ENERGY SAVING AND THE HYGROTHERMAL PERFORMANCE OF ENVELOPE PARTS OF BUILDINGS

Stopp H. ; Strangfeld P.; Mendes N.*

University of Applied Sciences
FH-Lausitz / FB ABV /PF 130233
D 03025 Cottbus/Germany
hstopp@bi.fh-lausitz.de, pstrangf@bi.fh-lausitz.de

*Pontifícia Universidade Católica do Paraná – PUCPR
Laboratórios de Sistemas Térmicos
Rua Imaculada Conceição, 1155 – Prado Velho
Curitiba – PR, 80.215 - 901 – Brasil

ABSTRACT

Without saying the energy saving - a worldwide goal- must be involved also to the building aspects. In the fields of heating-, cooling- and ventilation energy losses there is a large potential of energy saving. That is why the European Parliament and the Council have published a directive on energy performance of buildings including the building stock. The German ordinance prescribes permissible values of the primary energy considering the production, distribution and handing over of the heating energy. The reduction of energy losses should be reached without provoking damage by heat and moisture transfer within the building's envelope. Above all things the hygrothermal situation of the envelope parts must be observed. By means of a correct modeling of the coupled heat and mass transfer of porous materials a simulation of the processes is possible and the experimental work reduces at a minimum by use of computerizing. After the general introduction of the theme, section 2 presents the relevance of the facades of the buildings, while the section 3 describes European directives for saving energy for heating and cooling of buildings. The numerical simulation of the hygrothermal performance of building's envelopes is discussed in section 4. Apart from the modeling of the coupled heat and moisture transfer in capillary porous materials and some references to its development and current situation, this section shows as an application of the calculations the reduction of the cooling load by the evaporation cooling of hygroscopic absorbed moisture in appropriate climate zones. In section 5, the numerical simulation of the coupled heat and moisture transfer is demonstrated with the help of the following current examples: capillary active inside insulation, infrared reflecting coatings, enthalpy losses of inverted roofs, alga growth at the external surfaces of outside walls and drying out of basement masonry walls. Finally section 6 shows the effectiveness control of the measures with regard to the hygrothermal performance of envelope parts by means of a developed lambda-needle probe.

1. INTRODUCTION

Currently in many countries the economical and ecological strategy is characterized by activities concerning the reduction of the consumption of energy and raw materials. Changing climate conditions challenge the mankind to develop political strategies and to implement measures that reduce greenhouse gas emissions. Plans of European member states call for 20% to 40% decrease by 2020. Another key objective, which is linked to the environmental protection, is to make European states less dependent on oil and gas. Current forecasts indicate that without measures this dependency will jump to approximately 70% by 2030. This means - transferred to the fields of building physics - the heating and cooling energy losses and damage caused by unfavourable design and nonqualified workmanship are to be reduced. In this paper the performance of the envelope of buildings under climate boundary conditions of Middle Europe and Brazil are discussed. Nevertheless, the results can be used in a general way.

In order to use alternative energies with a limited density of their power, the transmission and ventilation losses through the envelope of buildings must be decreased during the heating or cooling period. Due to the low emission of glasses the production of modern windows is possible with a U-value less than 1,0 W/m^2-K. As a result of this, the opaque area of walls is to consider again.

In the face of the low turn-over rate of buildings with a lifetime from 50 to more than 100 years, it is clear that the existing stock of buildings contains the largest potential for improving energy performance in short and medium periods of time. About 41% of the total final energy demand of Europe is used in the residential and tertiary sectors. Space heating is by far the largest energy end-use of households in EU Member States, namely 57%. Therefore a directive of the European Parliament and of the Council on the energy performance of buildings [1] covers four main elements:

- Establishment of a general framework of a common methodology for calculating the integrated energy performance of buildings.

- Application of minimum standards on the energy performance to new buildings and certain existing buildings when they are renovated.

- Certification schemes for new and existing buildings on the basis of the above standards and public display of energy performance certificates and recommended indoor temperatures and other relevant climatic factors in public buildings and buildings frequented by the public.

- Specific inspection and assessment of boilers and heating and cooling installations.

About 32% of the current stock of the 150 million residential dwellings in the 15 EU Member States was built prior to 1945, about 40 % between 1945 and 1974 and 28% since 1974. An upgrade of thermal insulation regulations and improved efficiency for installed equipment for existing dwellings, bringing them close to current buildings codes, would help to realize an important saving potential, making it a very desirable and in most cases a cost-effective option.

A comparison of thermal building regulations in the European Union shows that there exist rather extreme differences even after they have been made comparable by correcting climatic differences. The comparison is made by using the model building regulation of Denmark and applying it to the other states after climatic correction. Consumption as measured by the application of this model building code is in most cases dramatically lower than with existing national thermal insulation codes.

The following sections represent methods and possibilities of energy savings owing to an improved building envelope. Moreover, the hygrothermal performance of envelope parts is discussed by means of numerical simulations and by measurements of the coupled heat and moisture transfer.

2. SIGNIFICANCE OF FACADES

The significance of building facades should be discussed in a comprehensive context. The subject is not only to deal with regard to the energy losses and gains and concerning the protection against the outdoor climate components but also with regard to the culture and the behavior of people. The last one is not to underestimate; it is a process that takes place daily by the influence of the pictures of architecture.

An original facade of old and historical buildings is a question of aesthetics. It is a matter of human behavior in general. We have to hand over the won goods from generation to generation. The tradition is a basic of mankind and the traditional architecture gives an identification with the own immediate environments and induces a social behavior – a problem worldwide. So the awareness for preservation of old buildings and sight facades is growing. But only by lastening use the buildings with historical facades are to preserve. This is guilty for residential houses, factories and castles too.

At the present, the situation of East Germany and Eastern Europe is complicated. On the one hand, many old buildings and worth preserving facades exist in this countries. On the other hand, the unemployment is more than 30 % in some districts and up to now the migration to the western countries is not closed. To stop the last one and in order to form foreign new structures we need an identification with the original environment. A retrofitting is to be done in a large extent. A lot of building ensembles are to improve concerning its heating energy losses. In order to fulfill the demands for energy reduction in all the improvement is to realize without exception concerning its thermal insulation level. This fact call for the installation of an inside insulation system in case of the worth preserving facades.

Besides there are facades of a new kind including new materials. Moreover the inhabitants expect the thermal comfort and inside climate conditions on a higher level than in former time. For instance in the past the wood of frame work houses were protected by a sufficient ventilation between the gaps of their envelope parts. Nowadays the consumption of water, the higher indoor temperature and the reduction of ventilation heat losses cause another indoor climate concerning hygrothermal stresses to the envelope parts. Due to this situation, many architects are unsure with regard to the thickness of insulation layer, the arrangement of the vapor retarder and other details of the inside insulation. Basing on this uncertainness and missing knowledges the result of administration's decisions are uninsulated retrofitted preserving facades. In connection with the decreased U-value of built-in glasses and windows and a better air-tightness, the fungus and mould are growing not only on surfaces of deficiencies in thermal protection.

Without saying the interior insulation is a risky method, but in connection with the retrofitting of worth preserving facades, the question does not read "if" but "how" is to improve the thermal insulation from the building physics point of view.

In order to save facades of existing buildings and to provide the practise with convenient solutions we have developed a progressive method of the inside insulation represented in section 5.2.

3. EUROPEAN ENERGY SAVING DIRECTIVES

The European climate change program aims at the realization of the large potential of energy consumption reduction in European building sector by introducting possible measures and inducing international and national activities. The draft of the directive of the European Parliament and of the Council on energy performance of buildings was published in May 2001, commented and decided by the institutions in February and October 2002. Now the article 1 of this directive lays down requirements as regards the application of minimum standards on the energy performance of new buildings and of large existing buildings that are subject to major renovation [2]. It should be recognized, that the largest potential for energy saving is in the renovation of the building stock.

Member states shall require for public buildings an energy performance certificate to be placed in a prominent place clearly visible to the general public.

3.1 European Standard EN 832

The standard EN 832 „Thermal performance of buildings" [3] represents the attempt to develop a cross-national method for calculation and thus a comparison of the building energy performance quality. It describes a steady state method for the calculation of energy use for heating, taking into account internal and external temperature variations and the dynamic effect of internal and solar gains. Moreover in the algorithm of this standard, the effectiveness of the heating system, the hot water preparation and the recovered heat are considered. It provides also the user with standardized input values or methods to obtain the necessary data, when the required information is not available from the national or European standards.

The method of the standard EN832 bases on the following balance equation:

$$Q = Q_h + Q_w + Q_t - Q_r, \quad \text{[Eq. 01]}$$

where:

Q: heating energy requirements;

Q_h, Q_w : heat requirements for room and hot water;

Q_t: heat losses of the total system for generation of space heat and hot water including the electrical supply for e.g. pumps and ventilation;

Q_r: renewable energy.

Some European Members States already has incorporated or are about to implement the EN 832 into their legal system. As the standard EN 832 represents a calculation method only, the criterion concerning the building energy performance is left to the decision of each member state.

3.2 German Ordinance of Saving Energy

Germany has done a step further [4]. Due to the different economical expenditure for heating by oil, gas, electricity or renewable energies a primary energy transformation number f_p is defined and by means of a so-called expense number e_p (reciprocal of efficiency), the primary energy is calculated by the equation

$$Q_p = e_p \cdot (Q_h + Q_w) \qquad \text{[Eq. 02]}$$

Besides the costs for generation of energies the number e_p and the primary energy respectively comprises also the transportation from the sources to the buildings and the losses of generation, distribution and transformation for the space heating and hot water within the buildings.

The annual heat requirements Q_h consist of transmission and ventilation heat requirements caused by heat losses through walls, windows, ceilings and roofs. In calculating the annual heat requirements, the internal gains (from lighting and technical equipment of households or offices) and solar heat gains (from solar energy collected by windows and unheated sunspaces adjacent to heated space) are taken into account.

3.2.1 New Buildings

By contrast with the past there is an adoption to an integrated and holistic consideration of new buildings that includes the service installations, also to achieve the savings target in a flexible and cost effective manner.

For a project of new buildings, it is reasonably easy to fulfill the requirements by above all use of new materials and progressive design. Also there is the possibility of compensation measures between thermal insulation and heating equipment.

Monthly balance method as the standard method of calculation and a simplified statement procedure (heating period balance) for residential buildings is available. The detailed application of all influential factors ensures optimum energy and economical planning and construction execution.

