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PARAMETRIC STUDY OF THE SUMMER BEHAVIOR IN TIMBER HOUSES – COMPARISON OF WOODEN CONSTRUCTIONS

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Abstract:
The thermal protection of wooden single family houses in summer is topic of a greater research project realized at Holzforschung Austria in Vienna. The following paper depicts investigations on the thermal behavior of external wall elements during summertime. The measurements were performed on a test house in the form of a two-storey detached house (L=10.7m / W=8.7m / H=8.3m) of wood. Measurements for construction behaviour, indoor room climate and venting patterns were carried out in rooms and throughout the whole building during the first two years of investigation. The aim of this part are measurement results whereby simulation tools for the prediction of heat protection in summer can be improved. To obtain reproducible results, the house was aligned into geographical orientation and possible thermal interactions between the individual wall elements, avoided by separation. The surface temperatures were measured in the component layers in order to better evaluate thermal factors (facade colour, insulation, construction method, internal cladding). By comparing temperatures, influencing factors could be categorised which will be the basis for further simulations. Further investigations on this subject should be related to Phase Change Material (PCM) in components.

Key words: *Summer; Constructions; external wall temperature; Comparison.*

INTRODUCTION

Construction method, shading and venting systems can be influencing factors on heat protection in summer. In the past the topic of heat protection in summer was an issue only covering the calculation of the energy storage capacity in the standards of proof (e.g. austrian standard; ÖNORM B 8110-3:1999, ÖNORM B 8110-3/AC1:2001). The calculation method is limited on a verification of thermal mass from a building. With this method lightweight constructions (e.g. wooden constructions) need to become heavier or heat sources (e.g. windows) need to be reduced. The topic of shading and (night-)ventilation was considered to be subordinated. As part of a research project of Holzforschung Austria investigations for summer heat protection are carried out amongst others on a 1:1 test building. The investigations are divided into several areas such as component behaviour, single room interior climate and building interior climate. In this study the component behaviour of various wooden wall constructions over a period of two half-years (April – September 2011 and April – September 2012) are presented (version 1 & 2).

Fig. 1
Full-scale-test building, Holzforschung Austria.

STATE OF THE ART

In the past several studies on “summer heat protection” on components have been conducted (Joščák and Niemz 2008, Lindberg *et al*. 2004, Rossi and Rocco 2012). Most of them (Handler *et al*. 2011, Hauser *et al*. 2011, Kendrick *et al*. 2012, Larsen *et al*. 2009, Lindberg *et al*. 2012, Manioglu and Zerrin 2008) dealt with mineral constructions (e.g. brick walls). Some papers (Alterman *et al*. 2012, Handler *et al*. 2011, Heathcote 2008, Lindberg *et al*. 2012, Porritt *et al*. 2012, Tablada *et al*. 2009) deal with the calculation of the temperature behaviour in summerlike ambient conditions

(Alterman *et al*. 2012) describes the dynamic determination of a value indicative of the internal temperature behaviour of a component in response to ambient conditions in his work. (Handler *et al*. 2011) compares measurement and simulation of a mineral office building with and without composite heat insulation system focusing on summer behaviour. In (Hauser *et al*. 2011), the effect of floor heating coupled with foundation slab cooling during summer is investigated in an inhabited house. Using a simple procedure, (Heathcote 2008) calculated the summer behaviour (e.g. peak-temperature, phase shift) of brick-houses in Australia. (Kendrick *et al.* 2012) compares various classical mineral exterior wall constructions of UK houses. Future climatic conditions are also included in the investigation. (Larsen *et al*. 2009) simulates the summer behaviour of mineral solid external walls in terms of energy savings and comfort climate. In a long-term study (Lindberg *et al*. 2012) investigates on the analogy of (Lindberg *et al*. 2004) the construction manner of brick walls. Furthermore, comparative FEM-simulations in terms of heat energy loss were conducted. (Manioglu and Zerrin 2008) show the importance of thermal mass storage based on classical Turkish architecture. (Porritt *et al*. 2012) studied the behaviour of UK-houses based on simulations during heat waves in summer. The behaviour of different types of houses in warm summer climate is investigated by (Tablada *et al*. 2009) means of measurements and simulations.

The next papers deal with measurements and calculations based on research about wooden constructions in summer climates.

