THE EFFECT OF EXTERNAL SURFACE PROPERTIES ON THE THERMAL BEHAVIOUR OF A TRANSPARENTLY INSULATED WALL

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ABSTRACT

The properties of transparent plaster covering transparent insulation materials (TIM) were investigated using a whole building simulation program (ESP-r). The outer plaster was made from glass balls of different diameter, glued together with synthetic resin. The transmittance of the whole transparent covering layer (plaster + TIM) was estimated for different solar incident angles by laboratory measurements. The innovative character of the materials required refining of ESP-r's optical database in order to take into account these new characteristics. The transparently insulated building facade was proposed as a solar energy storage system. The results of the initial analysis showed the desirable optical properties, estimated for sun incident angles on the façade at a latitude of 52 degrees north. Then, simulations based on real climatic data for Central Europe were conducted to predict the thermal TIM wall behaviour. The influence of the structure on the diurnal heat storage potential was investigated for selected periods of the year.

KEYWORDS

transparent insulation; transmission; solar

INTRODUCTION

The majority of traditional transparent materials such as glass, polycarbonate, polyethylene, etc. is regarded as having a poor thermal resistance. However, increasing the thermal resistance leads to a reduction in the direct solar transmittance, which consequently decreases solar radiation heat gains. Therefore, using an additional layer of Transparent Insulation Material (TIM) is reasonable in advanced, high efficiency passive solar systems.

The general arrangement of TIM constructions consists of an outer glass pane or plaster (to protect against weather conditions), a shading device (located optionally in the outer gap space) and a translucent capillary structure (in thermal contact with the massive, opaque part of the wall), (Braun et al. 1992). The shading device is necessary to prevent overheating in summer and to regulate energy gains during the transition periods. However, in the middle of winter (Central Europe weather conditions), the absorber temperature does not exceed 30°C (Heim and Klemm 2002) and blind/shutter control is not required. For TIM elements with an air gap between the absorber and the capillary material a plastic (polycarbonate) film or a thin glass pane covers the rear TIM face. In a modular construction, these components are held together by a frame.

The thermo-physical properties of transparent layers exposed to solar radiation play a key role in the energy efficiency of the whole storage system. Considering the energy balance during the whole year, the material properties should provide the maximum heat gains during the winter period and a minimum during the summer period. The part of the solar energy transmitted or reflected by the transparent layer strongly depends on solar incident angle. For flat glass panes the highest transparency is obtained for normal incidence of solar radiation.

The TIM systems are significantly more complex than single glass. First of all, the outer, protective layer can be rough or consist of small elements with different orientations. It means that the transmitting/reflecting characteristic of the first layer differs from a traditional glass covering. The main part, the capillary transparent insulation, is also non-homogeneous and the solar energy is transferred through multiple reflections, refraction and absorption by the elements of the honeycomb structure.

THEORETICAL ANALYSIS

Traditional passive elements operate optimally during transition periods - the start and end of the heating seasons. Then the solar heat gains during the day equal the heating energy requirements during the night. In these periods the gains mentioned above appear almost every day, relatively regularly, and the heat capacity of traditional building materials is sufficient for diurnal heat storage systems. Nevertheless, in winter, low external air temperature causes excessive heat losses into the external environment. Also the solar heat gains are low and occur periodically. Due to the factors mentioned above two kinds of problems are encountered. The first one is due to the unsatisfactory proportions between the solar heat gains and heat losses. The second concerns the transmittance and reflection of the outside layer exposed to the solar radiation with changeable incident angle.

For these reasons, it is reasonable to employ particular, additional strategies which improve solar systems efficiency. The strategies are usually those which aim at maximized transmittance during the winter and minimized transmittance during the summer period.

