Local and Individual Demand-Controlled Ventilation in a Passenger Train

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Abstract. Installing local, demand-controlled ventilation offers great potential in terms of improving the individual thermal comfort and the energy savings of the overall train air-conditioning system. In the experimental investigation, we set both reduced and increased mean temperatures in the compartment and measured the local equivalent temperature per body-segment on a selected seat which is equipped with an additional six-air-nozzle device attached to the backrest of the front seat. The single nozzles are oriented towards, e.g., the legs, the upper body and the head. First results revealed that at decreased mean temperatures in the compartment, the warm air jets are not capable to reach all body parts due to entrainment and mixing with the ambient air. Hence, in the current setup, individual heating seems more promising by, e.g., by infrared heating elements. In contrast, at increased mean temperatures the air vents provide a possibility to locally decrease the equivalent temperature.

1 Introduction

To achieve the desired shift of passenger transport from road to other modes – defined by the EU – passenger rail transport has to become more attractive. In addition to fostering the attractiveness of rail transport, the efficiency of existing air-conditioning systems must be increased to reduce the overall energy demand. The air-conditioning system is the second largest energy consumer during a train journey, accounting for up to 30% of the total energy demand. [1]

Nowadays, the ventilation of train compartments is optimized to provide overall comfortable conditions in the whole occupied zone, neither addressing whether the seats are occupied nor taking the individual demands of the passengers into account. Demand-controlled adjustment of the fresh air rate based on the CO_2 levels in the compartment is already well-established to save energy at low occupancy levels. However, still the whole compartment is maintained at comfortable conditions. New concepts are based on the idea to provide comfortable conditions only on occupied seats by generating localized climate zones. Thus, there is a potential so save energy as the conditioning effort for the whole compartment is reduced and the individual subjective demands on comfort can be addressed. In previous studies we presented infrared and seat heating elements to increase the individual equivalent temperature [2-5]. However, the concept of additional infrared and seat heating is only applicable in winter conditions. For summer conditions additional cooling would be needed, if the mean temperature in the compartment were maintained at increased levels to reduce the energy demand of the HVAC system.

In passenger aircraft individual air nozzles, the so-called gasper nozzles, are state-of-the -art and investigated in many studies. Du et al. (2017) [6], for example, investigated the optimal velocity configurations for gasper nozzles in aircraft at different temperature levels. Their results approved appropriate airflow rates at normal pressure for a nozzle to be 0-0.86 L/s at 24°C, 0.12-1.09 L/s for 26°C and 0.26-1.30 L/s for 28°C in order to maintain a passenger's thermal comfort with both thermal sensation and air movement sensation being within the range of -0.5 to +0.5.

In train compartments, however, the literature on personal air nozzles is rare. Liu et al. (2023) [7] for example investigated the impact of individual air nozzles in the arm rests on particle spreading in the train compartment. Their results revealed a reduction of approx. 25% in particle concentration in the breathing zone of the passengers. To our best knowledge, however, the application of individually controllable air nozzles in passenger trains has not been tested yet.

The present study focusses on the application of individually controllable air nozzles in a train compartment operated are different temperatures and volume flow rates.

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2 Experimental Set-Up and Methods

In the second section, we will provide a brief introduction to the laboratory and the experimental set-up, i.e., the multi-nozzle air-jet system. This section also includes a description of the applied methods used to acquire the additional velocity fields and the local equivalent temperatures as comfort measures.

2.1 Generic Train Laboratory (GZG)

The study was conducted in a generic laboratory, representing the lower cabin of the DLR's next generation train (NGT), see Figure 1. The inner dimensions of the compartment are 6.0 x 2.88 x 1.95 m^3 (length x width x height) and it is equipped with 24 seats. Thermal manikins are used to simulate the blockage and heat release of real passengers.

Fig. 1. View in the generic train laboratory fully equipped with thermal manikins.

