A COUPLED SIMULATION OF THE THERMAL ENVIRONMENT AND THERMAL COMFORT WITH AN ADAPTED TANABE COMFORT MODEL

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Summary: *A physiological comfort model based on the Tanabe model is combined with a psychological model based on the Zhang model for the prediction of thermal sensation and comfort. The whole model is programmed in the object oriented simulation language Modelica and its parameters have been adapted to own experimental investigations. The adaptation procedure is configured expandable to include future experimental results.*
The model can be coupled directly to three dimensional flow simulations using the commercial flow solver CFX. CFX is used to calculate the ambient conditions and it is able to use the Modelica model predicting the temperature distribution inside the human body as well as the resulting body surface temperatures.

Keywords: *Thermal comfort, thermal comfort model, model calibration, coupled simulation*
Category: *Human thermal physiology and mathematical models*

1 Introduction

Person's thermal comfort is a very important aspect indoors. To improve the thermal comfort in various indoor conditions simulation programs are very helpful. The modelling of the human thermoregulation system has been investigated for about one century and many different kinds of thermal comfort models exist in literature. Due to their simplicity the statistically based thermal comfort models are widely applied and integrated into standards. The best known model is the PMV-PPD model of Fanger [1]. PMV defines a thermal strain based on steady-state heat transfer between the body and the environment and it assigns a comfort vote (predicted mean vote – PMV) to that amount of strain. PPD is the predicted percent dissatisfied people at each PMV. As PMV moves away from zero on the thermal sensation scale in either positive or negative direction, PPD increases.
Considering the flow field inside an airplane cabin the thermal boundary conditions are non-uniform and transient. In figure 1 the percentage dissatisfied against mean vote is presented for an experimental study with test persons in a cabin mock-up at the Technical University of Berlin at very high thermal loads and ventilation rates. The data are subdivided in the voting of all passengers and of single seat rows. For all cases there is no clear correlation between percentage dissatisfied and mean vote. It seems that global quantities like PD, MV and acceptance have no consistent information and none of the global models is valid for more complex indoor climate situations. A closer look on the data shows that the focus has to be on local quantities of all body parts.

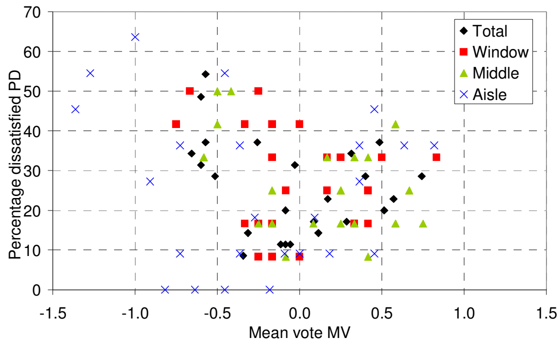

Fig. 1: Correlation between MV and PD in a cabin mock-up at very high thermal loads and ventilation rates

2 Human comfort model

The ability to predict more accurately the variation of physiological conditions throughout the body is only possible by physiological comfort models resolving various parts of the body. This paper outlines an approach based on the Tanabe model [2] combined with the Zhang model [3].
According to the Tanabe model the model divides the whole body into 16 body segments. Each of these body segments consists of core, muscle, fat and skin layer. As the Tanabe model is only a physiological model the results are the mean skin temperatures of each body segment based on the reactions of the passive and active body system according to the environmental conditions. To get information on the comfort situation of the person it is necessary to append a psychological model.
The appended psychological model is based on the Zhang model which is able to calculate the local and overall thermal sensation as well as the thermal comfort from the physiological state of the human body. Figure 2 shows the combination of the two models.

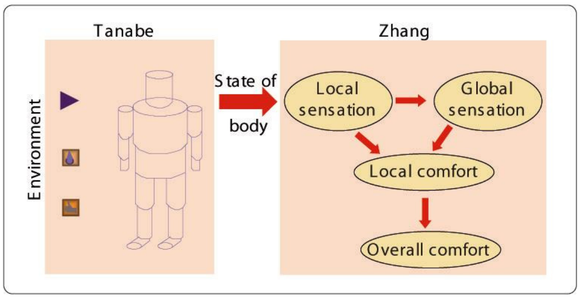

Fig. 2: Combination of Tanabe and Zhang model

The whole model is programmed in the object oriented simulation language Modelica.

3 Experimental investigations

The main focus of this research is the comfort situation of passengers in an aircraft cabin at very high loads and ventilation rates. The experimental database already includes more than 1000 test flights in a cabin mock-up. Figure 3 shows the setup for the experiments at the Technical University of Berlin. Each flight is arranged with two groups of 35 female and male persons. During the flights the test persons fill out questionnaires concerning their overall thermal comfort situation but also the thermal sensation of single body parts according to the Tanabe model.

Fig. 3: Test persons in the cabin mock-up

The flights with test persons are complemented by flights with thermal mannequins. During those flights detailed measurements on the temperature and velocity distribution inside the cabin are taken.