Heim and Puchala (2007) gave an example analysis of theoretical limits for incident solar radiation on the south oriented elevation at a latitude of 52 degrees north. The limit of maximum solar elevation is 61 degrees (in June) while the maximum (in December) is only 14 degrees. It means that only solar elevation angles from 15 to 60 degrees need to be considered. For sun elevation angles around 15 degrees (winter) the transmittance is close to 1 for solar radiation in the central part of the day. For elevation angles close to 60 degrees (summer) the minimum solar transmittance is required.

In ESP-r the optical properties are defined for angles 0, 40, 55, 70, 80 degrees from normal and linear interpolation is undertaken for intermediate values. It means that for purposes of further numerical analysis only two angles will play the crucial role for Central European latitudes. They are 40 and 55 degrees. The theoretical analysis of the optimal solar transmittance was done for material properties presented in Table 1. To find the optimal material properties, more than 200 analyses were done for a south oriented elevation. External weather conditions correspond to a moderate climate in Central Europe. Based on a ten years' real climate data set, the winter (with the lowest solar radiation) and the summer (with the highest solar radiation) periods were selected.

Figure 1 presents the maximum solar gains in the winter and summer periods for total transmittance of the transparent layer (south oriented façade).

Table 1 Solar transmittance at selected angles

SOLAR ELEVATION	SOLAR TRANSMITTANCE
0	0.9
40	0.1 to 0.9
55	0.1 to 0.9
70	0.0
80	0.0

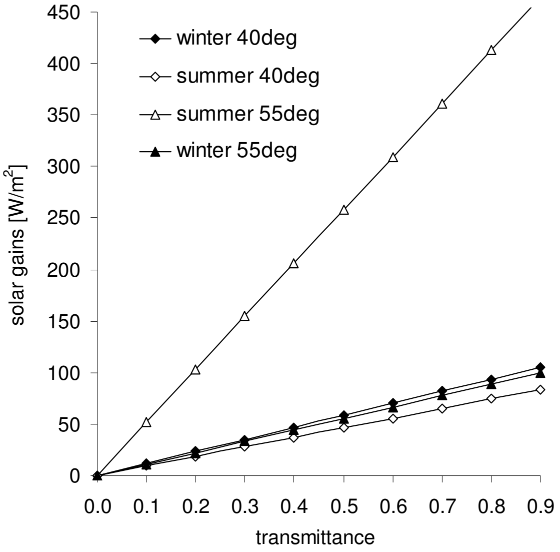

Figure 1 Solar gains through TIM for transmittance at 40 and 55 incident angles

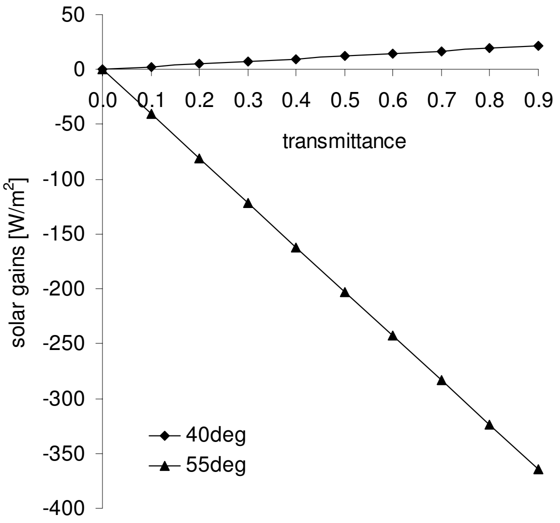

Figure 2 The differences in solar gains through TIM in summer and winter at 40 and 55 incident angles

The gains in summer at 55 degrees incidence angle are significantly (more than five times) higher than in winter. For 40 degrees, solar gains in winter only slightly exceed the gains in summer. Figure 2 shows the gain differences between winter and summer. It clearly shows that the maximum solar transmittance (about 0.9 or higher) is required for angles between 40 and 45 degree. Above 45 deg the total transmittance should be close to 0.1 or less. Theoretically the best, ideal solar transmittance is shown in Figures 3 and 4 (dotted lines). This characteristic was prepared only based on the five main angles in the ESP-r optical database. However, it is difficult to find a real material with such optical properties. The main assumption for the presented analysis was the absence of any additional shading devices. In the presented analysis the main parameter was the maximum value of heat gains during the day, but not the total balance of the TIM (average daily heat flux through the TIM).

