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Measurement of the environmental temperature using the sol-air thermometer

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Abstract

Heat flow measurement with a heat flow meter is a standardized method (ISO 9869-1) to estimate thermal transmittance (U-value) of a building element. The heat flow meter is a thin plate mounted on top of the surface of the element, and measures the heat flux q through the plate. The measured q is the product of the difference in temperatures between exterior and interior environment, and the U-value. The heat transferred from the element is based on the radiant and the convective heat transfer.

ISO 9869-1 specifies that the environment temperature T_e “is a notional temperature" and it "cannot be measured directly” (section A.3.1). The air temperature T_a is proposed as a reasonable approximation for the indoor environment, while overcast conditions and absence of significant solar radiation are specified conditions for replacing T_e with T_a for the exterior environment.

The sol-air thermometer (SAT) measures the sol-air temperature T_{sa}, i.e. the equivalent temperature of the convective and the radiative environment. In the absence of solar radiation, $T_e = T_{sa}$. SAT is a sensor consisting of a thin flat solid plate, of high thermal conductivity. The front side of the sensor is exposed to the environment, whose T_{sa} is to be measured, and the backside is thermally insulated. The temperature of the SAT-plate equals T_{sa}.

In this work we propose introduction of the measured T_e in the existing standard (ISO 9869-1). The method for measurement of T_{sa}, using the SAT, has been demonstrated experimentally for different periods, without solar radiation present and under stable climatic conditions.

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Keywords: Environmental temperature; Sol-air thermometer; Heat transfer coefficient; Thermal transmittance

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1. Introduction

The standard ISO 9869-1:2014 describes a heat flow methodology for measurement of the thermal transmission properties of plane building components [1]. The standard defines the thermal transmittance *U*-value of a building element as

$$U = q/(T_i - T_e) \tag{1}$$

, where q is the heat flux through the element, and T_i and T_e are the interior and exterior environmental temperatures, respectively. According to ISO 9869, the environmental temperature T_e of a building surface is properly defined by (cf. Eq. (A.3) in [1]; [2])

$$T_e = (h_r T_r + h_c T_a)/(h_r + h_c) \tag{2}$$

, where T_r is the mean radiant temperature (infrared radiation), T_a is the air temperature, and h_r and h_c are the radiative and convective heat transfer coefficients, respectively. Here we included the surface emissivity ε in the definition: $h_r = 4\varepsilon\sigma T_m^3$, where $T_m = (T_r + T_s)/2$, T_s is the surface temperature, and σ is the Stefan-Boltzmann constant.

The ISO 9869 states that T_e, as defined in Eq. (2), "is a notional temperature" and it "cannot be measured directly" (§A.3.1 in [1]). Our objective with this study was to falsify this statement. For this purpose, we performed direct measurements experimentally. The experimental results and the calculated T_e, which was obtained from Eq. (2), were compared.

Nomenclature

h_c	convective heat transfer coefficient ($Wm^{-2}K^{-1}$)
h_o	heat transfer coefficient ($Wm^{-2}K^{-1}$)
h_r	radiative heat transfer coefficient ($Wm^{-2}K^{-1}$)
I_s	total solar irradiation (Wm^{-2})
q	heat flux (Wm^{-2})
T_a	air temperature (K)
T_e	(exterior) environmental temperature (K)
T_i	interior environmental temperature (K)
T_m	mean temperature, used in h_r
T_r	mean radiant temperature (K)
T_s	surface temperature
T_{sa}	sol-air temperature (K), i.e., the equivalent temperature of the convective and radiative environment
U	thermal transmittance ($Wm^{-2}K^{-1}$)
α	absorptivity of solar radiation (unit-less)
ε	emissivity (unit-less)
σ	Stefan-Boltzmann constant = $5.67 \cdot 10^{-8}$ ($Wm^{-2}K^{-4}$)
w	wind speed (m/s)

2. Experimental

2.1. Sol-air thermometer

The concept of the sol-air temperature T_{sa}, was introduced as the equivalent temperature of convective and radiative environment for a surface. This definition includes solar radiation [3, 4]. T_{sa} is often expressed, according to [4, 5], as

$$T_{sa} = \alpha I_s/h_o + (h_r T_r + h_c T_a)/h_o \quad (3)$$

, where α is the absorptivity of solar radiation, I_s is the total solar irradiation (diffuse and direct, over the hemisphere), and the heat transfer coefficient $h_o = h_r + h_c$. By comparison of Eqs. (2) and (3), we observe that

$$T_{sa} = \alpha I_s/h_o + T_e \quad (4)$$

Therefore, in the absence of solar radiation, the environmental temperature is equivalent to the sol-air temperature.

