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Dynamics of aircraft cabin ventilation studied by in-flight infrared thermography

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Abstract

Aircraft Cabin Displacement Ventilation (CDV) was investigated during flight tests in an A320 aircraft cabin with an automatically rotatable infrared camera. For this purpose a programmable, step motor driven infrared camera setup was developed, allowing for time resolved acquisition of the temperatures on the interior cabin surfaces during the flights. Static measurements reveal a characteristic, yet homogeneous temperature distribution in the cabin for both scenarios, pinpointing to a homogeneous cooling of the heat loads in the whole cabin. Analysis of time resolved measurements discloses that the cooling performance of the cabin is limited by thermal diffusion of heat inside of the interior cabin materials. Switching from pure CDV to a hybrid scenario, where 30% of the air flow rate is provided by the pre-existing lateral air outlets, allows to increase the initial surface cooling rates up to a factor of 2.

1. Introduction

Displacement ventilation of aircraft cabins has gained increasing attention in the last years, see e.g. [1-5]. Low air flow velocities and a high ventilation efficiency are some of the most important benefits of this ventilation concept. Previous studies focused on the applicability of the new air ventilation system on low technology readiness levels either by means of computational fluid dynamics (CFD) [1-5] or experiments in aircraft cabin mock-ups [2,3]. Up to now, however, evidence of the applicability of CDV under flight conditions and the integrability of this concept into real aircraft cabins has been lacking. The objective of the reported study was to characterize the dynamic behaviour of CDV regarding surface cooling performance under flight conditions.

2. Ventilation concepts for aircraft cabins

Nowadays, state of the art ventilation systems for aircraft cabins rely on the principle of Mixing Ventilation (MV) (Fig. 1a). MV is based on the supply of fresh air via jets, e.g. below or above the hat racks at rather high momentum. Typical inflow velocities amount to about 1 m/s, which ensures mixing of fresh and used air in the associated shear layers. As a result, the jets grow by entrainment, and their velocity decreases accordingly while their temperature rises to a comfortable level before entering the passenger zone. In order to achieve uniform temperature distributions, low flow velocities near the passengers and efficient removal of contaminants, a precise dimensioning of the volume flow rates, lateral volume flow rate distribution and a suitable design of the air outlets is required. Among the advantages of MV are moderate temperature stratifications and high surface cooling rates. On the other hand, MV is prone to a high degree of short circuit flows and draft due to the turbulence generated by the air supply jets. Thermal passenger discomfort and exsiccation of mucosa are possible drawbacks, especially when it comes to removal of high heat load densities.

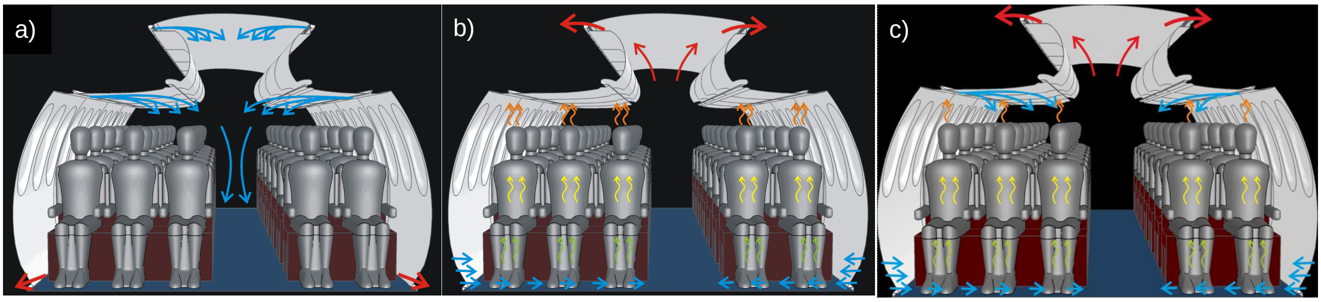

***Fig.1** Ventilation concepts for aircraft cabins a) Mixing Ventilation (MV), b) Cabin Displacement Ventilation (CDV) and c) Hybrid Ventilation (HV)*

