The DressMAN 3.2-System for evaluation of thermal comfort in the Passenger Cabin Ground Demonstrator

Michael Visser, Sume Park, Sebastian Stratbücker, Victor Norrefeldt, Andreas Lindner
Fraunhofer IBP, Fraunhofer Str. 10, D-83626 Valley, Germany
Victor.norrefeldt@ibp.fraunhofer.de

Abstract. This paper describes an improved measurement method and sensor development for the assessment of the indoor thermal environment. The disadvantage of the state of the art concept of the equivalent temperature to describe inhomogeneous environments is pointed out and how the DressMAN 3.2 sensor system provides improvements to this measurement principle. The measurement system has been prepared in order to accompany thermal tests in the Passenger Cabin Ground Demonstrator developed within the CleanSky2 Regional project. This shall allow the objective assessment of the passenger comfort in the mock-up without the need for extensive subject test campaigns.

1. Background

Thermal comfort has long been a topic of investigation in the aircraft cabin. Typically, thermal comfort is assessed by means of measuring the temperature stratification of cabin air between feet and head level, the airflow velocity in the neck level as a marker for draft and the envelope temperature. ISO 15251 [1] provides an assessment of the quality of the thermal environment and attributes it to the classes A, B and C. Nevertheless, the assessment of thermal comfort by this method bears some disadvantages. Especially local thermal discomfort cannot be detected. Sources for local thermal discomfort in the aircraft can originate from e.g. heat bridges in the floor area, where the supporting floor beams are thermally connected to the exterior skin without insulation layer. Another source of local discomfort may arise from or solar radiation through the aircraft window. In order to assess such local comfort, ISO 14505-2 [2] suggests the concept of the equivalent temperature. This temperature is an imaginary temperature that refers the state of local thermal balance of a heated surface in non-homogeneous conditions to a pre-calibrated homogeneous condition. An equivalent temperature sensor typically consists of a heated surface, which emits its heat by convection to the indoor air and radiation to enclosures. As a result, the surface temperature reaches an equilibrium between supplied and lost heat. In a pre-calibration in homogeneous environment without forced air movement, the same resulting surface temperature of the sensor is referred to the temperature of the calibration chamber – the equivalent temperature. A third way to assess thermal comfort is the Fanger PMV model (ISO 7730 [3]) that solves the energy equation of human thermal production, gains and losses and attributes a Predicted Mean Vote depending on this balance.

The Fraunhofer Institute for Building Physics IBP has developed the DressMAN (Dummy REpresenting Suit for Simulation of huMAN heatloss), to measure thermal comfort in inhomogeneous
environments. The first version of the sensor dates back to the 1990s, being developed as a measurement system for the equivalent temperature. It is designed according to the standard DIN EN 14505-2. In 2014, the DressMAN Sensor was further developed and deployed [4,5]. In the following years, a third version with smaller sensors thus carrying less thermal mass has been created. This made it possible to measure the rapidly changing environment during the cooling and heating phase of a cabin. In addition, data acquisition was realized with wireless sensor technology and the conversion of the data to the CAN protocol.

One disadvantage of the concept of equivalent temperature is that it is largely dependent on the heating power of the sensor. Especially in miniaturized sensors, the accurate measurement of the dissipated heat becomes challenging. As an example, if a sensor is heated with 50 W/m², it would in a calibration condition of 20 °C reach a resultant surface temperature of:

\[ RST = \frac{\dot{q}}{h_{c,cal} + h_r} + T_{eq} \]  
(Equation 1)

Assuming \( h_{c,cal} = h_r = 5 \) W/m²K for convection in stagnant air and for radiative heat exchange coefficient, the RST would thus be 5 K above the equivalent temperature.

Accordingly, for a sensor heated with 100 W/m²K, RST will be 10 K above equivalent temperature.