TRANSMITTANCE OF COVERING

Beginning in the early 1990s, the Department of Building Physics and Building Materials, Technical University of Lodz began investigating storage potential of solar walls. Many experimental analyses and investigations were done for the so-called "intelligent façade" including the potential of the storage part with phase change materials (Heim and Clarke 2004, Heim 2006) and also the optical properties of transparent coverings (Heim and Klemm 2003, Grudzinska 2004) including transparent insulation materials.

Based on the results from laboratory measurements two capillary transparent insulation materials were selected for further analysis:

- TIM layer thickness of 60mm with cells of 2mm width (60/2),
- TIM layer thickness of 120mm with cells of 10mm width (120/10).

The external glass plaster differs in total thickness (1, 2 or 3mm) and structure of component elements (the diameter of glass balls). The balls were sorted by diameter in four groups: 200-315μm, 315-400μm, 400-630μm and 630-800μm. Some experimental results of solar transmittance are presented in figures 3 and 4. The upper lines represent the highest solar transmittances obtained for 1mm plaster made from 630-800μm granulated glass (small squares, test-1mm). The bottom lines show the lowest solar transmittances received for the 3mm glass plaster made from 200-315μm diameter balls (big squares, test-3mm). The rest of the materials have the transmittance curve between those presented in the graphs. For normal incidence, the transmittance of material 120/10 is 10% higher than for material 60/2. The thickness of the plaster and diameter of glass balls can cause significant differences for low incident angles (for normal incidence, a factor of between two and three). The differences become less important for higher incidence angles and for 80 and 90 degrees, the transmittance is zero for all types of materials.

Based on the experimental results the optical characteristics for five main angles were calculated and introduced to the ESP-r optical database. The characteristic angles are marked by "x". The values for 55deg were approximated linearly between 50 and 60 deg.

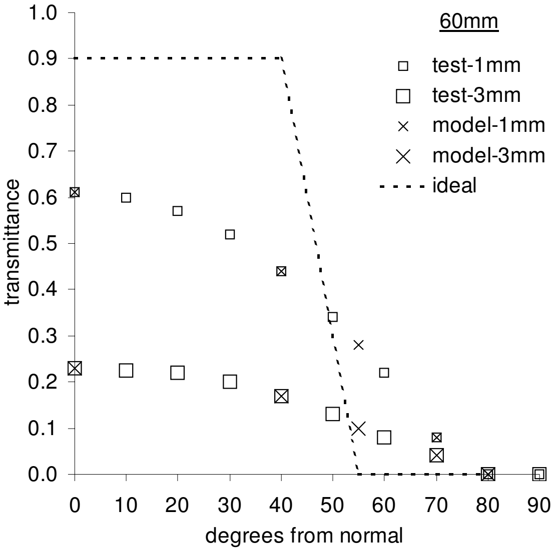

Figure 3 The optical characteristics of 60mm transparent insulation covered by glass plaster

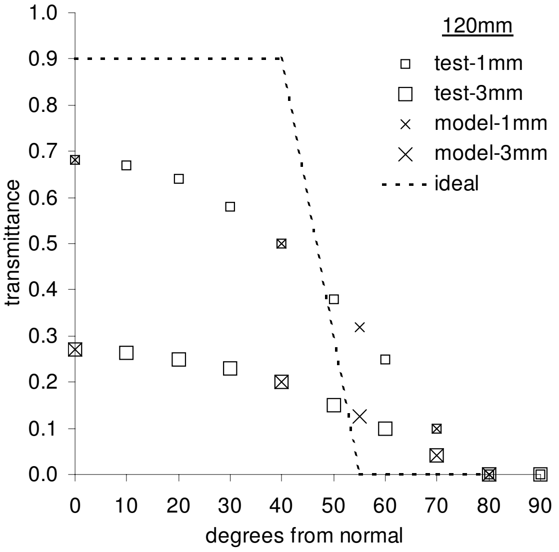

Figure 4 The optical characteristics of 120mm transparent insulation covered by glass plaster

Comparing the final results with the required characteristic for a south oriented façade (dotted line), the differences between 40 and 55 degree values is still not sufficient. However,, the excess of solar gains in summer can be eliminated by other strategies such as cutting off (shading), removing (ventilation) or isothermally storing (application of phase change materials).

