortable is achieved by minimising the dry thermometer temperature and relative humidity while compensating with an average radiant MRT temperature that is suitable to maintain comfort. Figure 2 (a, b) shows that with an increase in metabolic rate, the thermal comfort zone shifts to the left, which leads to a decrease in the boundaries of higher and lower temperature values.

Thermal insulation in clothing and its impact on the passenger's thermal comfort zone in summer and winter according to the Fanger models are shown in Figure 3 (a, b), respectively. In cold weather, the layering of insulating clothing can help keep a person warm. At the same time, if a person is involved in a high level of physical activity, such layers can prevent heat loss. Depending on the type of clothing material, air movement and relative humidity can reduce its insulating ability. Thus, all four mechanisms The main processes of heat exchange, including evaporation, convection, radiation, and thermal conductivity, are strongly influenced by clothing (hal.archives-ouvertes.fr). Shoes can reduce heat loss/gain from the floor. Clothing also usually prevents the movement of air near the skin surface, so convective and evaporative heat transfer from the skin can be neglected. Figure 3 (a, b) shows that with an increase in the amount of clothing or the level of thermal insulation, the thermal comfort zone shifts to the left, which leads to a decrease in the boundaries of higher and lower temperature values. On the other hand, when the amount of clothing or the level of thermal insulation decreases, the thermal comfort zone shifts to the right.

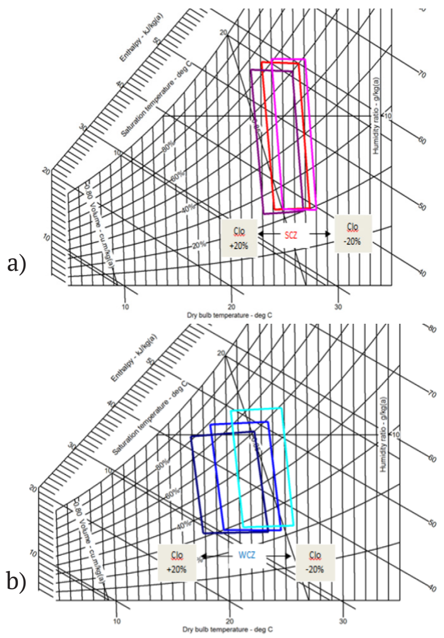


Figure 3. Effect of thermal insulation on the thermal comfort zone
Notes: a) in summer, b) in winter
Source: [13]

The sensitivity analysis associated with variations) in the air velocity in the cabin for the summer and winter passenger thermal comfort zones according to the Fanger models is shown in Figure 4 (a, b), respectively. The movement of air through the skin lowers body temperature through convective energy transfer and latent energy transfer, namely the evaporation of sweat from the skin. If the skin temperature is relatively high, the air removes some of the excess heat from the body. Thus, air velocity, especially if passengers wear light clothing, can be adjusted by modifying the fan settings to give passengers control over their local climate. Figure 3 (a, b) shows that as air speed increases, the thermal comfort zone is shifting to the right, which (doi.org) leads to an increase in the upper and lower temperature limits.

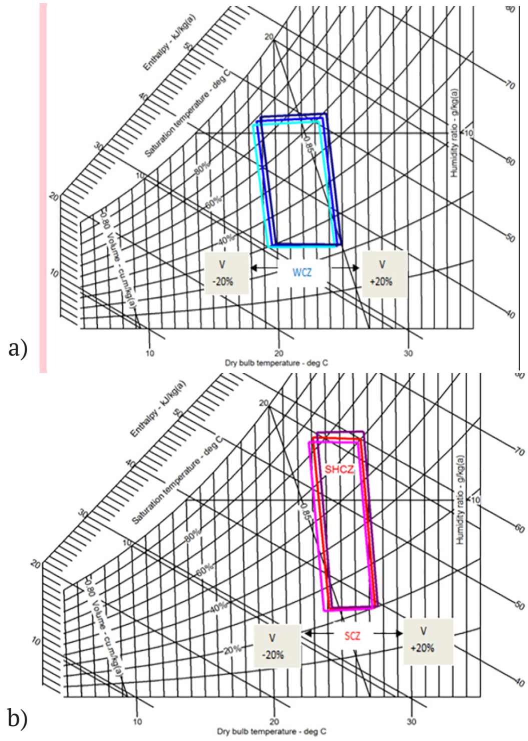


Figure 4. Influence of air velocity in the) cabin on the thermal comfort zone
Notes: a) in summer, b) in winter
Source: [13]

