A SIMPLE TROMBE WALL: COMPARISON OF DIFFERENT GLAZINGS

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Abstract – Trombe wall with transparent insulation used instead of an usual single glazing was investigated. Different calculation approaches known from publications on Trombe walls were compared. Intra-fabric temperature profiles calculated by these approaches are shown in this paper. Comparison results in requirement of a detailed dynamic simulation allowing an accurate prediction of transparently insulated walls behaviour. "Dynamic modelling" approach (ESP-r model) is used for investigation of different glazing systems (transparent insulations) applied to Trombe wall. Simulations were performed with a climate database typical for Prague (Czech Republic). Results were compared with an unglazed wall model and energy gains caused by individual glazings were determined. Annual total energy gains for Lexan Thermoclear structures range from 70 to 90 kWh/m^{2}yr, for Okalux Kapipane structures from 110 to 140 kWh/m^{2}yr, and for double low-e glazing around 90 kWh/m^{2}yr. Simple economic calculations are attached. It was determined that very high payback periods result for investigated transparent insulation glazings (25-30 years for Lexan Thermoclear and double low-e glazing, 50 years for Okalux Kapipane honeycombs), considering contemporary energy prices in Czech Republic. Further development should be led towards to decreasing the investment costs of transparent insulation glazings so that TI glazings can be introduced into retrofits of old buildings in Czech Republic

1. INTRODUCTION

At the present time, an increased attention in solar energy utilization is being paid to application of transparent thermal insulations (TI) as glazing elements in passive solar systems. Transparent insulations combine the characteristics of high optical transmittance with low heat loss. Thus, transparent insulation can preferably replace conventional glazing systems used in active or passive solar applications.

Promising application of transparent insulations lies in combination with a massive storage wall (Goetzberger A., 1984; Braun et al., 1992). Such a wall has a positive energy balance during heating period and thus contributes to heating the building. Moreover, delayed release of heat gains through the massive wall can be combined with direct solar gain through the windows.

Thermal behaviour of transparently insulated walls was subjected to extensive research. This led to number of different approaches in according to level of information required (Sodha, 1985; Platzer 1987; Duffie and Beckman, 1991; Sick and Kummer, 1992; Gorgolewski 1996). In this paper, the approaches are compared from the point of an accurate, detailed behaviour prediction (heating loads, solar gains, temperatures, overheating in summer).

Dynamic simulation tool ESP-r (Clark J.A., 1997), originally evolved for universal building behaviour prediction, was validated and extended for solar passive applications in framework of Passive Solar Programme (UK Department of Trade and Industry) and CEC's PASSYS project. This simulation tool is used for dynamic modelling of simple unvented Trombe wall (see Fig. 1.) with different TI glazings in Czech Republic (Prague) weather conditions. A few important conditions relating to Fourier numbers have to be considered in detailed simulation of massive walls to get an accurate mathematical description of TI walls (Hensen and Nakhi, 1994).

In Czech Republic, there is a increasing need for retrofitting of old post-war buildings. Transparent insulations show a large potential for this type of applications. Such systems, based on TI walls, can significantly reduce consumption environmentally damaging fuels and increase a fraction of renewable energy use in Czech Republic. Therefore, a simple economic calculations are made so that even economic effectiveness would be known for these purposes.

2. SIMPLE TROMBE WALL CONCEPT

One of the basic passive solar elements, unvented Trombe wall, can significantly improve its performance when traditional single glazing is replaced by transparent insulation. Trombe wall combines advantage of conventional opaque insulation with that of solar collector (see Fig. 1.). Solar radiation incident on outer surface of TI glazing is transmitted to dark coloured massive wall surface. Solar radiation is converted to heat resulting in absorber temperature increase. Part of the heat is conducted through the wall into interior (q_w), contributing to covering heat losses of other constructions. Part of the heat is stored in massive wall which cause that heat flux to interior is delayed. The time lag depends on thermal properties of the wall. Last part of the heat is transferred to outside as a heat loss of the glazing (q_{TI}). In case of transparent insulations, this heat loss is dramatically reduced in comparison with a single glazing.