CDV (Fig. 1b) relies on the supply of fresh air in the lower cabin part at very low momentum (u ~ 0.1 m/s). The fresh air accumulates above the floor, where it creates a “lake” of fresh air. Close to the passengers or electronics, the air heats up and rises due to buoyancy, removing the heat loads by thermal convection. The air is finally discharged in the upper cabin part and thus removes heat, carbon dioxide and contaminants from the cabin. Since the motion of the cabin air is mainly governed by thermal convection, very low flow velocities can be realized with CDV, making possible to minimize the risk of draft. On the other hand, CDV provides a very high cooling efficiency by minimizing the amount of short circuit flows because the air, which is discharged in the upper cabin part, has passed and thus cooled the heat loads by the principle.

3. Experimental set-up

The reported measurements were conducted in the rear cabin part of the “Advanced Technology Research Aircraft” (ATRA), an A320 aircraft from the test fleet of the German Aerospace Center. The cabin was reconfigured to provide CDV through low-draft air outlets, located at the position of the former DADO panels. Additionally, air could be supplied to a certain fraction through the lateral A320 MV air outlets. The air left the cabin through the pre-existing ceiling air outlets. Two scenarios will be discussed in the following: pure CDV and in addition, a hybrid case (HV - hybrid ventilation), where 30% of the fresh air was supplied through the lateral MV outlets (compare Fig. 1c)). In order to simulate the obstruction as well as the heat loads of the real passengers, the modified part of the cabin was equipped with 63 thermal passenger dummies, see Fig. 2b). In order to assess the surface temperatures of the cabin interior, a computer-controlled two-axis rotating stage infrared (IR) camera set-up was developed and installed, which allowed for a time-resolved acquisition of the required temperatures during the complete flights with a repetition rate of about 60 seconds, see Fig. 2a). In addition more than 200 temperature, air flow velocity, pressure and humidity sensors were installed in the measurement section.

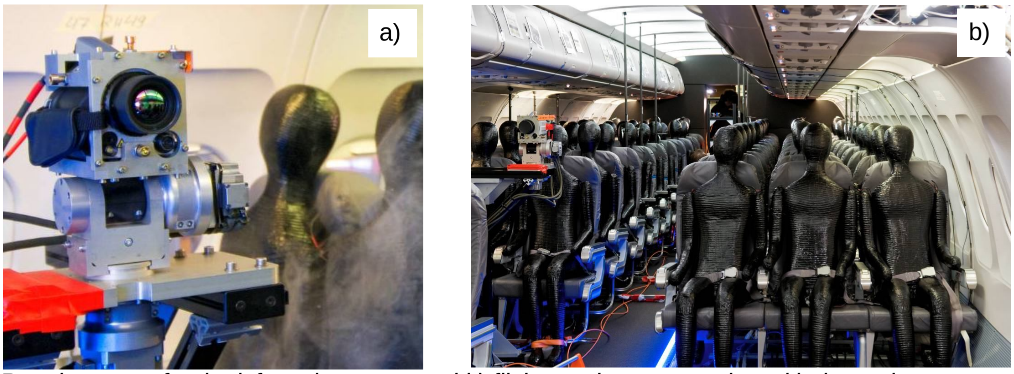

Fig. 2. *a) Rotation stage for the infrared camera, and b) flight test instrumentation with thermal passenger dummies in the modified cabin section*

To simulate the impact of the passengers during the flight tests, approved thermal passenger dummies were developed, see Fig. 3a and Fig. 3b. The core of the dummies consists of a flame-retardant foam. To simulate the human heat emission, the dummies were equipped with a heating wire, which provided a heat load of 75 watts for each dummy. Approval of the technical requirements comprised surface temperature measurements in a thermal box, see Fig. 3d. With an infrared camera, the heat-up process was recorded, by which the level as well as the homogeneity of the final surface temperatures was ensured for each dummy.

