INTEGRATION OF LOW-E SURFACES AND SHORTWAVE SOLAR RADIATION INTO HUMAN COMFORT CALCULATION IN TRNSYS 17

Marion Hiller, Johannes Aschaber, Marius Dillig
TRANSSOLAR Energietechnik GmbH, Stuttgart, Germany

KURZFASSUNG

Die mittlere Strahlungstemperatur (engl. mean radiant temperature, MRT) ist eine wichtige Eingangsgröße für die Bestimmung des thermischen Komforts. Bei einfachen Modellen basiert die Ermittlung der mittlere Strahlungstemperatur i.d.R. auf rein geometrischen Größen wie Flächengewichtungs- oder Viewfaktoren. Die Abbildung von optischen Eigenschaften wie nicht-schwarzen Oberflächen und Mehrfachreflektionen z.B. für low-e Effekten ist mit diesen Modellen nicht möglich.

Zur Berücksichtigung geometrischer und optischer Effekte verwendet das detaillierte Komfortmodell in TRNSYS 17 sogenannte Gebhart-Faktoren. Hierfür wird ein Sensor in Kugelform in Anlehnung an DIN EN ISO 7726 und VDI 3787 simuliert. Allerdings ist auch dieses Modell noch auf langwellige Infrarotstrahlung beschränkt.

In diesem Beitrag wird das detaillierte Komfortmodell von TRNSYS 17 kurz beschrieben. Darüber hinaus wird eine Erweiterung des physikalischen Modells vorgestellt, um auch den Einfluss kurzwellig direkter und diffuser Solarstrahlung auf den thermischen Komfort abbilden zu können. Zur Überprüfung werden die Simulationsergebnisse mit Messungen eines Sensors in einem Testraum verglichen. Die Messergebnisse stimmen gut mit den TRNSYS 17 Berechnungen überein und liegen im Rahmen der Messgenauigkeit.

ABSTRACT

The mean radiant temperature (MRT) is a key factor for determining thermal comfort. Simple models apply pure geometric factors like area weighted factors or view factors for calculation of the mean radiant temperature. The influence of optical properties as non-black surfaces and the multiple reflections necessary for low-e effects are generally neglected.

To account for both geometrical and optical properties, the detailed comfort model of TRNSYS 17 is based on Gebhart factors. A sphere shaped sensor on the base of DIN EN ISO 7726 and VDI 3787 is simulated. However, this model is currently restricted to long-wave radiation.

This paper briefly describes the detailed comfort model of TRNSYS 17 integrating the effect of highly reflecting surfaces and a generalization of the model including short-wave beam and diffuse solar radiation.

In addition, the results of a comparitive study between TRNSYS 17 calculations and measurements in a test environment are presented. Mean radiant temperature thereby is evaluated in different radiative environments including short wave radiation and effects of reflecting surfaces. The measurements show good consistency with TRNSYS 17 calculation results and validate the chosen model within the measurement accuracy.

1. INTRODUCTION

For indoor spaces the impact of solar radiation on the thermal comfort is mostly neglected due to the assumption that people are shaded. However, for highly glazed spaces this assumption may not be valid and the exposure of solar shortwave radiation has a large impact.

In the recently released version 17 of the dynamic simulation program TRNSYS a detailed model for thermal indoor comfort including low-e effects is available. However, this model is still restricted to longwave radiation. Therefore the model has been extended to solar shortwave radiation. The modelling approach is validated by a comparative study between TRNSYS 17 simulation results and measurements in a test environment.

2. MEAN RADIANT TEMPERATURE CALULATION

The mean radiant temperature (MRT) is a key factor for determining thermal comfort. Several well known climate indicies are based on the MRT.

The MRT in relation to a person in a given body posture and clothing placed at a given point in a room, is defined as that uniform temperature of black surroundings which will give the same radiant heat loss from the person as the actual case under study. (Definition by Fanger,1970)

Black environment without solar radiation (TRNSYS standard model)

Since most surface materials have a high emissivity, reflection is often neglected. Thus, all surrounding surfaces are assumed to be black. The mean radiant temperature depends on the surface temperatures and the view factor of a person in relation to the surrounding surfaces, which depends on the shape, size and arrangement of the area to the person:

$$\left(T_{MR}^{ir}\right)^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \ldots + T_n^4 F_{p-2} \qquad (1)$$

with:

T_{MR}^{ir} the mean radiant temperature in [K],

T_i the surface temperature of the surface i in [K],

F_{p-i} the view factor between a person and the surface i.