If now both sensors are exposed to a non-homogeneous environment, for example by increasing the airflow velocity to reach a convective heat transfer coefficient of 10 W/m²K, the heat balance becomes:

\[ \dot{q} = h_c \cdot (RST - T_{air}) + h_r \cdot (RST - T_{surf}) \]  
(Equation 2)

And thus RST:

\[ RST = \frac{\dot{q} + h_c T_{air} + h_r T_{surf}}{h_c + h_r} \]  
(Equation 3)

Assuming \( T_{air} = T_{surf} = 20 \) °C, the RST and consequently the equivalent temperatures adopt values depicted in Table 1 and hence give different results for the same thermal environment.

| Heat Flow Rate in W/m²K | RST in °C | Teq in °C |
|-------------------------|-----------|-----------|
| 50                      | 23.3      | 18.3      |
| 100                     | 26.7      | 16.7      |

This example shows that the classical approach to measure the equivalent temperature has the inherent difficulty of being dependent of the heat flow rate applied on the sensor. Therefore, within the CleanSky2 Regional project, it was sought to develop an improved sensor to validate passenger’s thermal comfort during an upcoming test campaign in the Regional Passenger Cabin Ground Demonstrator. The Passenger Cabin Ground Demonstrator will consist of a full-scale fuselage section of a future Regional aircraft consisting of the door/galley area and five rows of seats. The demonstrator’s aim is to validate innovative systems and human centered design concepts within the CleanSky2 Regional project. The Passenger Cabin is a Clean Sky JU Leader LEONARDO Aircraft Demonstrator for all aspects concerning research, technological maturation, design, manufacturing and integration. It will in the course of the project be transferred to Fraunhofer for thermal testing. Within Fraunhofer, the demonstrator will be equipped with an ECS emulation system and an exterior conditioning to be able to
thermally imitate the operation of the cabin section over a flight cycle. A sketch of the current planning status is shown in Figure 1.

2. The DressMAN 3.2 System

While all until now existing DressMAN sensor generations dealt with a heated sensor probe, the new DressMAN 3.2 only features a heated sensor to assess the convective heat transfer coefficient and additionally three further sensors: an air temperature sensor and two thermopile sensors, for long-wave and short-wave radiation measurement. These are used to calculate the mean radiant temperature. As a result, individual variables such as the intensity of solar radiation or air velocity and their contribution to thermal comfort can be discerned. In addition to the equivalent temperature, the sensor system has been extended with temperature measurement on the contact area of the seat. This allows taking into account heat conduction and its impact on the overall human body heat transfer. With this measurement kit (Figure 2), scenarios with heated or cooled seats are now assessable, too.
The further developed sensors are attached on 28 defined body segments with velcro fasteners (see Figure 3).

![Figure 3: Measurement positions on the DressMAN system](image)

2.1. Deduction of the equivalent temperature

This section describes the mathematical steps to deduce the equivalent temperature from the raw measurement of the DressMAN 3.2 sensor.

For the heat balance equation, the DressMAN 3.2 sensor delivers the convective heat transfer coefficient $h_c$, the air temperature $T_a$ and the resulting radiant temperature $T_r$ computed from the solar and long wave heat flux signals. Through this, the boundary conditions of the thermal environment are well described. The heat $q_1$ released by a human body segment depends on these boundary conditions and on the surface temperature of the clothing, $T_{cl}$.

$$ q_1 = h_c \cdot (T_{cl} - T_a) + h_r \cdot (T_{cl} - T_r) \quad \text{(Equation 4)} $$

By definition, the equivalent temperature $T_{eq}$ results in the same heat flow under calibration conditions ($h_c, cal = 5 \text{ W/m}^2\text{K}$) and under homogeneous temperature envelope. Thus, $q_1$ and $q_2$ must be equal.

$$ q_2 = h_{c,cal} \cdot (T_{cl} - T_{eq}) + h_r (T_{cl} - T_{eq}) \quad \text{(Equation 5)} $$

With this, the equivalent temperature can be determined as:

$$ T_{eq} = T_{cl} - \frac{(h_c(T_{cl} - T_a) + h_r(T_{cl} - T_r))}{(h_{c,cal} + h_r)} \quad \text{(Equation 6)} $$

The human body thermal regulatory system is assumed to strive for maintaining a skin surface temperature of 34 °C under any thermal condition. Discomfort thus is expressed as an increased heat requirement (= freezing) or excess heat to be removed (= sweating) in order to constantly maintain this skin surface temperature. Therefore, different body segments naturally have different heat flow densities (e.g. relatively high heat flow at head). The dry heat flow of the skin to the clothing surface depends on the clothing isolation value $I_{cl}$. ISO 7730 provides local and global clothing values for different combinations.
\[ q_3 = \frac{(34^\circ C - T_{cl})}{I_{cl}} \quad \text{(Equation 7)} \]