The heating/ventilation/air-conditioning (HVAC) unit of the GZG is realized using a stationary, high-precision HVAC system, which guarantees well-defined and precise supply air conditions with temperature and airflow rate fluctuations as low as 0.1 K and 10 l/s, respectively. The latter corresponds to an accuracy of approximately 4.3% with regard to the absolute supply air volume flow rate.
In previous investigations within the GZG, we analyzed different ventilation concepts regarding objective and subjective thermal comfort [8,9], individual infrared (IR) heating elements [2] and aerosol spreading [10].

2.2 Personal Multi-Jet Air Nozzle

A multi-jet air nozzle system was developed allowing for the ventilation of six zones in the first step. It consists of six adjustable air vents embedded in a 3D printed housing with the intention of influencing the following six main zones:

- Head
- Chest
- Right and left arm or hand
- Right and left leg or foot

The system was developed with a view to retrofitting as a seat attachment for our existing laboratory seats. In a later step it might be designed as an integral part of future seat generations. The individual diffusers can be adjusted in terms of flow rate and direction. Figure 2 shows a photograph of the system. The system is installed on the seat of the person in front and the six adjustable air vents can be seen. In addition, six pipes serve as air supply lines. These are equipped with individual electric heating elements to allow for an individual adjustment of the air temperatures of the single jets in the range of approx. 20°C to 60°C with a temporal stability better than 0.5 K to 2.5 K, respectively, i.e., between than 5% (standard deviation). Furthermore, the pipes are connected to a mobile HVAC unit, which supplies pre-conditioned air for all nozzles. Integrated volume flow rate sensors in connection with control valves in each pipe generate a controllable and well-defined airflow rate in each nozzle. Flow rates between 10 slm and 50 slm (slm = standard liter per minute) as well as zero can be realized and maintained with an accuracy better than 1.3 slm (standard deviation). The single air jet volume flow rates can be controlled both centrally from the test control center or via a mobile device, e.g., a smartphone or a tablet computer, directly by the passenger in front of the multi-air jet-nozzle.

Fig. 2. Image of the personal multi-jet air nozzle.

It should be noted that we are fully aware of the fact that a multi-jet air nozzle – as presented above – is not suitable for the integration into standard rail vehicles. However, for the current research project we accepted this fact as we want to evaluate, among others, which nozzles are used by the passengers and which nozzles combined with different settings provide a positive effect on which body part. Our aim is to answer the following questions: “What are the demanded airflow rates?” and “Do we need to provide different air temperatures in the nozzles?”. Based on the results of this objective and the upcoming subjective comfort assessment we will draw conclusions regarding the necessity and the effect of single nozzles which will help to design a second nozzle layout which might also be more suitable for integration.

2.3 Measurement Techniques

For the acquisition of the volume flow rates, air temperatures and humidity the mobile measurement system of the DLR was used [11]. Sensirion SHT85 and SFM3000 probes were used ensuring an accuracy of 0.2 K (temperature), 1.5% rh (humidity) and 1.5% of the measured value (volume flow rate). It should be noted that the mean temperature in the compartment T_{im} is calculated using four temperature probes at a height of 1.10 m arranged diagonally in the laboratory, in accordance with the EN13129 [12].

The 3D velocity field generated by the multi-jet air nozzle was measured using an optically tracked three-component ultrasonic anemometer (Streamwise Procab). This measurement system allows for non-time-resolved acquisition of all three velocity components and the fluid temperature in a pre-defined three-dimensional measurement volume. In the current study, the measurement volume is represented by a cubical box with a side length of 800 mm ranging from the multi-jet air nozzle to the ventilated thermal passenger manikin. The spatial resolution was set to 2 cm and the accuracy of the velocity probes is given as 0.1 m/s with an 0.01 m/s resolution.

Fig. 3. Individual climate control system installed on the seat of the person in front with direction of influence on a thermal human model with 16 equivalent temperature comfort sensors.

The assessment of the thermal comfort in terms of the individual body segments was performed using Comlogo's equites sensor system. [13]. It consists of 16 probes acquiring the equivalent temperature in accordance with EN 14505-2 [14]. Thus, the objective thermal comfort can be recorded and evaluated following international standards and well accepted comfort zones ranging from too cold via cool, neutral, slightly warm to too warm. These five zones are also represented as background color in the results images, which show the local equivalent temperatures, c.f. Fig. 6 to Fig. 10. It should be noted that it is distinguished between summer and winter conditions as the thermal comfort evaluation of similar equivalent temperatures differs, following EN14505-2 [14]. The installation of the equites sensors on a manikin seated in front of the multi-jet air nozzle is depicted in Figure 3.

