Thermal insulation versus overheating - monitoring results

T Kisilewicz

Cracow University of Technology, Institute of Building Materials and Structures,
31-348 Kraków, ul. Warszawska 24, Poland

Email: tkisilew@pk.edu.pl

Abstract. Initial design decisions regarding building external envelope may have important consequences for thermal comfort and total energy demand not only for heating but also for cooling. Before reaching for more energy-intensive solutions, effective use of passive measures to avoid overheating is necessary. In the article, special attention was paid to the influence of external wall structure on space overheating. On the basis of monitoring results it was found that the standard thermal insulation prevented excessive energy conduction into the space on very hot days and it should not be considered as a barrier for heat dissipation. The standard opaque wall was also compared with the uncovered transparent insulation, which is in summer an intensive source of energy gains. The basic dynamic characteristics of the monitored wall were analytically analysed by means of the periodic waves method.

Introduction

Low energy buildings require new experience, systems and tools for the design, which for obvious reasons are not commonly available. While conventional buildings may be characterized by a considerable tolerance to design errors in the field of building physics, the new ones are extremely vulnerable and demand new approach. The article deals with the influence of external wall properties on the comfort of office space use. The specific difficulty of the use of office buildings is associated with relatively high internal heat gains [1]. While the issues regarding heating demand are already quite well recognized, the protection of the building against overheating is usually left to the designers of the installation rather than the architects or constructors of the building. These initial design decisions can have important consequences for thermal comfort and total energy consumption. In the climate of Central Europe, before reaching for more energy-intensive solutions, effective use of passive solutions to protect against overheating is necessary.

Passive ways to protect the building from overheating are characterized by great simplicity, usually do not require significant investment expenditures, do not consume non-renewable energy, do not require costly system maintenance. To a large extent, these are solutions well known since a long time, such as appropriately selected size and orientation of the glazing, large heat capacity of the interior, night cooling etc. [2,3,4,5]. For a long time these were the only means to control the conditions in buildings. Nowadays it's necessary to specify again the conditions of their application and the rules of rational design [6].

The article focuses on the specific influence of external wall structure on indoor conditions in the warmest period of the year. Although no one disputes nowadays the sense of thermal insulation use, very thick insulation layers, as in passive buildings, are considered as the cause of space overheating [3,6,7]. According to the widespread opinion efficient thermal insulation of external building shell is a barrier for energy discharge to external environment during the hot period of the year.

2. Dynamic thermal characteristics of a building component

Ambiguities and myths associated with dynamic heat exchange through building components result to a large extent from computational difficulties related to dynamic conditions. Analytical calculations are very complicated and the numerical modelling is usually not used in the everyday design process. Designing process is therefore necessarily based on observations related to stationary heat exchange conditions. Meanwhile, the processes of heat storage and thermal inertia of the partitions have a great influence on the heat exchange and the actual conditions inside the buildings [3,7,8].

One of the simplest and best known heat transfer dynamic models is a theory of harmonic heat waves, based on Fourier analysis of the cyclic functions. Due to a quasi-periodic course of ambient temperature and Fourier analysis tool, this analytical approach allows accurate modelling of real conditions [5]. In International Standard EN ISO 13786 – 2017 [9] only sinusoidal boundary conditions are considered: building boundaries are submitted to sinusoidal variations of temperature or heat flow rate. Two basic dynamic features of building component are usually considered. Thermal admittance relates heat flow rate to temperature variations on the same side of the component. Transmittance is a complex quantity defined as a complex amplitude of the density of heat flow rate through the surface of the component adjacent to zone *m*, divided by the complex amplitude of the temperature in zone *n* when the temperature in zone *m* is held constant.

Combined thermal characteristics of the building component under the steady and periodic conditions may be expressed as a decrement factor i.e. ratio of the modulus of the periodic thermal transmittance to the value of the steady-state thermal transmittance *U*.

In this work thermal transmittance *Y* and decrement factor *f* were used as the dynamic wall characteristic. *D'Thermal* software was used to run the computations needed for this paper.

The structure and material data of the tested external envelope have been shown in table 1.

