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Solar Radiation Measurements and Modelling at the Humayun's Tomb, New Delhi

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ABSTRACT: Historical monuments are often damaged by the influence of climate: temperature variations, moisture, driving rain, solar radiation. Therefore, the analysis of the hygrothermic behaviour of a construction plays an important role within the preservation of historical monuments. An elaborate interaction of climatic measurement and numerical simulation helps to avoid damages in historical constructions.

The article presents the EU-funded project CLIMON which deals with the Indo-European knowledge transfer in building climatology applied on investigations on the Humayun´s Tomb in New Delhi. Furthermore, a revised engineering model for the calculation of solar radiation on arbitrarily oriented and tilted surfaces, taking into account the effects of self-shading, is presented. The well-rounded concept is suitable to be integrated in numerical programs for hygrothermal building part simulation. At the end of the article, calculation's results are compared with the measured radiation values.

1 THE PROJECT CLIMON

1.1 Background and project objectives

The protection of the cultural heritage is one of the very important tasks of the present generation. Both in India and Europe, there is a great diversity and number of buildings of cultural heritage. One major source of damages on these buildings is the influence of climate: temperature variations, moisture, driving rain, solar radiation. Therefore the preservation of such monuments requires elaborate tools and knowledge about the influencing climatic parameters and the construction's hygrothermic behaviour. This knowledge is insufficiently available in Europe and India. The CLIMON-project aims at exchanging these needed tools and knowledge, first between the project partners, and second with external experts.

The partnership consists of two European universities: TU Dresden, Germany, as main applicant and CU Leuven, Belgium. The other partners are: IIT Delhi and MNIT Jaipur as Indian scientific partners, and the Indian Council of Architecture, with its reputation and connections important for the spreading of the project results. The Archaeological Survey of India enabled and supported the practical work at the monument.

1.2 Project activities

To reach the project goal, three main work packages are used. First, during preliminary studies an equal state of knowledge among the partners is reached to ensure a smooth flow of the further work. The second section, theoretical modelling and human resources development, provides the scientific tools as a basic requirement: theoretical models on climate parameters, software and common work standards. In a third work package the practical work at one monument in India will serve as example for a common methodology for the investigation of the interaction between climate and a building of the historical heritage.

After consulting the Archaeological Survey of India, the Humayun´s Tomb in New Delhi was selected for the measurements. This Mughal tomb, built in 1570, is of particular cultural significance as it was the first garden-tomb on the Indian subcontinent. It inspired several major architectural innovations in the following centuries. The building materials – red sandstone and white marble – are representative for many historical buildings in India. The main climate parameters (air temperature, relative humidity, solar radiation, wind speed, wind direction and precipitation) are continuously measured. At the same time, the resulting state variables at the building are registered. The results of the numerical simulation, taking the measured climate parameters as boundary conditions, should correspond with the data measured at the tomb.

The planned investigations include also the measurement of the hygrothermic material properties of the building materials in Indian and European laboratories, because these are necessary as input for the simulation programs.

In April and May 2005 the measurement equipment was installed in and around the Humayun´s Tomb. Since this time the data collection process is running, it will be continued until the end of the project to cover a period of more than one year.

Figure 1 : View of the Humayun's Tomb from the garden

Figure 2 : Moisture related damages on the red sandstone of the Humayun´s Tomb

Figure 3 : Climatic measurement equipment at the Tomb

2 MODELLING OF SOLAR SHORTWAVE RADIATION

2.1 Hygrothermic simulation software DELPHIN 4

The renovation of historical monuments requires an extended analysis of the constructive and physical properties of the existing construction.
Therefore sophisticated numerical simulation tools for the determination of the hygrothermic behaviour of building envelope parts are needed. The Institute of Building Climatology at the Technical University of Dresden has developed such a simulation tool called DELPHIN 4.
After having read in construction details, material functions and climatic boundary conditions, the simulation software DELPHIN 4 is able to predict the transient hygrothermic performance of the building part, such as temperature, heat flux, relative humidity, water content or overhygroscopic water content. Continuing testing and improvement of this numerical program remain important work for researchers.

