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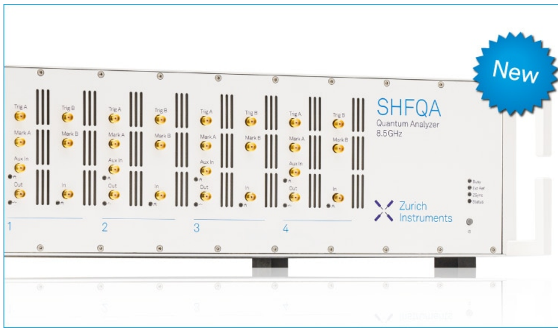

Analysis of a Wall Structure Thermal Transmittance Sensitivity in Function of Meteorological Parameters at Constant Internal Surface Temperature

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Abstract. The paper presents 231 thermal transmittance values of a wall structure in function of different meteorological parameters while the indoor surface temperature was kept constant. In the calculations a 2D wall of a nearly zero energy building was examined at the external air temperature, wind speed and solar radiation, in accordance with the Hungarian Decree on the Determination of the Energy Characteristics of Buildings, ISO 6946:2017 and with typical meteorological year dataset. Results were calculated with commercially available simulation software. The model assumed that the internal surface temperature was constant, the solar radiation is homogenous, the flow in front of the external wall surface did not contain any vortexes and the external wall surface was considered to be smooth. The goal was to showcase what are the influencing factors of the thermal transmittance values and give guidance estimating the yearly average of this value for a given location where surface cooling or heating is applied. The results were fitted linear function with 0.97 regressions that could be applied at dynamic parametric modelling.

INTRODUCTION

Simulation driven design and dynamic parametric models help the engineers and the researchers to better understand the complex problems. As many researches [1–4] show, in building energetics, it is essential to have a comprehensive view on the thermal properties of building structures. These thermal properties can be used for heat load or heat demand calculation, to let the engineer choose the energy source of the building or to calculate the annual energy demands or to make a more precise life cycle analysis.

The total thermal resistance (R_{tot}) is one from the thermal properties. The thermal resistance dependent on the structural material properties and the flow around the wall [5]. The total thermal resistance of a wall structure can be defined by the air temperature difference between the two sides of the wall at a certain heat flux (φ).

$$R_{tot} = (T_{i\,a} - T_{e\,a}) \cdot \varphi^{-1} \tag{1}$$

The total thermal resistance can be divided to two surface ($R_{i\,s}$ and $R_{e\,s}$) and one structural resistance (R_{str}).

$$R_{tot} = R_{i\,s} + R_{str} + R_{e\,s} \tag{2}$$

The inverse of the thermal surface resistance is the thermal transmittance (h). Which is the ratio of the heat flux and the temperature change between the surface (T_s) and the average air temperature (T_a).

$$h = \varphi \cdot (T_s - T_a)^{-1} \tag{3}$$

The scope of the paper was to make a computational model that could predict the deviation of the h values when the external and internal parameters (indoor surface temperature ($T_{i\,s}$), outdoor air temperature ($T_{e\,a}$), wind speed (u),

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and solar radiance (φ_{solar})) were changing in a wide range. The external parameter ranges were based on a meteorological data source [6]. In this work only the results of the simulation model are discussed. Even though the h could be measured [7–11] and it could help in the evaluation of computational models [7, 12].

MATERIALS AND METHODS

Heat Flux

The φ is constantly varying through the year, due to the external and internal environmental condition changes. These conditions can be heat gains or losses. When a heat load is applied some time is needed to warm up the whole building structure. In that case the amount of heat change is the stored heat.

$$\varphi_{sorage} = \varphi_{load} - \varphi_{loss} \tag{4}$$

If a building structure cannot gain or lose heat in a given condition, then thermal equilibrium is achieved. If a building structure is near the thermal equilibrium, then it can be considered to be in a steady state. For steady state the φ equilibrium equation can be the following:

$$\underbrace{\pm\varphi_{ind} + \alpha \cdot \varphi_{solar} + \varepsilon \cdot \varphi_{r\ load}}_{\text{specific heat load}} = \underbrace{\varepsilon \cdot \varphi_{r\ loss} + h_c \cdot (T_s - T_a) \pm \varphi_{latent}}_{\text{specific heat loss}} \tag{5}$$

where the φ_{ind} is the induced heat flux, this heat is induced by the building heating or cooling system. The parameter is positive when heat load applied (the heating system is active) and its negative when the cooling systems extracts the heat from the structure. In a more practical term this is the transmission heat flux or specific heat load or loss that the surface heating or cooling has to cover.