The view factor $F_{A \rightarrow B}$ is defined as the part of diffuse radiation, that leaves surface A (or a differential surface element) and strikes surface B on the direct path (Siegel et al., 2002). The view factor is a pure geometrical factor and does not include any optical properties.

If there is no geometric information available, the mean radiation can be assumed to be the area weighted mean surface temperature of all the surface of a zone:

$$T_{MR}^{ir} = \frac{T_1 A_1 + T_2 A_2 + \ldots + T_n A_n}{A_1 + A_2 + \ldots + A_n} \qquad (2)$$

This rough approximation neglects the effect of the location and the orientation of the person and the surrounding walls. Due to its simplicity this approach is widely used in practical engineering and is implemented in the standard longwave radiation model in TRNSYS 17.

Non-black (reflecting) environment without solar radiation (TRNSYS detailed model)

For taking into account different emissivities of surrounding surfaces especially of low-e effects the MRT calculation has to include reflection. Therefore, the view factors are replaced by the so called Gebhart factors. The Gebhart factor $G_{A\text{-}B}$. defined as the part of the emissions of a surface A (or a differential surface element) that is absorbed on a surface B including all possible paths (multi-reflections). For further details see Aschaber et al. 2008 & 2009.

In the detailed model a sphere shaped so-called bulb thermometer with a diameter of 0.07m based on DIN EN ISO 7726 and 3787 is modelled. A bulb thermometer can be used to determine the mean radiant temperature in a room by measurement. The sphere offeres practical advantages with respect to the view factor calculation of the sensor to surrounding surfaces and the validation procedure versus a "real (human) shaped"sensor.

The sphere's MRT can be used to approximate the mean radiant temperature of a more complex human body for most of the realistic situations. Particularly for seated persons viewfactors of the human body and a sphere match with very small deviations (Dillig, 2009). Compared to standing humans a sphere overestimates the influence of floor and ceiling on MRT. However, this does not create a remarkable error except for abnormally high temperature inhomogenities in a room.

If all surface temperatures of a thermal environment are known the mean radiant temperature is given by:

$$T_{MR}^{ir} = \left[\sum_{i=1}^{n} T_i^4 G_{s,i}^{ir}\right]^{1/4} \qquad (3)$$

with:

$G_{s,i}^{ir}$ the Gebhart factor from sensor surface s to surface i in the IR range

The equation is derived from Fanger's definition of the mean radiant temperature based on longwave radiation. It is important to notice that the surface of the sensor is part of the radiation exchanging environment. Consequently its surface temperature T_s has to be known in order to evalute MRT according to equation (3).

The sensor surface temperature T_s can be obtained by the thermal equilibrium condition between convection and radiation driven heat fluxes:

$$\dot{Q}_s^{conv} + \dot{Q}_s^{ir} = 0 \qquad (4)$$

A detailed description of this calculation procedure can be found in the TRNSYS 17 manual (Klein et al., 2009).

Non-black (reflecting) environment including shortwave solar radiation (extended detailed model of TRNSYS)

Since shortwave solar radiation has a major influence on the mean radiant temperature the existing model of the sensor was extended to the shortwave solar spectrum including direct, diffuse and reflected radiation effects. Therefore, the thermal equilibrium condition of equation 4 has to be extended by a direct solar and diffuse solar heat flux:

$$\dot{Q}_{dir}^{solar} + \dot{Q}_{diff}^{solar} + \dot{Q}_{s}^{ir} + \dot{Q}_{s}^{conv} = 0 \quad (5)$$

