# Experimental comparison of thermal comfort measurement techniques

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**Abstract.** We present a comparison of three measurement techniques used to evaluate thermal passenger comfort. The first system measured the fluid velocity and temperature in the vicinity of thermal passenger dummies (TPDs). It allowed to calculate the predicted mean vote (PMV) and the predicted percentage dissatisfaction (PPD) by means of additional humidity and operative temperature probes. Second, an equivalent temperature probe sensor system recorded and evaluated the thermal comfort of individual body segments. This enabled a body-segment wise assessment of the objective thermal comfort and an evaluation in accordance with the international standards (EN ISO 14505-2) on equivalent temperature. Third, a thermal-comfort manikin system simulated and evaluated a person's thermal comfort in realistic environments. Skin temperature and heat flux density were measured independently in 27 body zones. Overall, the results of the present study show similar comfort ratings for the probe system compared to the comfort manikin. The probe system detects local changes more quickly than the comfort manikin. However, localized heat or cold sources are more likely to affect comfort than the area-based measurement provided by the comfort manikin.

## 1 Introduction

Many studies have been conducted to assess thermal comfort. In 1986, the Predicted Mean Vote (PMV) was developed to predict the average thermal sensation of a group of people based on factors such as metabolic rate (met), clothing (clo), air temperature, radiant temperature, air velocity, and humidity [1]. A PMV value close to 0 indicates thermal comfort, while higher or lower values indicate environments that are too warm or too cold for the given met and clo combination. According to [2], the Predicted Percentage of Dissatisfied (PPD) can be directly calculated from the PMV value. This quantifies how many people in a group are likely to be dissatisfied with the indoor climate. The relationship is non-linear; even in a perfect climate (PMV = 0), the PPD value is 5 %.

The equivalent temperature ($T_{eq}$) is a measure used to assess human thermal comfort in environments with uneven conditions. It combines the effects of air temperature, radiant temperature and air velocity into a single value. The interpretation of $T_{eq}$ with respect to the physical heat balance is shown in [3]. In a series of experiments, the local heat fluxes of

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thermal manikins were determined under 30 different climatic conditions and compared with the thermal sensations reported by 20 subjects [4]. The individual sensations were averaged for each condition and reported as mean thermal vote (MTV), with MTV and $T_{eq}$ being subjected to linear regression analysis. Even today, Nilsson-$T_{eq}$ comfort zone diagrams are being reparametrized, as demonstrated by a study on relevant use cases of sedentary activities in autonomous cars [5]. Two climate chamber studies covered the temperature ranges of 12–24 °C and 22–34 °C, with thermal comfort in the colder and warmer ranges being highly dependent on the scenario.

Many studies have evaluated passenger thermal comfort in trains and airplanes using $T_{eq}$. In a generic train laboratory, two methods of assessing passenger thermal comfort were analyzed and compared [6]. First, investigations were conducted with test subjects addressing both temperature sensation and evaluation. For comparison, local equivalent temperatures were determined through objective measurements using a calibrated thermal manikin. Under steady-state thermal conditions, the results showed a good agreement between the subjective surveys and the objectively measured equivalent temperatures.

In previous studies at the German Aerospace Center (DLR), thermal comfort was investigated using two systems: The first is the Comlogo, Equites System, which provides information about $T_{eq}$ and the MTV. The second system is the Dantec Dynamics Comfort Sense, which outputs the PMV and PPD values for the whole body as well as local fluid temperatures and velocities. With a new thermal-comfort manikin system (PT Teknik Climate Comfort), which delivers local thermal comfort parameters such as $T_{eq}$ and MTV, but also the global values PMV and PPD, we can compare the measurement systems. In this study, we present a comparison of the systems in a well-defined generic test environment: a modular cabin mock-up with temperature-controlled boundary conditions and a short-range aircraft cabin (Dornier 728) [7].

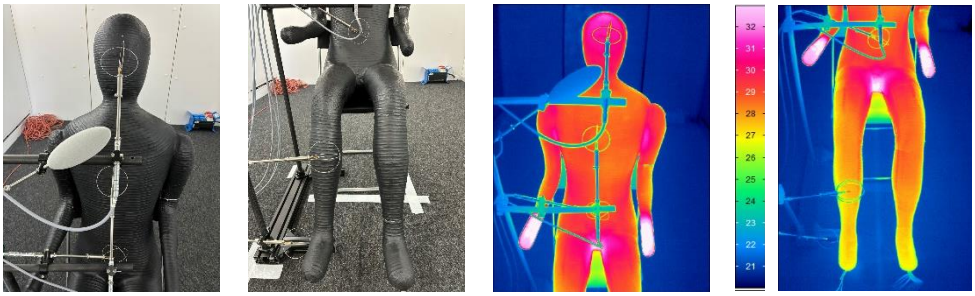
## 2 Measurement techniques

To control the boundary conditions in the two test facilities, resistance temperature detectors (RTDs) of type Pt100 (1/3 DIN B) with a calibration accuracy of 0.15 K were used. To ensure a realistic heat load and to simulate the dimensions of real people, thermal passenger dummies (TPDs) with volumes of 0.05 $m^3$ and surface areas of 1.52 $m^2$ were used in the experimental investigations, see Figure 1. The TPDs consist of a foam core wrapped with a resistance wire, which provides realistic surface temperatures and buoyancy forces through a homogeneous heat flow density (slightly increased in the head area). For the initial investigations in the modular cabin test facility, the TPDs were operated at 75 $W/m^2$ as specified in [2]. To determine the surface temperatures of the TPDs, an infrared (IR) camera with a resolution of 1.024 × 768 px and a sensitivity of 0.02 K was used (Figure 1 c and d) before the other investigated measurement systems were applied.