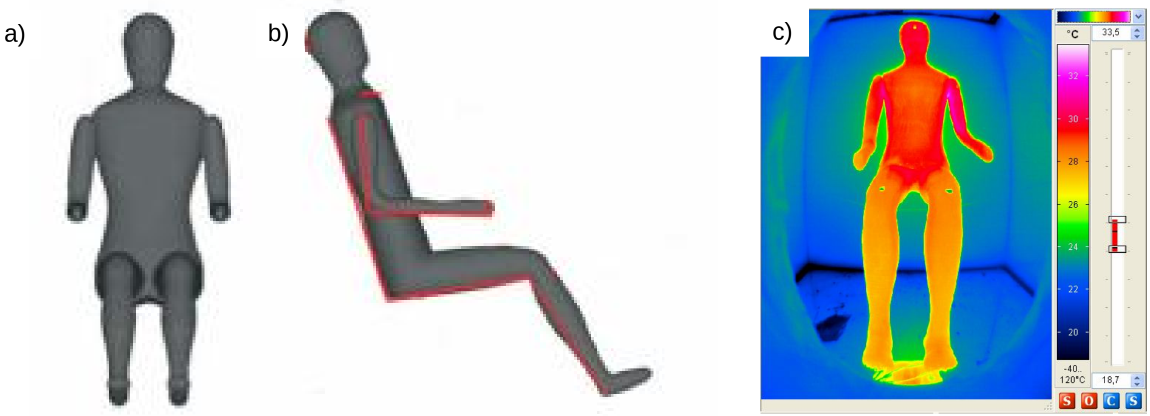

Fig. 3. *Thermal passenger dummies a) front view, b) side view and c) inside a test environment for approval of the technical specifications*

The cabin measurements in the ATRA were conducted at a flight level of about 37,000 ft and a Mach number of Ma = 0.78. Before considering the test data, we waited for at least 85 minutes after reaching flight level in order to achieve steady thermal conditions. Ground tests performed prior to take-off, which are not reported here, ensured that the passenger dummies and the cabin materials were already heated up homogeneously.

4. Results

In order to provide an overview of the complete cabin interior, panorama pictures were created from the single recorded IR views. Fig. 4 depicts the corresponding results for a) CDV and b) HV. For the sake of comparability, the mean inflow temperature has been subtracted from the temperature fields. Clearly, the heated passenger dummies can be detected, which reveal a characteristic and realistic temperature fingerprint. The latter results from the fact, that the dummies are constructed to provide a constant heat flux density over the whole surface. Only at the head the heat flux density is slightly increased in order to simulate the thermal impact of a real passenger in an experiment. In conjunction with the expectations on the CDV concept, the temperature distribution among the passenger dummies is very homogeneous in the whole cabin. Nevertheless, a characteristic temperature distribution can be detected on the surrounding surfaces, i.e. side panels, ceiling panels, hat racks and floor, which is very similar in CDV and HV. The main difference between CDV (Fig. 4a)) and HV (Fig. 4b)) to be observed in the panorama views are the slightly reduced temperatures at the lower hat rack and side panel surfaces as well as, of course, the lateral air outlets. Further the floor temperature in the aisle is slightly higher for HV due to the reduced volume flow rate at the CDV outlets.