2.4 Measurement Procedure

The HVAC system described in section 2.1 was used to maintain the desired setpoint temperature throughout the single measurement runs to avoid a drift of the mean temperature in the compartment caused, e.g., by the multi-jet air nozzle.

After an initial heat-up phase of all manikins and sufficient time for the HVAC system to ensure stable conditions within the compartment, the different parameter combinations of the multi-jet air nozzle were adjusted. The equivalent temperatures were recoded as soon as stationary conditions were reached, typically approximately 25 minutes after the change of the settings of the nozzle. The presented results are determined as a 5 minutes average of the equivalent temperatures in the stationary conditions.

3 Results

Firstly, we will briefly present and discuss the generated flow field induced by the multi-jet air nozzle. This knowledge is of utmost importance to understand and explain the findings regarding the thermal comfort, which will be discussed in the sections 3.2 and 3.3 for summer and winter conditions, respectively.

3.1 Exemplary Flow Field

Figure 4 shows the cross-section view of the velocity in the central plane between the multi-jet air nozzle and the thermal manikin obtained using the 3D velocity measurement technique. The volume flow of each single nozzle was adjusted to 50 slm. The cross section is aligned with the two nozzles guiding to the head and the upper body. There are two main findings: firstly, two high-velocity air jets are generated by the two nozzles in this plane. Secondly, the jets rather reach the chest and the lower stomach than the aimed head and chest region. In the jets, local velocities of up to 1 m/s can be found in the core region all the way to the passenger. Thereby, the jets' width is in the range of 10 cm highlighting the local orientation. The air jets of other nozzles for the legs and the arms are not visible in the cross section.

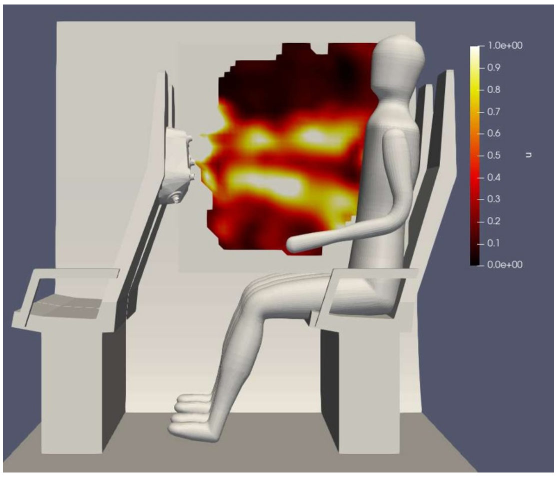

Fig. 4. Cross-section view of the velocity field color coded by the velocity magnitude in the range between 0 m/s and 1 m/s.

Additionally, Figure 5 represents the three-dimensional iso-surfaces of the velocity magnitude, color coded by the local temperature. Parts of the jet towards the left arm of the passenger are visible next to the two jets towards the chest and the lower stomach. Again, it is confirmed that the single jets can be used to affect the local air velocity at different body parts of the seated passenger and thus, direct effects on the local equivalent temperature, i.e., the local thermal comfort, are expected and will be addressed in the next sections.

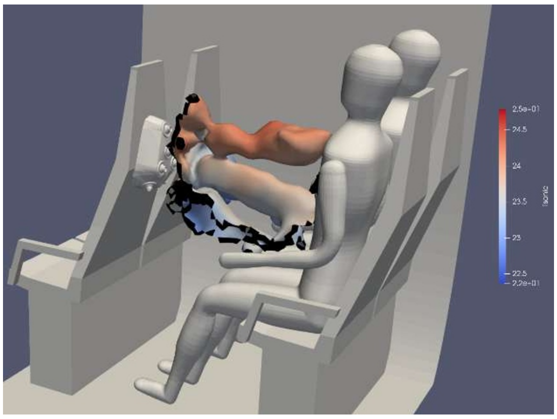

Fig. 5. Exemplary iso-surfaces of the velocity magnitude at $|\boldsymbol{U}| = \mathbf{0.5}\boldsymbol{m/s}$ of the resulting 3D velocity field, color-coded by the local temperature in the range between 22°C and 25°C.