3. CALCULATION APPROACHES

Preliminary analyses and designs of Trombe walls with transparent insulations require an accurate prediction of their thermal behaviour (intra-fabric temperatures, heating loads, solar gains, overheating during sunny periods). For transparently insulated Trombe wall, it cannot be simply claimed that better transparent insulation properties leads to better thermal performance. Using better transparent insulations can decrease heating demands, but on the other side it could increase cooling loads. This is always dependent on buildings structure (other constructions), climate, internal sources, and user behaviour as well. Design of Trombe walls is therefore an optimization process fitted to concrete building.

There are several techniques commonly used for performing calculations in Trombe wall cases. Their suitability generally depends on what sort of information we want to obtain. Some of them are suitable just for a design of heating system nominal power (in accordance to standard), others for determination of overall solar loads (approximate solar contribution to heating), or generally for detailed description of Trombe wall behaviour (temperature profiles, detailed simulation of "realistic" performance).

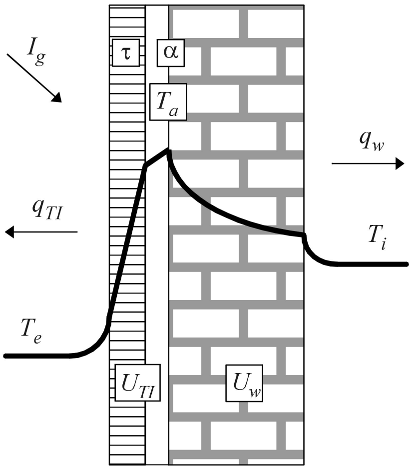

Fig. 1. Layout of Trombe wall with TI glazing

3.1 "Heat loss" approach

Simple "heat loss" calculation is a conventional approach for overall building heat loss calculation based on the time independent material parameters, considering no thermal storage capability of massive wall, and no solar radiation. This approach determines the heat flux through Trombe wall using only one parameter of construction, the overall U-value.

$$q_w = U\left(T_i - T_e\right) \tag{1}$$

Such approach is mostly used for calculation of nominal (peak) heating power according to standard. Overall heat loss is calculated from nominal values of internal temperature (20 °C), external temperature given for Czech Republic (-12, -15, -18 °C). This heating power is determined to cover heat loss of Trombe wall in case of extreme weather conditions (extremely low temperatures, no solar radiation, no heat stored in the wall).

For detailed analysis of heat loads (energy consumption), the heat loss through the wall can be calculated in hour steps (since databases of external temperatures are usually based on hourly values). "Heat loss" approach treats transparent insulations as opaque materials and the omission of the solar irradiation in general disqualifies this approach for any detailed prediction of Trombe wall ”real” behaviour.

3.2 "Solair temperature" approach

In general, "solair temperature" approach takes into account an influence of solar irradiation. Solar gain is included in ambient temperature, i.e. ambient temperature is increased according to solar irradiation value. Solair temperature is given by formula

$$T_{sa} = T_e + \frac{\alpha I_g}{h_e} \tag{2}$$

The heat flux through the wall (heat loss or gain) depends now on solair temperature.

$$q_w = U\left(T_i - T_{sa}\right) \tag{3}$$

Neither this approach can properly describe transparently insulated wall because TI glazing is not considered as transparent, i.e. solar flux is absorbed on TI glazing surface, not on the absorber surface. Therefore, transparent insulation is also treated as opaque material and thus this approach is not useable for any behaviour prediction of transparently insulated walls.

To come nearer to the principle of transparently insulated wall, we can simply replace the heat transfer coefficient h_e by heat loss coefficient of transparent insulation glazing U_{TI} and considering solar energy transmittance of TI glazing (Sodha, 1985).

$$T_{sa,c} = T_e + \frac{\tau\alpha I_g}{U_{TI}} \tag{4}$$

However, this “corrected solair“ approach is a misleading interpretation of Trombe wall behaviour, resulting in absorber temperatures exceeding 400 °C. These incorrect values are caused by neglecting the wall heat flux into interior.

