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Published in:
Proceedings of Roomvent 2007 : Helsinki 13-15 June 2007

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

CFD modeling of thermal manikin heat loss in a comfort evaluation benchmark test

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SUMMARY

Computer simulated persons (CSPs) today are different in many ways, reflecting various software possibilities and limitations as well as different research interest. Unfortunately, too few of the theories behind thermal manikin simulations are available in the public domain. Many researchers and companies still use several in-house codes for their calculations. The validation and association with human perception and heat losses in reality is consequently very difficult to make.

This paper is providing requirements for the design and development of computer manikins and CFD benchmark tests for comfort evaluation. The main idea is to focus on people. It is the comfort requirements of occupants that decide what thermal climate that will prevail. It is therefore important to use comfort simulation methods that originate from people, not just temperatures on surfaces and air.

INTRODUCTION

Researchers around the world have developed many different configurations in order to represent a computer simulated person (CSP) or a virtual CFD manikin (Figure 1). These manikins are different with respect to size, form, heat generation, turbulence models and computer codes used, etc [1, 2, 3, 4, 5 and 6]. The variations reflects the various possibilities and limitations in software as well as different subjects of interest as manikin effects on the airflow, thermal comfort as well as pollutant production and exposure. The levels of detail are also of great interest as well as recommendations on how and when to simplify a CSP.

In order to get good results from the numerical simulation the knowledge or correct simulation of the manikin surface heat transfer is of outmost importance. The near surface flow field in a room or around a heated body is characterized by a combination of natural, free and forced convection, developing boundary layers. The restricted validity of the heat transfer models often used originates from the assumptions that have been made to solve special boundary layer flows. These assumptions are consequently not always valid for flows that can be commonly found in the indoor environment.

Nielsen and co-workers [7] introduced two benchmark tests in 2003 focusing on the airflow around virtual thermal manikins or CSPs. Now a new benchmark test for a CFD manikin or a CSP will be introduced. One purpose with this test is to create a series of very detailed and accurate full-scale measurements to serve as comparison with CFD predictions. The idea behind a CFD manikin benchmark test, which define the boundary conditions around a real as well as CFD manikin, have the following reasons:

- It is of great importance to be able to verify that the simulated heat losses equals measured heat losses converted into equivalent “experienced” temperature in order to support comparisons with human experiences presented in clothing independent comfort zone diagrams.

- If different versions of virtual CFD manikins can be tested with the same boundary conditions, it is possible to make comparisons, and perhaps make some new decisions on geometrical level of details of the design, turbulence model used, type of grid etc.

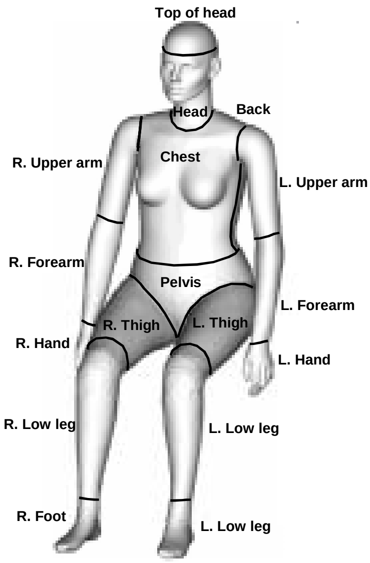

Figure 1. A CSP with modified zones to fit Comfortina, originally from the Technical University of Denmark.

It is very useful to have the results presented, not only as whole body influence, but also with local information on how the thermal climate varies over the human body [8]. The development of these virtual models gives us a more efficient and complete complement to traditional evaluation of the thermal environment.

METHODS

The experimental setup is a wind tunnel with box shaped geometry with a window on the side and dimensions Length × Height × Width = 2.44×2.46×1.2 m (Figure 2). The incoming air is distributed evenly over the full cross sectional area in front of the manikin. This unidirectional flow field is evacuated thru two circular exhaust openings behind the thermal manikin. The manikin is seated at a distance of 0.7 m from the inlet in the centre of the wind tunnel. Air velocities were measured with hot-sphere anemometers (Dantec Dynamics 54T21 transducers) in 5 levels in front of and behind the manikin. Temperatures were measured at 4 levels to the right close to the manikin. The air was supplied at 0.27±0.02m/s from a surrounding laboratory hall with a mean temperature of 20.4±0.1°C.

Figure 2. A photograph of the wind tunnel setup used for the experiments at Aalborg University. The large inlet to the far left followed by the chamber with a window; manikin and the two exhaust holes in the back with ventilation ducts.