The administration laid down permissible limits of the primary energy for buildings related to the user area depending on the ratio of the building’s envelope to its encircled volume. So it’s possible to assign for each building a proper energy requirement basing on the standard similar at the level of a low–energy house. Hence, actual consumption can be considerably reduced. This is, of course, contingent upon the habits of the user, primarily upon the user’s ventilation need.

Moreover the main requirements are the consideration of thermal bridges, the different airtightness and ventilation concepts and the summer insulation. Heat bridges can be incorporated into planning more precisely than they have been in the past (individual proof that bridges exist earns bonuses). Summer insulation is taken into account by applying maximum acceptable sun impact values. This measure ensures that for the residential sector no additional cooling is required during the summer period.

3.2.2 Retrofitted Buildings

The energy saving directive features the recording of building stock as a new element in a stricter way. The directive provides for more stringent energy-related requirements in case of major modifications of building components, which are renewed, replaced or installed for the first time, such as new stucco, windows, finalization of timber frames and slanted and flat roofs. Also the retirement of particularly old heating equipment (installed prior to 1975) is prescribed mandatory. Insulations of uppermost floors in buildings (if they can be installed) and pipes for heat distribution and hot water are to be installed by the end of 2005.

In case of worth preserving facades there is a conflict. On the one hand, the use of a thermal insulation composite system or another outside insulation is not possible and, on the other hand, owing to the requirements of the directive and to the demand for a comfortable room-climate, the temperature of the inside wall surface should be increased. An inside insulation may be an alternative if the hygrothermic and acoustic behavior is considered. A good solution is the so-called capillary-active inside insulation, as described in section 5.2.

4. COUPLED HEAT AND MOISTURE TRANSFER SIMULATION

In building energy and moisture analyses, calculated heat conduction through walls usually neglects the storage and transport of moisture in the porous structure of the walls. However, walls are normally submitted to both thermal and moisture gradients so that an accurate heat transfer determination requires a simultaneous calculation of both sensible and latent effects. Besides its effect on heat transfer, moisture has other implications, especially in humid climates. It is well known that moisture can cause damage to the building structure and can promote the growth of mold and mildew, affecting the health of building occupants. In the last two decades, many researchers have developed models for moisture transport in porous materials. Cunningham [5] developed a mathematical model for hygroscopic materials in flat structures that uses an electrical analogy with resistances for the vapor flow and an exponential approximation function with constant mass transport coefficients. Kerestecioglu and Gu [6] investigated the phenomenon using evaporation-condensation theory in the pendular state (unsaturated liquid flow stage). The application of this theory is limited to low moisture content. Burch and Thomas [7] developed a computer program, MOIST, using the finite-difference method to estimate the heat and mass transfer through composite walls under non-isothermal conditions. El Diasty et alli [8] used an analytical approach that assumed isothermal conditions and constant transport coefficients. Liesen [9] used evaporation-condensation theory and a response factor method to develop and implement a model of heat and mass transfers in the building thermal simulation program IBLAST (Integrated Building Loads Analysis and System Thermodynamics). Hygrothermal property variations were neglected and liquid transfer was not considered. In this way, IBLAST is restricted to very low moisture content, although requiring short calculation time. Yik et alli [10] developed a fast model integrated with air-conditioning system component models that employs evaporation-condensation theory with differential permeability. In fact, above described models originated many simulation programs to predict the heat and moisture transfer through porous building walls, but using calculation methods that are conditionally stable.

Bueno [11] studied the heat and mass transfer phenomena through roofs and concluded that condensation (or rain) on the roof at night followed by evaporation in the morning may be very important to reach naturally comfort conditions in hot and humid climates. However, yearly simulations were not executed since he had to use a 0.1s time step due numerical divergence problems. Mendes et al. [12-13] observed with their simulations that moisture effects are really significant on thermal loads calculation, specially when the air conditioner is turned on in the early morning, the latent heat flux rises substantially due the low relative humidity of the room air imposed by the machine.

As the present article is focused on the hygrothermal performance of building envelopes rather than on heat and mass transfer model itself, a complete discussion about mathematical models was avoided. Actually, all those models have nearly the same origin (heat and mass balance equations, Philip and De Vries or Luikov models and the laws of Fourier, Fick and Darcy). The main difference among them are related to the particular assumptions used. In IEA Annex 24 [14], 5 models are commented in detail:

1D-HAM, WUFIZ, MATCH, HYGRAN24, JOKE and LATENITE. In general, these codes do not have an algorithm with a robust solver to calculate simultaneously the temperature and moisture content distributions. Instead, they have stability criteria and time step control devices to reduce numerical convergence problems. In this section, a calculation method is presented, in order to enable yearly simulation of heat and moisture transfer in building porous walls, possible to be performed with reduced processing times, considering arbitrary material properties and boundary conditions. The method was conceived to preserve numerical stability as a result of two new considerations. The first considers the vapor exchanged between the wall surfaces and the air, as a linear function of temperature and moisture content, rather than vapor concentration. The second introduces a generic algorithm to solve, simultaneously, the governing equations. Those considerations are discussed in more details in Mendes et al. [15] and Mendes and Philippi [16].

4.1 Modeling

Heat and moisture transfer models have been considerably improved in the last two decades with the significant progress of computer processors and random access memory. In the 70´s and early eighties most of the codes for heat and moisture transfer prediction were based on simpler methods using constant transport coefficient properties such as the response factor method. However, simple methods may bring false results and in some cases must be avoided, especially when capillary migration should be taken into account.

Starting in the late eighties, in cold countries where high insulation material is needed, the air transport was included in the coupled formulation of heat and moisture through capillary porous materials of building envelopes. Additionally, in the nineties, salt diffusion has also been included in the formulation, but chemical reactions were not yet well explored. However, air and salt transfer may bring several numerical difficulties and also some problems on the the definition of boundary conditions.

Grunewald et al. [17] presented in a very understandable and useful way a mathematical model comprising differential Eqs. (3) and (4), which describe a heat and moisture transport without consideration of salt diffusion and air transfer:

$$\frac{\partial}{\partial x_k}\left[\left\{\lambda+\left(h_v+c_{pv}\cdot T\right)\frac{\delta_L}{\mu}\frac{\partial p_S}{\partial T}\cdot\varphi\right\}\frac{\partial T}{\partial x_k}+\left\{c_w T\rho_w a_w+\left(h_v+c_{pv}T\right)\frac{\delta_L}{\mu}p_S\frac{\partial\varphi}{\partial w}\right\}\frac{\partial w}{\partial x_k}\right]$$
$$=\frac{\partial}{\partial t}\left[\left(\rho_M c_M+\rho_W c_W\right)T+\left(\rho_v c_{pv}+\rho_A c_{pA}\right)\left(w_S-w\right)T+\rho_v h_v\left(w_S-w\right)-\frac{\partial U_{source}}{\partial V}\right]$$

[Eq. 03]

$$\frac{\partial}{\partial x_k}\left[\left(\rho_w a_w+\frac{\delta_L}{\mu}p_S\frac{\partial\varphi}{\partial w}\right)\frac{\partial w}{\partial x_k}+\frac{\delta_L}{\mu}\frac{\partial p_S}{\partial T}\varphi\frac{\partial T}{\partial x_k}\right]$$
$$=\frac{\partial}{\partial t}\left[\rho_V\left(w_S-w\right)+\rho_W w-\frac{\partial m_{source}}{\partial V}\right]$$

[Eq. 04]

where:

w	moisture content	$\delta_L/\mu(w,T)$	vapour transport function
w_s	saturated moisture content	$\lambda(w,T)$	thermal conductivity
T	temperature	$\varphi(w)$	sorption isotherm
p_S	saturated vapour pressure	h_v	heat of phase transformation
$a_w(w,T)$	capillary diffusivity function	x_k	space coordinate

At present the modelling and computerising is used in a comprehensive way at the University of Dresden [18]. Especially the determination of the moisture storage and moisture transport functions is investigated [19].

A well-known heat and moisture model is the Philip and De Vries [20] one, which was developed for soils and is based on temperature and moisture content gradients. As this model is widely used and comprises the water liquid transfer as well, which is important to be considered in Brazil due to the weather and the microstructure of materials utilized in the envelope, we present it, in this section, applying to a porous wall. The sequence is followed by presenting the usual boundary conditions and a robust numerical method to solve the set of governing differential equations.

The equations and the solver are used in the software Umidus so that simulations were carried out by using this program, which has been developed to model coupled heat and moisture transfer within porous building elements avoiding limitations such as low moisture content, high computer run time and low accuracy. Both diffusion and capillary regimes are taken into account that is the transfer of water in the vapor and liquid phases through the material can be analysed for any kind of climate. The model predicts moisture and temperature profiles within multi-layer walls for any time step and calculates heat and mass transfer. Input files containing hourly data provide information on the conditions at the interior and exterior of the wall. A library of material properties is also available. The orientation and tilt of the wall are considered and convection heat transfer coefficients at the exterior of the wall are calculated hourly from wind velocity and direction data. The software allows the simulation of walls, which have paint surfaces. The development and philosophy of Umidus are discussed by Mendes et al. [21].

The governing partial differential equations used in Umidus are given by equations (5) and (6). They were derived from conservation of mass and energy flow in an elemental volume of porous material.

Energy Conservation Equation:

$$\rho_0 c_m(T,\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T,\theta)\frac{\partial T}{\partial x}\right) - L(T)\frac{\partial}{\partial x}(j_v \qquad \text{[Eq. 05]}$$

Mass Conservation Equation

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{j}{\rho_l}\right) \qquad \text{[Eq. 06]}$$

Note that Eq. (5) differs from Fourier's equation for transient heat flow by an added convective transport term (due to moisture diffusion associated with evaporation and condensation of water in the pores of the medium) and by a dependence on the moisture content (so that it is coupled to Eq. 6). The driving forces for heat, liquid and vapor transfer are temperature and moisture gradients.

The vapor flow and total flow (vapor plus liquid) are expressed in terms of transport coefficients, D, associated with the thermal and moisture gradients. According to Philip and DeVries [20], the equations are:

For vapor flow

$$\frac{j_v}{\rho_l} = -D_{Tv}(T,\theta)\frac{\partial T}{\partial x} - D_{\theta v}(T,\theta)\frac{\partial \theta}{\partial x} \qquad \text{[Eq. 07]}$$

For total (vapor plus liquid) flow

$$\frac{j}{\rho_l} = -D_T(T,\theta)\frac{\partial T}{\partial x} - D_\theta(T,\theta)\frac{\partial \theta}{\partial x} \qquad \text{[Eq. 08]}$$

Where:

$D_\theta = D_{\theta l} + D_{\theta v}$;

$D_T = D_{Tl} + D_{Tv}$.

