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Solar Aperture of a Building Enclosure: The Case Study of a Well-Insulated Family House in Semi-Continental Climate

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Abstract. As thermal insulation of building enclosure has substantially improved over the last decades, solar heat gains comprise more important part in thermal balance of a building in semi-continental climate, often leading to overheating. The quality of the whole building enclosure should be assessed by its ability to transmit solar heat gains. Such thermal characteristic need to aggregate properties like glazing area in each facade, total solar energy transmittance of glazing, the efficiency of fixed shading devices and the operation of movable shading devices. In this paper, the surrogate horizontal effective collector area is used for the characterization of solar heat gains through a building enclosure. The parameter is called the solar aperture of a building enclosure. First, the formula for solar aperture is derived. Then, building energy simulation of a model family house is performed. The correlation of the solar aperture with overheating and space heating demand is analysed. Based on the analysis, the recommended trade-off values of the specific solar aperture are proposed for family houses in semi-continental climate. The trade-off values of the solar aperture will lead to reasonable promotion of solar heat gains during cold season and significant reduction of solar heat gains during warm season.

1. Introduction

The thermal balance of residential buildings is affected by a hexagon whose peaks represent the thermal quality of a building enclosure, heat flow induced by ventilation, heating or cooling power, solar heat gains, the thermal capacity of the envelope and internal building components and internal heat gains. The participation of the balance components changes during the year. Solar heat gains, ventilation heat flow and heat storage in resp. heat release from the material layers close to the internal environment are the main heat flows in the warm part of the year in semi-continental climate.

Traditionally, the reduction of space heating demand was the primary objective of residential buildings in the semi-continental climate. Overheating was not perceived as a problem until the recent past. However, the new buildings are lighter (pressure on the rational building process, efficient use of building materials and low costs), with higher window-to-wall ratios (availability of glass, fashion of glassy buildings), with efficient thermal insulation and good airtightness of the building enclosure (pressure on energy efficiency and CO_2 reduction) and with higher internal heat gains, especially from electrical appliances. In addition, global climatic conditions are gradually changing (global warming phenomena) and local climatic conditions can be further worsen by large urban areas, the lack of greenery, and a large asphalt and concrete surfaces in the landscape. These complex phenomena cause overheating of buildings to occur more frequently [1].

The objective of this paper is to define an aggregated thermal parameter describing the ability of the whole building enclosure to transmit solar heat gains into the internal environment. Such an aggregated thermal characteristic of the building enclosure is in this paper called the (effective) solar aperture. At first, a short theoretical derivation of the solar aperture will be performed. The follow-up case study of a well-insulated family house in semi-continental climate will reveal a strong correlation of the solar aperture with overheating. Subsequently, the recommended values of the solar aperture for prevention of overheating will be derived. Finally, the interval of recommended compromise values of the effective solar aperture (trade-off between cold and warm season) will be proposed.

2. Solar aperture of a building enclosure

Traditionally, the total solar heat gains through a building enclosure are expressed as:

$$Q_s = \sum A_{col,i} H_{Gt,i} \tag{1}$$

where $A_{col,i}$ [m^2] is effective collector area of *i*-th building component ($A_{col} = F_{sh} g A$, where A is the area of the building component, g is total solar energy transmittance of the building component, F_{sh} is the total shading correction factor) and $H_{Gt,i}$ [kWh/m^2] is global solar irradiation on the *i*-th building component. The effect of linear and thermal bridges was neglected in equation (1).