2.2 Modelling of solar radiation - background

Physical models for climatic conditions are available, but they are often realised for other purposes, such as agriculture. However, numerical simulation tools for building envelope parts require specially adapted physical models for climatic components, and the integrated approach could no longer satisfy the actual requirements.
Therefore, being a first step, a revised engineering model for the description of solar irradiation on arbitrarily oriented and tilted building envelope parts has been established and shall be presented in this paper. The calculation is based on measured values of direct and diffuse solar radiation on a horizontal surface.
The principal formulas are to be shown in the following.

2.3 Calculation of solar shortwave radiation on arbitrarily oriented and tilted surfaces

While crossing the earth's atmosphere, solar shortwave radiation is being partially absorbed and scattered. The part of the solar radiation that is not absorbed or scattered, arrives on the earth's ground as direct solar radiation. Scattering in the atmosphere and reflection of total radiation on the ground yield diffuse radiation on the wall. Both parts of total radiation, direct and diffuse radiation, have to be calculated separately for the arbitrarily oriented and tilted surface. At the end, they are summed up to the amount of total radiation on the wall.

2.3.1 Parameters of sun position

Sun declination. The sun declination $\delta(t)$ is defined as the distance of the sun from the celestial equator:

$$\delta(t) = \frac{-23{,}5° \cdot \pi}{180°} \cdot \sin\left[\frac{2\pi}{365} \cdot \left(t + 10 + \frac{365}{4}\right)\right] \; [\text{radian}] \tag{1}$$

where t = time [days].

Sun height. The height of the sun over the horizon is called sun height $h(t)$:

$$h(t) = \arcsin[\sin(\phi) \cdot \sin(\delta(t)) - \cos(\phi) \cdot \cos(\delta(t)) \cdot \cos(2\pi \cdot t)] \quad [\text{radian}] \tag{2}$$

where ϕ = location's latitude $[\text{radian}]$, $\delta(t)$ = sun declination (1).

Azimuth. The azimuth $a(t)$ represents the so-called celestial direction of the sun. The Sinus of the azimuth is defined as (Petzold 2002):

$$\sin(a(t)) = \frac{\cos(\delta(t)) \cdot \sin(2\pi \cdot t)}{\cos(h(t))} \tag{3}$$

where $\mathrm{h(t)} = \text{sun height}(2)$.

The azimuth $\mathrm{a(t)}$ has to be calculated in the following way (Finkenstein et al. 2006):

$$\mathrm{a(t)} = \arcsin(\sin(\mathrm{a(t)})) \qquad \text{if } \sin(\mathrm{a(t)} \geq 0 \cap \frac{\mathrm{d}}{\mathrm{dt}}\sin(\mathrm{a(t)}) \geq 0 \qquad [\text{radian}]$$

$$\mathrm{a(t)} = \pi - \arcsin(\sin(\mathrm{a(t)})) \quad \text{if } \frac{\mathrm{d}}{\mathrm{dt}}\sin(\mathrm{a(t)}) < 0$$

$$\mathrm{a(t)} = 2\pi + \arcsin(\sin(\mathrm{a(t)})) \text{ if } \sin(\mathrm{a(t)} \leq 0 \cap \frac{\mathrm{d}}{\mathrm{dt}}\sin(\mathrm{a(t)}) \geq 0 \qquad (4)$$

2.3.2 Direct solar radiation on arbitrarily oriented and tilted surfaces

Based on the measured or given data of direct radiation on a horizontal surface, it is possible to calculate the direct radiation on a surface with any orientation β and any inclination α.
The angle function for vertical surfaces $\mathrm{B_{ver}(t)}$ is defined as (Petzold 2002):

$$\mathrm{B_{ver}(t)} = \frac{\cos(\mathrm{a(t)} - \beta)}{\tan(\mathrm{h(t)})} \qquad [\,] \qquad (5)$$

where $\mathrm{a(t)}$ = azimuth (4), β = orientation [radian] ($\beta = 0$ means northern direction, $\beta = \pi/2$ means eastern direction etc.) and α = wall's inclination [radian] ($\alpha = 0$ means horizontal, $\alpha = \pi/2$ means vertical surface etc.).