Observe that the model does not take into account the gravity influence on the transfer of liquid water. This effect is very small compared to the capillary effect especially for microporous materials.

Boundary Conditions:

The associated conservation equations at the outside and inside wall surface are as follows. For the outside surface (x=0), it was considered the wall is exposed to short-wave radiation, convection heat and mass transfer, and phase change. Thus, the energy balance becomes

$$-\left(\lambda(T,\theta)\frac{\partial T}{\partial x}\right)_{x=0} - \left(L(T) j_v\right)_{x=0} = h\ (T_\infty - T_{x=0}) + \alpha q_r + L(T) h_m \left(\rho_{v,\infty} - \rho_{v,x=0}\right) \qquad \text{[Eq. 09]}$$

where: $h\ (T_\infty - T_{x=0})$ represents the heat exchanged with the outside air, described by the surface conductance h , $\alpha\, q_r$ is the absorbed short-wave radiation, L, the vaporization latent heat and $h_m\left(\rho_{v,\infty} - \rho_{v,x=0}\right)$, the phase change energy term. The solar absorptivity is defined as α and the mass convection coefficient as h_m, which is related to h by the Lewis' relation.

The mass balance at the outside surface (x=0) is described as,

$$-\frac{\partial}{\partial x}\left(D_\theta(T,\theta)\frac{\partial \theta}{\partial x} + D_T(T,\theta)\frac{\partial T}{\partial x}\right)_{x=0} = \frac{h_m}{\rho_l}(\rho_{v,\infty} - \rho_{x=0}) \qquad \text{[Eq. 10]}$$

Equations (9) and (10) show a vapor concentration difference, $\Delta\rho_v$, on their right-hand side. This difference is between the porous surface and air and is normally determined by using the values of previous iterations for temperature and moisture content, generating additional instability. Due to the numerical instability created by this source term, the solution of the linear set of discretized equations normally requires the use of very small time steps, which can be exceedingly time consuming especially in long-term soil simulations; in some research cases, a time period of several decades is simulated, taking into account the tri-dimensional transfer of heat and moisture transfer through a very refined grid.

In order to rise that simulation time step, Mendes et al. [15] presented a procedure to calculate the vapor flow, independently of previous values of temperature and moisture content. In this way, the term ($\Delta\rho_v$) was linearized as a linear combination of temperature and moisture content, viz.,

$$\left(\rho_{v,\infty} - \rho_v(s)\right) = M_1(T_\infty - T(s)) + M_2(\theta_\infty - \theta(s)) + M_3 \qquad \text{[Eq. 11]}$$

where

$$M_1 = A\frac{M}{\Re}\phi \qquad \text{[Eq. 12]}$$

$$M_2 = \frac{M}{\Re}\left(\frac{P_s(s)}{T(s)}\right)^{prev}\left(\frac{\partial \phi}{\partial \theta(s)}\right)^{prev} \qquad \text{[Eq. 13]}$$

$$M_3 = \frac{M}{\Re}\left[\left(\frac{P_s(s)}{T(s)}\right)^{prev} R(\theta^{prev}(s)) + \phi_\infty (R(T_\infty) - R(T^{prev}(s)))\right] \quad \text{[Eq. 14]}$$

4.2 Simulations

The available material data from Perrin [22] allow all the transport coefficients to be modelled as a function of moisture content.

4.2.1 Potential of Passive Latent Cooling

The aim of this work is to investigate the potential of passive latent cooling with brick and mortar walls which are widely used in Brazil - when subjected to the climatic conditions of the Brazilian cities of Belém, Brasília and Curitiba - and to identify a strategy to reduce conduction cooling load through hygroscopic walls.

4.2.1.1 Methodology

The approach chosen to evaluate passive cooling loads in porous building elements was done by using the Umidus code [21] by comparing building element configurations with different permeance values. The building element considered was a vertical wall composed by an intermediate layer of 100-mm brick and two 20-mm mortar layers at each side. The vertical wall is south facing.

A sensitivity analysis of paint permeance on heat fluxes was carried out for 3 different Brazilian weather data files (TRY): Belém (hot/humid), Brasília (hot/dry) and Curitiba (cold/humid).

4.2.1.2 Results and Discussions Focused on Brazilian Cities

Simulations were performed for the 3 cities and moisture contents and heat fluxes were calculated. In Figure 1, we see temperature averages within the wall for the 3 cities, noticing that Brasília has a mild weather.

Table 1 shows results of conduction heat fluxes through the wall with different values of paint permeance. The subscript p (positive) means that heat goes from outside to inside and vice-versa for the subscript n. The subscripts T, S and L mean total, sensible and latent. For the sake of clarity, results are presented in this table only for the case of Belém. It was noticed that for Curitiba - one of our coldest cities (see Fig. 1) -, the dominant heat flux leaves the room (negative flux). On the other hand, in Belém - one of the hottest -, it is noticeable that, for the same wall, the conduction cooling is 80% higher than that at Curitiba. However, Brazil has a predominantly hot weather and only a very few cities have weathers as cold as Curitiba's, which means that energy expenses for cooling should be truly high all over the country.

In Table 1, we show also the effects – in terms of percentage - of paint permeance on the heat fluxes and averaged moisture content. The infinite symbol means absence of paint (null vapor flow resistance). We note, from Table 1, that the best strategy to save energy by reducing conduction cooling loads is the one with no paint on the outside layer and zero permeance internal surface. This strategy is even better than that fully obstructing (null permeance) vapor flow at both sides, what can be explained by the fact of when moisture can freely enter or leave the external layer of the wall, it will naturally condense at night time and evaporate along the day, removing heat from the room. For example, we see that for Belém, the decrease in conduction cooling loads could be expected to be about 7.5%, and 5.7 and 5.6% for Brasília and Curitiba (not shown).

Table 1: Monthly integrated heat fluxes and wall moisture content (θ) at center of the wall for the city of Belém.

City	Permeance (ng/m^2-s-Pa)		$Q_{S,p}$ (kWh)	$Q_{S,n}$ (kWh)	$Q_{L,p}$ (kWh)	$Q_{L,n}$ (kWh)	θ (m^3/m^3)	$Q_{T,p}$ (kWh)	$Q_{T,n}$ (kWh)	$Q_{T,p}$ (%)*
	Out	In								
Belém	20	900	13436,82	-5001,66	1250,14	-593,66	5,20	14686,96	-5595,32	
	2000	900	13338,33	-4961,91	1240,36	-589,97	5,66	14578,69	-5551,88	-0,74
	∞	900	13322,41	-4949,83	1238,70	-588,82	5,67	14561,11	-5538,65	-0,86
	∞	0	13588,32	-5099,75	0,00	0,00	4,85	13588,32	-5099,75	-7,48
	0	0	13804,60	-5133,16	0,00	0,00	3,20	13804,60	-5133,16	-6,01

* This percent relative difference refers to the 1st case (permeance of 20 at outside and 900 inside)

The strategy of having a great vapor resistance at inside surface and 100% vapor permeable paint at ouside surface does not necessarily imply a high moisture content within the wall as we can see in Table 1.

Comparing the moisture contents of the walls in the 3 cities (Fig. 1), it was possible to see that the content is highest in the cold and humid climate of Curitiba, and as is to be expected lowest in Brasília. In the winter of Curitiba, June, July, August, September, there is a reduction in temperature and solar radiation, therefore less evaporation, hence more water enters than leaves the wall. In Brasília during the dry season, June, July, August, September, the solar radiation is high, so that the wall is dried out due to evaporation, more water leaves than enters the external surface.

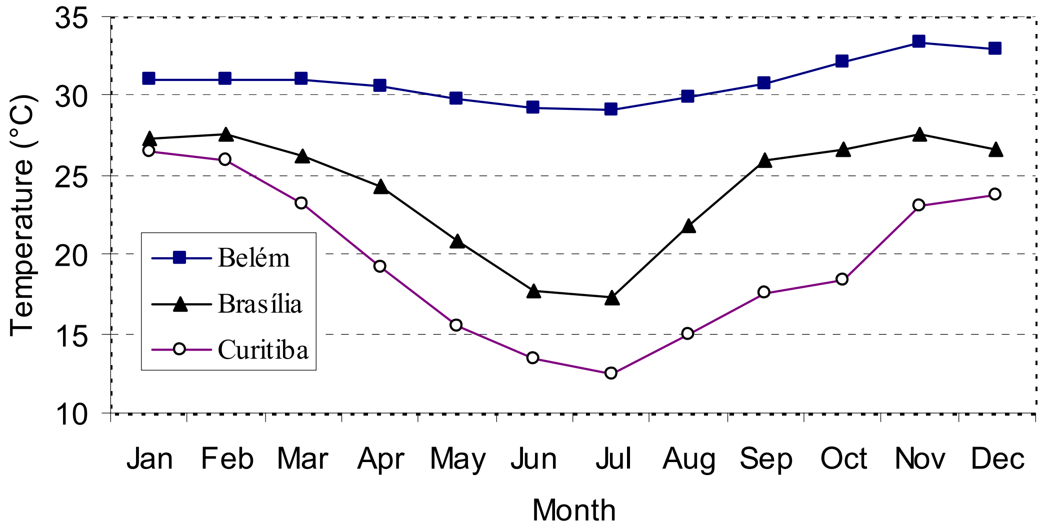

Figure 1 - Temperature averages within the wall.

The percentage of yearly conduction cooling loads due to latent heat is usually less than 10%. From this it can be seen the importance of using moisture migration to decrease conduction loads instead of increasing it.

In addition, to conclude, we believe that moisture movement effect can be reasonably enlarged, if we use a more hygroscopic material for the external layer, so that more moisture could enter and leave the wall in a such harmonious way during day and night to naturally save energy or even, in some cases, to avoid using air-conditioning systems. In section 5, it is presented a capillary active inside insulation system, which meets the needs discussed in this section.

4.3 Material Parameters

A very important precondition for good results oft the numerical simulation is the input of realistic material parameters such as the material functions of the Equations 03 and 04 of the differential equation system for the storage $c(w,T)$ and $w(a_w,T)$ and for the transport $\lambda(w,T)$, $a_w(w,T)$ and $\mu(w,T)$ in chapter 4.2. They must be available in order to get correct results. The idea is to represent the pore structure and the pore size distribution of the materials respectively by means of a function with suitable parameters characterizing the hygrothermal properties. The moisture storage function is the result of the integrated pore size function. The transport function can be derived by equilibrium of the capillary and the friction pressure [19]. Owing to this method there is a defined correlation between the material structures and their characterizing material properties. The arbitrary definition of material values should be replaced by the reasonable procedure. In this connection it is also necessary to develop and to install new measuring methods for the determination of the hygrothermal material parameters [18]. Currently at the University of Dresden and involving the Federal Institute for Materials Research and Testing Berlin and the FHLausitz a project is starting to set up a material database for materials of existing buildings, which is supported by the German government.