3.3 “Steady-state model" approach

At steady-state level, the realistic operation of transparently insulated wall can be modelled by a simplified thermal network, shown in Fig 2. (Goetzberger et al., 1984).

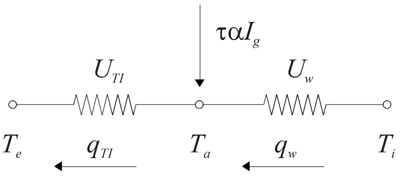

Fig. 2. Equivalent thermal circuit of Trombe wall

Heat flux through the wall is given by equation

$$q_w = U\left(T_i - T_e\right) - \tau\alpha I_g \tag{5}$$

Integrating of components gives the load of the wall (L_w) and solar contribution (Q_{sol}). For an additional load of considered interior space (L_a), the auxiliary energy which has to be supplied results in

$$Q_{aux} = L_a + L_w - NQ_{sol} \tag{6}$$

where N is an utilization fraction, which depends on the match between load $L_a + L_w$ and solar gains Q_{sol}, i.e. how much the solar gains are dumped.

Since this approach is based on steady-state calculation, the omission of dynamic characteristics of massive wall (thermal mass) limits the suitability of this approach for proper description of the wall behaviour. For example, the absorber temperatures are given by equation

$$T_a = \frac{U_w T_i + U_{TI} T_e + \tau\alpha I_g}{\left(U_w + U_{TI}\right)} \tag{7}$$

This approach results in high absorber surface temperatures, exceeding 150°C in heating season for transparently insulated Trombe wall. Such temperatures are not achieved in realistic operation.

Therefore such approach can be used only for the first approximation of TI wall potential. Calculated thermal gains of Trombe wall have to be corrected by utilization factors (experimental values).

3.4 "Dynamic modelling" approach

Unsteady-state (dynamic) modelling approach solves the problems of previous approaches. It is based on differential equations for unsteady-state heat transfer through the wall with an internal heat source in a thin absorber layer. In the case of transparently insulated wall, we can use one-dimensional heat conduction transfer equation

$$\lambda \frac{\partial^2 T}{\partial x^2} + Q = \rho c \frac{\partial T}{\partial t} \tag{8}$$

Internal volumetric heat source represents the solar irradiation transmitted through the transparent insulation and absorbed in the absorber surface layer.

$$Q(t) = \frac{\tau\alpha I_g(t)}{d} \qquad (9)$$

Differential equations can be solved by one of the numerical methods (finite differences, finite volumes, finite elements). Simulation results depend not only on a suitable numerical model (i.e. proper discretization), but also on the choice of boundary conditions (external temperatures, incident solar radiation). There is an effort to use climate databases based on the test reference years for individual cities. Use of artificial climate databases based on the characteristic climate data profiles (functions) is also possible.

Simulation inter-connects all the building input parameters and energy flows, and solves the correspondent mathematical equations. Thus, simulation gives a full information, not only the mean values.

Simulations are complementary to physical experiments, which are necessary to develop numerical models (to bring them to reality), lend confidence to corresponding mathematical models and understand component behaviour.

3.5 Correlation methods

Correlation methods give us information only on overall system solar loads and heating demands, but at relatively accurate level. These methods are based on correlations resulting from long performance extensive simulations or from experimental investigations of given types of passive components. Correlation functions (solar-load ratio *SLR*, utilization fraction *N*) are derived and used for simple calculations of annual requirements for auxiliary energy.

Correlation methods don't cover detailed analysis of Trombe wall behaviour (temperature profiles) but they give sufficiently accurate solar loads prediction because of large simulation and empirical background. They can be reasonably used for preliminary known systems, i.e. systems already subjected for extensive investigations. Any changes in the system parameters (thermal and physical properties) result in new need for simulation which is disadvantageous for design of new concepts (TI Trombe walls).