NUMERICAL ANALYSIS

Thermal simulation of dynamic building behaviour under changeable climatic conditions is perceived as essential to accurately assess the efficiency of employing TIM. Advanced mathematical models for calculating the energy transport in TIM systems have been incorporated into several simulation programs.. The most popular programs are HAUSSIM, TRANSYS and ESP-r. HAUSSIM is based on the mathematical model proposed by Hollands et al. (1984) which is able to numerically solve the non-stationary temperature response of a TIM wall. Within TRANSYS a special calculation procedure was developed to model the different properties of TIM (Platzer 1992).

The ESP-r program (Clarke 2001) is capable of modelling the energy and fluid flows within combined building and plant systems. ESP-r uses an advanced numerical method to integrate the various equation types which can be used to represent heat and mass balances within a building. At present, however, ESP-r does not contain a specific module or specific algorithms to model TIM explicitly. Considering the solar radiation transmission and absorption through the TIM honeycomb structure and the rest of the TIM facade, four possible ways of modelling a TIM wall within ESP-r were proposed (Strachan and Johnstone 1994). For the purpose of this work the “air gap as an extra zone” approach has been chosen (the air gap space was defined between the transparent and opaque part). A proposed model of the TIM wall within ESP-r was formed as part of the PASSYS program (Jensen 1993). Experiments were conducted in some of the PASSYS test sites, among others, in Belgium, Italy, Germany and Holland. The objective was to carry out the measurements under different climatic conditions in order to evaluate the performance of such solar components.

RESULTS

The numerical analysis was conducted using the real climatic data for a city at a latitude of 52 degrees north. The period of the year was chosen based on the lowest and the highest sun altitude angle. For December it is 14.6° and for June 61.5°. The façade with TIM was oriented to the south. The sun azimuth angle changes in the selected winter week from –40.6° to +40.6° and in the summer week from –116.0° to +116.0° relative to the surface normal.

The transparent insulation material was defined as homogenous, covered from the outside by the glass ball plaster and from the inside by polyethylene plate. On the inner side of the plate the 5cm wide space gap was defined and then the thermal storage, a massive concrete wall. Two capillary insulation thicknesses were considered: 60 mm and 120 mm. The total transmissions were assumed for the whole system (three transparent layers) from the measured data as presented in Figures 3 and 4.

Table 2 Solar absorption and reflection

PARAMETER	**INCIDENT ANGLE**				
	0	**40**	**55**	**70**	**80**
ABSORPTIVITY					
plaster 60-1-b	0.22	0.32	0.45	0.50	0.25
plaster 60-3-s	0.60	0.59	0.63	0.54	0.25
plaster 120-1-b	0.15	0.26	0.41	0.48	0.25
plaster 120-3-s	0.56	0.56	0.60	0.54	0.25
insulation	0.00	0.04	0.04	0.05	0.13
polycarbonate	0.09	0.10	0.11	0.12	0.12
REFLECTIVITY					
	0.08	0.10	0.12	0.25	0.50