3.2 Summer Conditions – Thermal Comfort

For the summer condition cases, additional cooling of the air jets is desired. Two different mean temperatures in the compartment are analyzed: $\boldsymbol{T_{im}} = \mathbf{23\,°C}$ and $\boldsymbol{T_{im}} = \mathbf{27\,°C}$ at various air nozzle temperatures and volume flow rates, i.e., different local air velocities.

The results presented in the following figures are depicted in terms of local equivalent temperatures for the different body parts, i.e., from the left and right feet to the head. The blue data points show the baseline configuration, i.e., without additional air jets, at the respective mean temperature.

3.2.1 Influence of the Air Velocity on the Thermal Comfort – Summer Conditions

To investigate the influence of different air velocities on the thermal comfort, we maintained the mean temperature in the compartment at $T_{im} = 23\,°C$ and operated the additional air supply at the same temperature: $T_{air-nozzle} = 23\,°C$. Figure 6 presents the results regarding the thermal comfort for the baseline configuration and three different volume flow rates: 50 slm, 30 slm and 10 slm. The given values correspond to the flow rate through each individual nozzle and all single nozzles are operated at the same configuration for each test case.

The first thing to note is that the thermal conditions are comfortable, i.e., the equivalent temperature is in the neutral area for most body parts for the baseline case, i.e., without additional air jets. Only the lower body parts – in specific the upper legs and the left foot (in the aisle area) – are slightly cool. The next thing to note is that the lowest airflow rates of the multi-jet air nozzle (red markers) do not change the thermal conditions of the seated passenger. Hence, the additional air jets do not reach the passenger at a flow rate of 10 slm per nozzle. For higher airflow rates (orange and green markers), the cooling effect of the multi-jet air nozzle is found for many body parts resulting in strongly decreased local equivalent temperatures for the upper body part. The most significant T_{eq} reduction of approx. 9 K was found for the highest flow rate and the lower chest region. However, the results also reveal that the lower body parts, except for the upper left leg at the highest flow rate, are not influenced by the multi-jet air nozzle. Furthermore, we found only a small effect on the head, which correlated directly to the findings of the velocity field analysis. There, the designated head air nozzle was found to reach rather the chest than the head of the seated passenger manikin.

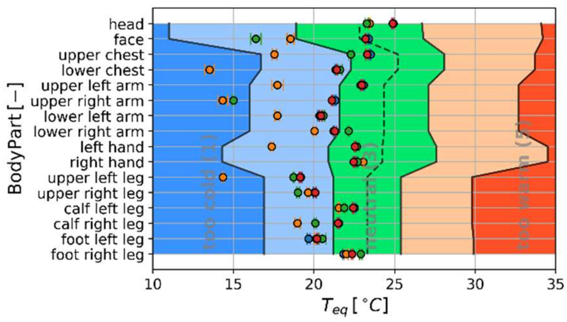

Fig. 6. Summer conditions @T_{im}=23°C: Influence of the air velocity at constant air temperature $\boldsymbol{T_{air-nozzle}} =$ $\mathbf{23\,°C}$. Blue: reference case without additional ventilation. Orange: $\dot{\boldsymbol{V}}_{\boldsymbol{air-nozzle}} = \mathbf{50}\,\boldsymbol{slm}$, green: $\dot{\boldsymbol{V}}_{\boldsymbol{air-nozzle}} =$ $\mathbf{30}\,\boldsymbol{slm}$ and red: $\dot{\boldsymbol{V}}_{\boldsymbol{air-nozzle}} = \mathbf{10}\,\boldsymbol{slm}$.

