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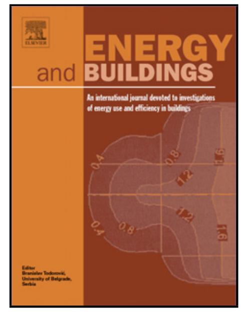

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Balance point temperature for heating as a function of glazing orientation and room time constant

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HIGHLIGHTS

- validation of EN ISO 13790 calculation methodology by measurements in the PASSOL laboratory
- investigation of the operative temperature variation in March and April months in the test room
- analysis of the effects of the glazed area, thermal mass and orientation on the operative temperature
- investigation of the utilization factor and balance point temperature for heating

Abstract
In continental climates heating accounts for a significant part of the total energy consumption of a residential building with average thermal characteristics of the envelope. Solar heat gains have to be used wisely in order to reduce the energy need for heating. Glazed ratio of the facades, orientation of the transparent area and thermal mass has to be properly chosen in order to obtain the desired utilization factor. In this paper the effects of window size, thermal mass and window orientation on the balance point temperature are analysed in case of a reference room. The calculation methodology given by EN ISO 13790 standard was used. Measurements were done in order to validate the model. Performing the calculus on 48 different cases it was shown, that differences of even 11% can appear between the energy demands for heating (for similar overall heat transfer coefficients of the external building elements).

Keywords: balance point temperature, energy saving, heating season, solar gains, thermal mass, utilization factor

1. Introduction

Energy saving is one of the most important research directions worldwide. Buildings account for 40 % of total energy consumption in the Union, [1]. Heating represents about 70% of the total energy use of a typical residential building in Hungary, [2]. The situation is similar in the other central European countries. Insulating properly the building envelope the energy need demand for heating can be reduced significantly. However, cost and energy analysis should be done in order to determine the optimal insulation layer thickness [3, 4, 5]. Furthermore, to perform accurate calculations the changes of the properties of the insulation material have to be taken into account [6, 7]. Fossil fuel consumption can be reduced further, by integrating renewable energy sources in the energy system of buildings. Schmidt proved that calculations based on the exergy may give useful information on the energy flows in buildings, [8]. Using low exergy sources for energy supply of buildings, authentic high performance buildings and substantial reduction of environmental pollution will be obtained, [9].

Solar radiation is one of the renewable energy sources which can be used in buildings either in a passive mode. Using properly the direct and indirect solar gains of a building the energy demand for heating can be reduced considerably. However, as it was concluded by Ballarini and Corrado the effects of the solar heat gains on the energy need depends on many factors, [10]. Oliveti et al. proposed an accurate model to determine the solar heat gains through glazed surfaces, [11]. Their model uses the effective absorption coefficient of the indoor environment, taking into account in the calculus the solar energy entering the building but reflected by the internal surfaces and dispersed outwards. The solar gains can be successfully used in indirect mode by properly designed sunspaces. Thermal performance of sunspaces was accurately analysed by Bataineh and Fayez [12], Oliveti et al. [13]. The useful solar gain for space heating in a building depends on the glazed area, thermal mass, heat storage capacity, heat loss coefficient and orientation of the transparent area [14, 15]. Yohanis and Norton proposed generalized expressions for the correlation parameters for use in the calculation of useful solar-energy absorption in office buildings, [16]. Karlsson et al. analysed the balance point temperature of buildings taking into consideration the useful solar gains for south and north orientation, [17].

Most papers are analysing the solar heat gains and the energy savings obtained, but the solar gains have an important influence on the length of the heating season. In this paper the operative temperature, heat gains utilization factor and balance point temperature is analysed depending on the orientation of transparent area and room time constant. The meteorological data of the typical day have been determined using the measured hourly mean dry bulb temperature and global solar radiation at the Agro-Meteorological Observatory (Debrecen) in March-April, 2011-2014. The calculation methodology, given by EN 13790 was validated by measurements in the PASSOL laboratory (University of Debrecen).

2. Utilization factor

According to EN ISO 13790 Standard the utilization factor of heat gains in the heating season depends on the ratio of heat gains and heat losses (γ_H), respectively on the room/building zone/building time constant (τ), [18].

According to Yohanis and Norton the heat gains utilization factor can be determined using equation (1), [16]:

$$\eta_H = 1 - e^{\frac{-k}{\gamma_H - D}} \qquad (1)$$

where k and D are correlation coefficients. For these coefficients Yohanis and Norton proposed the following relations, [16]:

$$k = 1{,}0785 + 0{,}0041\tau - 6\times10^{-7}\tau^2 \qquad (2)$$

$$D = -0{,}0087 - 0{,}007\tau + 7\times10^{-8}\tau^2 \qquad (3)$$

In Figure 1. the utilization factors calculated based on the EN ISO 13790 (monthly method) are compared with the utilization factors calculated using the Yohanis-Norton method.
It can be observed that the differences between the utilisation factors calculated with these two methods depend on the time constant and γ_H. For low time constant the Yohanis-Norton method gave higher values, while for hogh time constant the EN ISO 13790 method gave higher values for the utilisation factor. The differences are smaller in case of high γ_H and in case of lower time constant values.