(Joščák and Niemz 2008) conducted investigations on wooden construction elements. Three boxes constructed by different methods (timber frame, solid wood, modified timber frame) with a single pitch roof and a side length of 1.5m will be observed in the outdoor climate during a year. On these objects the annual climate is examined and the appropriate conclusions are drawn. Simultaneously, the measurements will be compared with DELPHIN-simulations. The final outcome of the work was the time of phase changing of the constructions, the exceeding duration of room temperature and also the relative humidity in the room.

The construction behaviour of external walls (Lindberg *et al.* 2004) is conducted in a long term study with focus on summer. The focus of the investigation is on the summer behaviour of the components. The reaction on temperature influence of various different materials is investigated in different small test buildings without windows which are situated in an inner yard protected from the weather.

Using simulation-software tools (Rossi and Rocco 2012) compare selected characteristics of the thermal storage capacity with the energy performance during summer in constructions made of brick and wood. The investigations that aim to optimize the constructions for summer were conducted in southern climates in different geographical locations.

In the present work the summer behaviour of a real and for this region typical house should be simulated under real boundary conditions (window opening, venting pattern, user behaviour etc.). Comparison between simulation and measurement results should enable to provide defined boundary conditions (e.g. user behaviour). Based on the variation of some materials and construction a large number of wall elements can show building material reaction on the hand of comparative measurements and simulations. In accordance with thermal conductivity λ, specific heat capacity c and density ρ the material parameter phase changing in summer is calculated for several layers or whole constructions with help of periodic penetration depth d_p (1) (Riccabona and Bednar 2010). A further parameter that helps to compare different construction methods is the areal heat capacity κ_m (2) (ÖNORM EN ISO 13786:2008).

$$d_p = \sqrt{\frac{T \cdot \lambda}{C \cdot \rho \cdot \pi}} \text{ [m]} \quad (1)$$

T – periodic time, in s;
λ – thermal conductivity, in W/mK;
C – specific heat capacity, in J/kgK;
ρ - density, in kg/m³.

$$\kappa_m = \frac{C_m}{A} = \frac{1}{\omega}\left|Y_{mm} - Y_{mn}\right| \text{ [W/m²K]} \quad (2)$$

C_m – heat capacity, in J/K;
A – Area, in m²;
ω – angular frequency, in rad/s;
Y_{mm} – thermal admittance, in W/m²K;
Y_{mn} – periodic thermal admittance, in W/m²K.

EXPERIMENTAL INVESTIGATIONS

Measurements

Testing material

The investigations on the thermal behaviour of components are carried out on experimental wall elements in a research house under real life conditions. (see Fig. 1) To see the different influences on the construction elements a measurement program for the investigation period (April – September) that depends on shading and venting helps to reach real environment conditions. The composition and structure of the individual wall elements was carried out by combining the materials to be examined and methods of construction.

Comparison of materials and construction methods:

- Construction method (timber frame – X-lam – concrete - brick)
- Insulation (stone wool – cellulose)
- External surface (Plaster, Colour)
- Internal cladding (single layer – double layer)

In the course of preparation procedure the element setting will expand on different U-Values to study the impact of insulation in summer. Out of these four comparison elements various combinations were formed which can be divided into four parts. Area 1 contains all elements on ground floor level facing north and south. On these elements insulation, construction method and facade colour were observed. The elements of area 2 on the east side on the ground floor have been studied regarding the influence of inner cladding. All used materials are specified in the first table (Table 1).

The solar absorption coefficient for the plaster amounts to 0.24 for white colour and 0.83 for the brown one. The selection of the colours stands for bright and dark plaster surfaces. The following tables (Table 2, Table 3) comprise the test walls matching the described areas. To notice the point of observation, the investigation period of Summer 2011 and 2012 is allocate in Version 1 and 2.

