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Capabilities of the Regional Cabin Demonstrator as digital twin for a future test mock-up

A J M Lindner and V Norrefeldt
Fraunhofer Institute for Building Physics IBP, Fraunhoferstr. 10, 83626 Valley, Germany
Andreas.Lindner@ibp.fraunhofer.de

Abstract. Digital twins are essential for Industry 4.0 and the digitalization of research, development and manufacturing. By now, the models contain more and more information and are already often highly complex systems. However, an important step is to keep the model as simple as possible in order to reduce computing resources and the associated simulation time. The Indoor Environment Simulation Suite (IESS) is a tool to generate a zonal model from a CAD geometry. It is designed to simulate the transient indoor climate in a short time, while still considering all important physical processes (heat conduction, radiation, convection). After the zonal model has been generated, the user can parameterize it specifically to the application and couple it with other models when needed. Here, a new approach is to integrate a thermo-physiological model of the human body in order to make statements about the human perception of thermal comfort. This is of particular interest in early development phases in order to assess air conditioning strategies as well as structural or technical adaptions due to thermal bridges or other influences on the cabin climate. In this paper a concept will be presented where the zonal model is coupled with the thermo-physiological model to investigate selected case studies on how thermal comfort in a regional aircraft can be assessed and considered in early design phases. The cabin model is based on a new type of regional aircraft for which a mock-up is currently being built in order to perform subject test at the Fraunhofer Institute in Holzkirchen. The thermal model can thus make statements in advance about how test scenarios should be carried out in order to gain the greatest possible benefit from the subject study tests, where the number of different tests is limited.

1. Introduction
In research, development and manufacturing, the use of digital twins and simulation has become a common tool. However, a high understanding of the physical processes and a high degree of knowledge of the respective software is still necessary to correctly determine the necessary inputs and properties of the digital twin. In addition, two mutual trends are developing, which must be brought together in digitalization. On the one hand, models are becoming more and more complex and detailed, which leads to further specialization. On the other hand, models are becoming more and more versatile and systems need to be represented holistically. This leads to the fact that more and more computing power is needed to simulate linked systems of complex degrees or to combine them into a complete model.

In this paper, one of these highly specific models will be combined with an approach that allows it to run without much computing power and will be presented as a case study with a digital twin of a regional aircraft as example.
The motivation for this work is that within the CleanSky2 Regional IADP the On-Ground Cabin Demonstrator of a future regional aircraft to conduct subject tests is to be integrated at the research facility of the Fraunhofer Institute IBP in Holzkirchen, Germany. This full scale cabin demonstrator will be used to validate and demonstrate new technologies and developments which increase passenger comfort and safety. Since the demonstrator is a section of a regional aircraft, namely the first 5 seat rows of the cabin and the adjacent galley including a wardrobe and toilet, the connection to the usual systems of an aircraft must be planned and prepared in advance. To what extent the Environmental Control System (ECS) can be simulated and which systems are required to provide the air conditioning can be clarified in advance by means of simulations. It must also be clarified whether, for example, the outer skin of the fuselage must be cooled to flight conditions in order to be able to represent realistic thermal bridges and their influence on the cabin and its passengers. With the gained insights, supply systems can be designed, the location of measurement systems can be improved and planned and the future behavior and the influence of the thermal environment on the passenger can be analyzed.

2. Method
The usual approach to evaluating the indoor climate is to use standards like ASHRAE 55 [1] or ISO 7730 [2]. Users can choose from a variety of standards depending on their level of knowledge and application. The most commonly used method is probably based on the work of Fanger [3] and is the calculation of the predicted mean vote (PMV) index that predicts the mean value of the thermal sensation votes of a large group of persons on a 7-point sensation scale. The PMV can be either obtained through questionnaires or by calculation. For the calculation of the value, however, not only information about the indoor climate such as the air temperature is needed, but also more complex parameters such as the air velocity, the convective heat transfer coefficient and the mean radiant temperature. The use of PMV is suitable for rather homogeneous and stationary cases. However, since the indoor climate inside an aircraft cabin is usually inhomogeneous and transient, other methods must be used. Today, thermo-physiological models are already very well developed and their application gain more importance. One of the most widely used models is that of Fiala [4]. In order to apply the Fiala model, it requires detailed knowledge of the indoor climate.