4 Numerical investigations

As the heat loss of a person is mainly driven by radiation and convection the most important parameters for the physiological comfort model are the convective and radiative heat transfer coefficients. There are no simple analytical solutions for both parameters. Consequently, additional investigations are necessary.

Experimental measurements are one possibility. In this case thermal mannequins can be used to measure local heat loss and specify the heat transfer coefficient on different body parts. In many cases experimental data are not available. Instead, a three dimensional of the flow field delivers the heat loss of the human body parts based on a virtual cabin design. For this study all simulations are done with the commercial flow solver ANSYS® CFX11. The simulation can run as a stand alone process and the essential parameters are taken during the post processing. But the simulations can also be coupled directly with the comfort model using a TISC® server by TLK-Thermo.

5 Model calibration

The given comfort models have a large number of parameters. Some of these parameters are linked to heat transfer processes and it values can be stated as “safe”. Other parameters are based on regressions from various experiments under different and only partly known conditions. These parameters have to be considered as “unsafe” and they can be adapted to the simulation process using new and existing experimental data. Therefore the comfort model is adapted to the own experimental investigations complemented by the information taken from the numerical investigations. Figure 4 shows the adaptation procedure. The human comfort model runs under the same boundary conditions as the experiments. The difference between the simulated and the experimental results for the local thermal sensation is the input quantity for the optimization process. In this process the difference will be minimized under variation of a set of “unsafe” parameters of the comfort model. The set of parameters is defined by a sensitivity analysis.

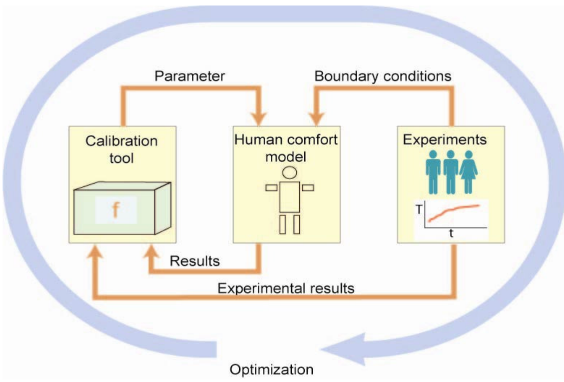

Fig. 4: Calibration procedure

The whole active system of the Tanabe model is based on error signals. The error signal indicates the deviation of a body part temperature from a control target temperature. The weighting of these error signals is a very insecure process and integrated in the optimization process. The second parameter of the Tanabe model is the effect of heat exchange due to counter current blood flow which is neglected in the original model.
The Zhang model assumes a correlation between thermal sensation and skin temperature given by a logistic function. The gradient of the logistic function is defined in the optimization procedure.
Altogether 28 parameters are optimized.

The automated optimization procedure is a combination of a least-squares optimization and a direct search algorithm.

The whole procedure is configured expandable. Further experimental results or improvements concerning the numerical models which give new boundary conditions can be included easily.

6 Results

Figure 5 shows the results of one single optimization process. The experimental data give the local thermal sensation voting on an aisle seat. It can be seen that the left side of the passenger is affected by the cold supply jet and the local thermal sensation is lower than for the right side. The experimental data and the simulation with standard coefficients taken from literature are not well correlated. The conformance can be clearly improved with the optimized coefficients.
It is very critical to ensure that the results from the three dimensional flow field calculations are in good agreement to experimental data. Otherwise the optimization process will give unreasonable parameters for the comfort model.

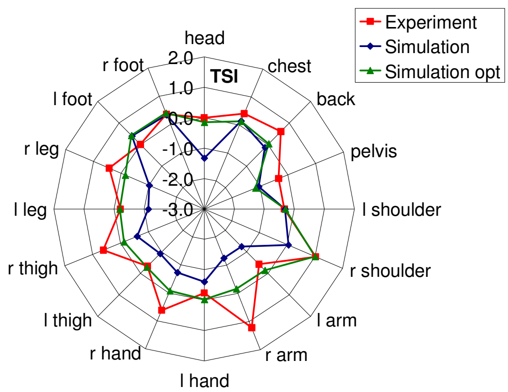

Fig. 5: Experimental and simulated local thermal sensation

7 Conclusions and perspectives

The Tanabe model is a good basis for a comfort prediction in non-uniform and transient environments. Based on the physiological results of the Tanabe model the local and overall thermal sensation as well as the thermal comfort can be predicted in the appended psychological model based on the theory of Zhang. The programming of the whole model in the simulation language Modelica gives a very flexible tool for all numerical investigations. The model can be directly coupled with three dimensional flow simulations and an automated optimization process. The optimization process is necessary as both models are only valid in a limited range of environemental conditions. The results of a first single optimization procedure show a relevant enhancement comparing the data to experimental results.

In a next step a multiparameter analysis will be carried out concerning the correlation between the local and global thermal sensation based on the mathematical assumptions of the Zhang model A first analysis of the whole thermal sensation indicates that in the examined cabin situation other body parts are the determining factor than the ones identified by Zhang.

The presented concept seems to be a very promising tool for reliable comfort predictions under variable environmental conditions.

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