Numerical Simulation of the Air Flow and Thermal Comfort in Aircraft Cabins

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Abstract. Results of a numerical study of the air flow and the thermal comfort of the passengers in an aircraft cabin which includes thermal radiation effects are presented. The computations have been performed by coupling flow simulations with the Computational Fluid Dynamics (CFD) code OpenFOAM with finite element simulations of the heat transport within the passengers using the code THESEUS. With the latter the bodies of passengers are modeled based on various layers with different heat transport characteristics to account the effects like blood flow, skin, clothing as well as activity levels and ambient humidity. Computations of the flow, thermal radiation and of the modeled passenger comfort in the cabin of the Airbus A320 and Do728 are discussed. The predicted numerical temperature distributions in the cabin of Do728 have been supported by experimental measurements.

Keywords. Thermal Comfort Model (TCM), CFD, cabin airflow, FIALA-Manikin-Model

1 Introduction

Thermal comfort and the well-being of passengers in aircraft cabin are import criteria for airlines to purchase a specific aircraft. The thermal comfort of passengers in particular is influenced by the air flow, the temperature distribution and the thermal radiation in a specific cabin configuration. The thermal comfort prediction in an aircraft cabin further depends on the numerous thermal sources, one of which is the passenger itself. Conventionally, in computations using Computational Fluid Dynamics (CFD) methods, the thermal boundary conditions are prescribed at the passenger/cabin air interface in terms of either of specified heat flux or isothermal temperature distributions. In this respect the passenger is considered as a passive heat source [1-3]. There are also more sophisticated thermal comfort models which consider a human body to consist of several layers with different heat conductivities and capacities also taking into account the heat transport in the cardiovascular system and the influence of clothing on the thermal comfort. Additionally, the influence of human activity levels and the ambient humidity on human physiology is also considered, albeit in empirical form.

The Thermal Comfort Simulations presented below are based on a coupling of the finite volume method OpenFOAM which solves the unsteady Reynolds-averaged Navier-Stokes (URANS) equations using the Boussinesq approximation with the commercial finite element method, THESEUS, developed by P+Z Engineering GmbH (FIALA-Manikin-Model) [4]. The model implemented in the latter considers all relevant thermo-physiological effects of a human body as described by D. Fiala et al. [5-6]. It allows the calculation the so-called Zhang Local Sensation Indices which describes the feeling temperature in a range from “very cold” to “very hot” [7]. Based on the latter the Zhang Local Comfort Indices is evaluated which describes the sense of comfort in a range from “very uncomfortable” to “very comfortable” [8]. Using the coupling approach computations of the flow and thermal comfort of passengers in cabin of the A-320 and the Do728 have been performed and are discussed below. Additionally, the calculated results are compared with those of subjective comfort obtained with of test persons in Do728 cabin.

2 Comfort Model

The heat transfer problems solved with THESEUS software [4] are based on a thermal manikin the so-called FIALA-Manikin Model. The body the latter is considered to consist of 54 body segments. For our simulations we reduced the number of segments to 14. So the head, face and neck of the FIALA-Manikin are combined to one segment of our Thermal Comfort Model (TCM). Further one segment represents the torso. There are also the left and right segments of the upper arm, lower arm, hand, upper leg, lower leg and foot. Each these body segments consist of several material layers. Additionally, it is possible to define an individual clothing layer for any of the above discussed segments. Finally, it must be noted that the core of each segment has own attributes and gender effects as well as differences in the human thermoregulation are not reflected. The distribution of body elements is shown in Figure 1.

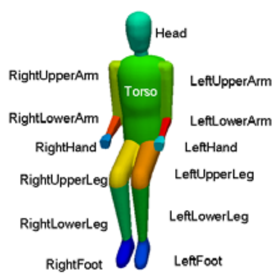

Fig. 1. Distribution the body elements for calculation of local comfort indices

For each body segment the following partial differential equation is solved for all layers to describe the energy changes at each material point:

$$\rho c \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial r^2} + \frac{\omega}{r}\frac{\partial T}{\partial r}\right) + q_m + \rho_b c_b w_b \left(T_{b,a} - T\right) \tag{1}$$

Here ρ is the density, c – the specific heat, k – the thermal conductivity, T- the temperature, q_m – the metabolic heat flow density, w_b – the blood perfusion rate and $T_{b,a}$ – the calculated arterial temperature. The term $\rho_b c_b w_b (T_{b,a} - T)$ describes the heating due to the arterial blood flow. Blood circulation is of vital importance for the dissipation of heat within the human body [5-6]. The brain temperature would reach unrealistic values of more than 70°C in a simulation without blood circulation. Body elements are simplified considering them cylinders with the exception of the head (sphere) and r is a body element radius. The dimensionless parameter ω is 1 for cylindrical body elements (for example leg) and 2 for spherical body element (head). Thus, equation (1) describes the law of energy conservation at each material point of a layer that might represent skin, fat, muscle, bone, brain etc.