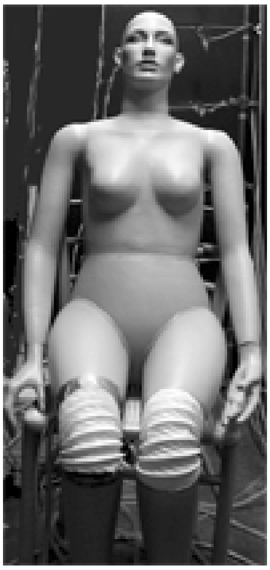

Figure 3. The full-scale Thermal Manikin Comfortina used in the heat loss measurements at Aalborg University

The measurements were made with a female manikin Comfortina [9] (Figure 3). The manikin run in constant surface temperature mode at 34ºC, without clothing in order to get fast and accurate heat loss levels. Comfortina was seated facing a unidirectional flow field similar to the flow field used in the previously benchmarked mixing ventilation case [10]. The flow field situation was made as identical to the earlier benchmarks with the intention that data will be interchangeable and comparable between the two tests.

RESULTS

Heat loss benchmark measurements

Heat loss measurements have been made with the full-scale manikin Comfortina and can be downloaded from cfd-benchmarks.com. Heat losses from the 17 manikin zones as well as whole body heat loss and air velocities plus air temperatures are reported in detail.

Table 1. Comfortina was operated in constant surface temperature mode at 34ºC without clothing in order to make the conditions particularly equal and simulation easy.

Heat Loss Benchmark Case	Mean Inlet velocity (m/s)	Mean Air temp. (°C)	Total Manikin Heat Loss (W/m^2)
1	0.27	20.4	122.3
2	0.27	20.4	122.6
3	0.27	20.4	123.3
4	0.27	20.3	123.8
5	0.27	20.3	124.0
6	0.27	20.3	124.1
Mean	**0.27**	**20.4**	**123.4**

The spreadsheet contains 6 worksheets one for each condition tested as well as a sheet with the mean values of very similar tests and an information sheet in the beginning. The local and total mean values are intended as this first "Manikin Heat Loss Benchmark".

Table 2. In order to make the thermal manikin method easy to handle in the calibration and measurement situation, as well as increase the repeatability, the manikin had no clothing.

Body Segments	Total Manikin Heat Loss (W/m^2)	Total insulation, seated, no clothing (m^{2}K/W)	Equivalent temperature (°C)
L. Foot	153.9	0.128	14.3
R. Foot	160.0	0.128	13.5
L. Low leg	144.2	0.128	15.5
R. Low leg	145.5	0.128	15.4
L. Thigh	101.1	0.128	21.1
R. Thigh	105.4	0.128	20.5
Pelvis	114.1	0.145	17.5
Head	120.2	0.125	19.0
Top of head	72.1	0.125	25.0
L. Hand	163.8	0.117	14.8
R. Hand	186.9	0.117	12.1
L. Forearm	152.7	0.122	15.4
R. Forearm	134.1	0.122	17.6
L. Upper arm	123.0	0.122	19.0
R. Upper arm	130.8	0.122	18.0
Chest	117.9	0.149	16.4
Back	111.6	0.145	17.8
All	123.4	0.134	17.5

As mentioned in the introduction is it often rather difficult to communicate the combined effects from different heat losses to people. It is consequently very useful to convert these values into something easier to understand, like "experienced" temperature, that is a more straightforward concept. This equivalent "experienced" temperature (t_{eq}) is then calculated with equation 1 according to [8]:

$$t_{eq} = t_s - R_T \cdot q''_T \qquad (1)$$

Where

q''_T	measured manikin heat loss during the actual conditions (W/m^2)
R_T	total insulation, seated, no clothing (m^{2}K/W)
t_s	manikin surface temperature (°C)
t_{eq}	equivalent temperature of the uniform, homogenous environment. (°C)

The equivalent temperature in table 2 shows low values, as could be expected. The results should be compared to the climate an unclothed person, sitting in the air stream during the same conditions as the manikin, experiences.

Presented as clothing independent comfort zone diagram evaluation output

In order to make the local comfort evaluation clothing independent, the construction of new comfort zone diagrams can now easily be made by inserting any seated whole body total insulation (I_T) between 0.9 and 1.9 clo. Equation 2 shows how the relationship between the equivalent temperature (heat loss) level and Mean Thermal Vote MTV [11] can now be established for each manikin body part. The heat loss corresponding to a certain level of comfort, or discomfort, in the diagram is considered to be the same. The shape of the zones is, however, changed according to the clothing used.

$$t_{eq,zone} = t_s - R_T \cdot (a + b \cdot MTV_{zone}) \qquad (2)$$

Where:

$t_{eq,zone}$	Equivalent temperature in the zone [°C]
t_s	Manikin surface temperature (here 34°C) [°C]
R_T	Total insulation, seated [m^{2}K/W]
a, b	Linear regression constants [W/m^2]
MTV_{zone}	Mean Thermal Vote in the zone [n.d.]