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Table 1

Material parameters: Detailed specification of the used Materials

Material	ρ [kg/m³]	C [J/kg,K]	λ [W/m,K]
Synthetic resin plaster (white)	1600	1000	0.80
Insulation by cork	200	1560	0.05
MDF	600	2100	0.10
OSB	680	1700	0.13
Gypsum plaster board	900	1050	0.21
Modified gypsum plaster board	1450	1100	0.26
Magnesia bounded wood wool board	450	1800	0.10
Cement bounded board	1150	1100	0.35
X-Lam-element	450	1600	0.13
Insulation by cork	200	1560	0.05
Stone wool	35	1000	0.039
Cellulose (injected insulation)	~50	1800	0.039
Cellulose (insulation batt)	70	2000	0.041
Air (20°C, 5cm vertical layer)	1.2	1000	0.277

Table 2

Timber Frame Construction: overview in Version 1 & 2

No.	Layer	Material/Properties	d [mm]	Reference
1	Synthetic resin plaster	Dark	5	Fig. 3, Fig. 7
		Bright		***Fig. 3, Fig. 4,Fig. 5,*** Fig. 6, Fig. 7
2	Plaster lath	Insulation by cork	50	***Fig. 3, Fig. 4,Fig. 5, ,*** Fig. 6, Fig. 7 (Version 1)
		Cement bounded board	12.5	Fig. 3, Fig. 7 (Version 2)
3	MDF		13	***Fig. 3, Fig. 4,Fig. 5,*** Fig. 6, Fig. 7 (Version 1)
4	Insulation	Stone Wool	100	***Fig. 5,*** Fig. 6, Fig. 7
			200	Fig. 3, Fig. 4, Fig. 5, Fig. 6
		Cellulose (injected insulation)		Fig. 3, Fig. 4
5	OSB		15	***Fig. 3, Fig. 4,Fig. 5,*** Fig. 6, Fig. 7
6	Installation layer	Empty (Air)	50	***Fig. 3, Fig. 5,*** Fig. 6, Fig. 7
		Stone Wool	100	Fig. 3, Fig. 4, Fig. 5, Fig. 6
		Cellulose (insulation batt)		Fig. 3, Fig. 4
7	Internal cladding	1 Gypsum plaster board (GPB)	12.5	***Fig. 3, Fig. 4,Fig. 5,*** Fig. 6, Fig. 7
		2 Gypsum plaster board (GPB)	25	***Version 1 - Fig. 3, Fig. 5, Fig.6***
		1 GPB + 1 modified gypsum plaster board	25	Version 2 - Fig. 3, Fig. 5
		1 GPB + 1 magnesia bounded wooden wool	62.5	***Version 2 - Fig. 3, Fig. 5, Fig. 6***

Table 3

X-Lam Construction: overview in Version 1 & 2

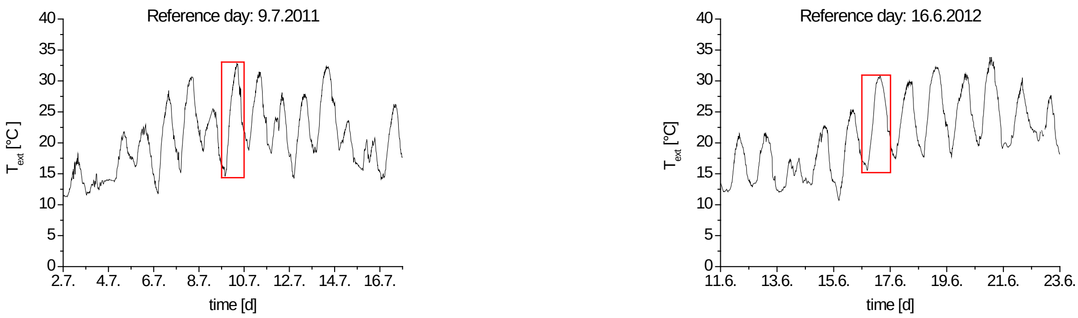
No.	Layer	Material/Properties	d [mm]	Reference
1	Synthetic resin plaster	Dark	5	Fig. 3, Fig. 7
		Bright		***Fig. 3, Fig. 4,Fig. 5,*** Fig. 6, Fig. 7
2	Plaster lath	Insulation by cork	50	Fig. 3, Fig. 4,Fig. 5, Fig. 7
3	MDF		13	***Fig. 3, Fig. 4,Fig. 5, ,*** Fig. 6, Fig. 7
4	Insulation	Stone Wool	80	***Fig. 3, Fig. 5,*** Fig. 6, Fig. 7
			260	Fig. 3, Fig. 4, Fig. 5, Fig. 6
		Cellulose (injected insulation)	260	Fig. 3, Fig. 4
5	OSB		15	***Fig. 3, Fig. 4,Fig. 5,*** Fig. 6, Fig. 7
6	X-Lam-Element		94	***Fig. 3, Fig. 4,Fig. 5,*** Fig. 6, Fig. 7
7	Internal cladding	1 Gypsum plaster board (GPB)	12.5	***Fig. 3, Fig. 4,Fig. 5,*** Fig. 6, Fig. 7
		2 Gypsum plaster board (GPB	25	Version 1-Fig. 3, Fig. 5, Fig. 6
		1 GPB + 1 modified gypsum plaster board	25	Version 2 - Fig. 3, Fig. 5
		1 GPB + 1 magnesia bounded wooden wool	62.5	Version 2-Fig. 3, Fig. 5, Fig. 6