In this paper, it is intended to express the total solar heat gains through a building enclosure as the product of the surrogate horizontal collector area A_s and the global solar irradiation on the horizontal plane H_{Gh}:

$$Q_s = A_s H_{Gh} \tag{2}$$

The surrogate horizontal collector area A_s is called the solar aperture of the building enclosure. Formula for A_s directly follows from comparison of equation (1) and (2). The area A_s is formed from the effective collector areas of the individual building components by weighting according to the ratios of the global solar irradiation H_{Gt}/H_{Gh}. In general, for the building enclosure with n transparent building components and m opaque building components, we have:

$$A_s = A_{s,w} + A_{s,op} = \sum_{i=1}^{n} A_{col,i} \frac{H_{Gt,i}}{H_{Gh}} + \sum_{j=1}^{m} A_{col,j} \frac{H_{Gt,j}}{H_{Gh}} \tag{3}$$

Solar heat gains through opaque building components can often be neglected due to sufficiently thick thermal insulation layer ($A_s \approx A_{s,w}$). If the amount of solar heat gains through all transparent building components over a time period is known (e.g. from building energy simulation model), the effective solar aperture of the whole building enclosure can be calculated by inversion of formula (2).

The calculated value of the solar aperture area represents the mean value over the selected period of time. It can either characterize the enclosure of the whole building or a smaller spatial unit (e.g. a room with a similar temperature regime). In order to compare various buildings, it can be advantageous to relate the solar aperture with the appropriate unambiguous geometric characteristics of the building, e.g. the built-up volume of the building (A_s/V [m^2/m^3]).

The solar aperture of a building enclosure depends on time. Glazing oriented to south, south-east and south-west have the dominant influence on the seasonal variability of the solar aperture. The monthly mean values of the solar aperture often tend to form a shape similar to cosine. The seasonal variation can approximately be characterized by two values – the mean value over the period November – February (denoted as $A_{s(XI.-II.)}$) and the mean value over the period May–August (marked $A_{s(V.-VIII.)}$).

The dependency of solar aperture on solar irradiation in various localities should be further evaluated. Presumably, solar irradiation ratios H_{Gt}/H_{Gh} appearing in equation (3) could take very similar values in various locations and also from year to year in a country belonging to one climatic zone. The irradiation ratios then could be fixed to default mean values. With this respect irradiation values H_{Gt} and H_{Gh} might not be directly needed for calculation of A_s.

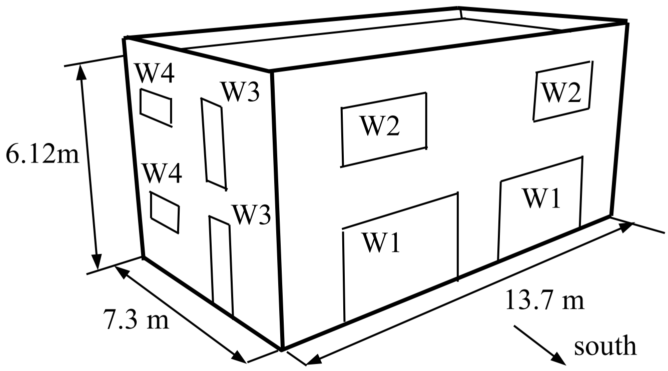
3. Dynamic thermal simulation of the model building

The main objective is to analyze how the decisive aggregated thermal parameters (mean thermal transmittance of building enclosure U_{em} and the specific solar aperture A_s/V) are correlated with the annual maximal internal air temperature and space heating demand. Overheating is in this paper defined as exceeding the annual maximum internal air temperature of 28 °C (simplification).

Thermal simulations of the model building were performed in repetitive manner with samples that were randomly selected from the defined intervals of the selected inputs (see Table 1 and Table 2). In total, 1000 samples of the model building were simulated. Simulations were performed with a lumped parameter thermal simulation model in which building components are represented by two temperature nodes (3R2C model). The model was programmed in Matlab and Simulink [2].

3.1. Model house

The model house is a standard family house with a simple rectangular shape (see Figure 1). The external dimensions of the house are fixed.