3.6 Comparison of approaches

In the calculations, transparently insulated wall was used. The layout of Trombe wall is shown in Fig. 1. Trombe wall consists of TI glazing (Okalux Kapipane 40 mm with a protection glass cover), an air gap (0.08 m), in which a roller blind can be situated, and a massive, dark painted wall made of brick (0.45 m).

Fig. 2. shows a comparison of intra-fabric temperature profiles in Trombe wall for a noon of sunny winter day (January 21st). Profiles were calculated with the given approaches. It can be seen that "heat loss" approach is not sensitive to solar radiation and temperature profile represents an opaque insulation case. "Corrected solair" approach gives too high absorber temperatures (T_a = 285,1 °C) which are obviously not correct values. Also the "steady-state model" approach gives high absorber temperatures (T_a = 139,0 °C) which are not realistic. All these approaches have a common attribute – steady-state based calculation, i.e. they don't include an influence of thermal mass of the wall into calculation (line profiles). Last mentioned "dynamic modelling" approach calculating with a storage capability of massive wall, gives reasonable absorber temperatures and real temperature profiles in the massive wall.

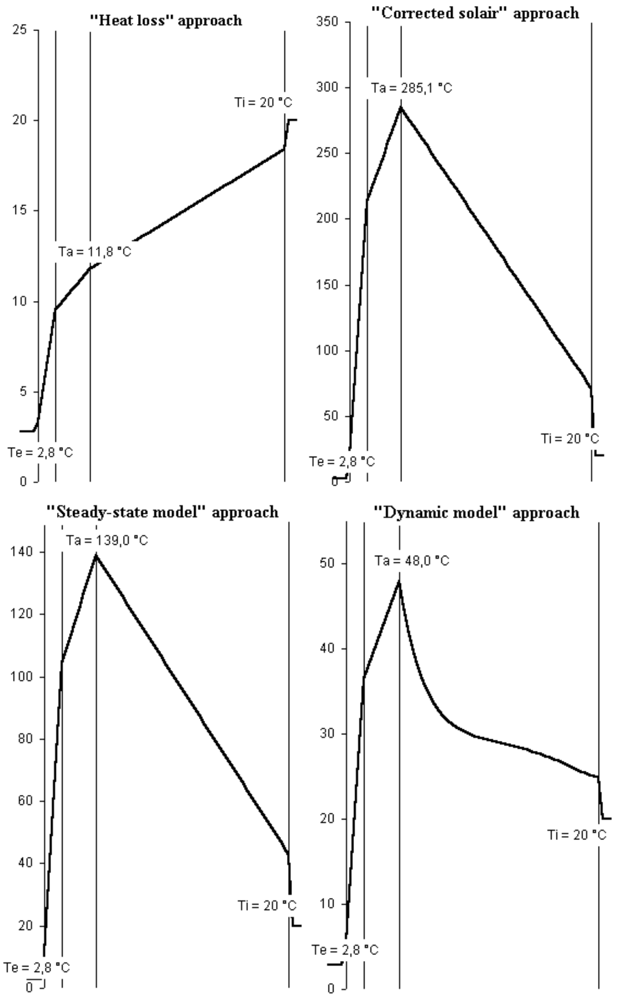

Fig. 2. Comparison of intra-fabric temperature profiles calculated by different approaches (note the different scales in graphs) for January, 21st

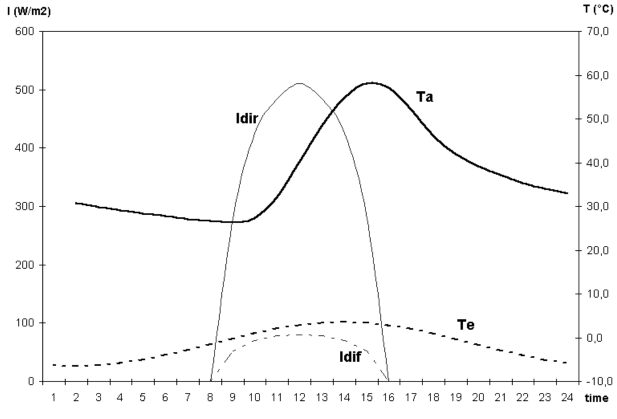

Fig. 3. Absorber temperature profile together with a climate profile (dynamic approach) during January, 21st