Radiative influence

Heat sources like the Sun has solar radiation intensity, which is a meteorological parameter that tell us how much heat radiated from the sun onto the building surface. If the solar absorbance factor (α) of the building surface is known a more precise value can be calculated. Warm surfaces can also radiate heat that can be expressed by the following [5]:

$$\varphi_{r\ loss} = \varepsilon \cdot \sigma \cdot T_s^4 \tag{6}$$

where ε is emission coefficient and σ is the Stefan Boltzmann constant. From the examined surface point of view this can be considered to be a heat loss. However, if there is another warmer surface in front of the examined surface it can gain heat. The sky, buildings and ground can be modelled as a surface which emits of long-wave radiation ($\varphi_{r\ load}$) onto the examined location, and is equal to:

$$\varepsilon \cdot \varphi_{r\ load} = \varepsilon \cdot \sigma \cdot T_{sky}^4 \tag{7}$$

$$T_{sky} = T_a - 6\ K \tag{8}$$

where T_a is the air temperature around the building. When the influence of radiation examined both radiation of the heat source and the surface temperature has to be taken in account.

Wind influence

The wind could generate complex flows around the building which could be modelled to determine the velocity magnitudes [13]. Many researchers [14–18] have shown strong connection between the convective heat transfer coefficient (h_c) and the magnitude of wind near the building surface, although the direction of the wind is not relevant [19]. This connection can be expressed by the following equation [5]

$$h_c = a \cdot u_s + b \tag{9}$$

Equation (9) shows a linear connection where the u_s is the wind speed [m·s^{-1}] near the surface (measurement position); the "*a*" and "*b*" are constants, these were gotten from the linear regression of measurement results. These "*a*" and "*b*" values and the position of the anemometer are collected in Table 1.

TABLE 1. h_c function parameters

a	b	position	source
1.7	5.1	wind speed measured 1 meter from the surface edge of building	[14]
1.4	6.5	windward side of the building	[14]
1.4	4.4	leeward side of the building	[14]
1.7	4.93	roof-top	[20]
4.1	5.8	local wind speed at a building surface	[21]
6	5.7	normal surface	[15]
6.1	11.4	exposed surface	[15]
4.35	7.55	roof-top wind speed	[16]
4	5.6	below 5 m·s^{-1} wind tunnel	[17]
4.58	9.23	undisturbed free stream speed	[18]

To avoid the difficulties of defining the position of the anemometer the ASHRE Task Group made an algorithm [14]. If the wind speed at 10 m height (u_{10}) is less than 2 m·s^{-1} they assumed that u = 0.5 m·s^{-1} and if it was more than 2 m·s^{-1} Eq.(10) was used for the windward side of the building

$$u_s = 0.25 \cdot u_{10} \tag{10}$$

For the leeward side Eq. (11) is used

$$u_s = 0.05 \cdot u_{10} + 0.3 \tag{11}$$

However, they calculated the h_c with an exponential function.

$$h_c = 18.6 \cdot {u_s}^{0.605} \tag{12}$$

Moisture influence

It was proven with measurements that the moisture has effect on the heat transfer [22]. Latent heat flux occurs when moisture transport is present in the structure. When the moisture mass flow is calculated many factors can be used, such as the relative humidity and T_a, moisture content (v [%$_v$]) in a V volume of structure and the quality of the surface where the evaporation occurs. For calculation of the mass flow the Lee model [23] can be used:

$$\dot{m}_f = V \cdot v \cdot e \cdot \rho \cdot \left(T_f - T_{saturation}\right) \cdot {T_{saturation}}^{-1} \tag{13}$$

where: e [–] coefficient for evaporation and condensation (usually it is 0.1 [23])); ρ [kg·m^{-3}] density of the moisture; T_f [K] temperature of the fluid (external air when condensation and surface temperature when evaporating); $T_{saturation}$ [K] saturation temperature. Knowing the mass flow and the latent heat of the moisture the latent heat flux can be calculated.