### 2.1 U-T-sensor system

Combined omnidirectional velocity and temperature probes were installed at five height levels with a distance of 5 cm to the TPD, see Figure 1 (a) and (b). They provide an accuracy of 0.2 K for the temperature and 0.02 m/s for the velocity. The velocity and temperature measurement system was combined with a humidity probe and an operative temperature ($T_{op}$) probe to determine the Predicted Mean Vote (PMV). For these measurements, a metabolic rate of met = 1.3 was set for a slightly active sitting person, and a clo = 1 (0.155 K•$W/m^2$) was set for a lightly clothed person. The conversion of PMV to $T_{eq}$ is performed using equation (1) specified in [4] with the linear regression constants a and b, which are given in [4] for the individual body parts in [$W/m^2$]:

$$MTV = a + b \cdot T_{eq} \quad (1)$$

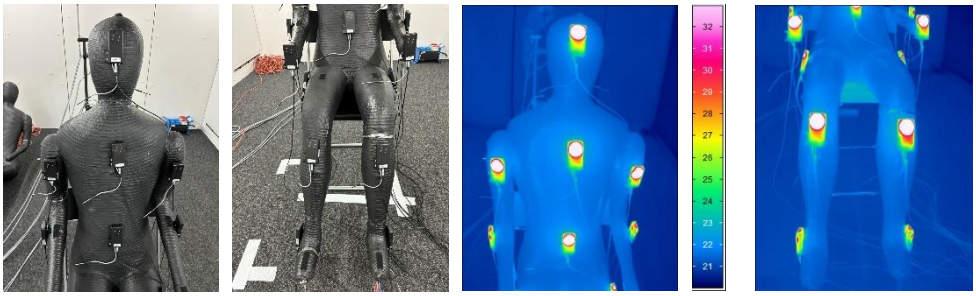



(a) (b) (c) (d)

**Figure 1.** (a) Upper and (b) lower body part of the thermal passenger dummy with combined omnidirectional velocity and temperature probes as well as infrared views of the upper (c) and lower (d) body parts.

### 2.2 $T_{eq}$-sensor system

The international standard DIN EN ISO 14505-2 [1] defines a measurement method of measuring the "perceived temperature" of humans as a climate parameter using heated sensors. The reference temperature, $T_{eq}$, is a function of the surface temperature of a heated sensor and other parameters such as the "Resultant Surface Temperature" (RST). $T_{eq}$ is an integral quantity combining air temperature, air velocity and radiation, for details see [8]. The RST is the result of a locally acting microclimate caused by heat loss. Extensive studies have defined differentiated comfort zones for different body parts, allowing for the objective and reproducible determination of a person's comfort level. 16 "Equites probes", which detect local heat flows, were mounted on a TPD, see Figure 2 (a) and (b).




(a) (b) (c) (d)

**Figure 2.** (a) Upper and (b) lower body part of the thermal passenger dummy with the $T_{eq}$-sensor system as well as infrared views of the unheated upper (c) and lower (d) body parts of the TPD.

Heated sensors are used simulating the heat output of the human, hence, the TPDs themselves were operated in switched-off mode, as shown by the IR images in Figure (c) and (d). The system enables objective comfort measurement in the form of local $T_{eq}$ with an accuracy of ±0.5 K.

### 2.3 Comfort manikin

The comfort manikin developed by PT Teknik ApS [9] is an advanced experimental instrument designed to replicate human thermoregulatory heat exchange. It is used to objectively evaluate thermal comfort and clothing properties, see Figure 3. The manikin has an anatomically realistic male body shape with a height of 1.75 m and is divided into 27 independently controlled body zones. Each zone can be controlled to maintain the same surface temperature or heat output or it can be controlled by thermo-physiological models.




(a) (b) (c) (d)

**Figure 3.** (a) Upper and (b) lower body part of the comfort manikin as well as infrared views of the upper (c) and lower (d) body parts.

The system automatically computes key thermal comfort and performance parameters, including $T_{eq}$, PMV, MTV and clothing insulation (clo).

The system's major advantages include its rapid thermal response, high spatial resolution of heat flux measurements, and exceptional temperature regulation stability. The manikin has an accuracy of ±0.2 K for temperature and 1 % for the heat flux with respective resolutions of 0.1 K and 0.1 W/m$^2$. The quality of the calibration determines the absolute accuracy. In the manikin, the sensor is a wire that covers the full body zone (averaging) and is located just below the skin surface. In other measurement systems, e.g., the $T_{eq}$-sensor system, it is a 'spot' sensor.

For the measurements in this study, the comfort manikin was operated in comfort mode, which is used to assess thermal sensation in complex, inhomogeneous environments. This mode combines data on skin temperature and heat loss to estimate thermal sensation and human well-being. It is particularly suitable for analyzing conditions that vary across different body regions, e.g., in vehicle cabins or ventilated indoor spaces. Integrating manikin measurements into this model allows us to evaluate the influence of fluctuations in air temperature, humidity, or airflow influence on the overall comfort. In comfort mode, the surface temperature for each zone of the manikin is controlled based on model calculations using heat flow and ambient conditions.