3. Measurements in the PASSOL laboratory

In the PASSOL laboratory (University of Debrecen) measurements were performed in March-April months (years 2011-2014). The PASSOL laboratory is practically a test room with external dimensions of 2.6×2.6×2.6 m, built from sandwich panels used specifically for refrigeration chambers (20 cm polyurethane foam between two metallic sheets). The overall heat transfer coefficient of panels is 0.146 W/m^{2}K. The double glazed 150×150 cm window, which was built in one of external walls at a height of 0.9 m, has a profile with six chambers. The overall heat transfer coefficient is 1.4 W/m^{2}K, and the solar energy transmittance of glass (*g* value) is 0.6 (the transparent area is 1.69 m^2). On the opposite wall, a special, built-in door that is used for refrigeration chambers is installed. The shadow mask had to be determined for each orientation of the window. The shading of the surrounding objects was analyzed for March and April using the specific sun path diagram for these months in Debrecen. The geographical location of Debrecen is 47° 31.8’ N and 21° 37.8’ E. This test room is fixed on a special frame, which permits the rotation of the box around its own axis (Figure 2). With this solution the transparent area of the test room can have different orientations.

In March-April 2011-2014 measurements have been performed in order to analyse the variation of indoor air temperature in the test room. In 2011 the glazed area was oriented to east, in 2012 to south, in 2012 to west and finally in 2014 the glazed area was oriented to north. It was proposed to analyse the indoor air temperature in each year for three consecutive days after 21st of March. Unfortunately, in 2013, the second half of March was extremely cold and abundant snow was registered, so we were forced to choose other days in April.
Having the global solar radiation measured by the Agro-Meteorological Observatory Debrecen, the incident solar radiation was calculated on vertical surfaces (direct and diffuse). Using the measured or calculated meteorological data the indoor air temperature was determined in the test room based on the methodology given by Standard EN ISO 13790. The measured and calculated indoor air temperatures are presented in Figure 3.

The daily average outdoor temperatures ($\bar{t}_e$) and the solar heat gains of the test room can be seen in Table 1. In the standards related to thermal comfort, the requirements are given related to the operative temperature. The operative temperature is what humans experience thermally in a space; it is the combined effects of the mean radiant temperature and air temperature. In the standard EN 15251 for II comfort category in offices and residential houses the minimum required value of the operative temperature in winter is 20 °C. In Table 1 can be seen the daily mean value of the operative temperature ($\bar{t}_{op}$) and the periods of time in which the operative temperature meets or exceeds 20 °C. It can be observed that, there are periods of time when the operative temperature in the test room exceeds even the maximum value allowed in aforementioned standard for II comfort category in summer (26 °C).

During the measurements, in the test room there were practically no internal heat gains. The air change rate was zero. Blower door measurements were performed and no infiltration was observed even at 200 Pa pressure differences between indoor and outdoor environment [19]. Discussion on thermal comfort makes sense, when in the analysed room occupants are performing different activities. Consequently the calculations were made assuming a person in the test room with 1.0 clo insulation of clothing and performing activity of 1.2 met between 8:00-21:00, and 0.7 met between 21:00-8:00. In this case in the calculus ventilation of the room was taken into account with 30 m^3/h air flow. The temperature of the fresh air was assumed to be similar to the temperature of the outdoor air. The calculated indoor air temperature values in the test room for different orientation of the window are shown in Figure 4.

The operative temperature values and the periods of time with operative temperatures equal or higher than 20 °C respectively higher than 26 °C are presented in Table 2.

It can be observed that in this case higher mean operative temperature values were obtained and the periods with higher operative temperatures than 20 °C respectively 26 °C are longer, even though the outdoor air is introduced directly the room.

4. Effects of the orientation and time constant on the utilization factor and balance point temperature

Having the meteorological data of selected days analysed in the previous chapter, the mean values were calculated both for outdoor temperature and solar radiation and a reference day was constructed. The meteorological data of the reference day are shown in Figure 5. It can be seen the asymmetry between the incident solar radiation for east and west orientations [20].

The standard deviations of the mean values are presented in Table 3.

Assuming a “reference” room with 4.0×5.0×2.8 m internal dimensions and a single external wall, the operative temperature, utilization factor of heat gains and balance point temperature was determined. The calculus was done assuming different building materials for walls (solid brick – SB, autoclaved aerated concrete - AAC and lightweight structure - LS) and for slabs, but the overall heat transfer coefficients of the building elements was similar in each case. The overall heat transfer coefficient of the external wall was 0.24 W/m^{2}K (for SB and AAC external insulation was assumed to meet this value). The window is built in the external wall, and its overall heat transfer coefficient is 1.00 W/m^{2}K. The calculus was done taking into consideration two window sizes: 150×150 cm and 300×150 cm. The main thermal properties of the analysed rooms are presented in Table 4 (M – total thermal mass; m – ratio of thermal mass and net floor area; C – heat capacity; T – room time constant).