The local clothing properties of each garment were predicted using the closed simulation model of McCullough [9]. The clothing is defined with thickness, clothing resistance, evaporate resistance, non-structural mass and specific heat. With the FIALA-Manikin surface (T_{sf}) and skin (T_{sk}) temperature are computed. For calculations of the convective and radiative heat transport in complete aircraft cabins the value of T_{sf} is of importance.

Different comfort evaluation indices can be modeled in our approach. First, an equivalent temperature T_{eq} is determined according to

$$T_{eq} = T_{sf} - \frac{q_{real}}{h_{cal}}, \tag{2}$$

$$q_{real} = R + C + E, \tag{3}$$

where q_{real}, R, C and E symbolize the realistic, radiation, convection and evaporation heat fluxes densities. Evaporation is estimated and calculated in THESEUS-FE by prescribed humidity. Further, h_{cal} denotes the combined heat transfer coefficient of this environment ($h_r + h_c$), where h_r is radiation and h_c convection heat transfer coefficient. The equivalent temperature is the temperature of homogeneous room with a radiation background temperature equal to the air temperature and low relative air speed.

The equivalent temperature and any other comfort indices (e.g. both Zhang indices) were calculated by THESEUS.

The Zhang Local Sensation (SI) is defined as a function of following parameters

$$SI = f\left(T_{sk,i}, \frac{dT_{sk,i}}{dt}, \overline{T}_{sk,i}, \dot{T}_{hy}\right), \tag{4}$$

where $T_{sk,i}$ is the skin temperature of the body segment i and T_{hy} – the hypothalamus temperature. The resulting sensation scale ranges from: 4 – “very hot”, 3 – “hot”, 2 –

“warm”, 1 – “slightly warm”, 0 – “neutral”, -1 – “slightly cool”, -2 – “cool”, -3 – “cold”, -4 – “very cold”.

Based on equation (5) the Zhang Local Thermal Comfort Index (Lc) is computed taking into account the Overall Thermal Sensation (*So*)

$$Lc_i = f\left(SI_i, So\right) \tag{5}$$

Zhang Local Comfort index ranges from 4 – “very comfortable”, 2 – “comfortable”, 0 – “just comfortable” to -2 – “uncomfortable”, -4 – “very uncomfortable”. For details on the calculation of *So* the reader is refereed to [8].

3 OpenFoam-THESEUS Coupling

The exchange the data between the flow simulations using OpenFOAM and the thermal comfort computation with THESEUS the following interface was developed. At the beginning of the simulations the initial temperature of the all body surfaces of the passengers is prescribed as follows: head – T = 308 K, torso – T = 308 K, the upper arms – T = 306 K, lower arms – T = 306 K, hands – T = 307K, upper legs – T = 305 K, lower legs – T = 304 K and feet – T = 304 K. Using these initial conditions the RANS simulations are started. After 100 iterations the heat flux densities due to radiation and convection are computed and written into an output file. From this file THESEUS obtains the heat flux densities and calculates a new set of surface temperature boundary conditions by solving the equation (1) of the FIALA-Manikin model. To obtain a good convergence of the solution in THESEUS-FE the number of inner iterations/time steps was chosen to be 10 and additionally steady state conditions as residual of 5e-4 have been prescribed. The results are an estimate of the response of a typical human body to the specified thermal loading. Further an “equivalent” temperature is computed which is used to assess thermal comfort, as well as surface (and skin) temperatures. The latter are then passed on to the RANS simulations by updating the surface temperature boundary condition through an intermediate output file. The whole procedure is repeated every 10 iterations.

4 Results of Coupled Simulations

The flow simulations were performed solving the RANS equations with the finite volume method OpenFOAM by coupling with THESEUS-FE. The air flows in the cabins of the A320 and the Do728 were investigated. For a A320 segment the computational domain features 6 rows and 36 passengers, while for the Do728 cabin 3 rows and 15 passengers were considered. This means that for the passengers in the A320 cabin 14 x 36 = 504 separate body segment boundary conditions are needed while 14 x 15 = 210 body segment boundary conditions were used for Do728 cabin. At all air inlet planes the volume flux and its temperature value were prescribed. At the walls representing the sides, bottom, ceiling and windows temperature and heat flux were calculated. For the light-bands in A320 cabin the heat flux density of 300 W/m² was given. The unstructured grids used for A320-computations consisted of 22 Mio. cells and of the one of Do720-cabin of 14 Mio. cells.