## 3 Experimental set-up

### 3.1 Modular cabin mock-up

The first experimental studies were performed in the modular cabin mock-up (see Figure ***4***). It represents a full-scale section of a passenger compartment in a railway vehicle with the following internal dimensions: 2680 x 4920 x 2110 mm³ (B × L × H). To achieve realistic thermodynamic boundary conditions – required for a comprehensive assessment of

ventilation concepts under different operating modes (e.g., heating and cooling scenarios) – the mock-up is equipped with temperature-controlled sidewall and floor elements, allowing tests to be conducted under strictly isothermal conditions with an accuracy of ±0.1 K. Since the room was not ventilated during the measurements, the airflow velocities were kept low. The measurement systems were compared under three different boundary conditions (wall and floor temperature $T_{wall}$ = 16 °C, 20 °C, 24 °C), with $T_{wall}$ being controlled by 20 RTDs. The boundary conditions (humidity, operative temperature, fluid temperature and velocity) were logged using the U-T-sensor system (Section 2.1).



(a) (b)

**Figure 4.** Modular cabin mock-up, (a) exterior view and (b) image of the interior with TPD in the middle of the cabin.

For cases involving the $T_{eq}$-sensor system and the comfort manikin, the room measurement system was positioned behind the manikin, see Figure ***4*** (b). The climate chamber with the temperature-controlled walls and measurement techniques is intended to control and comply with the clothing standard requirements [10] regarding local variations around the manikin: room size at least 2 x 2 x 2 m³, air temperature fluctuations ±1.0 °C (spatial) and ±0.5 °C (temporal), air velocity ±50 % of the mean (spatial) and ±20 % of the mean (temporal), relative humidity ±10 % (spatial and temporal) as well as spatial wall temperature fluctuations ($T_{wall}$) ±1 °C from the mean.

### 3.2 Dornier 728 (Do728) aircraft cabin

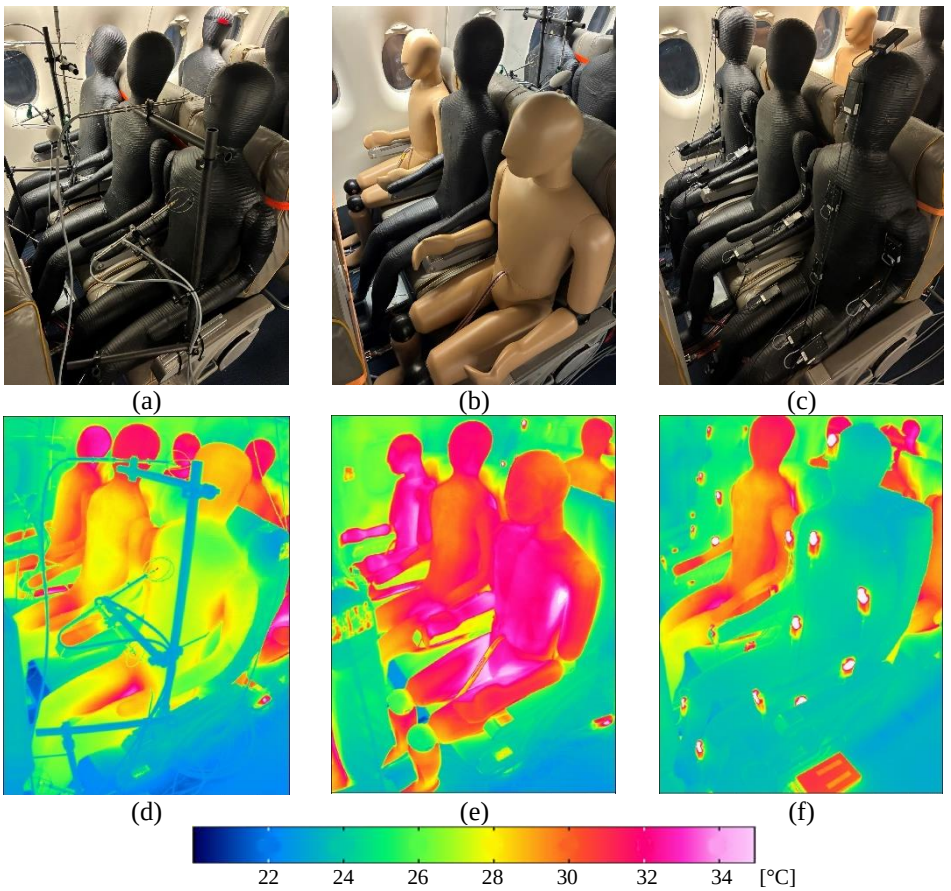
As a second test environment, we used the Do728 test facility of the German Aerospace Center in Göttingen, which is a realistic cabin structure of a short-range aircraft. This asymmetric single-aisle cabin is shown in Figure 5 (a) and has a total length of 16.9 m, a width of 3.25 m, a height of 2.14 m. The inner volume excluding seats and thermal manikins is approximately 54 $m^3$.

An external heating, ventilation and air-conditioning (HVAC) system provided fresh air at a nominal volume flow rate of QV = 600 l/s (8.2 l/s/PAX) at atmospheric pressure, yielding a nominal air exchange rate of 38 air changes per hour (ACH). Mixing Ventilation (MV) was used for ventilation. It is state-of-the-art in aircraft cabin ventilation and is characterized by a high degree of mixing of fresh air jets entering the cabin on both sides with operation at a half-half split of the airflow between lateral (LAO) and ceiling air outlets (CAO), see Figure 5 (b). The air supply to the passengers was split as follows: 40 % from the left and 60 % from the right in accordance with the 2-3 seating arrangement. Please note: orientations such as left and right refer to the direction of flight, whereas the images and sketches in Figure 5 face the rear of the cabin.



(a) (b)

**Figure 5.** (a) Image of the interior of the Do728 aircraft cabin and (b) sketch of the used ventilation system (Mixing Ventilation - MV).