Built-up area	100 m^2
Volume	612 m^3
Heat exchange area	457 m^2
Facade area	257 m^2
Total area of windows	55,2 m^2
Shape factor	0,75 m^2/m^3
Floor area (from overall external dimensions)	200 m^2

Figure 1. Model family house

3.2. Calculation settings

Two variants of the load bearing structure are considered. Variant "Z" is a brick house made of ceramic blocks lightened by air gaps. The thermal insulation is located on the external side of the masonry. The roof and ceiling between stories are made of ceramic blocks and a concrete reinforcement layer, which is in the case of the roof also covered by a thermal insulation layer. Variant "D" is a timber frame house with thermal insulation between columns and boards. Slab on the ground is considered to be adiabatic. This simplification underestimates the space heating demand and overestimates overheating.

The house is inhabited by a four-member family (two adults + two children). Three variants labeled Family 1, Family 2 and Family 3 (F1, F2, F3) are considered. Additionally, the theoretical variant completely without inhabitants and internal heat gains (labeled as "-") is considered. Occupancy profiles and internal heat gains were taken from literature [3]. The basic daily profile (see Figure 2) is repeated every working day. Weekend days are considered with a modified profile. The absence of residents due to vacations is not taken into account. The average heat gain from internal heat sources (average over a longer period of time) approximately corresponds to 1.5 W/m^2 (F1), 2.1 W/m^2 (F2) and 3.3 W/m^2 (F3).

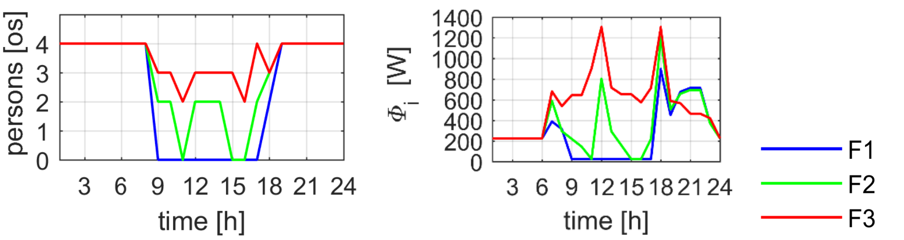


Figure 2. Time profile of internal heat gains and occupancy

Supply fresh air to the house is provided by a mechanical ventilation system with heat recovery (efficiency 85 %, the bypass of heat exchanger is activated when outdoor temperature exceeds 15 °C, the bypass is deactivated when outdoor temperature drops below 5 °C). The amount of fresh air in all variants is related to the number of present persons (25 $m^3/(h \cdot person)$). Supply air temperature equals to the outdoor air temperature.

The shading system (movable external blinds) is used in all samples of the model house. The shading system is activated on all windows if the internal air temperature exceeds 25 °C (in period 16.3.–15.10.), resp. 27 °C (in period 16.10.–15.3.). The shading is deactivated if the internal air temperature drops below 22 °C. The shading correction factor is randomly selected from the interval according to Table 2.

The more intensive ventilation is used for removal of excess heat from the internal environment. The increased ventilation is activated if the internal air temperature exceeds 25.2 °C and is deactivated if the internal air temperature drops below 22 °C. Air flow rate during increased ventilation is randomly selected from the interval in Table 2. The increased ventilation is activated only when the current external air temperature is at least 4 °C lower than the internal air temperature. The bypass of heat recovery is used if the increased ventilation is switched on.

Heating system has unlimited power and no thermal inertia. It maintains the internal air temperature 21 °C. The building was modelled as a single zone, so the calculated internal air temperature represents the volume-weighted average of the air temperatures in the individual rooms.

Calculations were performed with climatic data corresponding to Prague-Libuš in the recent past (1960–1990). Climate data were obtained from Meteonorm software [4]. These climatic data do not include a continuous hot periods (daily maximum external air temperatures higher than 30 °C) typical for the past decade.