The conducted turbulent flow simulations include modeling of thermal surface to surface radiation. They were carried out with the "buoyantBoussinesq" solver of OpenFOAM by Engys. It solves the Reynolds-averaged Navier-Stokes equations together with k-ω/SST model. The computed velocity and temperature fields in the A320 cabin is presented in Figure 2, where streamlines of the mean velocity emerging from the inlet and the resulting surface temperature distributions are visualized. At the four inlets region the volume flux and the temperature of 19°C are prescribed. The calculated mean temperature in the cabin A320 reaches although a value of 22.5°C.

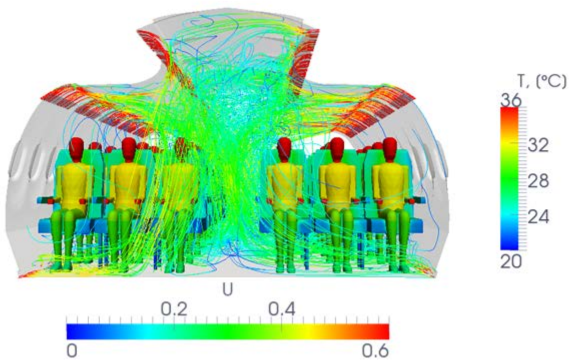

Fig. 2. Streamlines emerging from inlet surfaces and surface temperature distribution in A320

As mentioned above, heat flux densities on the passenger's surfaces are first computed and passed on to the finite-element code THESEUS. The latter updates the surface body temperatures with the FIALA-Manikin model. With these new temperature boundary conditions at the passenger surfaces the RANS simulations are continued. Additionally several comfort parameters such as the perceived temperature are also provided by THESEUS. The calculated surface and skin temperature underline that a realistic choice of clothing data is important for the below discussed thermal comfort predictions. The latter is obtained by making use of the Zhang Sensation and Local Comfort indices which are presented in Figure 3. The analysis of these indices reveals the correlation between perceived temperature and the perceived comfort of for each body segment of the passenger dummies. Thus, a perceived "neutral" temperature at the hands leads to comfortable situation, while a "slightly warm" perceived temperature at the lower arm is perceived not as comfortable.

5 Comparison of the Predicted and Measured Temperatures

The several experiments with test persons were carried out in the Do728 cabin test facility. In these test series the perceived thermal comfort was determined by analyzing questionnaires which were filled out by the test persons. The experimental boundary conditions are reflected by CFD simulations. To arise the mean cabin temperature of 24°C the initial temperature of 17°C by all four inlets region was given. The experimental whole volume flux was about 660 *l/s* for 14 passenger rows. The CFD calculations were performed for cabin segment of 3 rows and the flux value was scaled accordingly.

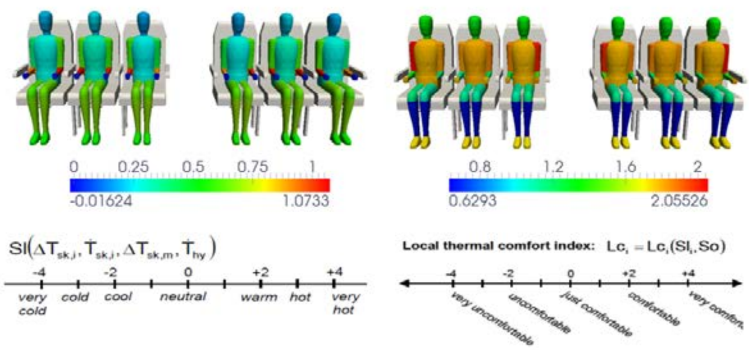

Fig. 3. Predicted distribution of the Zhang Sensation and the Local Comfort indices on the passengers in a row in of the A320 cabin

During these test series the surface temperatures were additionally measured with a "VarioCAM" high resolution infrared camera. In the Figure 4 the measured and computed mean surface temperature on the body segments of passengers in one row are presented.

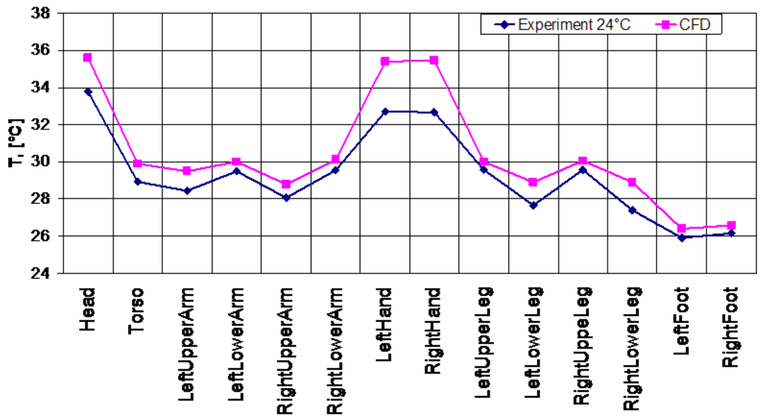

Fig. 4. Comparison of the computed (magenta) and measured (blue) temperature distribution on the body segments of a selected passenger obtained for a mean cabin temperature T_{cabin} = 24 °C