(a) (b) (c)

(d) (e) (f)

**Figure 6.** Measurement techniques installed in the Do728:
(a) and (d): U-T-sensor system at seat 5C and 5E;
(b) and (e): comfort manikin at 6C and 6E;
(c) and (f): $T_{eq}$-sensor system at seat 7C and 7E.

The air entered the cabin with nominal mean entry velocities of 1.7 m/s and the resulting air jets ensured efficient mixing of fresh and recirculated air generating the large-scale roll

structures, which are characteristic of MV as shown in Figure 5 (b). The air was removed from the cabin by active suction through air extraction slits behind the dado panels located in the lower side walls. For more details, see [7].

Following the initial basic measurements in the modular cabin mock-up, the systems were installed in the Do728, see Figure 6. The measurement positions were at the aisle (seat C) and window (seat E) in the three-seat row facing right in the direction of flight (FDR). The combined omnidirectional velocity and temperature probes were installed in front of the heated TPDs in row 5, see Figure 6 (a, d). The comfort manikins were seated in seats 6C and 6E, see Figure 6 (b, e). The $T_{eq}$-sensor system on the unheated TPDs was installed in row 7, see Figure 6 (c, f). The rest of the cabin was also equipped with heated TPDs.

# 4 Results

The following sections contain a detailed discussion of the results: Section 4.1 describes the results obtained in the modular cabin mock-up, while Section 4.2 illustrates the differences observed in the Do728 aircraft cabin. Finally, Section 4.3 compares the time responses of the three systems.

## 4.1 Modular cabin test facility

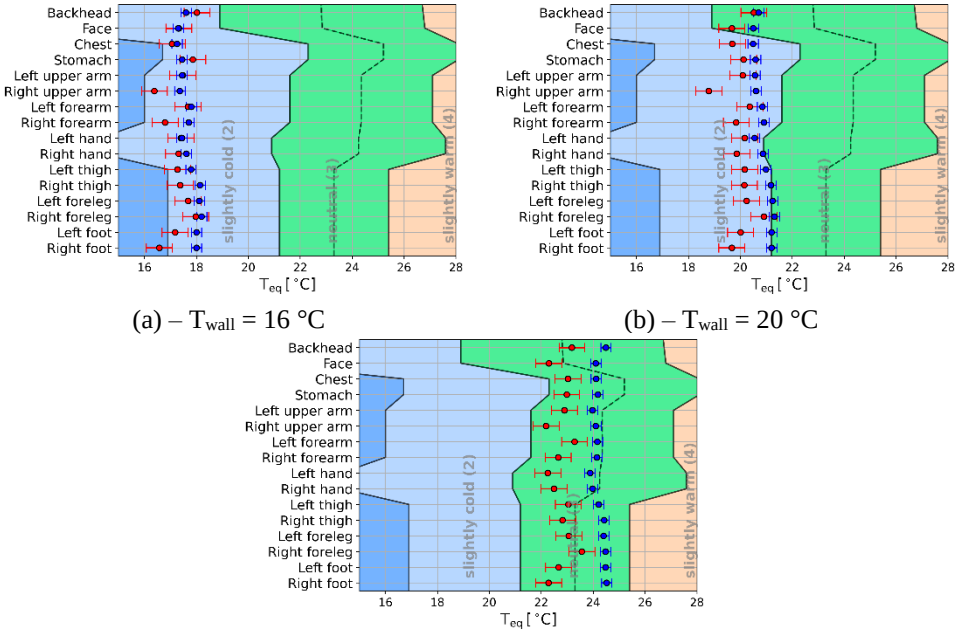
Before briefly discussing the results of the different cases, it should be noted that throughout all tests the modular cabin mock-up was not ventilated and the wall temperature ($T_{wall}$) – averaged using 20 RTDs behind the walls – was kept constant with maximum differences of 0.1 K, see Table 1.

**Table 1.** Investigated boundary conditions with $T_{wall}$, humidity rh, operative temperature $T_{op}$, fluid temperature $T_{air}$ and velocity U as well as mean equivalent temperature $T_{eq}$ with thermal comfort indices PMV and PPD for all investigates cases.

| | $T_{wall}$ [°C] | rh [%] | $T_{op}$ [°C] | $T_{air}$ [°C] | $U_{max}$ [m/s] | $T_{eq}$ [°C] | PMV [-] | PPD [%] |
|---|---|---|---|---|---|---|---|---|
| Case 1_1 (U-T-sensor) | 16.2 (±0.0) | 43 (±2) | 18.1 (±0.5) | 18.3 (±0.3) | 0.15 | - | -0.5 | 9 |
| Case 1_2 ($T_{eq}$-sensor) | | | | | 0.03 | 17.3 | - | - |
| Case 1_3 (manikin) | | | | | 0.03 | 17.6 | -0.4 | 9 |
| Case 2_1 (U-T-sensor) | 20.0 (±0.1) | 40 (±1) | 20.6 (±0.7) | 21.1 (±0.5) | 0.18 | - | 0.0 | 5 |
| Case 2_2 ($T_{eq}$-sensor) | | | | | 0.03 | 20.0 | - | - |
| Case 2_3 (manikin) | | | | | 0.03 | 20.8 | 0.1 | 5 |
| Case 3_1 (U-T-sensor) | 24.0 (±0.1) | 33 (±1) | 23.8 (±0.6) | 24.2 (±0.6) | 0.19 | - | 0.6 | 13 |
| Case 3_2 ($T_{eq}$-sensor) | | | | | 0.06 | 22.8 | - | - |
| Case 3_3 (manikin) | | | | | 0.03 | 24.2 | 0.8 | 18 |

The table summarizes the relative humidity (rh) and the operative temperature ($T_{op}$) in the room for all cases. Please note that rh and $T_{op}$ were recorded using the U-T-sensor system described in Section 2.1: for the cases 1_1, 2_1 and 3_1 in front of the heated TPD; for the other cases behind the manikin, as shown in Figure 4 (b). The relative humidity decreases with increasing $T_{wall}$. The $T_{op}$ values differ between 1.0 K and 1.2 K due to the different measurement positions and buoyancy forces in front of the heated TPD. Low velocities were found in cases 1_1, 2_1 and 3_1, which were slightly increased by the buoyancy forces near the TPD. As expected, due to the lack of ventilation in the modular mock-up, the Teq-sensor system and comfort manikin cases show very low velocities.