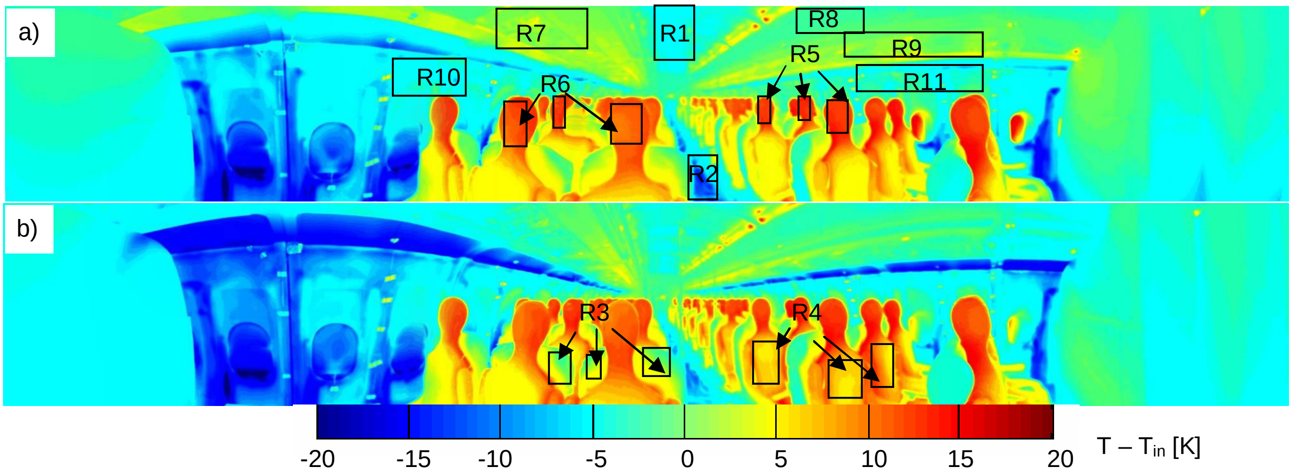

Fig. 4. *Cabin surface temperature distribution during flight tests of a) CDV and b) HV by panorama IR- thermography*

For acceptance of the new ventilation concept among the stakeholders, the performance of CDV is essential. In order to study this issue, dedicated “pull-up” and “pull-down” scenarios, those are abrupt changes of the inflow temperature with the objective to study the heating and cooling dynamics, were conducted during the flight tests subsequently to the static measurements. In the following, results for the pull-down scenario, where the inflow temperature was suddenly decreased by about $\Delta T_p \cong 10\ \mathrm{K}$ and kept constant at the flight level, are shown. While the air temperatures, which have been investigated in parallel, but are not shown here for the sake of brevity, follow the changed inflow temperature quite fast, a slow dynamics has been observed at the interior cabin components.

Panorama pictures of the surface temperature distribution at different points in time after begin of the pull-down are compiled in Fig. 5 for CDV. In order to allow for identification of temperature changes, the initial temperature distribution (T_0) prior to the pull-down has been subtracted from the data. The first panorama after 250 s shows that the surface temperature modifications are very small in most parts of the cabin since during this period, mainly the exchange of the cabin air with the cool air will take place, which is a prerequisite for surface temperature changes (Fig. 5a)). Figure 5b) and the following figures clearly reveal how subsequently the surface temperature changes take place, start first in the lower and later affecting also the upper cabin parts.

With the aim to judge which parts of the cabin interior adapt to the changed inflow temperature in the miscellaneous phases, the differences between subsequent temperature distributions in Fig. 5 were calculated and summarized in Fig. 6. In the first phase between 250 and 500s after pull down (Fig. 6a)) mainly the surface temperatures of the relatively warm dummies, which attract the cold air, decreases. During this period, the changes are mainly confined in the lower cabin part. In the second phase (Fig. 6b)), the temperature decrease of the dummies continues, but now temperature changes take place as well in the higher cabin part and now encompass noteworthy modifications at the side panel and hat rack surfaces. After 1000 s the spatial distributions of the ongoing temperature changes are spread very homogeneously among the cabin surfaces (Fig. 6c-e). Specific parts of the cabin, however, like the handrail and edges in the lining can be seen clearly in the temperature profiles even after 2000 s. In addition to the surface temperature changes described above, the influence of the solar radiation can be detected in the temperature modifications of the window shutters, which have been closed during the whole test. During the measurements, a change of the relative orientation of sun position and airplane axis occurred, which can be recognized in the temperature modifications of the window shutters.