$$\varphi_{latent} = \dot{m}_f \cdot \left(r_f + c_f \cdot T_{fluid}\right) \tag{14}$$

where r_f [J·kg^{-1}] is the latent heat of the fluid; c_f [J·kg^{-1}·K^{-1}] is the specific heat of the fluid. In previous research [24] it was shown that when the relative humidity is high near the wall structure, the plaster is acting as a moisture protecting layer and preventing the inner structure from the moisture. However, when the structure is wet it can have disadvantages, evaporation from the building surface is rare occurrence, if it becomes frequent extra protection is advised. For these mentioned reasons and relatively fast period of the phase change, the latent heat flux is disregarded in the calculation.

The general equation for the induced heat flux for the external surface becomes:

$$\varphi_{ind\ e} = \varepsilon \cdot \sigma \cdot (T_{e\ s}^4 - (T_{e\ a} - 6\ \mathrm{K})^4) - \alpha \cdot \varphi_{solar} + h_{c\ e} \cdot (T_{e\ s} - T_{e\ a}) \tag{15}$$

using Eqs. (1) and (15) the R_{tot} becomes:

$$R_{tot} = \Delta T_a \cdot \left(\varepsilon \cdot \sigma \cdot (T_{e\ s}^4 - (T_{e\ a} - 6\ \mathrm{K})^4) - \alpha \cdot \varphi_{solar} + h_{c\ e} \cdot (T_{e\ s} - T_{e\ a})\right)^{-1} \tag{16}$$

and using Eqs. (3) and (4) h_e can be expressed:

$$h_e = \left(\Delta T_a \cdot \left(\varepsilon \cdot \sigma \cdot (T_{e\ s}^4 - (T_{e\ a} - 6\ \mathrm{K})^4) - \alpha \cdot \varphi_{solar} + h_{c\ e} \cdot (T_{e\ s} - T_{e\ a})\right)^{-1} - h_i^{-1} - R_{str}\right)^{-1} \tag{17}$$

From Eq. (17) the $R_{i\ s}$ can be expressed with the simplification, that the radiation can be neglected (with the restriction that the $T_{i\ s}$ are equal and the internal side of the wall is not radiated). When it is possible to dissipate the heat to a colder surface (environment) the φ_{ind} will be higher

$$h_i = \left(\Delta T_a \cdot \left(h_{c\ i} \cdot (T_{i\ s} - T_{i\ a})\right)^{-1} - h_e^{-1} - R_{str}\right)^{-1} \tag{18}$$

Khalifa et al. [19] were shown that at low speed natural convection, when the $T_a - T_s$ and φ increasing the h is increasing (see Eq. (3)).

From Eq. (17) it can be seen that the h_e value is highly influenced by the external factors. That is why it cannot be considered to be constant throughout the whole year even if many structural parameters ($\alpha = 1$; $\varepsilon = 1$; $\sigma = 5.67 \cdot 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$) can be considered to be constant [18, 25]. From R_{tot}, (Eq. (3)) the R_{str} can be expressed, where in Hungary $R_{str} = 4\ \mathrm{m^2 \cdot K \cdot W^{-1}}$ [18, 25]. From the TMY the deviation ranges of $T_{e\ a}$; φ_{solar} and u parameters were collected. Based on the deviation solar radiations were given between 0 $\mathrm{W \cdot m^{-2}}$ and 1000 $\mathrm{W \cdot m^{-2}}$ in 200 $\mathrm{W \cdot m^{-2}}$ steps, and external air temperatures were given between −10 °C and 30 °C in 5 °C steps. Wind velocities were given 1.5; 2; 3; 4; 5; 7, and 10 $\mathrm{m \cdot s^{-1}}$, respectively in accordance of ISO 6946:2017 [5]. It has to be noted that the ISO 6946:2017 [5] recommends 1 $\mathrm{m \cdot s^{-1}}$ to be the lowest although in the paper to ensure the forced flow 1.5 $\mathrm{m \cdot s^{-1}}$ was the lowest. $T_{i\ s}$ was given 15 °C, 20 °C, and 25 °C. By giving surface temperatures the h_i did not have to be calculated. With this condition it had to be assumed that the interior wall surface was kept at a constant temperature with surface cooling or heating, and the φ was the φ_{ind}.