Furthermore, the table shows the averaged $T_{air}$ and $T_{eq}$ as well as the comfort indices PMV and PPD, which will be discussed in the following. The fluid temperature ($T_{air}$) was recorded by the U-T-sensor system measured at five different heights, as detailed in Section 2.1. The $T_{air}$ measurement position in the U-T-sensor system (1_1, 2_1, 3_1) was shifted behind the manikin for both the $T_{eq}$-sensor system and the comfort manikin, see Figure 4 (b). For all cases, the $T_{air}$ values were a little higher than the $T_{op}$. values. A $T_{eq}$-value for the entire body is only issued by the comfort manikin. This value is automatically determined by the program across all 27 body parts (including those that touch the seat/backrest, see Table ***1***). To enable comparison of the results, the values of the individual $T_{eq}$-sensor system for cases 1_2, 2_2, and 3_2 were averaged to obtain a single $T_{eq}$ value. For case 2_2, we observed a $T_{eq}$ of 20 °C at a $T_{wall}$ of 20 °C. At lower or higher wall temperatures, $T_{eq}$ deviated slightly from $T_{wall}$. At 16 °C, $T_{eq}$ was 1.3 K higher, and at 24 °C, it was 1.2 K lower. By comparison, we found higher values for the comfort manikin, with the difference increasing as $T_{wall}$ rises. The comfort indices PMV and PPD were also determined based on $T_{eq}$ for the comfort manikin cases (1_3, 2_3, 3_3). The PMV and PPD values are highly comparable to those of the U-T-sensor system. Case 2_1 (PMV = 0.0) shows a PPD of 5 %, which is the lowest specified value [2].




(a) – $T_{wall}$ = 16 °C

(b) – $T_{wall}$ = 20 °C

(c) – $T_{wall}$ = 24 °C

**Figure 7.** Comparison of equivalent temperatures for a wall temperature of 16 °C in (a), 20 °C in (b) and 24 °C in (c) measured with the $T_{eq}$-sensor system (red) and the comfort manikin (blue).

Figure 7 provides a more detailed evaluation of the measurement systems. It shows the time-averaged $T_{eq}$ over 1800 seconds on 16 different body parts, as measured by the $T_{eq}$-sensor system and the comfort manikin at $T_{wall}$ = 16 °C (a), 20 °C (b) and 24 °C (c). To facilitate comparison of the three different temperatures, the X-axis shows the full range of values for all three measurement cases, from the lowest ($T_{wall}$ = 16 °C) to the highest ($T_{wall}$ = 24 °C). For the evaluation of the measuring systems, the comfort zones (according to [3]) for summer conditions with light clothing (0.6 clo = 0.09 m²K/W) were colour-coded in the background. The error bars of the $T_{eq}$-values reflect the uncertainties of the systems.

At $T_{wall}$ = 16°C, shown in Figure 7 (a), a mean value of 17.3 °C with differences of up to 1.6 K was found between maximum and minimum for the $T_{eq}$-sensor system. In comparison, the comfort manikin results show a slightly higher mean value of 17.6 °C, but a lower maximum difference of 1.0 K for the depicted body parts (i.e., excluding the body parts touching the seat and backrest). Especially for the upper body parts – including the hands – similar values were measured. The only exception is the right arm. Greater deviations were found in the leg and foot area. Here, the $T_{eq}$-sensor system determined an average temperature of 17.3 °C, whereas the comfort manikin acquired higher values with an average of 18 °C. Similar values were found for the face and the right foot for the U-T-system. However, larger differences of up to 4.5 K were found for the chest, stomach and foreleg. Overall, all measurement positions were classified as slightly cold, except for the right foot in the $T_{eq}$-sensor system, which was classified as too cold.

The results for $T_{wall}$ = 20 °C depicted in Figure 7 (b) show a $T_{eq}$ mean of 20 °C for the $T_{eq}$-sensor system (see also Table 1). Single values of the $T_{eq}$-sensor system deviate by less than 1.5 K from this mean value, with a standard deviation of just 0.45 K. In contrast, the comfort manikin shows a higher average value of $T_{eq}$ = 20.8 °C, but with a smaller range of values (20.4 °C – 21.3 °C). Overall, the shape of both curves is similar to that of the previous measurement at $T_{wall}$ = 16 °C in Figure 7 (a), shifted on average by 2.6 K for the $T_{eq}$-sensor system and by 3.2 K for the comfort manikin. With the exception of the head position, all measurement positions are classified as slightly cool by the $T_{eq}$-sensor system, whereas the lower body of the comfort manikin falls into the neutral comfort range.

Further increasing $T_{wall}$ by 4 K to 24 °C resulted in an average increase of 3.4 K in the $T_{eq}$ value for the comfort manikin, while the $T_{eq}$-sensor system measurement increased by only 2.8 K, resulting in a greater difference in the equivalent temperatures acquired by the two systems. All values are rated as comfortable for $T_{wall}$ = 24 °C with a comfort classification of light clothing (clo = 0.6).