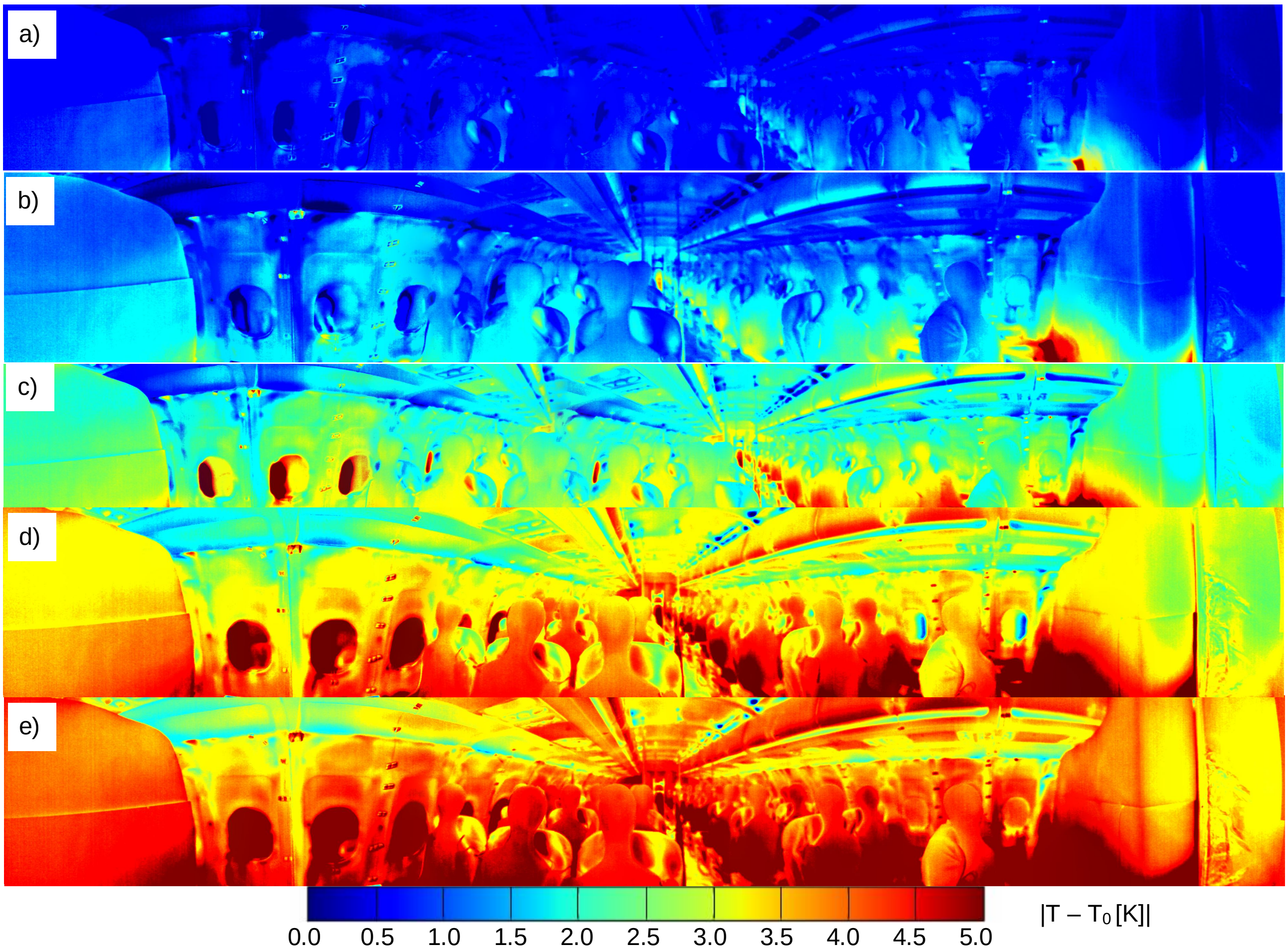

Fig. 5. *Absolute differences of surface temperatures $|T – T_0|$ upon pull down for CDV after a) 250s b) 500s c) 1000s d) 1500s e) 2000s as measured by panorama IR- thermography. T_0 denotes the surface temperature distribution before the pull down.*