Methods of increasing comfort

One of the options for providing a microclimate for passengers and improving the driver's working conditions is increasing the volume of fresh air supply. At a normal ambient temperature of +8 to +26°C, the air conditioning system provides the maximum level of fresh air supply (80-100%). In such conditions, air exchange is continuous and fast. At both low and high temperatures, the air conditioning system operates in what is known as mixed air flow mode. In this mode, fresh air) is supplied to the cabin every 4-7 minutes. At the request of the passenger, the maximum volume of fresh air supplied by air conditioning systems, for example, in Mercedes-Benz Tourismo, Setra ComfortClass 500, TopClass 500 and S 531 DT double-decker buses, can be increased by 33-40% due to the additional supply of outside air [17]. For example, in Setra TopClass coaches, fresh air passes through additional roof filters of the air conditioning system built into the La Linea construction elements. As a result, air exchange in these buses occurs every 5 minutes. In the Setra S 531 DT model, exhaust air is removed on the second floor through two ventilation diffusers and through the steps on the lower floor. The lower floor of the bus is ventilated through grilles in the driver's cab and in the floor. In all city buses and low-entry buses, the doors open at bus stops to provide a regular supply of outside air.

Paper [18] analysed Influence of different supply air velocities on air distribution in the car cabin. Figure 5 presents the temperature distribution at various values of the supply air velocity. At the supply air velocity) of 2 m/s and 3 m/s, the air velocity in front of the passengers' faces will be approximately 0.1~0.2 m/s. In this case, no passenger will feel cooling and will be very hot. If the supply air velocity is 4 m/s, the airflow velocity) in front of the passengers' faces will be about 0.3 m/s. In this situation, the air velocity is good – the dryness of the face is moderate and the passengers feel cool. If the air velocity is 5 m/s, the wind sensation on the face will be too intense.

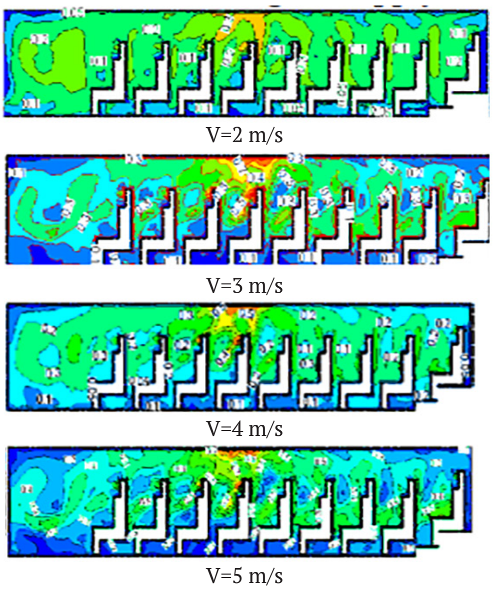


Figure 5. Effect of air velocity in the cabin on the temperature distribution in the bus cabin

Notes: a) in summer, b) in winter

Source: [19]

Simulation of air blowing and intake in the bus driver's cab

Let's consider the option of ventilating the workplace of a city bus driver with blower fans mounted in the roof of the bus. One fan works to draw fresh air into the cabin, and the other to force it out. Figure 6 shows the air inlet and outlet diagram.

Figure 7 shows the results of modelling the distribution of air masses at the bus driver's workplace at air blowing speeds of 0.1, 0.25, 0.35, and 0.5 m/s.