Complementary, we performed similar measurements at an increased mean temperature in the compartment, see Fig. 7. In this case, $\boldsymbol{T_{im}} = \mathbf{27\,°C}$ and $\boldsymbol{T_{air-nozzle}} =$

$\mathbf{25\ °C}$ were chosen as temperatures, representing a warm summer scenario in accordance with DIN EN13129 [12], where set point temperatures of 27°C are proposed for outside temperatures above 35°C. As expected, the temperatures without additional air jets are mostly evaluated as slightly warm. However, single body parts like the left foot on the aisle side are evaluated as neutral, that is, best thermal comfort is expected. Similar to the previous case, the lowest air supply rates at the nozzles, i.e. 10 slm, do not change the comfort evaluation. For higher airflow rates of 30 slm and 50 slm (green and orange markers), the upper and lower chest as well as the upper and lower arms are cooled efficiently. Except for the face region, higher airflow rates correlate with lower equivalent temperatures for the single body parts. In contrast to the case at $\boldsymbol{T_{im} = 23\ °C}$, we found an additional cooling effect for the highest flow rate at both upper legs and the right calf at $\boldsymbol{T_{im} = 27\ °C}$. Consequently, it seems that the different temperature levels of the air jets and the compartment do also influence the propagation direction of the air jets on single body parts. Here, the jets in the upper body regrion seem to be more stable compared to those guiding to the feet.

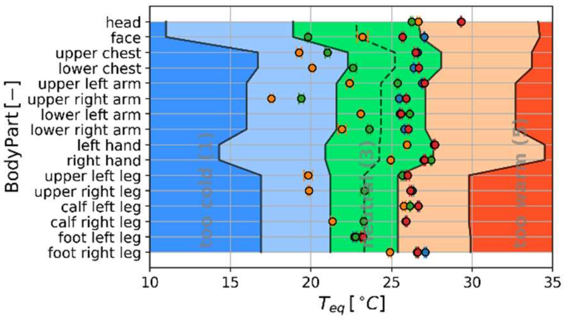

Fig. 7. Summer conditions @T_{im}=27°C: Influence of the air velocity at constant air temperature $\boldsymbol{T_{air-nozzle} = 25\ °C}$. Blue: reference case without additional ventilation. Orange: $\boldsymbol{\dot{V}_{air-nozzle} = 50\ slm}$, green: $\boldsymbol{\dot{V}_{air-nozzle} = 30\ slm}$ and red: $\boldsymbol{\dot{V}_{air-nozzle} = 10\ slm}$.

3.2.2 Influence of the Jet-Air Temperature on the Thermal Comfort – Summer Conditions

To investigate the influence of different jet air temperatures on the thermal comfort, we maintained the mean temperature in the compartment at $T_{im} = 23\ °C$ and operated the additional air supply at a fixed airflow rate of $\dot{V}_{air-nozzl} = 50\ slm$ with different temperatures $T_{air-nozzle}$ of the air jets.

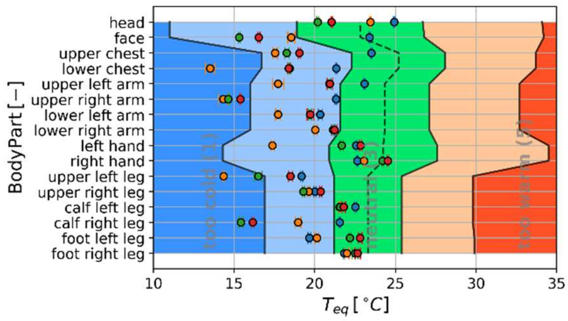

Fig. 8. Summer conditions @T_{im}=23°C: Influence of the air temperature at a constant air flow rate of $\boldsymbol{\dot{V}_{air-nozzle} = 50\ slm}$. Blue: reference case without additional ventilation. Orange: $\boldsymbol{T_{air-nozzle} = 23\ °C}$, green: $\boldsymbol{T_{air-nozzle} = 43\ °C}$ and red: $\boldsymbol{T_{air-nozzle} = 53\ °C}$.

