RADIATION BETWEEN SEGMENTS OF THE SEATED HUMAN BODY

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Summary
Detailed radiation properties for a thermal manikin were predicted numerically. The view factors between individual body-segments and between the body-segments and the outer surfaces were tabulated. On an integral basis, the findings compared well to other studies and the results showed that situations exist for which radiation between individual body segments is important.

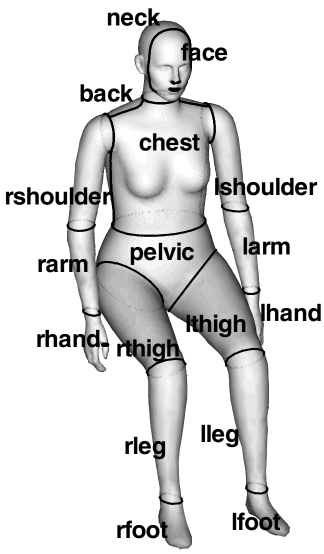
Introduction

Heat loss due to radiation is important in relation to thermal comfort (Fanger, 1970). Usually, the radiative heat loss to the surroundings is predicted by empirical relationships developed for the whole body. For most applications, the accuracy of these relationships is adequate. However, for applications with high demands for accuracy and with large temperature differences between different body-parts, the radiation between these may be important (Jones et al, 1998). This segment-to-segment radiation is the subject of the research presented here.

Normally, the view factors are obtained by photographic methods (Fanger, 1970). However, to prevent distortion, a significant distance between the camera and the body is required. Thus, segment-to-segment view factors are difficult to obtain by photographic measures.

Methods

A numerical method was used to calculate the view factors between individual segments of the manikin, requiring a detailed description of the surface of the manikin. This was accomplished by a laser scanning method with an accuracy of around 0.5 mm (Voigt, 2001). The geometry of the unclothed, bald and seated manikin is shown in Figure 1, where the division of the manikin into segments is sketched. The set-up of the present study considered the manikin positioned in a room of length, width and height of 2.95, 2.95 and 2.4 m, respectively. The tip of the nose of the manikin was centred between the walls at a height of 1.25 m, whereby the feet were raised 20 mm above the floor.



Segment	Area [m^2]
R. foot	0.0456
R. leg	0.1083
R. thigh	0.1894
L. foot	0.0452
L. leg	0.1081
L. thigh	0.1858
L. hand	0.0340
L. arm	0.0507
L. shoul	0.0745
R. hand	0.0315
R. arm	0.0525
R. shoul	0.0779
Pelvic	0.1744
Chest	0.1530
Back	0.1421
Head	0.1206
Total	1.594

Figure 1. The division of the manikin into segments. The head segment comprises face, neck, mouth and nostrils (Tanabe, 1994).

The view factors were calculated by the radiation module of the commercial CFD program STAR-CD (2001). A brief outline of the method is as follows: The boundaries of the calculation domain are divided into a number of contiguous radiation patches. From the centre of each patch, a number of beams are emitted, at equal solid angles, over the enclosing hemisphere. Each beam is traced until it intercepts an opposing patch, thereby defining a pair of patches that may exchange radiant energy. Each entity of the body (e.g. an arm) comprises many radiation patches and the number of radiation pairs that exist between two entities thus express the view factor between these entities. The surface of the manikin comprised 23.000 triangles, which ensured a good representation of the geometry. Except for very small elements, each boundary triangle was defined as a radiation patch, thereby ensuring a good resolution of the surface with respect to radiation. From each of these patches, 2500 radiation beams were emitted. The number of boundary patches and radiation beams ensured a solution that was essentially grid-independent.

