Building and Environment 111 (2017) 256–264

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Thermal comfort of different displacement ventilation systems in an aircraft passenger cabin

Julia Maier [a,*], Claudia Marggraf-Micheel [a], Tobias Dehne [b], Johannes Bosbach [b]

[a] *Aviation and Space Psychology, German Aerospace Center, Hamburg, Germany*
[b] *Institute of Aerodynamics and Flow Technology, German Aerospace Center, Göttingen, Germany*

ARTICLE INFO

Article history:
Received 2 September 2016
Received in revised form
24 October 2016
Accepted 8 November 2016
Available online 10 November 2016

Keywords:
Displacement ventilation
Mixing ventilation
Aircraft passenger cabin
Thermal comfort
Empirical data

ABSTRACT

Of current interest is the question whether ordinary mixing ventilation (MV) systems in an aircraft can be replaced by or combined with displacement ventilation (DV) systems without risking a decrease in thermal comfort. A reduction of energy consumption is a valuable gain.

Three different versions of DV were analysed employing the Do 728 cabin test facility of the German Aerospace Center as cabin environment. Three human subject tests were carried out using 40 participants each: They aimed at analysing the thermal comfort of a) 100% DV, b) a 70:30% hybrid system combining DV and MV and c) a 50:50% hybrid system of DV and MV. Objective and subjective data were gathered to gain a differentiated image of the climate situation. Results were compared with results for MV that were obtained from an earlier study.

Measurement data revealed a clear vertical temperature gradient for the DV systems; the relatively smallest temperature difference between feet and head was found for 100% DV and MV. Air velocity was lower in DV and increased with the amount of mixing ventilation that was provided. Regarding subjective sensations, thermal comfort was given in all three DV systems. The overall satisfaction with the climate tended to be highest in the 50:50 hybrid system.

In summary, our results demonstrate that displacement ventilation can be used to provide a comfortable climate in an aircraft cabin. Known constraints of DV as e.g. large vertical temperature differences did not have any negative influence on climate comfort ratings of the passengers.

1. Introduction

For the development of new aircraft types, one important design criterion is the thermal comfort that can be provided for the passengers.[1] Nowadays demands are changing, as for example the usage of electronic devices has become very common while traveling. Most airlines install individual screens for the entertainment of the passengers and the principle of using a "second screen" via mobile devices is of current interest. One result of the additional electronic equipment in the aircraft cabin is the additional amount of heat load that is created. Until now, mixing ventilation systems have been used to dissipate the contaminated air in aircraft cabins, but this air distribution system has some deficiencies, especially when cooling large heat loads [2], as it may lead to uncomfortable draughts [3,4], noise [5] or distribution of pollutants [6,7]. As a consequence, advanced ventilation systems are being assessed by researchers and the aircraft industry. In addition to the improvement of conventional mixing ventilation (MV) systems [8], new ventilation principles are being developed and investigated. Displacement ventilation (DV) is one of the systems that have been evaluated for use in aircraft cabins for a few years [2,9–12]. Of current interest is the question of whether ordinary mixing ventilation systems can be replaced by or combined with DV to gain a comparable or even increased thermal comfort for the passengers.

1.1. Displacement ventilation in aircraft cabins

Displacement ventilation is an air distribution system which supplies cool fresh air with low velocity, generally at floor level and extracts exhausted air at the ceiling. Supply air is 1–4 K lower than room air temperature. Air velocity and turbulence is very low

* Corresponding author. Sportallee 54a, D-22335, Hamburg, Germany.
E-mail addresses: Julia.Maier@dlr.de (J. Maier), Claudia.Marggraf@dlr.de (C. Marggraf-Micheel), Tobias.Dehne@dlr.de (T. Dehne), Johannes.Bosbach@dlr.de (J. Bosbach).
[1] An earlier version of this paper was presented at 62. DGLR conference [1].

http://dx.doi.org/10.1016/j.buildenv.2016.11.017
0360-1323/

(<0.3 m/s) as heat sources – like aircraft passengers – generate the vertical air movement via convection [13]. The temperature distribution is characterised by stratification: while cool, fresh and clean air can be found at floor level (in the occupied zone) the contaminated air rises up to the ceiling and is extracted there very efficiently. Air quality in the occupied zone is thus improved.

But there are also disadvantages using DV: Melikov, Pitchurov, Naydenov and Langkilde [14] identified high air velocities and low air temperatures at floor level, i.e. next to the diffusers and the passengers' feet. These may lead to discomfort. Further, according to the ISO comfort standard (ISO 7730, [15]), the vertical temperature gradient in a room should be less than 3 K – since cool air is supplied in DV, there is a risk of causing larger differences between floor and ceiling, where warm air gathers. DV is usually not used for heating purposes, as cool air is required for the convection principle [13]. Nevertheless, under certain circumstances, it is possible to supply warmer air to the cabin [9].