The variation of the operative temperature depending on the orientation, thermal mass and window size are presented shown in Figure 6.

It can be observed that for the reference day the operative temperatures are almost similar for east and south, respectively north and west orientations of the glazed area. At similar room time constant, if the window size is doubled, the amplitude of the operative temperature will be higher with 1 K (heavy structure) and 2 K (light structure). At similar window size the differences between the amplitudes, depending on the thermal mass, are lower than 1K (A_w=2.25 m^2) and 2.5 K (A_w=4.5 m^2). At similar window size and similar thermal mass, the differences between the amplitudes, depending on the orientation, are between 0.5 K (A_w=2.25 m^2 and heavy structure) and 4.5 K (A_w=4.5 m^2 and light structure).

The statistical analysis of the results was performed at p=0.05 significance level (Table 5). The null hypothesis was that the differences between the operative temperatures is lower than 0.5 K. The alternative hypothesis was that the temperature difference is higher than 0.5 K. The normal distribution was investigated using the Kolmogorov-Smirnov method, the hypothesis was investigated using the *pair-sample t-test*.

The variation of the utilization factor on the reference day is presented in Figure 7.

It can be observed that the utilization factor is higher in case of larger windows and heavier structures in that period of the day when there is no solar gain. Between 6:00-19:00 the utilization factor is higher in case of heavier structures and smaller windows.
Assuming the calculated daily mean utilization factors as the characteristic values for March-April months, and taking into consideration the average solar gains and average heat losses of the reference day, the balance point temperature can be determined for the analysed rooms, using the following equation:

$$t_b = t_i - \eta_H \frac{\dot{Q}_s + \dot{Q}_i}{K} \quad (4)$$

where: $\dot{Q}_s$ - daily mean value of solar gains, [W]; $\dot{Q}_i$ - daily mean value of internal gains, [W]; η_H - daily mean value of the heat gains utilization factor; t_i – internal set point temperature, [°C]; K – heat loss coefficient of the room, [W/K].

The maximum values of the energy demand for heating (avoiding heat gains) can be determined using the relation:

$$E_H = K \cdot DD = K \int_{j=1}^{N} (t_i - \bar{t}_{ej})dt \quad (5)$$

where: DD – is the degree day value of the heating season, [hK]; $\bar{t}_{ej}$ - mean outdoor temperature of the j heating day; t – time; N – number of days in a heating season.

Taking into consideration the degree day curve determined for Debrecen based on the hourly mean outdoor temperatures in 2008-2012 years [21], the length of the heating season and the maximum value of the energy demand for heating can be calculated (Table 6).

5. Conclusions

In the PASSOL laboratory of the University of Debrecen a series of measurements were carried out in years 2011-2014 (March-April months) in order to see the variation of the indoor air temperature. The main goal was the analysis of the balance point temperature for heating. Using the methodology given by standard EN ISO 13790 the expected air temperatures in the test room were calculated. The measured temperatures were compared with the calculated values. The periods of the days when the operative temperature in the test room exceeds 20 °C respectively 26 °C were identified. Based on the meteorological data (dry air temperature and solar radiation) of the analysed 12 days (2011-2014) a "reference day" was worked out.

Using the outdoor temperature and solar intensity data of the reference day, the operative temperature variation in rooms with different thermal mass, different glazing areas and different orientations of the glazed area was analysed. The hourly values of the utilization factor have been determined. Using the degree day curve of the years 2008-2012 the degree day values respectively the heating energy demand of the analysed rooms (48 types) were determined.

The differences between the heating energy demands can reach even 11% depending on the orientation, glazed area and thermal mass of the room. The highest energy demand for heating was found in the case of N orientation of the glazed area, lowest thermal mass and highest window area. At a given window area and thermal mass, the lowest energy demand for heating was obtained for S and E orientation of the glazed area. At a given window size and orientation of the window, the lower energy demand for heating is obtained at higher thermal mass.

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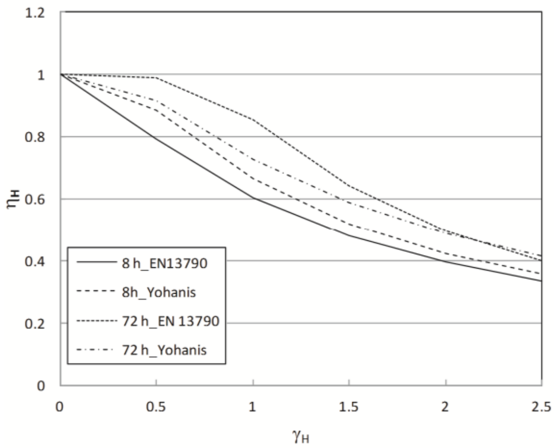