As the $T_{eq}$-sensors were individually calibrated in a climate chamber, and the comfort manikin was calibrated in the modular cabin mock-up, it is possible that any temperature stratifications were eliminated by the “nude calibration” of the comfort manikin.

### 4.2 Dornier Do728

Finally, the systems were installed in the aircraft in three rows, as described in Section 3.2 and compared with each other under defined boundary conditions. Since the Do728 is actively ventilated, sensors were installed in the air outlets to determine the supply air temperature ($T_{in}$). In contrast to the modular cabin mock-up, the interior surfaces of the Do728 cannot be temperature-controlled. This means that $T_{wall}$ is determined by ventilation and the heat output of the TPDs. The resulting exhaust temperature ($T_{out}$) was measured in the Dado outlets in the lower lateral sidewalls. The additional values for operative temperature ($T_{op}$), relative humidity (rh) and maximum velocity ($U_{max}$) were measured using the U-T-sensor system in row 5. Table 2 summarizes the boundary conditions.

**Table 2.** Boundary conditions of the Do728 measurement.

| | $T_{in}$ [°C] | $T_{out}$ [°C] | $T_{air}$ [°C] | $T_{wall}$ [°C] | $U_{max}$ [m/s] | rh [%] | $T_{op}$ [°C] |
|---|---|---|---|---|---|---|---|
| Do728 | 15.5 | 21.6 | 21.8 | 23.8 | 0.27 | 29 | 23.4 |

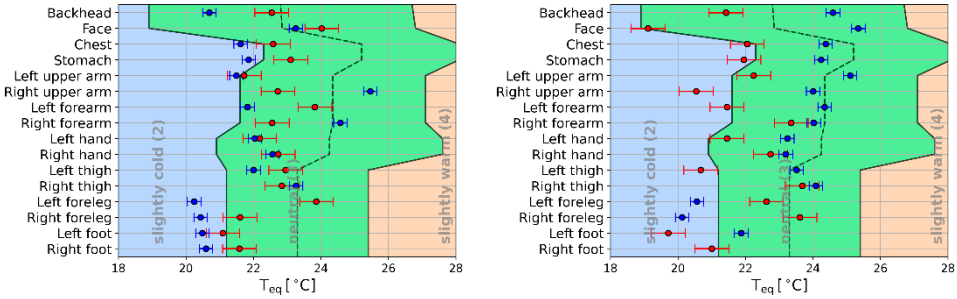
Table 3 shows the average results for rows 5 (U-T-sensor system), 6 (comfort manikin) and 7 ($T_{eq}$-sensor system) for seats C (aisle) and E (window). The table contains two different $T_{eq}$ values: The first column contains the value for the entire body, which the comfort manikin automatically outputs. To compare the equivalent temperatures, the values measured at different heights for all measurement systems were averaged to generate a second value, which is shown in column five. Body parts of the comfort manikin that touch the seat and backrest have been omitted. As the right foot of the comfort manikin in seat 7E was defective, the average values for $T_{eq}$, PMV and PPD are not included in the table. The measurement position "right foot" was also not included in the averaging of the remaining values or in Figure 8. A comparison of the comfort manikin values across all body parts (23.9 °C) with the average $T_{eq}$ of the body parts not in contact with seating surfaces (22.0 °C) shows a difference of 1.9 K. Therefore, in this study we refer to the average values indicated in column five ($|T_{eq}|$), which can be more easily compared with the $T_{eq}$-sensor and the U-T-sensor system. Similar values were observed for seat C with 22.6 °C ($T_{eq}$-sensor system - 7C) and 22.0 °C (comfort manikin - 6C). However, the value for the window seat E is almost 2 K higher for the comfort manikin as compared to the $T_{eq}$-sensor system. A significantly lower mean $T_{eq}$ was observed for the U-T-sensor system at both seats. With associated PMV values between -1.3 and -1.5 and resulting PPD values between 38 % and 49 %, the climate is rated as too cold and uncomfortable.

**Table 3.** Mean results for the Do728 with three measurement systems: U-T-sensor, comfort manikin and $T_{eq}$-sensor in three different rows at the aisle (C) and window seat (E).

| | $T_{eq}$ [°C] | PMV | PPD [%] | DR [%] | $\|T_{eq}\|$ [°C] | $\|T_{eq}\|$ Max - Min | $\|T_{air}\|$ [°C] |
|---|---|---|---|---|---|---|---|
| 5C (U-T-sensor) | - | -1.5 | 49 | 24 | 15.1 | - | 21.4 |
| 6C (manikin) | 23.9 | 0.3 | 7 | - | 22.0 | 5.5 | - |
| 7C ($T_{eq}$-sensor) | - | - | - | - | 22.6 | 2.9 | - |
| 5E (U-T-sensor) | - | -1.3 | 38 | 12 | 16.2 | - | 22.3 |
| 6E (manikin) | - | - | - | - | 23.6 | 5.2 | - |
| 7E ($T_{eq}$-sensor) | - | - | - | - | 21.7 | 4.6 | - |