Both solar heat fluxes have to include the primary as well as the reflected solar radiation. Therefore, a new set of Gebhart factors is computed for the shortwave spectrum and the fluxes can be described by

$$\dot{Q}_{dir}^{solar} = f_p A_s \alpha_s^{solar} i_n^{dir} + \sum_{i=1}^{n} I_i^{dir} \rho_i^{solar} G_{i,s}^{solar} \quad (6)$$

$$\dot{Q}_{diff}^{solar} = \sum_{i=1}^{n} I_i^{diff} G_{i,s}^{solar} \quad (7)$$

With

f_p the projection factor of the sensor

A_s the sensor surface

α_s^{solar} the solar absorbance of the sensor

i_n^{dir} incident direct solar radiaton density on a surface perpendicular to the incident radiation direction

ρ_i^{solar} the solar reflectivity of a surface i

I_i^{dir} incident direct solar radiation on surface i

I_i^{diff} transmitted diffused radiation through surface I (=0 for opaque walls and >0 for windows)

$G_{i,s}^{solar}$ shortwave Gebhart factors from surface i to sensor surface s

Consequently, the total mean radiant temperature including infrared as well as solar effects can be obtained by:

$$T_{MR} = \left[\left(T_{MR}^{ir}\right)^4 + \frac{1}{\varepsilon_s^{ir} \sigma \cdot A_s} \left(\dot{Q}_{diff}^{solar} + \dot{Q}_{dir}^{solar}\right) \right]^{1/4} \quad (8)$$

For outdoor spaces, VDI 3787 gives an equation for the MRT including solar effects. However, this equation is valid only for perfectly black surrounding surfaces. The equation given by VDI can derived from Eq. 8 by setting all emissivities to 1.

Comparability to MRT of human body

Equation (8) allows computing mean radiant temperature of the sensor. To gain comparability to the more complex human body optical properties have to be fixed to specific values that represent the thermal relations at the human body surface. For a 0.07m sized sphere an IR emissivity of 0.82 and solar absorbance of 0.53 were chosen (Dillig, 2009).

Additionally, the high intensity of direct solar radiation demand closer consideration of the differences in shape between the human body and the sensor. Direct solar heat flux depending on the projection factor f_p (eq. 6) causes an important dependency of human MRT on solar altitude angle. Consequently, the projection factor of the sphere, being constantly at 0.25, is replaced by the angle depending projection factors of the human body (see table 1). Thereby a correction of the direct solar heat flux is done. The low intensity diffuse and reflected solar radiation fluxes however can be well approximated using the sphere as a human body representation.

γ	**0°**	**10°**	**20°**	**30°**	**40°**
f_p	0.308	0.304	0.292	0.271	0.237
γ	**50°**	**60°**	**70°**	**80°**	**90°**
f_p	0.205	0.174	0.140	0.108	0.082

Table 1: Surface projection factor f_p of the human body as a function of the angle γ of the solar altitude angle (VDI 3787, 2008)

3. IMPLEMENTATION INTO TRNSYS17

The previously described extended detailed model has been implemented as a prototype into TRNSYS 17.

In addition, the existing insolation calculations for direct radiation have been extended to determine if a given point is sunlit (depending on external shading), and from which external windows it receives sunlight. The sunlit factor's are written to an external file (*.IPM) which is read in by the multizone building model at the start of the simulation.

4. EXPERIMENTAL VALIDATION USING GLOBE SENSORS

In order to verify the above introduced modelling approach and to proof correctness of the numerical mean radiant temperature calculations within TRNSYS 17 a comparison between simulation results and experimental data was carried out. Therefore it was necessary to measure mean radiant temperatures in a well known thermal environment, i.e. surface and air temperatures.

To obtain mean radiant temperature data a sphere shaped sensor on base of DIN EN ISO 7726 and VDI 3787 was placed into different radiation environments in a climatic chamber at the Institute for Energy Economy and Application Technology of the TU Munich. At TU Munich, well resolved surface temperature measurements were possible due to fine grid, radiation shaded contact sensors at all wall surfaces. Additionally air temperatures at different positions within the climate chamber were recorded by radiation shaded platinum resistance thermometers (PRTs, sensor accuracy ± 0.2 K). In front of the façade of this chamber an artificial sun, i.e. a lighting platform (1 m2) consisting in metal halide lamps (26 x 400 W) and halogen lamps (80 x 150 W) were installed. These spotlights are thereby combined in a way to obtain a realistic simulation of the terrestrial solar spectrum and almost isotropic radiation intensities on the window plane of the climatic chamber.