The day length function $\mathrm{D(t)}$, which describes whether sun is over the horizon or not, has to be calculated as:

$$\mathrm{D(t)} = \Phi(\mathrm{h(t)}) \qquad [\,] \qquad (6)$$

where $\Phi(\mathrm{x})$ = Heaviside jump function ($\Phi(\mathrm{x}) = 0$ if $\mathrm{x} \leq 0$ and $\Phi(\mathrm{x}) = 1$ if $\mathrm{x} \geq 0$).

The self shading function $\mathrm{S(t,\alpha,\beta)}$ is defined as:

$$\mathrm{S(t,\alpha,\beta)} = \cos(\alpha) + \sin(\alpha) \cdot \mathrm{B_{ver}(t)} \qquad [\,] \qquad (7)$$

where $\mathrm{B_{ver}(t)}$ = angle function for vertical surfaces (5).

From (7) we get the total self shading function $\mathrm{S_{\Phi}(t)}$:

$$\mathrm{S_{\Phi}(t)} = \Phi(\mathrm{S(t,\alpha,\beta)}) \qquad [\,] \qquad (8)$$

where $\mathrm{S(t,\alpha,\beta)}$ = self shading function (7).

Angle function for direct radiation on arbitrarily oriented and tilted surfaces. While using equations (1) – (8) we note that the angle function $\mathrm{B(t,\alpha,\beta)}$, which has to be multiplied with the direct radiation on horizontal surfaces in order to get direct radiation on arbitrarily oriented and tilted surfaces, is defined as (Finkenstein et al. 2006):

$$B(t,\alpha,\beta) = [\cos(\alpha) + \sin(\alpha) \cdot B_{ver}(t)] \cdot D(t) \cdot S_{\Phi}(t) = \left[\cos(\alpha) + \sin(\alpha) \cdot \frac{\cos(a(t) - \beta)}{\tan(h(t))}\right] \cdot D(t) \cdot S_{\Phi}(t) \qquad (9)$$

where $D(t)$ = day length function (6) and $S_{\Phi}(t)$ = total self shading function (8).
With (9) and the measured or otherwise given data, we calculate the direct radiation on arbitrarily oriented and tilted surfaces $Q_{dir,\alpha,\beta}(t,\alpha,\beta)$ as:

$$Q_{dir,\alpha,\beta}(t,\alpha,\beta) = Q_{dir,hor}(t) \cdot B(t,\alpha,\beta) \qquad [W/m^2] \qquad (10)$$

where $Q_{dir,hor}(t)$ = direct radiation on a horizontal surface, $B(t,\alpha,\beta)$ = angle function (9).

2.3.3 Diffuse solar radiation on arbitrarily oriented and tilted surfaces

Besides the direct radiation, a building part is also loaded by solar diffuse radiation which consists of two parts: a) radiation having been scattered while crossing the atmosphere and b) total radiation having been reflected and scattered on the ground. Diffuse radiation is – contrarily to direct radiation – not dependant on the surface's orientation. Diffuse radiation on a arbitrarily tilted wall $Q_{dif,\alpha}(t)$ can be described as:

$$Q_{dif,\alpha}(t,\alpha) = Q_{dif,hor}(t) \cdot \cos^2(\alpha/2) + \rho_e \cdot Q_{tot,hor}(t) \cdot \sin^2(\alpha/2) \quad [W/m^2] \qquad (11)$$

where $Q_{dif,hor}(t)$ = diffuse radiation on a horizontal surface, ρ_e = surrounding's Albedo [ ] , $Q_{tot,hor}(t)$ = total radiation on the horizontal surface.

3 MEASURED SOLAR RADIATION DATA AT THE HUMAYUN'S TOMB, NEW DELHI

3.1 Measurement at Humayun's tomb

As already noted before, all relevant climate parameters are being measured at Humayun's Tomb such as air temperature, relative humidity, solar shortwave radiation, wind speed, wind direction and precipitation. At the same time, several state variables at the Tomb's southern facade are registered such as surface temperature in- and outside, relative humidity at several locations inside of the construction or heat flux density.