For a more detailed evaluation of the measurement systems, Figure **8** shows $T_{eq}$ time-averaged over 1800 s for 16 different body parts measured by the $T_{eq}$-sensor system and the comfort manikin on seat C in (a) and on seat E in (b). First of all – unlike in the modular cabin mock-up – we found that there is no clear trend in these values. Furthermore, there is quite a large range of recorded $T_{eq}$-values from 19.1 °C to 25.5 °C for seat E. The distribution differs significantly between seat C and seat E, reflecting the inhomogeneity of the ventilated

aircraft cabin. At seat C (see Figure 8 a) we recorded almost the same values in the lower leg area and at foot level for the comfort manikin with slightly lower values on the left side of the body. This is probably caused by the fresh air flowing down the aisle. The $T_{eq}$-sensor system also showed this left-right difference at the feet. However, an elevated temperature of 2.3 K at the left leg cannot be explained, as lower temperatures would be expected due to the airflow in the aisle section. A temperature difference between the left and right sides was also found on the thighs of the comfort manikin, whereas the $T_{eq}$-sensor system showed almost the same value. The comfort manikin method indicated that all areas of the left side of the body felt colder. However, the results for the $T_{eq}$-sensor system were very different. As expected, lower values were found on the left side of the hands and upper arms, while a higher $T_{eq}$ was observed on the right side of the forearms. The systems also produced different results for the head area: While similar values were found on the face, the back of the head showed differences of almost 2.0 K.




(a) – seat C (b) – seat E

**Figure 8.** Comparison of equivalent temperatures for seat C in (a) and seat E in (b) measured by the $T_{eq}$-sensor system (red) and the comfort manikin (blue).

As expected, the fresh air supply in the aisle section and the large-scale flow structure resulted in rising air near the window and in a different $T_{eq}$ distribution on seat E. As highlighted in Table 3, Figure 8 (b) also shows a less homogeneous temperature distribution for the $T_{eq}$-sensor system. While the comfort manikin indicated a slight temperature stratification, the $T_{eq}$-sensor system showed a fluctuation around the mean value of 21.7 °C. Both systems showed higher temperatures on the left side of the upper arms due to the heated neighbouring TPD on the middle seat D. This is also reflected by the measurements on the forearms of the comfort manikin. However, higher values were found on the right side using the $T_{eq}$-sensor system, which was probably caused by the positioning of the sensor. There was no clear trend for the legs. While both systems revealed a similar $T_{eq}$ on the right thigh, the values on the left thigh differed by almost 3 K. Furthermore, while the comfort manikin indicated that the left lower leg was warmer, the $T_{eq}$-sensor system reported the opposite. However, this discrepancy could also be due to the different measurement methods: unlike the comfort manikin, which takes an area measurement, the $T_{eq}$-sensor system records temperatures at specific points. Finally, it should be noted that the large-scale structures in a ventilated aircraft cabin also occur in longitudinal direction. Hence, the observed differences between the sensor systems might partially also be caused by their position in different seat rows.

### 4.3 Comparison of the time responses

In the previous sections, the mean values averaged over the 1800 s duration of the measurement run were compared and discussed. In the following, we will briefly present the

time responses of the different measurement systems. It should be noted that the ambient conditions were maintained at stationary conditions in the modular cabin mock-up and the Do728. For the sake of brevity, only the results for the face sensors are presented here.

Figure **9** depicts the results recorded in the climate-chamber-like modular cabin mock-up without external ventilation. The temperature range of the plots is maintained at 0.7 K, but shifted to the capture the recorded values of the individual sensor systems. In the top row (red), the equivalent temperatures recorded by the $T_{eq}$-system are shown. These were measured on an unheated manikin. The data, measured at 1 Hz, revealed small fluctuations of generally less than ±0.1 K over a time-scale of a few seconds. Additionally, some low-frequency fluctuations with a period of approximately 900 s were identified. In contrast, the equivalent temperatures recorded by the comfort manikin (middle, blue), showed no fluctuations at all. It should be noted that the data was measured at a frequency of 1/5 Hz and the stored $T_{eq}$-values only have one decimal digit. Averaged over 1800 s, the recorded equivalent temperatures were about 0.9 K higher compared to the $T_{eq}$-sensor system. This difference can be attributed to the heat release of the manikin body itself, which resulted in slightly elevated temperatures in the facial region. In the bottom row, the individual measurement quantities of the U-T-system are presented. Both were acquired at a frequency of 1/2.5 Hz. The temperature (green) revealed only high-frequency fluctuations with amplitudes lower than 0.05 K. The measured omnidirectional velocity magnitude (orange) exhibited similar fast, small-scale fluctuations around the mean value of just under 0.2 m/s.

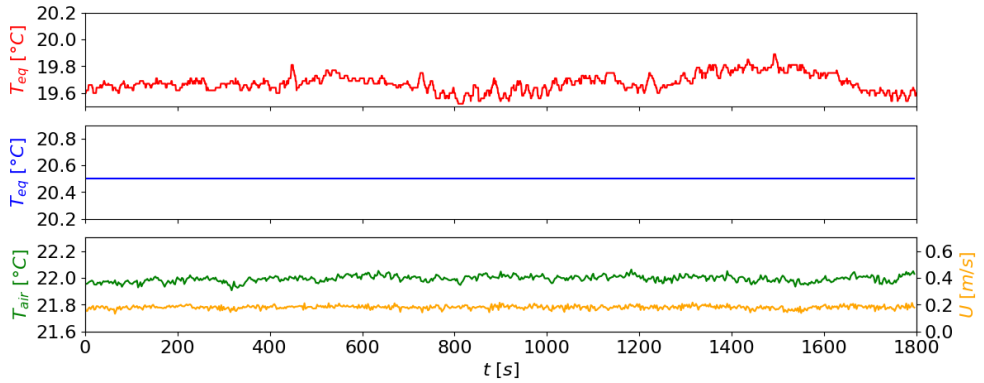



**Figure 9.** Evaluation of the time responses of the measurement systems in the modular cabin mock-up. Top: $T_{eq}$ (red) recorded by the $T_{eq}$-sensor system; middle: $T_{eq}$ (blue) recorded by the comfort manikin; bottom: $T_{air}$ (green) and U (orange) recorded by the U-T-system.