Table 1. Wall structure and material data.

	thickness d [m]	density ρ [kg/m^3]	thermal conductivity λ [W/mK]	specific heat c [J/kgK]
internal plaster	0.02	1700	0.8	840
ceramic blocs	0.188	800	0.21	880
expanded polystyrene	0.1	10	0.045	1460
external plaster	0.01	2000	1.0	840

The standard dynamic characteristics, according to EN ISO 13786 (2017) and for the period of 24 h, have been calculated and the results of calculation have been compiled in table 2.

Table 2. Dynamic characteristics of the tested wall – 24 hour period (surface thermal resistances excluded).

	complex number	modulus [W/(m^{2}K)]	time lead/shift [h]
external admittance	0.416+1.292i	1.357	4.811
internal admittance	2.513+4.003i	4.726	3.859
transmittance	-0.051-0.082i	0.096	-8.136

Calculated internal areal heat capacity of the wall (without surface resistances) is equal to 66.316 kJ/m^{2}K, while external areal heat capacity is only 19.951 kJ/m^{2}K. Decrement factor is equal to 0.220.

Periodic thermal transmittance is responsible for propagation of thermal waves across the building component. External environment variations are the result of ambient temperature changes but also of solar radiation absorbed upon external surface of a building shell. Low transmittance on one hand may prevent heat dissipation but on the other hand it protects space against conduction of absorbed by external face solar energy [8]. Large phase shift is an important aspect of heat transfer, that allows to separate in time solar gains through the windows and those due to the conducted heat wave [5]. “Delayed’ energy may be efficiently removed by intensive night ventilation [10].

In order to exemplify the significance of a massive material for non-stationary heat transfer, the dynamic characteristics of the wall without the ceramic blocs have been calculated. Thermal resistance of the removed ceramic layer was compensated by increased up to 14 cm expanded polystyrene thickness. Major reduction of thermal capacity would result in the significantly increased value of the transmittance modulus: 0.317 W/(m^{2}K) and heavily reduced phase shift: -0.423 h. In spite of the same thermal resistance in the stationary conditions, the lightweight wall would transmit in real dynamic conditions much more energy than the heavyweight one.

A specific feature of non-stationary conditions is the sensitivity of building elements to the frequency of changes. As a result the same element has different properties depending on the environmental variation conditions. All the above dynamic features have been calculated for 24 hour period of the boundary condition changes. The daily changes of the boundary conditions are, of course, of a great practical importance due to the standard variability of the outside temperature, solar radiation and interior use. However, it is also important to consider the changes taking place in a much longer period of time, e.g. a few days. Long heat waves occur many times every year, regardless of global warming.

Calculated dynamic features of the tested wall for 72 hour period are presented below in table 3.

Table 3. Dynamic characteristics of the tested wall – 72 hour period (surface thermal resistances excluded).

	complex number	modulus [W/(m^{2}K)]	time lead/shift [h]
external admittance	0.366+0.471i	0.596	10.430
internal admittance	1.299+2.150i	2.512	11.772
transmittance	0.111-0.199i	0.228	-12.183

Decrement factor for 72 hour period is 0.621, it is almost 3 times bigger than for 24 h period, internal heat capacity due to the bigger than before penetration depth is now 108.602 kJ/m^{2}K and external capacity is 29.572 kJ/m^{2}K. Much bigger than before values of transmittance modulus and decrement factor mean that the longer heat wave will easily propagate across external building shell and despite low amplitude would significantly affect internal thermal comfort.

3. Field testing of the two-layer external wall

Figure 1. South oriented wall of the tested space with two windows and the transparent insulation panel in between

The author had an opportunity to monitor long time thermal performance of the south oriented office building wall, figure 1. The central part of this wall was covered with the transparent capillary insulation.

Results related to transparent insulation have been in detail discussed in the former papers, in this paper mostly data connected with the standard opaque insulation will be presented and discussed.

The structure of the standard south oriented double layered wall was the same as in Table 1: internal lime plaster of 0.02 m, ceramic blocks of 0,188 m, **E**xternal **T**hermal **I**nsulation **C**ompound **S**ystem (ETICS) with 0.10 m of expanded polystyrene and mineral plaster. Calculated value of the thermal (stationary) transmittance coefficient was 0.301 W/(m^2·K).