Concerning solar radiation, a pyranometer has been installed in order to register total radiation on the horizontal surface, being one of the climate parameters. Belonging to the state variables of the construction, the total radiation on the Tomb's southern facade is being measured. Both pyranometers are continuously registering total radiation data every 5 minutes.

3.2 Generating direct and diffuse radiation data

The objectives within the solar radiation related investigations on the Humayun's tomb are to find a good correspondence between the measured data of total radiation at the southern facade and the calculated total radiation data based on the (measured) radiation data on the horizontal surface. As we have seen before, a division of total radiation into a direct and a diffuse part is needed for the calculation of solar radiation incident on an arbitrarily oriented and tilted wall.
Therefore, the measured data of total radiation on the horizontal surface have been processed into direct and diffuse radiation by the correlation of Reindl, Beckman und Duffie (Reindl et al. 1989). The correlation is based on the research work of Liu and Jordan (Liu, Jordan 1960). It is the result of the statistical analysis of measured data in Northern Europe and North America.

Reindl, Beckman and Duffie define firstly the transient clearness index $k_T(t)$:

$$k_T(t) = \frac{Q_{tot,hor}(t)}{Q_{0,hor}(t)} \qquad [\ ] \qquad (12)$$

where $Q_{tot,hor}(t)$ = total radiation on the horizontal surface, measured on Earth's ground, $Q_{0,hor}(t)$ = extraterrestrial solar radiation on the horizontal surface (based on Solar constant, applied on the horizontal surface, to be calculated with regard to the transient distance Earth-Sun and – voluntarily- Equation of Time).

We get then the diffuse part of the total radiation from (Reindl et al. 1989):

$$Q_{dif,hor}(t) = Q_{tot,hor}(t) \cdot (1{,}020 - 0{,}254 \cdot k_T(t) + 0{,}0123 \cdot \sin(h(t))) \qquad \text{if } k_T(t) \le 0{,}3$$

$$Q_{dif,hor}(t) = Q_{tot,hor}(t) \cdot (1{,}400 - 1{,}749 \cdot k_T(t) + 0{,}177 \cdot \sin(h(t))) \qquad \text{if } 0{,}3 \le k_T \le 0{,}78$$

$$Q_{dif,hor}(t) = Q_{tot,hor}(t) \cdot (10{,}486 + 0{,}182 \cdot \sin(h(t))) \qquad \text{if } k_T(t) \ge 0{,}78$$

$$\left[W/m^2\right] \qquad (13)$$

As direct and diffuse radiation sum up to total radiation, we can easily calculate direct radiation with (13) by subtracting the diffuse radiation part from the given (measured) total radiation on the horizontal surface.

The correlation remains important for a lot of radiation measurement investigations, as the registering of only total radiation is very often the case. In Fig. 4 one can see very clearly the “arbitrary” amount of direct radiation caused by the differing cloudiness. Contrasting to that, Fig. 5 shows the quite constant course of the maximum values of diffuse radiation while rising smoothly, with a minimum at the end of the year.

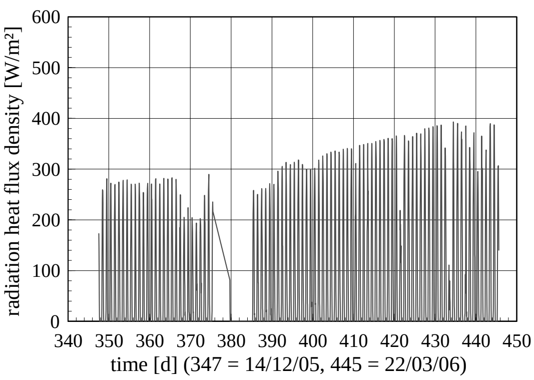

Figure 4 : Direct solar radiation on the horizontal surface at Humayun’s Tomb, New Delhi