4.4 Computer Codes

The computer code DELPHIN has been developed and is supported at the University of Dresden/ Germany (www.tu-dresden.de) in order to solve the differential equation system Eqs. 03-04, completed by equations for air and salt transfer. By means of the program it is possible to simulate the performance of building materials and structures close to the reality. The calculations can be carried out as one-dimensional or two-dimensional and - for radial symmetric geometry - also as a three-dimensional problem. Beside a small material database there is also a climate database which contains test reference years for some Middle Europe districts, this means the hourly values of the climate components air temperature, relative humidity, short- and long-wave radiation, wind speed, -direction and precipitation (driving rain). Without saying the usage of constant climate conditions, such as national standards is possible. The necessary work to set up the task and to analyze the calculation results can be reduced by the involved pre- and post-processing tools.

In the Thermal Systems Laboratory (www.pucpr.br/lst) at the Pontifical Catholic University of Parana, three enginering-purposes computer programs – Umidus, Domus and Solum – have been developed as well. As described above, Umidus models coupled heat and moisture transfer within porous media and it is especially useful for studies of hygrothermal behaviors of building envelope and roofs. Users can quickly build different construction elements and compare them in terms of heat flux, mass flow and moisture content and temperature profiles. Reports of building parameters and graphs of results can be effortlessly exhibited.

However, the Umidus program internal boundary conditions are either constant or supplied by a whole-building simulation program. In this way, the Domus Program has been developed to model coupled heat and moisture transfer in multi-zone buildings. Its models are able to predict profiles within multi-layer walls for any time step and the temperature and relative humidity for each zone. Another developed simulation program is the software Solum, which is dedicated to the analysis of heat and moisture transfer phenomena in soils. The main goal with this software is to build and couple 3-D modelling routines into the Domus code, providing a more accurate prediction of internal conditions for low-rise or underground buildings.

5. RESULTS OF THE NUMERICAL SIMULATION REGARDING ENERGY SAVING AND THE HYGROTHERMAL SITUATION

5.1 Alga Problems

At present the so called „green facades "take place especially on the north orientated, retrofitted outside walls in numerous regions of Germany. They are caused by growing of different species of algae on thermal insulation composite systems (not only in districts by the seaside). Independent on the species algae need a continuous supply of moisture for their plant life. By long-wave emission, the temperature at the external surface of outside walls can fall below the dew point. In former time the long-wave emission of the surfaces was equalized by the heat transmission through the only moderate thermal insulated wall from the inside to the outside. Nowadays the external surface of envelope parts of buildings are uncoupled from the structure due to the large thickness of the insulation layer so that the surfaces of external walls tends to be natural surfaces of the external environment.

The following study demonstrates the influences of sunshine radiation, storage of rendering, position of insulation layer, emission coefficient and wall structure on the moisture content within 1-mm layer thickness outside of a north facing outside wall, see Figs. 2-11. The climate boundary conditions are the test reference year of Middle Europe TRY-north combined with a yearly harmonic function of the indoor climate (21°C+-1K; 55%+-10%).

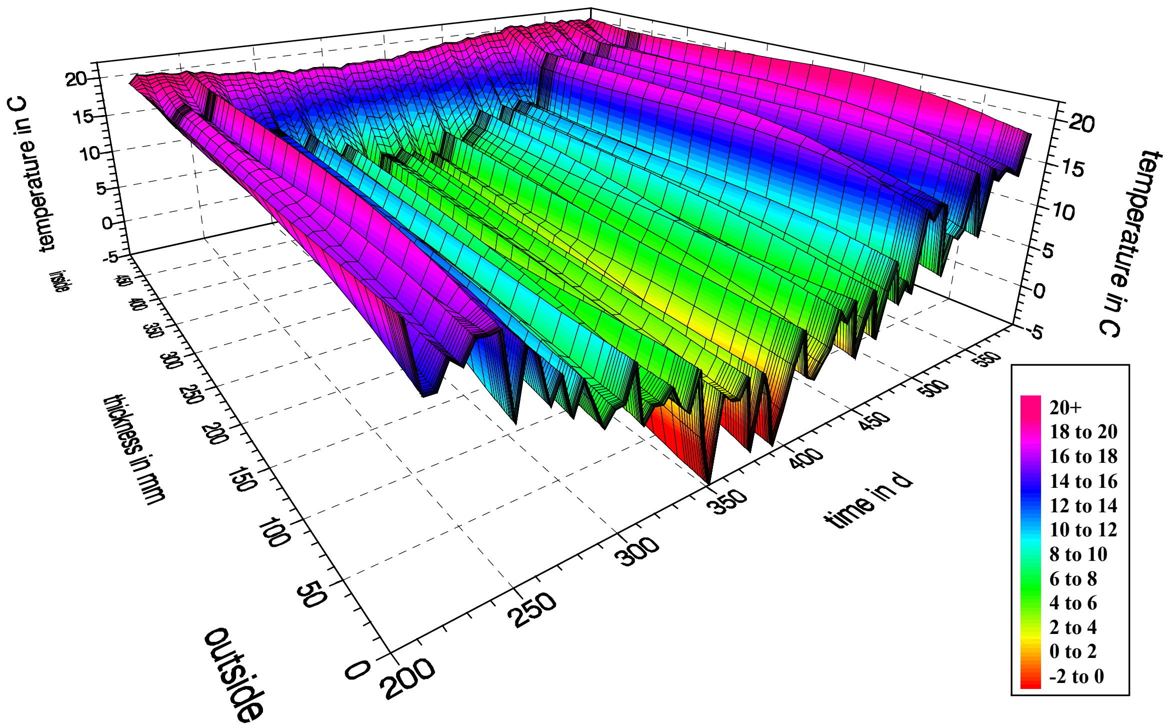

Figure 2 - Temperature field of a finished brick masonry wall without thermal insulation layer calculated by the coupled heat and moisture transfer.

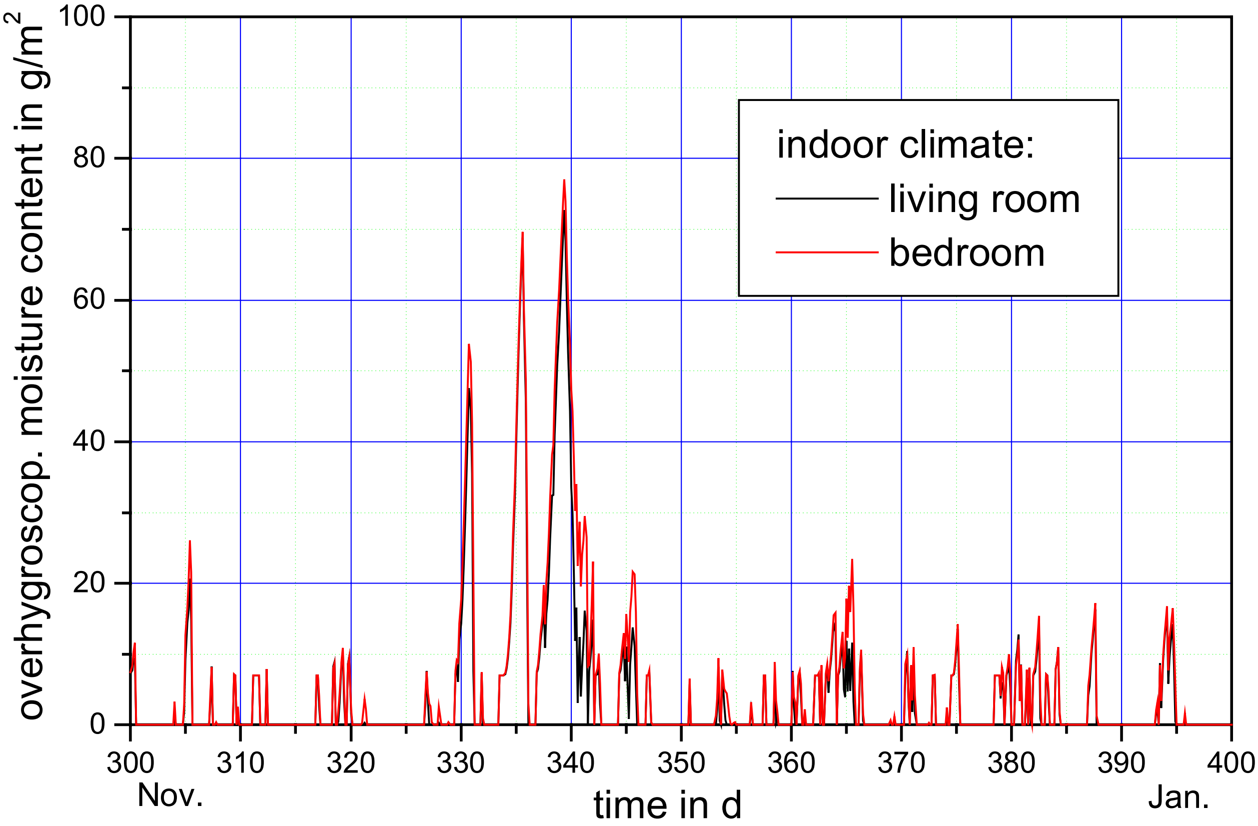

Figure 3 - Moisture content at the outside surface area of the not thermal insulated brick masonry wall.