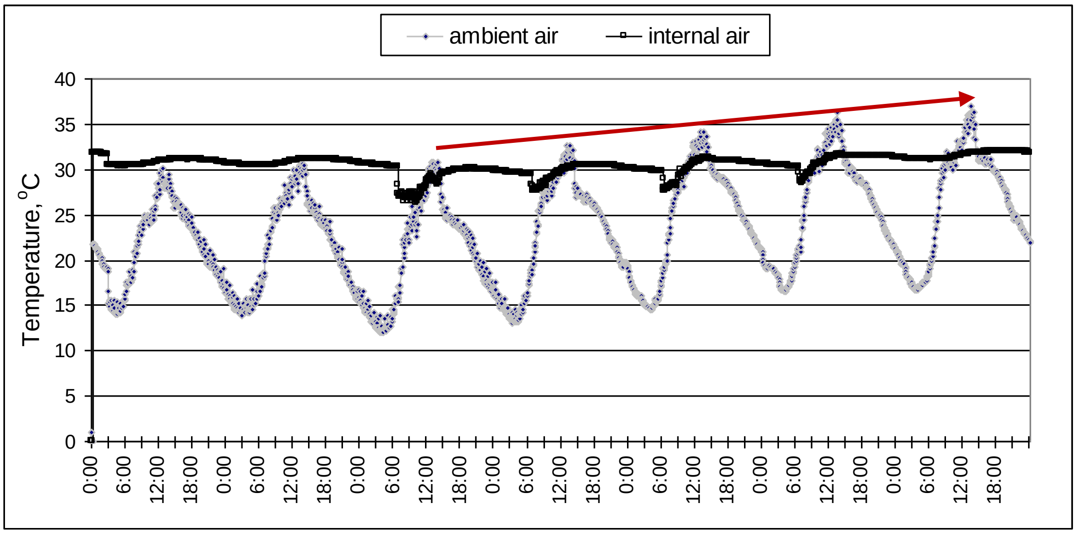

Figure 2. Hot summer week in July, internal and external air temperature

The following sensors have been applied to monitor tested elements:

- Pt-100 resistors, class A, to measure temperature of external and internal air and temperature of internal surface of the tested wall, accuracy ±(0.15 +0.002[t]),

- heat flow transducer placed on internal surface of the wall, accuracy 5%,

- vertical pyranometer, accuracy 5%.

All the sensor data have been gathered, digitalized and stored in the 16-channel scanner MPI-LAB with five minute intervals.

In figure 2 data of internal and ambient air temperature, recorded during one hot summer week, have been presented. Due to the large glazed area and transparent insulation panel, the tested space was heavily overheated. Internal air temperature was very high during the whole period with merely slight fluctuations in diurnal cycle. Only a small drop of internal air temperature during night may be partially explained by intensive heat flux released to the space in this time from massive accumulator in transparent system. During the whole analyzed period external air temperature was significantly fluctuating, falling down in night even below +15 °C, thus making possible night cooling of intensely overheated space [7,8,10,11]. Unfortunately, this opportunity was practically not used, with the exception of short morning periods, when the windows were opened by the cleaning staff. It may be easily observed on the third day of analyzed period, figure 2, as a sudden drop of internal air temperature at 6.00 a.m.

As it may be observed in figure 2 (red arrow), mean ambient air temperature was since the third day slowly but constantly rising reaching its maximum of 37°C on the 7-th day. So in fact the tested wall was exposed not only to 24 h heat waves but also to much longer wave with low amplitude. Accumulation capacities of massive buildings, with a thickness of heavyweight structural layers up to 25 cm, are sufficient to effectively dampen the daily fluctuation of boundary conditions. In the case of longer waves, with a few-day period of changes, the wave attenuation is very limited, as shown in Table 3, and mean internal air temperature is gradually rising.

Solar irradiance within the analyzed summer week was very intensive and followed nearly the same pattern each day, figure 3. Due to the building shape, pyranometer located close to the corner was partially shaded against direct radiation in the afternoon, what resulted in abrupt irradiance drop after 14.00 (right side of each peak).