Figure **10** shows the data recorded in the Do728 for the face sensor represented in the same way as in Figure **9**. However, the ranges of the temperature data was increased to 2 K in order to capture the dynamics. As a reminder, the Do728 was operated under steady-state temperature and volume flow rate conditions with standard state-of-the-art mixing ventilation during the measurements. The $T_{eq}$-sensor data (top row, red) did not capture the high-frequency fluctuations, which were found in the modular cabin mock-up without forced airflow (also not visible when zooming into the data). Accordingly, it seems that the sensor reduces small-scale fluctuations when it is imposed to a forced flow. However, the sensor measured some fluctuation with a period of approximately 20 s and an amplitude slightly larger than 0.1 K. At this point it is assumed – though not yet confirmed – that these fluctuations are caused by the airflow in the Do728 rather than by the sensor itself. Again, the comfort manikin measured almost no changes in $T_{eq}$. Only towards the end of the measurement period did some changes to the next digit become apparent. In contrast, the U-T-sensor system (bottom, green and orange) recorded rapid temperature and velocity

magnitude fluctuations next to the manikins' face. Amplitudes as high as 1.5 K and 0.2 m/s were measured, reflecting the turbulent nature and small-scale fluctuations of the airflow in the Do728 in case of mixing ventilation.

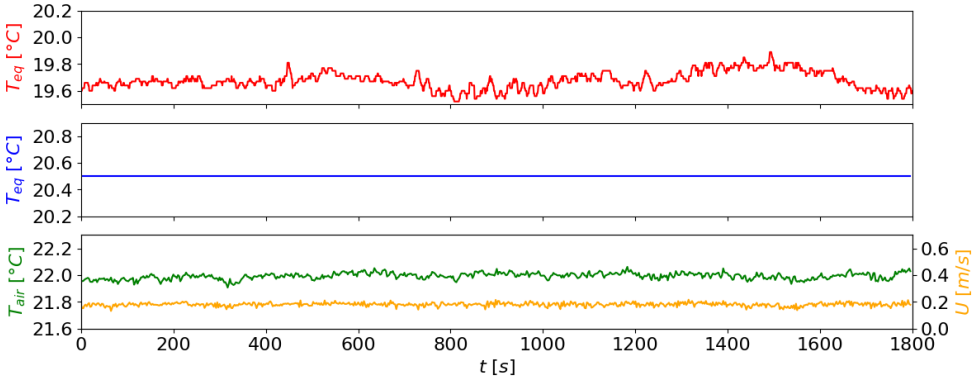



**Figure 10.** Evaluation of the time responses of the measurement systems in the ventilated Do728. Top: $T_{eq}$ (red) recorded by the $T_{eq}$-sensor system; middle: $T_{eq}$ (blue) recorded by the comfort manikin; bottom: $T_{air}$ (green) and U (orange) recorded by the U-T-system.

Taking into account the measured air temperature and velocity magnitude fluctuations, which are present in the Do728, it must be concluded, that neither the comfort manikin nor the $T_{eq}$-sensor system was capable of acquiring such high-frequency changes in the local conditions. Therefore, if one is interested in these high-frequency fluctuations, i.e., in the order of a few seconds, then individual sensor systems are preferable over the comfort manikin systems. The $T_{eq}$-sensor system provides an intermediate solution, since the small local sensors detect local changes much faster compared to the body-segmented comfort manikin. However, whether such air temperature fluctuations and changes in the local air velocities in the range between 0.1 and 0.3 m/s, as determined in the Do728, are felt by normally dressed passengers at all, is a different question. As most changes in temperature and airflow conditions rather occur within a few minutes, the $T_{eq}$-sensor system and the comfort manikin will most likely also resolve the relevant time-scales.

## 5 Conclusion

This paper presents a comparison of measurement techniques used to record thermal passenger comfort. The experiments were conducted in a modular cabin mock-up – a climate-chamber like compartment – and in the Dornier 728 aircraft cabin test facility of the German Aerospace Center in Göttingen. Three measurement techniques were investigated: First, a fluid velocity and temperature measurement system (U-T-system) was used in the vicinity of heated thermal passenger dummies (TPDs). Second, an equivalent temperature probe sensor system ($T_{eq}$-sensor system) was used and third, a thermal-comfort manikin system simulated and evaluated a person's thermal comfort in realistic environments. The most important findings when comparing the measurement systems in the modular cabin mock-up and the Do728, are as follows:

- The $T_{eq}$-sensor system with the local, point-based probes and the comfort manikin acquired similar comfort ratings.
- The small, local sensors of the $T_{eq}$-sensor system can detect local changes significantly faster than the segmented comfort manikin.

- Localized cooler or warmer air jets can distort the comfort assessment of the local $T_{eq}$-sensors if they directly hit the sensor element. The body-segment averaging comfort manikin provides a more robust comfort assessment.
- The U-T-system is highly sensitive to fast small fluctuations of the airflow conditions. However, a trade-off must be considered: either placing the probes close to a heated TPD to ensure realistic overall flow structures – but this increases the specific local temperature readings – or placing the probes without a heated TPD above the empty seat.

An important point in assessing thermal comfort is the clothing factor (clo), which results in the mean thermal vote (MTV) being rated differently for all body parts. The comfort manikin allows users to determine the clothing factor by actively dressing the manikin. This should be considered for future measurements.

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