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IMPROVEMENT OF THERMAL COMFORT IN A PASSENGER CAR BY LOCALIZED AIR DISTRIBUTION

ABSTRACT:
The thermal environment and air quality in a passenger car can affect driver's and passengers' health, performance and comfort. Due to spatial and temporal variation of state variables and boundary conditions in the vehicle cab, the heating, ventilating and air-conditioning (HVAC) does not have to be designed to provide a uniform environment, especially because of individual differences regarding to physiological and psychological response, clothing insulation, activity, air temperature and air movement preference, etc. Therefore the system should be able to generate preferred local environmental conditions, even on individual body part level.
Comfortable thermal conditions in the vehicle are easier to achieve in cold conditions than in warm conditions, therefore this paper focuses on human thermal sensation in warm ambient. Vehicle HVAC system delivers conditioned air into the cab space, and human body is cooled by convection and sweat evaporation. The heat loss from the body will mainly depend on air velocity and temperature over the individual body part. The resulting distribution of skin temperature over the body surface will dictate human thermal sensation and thermal comfort.
The aim of this paper is to provide an overview of local microclimate parameters which HVAC system should achieve in vehicle cab in warm ambient, regarding thermal sensitivity of individual parts of human body obtained from empirical data. Required conditions are prerequisite for air distribution design that would have optimized performance from the point of view of thermal comfort as well as energy consumption, in comparison with the conventional approach.

KEYWORDS:
cab, thermal comfort, thermal sensation, air distribution, air-conditioning

INTRODUCTION

Thermal environment in passenger cars differs from those in buildings and is often highly non-uniform and asymmetric, from the following reasons:

- *interior volume is small, compared with the number of persons;*
- *changing of microclimate parameters could be rapid (vehicle is changing the orientation to the sun, etc);*
- *the shape of the cab interior is complex;*
- *glazing area is large in comparison to cab surface;*
- *passengers seat near surfaces with temperatures which could be significantly higher or lower than interior air temperatures;*
- *passengers are not able to change position within the cab, and changes of body posture are limited;*
- *the air-conditioning is usually not activated when there is nobody in the car or when the engine is not running, resulting in occurrence of extreme microclimate conditions.*

Nevertheless, conditions for human thermal comfort should be the same as in buildings. Standards for thermal comfort suggest that combination of microclimatic parameters of indoor environment (air and radiant temperature, air velocity and relative humidity) and individual parameters (clothing and activity) should be within certain limits, spatially homogeneous and steady state. Vehicle HVAC system obtains desired interior environment by introducing the cooled/heated/dried air into the cab air through the system's outlets, usually placed on the instrument panel and in the front footwell region. From these reasons, obtaining both the uniform and comfortable conditions in the cab is not a simple task. Other restrictive factors will be shape and dimensions of the cab interior, demands for visibility, and other technological features regarding air distribution system. Considering the preferred microclimatic conditions under the different outdoor conditions, there are also inter- and intra-individual differences within the passengers, for example age, gender, mood *etc. Furthermore, passenger's clothing is set according to outdoor conditions. Consequently, desired local microclimatic parameters within the cab could be very different among the passengers.*

As the system control is based on the change of airflow characteristics (temperature, velocity and direction), this paper is dealing with local air temperature and velocity as controllable microclimate parameters around the head and upper body as the thermally most sensitive parts of human body. Obtaining the preferable environment in warm ambient inside the vehicle cab with proper distribution of conditioned air would lead to improvement of the efficiency of vehicle HVAC system, owing to higher comfortable operative temperature and higher air velocities and to less dependency from size and shape of the cab. In order to determine these values, it is necessary to be familiar with human thermal sensation, thermal characteristics of human body and human thermoregulatory system.

PASSENGER THERMAL SENSATION AND THERMAL COMFORT

Even in moderate outdoor conditions, vehicle passenger compartment is subjected to various heat loads, such as direct and reflected solar radiation, heat transfer through the cab walls due to the temperature difference, heat released by the passengers (sensible and latent), and heat gain from the powertrain. This can lead to the rise of the interior air and surfaces temperatures above the acceptable values, making the ambient uncomfortable, decreasing the driving performance, possibly leading to the risk of hyperthermia.