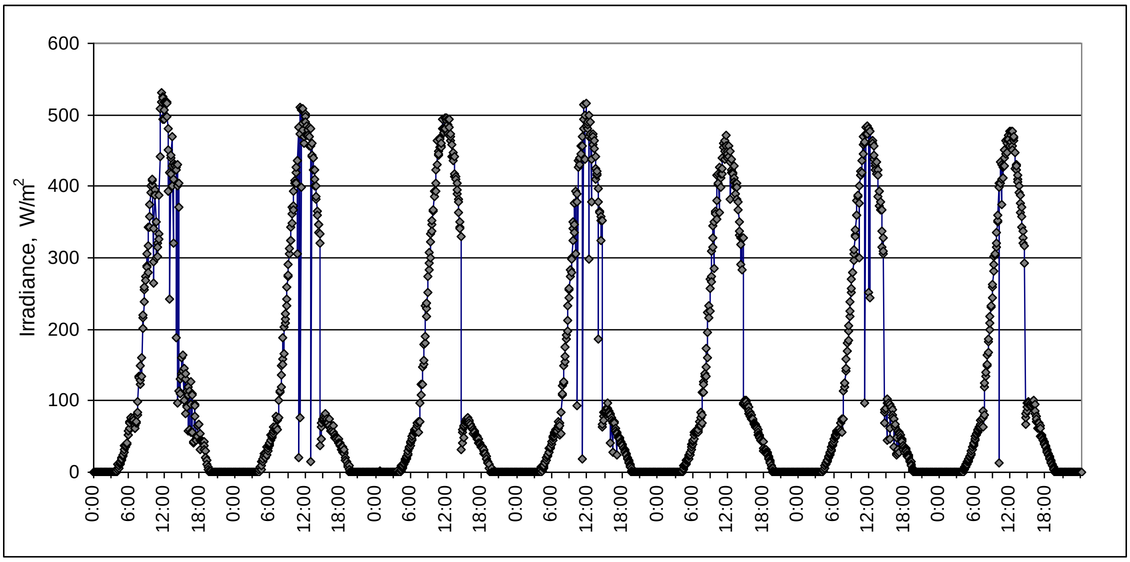

Figure 3. Solar irradiance measured at south oriented wall

Heat flux intensity, measured on internal surface of the discussed double-layer wall has been shown in figure 4. Positive number means heat flow into the wall while negative number heat delivered to the interior.

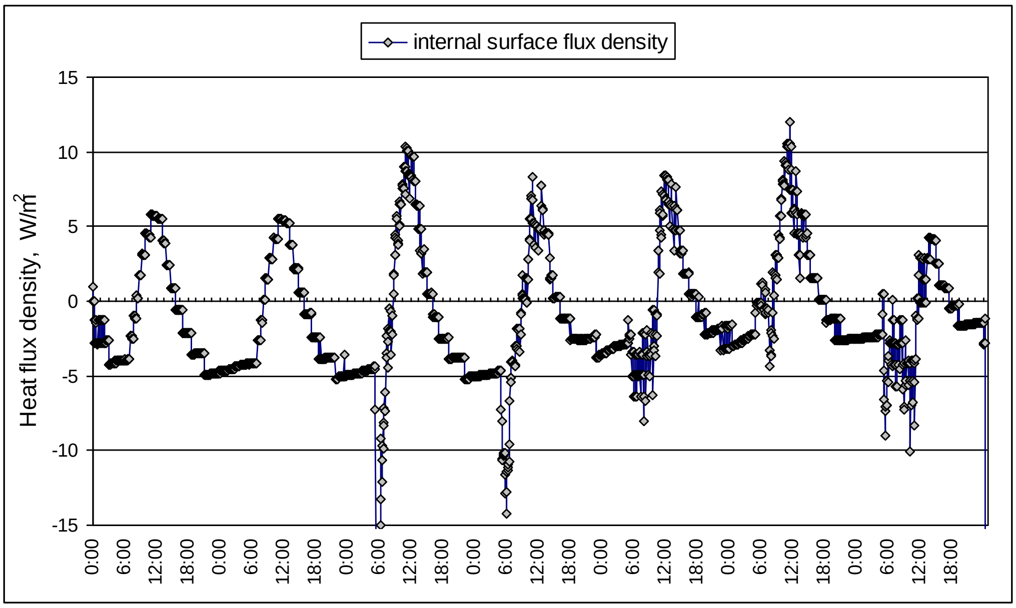

Figure 4. Hot summer period in July, heat flux intensity on internal face of the south oriented wall