To obtain this data, however, often more complex computation is required such as computational fluid dynamics (CFD). For the calculation of larger or more complex geometries such as an aircraft cabin, however, relatively high computing power and time are required, especially if transient processes are to be simulated in CFD. A good compromise between accuracy and required computing power are zonal models, which divide a room into typically 20 to 200 zones exchanging air through flow paths.

In order to show that on the one hand the zonal model is sufficient to adequately describe the indoor climate in the cabin and on the other hand, the coupling with a thermo-physiological model provides better information about the thermal impact on the passenger, a case study is used to present the capabilities of both models.

2.1. The thermo-physiological model
As mentioned above, the well-known thermo-physiological model of Fiala was used. Since the original model has a mathematical structure, the approach of Wölki [5] was used to represent the model in Modelica and to couple it with the zonal model, which is also represented in Modelica.

The model is divided into two systems, a controlled passive system and the active system. The passive systems represents the physical human body and the heat transfer within as well as with the environment. The metabolism is continually generating heat and that is distributed over the body segments by blood circulation, heat transfer within the tissue and conduction. Hereby, thermal properties of the blood, muscle, fat and bones are important parameters which are dependent on body size, weight, age and gender whereby the Fiala Model only uses average values for the human body. For the heat exchange with the environment, the complex combination of convection, conduction, radiation, and evaporation must be considered. A schematic layout of the model is presented in figure 1.
Figure 1. Schematic diagram of the thermos-physiological model of Fiala (modified from [6])

The passive system is controlled by the so called active system which regulates temperature in a changing environment. It represents the body’s regulatory response to the environment. If it is too cold, the body starts to shiver to increase the metabolism and and/or vasoconstriction occurs. The opposite reactions are sweating and vasodilation when the body gets too warm.

In the presented approach, the boundary conditions for the thermo-physiological model are generated by the IESS zonal model. Since the different types of heat transfer are described separately in the zonal model, the coupling of each body part with the respective nodes of the zones or surfaces is relatively easy although the process is currently still done manually.

2.1.1. The zonal cabin model.
The zonal model is created with the Indoor Environment Simulation Suite (IESS) [7]. The aim of this tool is to enable the user to set up a geometrically correct thermal model for complex geometries that allows predicting the impact of heat sources and their location both in terms of airflow pattern and radiation distribution. Using a geometry file exported from CAD software, the tool distributes wall facets, air nodes and computes the long-wave radiant view factor matrix for obstructed and unobstructed surfaces automatically. This information is exported as ready to use Modelica code. The zonal model predicts airflow and air temperature distribution in space on a coarse mesh and thus computes significantly faster than classical CFD computations. Walls are subdivided on the same grid as the zonal model is set upon. For each wall facet, the view factors are computed to the other facets or obstructions in the domain.

For this case study, the CAD geometry of the regional aircraft cabin demonstrator was read in and divided into 125 uniform zones. The general process of the generation of the zonal model is given in figure 2. After the zonal model is generated, the thermal properties and heat sources need to be specified according to the desired case study.
A composite structure was defined for the heat exchange with the exterior. The main heat sources in the cabin are represented by the passengers. For the first case a 100% occupancy rate was chosen, which corresponds to 25 passengers for the seat layout of 2 + 3 chairs and 5 rows. For the second case, the cabin was defined with a 50% load factor.

### 3. Case Study

The boundary conditions of the simulation are based on a typical regional flight. As flight altitude, 23,000 ft, were chosen which corresponds to an outside temperature of about -30 °C [8]. The flight profile and thus also the course of the simulation is given in Table 1. The ambient temperature on ground was selected to be 20 °C. Two cases were simulated, one with a passenger load of 50 % (corresponding to 13 passengers representing evenly distributed in the cabin) and one case with a passenger load of 100% (corresponding to 25 passengers).