Figure 8 presents the results of the thermal comfort for three different air nozzle temperatures between 23°C and 53°C. It should be noted that we just want to evaluate the effect of different supply air temperatures on the local thermal comfort. We are fully aware that supply air temperatures of up to 53°C are not reasonable for summer conditions, where an additional cooling is desired. However, as our mobile HVAC system cannot supply air temperatures below 15°C due to icing of internal components and rather long pipe lengths from the unit to the multi-jet air nozzle, we decided to test different increased temperatures to capture the cooling effect at different temperature levels.

The baseline datapoints in figure 8 (blue) are the same as in figure 6, showing comfortable to slightly cool temperatures for the different body parts. The activation of additional air nozzles at a low supply air temperature (orange) strongly reduced the equivalent temperature for many body parts. The higher supply air temperatures (green and red) of the air jets have complementary effects on the thermal comfort for different body parts: the head and the face experience a stronger cooling for increased supply air temperatures. Here, the higher temperatures of the supply air seem to lead to a different propagation direction of the air jets due to the thermal buoyancy, i.e., the jets of the head and chest nozzle impact on the passenger at higher body parts compared to the lower supply air temperatures. For all other body parts – except for the right calf – the higher supply air temperatures (green and red) lead to higher equivalent temperatures compared to the case with low supply air temperatures (orange). Thereby, the local equivalent temperatures are generally still below the values of the baseline configuration. Hence, we can conclude that the cooling effect of the additional airflow outbalances the heating effect of the higher temperatures. Furthermore, the different supply air temperatures, varying between 23°C and 53°C, only change the local equivalent temperatures by maximal 5 K (left hand) and in average by less than 2 K. Moreover, we attribute the strongest effects to the changed direction of propagation of the air jets due to buoyancy and not to the effect of the different temperatures on the passenger.

3.3 Winter Conditions – Thermal Comfort

In the previous section the positive cooling effect of the multi-jet air nozzle on the equivalent temperature under summer conditions was confirmed. Analogously, we investigated the effect of the additional air jets under winter conditions, i.e., the mean temperature in the compartment was adjusted to $T_{im} = 21\,°C$ in accordance with DIN EN13129 [12], where setpoint temperatures of 21°C are proposed as lower limit for outside temperatures below 17.5°C.
It should be noted that we use the winter comfort thresholds in accordance with DIN EN14505-2 [14] for the equivalent temperature evaluation in figures 9 and 10.

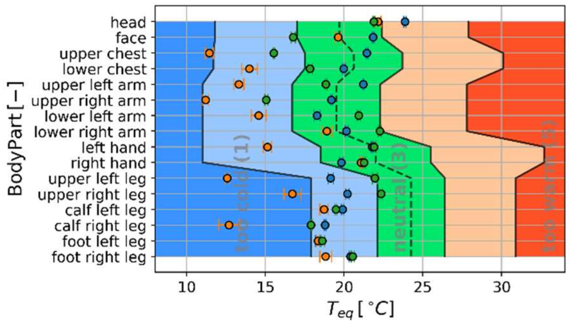

Fig. 9. Winter conditions @T_{im}=21°C: Influence of the air velocity at a constant air temperature $\boldsymbol{T_{air-nozzle} = 50\,°C}$. Blue: reference case without additional ventilation. Orange: $\boldsymbol{\dot{V}_{air-nozzle} = 50\,slm}$ and green: $\boldsymbol{\dot{V}_{air-nozzle} = 30\,slm}$.

Figure 9 shows the influence of different volume flow rates on the thermal comfort at a constant air nozzle temperature of $\boldsymbol{T_{air-nozzle}} = 50\,°C$. Once again, the baseline configuration is shown in blue. The results reveal that the configuration without additional air supply is perceived as comfortable for the whole upper body including the arms and hands, while the lower body parts are evaluated as cool and for the left foot even too cold. Unfortunately, the activation of the additional air supply with the high supply air temperature resulted in a decrease of the equivalent temperature for most body parts. Only for the intermediate flow rate (green markers) and for some selected body parts, e.g., lower arms and upper legs, a heating effect of the additional air supply was measured. For all other body parts and for the high flow rate, the cooling effect of the additional airflow outbalances the effect of the warmer air. In summary, the currently installed system is not suitable for individual heating at cool ambient conditions.