3.3. Variable input data

The thickness of the thermal insulation layer in the external walls and roof, thermal transmittance of windows, the area of windows in individual facades, shading correction factor of the external shading system, the orientation of the building, maximum air flow rate and internal heat gains were considered to be variable (see Table 1 and Table 2). The houses with the similar thermal quality of building enclosure are marked as „B1“ and „B2“. Mean thermal transmittances of building enclosure cover interval from 0.13 $W/(m^2K)$ to 0.23 $W/(m^2K)$ in case of group "B1", and interval from 0.22 $W/(m^2K)$ to 0.33 $W/(m^2K)$ in case of group "B2".

Table 1. Variable input data in building energy simulation (thermal quality of the enclosure)

Group of houses	Thickness of thermal insulation in walls [cm]		Thickness of thermal insulation in roof [cm]		Thermal transmittance of windows [$W/(m^2K)$]	
	min	max	min	max	min	max
"B1"	20	28	25	35	0.6	0.8
"B2"	10	16	16	26	0.8	1.0

Table 2. Variable input data in building energy simulation (other variables)

Window-to-wall ratio F_w [-]					Shading correction factor (movable blinds) F_{sh} [-]		Building orientation [°]		Maximal air flow rate [m^3/h]		Profile of internal heat gains	
min	max (E,S,W,N)				min	max	min	max	min	max	min	max
0,07	0,5	0,7	0,5	0,3	0,08	0,4	-45	+45	150	450	0	R3

4. Results and discussion

The calculated output data (space heating demand and the annual maximum internal air temperature) are depicted in relation to the decisive aggregated thermal parameters of the building enclosure. It is expected that such decisive aggregated thermal parameters are the mean thermal transmittance of building enclosure U_{em} and the specific solar aperture A_s/V.

4.1. Annual maximal internal air temperature

The correlation of the maximal annual internal air temperature $T_{ai,\,max}$ [°C], and the specific solar aperture of the model house $A_{s(V.\text{-}VIII.)}/V$ is depicted in Figure 3. The only results of the model buildings "B1" are depicted.

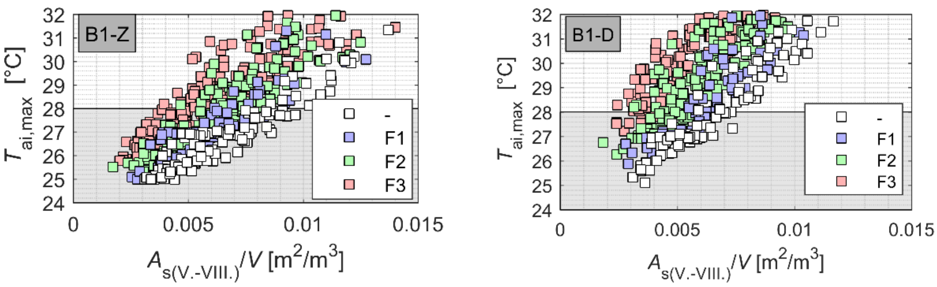


Figure 3. Correlation of annual maximal internal air temperature and the specific solar aperture $A_{s(V.\text{-}VIII.)}/V$ – different levels of internal heat gains are highlighted

A clear trend is visible in Figure 3. The higher the value of the solar aperture was, the higher the annual internal air temperature was. The scattering in the direction of the vertical axis is largely related with two factors. The first factor is the level of the internal heat gains (see the tilted colored stripes in Figure 3). The second factor is how well the heat stored in building components during daytime is extracted by the more intensive night ventilation.

The points near the lower sides of the tilted colored stripes belong to samples with more efficient extraction of excess heat by the increased ventilation. Simultaneously, it is likely that the increased ventilation is used in reality (e.g. manual opening of windows in night time). Therefore, the only points corresponding to maximum air flow rates greater than 350 m^3/h (350 $m^3/h \approx$ air exchange rate 0,6 h^{-1}) are shown (see Figure 4).