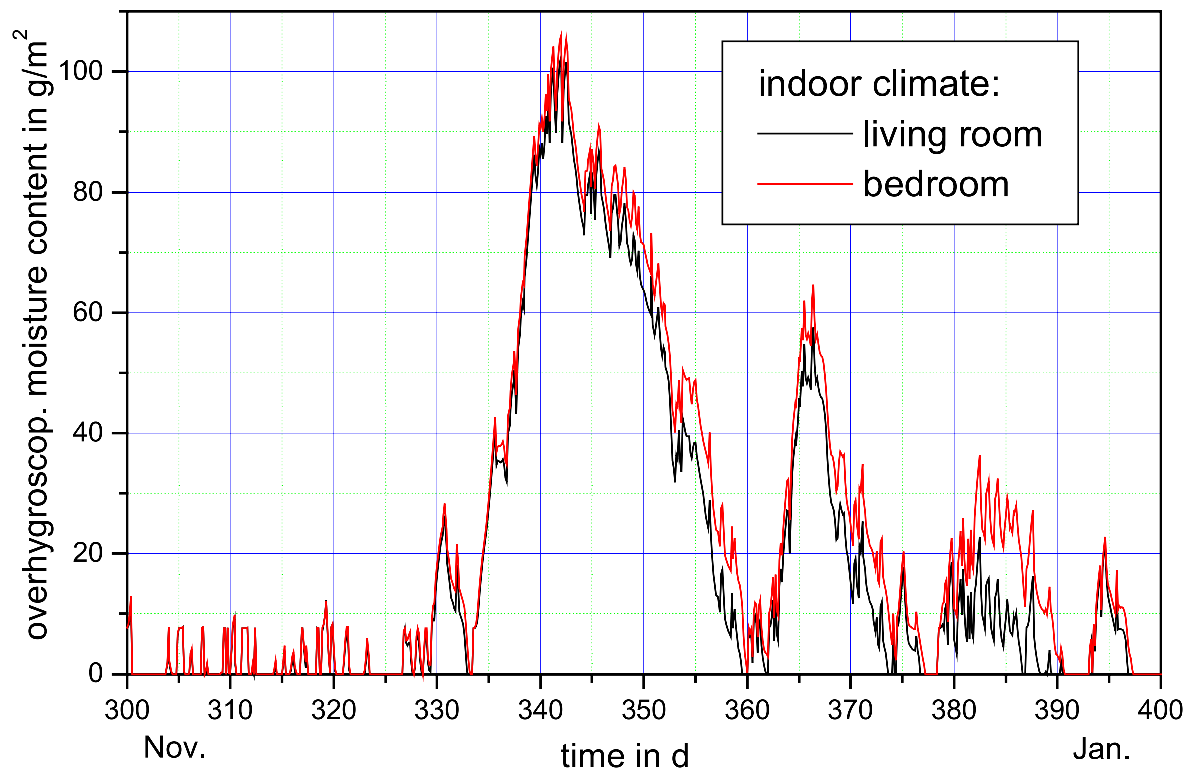

Figure 4 - Moisture content at the outside surface area of a brick masonry wall with a thermal insulation composite system, 60mm polystyrene.

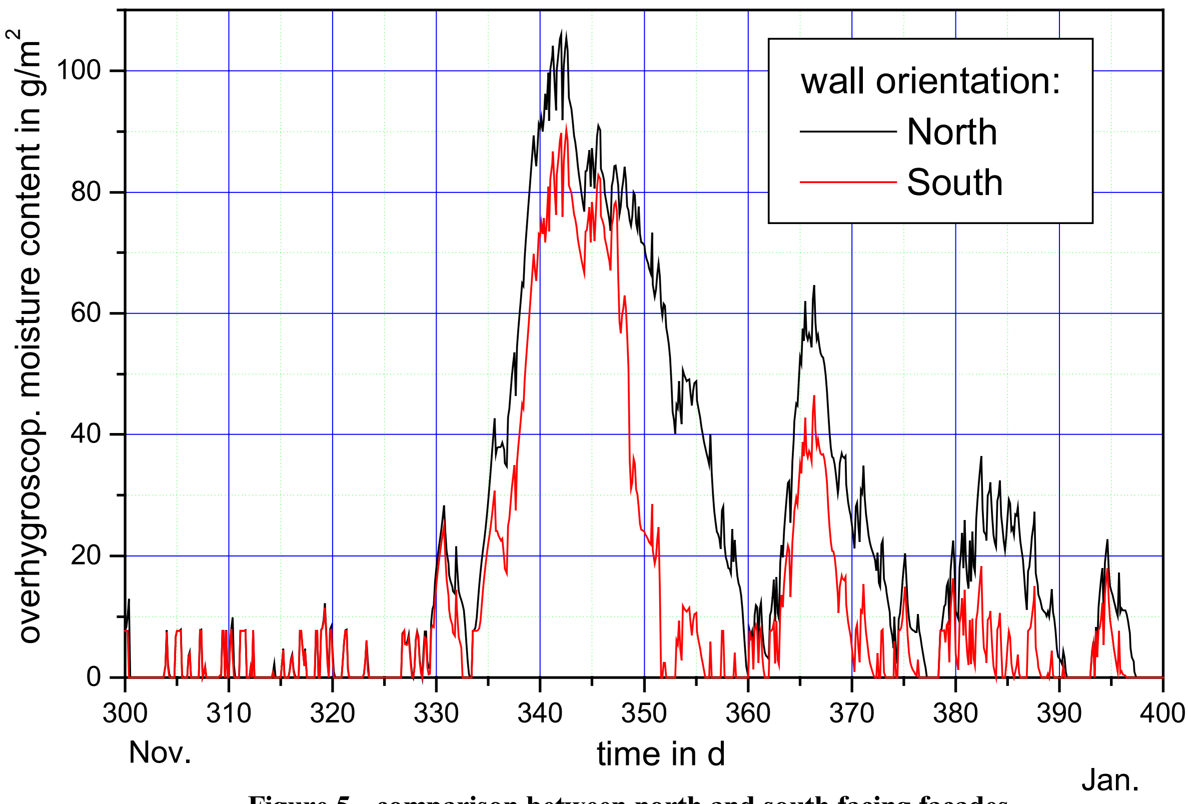

Figure 5 - comparison between north and south facing facades.

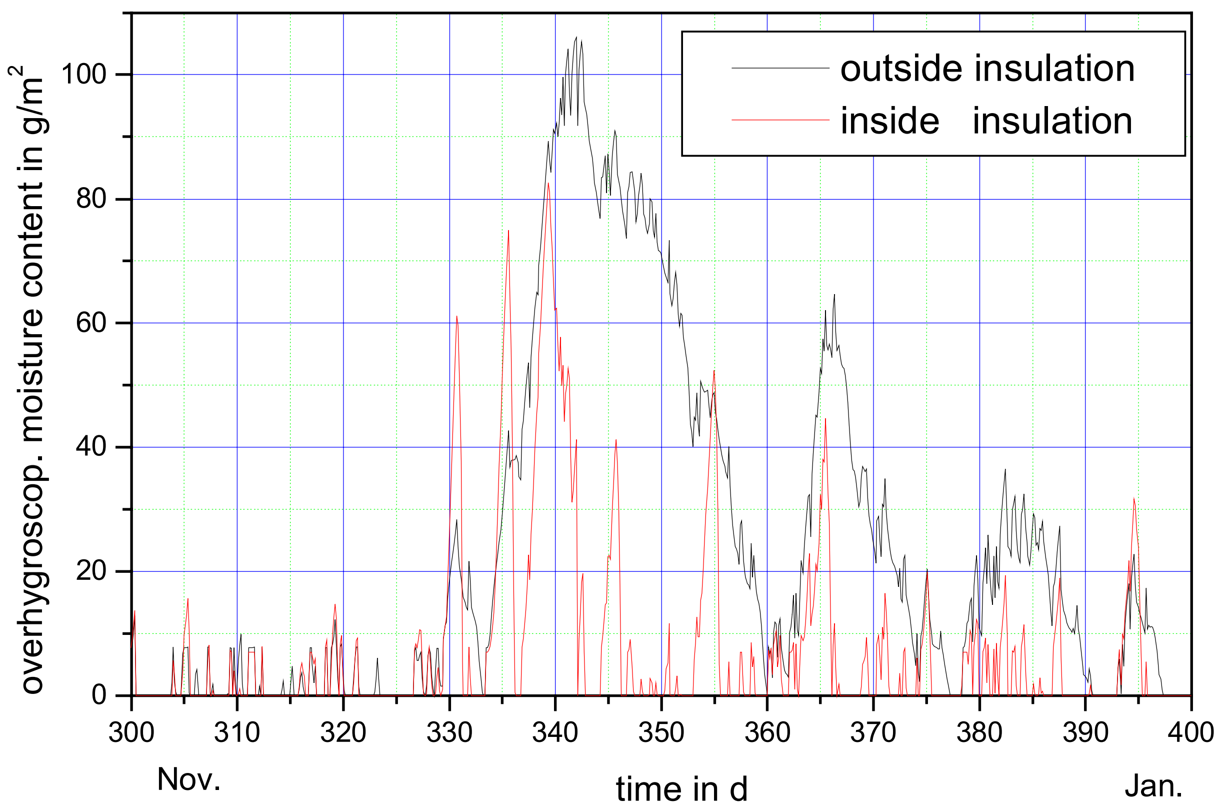

Figure 6 - comparison between outside and inside insulation system, 60 mm polystyrene.

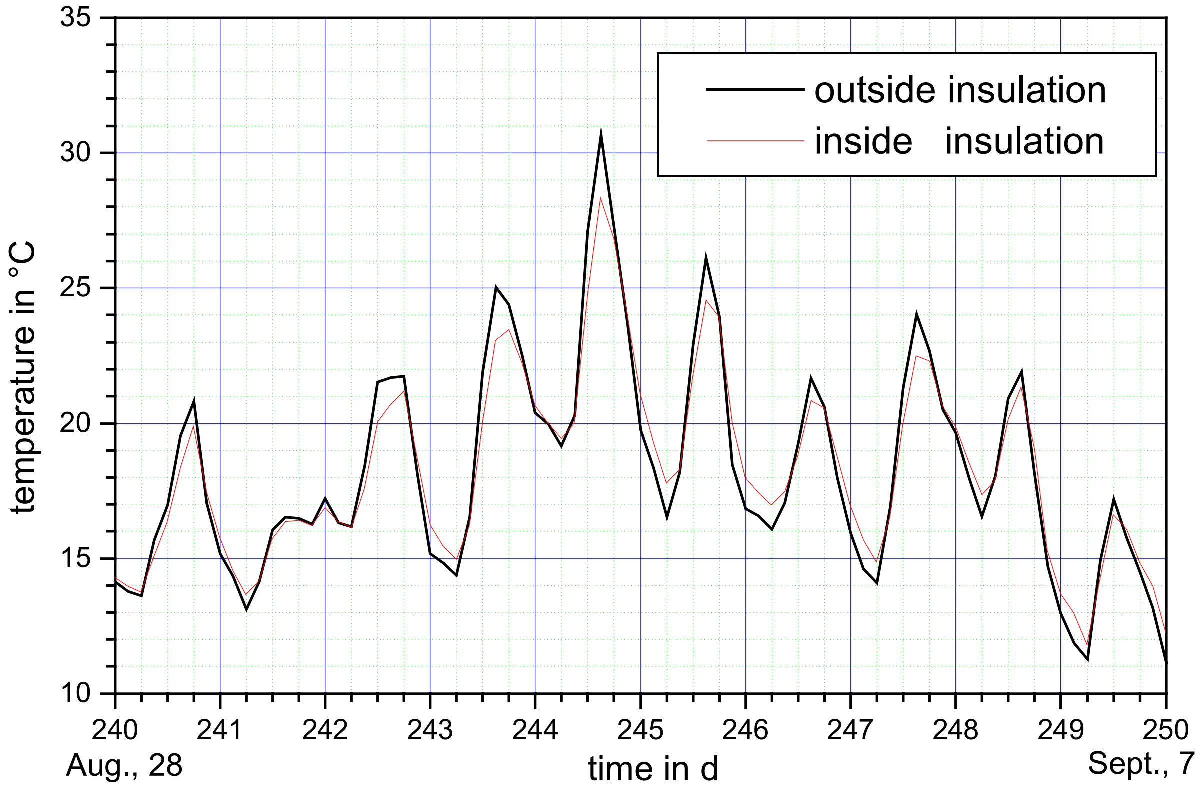

Figure 7 - Temperature course at the outside surface of the brick masonry wall.