The experimental set up including dimensions and sensor positioning for mean radiant temperature measurement are indicated in Figure 1. Three different sensor locations where defined to show the influence of position on MRT calculation. During each test the sensor was placed in one of these positions in a height of 1.20 m. Normal incident solar radiation intensity at the sensor position was detected using pre-calibrated pyranometer measurements near to the actual sensor position. The used pyranometer was a KippZonen CM11 installed perpendicular to the incident beam direction.

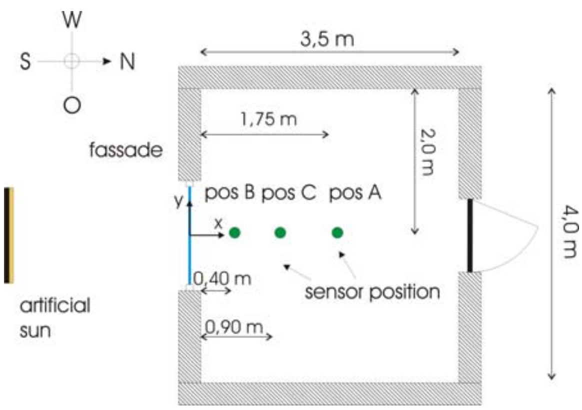

Figure 1: Test facility: climatic chamber dimensions and set up for different measurements

To determine experimentally mean radiant temperatures at a certain position in the climate chamber a metal globe sensor on base of DIN EN ISO 7726 was used. In the center of the metal sphere with 5cm of diameter a PRTs (Pt100 1/3 DIN class B, accuracy: $\Delta T = \pm 1/3\ (0.30°C + 0.005\ t)$) was placed to determine the mean sensor body temperatures. Its optical surface properties, i.e. emissivities for IR-radiation ε_s^{ir} as well as for the solar spectrum α_s^{solar} were determined to 0.87 / 0.57 using spectral reflectivity measurements. Figure 2 shows an image of the used sphere sensor including its thermally detached support.

Figure 2: Example of the sphere shaped sensor used to determine mean radiant temperatures

The mean radiant temperature of the sphere sensor T_{mr} can be calculated for steady state values using the measured mean sensor temperature T_s as well as the air temperature at the sensor position (T_a) by conversion of relation (4):

$$T_{mr} = \left[\frac{h_{conv}}{\varepsilon_s^{ir} \sigma} (T_s - T_a) + T_s^4 \right]^{1/4} \qquad (9)$$

With

T_a the air temperature,

T_s surface temperature of the sensor,

h_{conv} convective heat transfer coefficient

ε_S^{ir} IR - emissivity of the sensor

σ Stephan-Boltzmann constant

During each test the dynamic behaviour, i.e. evolution of temperature values, of sphere sensors and surroundings was recorded. It was aimed to reach steady state room conditions, however due to large time constants of the climate chamber only quasi equilibrium conditions could be reached. As T_{mr} calculations of TRNSYS 17 do not account for heat capacities of the sensing device, Equation 9 was adapted to obtain mean radiant temperature for non-equilibrium conditions and to eliminate deviations due to dynamic delays.

These are compared to the result of a T_{mr} calculation procedure of TRNSYS 17 (see chapter 1) fed with the measured boundary conditions of the climatic chamber. Thereby the dynamics of room were not computed but surface and air temperatures were forced to the measured data of the experiments in the climatic chamber.

Measurement 1: Inhomogenic IR- radiation environment

An objective of this test was to verify correctness of mean radiant temperature calculation in a purely IR-radiation environment for different sensor positions. To generate significant results large temperature inhomogeneities were produced. Therefore the climatic chamber was cooled overnight down to 3 °C wall surface temperatures. After starting the measurement the 100% shaded window surface (IR-emissivity of 0.89) was heated up using the artificial sun as continuous, homogeneous heating device. The sphere shaped sensor was placed in pos B initially. After the room reached an almost steady state condition the sensor was moved to position C resulting in a drop in mean radiance temperature of 13 K. Analyzing Figure 3 with a comparison of measured (crosses) and TRNSYS17 computed mean radiant temperatures for the three predefined position (continuous, dashed, and dotted and dashed line) leads to the conclusion of great conformity within the measuring accuracy. The non-immediate change of MRT when moving the sensor from pos B to C is caused by an averaging approach in MRT calculation. The influence of low-e surfaces, i.e. highly IR-reflecting, could not be shown in this experiment due to high absorption wall surfaces.