To reduce the numbers of the case combinations the solar radiation was 0 $\mathrm{W \cdot m^{-2}}$ when the indoor temperatures were higher than the external temperature. With this statement 231 case combinations were applied for the calculations.

Owing to speed and temperature distribution from the wall were different in each case in relation to the given parameters and the fact that it can be only solved with iteration, simulation was needed. It was assumed that the internal wall surface was kept at constant temperature to disregard h_i from Eq. (17). From Eqs. (3) and (4) $T_{s\ e}$ was expressed to show that the h_e calculated with iteration

$$h_e = \left((T_{i\ s} - T_{e\ a}) \cdot \left(\varepsilon \cdot \sigma \cdot (T_{e\ s}^4 - (T_{e\ a} - 6\ \mathrm{K})^4) - \alpha \cdot \varphi_{solar} + h_{c\ e} \cdot (T_{e\ s} - T_{e\ a})\right)^{-1} - R_{str}\right)^{-1} \tag{19}$$

$$T_{s\ e} = (h_e \cdot R_{str} \cdot T_{a\ e} - T_{s\ i}) \cdot (h_e \cdot R_{str} - 1)^{-1} \tag{20}$$

Metrological dataset

To know the h yearly distribution metrological values had to be set. The Climate Monitoring Satellite Application Facility (CM-SAF) satellite database served as source of the calculations [6]. These hourly resolution data have shown less than 5 % error at the validation sites. The dataset is mostly used for photovoltaic panels performance evaluations, since it has detailed radiation values. However, it also contains data for the wind and temperature values that can be beneficial to set the examined conditions.

The hourly data was selected between 2007 and 2016 for a given geographical location. With this method a typical meteorological year (TMY) was created. The chosen geographical location was Debrecen where the paper was written, though, the goal was to showcase the method of this calculation. The collected parameters were the $T_{e\,a}$, φ_{solar}, and u.

Model setup

For the calculation finite volume method was applied and the calculation made with Fluent 2019 R3. The reason of the usage of the method is that the h calculations have many degrees of freedom that had high decency of the parameters.

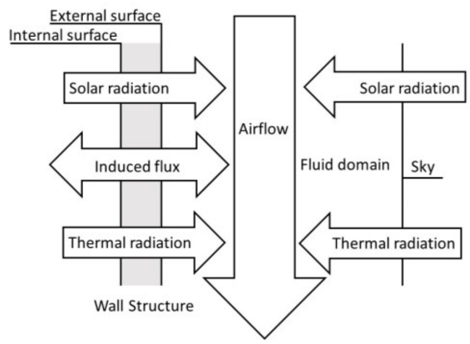

FIGURE 1. Sketch of the model

The examined domain was 2D since only the velocity and temperature distribution had to be modelled. Complex geometries were intentionally avoided in purpose to have more generalized results. The model (Fig. 1) was built up from two 2D rectangles which were made of 20 mm large mesh elements. The "Wall structure" was a 0.5 m high and 4 m long solid material. On the wall structure a 7.5 m high fluid domain was placed. At the near wall region 20 pieces of 1 mm thick layers were placed.

In the fluid domain a steady layered flow was intended to be set. Papers have discussed that the recommended turbulence model for 3D dimensions is the standard k-ε [20, 26–28]. In the previous paper [18] near wall flow h_c was examined both with numerical simulation and with measurements. SST, k-ε and laminar turbulence models were compared and the smallest difference was observed at laminar flow [18]. Furthermore, in the initial simulations when standard k-ε was modelled, it was found out that the eddy dissipation rate (ε) in the fluid domain was negligible. Consequently, the turbulence model was simplified to laminar. It has to be mentioned that in real life measurements it is essential to apply a turbulence model due to the complex fluid solid interfaces.

Since the evaporation and the heat storage was not modelled, steady state was applied [20]. The radiation between the external surface and the environment was modelled with surface to surface radiation modelling where the sky was emitting the φ_{solar} and when it was pitch-black the sky was set to T_e temperature. The material of the fluid was considered to be ideal air. The only property that was given for the wall structure was the thermal resistance. Due to the multiphase simulation a coupled Pseudo transient solver was used. During the simulation in every case the velocities, the pressure and the energy converged to 10^{-5} residuals.