In order to characterize the dynamic response of the cabin interior, time series of spatially averaged surface temperatures of different cabin parts (see Fig. 4) have been calculated from the thermography images and plotted in Fig. 7 for the pull-down scenario at CDV and HV. Depicted are the differences of the actual temperatures and those directly before the pull-down, normalized to the temperature jump. During the first 200 s, no major temperature difference can be observed, since during this time period the cabin air has to be exchanged first in order to allow for surface temperature changes to occur. During the next 300 s, a rather steep temperature decrease occurs, which we refer to in the following as “initial cooling rate”. In the following the temperature changes become much slower. We ascribe this observation to the fact that the heat has to be conducted inside of the interior cabin materials, which consist to a high fraction of air, to the respective surfaces prior to the heat exchange with the fluid. This retards the cooling process and results in a time series, which deviates significantly from a simple exponential function. As a consequence, even after 2500 s the surfaces do not reach the externally applied temperature jump with any of the two ventilation systems. A very similar behaviour was observed for the pull-up scenarios, which are not shown here for the sake of brevity. While for pure CDV, the temperature change of the passenger dummies is the fastest among the investigated surfaces due to the inherent air conveyance principle, which provides cool air first to the heat loads, switching to HV allows for a remarkable increase of the cooling rate for the linings. All surface cooling rates are larger for the hybrid system due to the higher turbulence levels and pressure gradients induced by the lateral wall jets.

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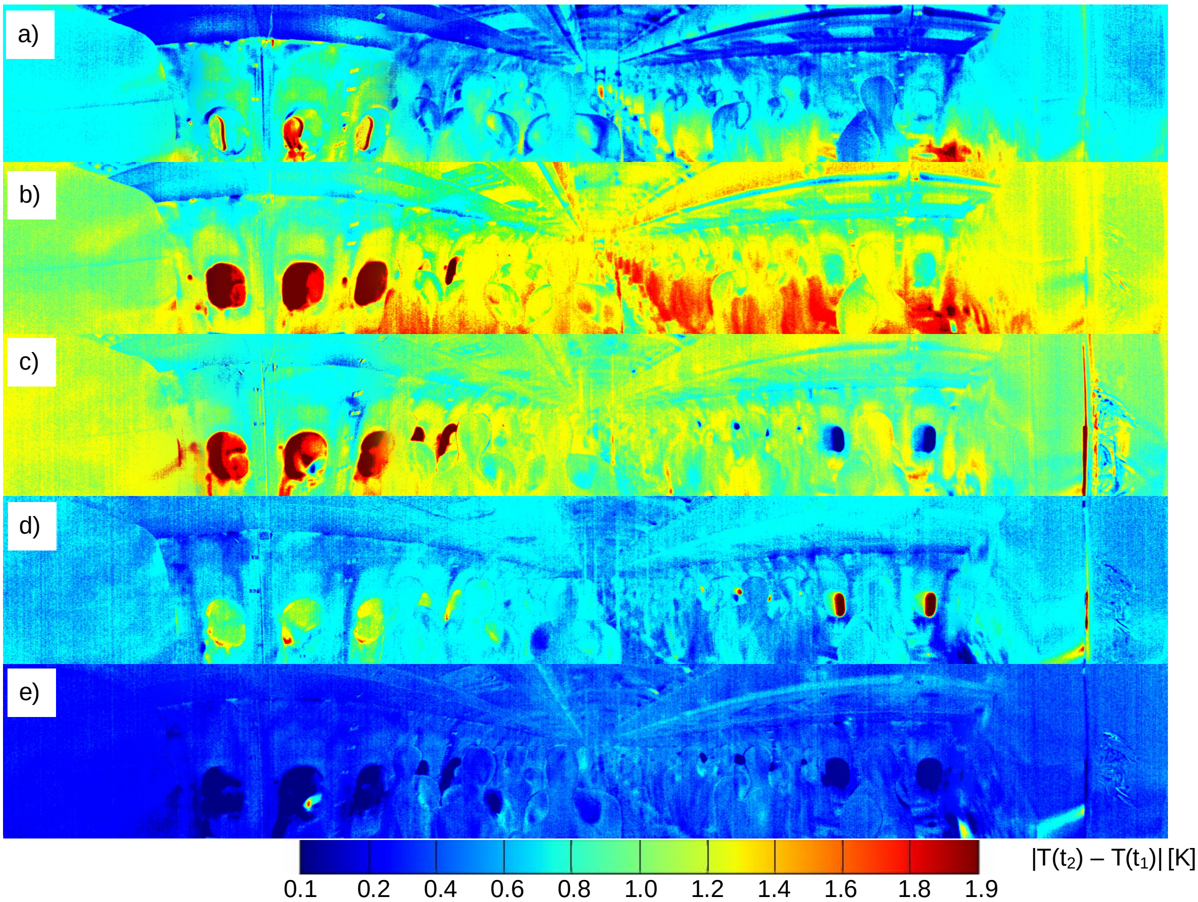