Measurement technique

With NTC-sensors that have small sensor elements and a short response time, the surface temperature in relevant layers is measured to receive a good thermal distribution about the constructions. The metrological conditions (e.g. temperature, humidity, solar radiation etc.) are captured with a weather station on the roof of the company building. The measurement data collected in measurement intervals of 1min is transformed into 10min averages.

Analysis

The analysis of the present work is limited to the evaluation of indoor surface temperatures. A real view on different wall elements and their properties is given by differences between the minimum and maximum of surface temperature $\Delta T_{S,i}$. For evaluation of thermal storage effects, the areal heat capacity κ_m is calculated based on thermal conductivity λ, specific heat capacity c and bulk density ρ. This parameter helps to evaluate the thermal behaviour of the wall element layers. To keep track of all data two representative days (transition time, high summer) are selected (see Fig. 2). For the comparability of values of two reference days in different years the selection process regards similar outdoor temperatures, the average of this and the global solar radiation.

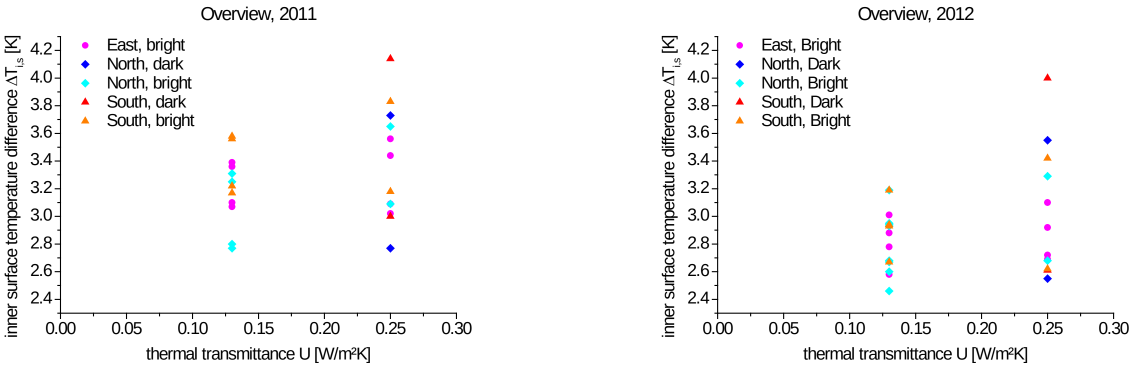


Version 1 **Version 2**

Fig. 2
Reference high summer day – diagram of choosing method.

RESULTS

The following charts present the comparison of inner surface temperature differences at the "high summer"-reference day. The aspect of geographical orientation is included at the charts "construction method", "insulation" and "external facade".



Version 1 **Version 2**

Fig. 3
Comparison of inner surface temperature difference and thermal transmittance – all elements.

The difference at inner surface temperature difference based on thermal transmittance (U-Value) is depicted in Fig. 3. The different geographical orientations are marked by different geometrical forms and different colour groups. Magenta circles mean east oriented elements. North side elements are shown by blue coloured diamonds. Red coloured triangles mean elements on south side. The bright and dark colours in diagram indicate elements with bright and dark facade colours. The two categories represent the different U-Value. On the left side, elements with U=0.13W/m²K are shown. Elements with U=0.25W/m²K are part of the right column.

Two regularities can be observed in the Figure. The group of points on the left side stand closer together than on the right side. The distances between some marks in the right column are higher than in same category on the left side (e.g. north dark, south dark).