The sol-air thermometer (SAT) measures T_{sa} by exploiting the fact that $q = h_o(T_s - T_{sa})$, and that, due to insulation of the backside of the SAT, q always equals zero for the SAT unit [6, 7]. Therefore $T_s = T_{sa}$, for the SAT. There are two basic SAT designs: (i) the Mackey and Wright (MW) design, where the SAT body is a 0.20 m cubic construction [6], and (ii) the Muncey and Holden (MH) design, where the SAT consists of a circular thin metallic disk, which is mounted with its outer surface in plane with the surface of interest [7]. Rao and Ballantyne evaluated these two SAT designs by comparing measurement results with calculated values. That calculation was based on an expression similar to Eq. (3), with measured and assumed estimates of the input quantities [4]. Their conclusion was that the thin plate MH design had the best performance of the two, but the results were still not in agreement with the calculated values.

The SAT used in the present work was of the MH design. The SAT temperature (= T_{sa}) was measured using a platinum resistance thermometer, which was inserted into the SAT copper plate, see Fig. 1. The SAT surface was matt black painted, with α close to one, and $\varepsilon = 0.943$ (Nextel-Velvet coating 811-21, ref. [8]). The SAT was equipped with an electric resistive heating-foil, for purposes described in Section 2.2 below. The SAT plate was inserted into an extruded polystyrene insulation plate. The plate top surface aligned with the insulation top surface.

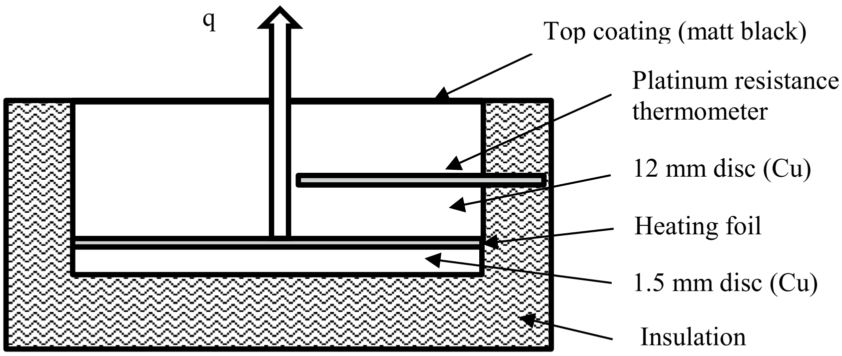

Fig. 1. Solar air thermometer (SAT) unit.

2.2. Estimating input quantities

In this work, a comparison was conducted with measured values of the environmental temperature ($T_{e,meas}$) against calculated values ($T_{e,calc}$), where the latter was obtained by inserting estimates of input quantities into Eq. (2). The T_a, T_r, and h_c were estimated as follows: T_a was measured using a ventilated and shielded air thermometer (Young, model 41342); T_r was measured using a pyrgeometer (Hukseflux, model IR20-T1); h_c was measured according to the Ito-method [9, 10]. That methodology was conducted with two heated SAT units (one heated and the other unheated), with supplied heat flux measured electrically. The h_r quantity is a function of T_s, which is the surface temperature. In this particular case, where the surface equals the surface of the SAT, and where there is no solar radiation present, we find that $T_s = T_e$. By insertion of input estimates into Eq. (2), we obtain

$$T_{e,calc} = \left(h_r(T_{e,calc})T_r + h_c T_a\right)/\left(h_r(T_{e,calc}) + h_c\right) \quad (5)$$

, which implicitly yields the sought value of $T_{e,calc}$. Eq. (5) was solved iteratively, and for that purpose we needed an initial estimate of $T_{e,calc}$. Eq. (2) shows that T_e is always limited to be in the range between T_r and T_a. Therefore we initially estimated $T_{e,calc} = (T_r + T_a)/2$, inserted this value into the right-hand side of Eq. (5), and performed the calculation to arrive at a new estimate of $T_{e,calc}$. This procedure was repeated until the estimates converged, usually after only 3-4 iterations.

3. Results and Discussion

Parameters of the set of collected experimental data were T_a (measured by the ventilated and shielded air thermometer) and T_r (measured by the pyrgeometer). Three SAT units were used; referred to as SAT0, SAT1 and SAT2. Data from the heated SAT0 and unheated SAT2 were used for estimation of h_c, according to the Ito method. The unheated SAT1 provided measured environmental temperature data, referred to as $T_{e,meas}$.

All measurements were performed in December 2016 to January 2017, at the Umeå University campus, Sweden. The analyzed data were collected at nighttime, in order to exclude the influence of the solar irradiation. Thirteen periods that consisted of two to five hours continuous (0.02 Hz) data sampling, and where outdoor conditions were stable, were selected for use in this study. Weather conditions, measured temperatures and the calculated heat transfer coefficients are presented for these periods in Table 1.