Measurement 2: Influence of direct solar radiation

In a second measurement the influence of direct solar radiation at sensor position was studied. Therefore the sensor was placed in position A being irradiated by the artificial sun outside the climatic chamber. In Figure 4 mean radiant temperatures obtained by sphere sensor measurement (crosses) and TRNSYS calculation (dotted-and-dashed line) are plotted on left y-axis, while direct normal irradiance (continuous line) is plotted on the right y-axis. One can see the solar radiation induced an immediate step in mean radiant temperature of about 14 K while rising surface temperature only caused a small delayed effect. This underlines the great importance of correct consideration of solar influences on human comfort calculation. Furthermore the plot shows the good agreement of measured and computed mean radiant temperatures within a certain measurement accuracy, i.e. a correct calculation of mean radiant temperatures for thermal comfort evaluation in sun exposed spots based on DIN EN ISO 7726 and VDI 3787. In the case shown horizontal irradiation from south was chosen, but due to the sphere-shaped sensor solar position theoretically has no influence on mean radiant temperature (as long as sensor is not shaded). The sensor hanging however causes some measurement deviation for low zenith-angles of the artificial sun due to partly shading the sensor surface. This imperfection of the physical sensor is not represented numerically; hence, a comparison is only reasonable for horizontal irradiation.

Measurement 3: Diffuse/Reflected solar radiation

To show the reasons and effects of mean radiant temperature calculation using the Gebhart factors (see chapter 1) instead of a simple, viewfactor based approach, a test environment with highly reflective surfaces is necessary. Consequently, considering surface properties of the test facility, the available climatic chamber did not allow a verification of reflected radiation influence in the IR-spectrum, but only for the solar radiation. To obtain significant test results, the overwhelming influence of direct solar radiation had to be suppressed. Thus, an experimental set up was chosen where the sphere shaped sensor in position A is shaded against direct solar radiation entering the room from an artificial sun turned 40°. Thereby the total amount of incident radiation through the window was calculated and could be distributed to the different wall surfaces using the geometrically computed insolation matrix (see chapter 1). The local distribution of solar

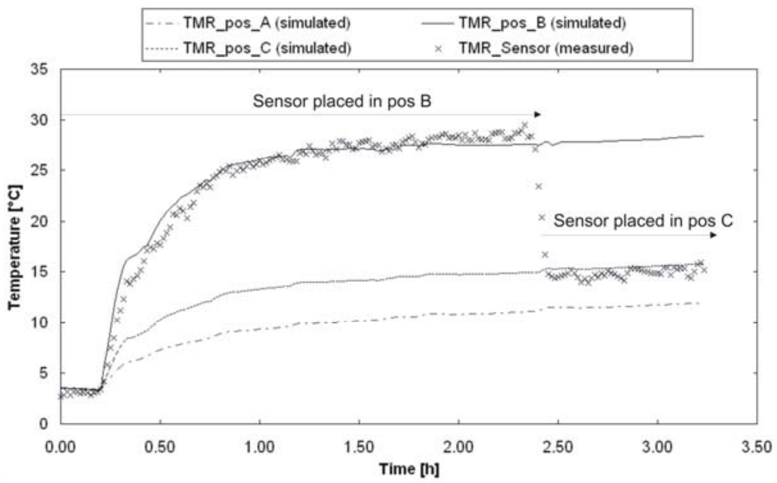

Figure 3:

Measurement 1 showing a comparison of measured and TRNSYS 17 computed mean radiant temperature values for purely IR-radiation environments