Fig. 3. shows an absorber temperature profile during the whole sunny winter day (January 21st) together with a climate profile. It is obvious that approaches neglecting the thermal capacity of massive wall material (see section 3.1 - 3.3) don't show any time lag between solar irradation profile and absorber

temperature. Dynamic approach, based on unsteady-state calculations covers this principal property of Trombe wall. Absorber temperature maximum is delayed approx. of 3 hour after solar irradiation maximum.

4. COMPARISON OF TI GLAZINGS VIA MODELLING

Three different types of TI glazings used for Trombe wall were compared using the "dynamic modelling" approach in computer aided simulation tool ESP-r, double low-e glazing, Lexan Thermoclear structure, widely used for industry fenestration (skylights) and mature honeycomb structures Okalux Kapipane.

4.1 Simulation tool ESP-r

ESP-r is a dynamic thermal simulation environment for the analysis of energy and mass flows and environmental control systems within the building environment. It may be used to explore a range of problem types including building fabric, mass flow, ideal and detailed plant systems - separately or in combination. Unlike the simulation programs specialized for solar passive systems, ESP-r is an universal simulation tool. It allows to incorporate a passive component (Trombe wall) into a complex building structure.

ESP-r uses an advanced numerical method to integrate the various equation types (algebraic, ordinary differential and partial differential) which can be used to represent heat and mass balances within buildings. The object continuous structure is divided into many small, but finite, volumes of space. These finite volumes represent the various regions of the building and plant within and between which energy and mass can flow. Throughout any subsequent simulation, ESP-r tracks the energy and mass balance for all finite volumes as they evolve under the influence of the system boundary conditions (climate and control) and the constraints imposed by the inter-volume links. Within the simulation, all flow-paths are evolved simultaneously to fully preserve the important spatial and temporal relationships.

Continuous material, e.g. massive wall, is in ESP-r represented by a network of nodes and associated thermal capacities. The number of nodes used must be on the one hand large enough to achieve a sufficient level of accuracy, but on the other hand must be small to avoid excessive computational effort. The accuracy doesn't only depend on the number of nodes but also on the discretization scheme. The current implementation assumes one-dimensional heat flow and uses a mixed implicit-explicit discretization scheme (Crank-Nicholson). Each single layer of material is represented by one central node (representing 1/2 of the layer's thermal capacitance), and two nodes at each boundary of the layer (representing 1/4 of the layer's thermal capacitance each). Within the layer, the nodes are connected with two (equal) thermal resistances. This nodal scheme is symmetrical for each layer, which implies major numerical and implementation advantages.

4.2 Numerical model of Trombe wall

In ESP-r, a simple cubic building model with unvented Trombe wall was created. Important parameters of the model were:

- 2 zones model (glazing, interior)
- mass wall - brick, 0.45 m, $U_w = 1.43$ W/m^{2}K (includes an absorber surface heat transfer coefficient)
- outer layer of mass wall is blackened ($\alpha = 0.9$).
- air gap 0.080 m (unvented)
- other walls of the interior made of brick (0.45 m)
- south orientation of Trombe wall
- model is not shaded by surrounding objects
- ideal control strategy (set-points: heating 20 °C, cooling 27 °C)
- shading control of TI elements

Model layout of Trombe wall uses a typical composition of old post-war buildings (0.45 m brick) in Czech Republic which have to be retrofitted.

Model covers a theoretical performance of transparently insulated Trombe wall, not considering any internal gains or occupancy, which have a large influence on the thermal behaviour of the real building. No windows were included into the model to characterize Trombe wall energy gains alone.