Fig. 6. *Absolute differences of surface temperature distributions ($T(t_2) – T(t_1)$) between two points in time t_1 and t_2 during pull down with CDV a) t_2 = 500s , t_1 = 250s, b) t_2 = 1000s , t_1 = 500s, c) t_2 = 1500s, t_1 = 1000s, d) t_2 = 2000s, t_1 = 1500s, e) t_2 = 2500s , t_1 = 2000s*

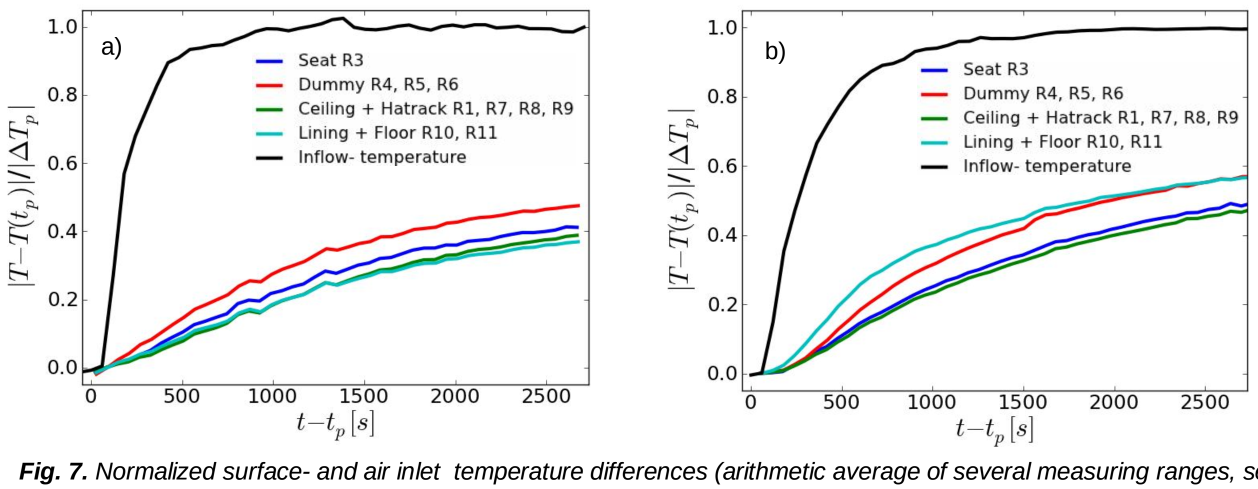

Fig. 7. *Normalized surface- and air inlet temperature differences (arithmetic average of several measuring ranges, seen in Fig. 4) for the pull down of a) CDV and b) HV under flight conditions*

Calculation of the initial cooling rates from the consecutive IR recordings allows to spatially resolve the temperature dynamics of the internal cabin surfaces. Fig. 8 depicts the inverse of the initial cooling rates, normalized to the temperature jump for both ventilation scenarios, $\Delta T_p \cdot dt\,/\,dT$, evaluated during a period of 300 s after the first noticeable temperature reaction of the surfaces to the pull up. We would like to note, however, that depending on the dynamic scenario up to 200 s might elapse before a noticeable surface temperature change can be detected. Large values of the inverse initial heating rates indicate slowly changing surface temperatures, while low values identify faster temperature responses. The plot of $\Delta T_p \cdot dt\,/\,dT$ in Fig. 8 reveals that the initial surface heating rates for HV are overall higher as compared to CDV. In some parts of the cabin such as linings and hat racks, the ratio amounts to even a factor of 2.