RESULTS AND DISCUSSION

At those cases when there was no temperature difference between the wall surfaces the h_e values were 0 $W{\cdot}m^{-2}{\cdot}K^{-1}$. These results are not presented on the figures. The calculated external thermal transmittances are presented in Figs. 2 and 3 For the better presentation the results were dived into two sections, where there was no solar load and where was. Figure 2 presents h_e values when the internal surface temperature was 15 °C, 20 °C, and 25 °C, respectively.

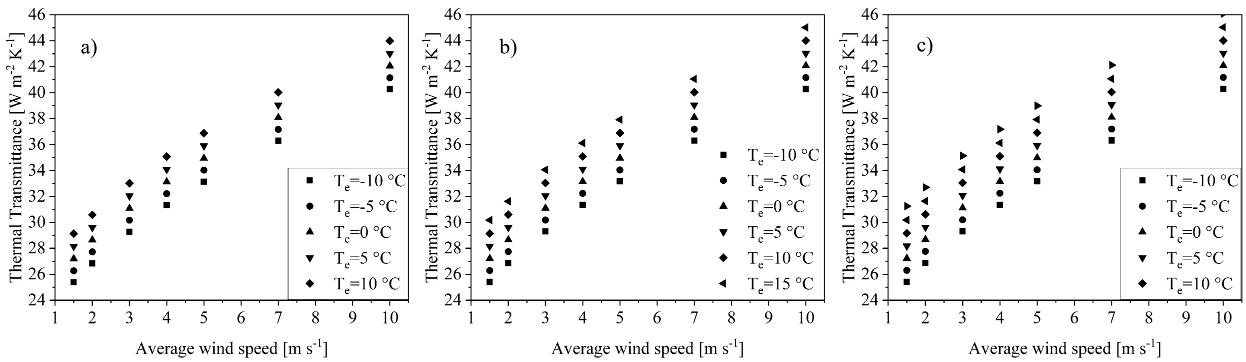

FIGURE 2. h_e distribution when there was no solar load and a) T_i = 15 °C, b) T_i = 20 °C, c) T_i = 25 °C.

Results showed that when forced convection was present a slight h_e increases occurred when the total air temperature difference ($T_{i\,a}$–$T_{e\,a}$) decreased. In Fig. 2 a strong h_e relation can be observed with the wind speed. The maximum transmittance was the same independently from the internal temperature values.

When solar load was applied (Fig. 3) considerable thermal transmittance drop had been observed, from 20–45 W·m^{-2}·K^{-1} to 1.2–4.5 W·m^{-2}·K^{-1}. With the increase of the solar intensity the dependency on the wind speed was decreased.

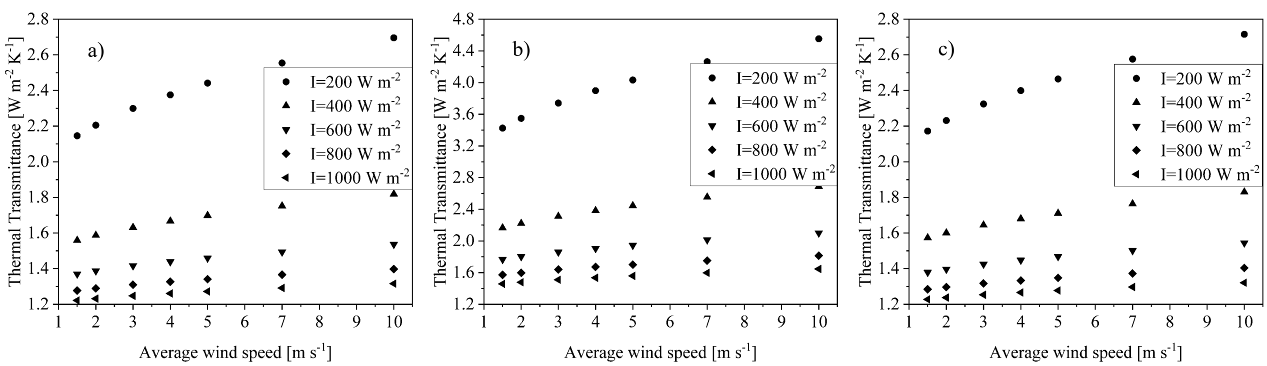

FIGURE 3. h_e distribution when there was solar load and a) T_i = 20 °C; T_e = 25 °C, b) T_i = 20 °C; T_e = 30 °C, c) T_i = 25 °C; T_e = 30 °C

For these plotted points linear regressions were set and the "*a*" and "*b*" constants were calculated for Eq. (9).