	Pelvic	Chest	Back	Head	L. foot	L. leg	L. thigh	L. hand	L. arm	L. shoul
R. foot	0.038	0.016	0.000	0.002	1.907	0.746	0.155	0.133	0.001	0.015
R. leg	0.210	0.044	0.000	0.009	1.753	4.688	1.258	0.665	0.024	0.120
R. thigh	2.715	1.281	0.046	0.218	0.626	2.140	6.159	0.781	0.353	0.394
L. foot	0.032	0.016	0.000	0.001	0.680	0.287	0.085	0.139	0.026	0.006
L. leg	0.192	0.040	0.000	0.007	0.685	0.216	0.868	1.250	0.127	0.011
L. thigh	2.247	1.332	0.053	0.225	0.347	1.492	0.121	17.307	13.322	0.980
L. hand	0.013	0.015	0.007	0.003	0.105	0.394	3.170	7.133	0.053	0.009
L. arm	2.392	0.841	0.293	0.026	0.029	0.059	3.638	0.079	0.200	0.053
L. shoul	0.724	4.241	3.366	0.365	0.010	0.007	0.393	0.019	0.078	0.343
R. hand	0.008	0.029	0.007	0.004	0.105	0.215	0.093	0.149	0.000	0.000
R. arm	2.218	0.892	0.315	0.026	0.001	0.009	0.093	0.000	0.000	0.000
R. shoul	0.713	3.907	4.329	0.307	0.022	0.075	0.127	0.000	0.000	0.000
Pelvic	0.260	0.231	0.792	0.002	0.125	0.310	2.109	0.067	8.221	1.696
Chest	0.202	2.545	0.051	3.026	0.053	0.057	1.097	0.066	2.535	8.711
Back	0.645	0.047	1.079	1.413	0.000	0.000	0.040	0.031	0.821	6.420
Head	0.001	2.385	1.199	3.529	0.001	0.008	0.146	0.009	0.061	0.591
Body	12.61	17.86	11.54	9.16	6.45	10.70	19.55	27.83	25.82	19.35
Floor	23.676	11.606	14.156	9.579	51.452	36.883	34.688	31.296	17.647	12.324
Ceiling	8.201	14.310	12.855	20.523	6.011	4.424	10.252	3.540	6.788	11.868
Front W	10.953	30.938	0.930	12.869	11.191	17.960	10.816	8.779	13.802	14.086
Back W	24.528	0.869	41.202	15.428	4.651	6.745	4.186	9.814	13.029	17.403
Left W	10.076	11.853	9.945	16.283	13.346	15.246	15.403	16.403	19.834	23.152
Right W	9.955	12.560	9.374	16.156	6.892	8.039	5.101	2.341	3.084	1.822

Table 1. View factors for the segments of the manikin (see Figure 1). The presented values are in percent. Because of the symmetrical set-up, only the left side of the manikin is considered. Note that the row labelled "Body" is a summation of the individual body segments.

Results

Table 1 provides the segment-to-segment view factors for the set-up described in the previous section. The data is ordered in columns for each segment and as an example, consider the column for the left leg (labelled "L. leg) The right foot (labelled "R. foot") intercepts $F_{L.leg\rightarrow R.foot}$=0.746% of the radiation leaving "L. leg", "R. leg" intercepts $F_{L.leg\rightarrow R.leg}$=4.69%, etc.

Table 1 only includes values for the left side of the manikin. Because of the symmetrical set-up (Figure 1), the influence of the left side is similar to the influence from the right side. E.g. the left foot intercepts the same radiation from the right hand as the right foot intercepts from the left hand. Table 2 contains the view factors for the outer surfaces.

Since we consider an enclosure, the summation of all values in each column results in 100% (excluding the "Body" row, which is a summation of the individual segments). Also, the view factors for each column are additive, enabling various combinations of segments. The reciprocity theorem may be used to determine view factors that are not explicitly stated in the tables. As an example, consider the radiation leaving the body that is intercepted by the front wall ($F_{Body\rightarrow Front\ W}$). From the reciprocity theorem, this value may be calculated from

$$F_{Front\ W\rightarrow Body}\cdot A_{Front\ W} = F_{Body\rightarrow Front\ W}\cdot A_{Body},$$

where $F_{Front\ W\rightarrow Body}$ is found from Table 2, A_{Body} from Figure 1, and $A_{Front\ W}$ is the area of the wall in front of the manikin. Thus,

$$F_{Body\rightarrow Front\ W}=3.02\%\cdot(2.95\cdot 2.4/1.594)=13.4\%.$$

Applications

In the following, comparisons are made with normally used methods for obtaining the view factors on a full-body basis. Furthermore, some examples are shown on the specific use of the results on a segment-to-segment basis.