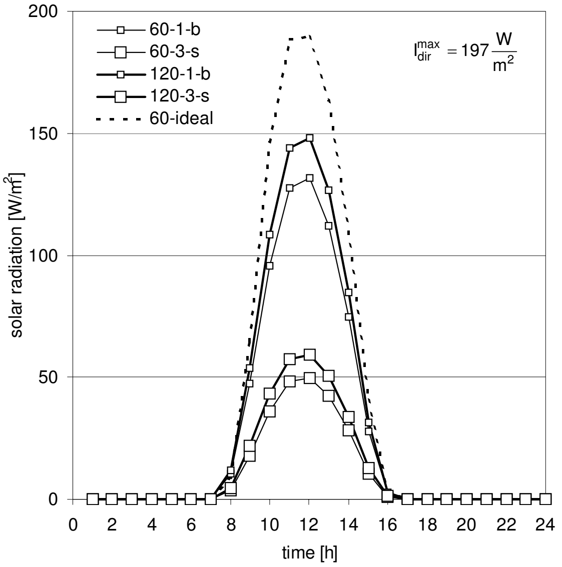

Figure 5 Solar energy transmitted through different types of TIM panels in winter

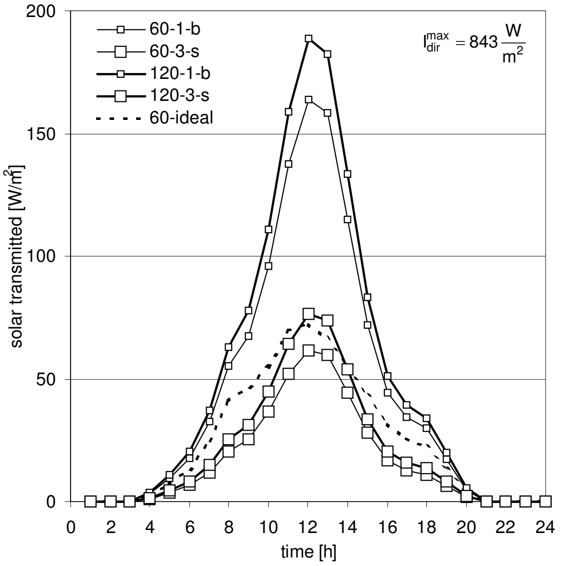

Figure 6 Solar energy transmitted through different types of TIM panels in summer

The absorptivities of the each element (plaster, TIM and polycarbonate) and the reflectivity are presented in Table 2. The reflectivity is assumed to be constant for each type of the plaster as is the absorptivity of the TIM capillary structure and the polycarbonate. The absorptivities of several plaster types are derived from the overall reflectivity and transmissivity data.

Solar gains

The total solar energy transmitted through the TIM system with outer glass plaster and inner polycarbonate is presented in Figures 5 and 6, for winter and summer respectively. The dotted line represents material with "ideal" transmission. Maximum direct solar radiation for the analyzed winter day is 197 W/m^2 and for the summer day it is 843 W/m^2.

In winter the best characteristics were obtained for thin, 1mm glass plaster where the diameters of the balls does not make a big difference. The energy transmitted through 120mm of TIM is about 10% greater than through two times thinner insulation (60mm). In summer the best characteristics are observed for materials with 3mm of plaster. The material with 60mm TIM seems to work better than "ideal" TIM. However, two times more energy is transferred by the "ideal" material in winter than in summer, although the direct solar radiation is four times higher. The other materials transmit similar amounts of solar energy in both periods. The optical properties of materials with the thin 1mm plaster covering seems to be insufficient for the summer period and there is a danger of overheating.

Energy balance

The energy balance at the external transparent part of collector wall is presented in Figures 7 and 8. In the zone under consideration no heating and cooling system was defined. Also casual gains from equipment, light and occupants were set to zero in order to remove their impact on the simulations and so make the results interpretation easier.

The positive surface convective flux in winter is noticed from 9:00 to 14:00. For 120mm of TIM with both kind of plaster coverings, the maximum gains at noon are two times higher than losses at midnight. For 60mm of TIM the extreme fluxes are similar, but the balance over the day is negative. For the winter time the best seems to be 120mm of TIM with 1mm of transparent plaster. In summer the best characteristics are observed for 60mm of TIM, with the same 1mm glass balls plaster. However, the differences in energy balance are small. The extreme positive surface convective flux (at 12:00) in summer is unfortunately three times higher than in winter.