To prevent the rise of body temperature and therefore the risk of hyperthermia, it is necessary to release heat from the body or to make ambient comfortable by cooling. Both of these methods can be used in vehicles, especially in transient (cool-down) conditions. Largest part of heat loss from the body surface in warm conditions is consisted of convective heat loss and heat loss by sweat evaporation from the skin [8, 17]. These modes of heat transfer are more intense if difference between skin surface temperature and air temperature is increased and with increase of local air velocity. For that reason, local and overall thermal sensation of the human body should be the reference for determination of suitable microclimate condition in the cab generated by vehicle HVAC system.

Human senses the warmth of an environment through thermoreceptors located in the skin and body core, which send signals about thermal sensation to the brain. Thermal sensation of individual body parts is different due to different properties and different sweating rate [1, 9, 24]. Consequently, individual body parts have different sensibility for thermal sensations [24]:

- *Back, chest, and pelvis strongly influence overall thermal sensation, which closely follows the local sensation of these parts during local cooling.*
- *Head region, arms and legs have an intermediate influence on the overall thermal sensation.*
- *Hands and feet have the least impact on overall sensation.*

PREFERABLE LOCAL MICROCLIMATE CONDITIONS

Main requirements regarding preferable combination of local air velocity and temperature the system should meet are:

- *to attain and keep local skin temperature within comfort range, which will give sensation of thermal comfort,*
- *to penetrate natural airflow around the body,*
- *to avoid draught or eye irritation,*
- *to supply the breathing zone with fresh clean air.*

In other words, avoiding the discomfort is not guarantee that thermal comfort will be obtained, and vice versa. Preferable and allowed values for combination of local air/operative temperature and velocity given in this paper are collected from the overview of the relevant literature.

According to Standard ISO 7730, the local discomfort can be evaluated by the index of predicted percentage of people dissatisfied due to draught (DR). This index is applicable in steady-state moderate indoor environment for sedentary (~1 Met), thermally neutral persons dressed in normal indoor clothing, but without possibility of control over the air velocity/ temperature. Percentage of dissatisfied of 20% is stated as upper allowable limit. DR is calculated from local air temperature t_a (°C), local air velocity v_a (m/s) and turbulence intensity TU (%) [8, 12]:

$$DR = (34 - t_a)(v_a - 0.05)^{0.62}(3.14 + 0.37 v_a \cdot TU)\ \%$$

However, moderate conditions rarely occur in passenger car during the transients and DR cannot be extrapolated for elevated temperatures, therefore different models and criterions are needed.

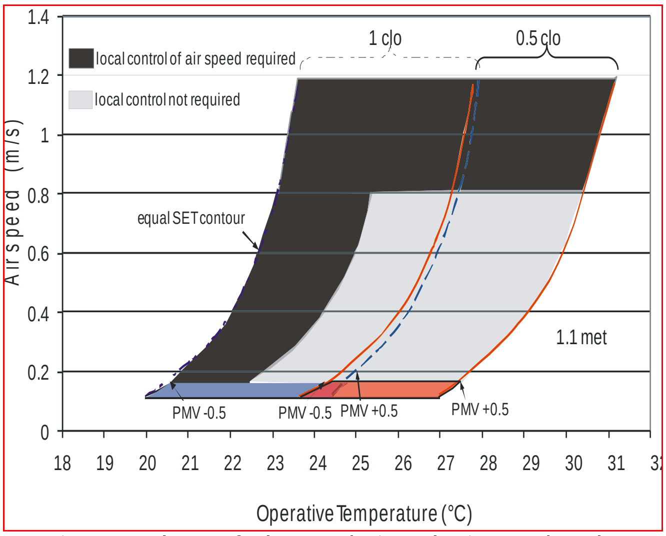

Fig. 1. Values of elevated air velocity under the increased operative temperature, with and without possibility of control, which gives Predicted Mean Vote (PMV) between -0.5 and 0.5 [5]

Standard ASHRAE 55-2009 suggests elevated air velocities up to 1.2 m/s, to increase the maximum temperature for acceptable comfort, if the air speed is under the control of exposed person. These values apply to a lightly clothed sedentary person (0.5 - 0.7 clo) with metabolic rates between 1.0 and 1.3 Met [2, 5] (Fig. 1.).