Full-body radiative heat loss to outer walls

If the surface temperature of the body and of the outer surfaces is assumed constant (at different levels), it is possible to calculate a radiative heat transfer coefficient for the heat transfer between the manikin and the outer surfaces. To do this, the view factors between the body and each of the six outer surfaces are required.

	Floor	Ceiling	Front W	Back W	Left W	Right W
R. foot	0.269	0.032	0.072	0.030	0.044	0.086
R. leg	0.459	0.055	0.273	0.103	0.122	0.234
R. thigh	0.755	0.220	0.289	0.116	0.135	0.407
L. foot	0.267	0.031	0.071	0.030	0.085	0.044
L. leg	0.458	0.055	0.274	0.103	0.233	0.123
L. thigh	0.740	0.219	0.284	0.110	0.404	0.134
L. hand	0.122	0.014	0.042	0.047	0.079	0.011
L. arm	0.103	0.040	0.099	0.093	0.142	0.022
L. shoul	0.105	0.102	0.148	0.183	0.244	0.019
R. hand	0.111	0.015	0.038	0.036	0.008	0.079
R. arm	0.114	0.041	0.103	0.094	0.023	0.144
R. shoul	0.105	0.109	0.155	0.195	0.019	0.251
Pelvic	0.474	0.164	0.270	0.604	0.248	0.245
Chest	0.204	0.252	0.668	0.019	0.256	0.271
Back	0.231	0.210	0.019	0.827	0.200	0.188
Head	0.133	0.284	0.219	0.263	0.277	0.275
Body	4.65	1.84	3.02	2.85	2.52	2.53
Floor	0.000	24.080	21.735	22.078	21.866	21.921
Ceiling	24.080	0.000	22.760	22.743	22.793	22.759
Front W	17.682	18.517	0.000	15.664	18.422	18.394
Back W	17.962	18.503	15.664	0.000	18.335	18.327
Left W	17.790	18.544	18.421	18.335	0.000	16.064
Right W	17.835	18.516	18.394	18.327	16.064	0.000

Table 2. View factors for the outer surfaces. The presented values are in percent. Note that the row labelled "Body" is a summation of the individual body segments.

Using $F_{Body \rightarrow Front\ W}$ from the previous section, doing the same for the other five outer surfaces (see Table 3, column 1) and adding the values, the view factor between the body and the outer surfaces is determined to be $F_{Body \rightarrow Walls}$=84.0%. Some of the radiation that leaves the body is intercepted by other parts of the body. Consequently, the above view factor is below one as it refers to the full surface area of the manikin.

Consider a situation with a body temperature of T_{Body}=304K (31°C) and an outer surface temperature of T_{Walls}=293K (20°C). Assume an emissivity of ε=0.95 for the body, and of 1 for the outer surfaces. The radiative heat loss may be calculated from

$$q_{Body \rightarrow Walls} = F_{Body \rightarrow Walls} \cdot A_{Body} \cdot \varepsilon \cdot \sigma \cdot (T_{Body}^4 - T_{Walls}^4),$$

where $\sigma = 5.67 \cdot 10^{-8}$ W/(m^{2}K^4) is the Stefan-Boltzmann constant, resulting in a total radiative heat loss of $q_{Body \rightarrow Walls}$=84.4 W. Dividing by the surface area of the body and by the temperature difference results in a radiative heat transfer coefficient of 4.82 W/(m^{2}K), a value in excellent agreement with the normally accepted value of 4.7 W/(m^{2}K) from ASHRAE (1993).

Full-body data – view factor to front wall

When the view factors in Table 3 are normalized (second column), a direct comparison to the "angle factors", described in Fanger (1970), can be made. With the present set-up, the graphical method of Fanger predicts the values in Table 3, third column. The discrepancies between second and third column in Table 3 can be explained by the differing postures in the two cases. Here, the manikin had arms hanging down by the side, whereas the hands of the human subjects are resting on their thighs (Fanger, 1970). Consequently, the projected area of the present manikin is larger when seen from the front or back and smaller when seen from the sides, resulting in the differences of Table 3.