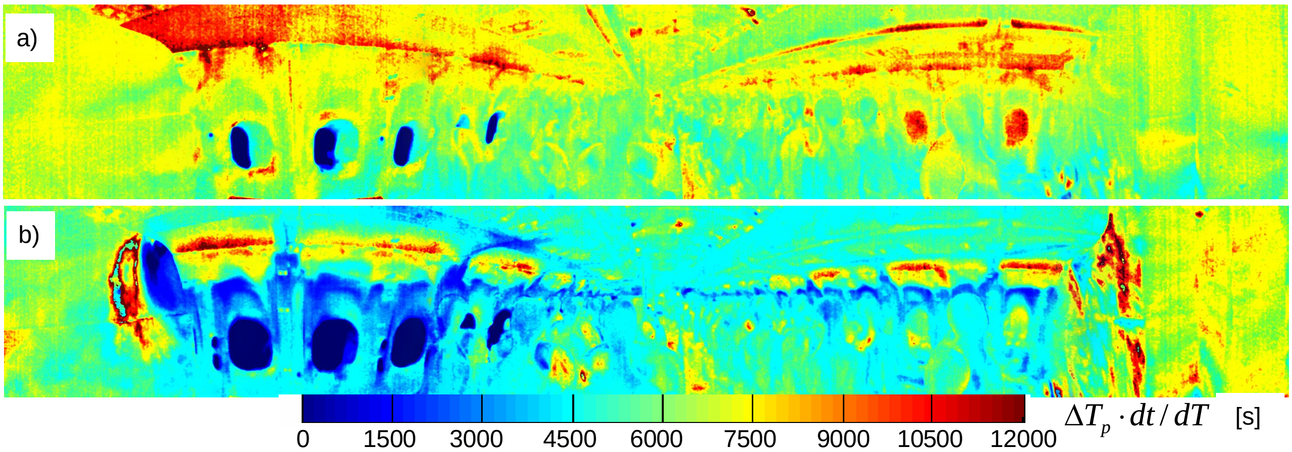

Fig. 8. *Panorama plot of normalized inverse initial cooling rate during pull-down for a) CDV and b) HV. For details see text.*

5. Summary

Surface temperature distributions and surface cooling rates have been investigated for two ventilation systems in the A320 “Advanced Technology Research Aircraft” (ATRA) of the German Aerospace Center under flight conditions employing an automatically rotatable infrared camera. The studied ventilation systems comprise pure CDV as well as a hybrid system (HV), where 30% of the fresh air was supplied through the original lateral outlets. Static measurements at the cruise level reveal a characteristic surface temperature distribution with a laterally homogeneous temperature level among the different seat positions. Supply of air through the lateral outlets during HV results in slightly reduced temperatures below the hat racks and at the side panels. During the pull-down scenarios long reaction times of the interior cabin surfaces have been observed, and even after several thousand seconds the surfaces do not reach the externally applied temperature jump, which we ascribe to the coupling between the cabin air flow and the thermal diffusion inside the interior cabin materials. Initial surface cooling rates can be increased up to a factor of 2 upon switching from CDV to the hybrid case (HV).

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REFERENCES

[1] Yin S., Zhang T., “A new under- aisle displacement air distribution system for wide- body aircraft cabins”, Eleventh International IBPSA Conference, July 27-30, 2009, Glasgow, Scotland
[2] Müller D., Schmidt M., Müller B., "Application of a displacement ventilation system for air distribution in aircraft cabins", AST 2011, March 31 – April 1, 2011, Hamburg, Germany
[3] Zhang T., Chen Q., “Novel air distribution systems for commercial aircraft cabins”, Building and Environment, vol. 42, pp. 1675-1684, 2007
[4] Schmidt M., Müller D., Gores I., Markwart M., „Numerical Study of Different Air Distribution Systems for Aircraft Cabins“,11th International Conference on Indoor Air Quality and Climate, 17th August to 22nd August, 2008, Copenhagen, Denmark
[5] Zhang T., Chen Q.: Comparison of Different Ventilation Systems for Commercial Aircraft Cabins, Proceedings of Indoor Air 2005, Vol. IV, pp. 3205-3210, Beijing, China