From Tables 2 and 3 it can be concluded that the connection between the wind speed and thermal transmittance is strong the R^2 = 0.97. With "*a*" and "*b*" linear connection can be made between the wind speed and thermal transmittance where "*a*" and "*b*" are influencing factors. The intercept of the functions ("*b*") increased slightly when the external temperature was rising. It can also be concluded that when the solar radiation increased the slope ("*a*") of the functions decreased significantly.

For buildings where the internal surfaces are kept at constant temperature (e.g. wall cooling) the h_e become small (1–1.4 W·m^{-2}·K^{-1}) which could lead the R_{tot} to be 5 m^2·K·W^{-1} when the radiation is above 600 W·m^{-2}. From the TMY mean h_e value for Debrecen (knowing the $T_{e\,a}$ = 11.3 °C; u = 2.96 m·s^{-1}, φ_{solar} = 146 W·m^{-2}, $T_{i\,s}$ = 20 °C [6]) was 1.64 W·m^{-2}·K^{-1}.

The limitations of the research are as follows: $T_{i\,s}$ is constant; φ_{solar} is homogenous; thermal equilibrium is achieved; the flow in front of the external wall surface does not contain any vortex; external wall surface is considered to be smooth.

TABLE 2. Linear regression values when there was no solar radiation

T_e [°C]	T_i [°C]	φ_{solar} [W·m⁻²]	a ±a [W·m⁻²·K⁻¹]		b ±b [W·s·m⁻¹·K⁻¹]		R^2
–10	15	0	23.751	±0.564	1.731	±0.104	0.979
–5	15	0	24.635	±0.564	1.731	±0.104	0.979
0	15	0	25.553	±0.564	1.731	±0.104	0.979
5	15	0	26.506	±0.564	1.730	±0.104	0.979
10	15	0	27.494	±0.564	1.730	±0.104	0.979
–10	20	0	23.769	±0.564	1.731	±0.104	0.979
–5	20	0	24.653	±0.564	1.730	±0.104	0.979
0	20	0	25.571	±0.564	1.730	±0.104	0.979
5	20	0	26.523	±0.564	1.730	±0.104	0.979
10	20	0	27.512	±0.564	1.729	±0.104	0.979
15	20	0	28.537	±0.564	1.729	±0.104	0.979
–10	25	0	23.787	±0.563	1.730	±0.104	0.979
–5	25	0	24.671	±0.563	1.730	±0.104	0.979
0	25	0	25.589	±0.564	1.729	±0.104	0.979
5	25	0	26.541	±0.564	1.729	±0.104	0.979
10	25	0	27.529	±0.564	1.729	±0.104	0.979
15	25	0	28.554	±0.564	1.728	±0.104	0.979
20	25	0	29.616	±0.564	1.727	±0.104	0.979
	mean		26.155	±0.564	1.73	±0.104	0.979

TABLE 3. Linear regression values when there was solar radiation

T_e [°C]	T_i [°C]	φ_{solar} [W·m⁻²]	a ±a [W·m⁻²·K⁻¹]		b ±b [W·s·m⁻¹·K⁻¹]		R^2
25	20	200	2.093	±0.024	0.064	±0.004	0.971
25	20	400	1.534	±0.011	0.030	±0.002	0.972
25	20	600	1.353	±0.007	0.019	±0.001	0.973
25	20	800	1.265	±0.005	0.014	±0.001	0.973
25	20	1000	1.212	±0.004	0.011	±0.001	0.974
20	30	200	3.317	±0.050	0.130	±0.009	0.971
20	30	400	2.114	±0.023	0.061	±0.004	0.972
20	30	600	1.734	±0.014	0.039	±0.003	0.973
20	30	800	1.548	±0.010	0.028	±0.002	0.973
20	30	1000	1.439	±0.008	0.022	±0.001	0.974
25	30	200	2.120	±0.024	0.063	±0.004	0.971
25	30	400	1.548	±0.011	0.030	±0.002	0.972
25	30	600	1.363	±0.007	0.019	±0.001	0.973
25	30	800	1.272	±0.005	0.014	±0.001	0.973
25	30	1000	1.218	±0.004	0.011	±0.001	0.974
	mean		1.675	±0.014	0.037	±0.003	0.973