In summary, a good thermal insulation (U=0.13W/m²K) helps to decrease the inner surface temperature difference and reduce influences from outside. Another impact is smaller reactions on smooth changes in construction methods or insulation materials. The differences caused by geographical orientation can be observed in all wall elements.

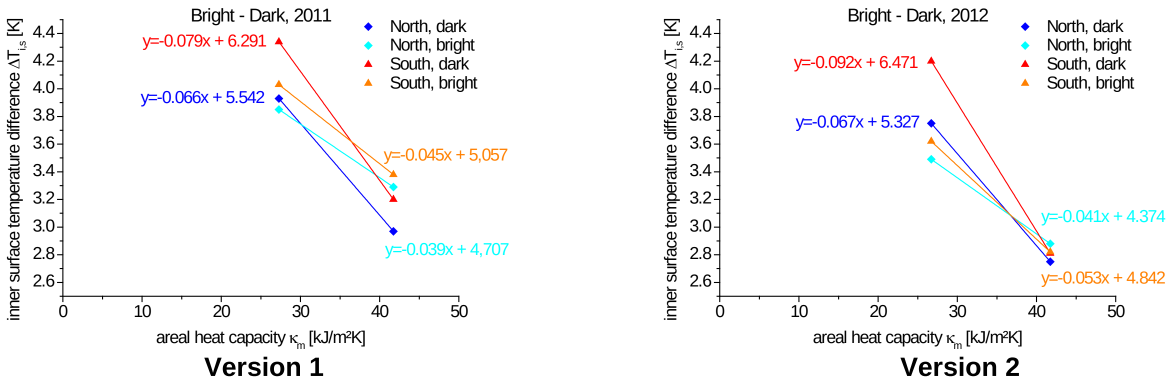


Fig. 4
Comparison of inner surface temperature difference and areal heat capacity – facade colour

In Fig. 4 the differences at faced colours based on the inner surface temperature difference and areal heat capacity is shown. The different geographical orientations are marked by different geometrical forms and different colour groups. Blue coloured diamonds represents north faced elements. Red coloured triangles mean south oriented elements. Bright and dark colours indicate the brightness of facade colour.

The inner surface temperature differences at facade colour are the highest on all evaluated parameters. The effect of geographical orientation is shown by distance of curves between north- and south orientation. The different inner surface temperature differences at one value of areal heat capacity illustrate the need to consider the solar absorption coefficient at calculations.

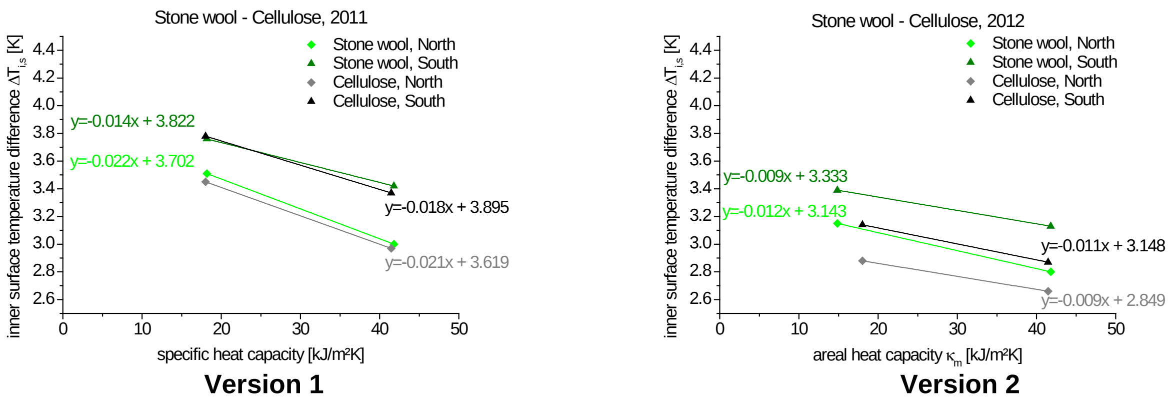


Fig. 5
Comparison of inner surface temperature difference and areal heat capacity – insulation

The differences between insulation materials (stone wool, cellulose) are displayed in Fig. 5 on the basis of inner surface temperature difference and effective site specific heat capacity. The bright coloured diamonds show north oriented constructions. The dark triangles symbolize south sided constructions. The green colours indicate stone wool insulation in the core. The black colours represent a core insulation of injected cellulose. (Another interesting detail that can be observed is the application of cellulose batts in the installation layer of respective timber frame elements in Version 1). (The inner surface temperature difference and the areal heat capacity at timber frame elements in Version 1 are equal at north sided and nearly equal at south sided element.)