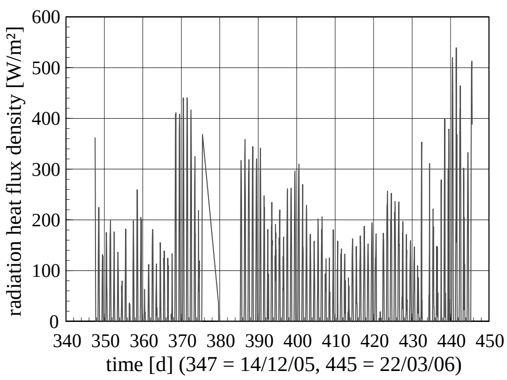

Figure 5 : Diffuse solar radiation on the horizontal surface at Humayun’s Tomb, New Delhi

3.3 Comparison of calculated and measured results

After having calculated direct and diffuse parts of radiation measured on the horizontal surface (13), total radiation can be processed by using equations (1)-(11).

Fig. 6 represents the total radiation on the south wall, calculated with the described engineering model of radiation on arbitrarily oriented and tilted surfaces. The direct and diffuse radiation on the horizontal surface, normally given per measurement, have been correlated from the measured total radiation on the horizontal surface by the correlation of Reindl, Beckman, Duffie (13).

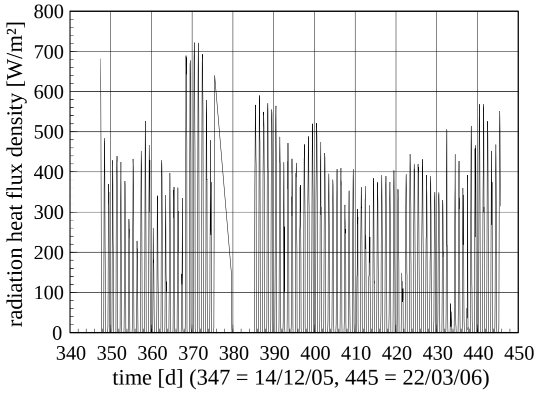

Figure 6 : Calculated total radiation on the South facade of Humayun's Tomb, New Delhi

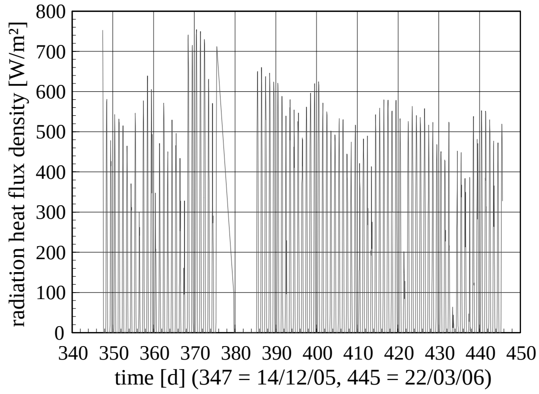

Figure 7 : Measured total radiation on the South facade of Humayun's Tomb, New Delhi

If we compare Fig. 6 and 7, we will find a satisfying correspondence between measured and calculated radiation data. While considering the difficult data situation having only total radiation data on the horizontal surface, the correspondence is to be judged very good.
The following Fig. 8 and 9 show again the calculated and measured total radiation at the south facade, this time for shorter time periods of ten days in January and March 2006.
For the shorter time periods in January and March 2006 in Fig. 8 and 9, the correspondence between measured and calculated total radiation data is very good.
Fig. 8 presents clear sky days (days 368 - 372) corresponding to high values of the clearness index k_T at noon of approximately 0,7. On clear sky days the amount of direct radiation is relatively high, therefore the total radiation on the wall reaches high values of approximately 700 W/m². For the time period in March 2006, shown in Fig. 9, the values of the clearness index k_T at noon vary from 0,29 to 0,68- the figure shows therefore overcast days.