Finally, figure 10 shows the influence of different supply air temperatures on the thermal comfort at a constant air nozzle volume flow rate of $\dot{V}_{air-nozzle} = 50\,slm$. In correspondence with the previous results we also only found cooling effects for the upper body parts for all other supply air temperatures despite the fact that the temperature of the air nozzle was 10, 20 or 30 K warmer than the mean temperature in the compartment. At this volume flow rate, the cooling effect of the additional airflow has a higher impact on the local equivalent temperatures compared to the heating effect of the higher temperature of the air jets. Furthermore, we found that changing the supply air temperature from 21°C to 51°C, i.e., a change of 30 K, influences the local equivalent temperatures by less than 3 K, except for the left upper leg. Here the change in the supply air temperature seems to influence the propagation direction of the jet in a way that it reaches the measurement position only for $\boldsymbol{T_{air-nozzle} = 21\,°C}$ (orange) and 31°C (green) as the local equivalent temperatures are decreased for these cases compared to the baseline and the high supply air temperature cases. Consequently, two main conclusions can be drawn from these winter case findings: firstly, different supply air temperatures change the local equivalent temperatures only weakly. Secondly, the cooling effect of the additional air jet predominated the heating effect of the higher air jet temperatures. Hence, warm air jets cannot be used in the current configuration for individual, local heating of the passengers in winter configurations.

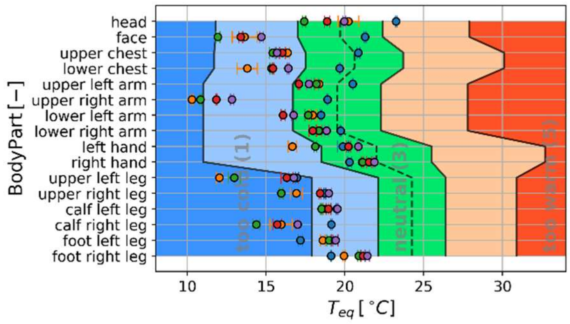

Fig. 10. Winter conditions @T_{im}=21°C: Influence of the air temperature at a constant airflow rate of $\boldsymbol{\dot{V}_{air-nozzle} = 50\,slm}$. Blue: reference case without additional ventilation. Orange: $\boldsymbol{T_{air-nozzle} = 21\,°C}$, green: $\boldsymbol{T_{air-nozzle} = 31\,°C}$, red: $\boldsymbol{T_{air-nozzle} = 41\,°C}$ and purple: $\boldsymbol{T_{air-nozzle} = 51\,°C}$.

4 Conclusions and Outlook

This paper presents an experimental investigation on the effect of localized individual and demand-controlled ventilation generated by a multi-jet air nozzle on the thermal comfort in a generic train configuration. First results revealed that at decreased mean temperatures in the compartment, the warm air jets are not capable of reaching all body parts due to entrainment and mixing with the ambient air. Furthermore, the cooling effect of the additional air jets predominates the heating effect of the warm air. Hence, in the current setup, individual heating seems more promising by, e.g., infrared heating elements, which have been investigated in previous measurement campaigns. In contrast, at increased mean temperatures the air vents provide a possibility to locally decrease the equivalent temperature and thus hold the potential to increase the thermal comfort at warm ambient conditions. It was found that the temperature of the air nozzle has only a weak impact on the equivalent temperature compared to the airflow rate of the individual nozzles, which is also in agreement with the finding of Fang et al. (2017) [15]. Consequently, it might be sufficient to provide these additional air jets

without additional pre-conditioning of the supplied air, i.e., the air for the nozzles can either be branched off from the main ventilation system or operate as a pure recirculation system. Both solutions will strongly decrease the effort in terms of the technical installations compared to individually pre-conditioned air.
In upcoming studies, we are going to perform subject tests in close cooperation with DLR psychologists to evaluate the personal comfort sensation at individually chosen air-jet configurations. Following the results of the presented objective thermal comfort evaluation, the subject tests are going to be performed at an increased mean temperature in the train carriage where the multi-jet air nozzle can be individually controlled via a mobile end device to provide a cooling as demanded by the subjects.

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