Some studies have been published comparing DV with other ventilation systems. Lin et al. [11] analysed the performance of DV and MV in different kinds of rooms (office, workshop). Computational Fluid Dynamics (CFD) models were used to compare DV and MV regarding airflow, temperature and comfort indices. DV turned out to provide a comparable or even better comfort level than MV, except for the space in the vicinity of floor diffusers or major heat sources. Zhang and Chen [12] analysed DV, MV and personalised ventilation in a section of a Boeing 767 cabin using CFD modelling. Temperature stratification was found in DV and personalised air distribution systems but the vertical gradient was less than 3 K. While in MV, high air velocities (and CO_2 concentrations) were found, DV provided more comfort. Taking into account the possibility to reduce effectively CO_2 concentration in the breathing zone, personalised ventilation was seen as creating the best cabin environment. Müller et al. [2] compared DV, MV and DV with lateral support in a mock-up based on the Airbus 320 geometry. Air flow and temperature measurements were made as well as experiments with test persons and CFD simulations. The vertical temperature difference in DV and in DV with lateral support was in line with the standards for a volumetric flow rate of 77.8 $l/s/m_{cabin}$ and low air velocities were measured (< 0.2 m/s). Moreover, comfort advantages were found for DV compared to MV for middle and aisle seats, but at the window seats, temperatures were rated as rather cold and uncomfortable. The authors concluded that in both ventilation systems, thermal comfort cannot be fully guaranteed and suggested further research.

With the intention to combine the advantages of both MV and DV systems, Bosbach et al. [9] set up and analysed a hybrid DV/MV system (HV) that used air supply from lateral MV air outlets in addition to DV. The systems were tested during a flight test campaign in an Airbus A320-232 with thermal dummies and thorough measurement equipment. It was found that the hybrid system led to lower temperature stratification but tended to produce more turbulences and higher velocities in the aisle seats, but this was not judged as impairing the passengers' comfort. In DV, low air velocities and turbulence was observed and heat removal efficiency was highest.

So far, mostly numerical simulations or experimental measurements have been performed to analyse and evaluate air distribution by DV systems in aircraft cabins. Human subject tests have rarely been published, even though the judgment of potential passengers is an important source to gather valid information about the comfort that is offered by a ventilation system [16]. Thus this study focuses on the thermal comfort passengers feel when sitting in an aircraft cabin that is ventilated by DV with different configurations. Results are compared with thermal comfort assessments for MV [4].

1.2. Aims and objectives

This study analysed three different DV concepts with respect to the thermal comfort they offer to passengers compared to MV. In three human subject tests, a 100% DV system and two versions of hybrid ventilation were analysed. The latter systems were designed to combine displacement and mixing ventilation principles: In these hybrid scenarios, two different ratios of volumetric flow rates for DV and MV were selected according to prior findings and theoretical considerations. Table 1 gives an overview of the flow cases investigated. The volumetric flow rates have been split between the two sides of the cabin according to the number of passengers, i.e. 3/5 and 2/5. Thermal comfort was described on the basis of test subjects' judgments. Comparable data for MV had already been assessed in a similar experimental setting in a previous study [4]. In addition to the volumetric flow rates, mean air velocities of the DV and MV outlets are given in Table 1. They were calculated by dividing the partial volume flow rate by the active surface of the respective outlet types and are given for orientation. The respective values underpin that the air velocities of MV and DV outlets are distinguished by at least one order of magnitude in the investigated scenarios.

2. Materials and methods

2.1. Test environment

The Do 728 cabin test facility of the German Aerospace Center in Göttingen was used as environment for the human subject tests. Its design is based upon the original test aircraft 728 Nr. 1 of Fairchild Dornier. The cabin provides a single aisle layout with a complete interior, comprising 70 seats at a pitch of 33″ in 14 rows. It has a length of 16.9 m, a width of 3.25 m and a height of 2.14 m with three seat rows on the right and two on the left side of the cabin. An external heating, ventilation and air conditioning (HVAC) system supplies air flow with controlled temperature and humidity to the cabin at ground pressure conditions. It also allows for controlled air extraction. The cabin does not provide individual air outlets (e.g. via nozzles).

As a precondition to the study, it was necessary to equip the

Table 1
Summary of the investigated flow cases. Given are the nominal volumetric flow rates of the different air outlet types as well as the mean inlet velocities. The different values for the MV outlets refer to the left and right hand side of the cabin (Hybrid cases) as well as to lateral and ceiling outlets (MV).

Label	Volumetric flow rates [l/s]					Mean air velocities [m/s]	
	DV	Lateral MV outlets	Ceiling MV outlets	Dado exhaust	Total flow rate per passenger	DV outlets	MV outlets
100% DV	610	0	−610	0	9.4	0.07	0
70% : 30% Hybrid	410	200	−610	0	9.4	0.05	0.4, 0.6
50% : 50% Hybrid	305	305	−610	0	9.4	0.035	0.6, 0.9
MV	0	264	396	−660	9.4	0	1.3, 2.1

Note. Data for MV originate from Ref. [4].