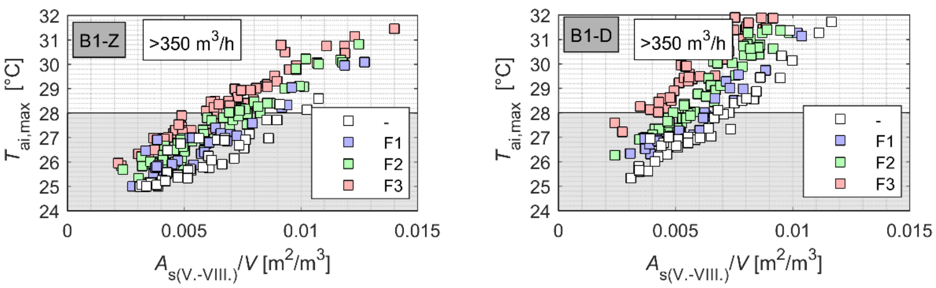


Figure 4. Correlation of annual maximal internal air temperature and the specific solar aperture $A_{s(V.\text{-}VIII.)}/V$ – different levels of internal heat gains are highlighted, only samples with maximal airflow rate higher than 350 m^3/h are taken into consideration

The approximate range of reasonable values of the specific solar aperture can be deduced for both material variants of the model house (see intersections of the stripes with 28 °C in Figure 4). To avoid overheating the specific solar aperture should not exceed 0.006 m^2/m^3 – 0.010 m^2/m^3 in the case of a model building with the higher heat storage capacity (variant “Z”), respectively 0.004 m^2/m^3 – 0.008 m^2/m^2 in the case of buildings with the lower heat storage capacity (variant “D”). The higher limit corresponds to a theoretical building without internal heat gains. The lower limit corresponds to a building with high internal heat gains (family F3).

A similar procedure for detecting the limit values of the specific solar aperture was repeated with the samples corresponding to thermal quality of building enclosure “B2”. Moreover, the calculations were also performed with the climatic data representing the expected typical year in far future (2070–2100). The approximate reasonable specific solar apertures $A_{s(V.–VIII.)}/V$ are summarized in Table 3.

Table 3. Approximate values of reasonable specific solar aperture of building enclosure of family houses for keeping internal air temperature below 28 °C (climatic conditions: Prague, Czech Republic)

Weather data	Building enclosure	Construction variant	Interval* of values $A_{s(V.–VIII.)}/V \times 10^{-3}$ [m^2/m^3]													
			0	1	2	3	4	5	6	7	8	9	10	11	12	13
1960–1990	„B2“	„Z“									8				12	
		„D“							6				10			
	„B1“	„Z“							6				10			
		„D“					4				8					
2070–2100	„B2 “	„Z“					4				8					
		„D“			2				6							
	„B1“	„Z“			2				6							
		„D“	0				4									

* The upper limit is related to theoretical buildings without internal heat gains. The lower limit is related to the highest level of interval heat gains considered in this study (family F3).

The reasonable values of the specific solar aperture (see Table 3) quantify solar heat gains the model building "can afford" in the warm part of the year. The recommended values for climatic conditions expected in far future are approximately half of the recommended values derived by using recent past climatic data. Even the higher values in Table 3 cannot be achieved without efficient shading provisions.

4.2. Annual space heating demand

The correlation of the annual space heating demand e_H and the mean thermal transmittance of the building enclosure U_{em} is shown in Figure 5. It is obvious that the level of the internal heat gains has a relatively large influence on the values of space heating demand in the given category of buildings.