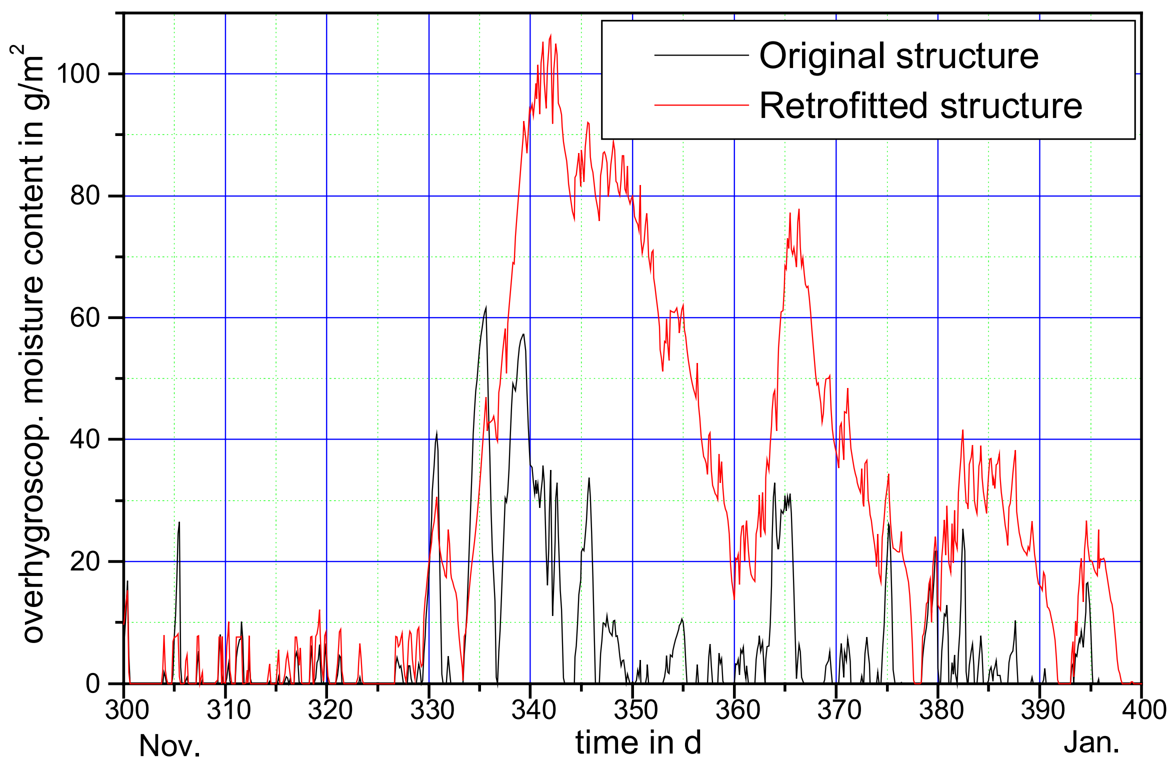

Figure 8 - Panel construction with thermal insulation composite system 60mm polystyrene.

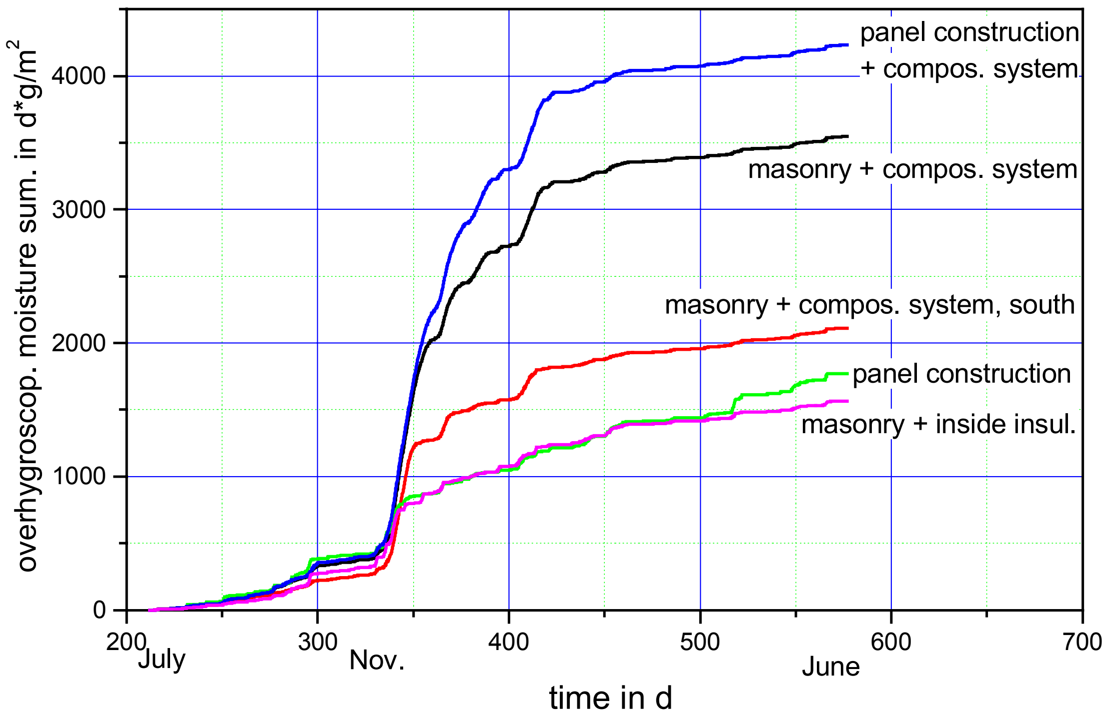

Figure 9 - Yearly sum line of the moisture content at the outside surface area (1mm layer thickness) of different wall structures.

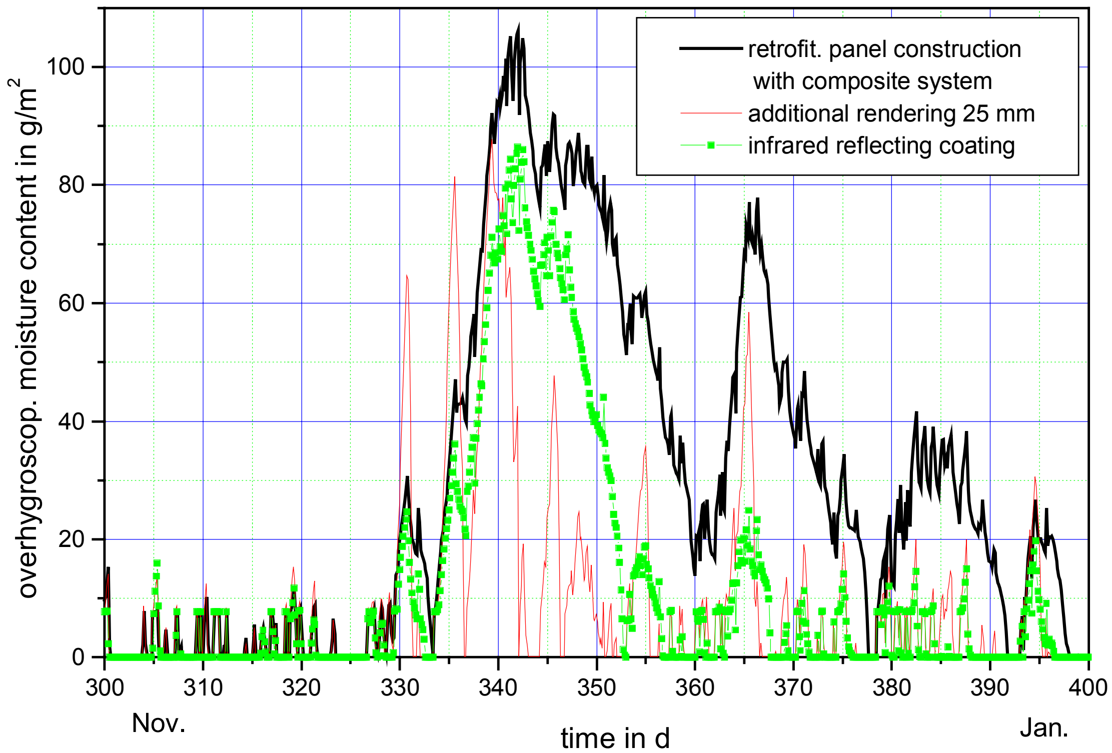

Figure 10 - Moisture content of the outside surface area of a panel construction dependent on different measures.

Summarizing it is to see, that the technology of the thermal insulation layer of an outside insulation system should be determined not only with regard to the energy saving aspect. Dependent on the climate boundary conditions an optimized thickness is to calculate in order to avoid other negative effects. For instance by means of storage (thickness of rendering of thermal insulation composite systems, inside insulation) or an infrared reflecting coating the danger of dew point at the outside surface is decreased at night and the plant life of algae is reduced.

5.2 Inside Insulation Systems

It is without saying in connection with a cold outdoor climate the inside insulation method is a risk method from the building physics point of view. Nevertheless, in case of historical and worth preserving facades of existing buildings there is no other method to reduce the heating or cooling energy consumption and to improve the thermal and hygienic comfort [23]. The traditional approach when using an internal insulation system is that insulation and a vapor retarder is fixed at the inside. Such a system is dependent on the performance of the vapor retarder. Thin membranes may be easily perforated by nails and calls for workmanship. Another aspect is the drying potential of built in moisture to the indoor. It is decreased by a vapor retarder or an insulation material with a large vapour resistance. Besides the penetrating moisture by driving rain at fair-faced masonry or wooden framework is to consider.