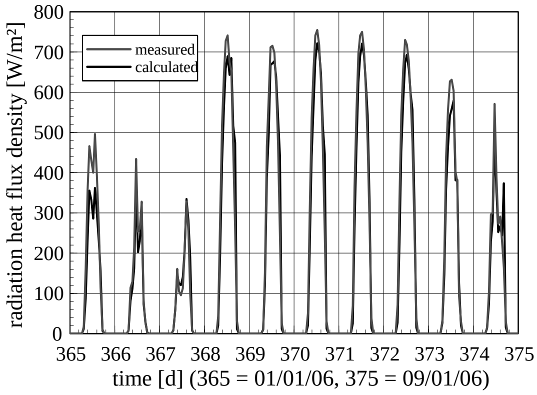

Figure 8 : Total radiation at the South facade of Humayun's Tomb, New Delhi, in Jan. 2006 - Comparison of measured and calculated values

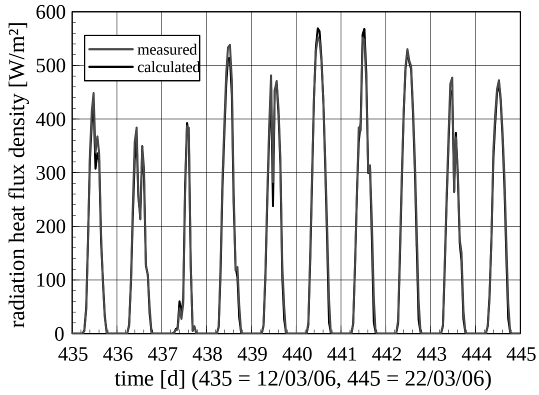

Figure 9 : Total radiation at the South facade of Humayun's Tomb, in March 2006-Comparison of measured and calculated values

4 CONCLUSIONS

As one of the major sources of damages on historical constructions is the influence of climate, the analysis and understanding of their hygrothermic behaviour remain of great importance in the protection of historical monuments.

Within the EU-India project CLIMON an exchange and knowledge transfer on tools and methodologies in building physics having the regard on historical monuments could be started.

The ongoing climatic measurements at the Humayun's Tomb, New Delhi provide a good data base for further common research work. All important climatic parameters, such as temperature, relative humidity, heat flux, solar radiation, wind speed, wind direction and driving rain will be investigated.

Another important tool in the protection of historical monuments is the numerical simulation of the hygrothermic behaviour of building parts. Based on construction details, material functions and given boundary conditions it is possible to predict temperature variations or hygric loads. These are responsible for many damages at historic constructions and monuments. Continuing testing and improvement of the simulation programs remain therefore important research work.

As a first example for the investigations conducted at the Humayun´s Tomb, the measurements on solar shortwave radiation have been shown. Furthermore, an engineering model for the calculation of solar shortwave radiation on arbitrarily oriented and tilted surfaces, suitable for numerical simulation programs of coupled heat and moisture transfer, was presented. Data base for the engineering model is the direct and diffuse radiation data on the horizontal surface, which were, in this case, not available. Therefore, a correlation model to separate the total radiation into its direct and diffuse parts has been applied.

At the end, the results of calculation and measurements show a very good correspondence.
The presented procedure, being an important tool to calculate the boundary condition of shortwave radiation on the surface, has already been included in the numerical simulation program DELPHIN 4.

REFERENCES

Finkenstein C., Fechner H. and Häupl P. 2006. Modellierung von kurzwelliger solarer Strahlung bei der hygrothermischen Bauteilsimulation – num. Lsg. und analytischer Ansatz. *Bauphysik* 28(1), p. 1-12.

Grunewald J., Fechner H. 2006. *DELPHIN 4* – Simulation software for coupled heat, moisture and salt transfer. http://www.bauklimatik-dresden.de

Häupl, P., Jurk, K., Petzold, H. 2003. *Inside thermal insulation for historical facades*. Proceedings 2nd International Conference on Building Physics, Leuven, Sept. 14th-18th, 2003 p. 463-47

Häupl P. 2005. *Bauphysik für Ingenieure*. Lecture notes at TU Dresden. Institute of building climtology.

Iqbal M. 1983. *An introduction to solar radiation*. Academic Press Toronto.

Liu B., Jordan R. 1960. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy* 4, p. 1-19.

Petzold K. 2002. Klima. In Lutz et al, *Lehrbuch der Bauphysik*, Teubner-Verlag, p. 613-633.

Reindl D., Beckman W. and Duffie J. 1989. Diffuse Fraction Correlations. *ISES Solar world conference*, p. 2082-2089.