Figure 1. Comparison of the calculated utilization factor (EN ISO 13790 vs. Yohanis-Norton method)

Figure 2. PASSOL laboratory

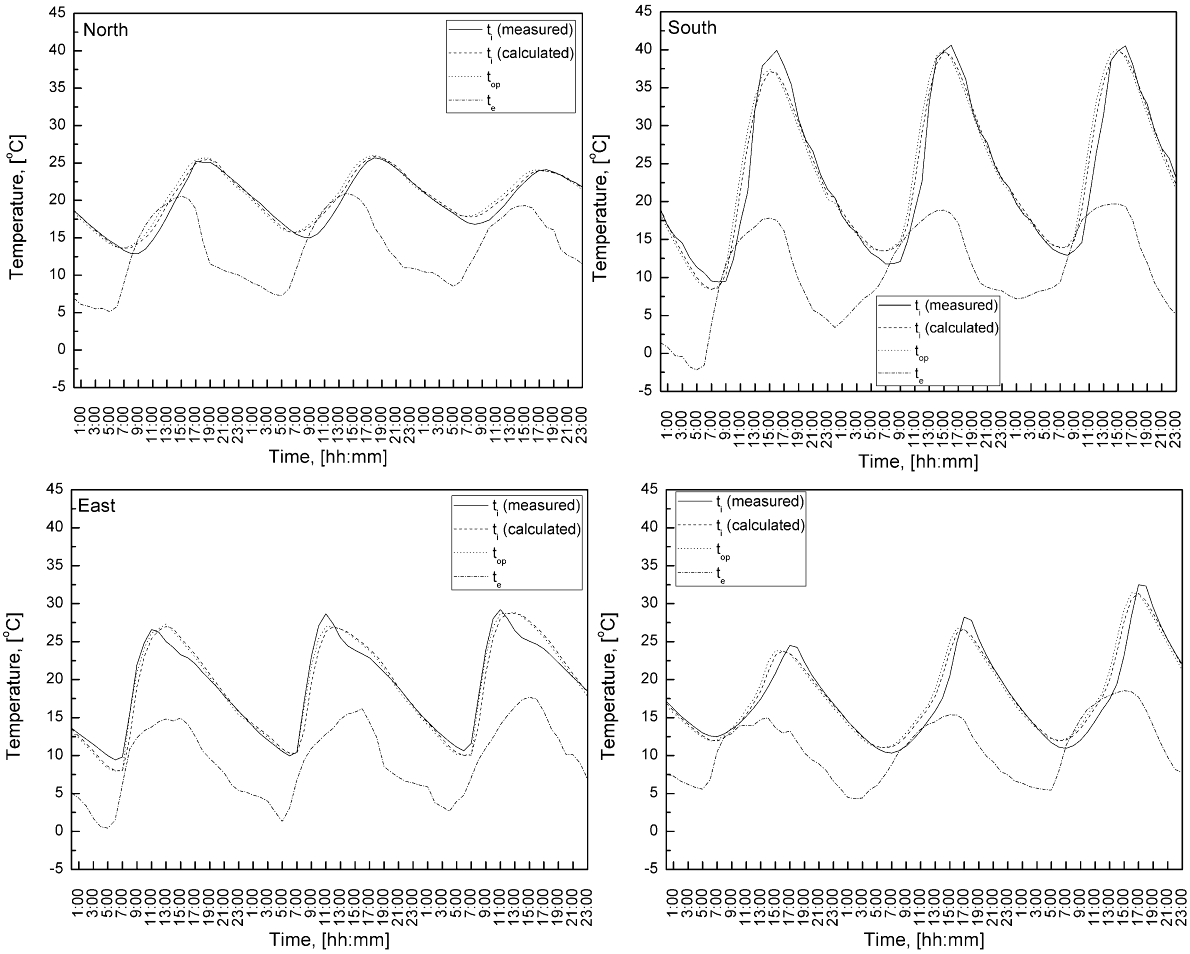

Figure 3. Comparison of calculated and measured indoor air temperature in the test room (without internal heat gains and no ventilation)