4.3 Glazings (TIMs)

Glazings submitted to comparison represent three basic types of transparent insulations:

- low-e double glazing (air gap 12.7 mm, e = 0.2 on 2nd surface)
- Lexan Thermoclear multiwall sheets (LTC10/2RS, LTC16/3TS, LTC 20/5RS)
- Okalux Kapipane honeycomb structures (40, 82, 122 mm) with single glass cover (4 mm)

As a reference case, a traditional single glazing (4 mm) was used.

Optical and thermal properties of glazings are shown in Table 1. In ESP-r, transmittance of direct solar radiation dependent on the angle of incidence is used. Dependence is described by transmittances at 5 angles, assuming zero transmittance for the incidence angle 90°. Diffuse solar transmittance is implicitly calculated as direct solar transmittance for 51° (general assumption in ESP-r). Angle dependent solar energy transmittance characteristics of analysed TI glazings were obtained from measurements performed in solar laboratory of our Department using ASTM E 1084-86 Standard method.

Since ESP-r was evolved for conventional building structures, not specially for passive solar elements, it calculates heat flows using the constant thermal properties of constructions. Therefore, nominal U-values given by manufacturers were used. For the U-values of TI glazings, an external heat transfer h_e coefficient was assumed to be 23 W/m^{2}K, an internal heat transfer coefficient h_i corresponds approximately with thermal resistance of the air gap.

TI glazing	**0°**	**40°**	**55°**	**70°**	**80°**	**U_{TI}**
LTC10/2RS	0.77	0.72	0.65	0.50	0.30	3.5
LTC16/3TS	0.70	0.67	0.60	0.45	0.25	2.7
LTC20/5RS	0.60	0.57	0.51	0.39	0.25	1.8
Kapipane 40	0.80	0.73	0.68	0.53	0.31	1.5
Kapipane 82	0.78	0.71	0.65	0.49	0.28	1.1
Kapipane 122	0.77	0.70	0.63	0.48	0.27	0.8
double low-e gl	0.65	0.63	0.58	0.43	0.22	2.0

Table 1. Transparent insulation glazings properties used in simulations

4.4 Simulation

There are few factors influencing the simulation process and accuracy of results we have to consider. Massive wall has to be divided into several layers in order to achieve appropriate dimensional step according to Fourier number which has to be maintained in certain region dependent on discretization scheme of simulation tool (Hensen and Nakhi, 1994). Incorrect Fourier number can lead to inaccurate results (stable oscilations).

Calculations were performed for usual heating season (1.9. - 31.5.) in Czech Republic. A climate database typical for Prague (Czech Republic) was used. It comprised solar direct and diffuse irradiation, external temperature, relative humidity, wind speed and orientation. Heating and cooling energy consumption and solar contribution were observed.

4.5 Results

From simulations, energy consumption values of the building model were investigated for different glazing systems. These values were compared with that of the model without the front glazing, i.e. single brick wall model. This comparison resulted in total energy gains $Q_{g,tot}$ caused by individual glazing systems during the heating season.

Then, just thermal properties of glazing systems were considered for simulations, i.e. solar energy transmittances of glazings were set to zero for all angles of incidence. From these simulations, net energy gains $Q_{g,ins}$ caused just by insulative properties of glazings were obtained. Subtracting them from the total energy gains, we get net energy gains $Q_{g,TI}$ caused by transparency character of TI glazings.

TI glazing	$Q_{g,tot}$ **(kWh/m²yr)**	$Q_{g,ins}$ **(kWh/m²yr)**	$Q_{g,TI}$ **(kWh/m²yr)**
Single glazing	**59**	11	48
LTC10/2RS	**74**	28	46
LTC16/3TS	**81**	36	45
LTC20/5RS	**86**	46	40
Kapipane 40	**114**	54	60
Kapipane 82	**125**	65	60
Kapipane 122	**140**	77	62
Double low-e gl	**93**	43	51

Table 2. Annual energy gains of investigated transparent insulation glazings

Utilization of incident solar energy gains for heating purposes, i.e. reducing energy consumption, is given by relation between these gains and thermal properties (quality) of other building constructions. If other constructions would be well insulated, utilization of solar gains would be lower because the gains would cover just TI wall heat loss and much of energy would be dumped. Interior would be overheated and additional cooling loads required. The values shown in Table 2. are the upper limits of energy gains since model used for simulations had other constructions made of brick (no insulation). Therefore no cooling loads were required and no dumped energy occured. All energy gains were used to cover heat losses of other walls.