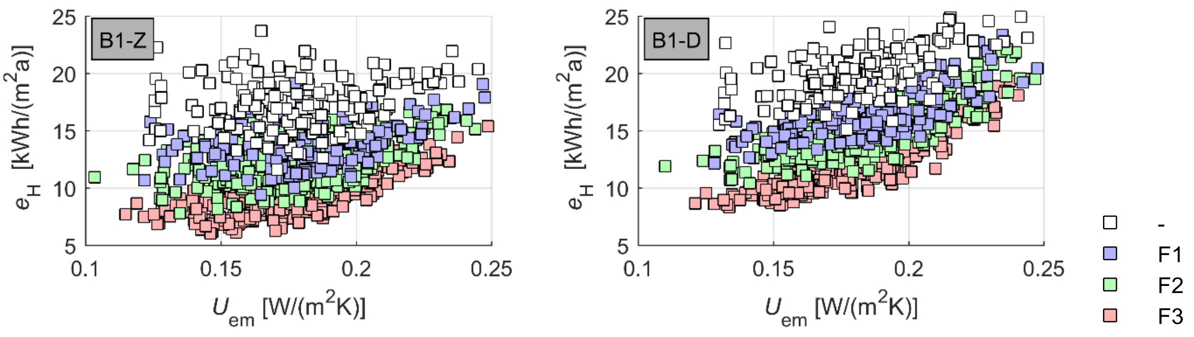


Figure 5. Correlation of mean thermal transmittance of building envelope U_{em} and annual space heating demand e_H – levels of internal heat gains are highlighted

Scattering exists even if space heating demand corresponding to the same level of internal heat gains is taken into consideration. It is expected, that the scattering could be attributed with the unequal size of solar heat gains. Therefore, only space heating demand for F2 family (medium level of internal heat gains) is depicted in the next step (see Figure 6). Additionally, three different levels of the specific solar aperture $A_{s(XI.–II.)}/V$ are highlighted there.

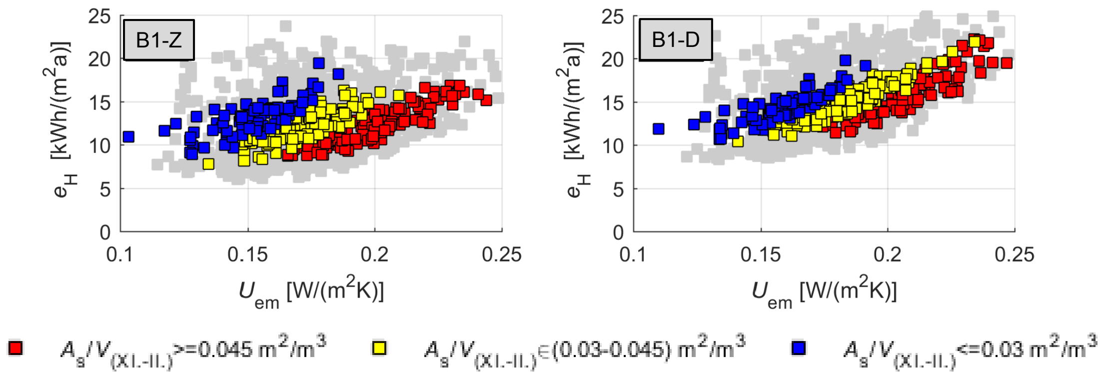


Figure 6. Correlation of mean thermal transmittance of building envelope U_{em} and annual space heating demand e_H – results for family F2

The space heating demand e_H can be influenced to some extent by specific solar aperture $A_{s(XI.–II.)}/V$, see Figure 6. The higher value of the effective solar aperture can compensate for a higher value of the mean thermal transmittance of building enclosure. Conversely, if the mean thermal transmittance of building enclosure is sufficiently low, higher values of the specific solar aperture may not be necessary. The space to influence space heating demand by changing the solar aperture in the cold part of the year is not high and varies in this case around 5 kWh/(m^{2}a). However, the strategy of the higher values of the solar aperture in the cold part of the year unfortunately increases the likelihood that it will not be possible to achieve sufficiently low values of the solar aperture in the warm part of the year. A small energy benefit in heating can turn into overheating in the warm part of the year.

4.3. Trade-off in building design

Generally, residential buildings should reach the sufficiently low space heating demand and sufficient thermal comfort of the internal environment (no overheating), while keeping sufficient daylight. The target space for houses “B1” could be defined by the space heating demand lower than 15 kWh/(m^{2}a) and the maximum annual indoor air temperature of 28 °C (whereas for houses “B2” < 35 kWh/(m^{2}a)).