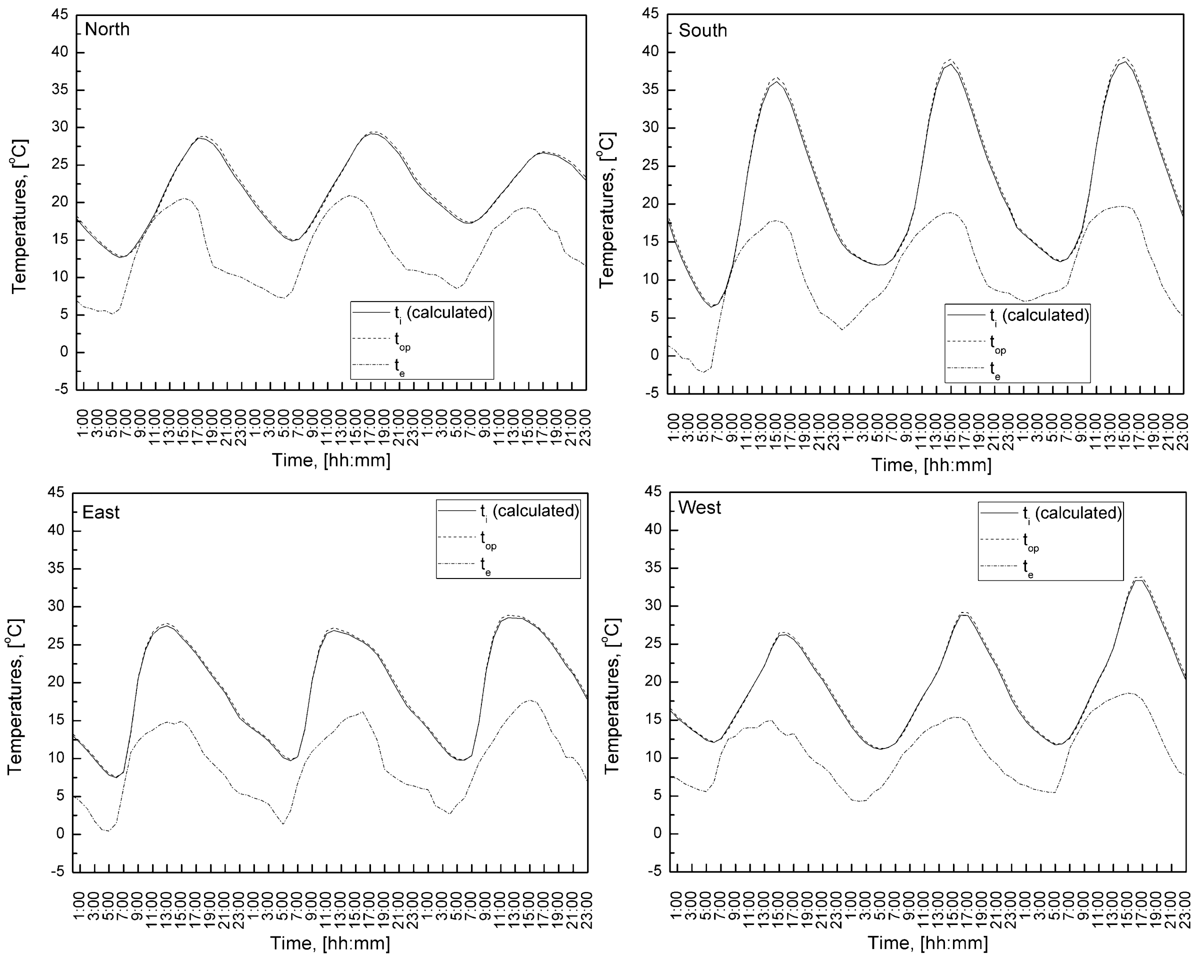

Figure 4. Calculated indoor air and operative temperature in the test room (with internal heat gains and ventilation)