The distance between north - and south sided elements underlines the dependence of material properties by geographical orientation. The parallelism of all curves in version 1 and 2 shows a good correlation, especially in version 2, between areal heat capacity and inner surface temperature difference at different materials. In short, the material parameters of insulation, pictured in areal heat capacity, directly have an impact on the inner surface temperature behaviour of construction.

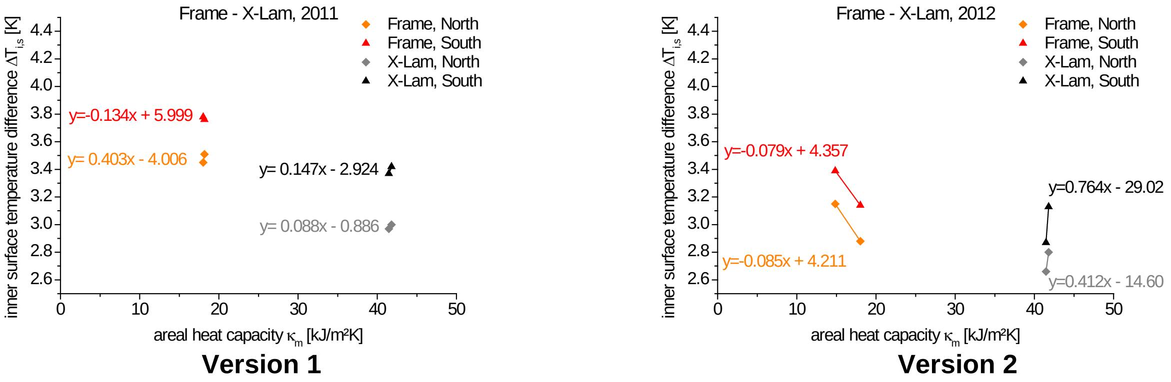


Fig. 6

Comparison of inner surface temperature difference and areal heat capacity – construction method

In Fig.6 the differences of construction methods (timber frame, X-Lam) are depicted, by means of the inner surface temperature differences and the effective site-specific heat capacity. Bright coloured diamonds indicates on north side aligned elements. Dark triangles point at south sided elements. Red colours mean timber frame constructions. The black colours stand for X-Lam elements. In Version 1 at timber frame elements, there is no difference between the specific heat capacity, caused by cellulose batts in installation layer with unequal core insulation. In Version 2 the insulation in the installation layer and the core is equal. In Version 2 the dependence of the construction at timber frame elements is visible on the hand of red coloured parallel line. A lower interaction between construction method and insulation is shown in Version 2 on the hand of the nearly parallel black coloured lines. At X-Lam elements in Version 1, the same correlation is visible.

In summary, there is a connection between insulation and construction method. Constructions with higher density construction have a lower dependence from the interaction between inner surface temperature difference and areal heat capacity and in general a lower indoor temperature. The geographical orientation is a relevant factor. The density of available installation layer insulation has an impact on construction method.