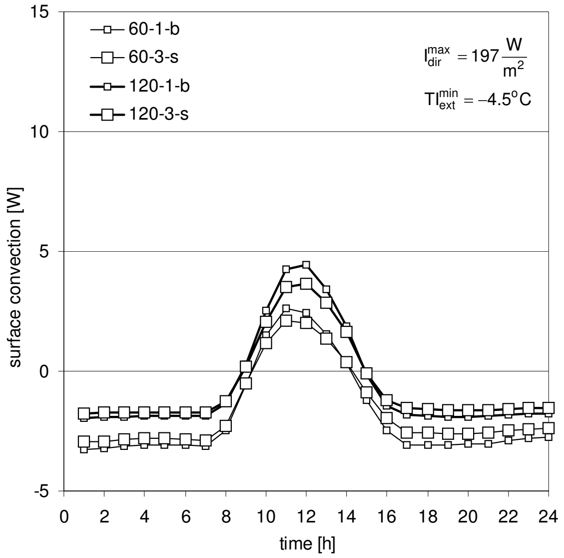

Figure 7 TIM surface convection in winter

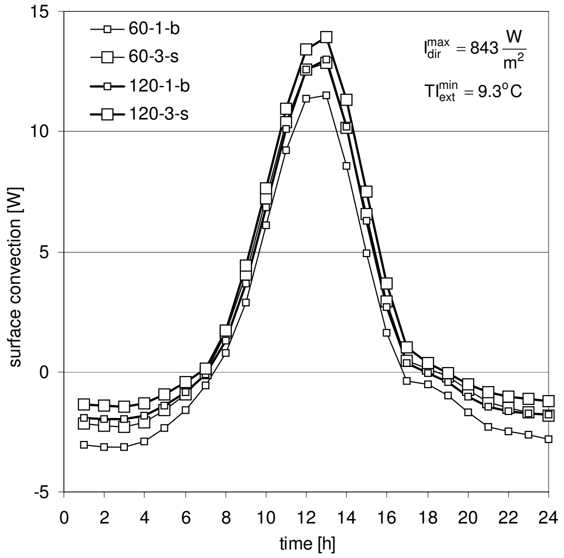

Figure 8 TIM surface convection in summer

SUMMARY AND CONCLUSIONS

This study is a contribution to developing the numerical model of radiation processes and refining the optical material databases in ESP-r. The additional transmittance characteristics added to the program were obtained by laboratory measurements of existing transparent insulation materials covered on the outside by glass ball plaster. An analysis was undertaken to determine desirable TIM/plaster combinations for Central European climatic conditions.

The obtained results show the effect of angle-dependent solar transmittance on the thermal behaviour of the collector wall. This effect causes a considerable difference in solar energy absorbed by the massive part of storage wall as well as in the energy balance of its transparent part.

Comparing the solar energy transferred by the TIM structure, the 120mm of TIM covered by 1mm of plaster made from glass balls (200-315μm diameter) turned out to be the best option in winter. However, in the hottest period with significantly higher direct solar radiation it was found that 60mm of TIM with 3mm of glass ball plaster (630-800μm) was more suitable. None of the analyzed material combinations were found to be optimum for all seasons.

On the other hand, the technical solutions of TIM systems allowed the reduction of summer overheating by the use of additional strategies such as shading and night ventilation. It leads to the conclusion that systems should be designed to maximise solar gains in winter periods. Assuming that transparent insulation is cut off from solar radiation during the summer to avoid overheating, maximum transmittance is required during winter for the low solar elevation. The highest transmittance arises from the use of a very small thicknesses of the outer layer, in the order of 1mm. Such a thin covering, with the additional requirement for safety, is possible only with the glass plaster and not with the ordinary glass pane. Looking at the materials under consideration, the 120mm of TIM covering with 1mm of glass plaster made from small balls is preferred.

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