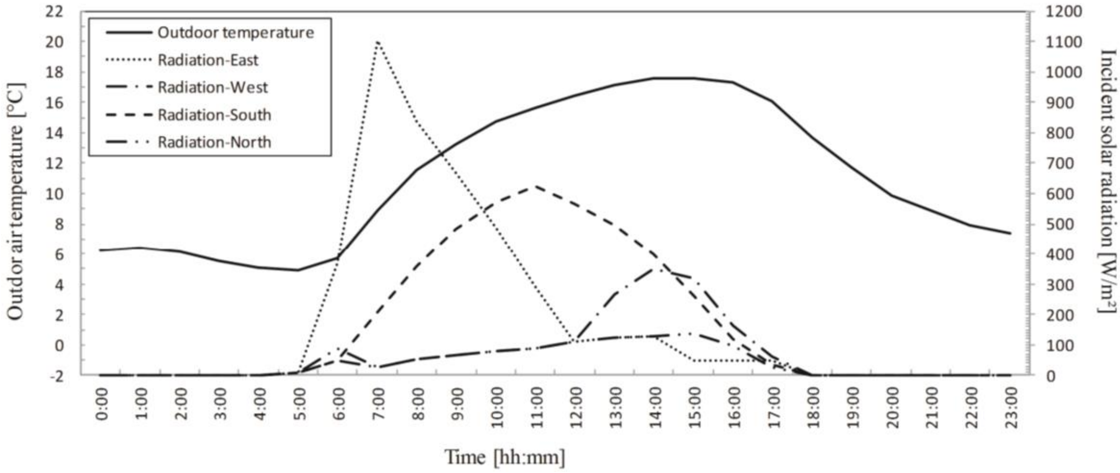

Figure 5. Meteorological data of the reference day

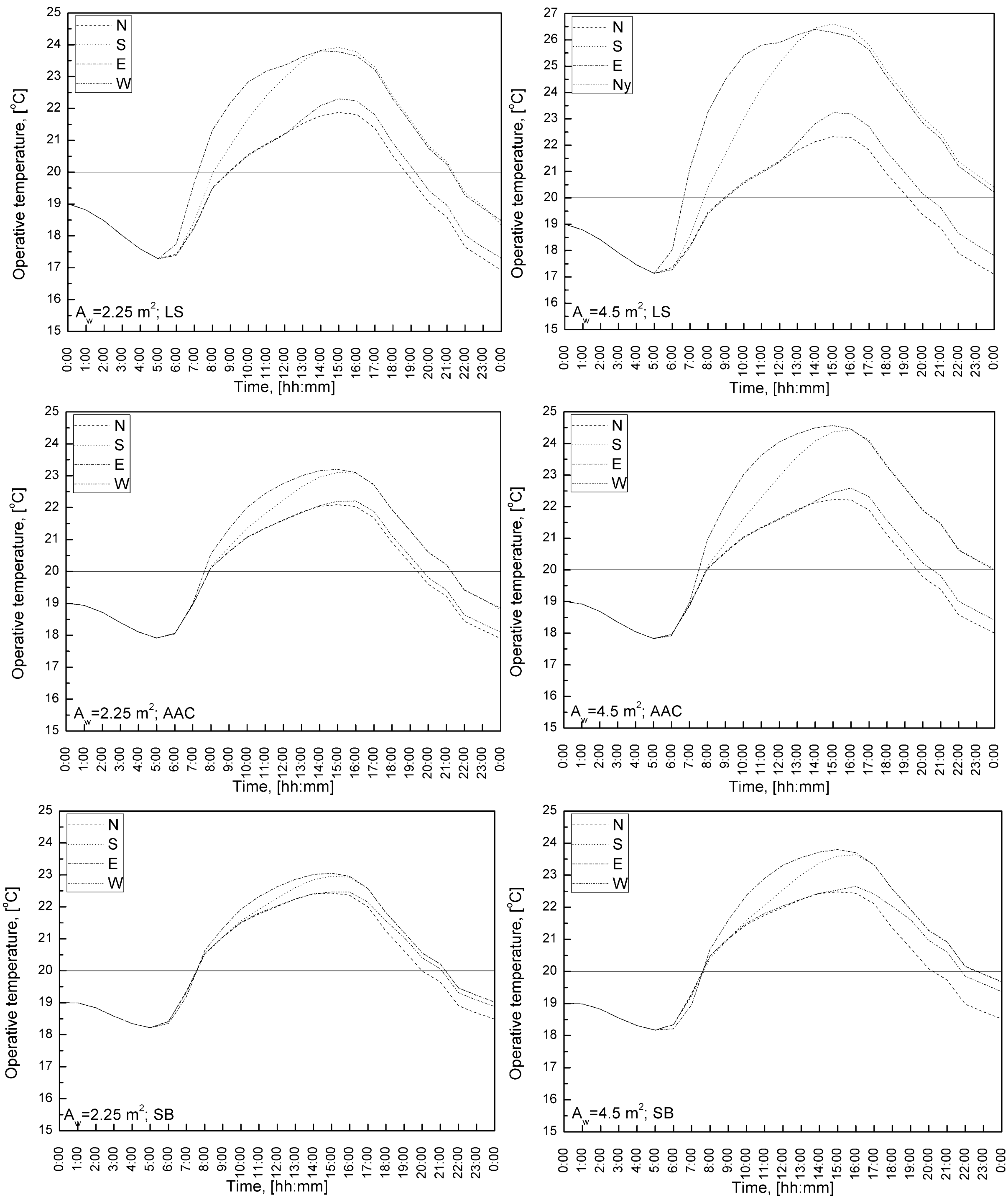

Figure 6. Daily variation of the operative temperature

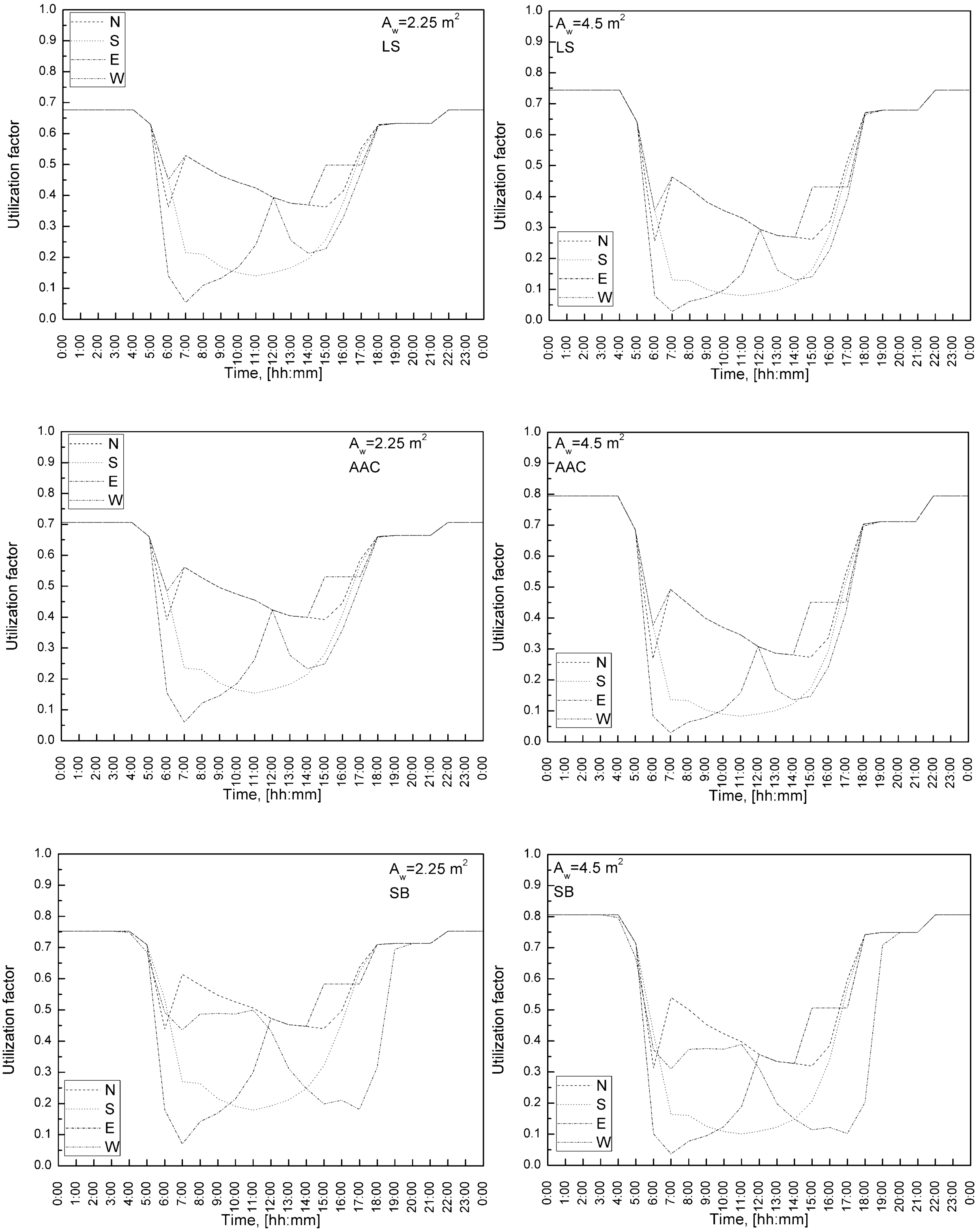

Figure 7. Daily variation of the utilization factor

Table 1. Operative temperatures in the test room (only solar radiation)

Window orientation	Date	$\bar{t}_e$, [°C]	Solar gains, [W]	$\bar{t}_{op}$, [°C]	Time, [h] (t_{op}≥20 °C),	Time, [h] (t_{op}≥26 °C),
East	2011.03.23.	8.64	97.21	17.86	10:00-19:00	12:00-14:00
	2011.03.24.	9.10	102.83	18.93	9:00-20:00	11:00-14:00
	2011.03.25.	10.30	104.71	20.00	9:00-22:00	11:00-16:00
South	2012.03.21.	8.11	138.29	21.83	11:00-23:00	13:00-20:00
	2012.03.22.	11.95	128.6	24.41	11:00-24:00	12:00-21:00
	2012.03.23.	12.35	128.71	25.18	10:30-24:00	12:00-21:00