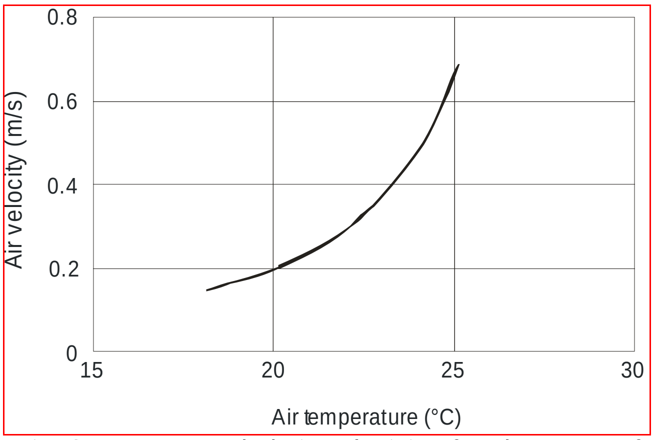

Fig. 2. Recommended air velocities for the range of air temperature inside the cab, according to the standard DIN 1946-3 [6]

Fountain et al. (1994) have performed preferred condition tests on 54 subjects in four different warm isothermal conditions [10]. Temperature of ambient air was set on 25, 26, 27 and 28°C. Subjects were requested to adjust the air velocity (up to 2 m/s), in order to make them comfortable. Localized air was distributed by desk fan, floor-mounted diffuser or desk-mounted diffuser. Regression analysis of the results gave the model of Percentage of satisfied, as function of operative temperature t_o (°C) and local air velocity v (m/s) [10]:

$$PS = 1.13t_o^{0.5} - 0.24t_o + 2.7v^{0.5} - 0.99v \text{ , \%}$$

Arens et al. (1998) have performed the experiments with 119 subjects regarding the preferred air velocities and air temperatures in ambient temperatures from 24 to 31°C, and air velocities within the range of 0.05 to 1.04 m/s. The results showed that in this case neutral thermal sensation, neutral thermal preference and neutral air movement preference followed each other closely, which can be concluded from the respective regression lines [3]:

- $v_a = 0.107t_a - 2.1875$, *m/s, for neutral thermal sensation,*
- $v_a = 0.1025t_a - 2.0912$, *m/s, for neutral thermal preference, and*
- $v_a = 0.1126t_a - 2.3587$, *m/s, for neutral air movement preference.*

The same authors cited the results of Kubo et al., where the influence of air relative humidity (RH) under the similar conditions is given. It was found that with increase of relative humidity from 30% to 80% leads to slightly increase in preferable air velocity.

The preferred air velocities obtained from experiments conducted by Tanabe and Kimura are also given in this paper (Table 1) [3]. Table 2 shows the values from experiments of study of the preferred velocities at the elevated temperatures performed by Toftum [22].

Table 1. Values obtained by Tanabe and Kimura, for horizontal, isothermal air flow and RH= 50% [3]

Air temperature, °C	Air velocity, m/s
28	1
29.6	1.2
31.3	1.6

Table 2. Values obtained by Toftum [22]

Air temperature, °C	Air velocity, m/s
26	0.2
28	0.6
29	1.4

All above-mentioned results from experimental determination of preferred air velocity and temperatures, for isothermal airflow are summarized in the graph on Fig. 3.