4.6. Discussion of modelling

Although ESP-r is a powerful simulation tool in building modelling, it has also few disadvantages for transparent insulations modelling. It was already mentioned above that ESP-r uses constant thermal parameter of constructions. U-values of transparent insulations should be treated, unlike conventional constructions, as temperature dependent variables.

Simulations should be validated by physical experiments to create proper design models, describing the "reality". Unfortunately, there is no transparently insulated structure which could be experimentally investigated in Czech Republic to validate numerical models. Therefore, such a non-calibrated model can serve in the meantime only as a preliminary mathematical description of thermal processes in building with transparently insulated Trombe wall.

5. ECONOMIC COMPARISON

Transparent insulation glazings can be applied to both new and old buildings. In Czech Republic, retrofit applications have a great potential due to the large stock of old buildings (brick, prefabs) and increasing need for their retrofit (buildings regeneration).

Each retrofit is also a question of investment costs. To introduce the TI glazings into retrofits in Czech Republic, the overall costs have to be known. Since no project on transparently insulated facades is known in Czech Republic, the approximate costs can be obtained from prices of conventional glass facades or industrial fenestration systems based on Lexan structures.

TIM structure	**Material (CZK/m²)**	**Mounting (CZK/m²)**	**Total (CZK/m²)**	t_p **(yr)**
LTC10/2RS	530	210+1000	1740	24
LTC16/3TS	870	230+1100	2200	27
LTC20/5RS	1020	250+1150	2420	28
Kapipane 40	1110	800+4000	5910	52
Kapipane 82	1880	800+4000	6680	53
Kapipane 122	2630	800+4000	7430	53
double low-e	1200	220+1500	2920	31

Table 3. Transparent insulation material, mounting (assemblage + add-ons) and total costs and associated payback period t_p

Material costs given in Table 3. represent TI structures prices (1999). Mounting costs include complexity of handling and assembling the glazings to wall and add-on costs (frames, holders, etc.). Mounting costs for Lexan structures, given in the Table 3., were obtained from Czech suppliers. Okalux Kapipane structures have to be assembled to glazed units or a single cover glass panes have to be placed in the front of them. This leads to the large increase of mounting costs and add-on costs.

Total costs of investigated TI glazing systems range from 1800 CZK/m² (Lexan structures) to 7500 CZK/m² (Kapipane honeycombs). For comparison, total costs of opaque thermal insulation systems range from 1000 to 1500 CZK/m².

Calculation of simple payback periods t_p for individual glazings was done considering contemporary average energy prices for central heating based on natural gas in Czech Republic (1,0 CZK/kWh). Payback periods for Lexan Thermoclear structures and double low-e glazing were from 25-30 years, for Okalux Kapipane honeycombs around 50 years. It can be stated that mature transparent insulations, as Okalux Kapipane honeycombs, are less efficient then cheap Lexan Thermoclear structures from the point of economical view. On the other side, Lexan payback periods are also very high, partially caused by low energy prices in Czech Republic.

6. CONCLUSIONS

Different approaches used for calculations of Trombe walls were compared to investigate their suitability for prediction of realistic behaviour of Trombve walls From the comparison, need for dynamic modelling as an universal and comprehensive approach resulted.

Dynamic thermal simulation environment ESP-r was used for evaluation of different transparent insulations in simple unvented Trombe wall for Czech Republic (Prague) climate. Total energy gains for Lexan Thermoclear structures range from 70 to 90 kWh/m²yr, for Okalux Kapipane structures from 110 to 140 kWh/m²yr, and for double low-e glazing around 90 kWh/m^{2}yr. These results shown a large potential of transparent insulations to reduce energy consumption of buildings.