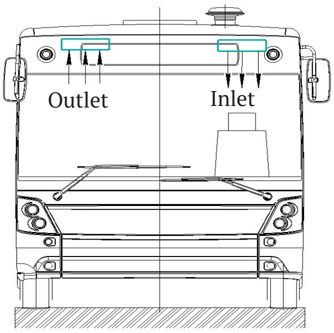


Figure 6. Scheme of air blowing and intake in the bus driver's cab

Source: developed by the authors

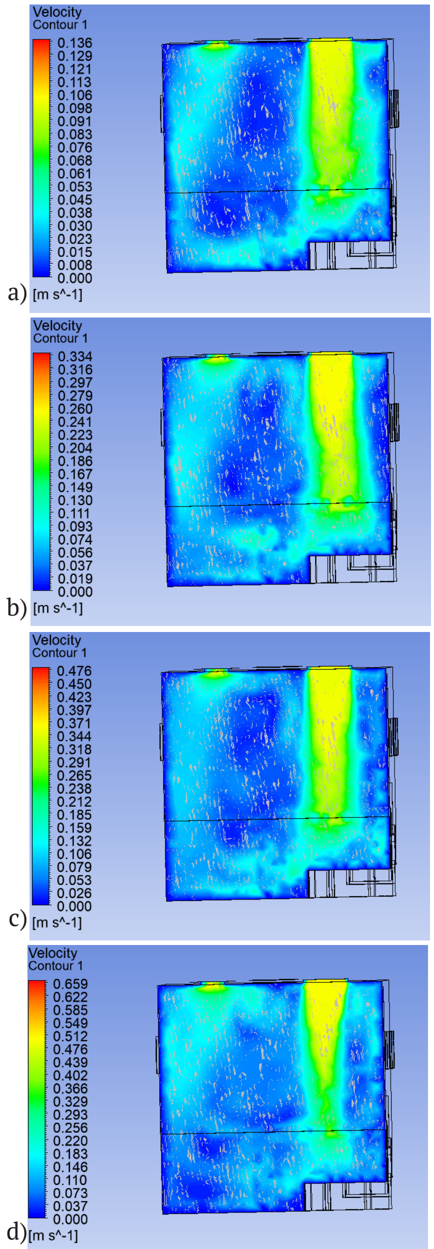


Figure 7. Distribution of air velocities at the bus driver's workplace

Notes: a) 0.1 m/s; b) 0.25 m/s; c) 0.35 m/s and d) 0.5 m/s

Source: developed by the authors

As can be seen from Figure 7a, the air blowout in the 1st mode is quite small. In the area of the driver's head, the air velocity fluctuates within 0.06-0.09 m/s, which is quite low to ensure the standard values of the ventilation system. Especially in hot weather, this air exchange may not be enough. Figure 7b illustrates that the driver's workplace in the 2nd mode of operation is better ventilated. We will have a velocity distribution in the range of 0.15-0.22 m/s, which significantly improves the ventilation of the driver's cab. At the 3rd mode (Fig. 7c) of fan operation in the driver's head area, the air velocity is 0.25-0.31 m/s, which corresponds to the standards, i.e., the ventilation works very well. In the area of the driver's legs, the air velocity drops to 0.21 m/s. When blowing with an air velocity of 0.5 m/s, which is the most intense ventilation, Figure 7d shows that at the level of the bus driver's head (doi.org) the air velocity will be (doi.org) in the range of 0.4-0.5 m/s (theses.ncl.ac.uk), and at the level of the legs and waist it will decrease to 0.25-0.3 m/s. Obviously, at the level of the head there is an excess of normalized values. From this we can conclude that the 4th maximum fan operation mode should be used for particularly hot weather.

Conclusions

We have modelled the air exchange at the workplace of a city bus driver with induction fans mounted in the roof of the bus, one of which works to draw fresh air into the cabin and the other to force it out at air blowing speeds in four modes from 0.1 to 0.5 m/s. In the first mode, the air velocity in the driver's head area ranges from 0.06 to 0.09 m/s, which is quite low to ensure the standard values of the ventilation system. The mode with the maximum supply air velocity is recommended for use only in hot weather.

In the future, it is worth investigating the organisation of air exchange in ventilated seats. For backrests with only one fan, only the suction mode should be considered, for two, one should be placed in the middle part of the backrest for suction, and the other in the lower part for discharge. Alternatively, a combined blower is possible, where it is first used in suction mode and then for longer periods of time in the discharge mode. For a cushion, in the case of a standard inflator, we can definitely recommend the suction mode for the entire time. If two inflators are considered, one should be placed in the buttocks for suction and the other in the thighs for inflation.

A suggestion for further research would be to continue the simulation by changing the environmental conditions, for example, driving in a convertible, or further in the vehicle interior, but taking into account the time of year, for example, a spring day with an ambient temperature of about +15°C, while the temperature in hot summer is +40°C. The option of simulating warm/cold air being blown through the headrest is also worthy of note. This would allow monitoring of thermal comfort in a different situation and provide other data to identify more significant differences between the modes. This could also be extended to observe the homogeneity of air distribution, which is another parameter that affects the final thermal comfort.

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Дослідження повітрообміну на робочому місці водія автобуса

Анотація. Акцент на тепловому комфорті водія і пасажирів є важливим не тільки з міркувань зручності, але і з міркувань безпеки. У статті досліджується мікроклімат на робочому місці водія, який формується на основі теплообміну як між зовнішнім і внутрішнім простором салону, так і в самому салоні. Проаналізовано вплив різних чинників та умов експлуатації на мікроклімат в салоні автобуса. Увагу зосереджено на локальних пристроях теплового комфорту, оскільки термокомфортні установки працюють тепер комплексно, приділяючи особливу увагу локальному тепловому комфорту. Проведено моделювання системи вентиляції, яка працює на забір свіжого повітря в салон з примусовим видаленням назовні. Змодельовано процес повітрообміну на робочому місці водія міського автобуса з вмонтованими в дах автобуса нагнітаючими вентиляторами, один з яких працює на забір свіжого повітря в салон, а інший на примусове видалення назовні при швидкостях видування повітря від 0,1 до 0,5 м/с для чотирьох режимів роботи вентиляторів. Запропоновано організацію повітрообміну на робочому місці водія, яка може бути застосована при проєктуванні теплового комфорту в нових моделях транспортних засобів, особливо великогабаритних, до яких належать автобуси

Ключові слова: мікроклімат салону; тепловий комфорт; система вентиляції; автобус; водій