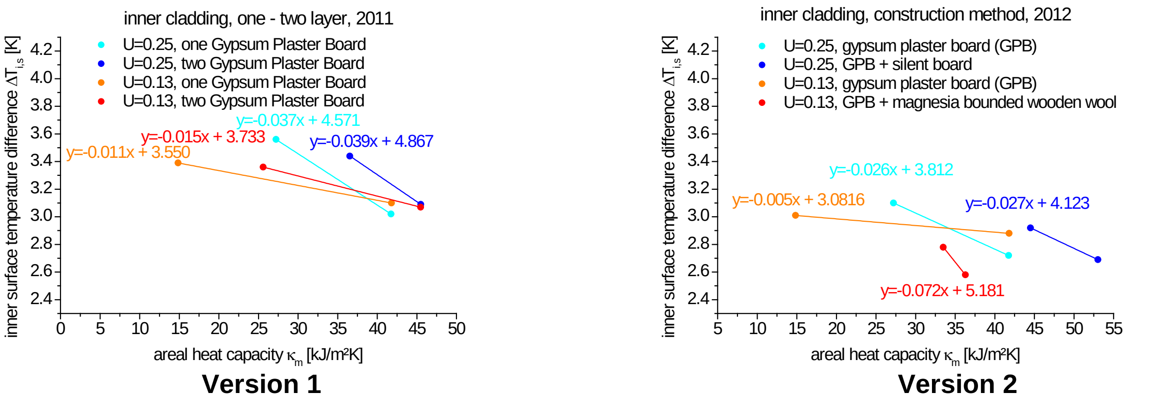


Fig. 7

Comparison of inner surface temperature difference and areal heat capacity – internal cladding

At the last comparison of inner surface temperature difference and areal heat capacity, the effect of internal cladding is shown in Fig. 7. Bright colours indicate single layer internal cladding. Dark colours stand for double layer internal cladding. Blue colours stand for constructions with low insulation (U=0.25W/m²K). Red colours indicate constructions with high thermal insulation (U=0.13W/m²K). For the evaluation process of inner cladding systems some systems were designed. In Version 1 the compared systems consists of single and double layer constructions, cladded with gypsum plaster boards. In Version 2 the test configuration was built from one layer gypsum plaster board and the second layer with modified gypsum plaster boards (Silent Board) or magnesia bounded wooden wool (BM-W).

The figures show a strong correlation at systems with low insulation (U=0.25W/m²K) between inner surface temperature difference and effective heat capacity. That means that lower insulated constructions has greater interaction on internal cladding systems. The smaller correlation at the system with higher level insulation (U=0.13W/m²K) in Version 1 can be explained as small change of material properties caused by second layer of gypsum plaster board in the areal heat capacity.

CONCLUSION

The further table contain an order of relevance of the evaluated parameter results.

Comparison of materials and construction methods:

- External surface (light - dark)
- Insulation (stone wool – cellulose)
- Construction method (timber frame – X-lam)
- Internal cladding (single layer – double layer with different materials)

The parameter "facade colour" especially dark colours acts as a heat source in each geographic orientation and produce the highest inner surface temperature differences of all investigated parameters. Interesting for the use of simulation tools is the fact of different surface temperature differences at same areal heat capacity. This issue can produce an error of results, if the solar absorption coefficient is neglected.

The parameter "insulation" depends heavily on the material values density, specific heat capacity and heat conductivity and depends on geographical orientation. In the categorization of wall parameters with inner surface temperature difference, the parameter of insulation becomes the second position. In the investigation the used insulation material have different bulk density and other material parameters. The displayed results correlated well between inner surface temperature difference and areal heat capacity. That shows an interaction between insulation and inner surface temperature with all tested insulation types.

The parameter "construction method" also depends on the material parameter of core insulation. Solid constructions with high density insulation material have lower inner surface temperature and temperature differences between it than low density insulation material. The impact of geographical orientation on light weight constructions is more visible than the effect of surface temperature. The difference between version 1 and version 2 of the insulating material in respect of the installation layer is negligible.

The parameter "internal cladding" depends on the storage behaviour of cladding material. The comparison of material properties from the second layer in double layer system is investigated in Version 1 & 2. Systems with smaller insulation (U=0.25W/m²K) have a higher correlation between inner surface temperature difference and areal heat capacity. The impact of internal cladding as a heat storage is higher than higher insulated wall constructions. The effect of internal cladding at systems with higher insulation (U=0.13W/m²K) is lower because the temperature influence of outside conditions is lower. The use of magnesia bounded wood wool boards in second layer at Version 2 show effects of insulation and storage reaction.

A further summary of the measured results is the evaluation of the temperature differences by reference of thermal transmittance (U-Value). High thermal insulated constructions (U=0.13W/m²K) have lower inner surface temperatures. Small changes in well insulated constructions, will take small changes in temperature distribution of these constructions. Small insulated elements (U=0.25W/m²K) have a higher impact of all described parameters in the sequence above. All parameters depend from geographical orientation.