On the other side, economic calculations are not so promising. Long payback periods of all types of transparent insulations shown that transparently insulated walls (retrofits or new ones) cannot compete with traditional fuels at contemporary energy prices level in Czech Republic and TI glazing costs.

Performed calculations indicated that further developments in TI technology should be oriented towards to decreasing the investments costs of thermally efficient TI glazings.

NOMENCLATURE

c	specific heat (J/kgK)
d	absorber surface thin layer thickness (m)
h_e	external heat transfer coefficient (W/m^{2}K)
h_i	internal heat transfer coefficient (W/m^{2}K)
I_g	global solar irradiation (W/m^2)
L_a	additional heating load (kWh)
L_w	wall heating load (kWh)
N	utilizability fraction
q_w	thermal flux through the wall (loss, gain) (W/m^2)
$Q(t)$	internal heat source (W/m^3)
Q_{aux}	auxiliary heating load (kWh)
Q_{sol}	solar contribution to space heating (kWh)
$Q_{g,tot}$	total energy gain (kWh/m^{2}yr)
$Q_{g,ins}$	energy gain caused by insulative properties of TI glazing (kWh/m^{2}yr)
$Q_{g,TI}$	energy gain caused by transparency character of TI glazing (kWh/m^{2}yr)
t	time (s)
t_p	payback period (yr)
$T(x,t)$	temperature profile in the Trombe wall (°C)
T_a	absorber temperature (°C)
T_e	external temperature (°C)
T_i	interior temperature (°C)
T_{sa}	solair temperature (°C)
$T_{sa,c}$	solair temperature, corrected for TI glazing case (°C)
SLR	solar load ratio factor
U	overall heat transfer coefficient (U-value) (W/m^{2}K) $U = \frac{U_w U_{TI}}{\left(U_w + U_{TI}\right)}$
U_w	heat transfer coefficient of the wall (W/m^{2}K)
U_{TI}	heat transfer coefficient of the transparent insulation (W/m^{2}K)
x	position coordinate along the direction of heat flow
α	solar absorptance (-)
δ	thickness of construction (m)
λ	thermal conductivity (W/mK)
ρ	density (kg/m^3)
τ	solar energy transmittance (-)

REFERENCES

Goetzberger A., Schmid J., Wittwer V. (1984). Transparent insulation system for passive solar energy utilization. *Int. J. Solar Energy* 2, 289-308.

Hensen J. L. M. and Nakhi A. E. (1994). Fourier and Biot Numbers and the Accuracy of Conduction Modelling. *In Proceedings of Building Environmental Performance '94*, York, April 1994.

Sodha M.S. et al. (1985) *Solar Passive Building - Science and Design*. pp. 195-196. Pergamon Press, Oxford.

Duffie J.A. and Beckman W.A. (1991) *Solar Engineering of Thermal Processes*, 2nd ed. pp. 750-758, 734-743. Wiley Interscience, New York.

Platzer W.J. (1987). Utilization of heat gains from transparently insulated collector-storage walls. *In Proceedings of the Biennial Congress of the International Solar Energy Society*, 13-18 September Hamburg, FRG, Bloss W.H. and Pfisterer F. (Eds), pp 3498-3502, Pergamon Press, New York.

Clarke J.A. et al. (1997). The ESP-r System for Building Energy Simulation, User Guide Version 9 Series, ESRU Manual U97/1, University of Strathclyde, Glasgow.

Braun P.O., Goetzberger A., Schmid J., and Stahl W. (1992). Transparent insulation of building facades - Steps from research to commercial applications. *Solar Energy* 49 (5), 413-427.

Sick F., Kummer J.P. (1992). Simulation of transparently insulated buildings. *Solar Energy* 49 (5), 429-434.

Gorgolewski M. (1996) Transparent insulating materials: Steady-state model for assessing thermal performance. *Proc. CIBSE A: Building Serv. Eng. Res. Technol.* 17 (3) 141-146.