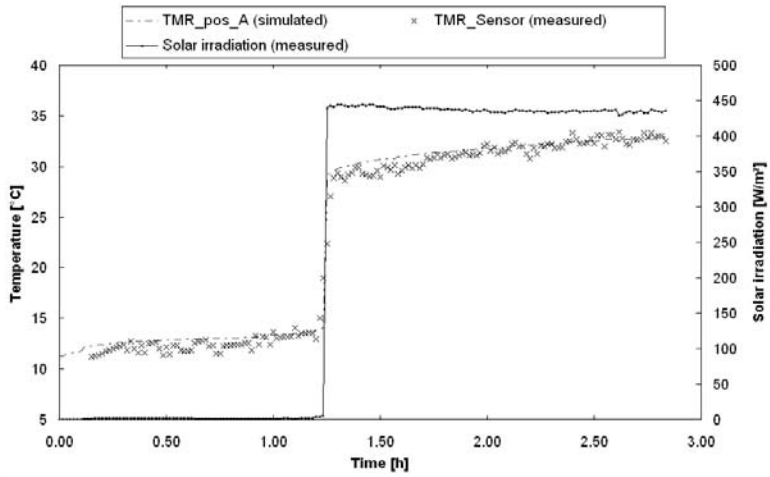

Figure 4:

Measurement 2 showing a comparison of measured and TRNSYS 17 computed mean radiant temperature values for the case of direct solar irradiation

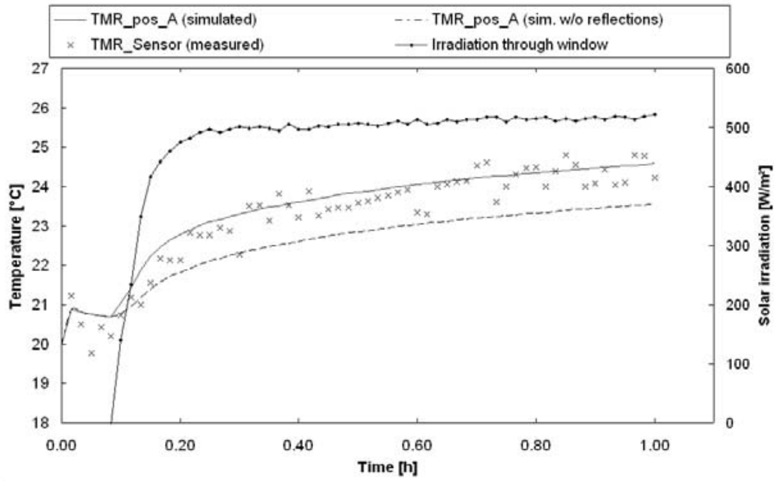

Figure 5:

Measurement 3 showing a comparison of measured and TRNSYS 17 computed mean radiant temperature values for the case of reflected solar irradiation.

radiation was supposed to be homogeneous in order to simplify calculations. In Figure 5 the results of the experiment can be found. The continuous line represents the TRNSYS 17 calculation of mean radiant temperatures considering reflections while the dashed line shows the same calculations ignoring wall reflectivities. Since total amount of incident radiation into the room is rather small due to a low effective window area, the final difference in mean radiant temperature caused by reflected sunlight is 1 K. Hence, the measured T_{mr} values from the sphere shaped sensor (crosses) do not clearly indicate the necessity of the Gebhart approach. However, a trend showing an improvement of the calculated results can be deduced from this measurement. To obtain more reliable conclusions experiments with higher total incident radiation or higher surface reflectivities would have to be carried out.

4. CONCLUSION AND FURTHER WORK

The mean radiant temperature (MRT) is a key factor for determining thermal comfort. In this paper an extension of the detailed comfort model (including highly reflecting/low-e surfaces) of TRNSYS 17 is presented, which integrates short-wave beam and diffuse solar radiation. The derived relationship for the mean radiant temperature includes the MRT equation of VDI 3787 as a special case, which is valid for perfectly black surrounding surfaces only. The derived MRT expression can be used for all approximated geometrical shapes of the human body. In the detailed comfort model of TRNSYS 17 a sphere shaped sensor was used due to computational issues. The extended solar comfort model pursues this approach and uses specific values for the optical properties to achieve a good correlation to the more complex human body.

The experiments clearly confirm the need of a detailed radiation modeling approach. Effects of position, solar radiation and reflecting surfaces have a major influence on mean radiant temperature calculation and thus, on comfort evaluation in buildings. The measurements show good consistency with TRNSYS 17 calculation results and validate the chosen model within the measurement accuracy. In order to clearly proof the correctness of the IR Gebhart model, further measurements in a low-e environment would have to be performed.

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