By postprocessing of infrared pictures each body element have been adopted in one polygon in which the mean temperature was determined. Although, the results on head and hands differ by about 2°C the overall qualitative agreement is good. Probably infrared camera has not enough resolution for these domains. For the investigated case the mean aircraft cabin temperature amounted to T = 24°C. Additionally, the comparison of predicted and measured surface temperatures in the Do728 cabin is shown in Figure 5. The both pictures have the same scale temperature. Again, a qualitative agreement is obtained. The major reasons for the observed quantitative differences are the differences in clothing in the test series and the computations.

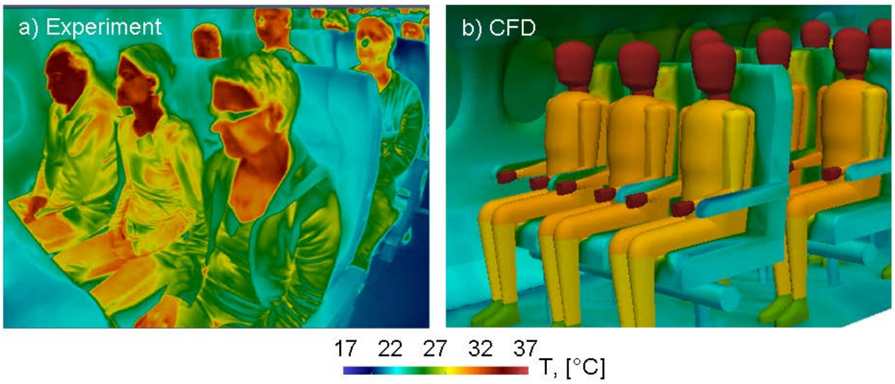

Fig. 5. Comparison of the measured (left) and the computed (right) surface temperature distribution in the cabin of Do728 at a mean temperature of T_{cabin} = 24°C

Finally, the obtained Zhang Indices for this test case are visualized in Figure 6. The Sensation indices values of the head and hands reveal a nearly neutral comfort sensation. At the lower arms the indices are higher which indicates that there the temperature might be perceived as slightly to warm. Still, the predicted local comfort values show, that the heads, hands, torso and feet perceive the conditions as comfortable. Only, the lower arms are reflected as just comfortable, because they due to the warm Sensation index.

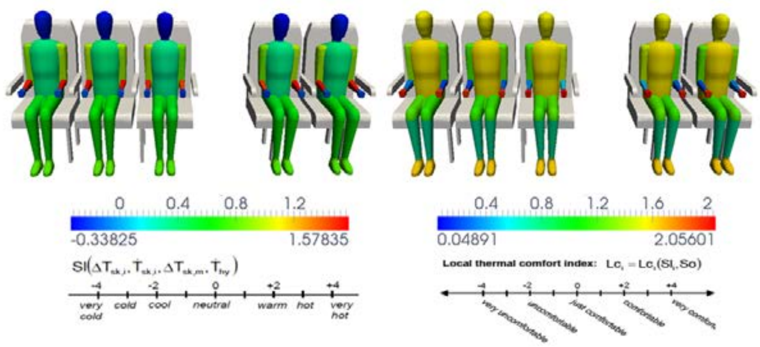

Fig. 6. Zhang Sensation (left) and Local Comfort (right) indices on the in the cabin of Do728

6 Conclusions

The presented numerical thermal comfort predictions are based on the solution of the Reynolds-averaged Navier-Stokes equation using the Boussinesq approximation and modeling of surface to surface thermal radiation in two different aircraft cabins and the coupling with the finite element code THESEUS. The latter allows to simulate the heat transport within the passengers and the perceived temperature and comfort of passengers. It was shown that with the presented approach a qualitative and quantitative thermal comfort prediction is possible. The analysis of the results further revealed that a proper modeling of the clothing of a particular importance for a realistic prediction of the thermal radiation within cabin. The comparison of the results obtained in numerical simulations and those of test series with human beings in the Do728 cabin demonstrate a good agreement.

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Acknowledgments

We thank Dr. Stefan Paulke from P+Z Engineering GmbH for helpful discussions and perfect suggestions.

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