Therefore we have developed and preferred a capillary active inside insulation system [24]. In spite of a missing vapor retarder the overhygroscopic moisture content is limited to an insignificant amount because due to the distribution of the overhygroscopic moisture (condensate) to the warm side the interior vapor pressure gradient decreases. Within the area of overhygroscopic moisture the line of saturation pressure dependent on the temperature course and the capillary conductivity function of materials are to consider. If there are stationary climate boundary conditions the diffusion process comes to an end in opposite to the so-called Glaser scheme after a finite time.

The following figures demonstrate the influence of the hygrothermal parameters on the moisture content and energy losses. Fig. 11 represents the moisture field of the coupled heat and mass transfer trough an masonry wall inside insulated by means of 50mm calcium silicate type A (max. capillary conductivity a_0 = 10^{-5} m^2/s, thermal conductivity λ = 0.08 W/m-K) without vapor retarder. In Fig. 12 is shown the comparison of the total moisture content between the three wall structures with calcium silicate type A, type B (a_0 = 10^{-8} m^2/s, λ = 0.06 $W/m^2.K$) and type C (a_0 = 10^{-5} m^2/s, λ = 0.06 W/m-K). Fig. 13 compares the heat flow densities at the interior surface (energy losses) of these structures. The effect of the increased thermal conductivity of the type A by 20% is reduced nearly by the decreased moisture content of the capillary active structures.

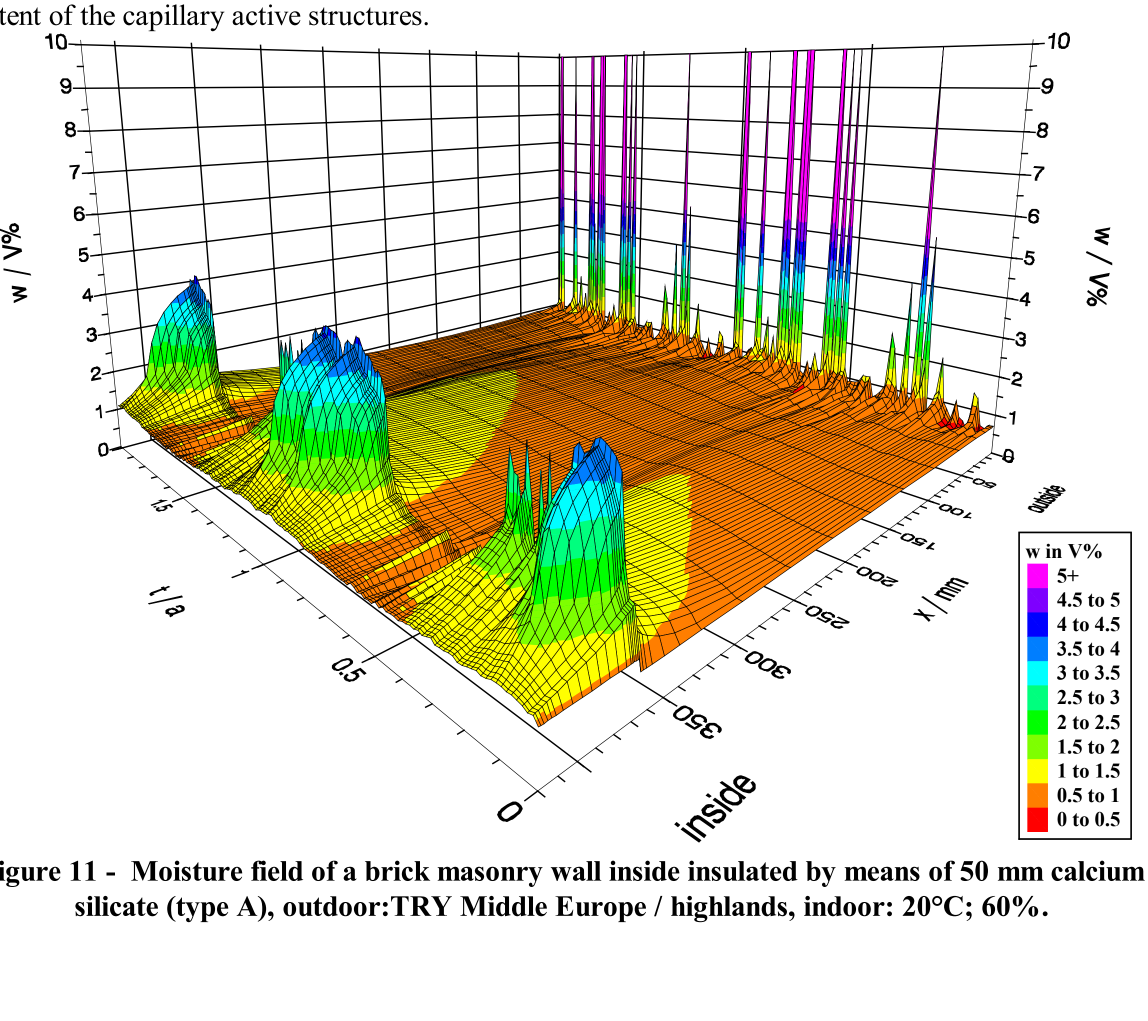

Figure 11 - Moisture field of a brick masonry wall inside insulated by means of 50 mm calcium silicate (type A), outdoor:TRY Middle Europe / highlands, indoor: 20°C; 60%.

Figs. 14 and 15 describe an unfavorable hygrothermal situation at the edge (corner) of two outside walls inside insulated by 6mm polystyrene hangings (outdoor climate: TRY Middle Europe west; indoor climate: harmonic function of temperature and relative humidity with 21°C+-1K and 55%+-10%). One year after the retrofitting by means of this special insulation at the brick masonry outside wall mould was noticed in some rental units.

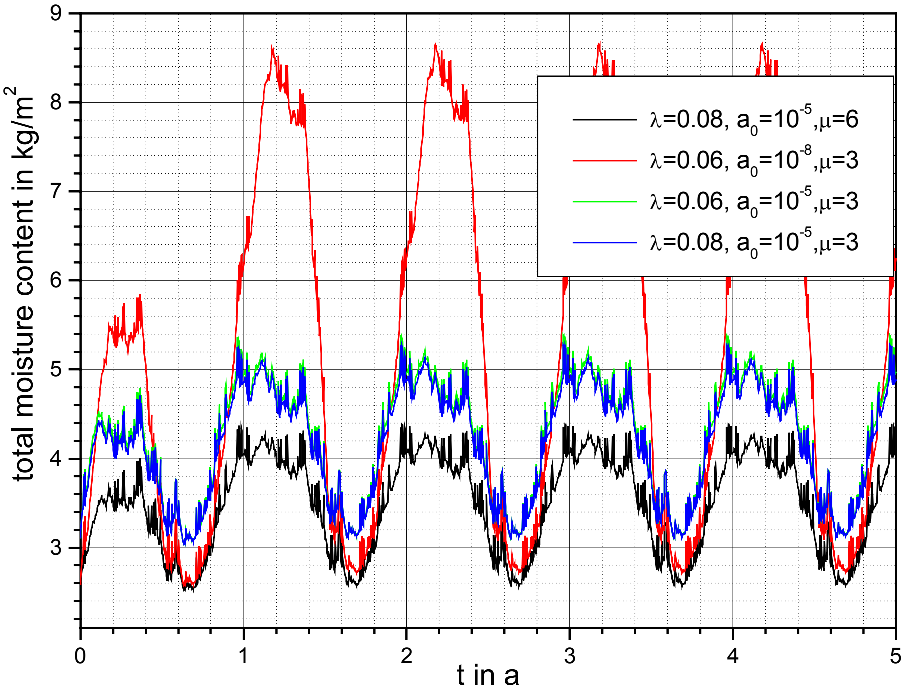

Figure 12 - Total moisture content of inside insulated external walls carried out by means of capillary active types of calcium silicate A, C ($a_{o,max}$ =$10^{-5}$$m^2$/s) and the capillary inactive type B ($a_{0,max}$ = $10^{-8}$$m^2$/s), climate acc. Fig. 11.

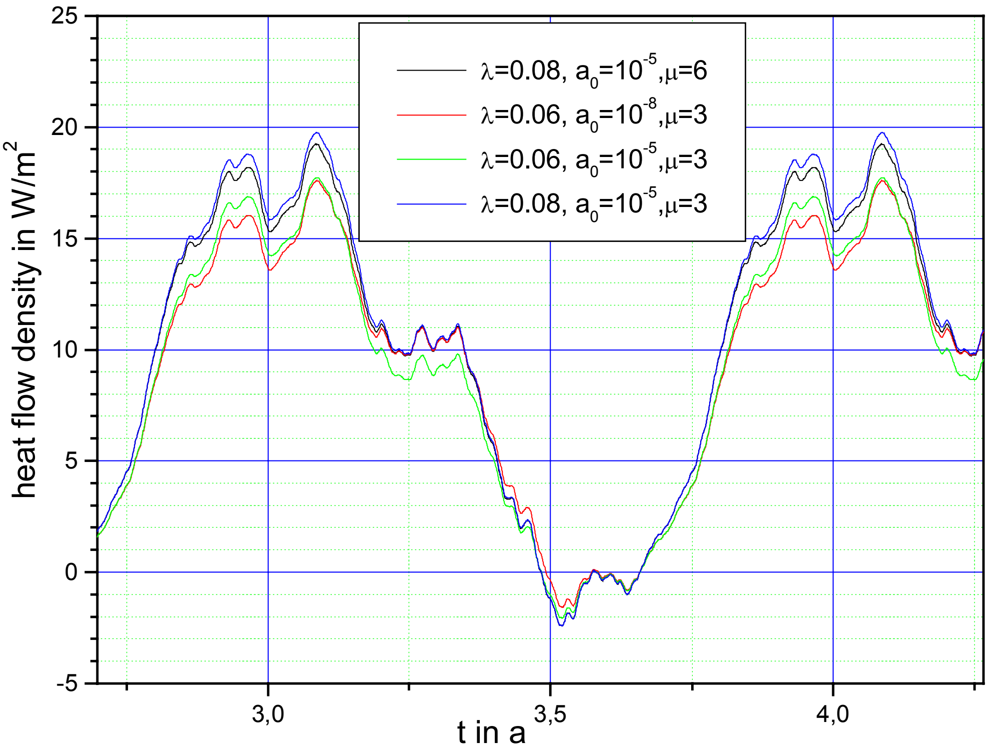

Figure 13 - Heat flow densities at the interior surfaces of the inside insulated external walls compared between the types of calcium silicate A, B and C acc. Fig. 12.