CONCLUSIONS

The Hungarian Decree on the Determination of the Energy Characteristics of Buildings [25] said that R_{tot} has to be 4.16 $m^2 \cdot K \cdot W^{-1}$ for new buildings and there the surface resistances are included in the value, however with standardized h_e and h_i value are collectively R_s = 0.04 $m^2 \cdot K \cdot W^{-1}$. Results showed that it could be said that the R_s = 0.04 $m^2 \cdot K \cdot W^{-1}$ can be only achieved when there is no solar radiation. It can be also concluded that for a yearly energetic calculation the mean value of h_e should be 1.64 $W \cdot m^{-2} \cdot K^{-1}$ at the examined location. Finally, the recommended R_{str} = 4 $m^2 \cdot K \cdot W^{-1}$ could be reduced by 0.57 $m^2 \cdot K \cdot W^{-1}$. Which could reduce the implemented amount of insulations. The model assumes that the internal surface temperature is constant, the solar radiation is homogenous, thermal equilibrium is achieved, the flow in front of the external wall surface does not contain any vortex and the external wall surface is considered to be smooth. With these restrictions generalized conclusions was made. In other cases, when it cannot be generalized, new simulations have to be made to get accurate results. Further investigation will lead to examine the h_e and h_i relations when the internal/indoor climate is changing with different cooling apparatus and transmittance measurements where radiations emitted on the examined wall.

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REFERENCES

1. G. L.Szabó and F. Kalmár, Energies **11**, 3291 (2018).
2. Z. Verbai *et al.*, Energy **76**, 780–787 (2014).
3. Á. Lakatos, Energy Build. **139**, 506–516 (2017).
4. I. Csáky and F. Kalmár, J. Build. Eng. **12**, 1–7 (2017).
5. MSZ EN ISO 6946, (2017).
6. T. Huld *et al.*, Sol. Energy **86**, 1803–1815 (2012).
7. A. Hagishima and J. Tanimoto, Build. Environ. **38**, 873–881 (2003).
8. K. E. A. Ohlsson *et al.*, J. Build. Eng. **7**, 239–245 (2016).
9. J. Chávez Galán *et al.*, Concreto y Cem. Investig. y Desarro. **5**, 26–38 (2014).
10. M. Davies *et al.*, Energy Build. **37**, 141–145 (2005).
11. F. Szodrai and Á. Lakatos, Int. Rev. Appl. Sci. Eng. **8**, 67–73 (2017).
12. T. Defraeye *et al.*, Energy Convers. Manag. **52**, 512–522 (2011).
13. M. Ferrucci and M. Brocato, Build. Serv. Eng. Res. Technol. **40**, 109–128 (2019).
14. S. Sharples, Build. Environ. **19**, 31–39 (1984).
15. N. Sturrock, *PhD Thesis*. University of Liverpool, (1971).
16. K. Nicol, Build. Environ. **12**, 215–219 (1977).
17. W. Jürges, Beizh. z. GesundhIng. **1**, (1924).
18. F. Szodrai, Int. Rev. Appl. Sci. Eng. **10**, 207–212 (2019).
19. A. J. N. Khalifa, Energy Convers. Manag. **42**, 491–504 (2001).
20. D. L. Loveday and A. H. Taki, Int. J. Heat Mass Transf. **39**, 1729–1742 (1996).
21. CIBS, *CIBS Guide Book A, Section A3* (London, 1979).
22. Á. Lakatos and F. Kalmár, Build. Serv. Eng. Res. Technol. **35**, 507–515 (2014).
23. W. H. Lee, Technical Report LA-UR 79-975', (1979).
24. F. Szodrai, , *PhD Thesis*. University of Debrecen, (2018).
25. 7/2006 TNM, *Decree on the Determination of the Energy Characteristics of Buildings*. (2006).
26. O. Acikgoz and O. Kincay, Energy Build. **108**, 257–266 (2015).
27. H. Manz, Energy Build. **35**, 305–311 (2003).
28. M. F. P. Lopes *et al.*, Wind Struct. An Int. J. **13**, 487–498 (2010).