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground</td>
<td>60 minutes</td>
<td>steady state used to initialize simulation</td>
</tr>
<tr>
<td>Boarding</td>
<td>15 minutes</td>
<td>increase of heat sources (passengers)</td>
</tr>
<tr>
<td>Take-off</td>
<td>20 minutes</td>
<td>reduction of cabin pressure and ambient temperature</td>
</tr>
<tr>
<td>Cruise</td>
<td>60 minutes</td>
<td>normal ECS operation</td>
</tr>
<tr>
<td>Descent</td>
<td>30 minutes</td>
<td>increase of cabin pressure and ambient temperature</td>
</tr>
<tr>
<td>Deboarding</td>
<td>10 minutes</td>
<td>reduction of heat sources (passengers)</td>
</tr>
<tr>
<td>Ground</td>
<td>60 minutes</td>
<td>steady state and normal ECS operation</td>
</tr>
</tbody>
</table>

Exemplary for the cabin temperature, the air temperatures in the middle of the cabin at different heights are shown in figure 3 (for case 1 with 100% load) and 4 (for case 2 with 50% load). After ground phase is completed and the start of boarding in minute 60, the cabin temperature rises relatively quickly. Only after take-off the temperature inside the cabin decreases due to the ventilation system and the temperature difference to the outside. With the descent, the cabin temperature rises slightly with the outside temperature. Finally, after the aircraft has landed and passengers have left the cabin, the air temperature drops to the level of the first ground phase.
Figure 3. Air temperatures in different heights (30cm, 80cm, 130cm and 170cm) in the center of the cabin for the case with a passenger load of 100%.

When figure 3 is compared with figure 4, the main difference lies within the temperature difference during the cruise phase where in the 50% case, the air temperature decreases to a minimum value of 19.6 °C whereas in the 100% case, all temperatures stay above 22°C.

Figure 4. Air temperatures in different heights (30cm, 80cm, 130cm and 170cm) in the center of the cabin for the case with a passenger load of 50%.

To evaluate the thermal influence on the body, the skin temperature of the thermo-physiological model was exemplarily evaluated at two different seat positions at the end of the cruise phase (minute 150) in figure 5.
Figure 5. Local skin temperature of different body segments at different seat positions 1A (next to window) and 1E (middle seat) for both cases.

Seat 1A is in the first row directly at the window and has for case 100% a neighbour to his right. Seat 1E is also in the first row, but between two neighbours. The general distribution of skin temperature at the different body segments is on the one hand due to the stratification (colder air at the bottom), but on the other hand mainly to the thermo-physiological structure of the body. The lower arms are colder due to the lack of clothing (T-Shirt) while the upper body is warmer due to its mass, heat capacity and blood distribution. The skin temperature is generally higher in case 100% than in case 50% due to the higher air temperature. Comparing the skin temperature of both cases in detail, however, it can be determined that the colder surface temperature of the lining and window have an influence on the left facing body segments in seat 1A. If seat 1E is compared to this, it can be observed that the left and right sides of the body are relatively symmetrical due to the seat neighbours.

This demonstrates very well the influence of the different physical processes and how they affect the body. The cold air temperature on the floor can be seen on the cold feet whereas the cold surface of the lining or window on seat 1A shows the influence of radiation.

4. Conclusion
The case studies show that the zonal model, despite its coarser resolution, provides detailed information about the future thermal behaviour of the demonstrator. Due to the short computational time, transient processes can be simulated which give better insights of the behaviour during a flight because events like boarding or flight level changes can be represented. By coupling the zonal model with a thermo-physiological model, the thermal interaction between body and room climate can be shown and analysed. This method gives more detailed information about the indoor climate and the well-being of the passengers than just the evaluation of air temperature.

With the help of the models, future test setups and subject studies can be better designed in advance. Measurement sensors can be placed in areas of greater interest and can be reduced in other areas because results from the digital twin can also be used.
For the future, it is intended to further enhance the usability of the thermo-physiological model by coupling the results with thermal comfort models from literature which use the body core and skin temperature of the presented model to evaluate human thermal sensation and comfort in non-uniform and transient environments. In addition, the coupling of the zonal model with the thermo-physiological model is to be automated to simplify the application.

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