Fanger (1970) uses the "effective radiation area factor", f_{eff}, which is the ratio between the surface area that is "seen" by the outer surfaces and the full surface area, and a value of f_{eff}=0.696 is provided. This value is directly comparable to the view factor of 0.84 found in the present study and thus the agreement is not very good. Indeed, all of the body parts in Table 1 radiates more than 70% to the outer surfaces. One explanation for the discrepancy is the differing posture in the two studies. The present manikin has legs apart at an angle of more than 90 degrees from the torso (leaning backwards), with arms hanging down by the side. This contrasts the posture in Fanger (1970), where the subjects were placed with legs together and with hands resting on the thighs and thereby the arms close to the torso, and a torso close to vertical position.

The dependency of the view factor on the posture was investigated by decreasing the space between the legs and moving the hands closer to the thighs. This change was small compared to the difference between the present posture and the posture in Fanger (1970), but resulted in a decrease in view factor from 84% to 79%. Thus, the differences between the present work and the work by Fanger (1970) can probably be explained by differing posture. As a consequence of the larger radiation to the outer surfaces for the present geometry, the influence of the segment-to-segment radiation is expected to be smaller than for the posture in Fanger (1970).

	Present	Relative	Fanger
$F_{Body \rightarrow Floor}$	25.39	30.2	30.6
$F_{Body \rightarrow Ceiling}$	10.05	12.0	12.2
$F_{Body \rightarrow Front\ W}$	13.41	16.0	14.0
$F_{Body \rightarrow Back\ W}$	12.67	15.1	14.8
$F_{Body \rightarrow Left\ W}$	11.19	13.3	14.1
$F_{Body \rightarrow Right\ W}$	11.24	13.4	14.1
Total	84.0	100	99.8

Table 3. View factors from the body to the outer surfaces. The first column is the view factors; the second is normalized by the total view factor; and the third column is calculated by the method described in Fanger (1970).

Segmental data

Consider a hypothetical situation where the manikin is dressed in thick long shorts and a thick T-shirt with the rest of the body being unclothed and assume a temperature for the clothed body-parts of 298 K (25°C), 305 K (32°C) for the unclothed body-parts, and 295 K (22°C) for the outer surfaces (S1). Find the heat exchange between these three regions, where the clothed region (S2) comprises thighs, pelvic, chest, back, and shoulders, and the unclothed region (S3) comprises feet, legs, hands, arms, and head. The heat exchange between the clothed region and the outer surfaces is

$$Q = \sigma\left(298K^4 - 295K^4\right)\sum_{\mathrm{i}} F_{\mathrm{S2,i}\rightarrow\mathrm{S1}} A_{\mathrm{S2,i}} ,$$

where the summation is for all segments in S2.

Inserting the view factors from Table 1 and the areas from Figure 1, the heat exchange between the clothed parts and the outer surfaces becomes $Q_{2\rightarrow1}$ = 14.7 W = $-Q_{1\rightarrow2}$. Similar calculations for the heat exchange between the clothed and unclothed regions results in $Q_{2\rightarrow3}$ = -2.4 W = - $Q_{3\rightarrow2}$. Finally, the heat exchange between the unclothed region and the outer surfaces becomes $Q_{3\rightarrow1}$ = 31.3 W = - $Q_{1\rightarrow3}$.

For the above case, which is not too atypical, the relative magnitude of the segment-to-segment heat transfer is around 10%. For normal applications, this is not of significance. However, for situations with heavy clothing, where high accuracy is required, radiation between segments may be significant. Furthermore, the local differences in radiative heat loss may result in discomfort.

Conclusions

View factors between different body segments and between the outer surfaces and the body segments were tabulated. The data agreed well with values from the literature and the differences were explained by differing posture. An example of segment-to-segment radiation was made and it was argued that some situations may exist were radiation between segments cannot be ignored.

Acknowledgements

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