The influence of incoming heat e.g. through windows can be observed and makes it necessary to deal with the issues of shading and window geometry. In general the heat introduction through windows is higher than through opaque walls. Further investigations in the research project are performed with Phase Change Materials (PCM) and the Comparison of simulation methods and experimental Investigations.

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REFERENCES

Alterman D, Moffiet T, Hands S, Page A, Luo C, Moghtaderi B (2012) A concept for a potential metric to characterise the dynamic thermal performance of walls. In: Energy and Buildings 54:52–60

Handler S, Korjenic A, Bednar T (2011) Einfluss von Wärmedämmverbundsystemen auf das Sommerverhalten von Gebäuden. In: Bauphysik 33(4):225–233

Harreither C (2009) Vergleich verschiedener Berechnungsverfahren zur Ermittlung der sommerlichen Überwärmung von Wohnbauten unter Berücksichtigung von Lüftungsanlagen. Diplomarbeit. TU Wien, Wien

Hauser G, Lindauer E, Nimtsch A, Sinnesbichler H (2011) Kühlwirkung einer an die Sohlplatte gekoppelten Fußbodenheizung - demonstriert an einem bewohnten Einfamilienhaus. In: Bauphysik 33(2):94–98

Heathcote K (2008) Comparison of the Summer Thermal Performance of Three Test Buildings with that Predicted by the Admittance Procedure. In: Architectural Science Review 51(1):31–38

Joščák M, Niemz P (2008) Vergleichende Untersuchungen zum optimierten Wärmeschutz in unterschiedlichen Holzbausystemen. Forschungsprojekt Nr. 2-71114-07. Unter Mitarbeit von Fritz Bächle, Walter Sonderegger und Rudolph Plagge. ETH Zürich, Institut für Baustoffe

Kendrick C, Ogden R, Wang X, Baiche B (2012) Thermal mass in new build UK housing: A comparison of structural systems in a future weather scenario. In: Energy and Buildings 48:40–49

Larsen SF, Filippín C, Lesino G (2009) Thermal behavior of building walls in summer: Comparison of available analytical methods and experimental results for a case study. In: Build. Simul 2(1):3–18

Lindberg RW, Rantala JV, Leivo VM, Kiviste M (2012) Effect of massive outer leaf of an insulated cavity brick wall on heat loss. In: Journal of Building Physics 36(2):198–211

Lindberg R, Binamu A, Teikari M (2004) Five-year data of measured weather, energy consumption, and time-dependent temperature variations within different exterior wall structures. In: Energy and Buildings 36(6):495–501

Manioglu G, Zerrin Y (2008) A Comparative Evaluation of the Importance of Thermal Mass of Traditional Architecture in Hot and Dry Region in Turkey. Istanbul Technical University. Istanbul

Porritt SM, Cropper PC, Shao L, Goodier CI (2012) Ranking of interventions to reduce dwelling overheating during heat waves. In: Energy and Buildings 55:16–27

Riccabona C, Bednar T (2010) Baukonstruktionslehre 4. Bauphysik. Lehrbuch. Unter Mitarbeit von Christoph Deseyve, Tanja Höfer, Michael Jung, Hannes Konder, Dieter Marhold und Mario Sofic. 8. Aufl. Wien: Manz (Baukonstruktionen, 4)

Rossi M, Rocco VM (2012) External walls design: The role of periodic thermal transmittance and internal areal heat capacity. In: Energy and Buildings

ÖNORM B 8110-3:1999, 01.12.1999: Wärmeschutz im Hochbau: Wärmespeicherung und Sonneneinflüsse; ÖNORM B 8110-3:1999

ÖNORM B 8110-3/AC1:2001, 01.06.2001: Wärmeschutz im Hochbau: Wärmespeicherung und Sonneneinflüsse [Berichtigung]; ÖNORM B 8110-3/AC1:2001

ÖNORM EN ISO 13786, 01.04.2008: Wärmetechnisches Verhalten von Bauteilen - Dynamisch-thermische Kenngrößen – Berechnungsverfahren; ÖNORM EN ISO 13786:2008

Tablada A, Troyer F, Blocken B, Carmeliet J, Verschure H (2009) On natural ventilation and thermal comfort in compact urban environments – the Old Havana case. In: Building and Environment 44(9):1943–1958.