With equation 2 is it easy to make a comfort zone diagram (Figure 4) that applies to a specific clothing combination used in a given situation. Now $t_{eq,zone}$ can be calculated for the four borders of the three shaded comfort zones (blue – green – red) for all zones and the whole body. The result, plotted in a diagram, forms the evaluation background in the clothing independent comfort zone diagram. This is only done once for each clothing combination, and reflects the insulation distribution of the clothing used. Your own clothing independent comfort zone diagrams can be downloaded from the Thermal Manikin Network site [12].

These methods are now subject to International Standardization "ISO 14505, Ergonomics of the thermal environment - Thermal environment in vehicles". The comfort zone diagram shown in figure 4 corresponds to the figures D1 and D2 in the new standard ISO 14505-2:2006 [13].

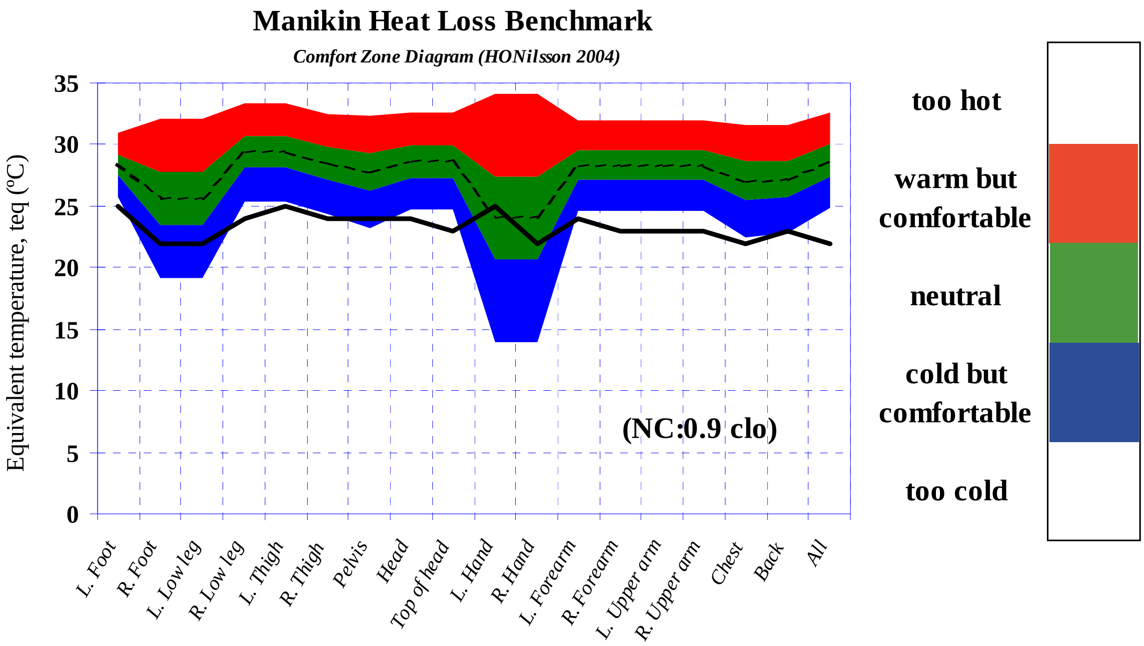

Figure 4. Comfort zone diagrams adapted for Comfortina type of manikins. This diagram shows the results with no clothing (I_T=0.9 clo) for 17 segments and "All" of the manikin body. Abbreviations refer to L = left, R = right, U = upper. A spreadsheet can be downloaded from the Thermal Manikin Network as well as the CFD-Benchmark site (ComfZonDiagr_v5_hn.xls).

CONCLUSIONS

This paper demonstrates the integrated use of new heat loss benchmark tests and new standardized evaluation methods for the CFD modeling of thermal manikin heat loss for comfort evaluation. These methods are intended to connect results from thermal manikin measurements with human experiences in order to form a evaluation methodology based on a virtual manikin positioned in a CFD simulated environment. The results can be presented as whole body influence with local information on how the thermal climate varies over the real or simulated human body.

The new benchmark test focuses on the different heat losses from the manikin with the aim to predict how humans will react to different climatic situations. This will hopefully lead to a more focused development of a simplified, comparable, easy to use virtual CFD manikin with respect to both geometrical and physiological properties also taking into account usability and limitations. This research will give us some general requirements for the design and development of future CSPs and CFD manikin systems.

ACKNOWLEDGEMENT

The first author greatly appreciates the contacts and discussions with all personnel at the department of Indoor Environmental Engineering as well as for the opportunity to be able to make this research at Aalborg University.

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