West	2013.04.14.	10.44	70.22	17.13	14:00-20:00	-
	2013.04.15.	9.94	81.74	17.39	14:00-22:00	16:00-18:00
	2013.04.16.	12.13	89.75	19.80	13:00-23:00	15:00-20:00
North	2014.03.21.	12.34	88.29	19.10	14:00-23:00	-
	2014.03.22.	13.92	70.02	20.66	13:00-24:00	-
	2014.03.23.	13.91	65.56	20.96	12:00-24:00	-

Table 2. Operative temperatures in the test room (solar radiation, internal gains and ventilation)

Window orientation	$\bar{t}_{op}$, [°C]	Time, [h] (t_{op}≥20 °C),	Time, [h] (t_{op}≥26 °C),
East	18.29	9:00-20:00	11:00-15:00
	19.12	9:00-20:00	11:00-15:00
	20.24	9:00-21:00	10:00-17:00
South	20.77	11:00-21:00	12:00-19:00
	22.92	11:00-22:00	12:00-20:00
	23.76	10:00-22:00	11:00-20:00
West	18.71	12:00-21:00	15:00-17:00
	18.93	13:00-22:00	15:00-19:00
	21.19	11:00-23:00	14:00-20:00
North	20.44	12:00-23:00	15:00-20:00
	22.22	11:00-24:00	15:00-21:00
	22.22	11:00-24:00	16:00-19:00