In spite of the momentary temperature difference between internal and external environment, direction of heat transfer across internal surface of the wall was changing in a regular way: into the wall during daytime and out of the wall during night. The relation between external and internal air temperature is definitely different. Within the observed period heat flow was not induced by the instantaneous temperature difference between the two environments but by the local conditions at the internal surface of the massive structural part of this wall. Discussed earlier sudden drop of the internal temperature at 6.00 a.m. resulted immediately in intensive heat flux change and maybe easily observed in figure 4 in form of regular variations. Weekly heat flow balance at internal face of the tested wall is negative and equal to -193.5 Wh/m^2, while the sum of the absolute values of heat flow is three times higher: 586.4 Wh/m^2. Sum of the absolute values was intended here as a measure of total heat exchange at internal face. During the whole week more energy was delivered to the space than to external environment. In spite of the recorded big environmental temperature differences, there was no effect of energy discharge to external environment.

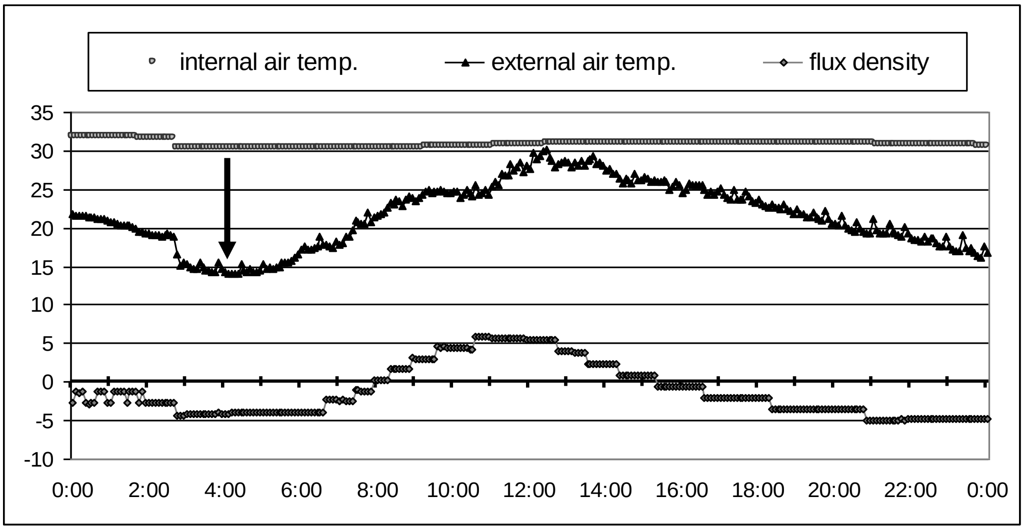

Figure 5. First day of the hot summer week in July, internal and external temperature (upper curves) and internal face heat flux density (bottom curve),

On the first day of monitored period, figure 5, despite the significant temperature difference, especially in night, heat stored in the massive wall was still delivered to the space (negative heat flux).

According to the simplistic stationary understanding of heat transfer across the external building wall, heat flux direction and its intensity would depend on the instantaneous environmental conditions with no space for history of temperature fluctuations and energy storage. In reality, in case of the massive and well insulated wall, momentary night conditions in both environments do not result in the immediate heat conduction to external air and discharge of the accumulated gains.

The reversed heat flow, that started at ca. 8 o'clock a.m., is partially an effect of the transmitted external temperature wave [8], but also a result of the morning solar gains delivered through the big glazed area, figure 5. Daily heat flux balance for internal surface is also in this case negative and equal to -26.7 Wh/m^2, while the total energy exchange within 24 h period was – as before - three times higher and equal to 78.0 Wh/m^2.

In figure 6 heat flux density values recorded on the internal faces of the standard double layered wall and the wall covered with transparent insulation have been compared. Although both diagrams look apparently similar, it should be noted that in case of the standard wall heat flux values were positive only during day hours i.e. energy was stored in the wall. While in case of the wall covered with transparent insulation intensive and continuous heat delivery to the tested space may be observed. Heat flux intensity is strongly fluctuating but its direction is uniform during the whole analyzed period.