Through this approach, the actual local clothing of people or seasonal adaption can be accounted for. Using the condition that heat flows \( q_1 \) and \( q_3 \) are equal, the clothing surface temperature can be determined:

\[ T_{cl} = \frac{(34^\circ C + I_{cl} (h_c T_a + h_r T_r))}{1 + I_{cl} (h_c + h_r)} \quad \text{(Equation 8)} \]

By default, the DressMAN 3.2 evaluation procedure determines the local equivalent temperatures using actual clothing insulation values, values used by Nilsson [6] or with a uniform insulation value of 0.8 clo for all local body segments. A clothing value of 0.8 corresponds to slightly warmer clothing than a combination of underwear, shirt, trousers, socks and shoes. With equations 6 and 8, the local equivalent temperature is computed from the available sensor signals.

2.2. Extension with surface temperatures

For body parts exposed to conductive heat exchange, the measurement of the contact temperature provides the clothing surface temperature. The heat flow is deduced straightforward based on the clothing insulation value and the skin temperature of 34 °C by using equation 7.

2.3. Comfort rating

The DressMAN 3.2 systems allows comfort rating based on the classical approach described in ISO 14505-2 by using the air sensors only. The 28 identified equivalent temperatures are then assigned to 12 body segments, to find the local equivalent temperature. These local equivalent temperatures are compared with the comfort diagram in the standard ISO 14505-2 and used to evaluate the local thermal comfort of each body segment (Top branch of Figure 4).

A second way to assess the overall comfort includes the seat contact area. For this, local heat flow densities are determined by using Eq.2. These are area-weighted together with the heat flow density from the contact area, to calculate the overall heat flow density. From this average overall heat flow density, the extended equivalent temperature \( T_{eq} \) is determined with the help of equations 7 and 5. This extended equivalent temperature can be used in other models such as the Fanger PMV model described in ISO 7730 to create the predicted mean vote (PMV) for the thermal environment.
3. Application example

An application example was set up to assess the impact of solar radiation through an aircraft window on solar radiation. For this, an original aircraft exterior window and interior sidewall window frame were integrated in a box. The DressMAN 3.2 was placed in this box reflecting the actual distance and elevation of a cabin arrangement. The solar zenith and azimuth were varied by changing the inclination and orientation of the box, leaving the solar lamp fixedly installed. The lamp produces a realistic wavelength reproduction of solar radiation. The test setup is integrated in the temperature and flow controlled chamber Indoor Air Test Center (IATC) at Fraunhofer IBP, Holzkirchen, Germany.

Figure 5: Test setup of DressMAN 3.2 behind aircraft window

Figure 6 shows the measurement result for the left arm sensors for the test setting of a solar load of 830 W/m², an azimuth of 0° and elevation angle of 80° and a chamber air temperature setpoint of 22 °C. In a first stage, no forced convection was directed towards the DressMAN 3.2 system and the solar lamp was switched off. Thus, the equivalent temperature for all left arm measurement locations is close to the air temperature, the convective heat transfer coefficient is close to 5 W/m²K (natural convection) and no solar load is measured.

At 13:16, the solar lamp is activated leading to a direct impact on the left oriented sensor on the left upper arm. Due to the increase solar load, the equivalent temperature at this position increases. The convective heat transfer coefficient is not impacted and remains close to natural convection.

At 13:28, the air movement in the test chamber is increased leading to an increased reading for the convective heat transfer coefficient. As a result, the equivalent temperature drops. For the left upper arm, the solar impact thus is compensated by increased air movement.
Figure 6: Measurement signals on left arm
4. Conclusion

The new implementation of the DressMAN 3.2 system to objectively assess thermal comfort in indoor spaces has been shown in this publication. This system has been prepared in order to assess human centered thermal design aspects in the Passenger Cabin Ground Demonstrator. A proof of concept measurement shows the large potential of this system to assess thermal comfort in the cabin and to identify root causes of discomfort.

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Authors are responsible for the content of the publication.

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