Table 1. Weather conditions, measured temperatures and the calculated heat transfer coefficients for the selected thirteen periods. The values for the wind speed w were obtained from an anemometer positioned ca 10 m above the SAT units, and were not used in the estimation of h_c or $T_{e,calc}$.

No.	Weather conditions	w (ms^{-1})	T_a (K)	T_r (K)	h_c (Wm^{-2}K^{-1})	h_r (Wm^{-2}K^{-1})
1	clear sky; stable temps	1,52	260,2	244,8	10,9	3,37
2	clear sky; stable temps	1,03	272,0	265,0	11,9	4,10
3	clear sky; stable temps	2,46	275,4	261,1	21,1	4,08
4	cloudy	1,87	275,8	274,7	16,7	4,46
5	cloudy; windy; stable	3,74	274,7	272,4	23,3	4,37
6	clear; stable	1,38	273,9	257,6	14,5	3,94
7	clear; rather stable	2,14	272,4	255,5	15,9	3,86
8	clear; stable	-	273,4	255,1	19,5	3,88
9	cloudy	2	274,6	269,1	17,6	4,27
10	clear	3,63	276,5	259,9	22,0	4,07
11	clear	4,20	277,3	259,7	21,2	4,07
12	cloudy	1,95	274,3	273,1	16,6	4,38
13	clear; no wind	-	262,8	255,7	9,88	3,67

An estimate of $T_{e,calc}$ was obtained using the iterative process, based on measurements of T_r, T_a, and h_c according to section 2.2 above. In Fig. 2, the $T_{e,calc}$ values for the thirteen studied periods were compared to the simultaneously measured $T_{e,meas}$.

Four periods (nr 4, 5, 9 and 12) were characterized by cloudy weather. For these periods the measured temperature spread of T_r, T_a, $T_{e,calc}$ and $T_{e,meas}$ is relatively small, due to the prevailing overcast condition, where the sky temperature ($\approx T_r$) is close to T_a (c.f. Table 1.). For those cloudy periods $T_{e,calc}$ and $T_{e,meas}$ is almost equal to T_r and T_a. But even during periods of clear skies, $T_{e,calc}$ and $T_{e,meas}$ has equal values. These can be found between the measured Tr and T_a (c.f. Fig 2.). The similar results obtained for $T_{e,calc}$ and $T_{e,meas}$ in this study suggest that the experimental measurements of the environment temperature can provide reasonable results. The similar results of $T_{e,calc}$ and $T_{e,meas}$ is also an support for that both h_r and h_c was modelled accurately.

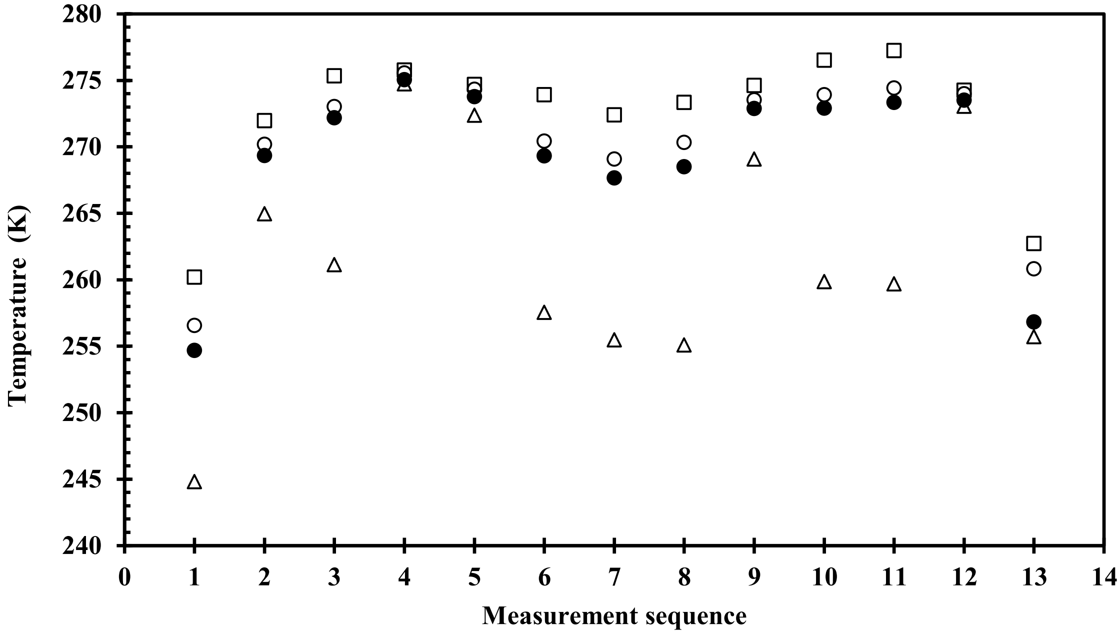

Fig. 2. Comparison of T_a (squares), T_r (triangels), $T_{e,calc}$ (open circles) and $T_{e,meas}$ (filled circles) for the nine measurement periods.