The results of the measurements presented above concerned the hottest short period of the year, design-relevant results should be related to the longer periods. Taking into account the whole summer period (June – September, the total measured balance of heat flux was positive. More energy collected in this space was discharged by conduction to external environment than transmitted inside. Such a result was, of course, easy to predict.

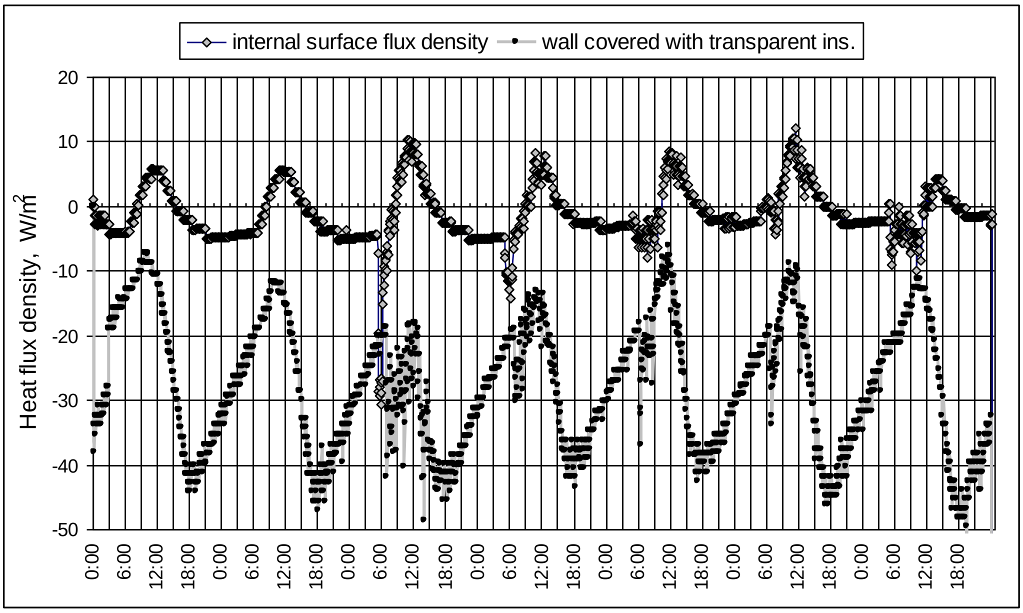

Figure 6. Hot summer period in July, heat flux intensities on internal surface of the wall with standard and transparent insulation

4. Conclusions

Rational design of low energy buildings requires linking basic architectural and structural decisions with their effects. Such a feedback should be observed already at the stage of preliminary design concept, even when a basic concept regarding wall structure and insulation thickness is considered. Improper design decisions often result in increased energy consumption and discomfort. For the future user, these aspects may be particularly troublesome and difficult to accept.

Presented above results of building monitoring and related to them results of calculations authorize the following conclusions:

1. It is not commonly understood that the massive layers of external building wall reduce significantly its dynamic thermal transmittance. Thermal transmittance modulus of the lightweight variant of the wall with the same resistance as the massive one, would be 3.3 times bigger and its time shift even 19 times shorter than of the analyzed and tested massive wall. It means that the external heat wave would propagate much easier across the lightweight wall, thus increasing thermal load and overheating intensity. Big time shift of a massive wall allows to separate heat gains in time and reduce maximum heat load during a day.
2. Dynamic heat transfer is not only a function of a wall structure but also of a heat wave length (or frequency). In case of the analyzed massive structure, decrement factor for 72 hour heat wave is almost 3 times bigger than for 24 h period. The damping effect of this wall is significantly reduced in such circumstances and slow changes of external conditions will be easily transferred inside the building.
3. Collected results of measurements confirm that night ventilation could be a reasonable way to reduce overheating. Unfortunately in the tested building this passive method was used only to a negligible extent, despite encouraging external conditions (low temperature at night).
4. During a hot and sunny week more energy was delivered to the space than transferred into the wall. In spite of the recorded big environmental temperature differences, there was no evident effect of surplus energy discharge to external environment during this week.
5. Unshaded transparent insulation is a potential source of intensive space overheating. Even though it had a horizontal capillary structure, that was supposed to block efficiently radiation coming from the sun high above the horizon, transparent insulation was not “switched off”. An efficient shading system is necessary.

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