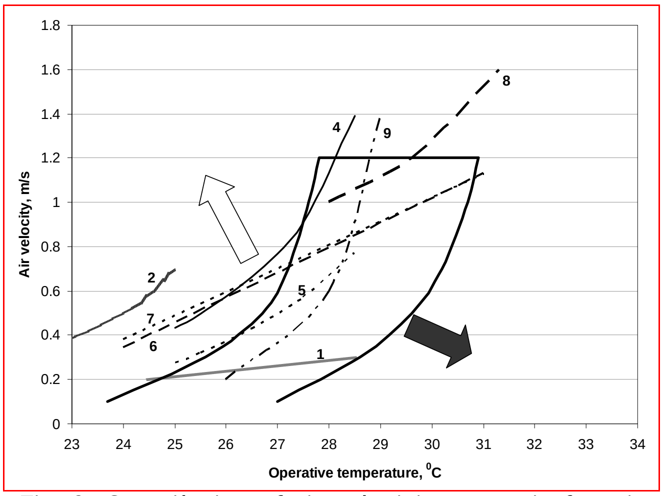

Fig. 3. Compilation of air velocities range in function of operative temperature, for sedentary subject with clothing insulation in range of 0.35 - 0.5 Clo (0.73 Clo with chair) and metabolic activity in range of 1 - 1.2 Met:

1 - DR = 20% of dissatisfied (ISO 7730) calculated for TI = 50%; 2 - Air velocity according to DIN 1946-3 [6]; 3 - Limits for air velocity under control of exposed person for PMV = ±0.5, 1.1 Met and 0.5 Clo (ASHRAE 55-2009) [5]; 4 - PS = 100% by Fountain et al. [10]; 5 - PS = 80% by Fountain et al. [10]; 6 - Regression line for neutral air movement preference by Arens et al. [3]; 7 - Regression line for neutral thermal sensation by Arens et al. [3]; 8 - Preferred velocities by Tanabe and Kimura [3]; 9 - Preferred velocities by Toftum [22]

It could be noted that area recommended by the recent version of Standard ASHRAE 55 gives good guide for setting the local ambient conditions in warm ambient in the area of head and upper body. Limits for discomfort due draught proposed by Standard ISO 7730 is obviously too strict, in comparison with empirical values. Therefore, this criterion is not suitable for vehicle interior in warm conditions. Grey arrow shows the region of conditions of possible complaints due to insufficient air movement and/or high air temperature - corresponding to warm sensation. On the other side, values recommended by DIN 1946-3 are almost in zone that corresponds to the risk of draught due to too cold air stream (white arrow), but these values are stated for lower temperatures (up to 25°C). According to some authors, there is possible to further increase the air velocity under some conditions [3, 22, 25].

In the case of non-isothermal conditions, when there is need to cool interior of the car under hot outdoor conditions, the only way to lower the temperature and humidity of air is the use of air-conditioner. In this case, airflow that is colder than surrounding air will be passing over the body surface. The experiments performed in non-isothermal conditions showed that preferable velocity also increases with increase of surrounding air temperature and/or airflow temperature. On the other hand, the increase in difference between the temperatures of ambient air and (colder) local airflow leads to preference for lower air velocities [11, 25].

CONCLUSION

An overview of preferable microclimate conditions in warm indoor ambient is given in this paper. The data presented here are based on numerous experiments with human subjects under different ambient conditions. Focus was on combination of air temperature and local velocity of airflow in the region of head and upper body, as thermally most sensitive parts of human body.

The results showed that values proposed by standards for thermal comfort, generally used for assessment of indoor thermal environment, could be too restrictive. Preferable conditions are shifted towards higher air velocities. Furthermore, microclimate parameters that will provide thermal balance of the passenger's body with the surrounding (cab interior) and thermal comfort could not be presented by single value, but by the range of values. The chosen combination of the values will be dependent of individual preferences and local and overall microclimate conditions around different parts of the body. This means that the system must allow precise regulation of local air temperature and velocity in several zones around each passenger's body.

Based on the fact that vehicle air-conditioning system should cool the occupant, not the entire passenger compartment, energy saving potentials of individual localized control of airflow parameters could be achieved by increasing the average air temperature in the cab. In the same time, higher air velocities would keep heat loss from the body within the comfortable limits. Of course, air discharge must be under full control of the passenger.

Further investigation should be directed to optimization of local microclimate parameters and to expansion of the research on investigation of the influence of radiation as well as direct local cooling of the body by ventilated seat. Within the scope of these researches, it is necessary to make link among different science disciplines, such are human thermal sensation and physiology, psychology, thermal and fluid engineering.

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