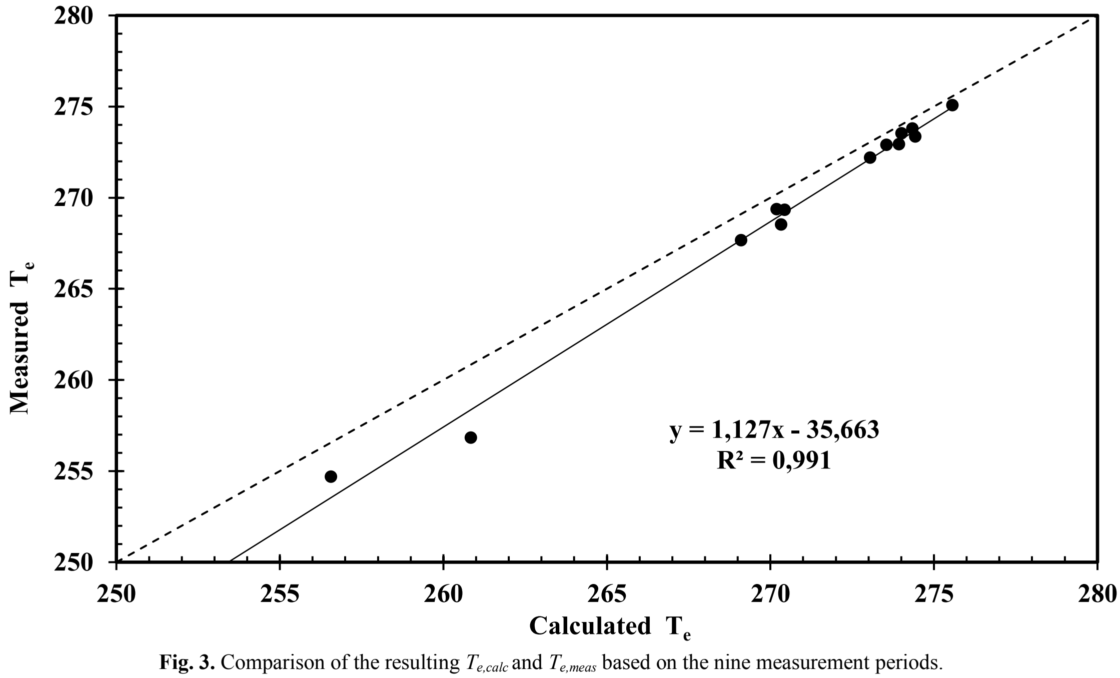

Fig. 3. Comparison of the resulting $T_{e,calc}$ and $T_{e,meas}$ based on the nine measurement periods.

A linear regression was performed to investigate the accuracy of the resulting $T_{e,calc}$ and $T_{e,meas}$, see Fig. 3. It showed a very good correlation with an $R^2 = 0,997$ based on the equation y = 1,127x - 35,663 (standard errors were 0.033 and 8.9 for the slope and intercept, respectively). The deviation from the 1:1 line (with slope = 1 and intercept = 0) cannot be fully explained in this study. We suspect that measurement no. 1 could have been biased due to low heater power supplied to SAT0 for the h_c measurement (cf. [10]), and that measurement no. 13 was affected by a thin layer of ice formed onto the SAT1 surface. Further studies should consider an expanded selection of stable measurement periods covering a wider range of climatic conditions. The main source of random variations in the results of Fig. 3 is probably $T_{e,calc}$, since this variable includes several measurements, while $T_{e,meas}$ is estimated from one single temperature measurement.

4. Conclusions

The objective of this study was to question the stated limitation for direct measurement of T_e, as specified in [1]. Although there is an identified deviation between calculated and measured values, we will argue that the obtained good correlation is an evidence that the proposed methodology can be used to directly measure the environmental temperature T_e. We thus conclude that a single SAT, in the absence of solar radiation, enables the direct measurement of T_e. The experimental support for this conclusion was demonstrated under stable climatic conditions, as measured in thirteen periods from December 2016 to January 2017, in Umeå, Sweden, where air temperatures ranged from -13 °C up to +4 °C, and with wind speeds between 1.0 and 4.2 ms^{-1}. In contrast to [1], this study suggests an opportunity (with the SAT) to measure T_e directly, during both overcast and clear sky stable conditions, and at any convection stable condition.

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