The recommended trade-off values of three decisive aggregated thermal parameters were found from the statistical evaluation of samples, which fulfilled the limit conditions of the target area (see Table 4). The only samples of model house with inhabitants were taken into account. Limit values for the interval of recommended values were defined as the 5th and 95th percentile of the statistical set of the relevant thermal parameter.

Table 4. Compromise values to achieve low space heating demand without overheating

Target space	Building enclosure	Construc-tion variant	U_{em} [W/m^{2}K]	$A_{s(XI.-II.)}/V$ ×10^{-3} [m^2/m^3]	$A_{s(V.-VIII.)}/V$ ×10^{-3} [m^2/m^3]	Ratio $A_{s(XI.-II.)}/A_{s(V.-VIII.)}$ [-]
e_H<35 kWh/(m^{2}a) $T_{ai,max}$ < 28 °C	„B2“	„Z“	0.24–0.32	33–60	8–13	3.5–6.2
		„D“	0.22–0.29	19–43	5–8	3.1–6.8
e_H<15 kWh/(m^{2}a) $T_{ai,max}$ < 28 °C	„B1“	„Z“	0.14–0.22	22–56	5–9	3.6–8.2
		„D“	0.14–0.21	19–44	3–7	4.1–9.8

In order to meet the target space of houses "B1", the mean thermal transmittance of building enclosure should not exceed the value of 0.20 W/(m^{2}K), while the mean specific solar aperture of the building enclosure over time period XI.–II. should at the same time reach values higher than 0.02 m^2/m^3. In order to avoid overheating, the mean specific solar aperture of the building enclosure over time period V.–VIII. should be less than 0.009 m^2/m^3 for house "Z", respectively less than 0.007 m^2/m^3 for house "D". These values are in line with the recommended values already presented in Table 3.

4.4. Limitations of this study and recommendation for further research

The recommended approximate values of the specific solar aperture were derived for a relatively low influence of increased ventilation. Moreover, the model assumed the adiabatic floor on the ground. Both assumptions should help to ensure that the obtained recommended values of solar aperture are on the safe side. The simulation model, however, may not be a perfect picture of reality due to uncertainties in the formulation of the model and input data. Therefore, the recommended values of the specific solar aperture could be verified in a larger case study, preferably carried out by several independent persons, using different simulation software, and a larger number of model houses.

The approximate reasonable values of solar aperture could also be derived by a mathematical analysis. The analysis could be based on the analytical solution of a simplified building model under specified boundary conditions (e.g. quasi stationary solution). The impact of increased ventilation rate during night period and the effect of thermal inertia could then be unambiguously incorporated in the analysis. It is expected that the approximate reasonable values of specific solar aperture A_s/V can be expressed as function of the most decisive building parameters and characteristics of ambient environment.

Finally, the analysis of achievable values and typical time profiles of the specific solar aperture for various window-to-wall ratios, various fixed or movable shading devices should be performed. For example, the unresolved question is whether well-designed fixed shading with ventilative cooling can avoid overheating in residential buildings located in semi-continental climate.

5. Conclusions

This paper dealt with the thermal characteristic of the building enclosure, which characterizes the ability of the building enclosure to transmit solar heat gains to the interior of a building. Such a thermal characteristic was called the solar aperture of a building enclosure.

Thermal simulations of a model family house were performed for climatic conditions of the Czech Republic. The overheating of the model family house strongly correlated with the solar aperture. The approximate recommended values of the specific solar aperture for avoiding overheating have been proposed. The paper also proposed trade-off values of the most decisive aggregated thermal parameters of building enclosure (mean thermal transmittance, solar aperture), for which building will probably achieve the low space heating demand while providing adequate thermal conditions during the warm part of the year.

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