Table 3. Standard deviation of mean outdoor temperature and solar radiation

Time, [hh:mm]	Outdoor temperature, [°C]	Incident solar radiation, [W/m^2]			
		S	E	W	N
0:00	2.81	0.00	0.00	0.00	0.00
1:00	2.55	0.00	0.00	0.00	0.00
2:00	2.92	0.00	0.00	0.00	0.00
3:00	2.89	0.00	0.00	0.00	0.00
4:00	3.27	0.00	0.00	0.00	0.00
5:00	3.35	9.72	9.72	9.72	9.72
6:00	3.20	36.10	569.95	36.10	55.70
7:00	2.38	65.21	118.12	13.09	13.09
8:00	1.70	93.39	202.74	23.06	23.06
9:00	1.74	111.52	145.17	30.24	30.24
10:00	2.02	138.06	108.50	36.16	36.16
11:00	2.03	142.46	48.20	44.63	44.63
12:00	2.11	185.00	50.16	50.16	50.16
13:00	2.08	163.77	50.52	70.23	50.52
14:00	2.10	140.34	62.10	120.25	62.10
15:00	2.18	100.20	0.00	122.11	61.48
16:00	2.19	62.20	0.00	87.73	51.20
17:00	1.96	18.06	0.00	38.69	20.51
18:00	1.84	1.96	1.96	3.67	2.15
19:00	2.25	0.00	0.00	0.00	0.00
20:00	2.16	0.00	0.00	0.00	0.00
21:00	2.25	0.00	0.00	0.00	0.00
22:00	2.13	0.00	0.00	0.00	0.00
23:00	2.45	0.00	0.00	0.00	0.00

Table 4. Main thermal characteristics of the analyzed rooms

Window	Wall material	M, [kg]	m, [kg/m^2]	C, [MJ/K]	T, [h]
A_w=2.25 m^2	SB (heavy weight structure)	15009	750.45	13.162	124.97
	AAC (medium weight structure)	7687	384.36	6.931	65.61
	LS (lightweight structure)	3815	190.75	3.317	31.24
A_w=4.50 m^2	SB (heavy weight structure)	14623	731.17	12.82	113.03
	AAC (medium weight structure)	7505	375.25	6.768	69.5
	LS (lightweight structure)	3757	187.86	3.271	28.63

Table 5. Statistical hypothesis test (significant differences depending on the orientation of the glazed area)

Window size	Building material	Orientation	N	S	E	W
A_a=2,25 m^2	SB (heavy weight structure)	N	N	N	N	N
		S	N	N	N	N
		E	N	N	N	N
		W	N	N	N	N
	AAC (medium weight structure)	N	N	N	Y	N
		S	N	N	N	N
		E	Y	N	N	N
		W	N	N	N	N
	LS (light structure)	N	N	Y	Y	N
		S	Y	N	N	Y
		E	Y	N	N	Y
		W	N	Y	Y	N
A_a=4,50 m^2	SB (heavy weight structure)	N	N	N	Y	N
		S	N	N	N	N
		E	Y	N	N	N
		W	N	N	N	N
	AAC (medium weight structure)	N	N	Y	Y	N
		S	Y	N	N	Y
		E	Y	N	N	Y
		W	N	Y	Y	N
	LS (light structure)	N	N	Y	Y	N
		S	Y	N	N	Y
		E	Y	N	N	Y
		W	N	Y	Y	N

Table 6. Balance point temperature, degree-day and heat demand for analysed rooms

Window size	Wall material	Orientation	η_H	t_b, [°C]	DD, [hK]	E_H, [kWh]
A_w=2.25 m^2	SB	N	0.629	17.28	82285.92	2407.43
		S	0.532	15.42	79833.12	2335.67
		E	0.564	15.18	79409.28	2323.27
		W	0.621	15.96	80464.32	2354.13
	AAC	N	0.581	17.50	82462.56	2419.70
		S	0.489	15.79	80361.60	2358.05
		E	0.508	15.56	80047.20	2348.82
		W	0.560	17.12	82162.32	2410.89
	LS	N	0.550	17.65	82550.40	2434.85
		S	0.464	16.03	80617.20	2377.83
		E	0.482	15.81	80381.52	2370.86
		W	0.531	17.29	82286.64	2427.07
A_w=4.50 m^2	SB	N	0.604	16.82	81830.64	2578.23
		S	0.509	13.02	75877.92	2390.68
		E	0.532	12.56	74897.76	2359.79
		W	0.508	14.24	78300.96	2467.02
	AAC	N	0.563	17.05	82093.92	2593.59
		S	0.477	13.48	76875.36	2428.72
		E	0.498	13.06	76000.08	2401.07
		W	0.542	16.26	80967.84	2558.01
	LS	N	0.538	17.19	82214.40	2609.92
		S	0.457	13.78	77520.48	2460.91
		E	0.477	13.38	76670.40	2433.93
		W	0.518	16.45	81297.60	2580.82