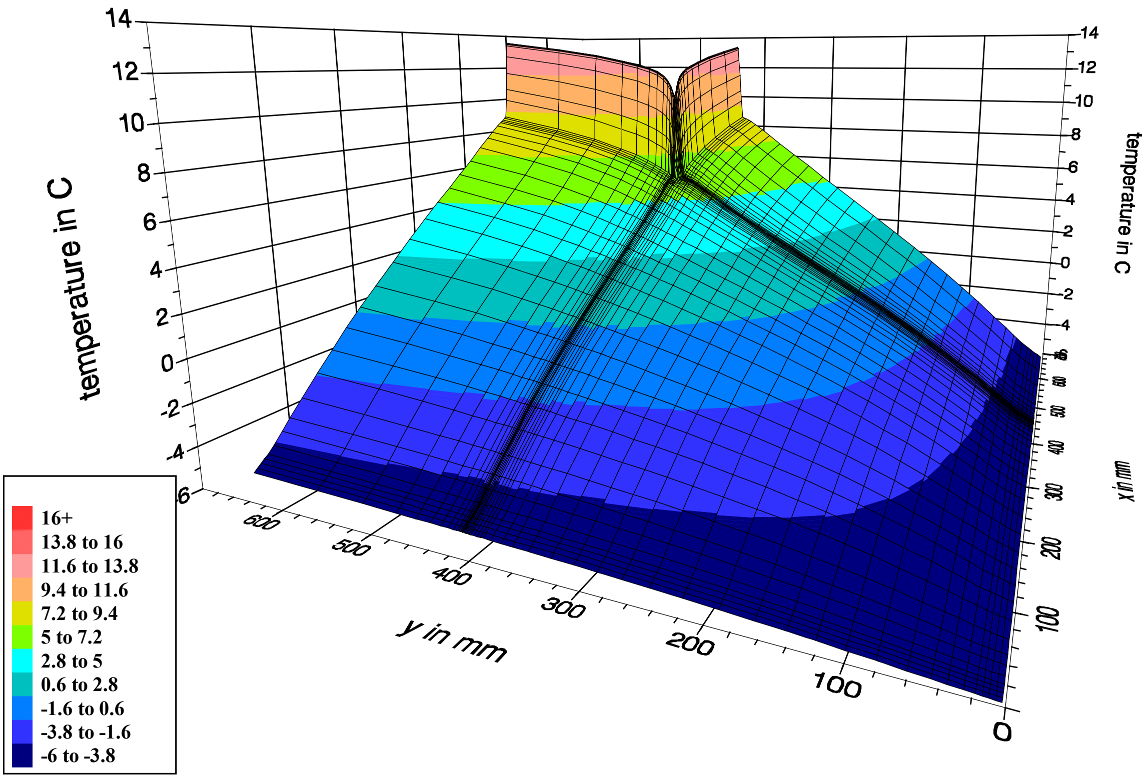

Figure 14 - Vertical edging of a wall panel inside insulated by 6mm polystyreen (λ = 0.035 W/m.K; μ = 450); temperature field, Dec. 18th: view from the outdoor to the indoor.

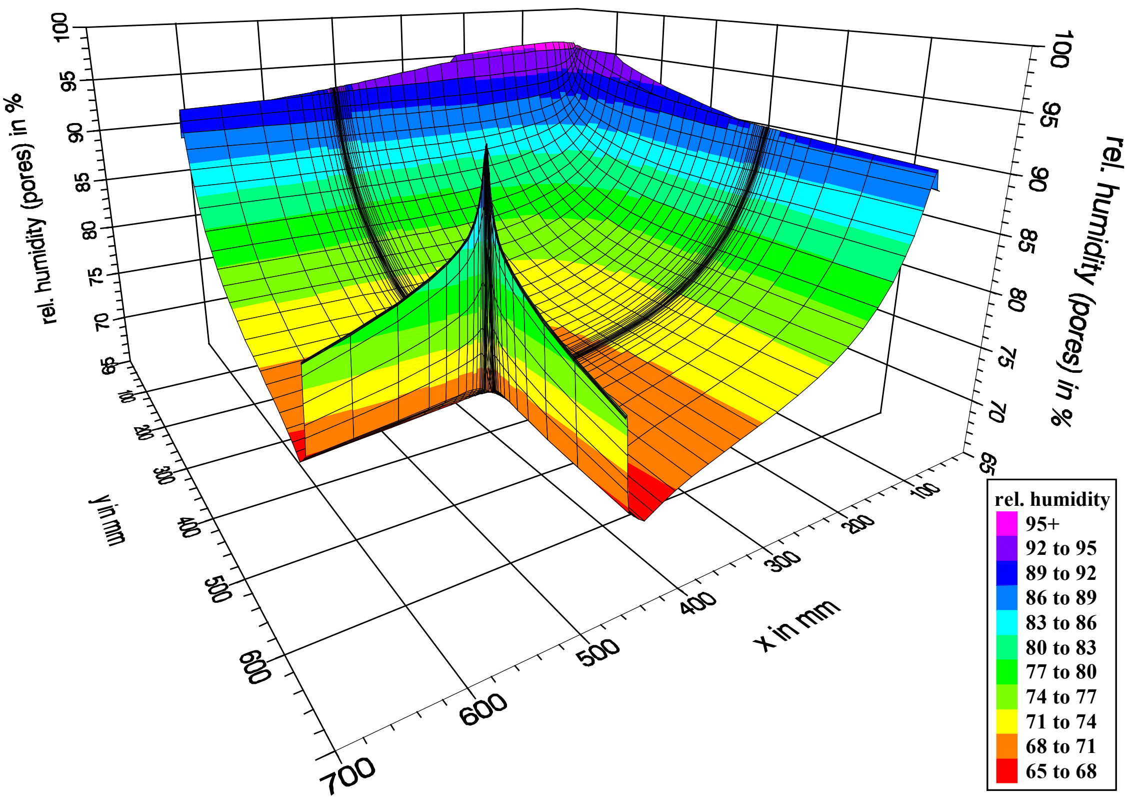

Figure 15 - Acc.Fig.14, moisture field (relative humidity of the pores), Dec. 18th: view from the indoor to the outdoor.

5.3 Infrared Reflecting Coatings

In connection with special problems small effects to provide solutions in the fields of building physics, e.g. see alga problems in section 5.1. Besides the temperature at the exterior surface of an outside wall insulated on the warm inside, the temperature profile can be influenced in a favorable way by low emission coatings on the facade. Owing to a reduced emission of long-wave radiation, the temperature at the cold side of the thermal insulation reaches a higher level. This means a decreased relative humidity and a shorter condensation period.

To estimate the energy saving effect of an infrared reflecting coating, the emission coefficient of the external surface of an outside wall with an inside insulation is varied between 0 and 0.9. The result of the calculation with regard to the heat flow density at the interior surface is shown in Fig. 16. The numerical simulation is carried out under consideration of all outdoor climate components driving rain included. The last one means an additional evaporation cooling effect dependent on the capillary conductivity of the rendering.

Summarizing it is to recognize that in case of a diminished long-wave emission and the emission coefficient ε tending to zero respectively the U-value of an external wall can be decreased up to about 7% (Fig. 16). With regard to the heat losses the max. effect of the evaporation cooling reach the same magnitude. In case of roof constructions due to a bigger hemisphere the effect of heating energy saving by infrared reflecting coatings can pass more than 10%, provided that the property of coating with regard to the small ε is durable.

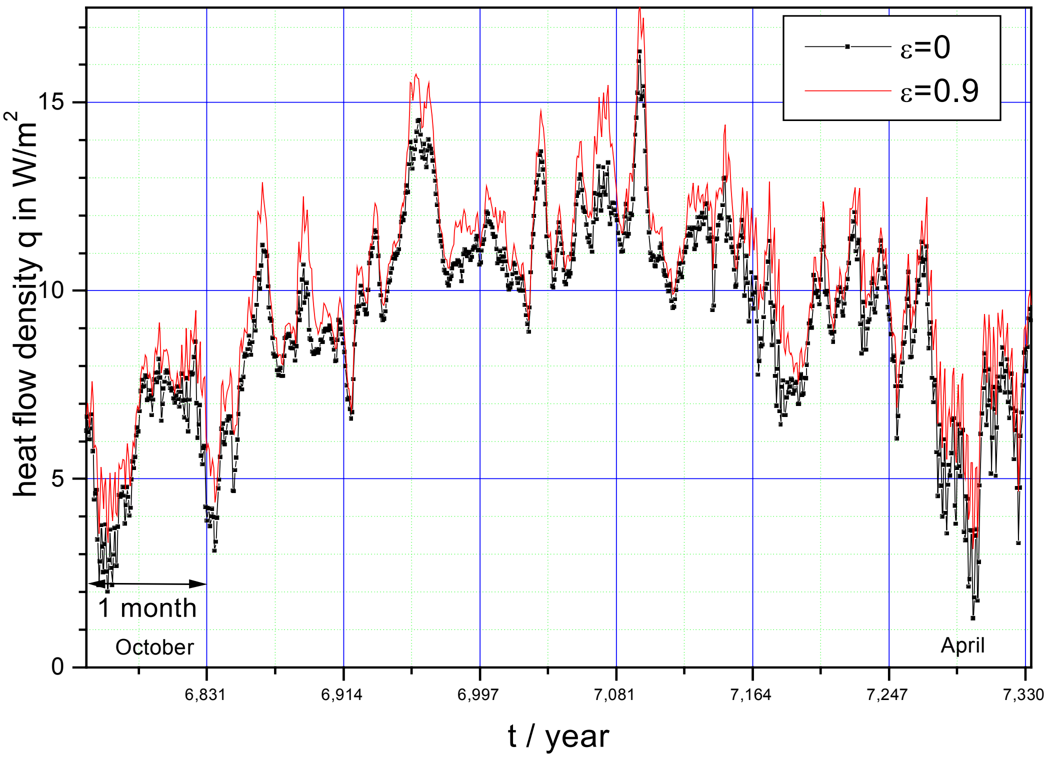

Figure 16 - Heat flow densities at the interior surface of a plastered brick masonry wall with an inside insulation system of 60mm super insulating aerated concrete and varied ε - coefficient at the exterior surface.

5.4 Heat losses by enthalpy flow

The energy saving is not only a question of the thermal conductivity and its dependence on moisture. The transfer of enthalpy itself by the temperature and moisture gradients can be very important too. E.g. in case of the measurement of the thermal conductivity of moist insulation materials acc. to the standard ISO 10 051 and EN 12 667 respectively the enthalpy transfer influences the result in a very strong way. Another example of energy losses caused directly by enthalpy flow is described in the principle sketch of an inverted roof, see Fig. 17.

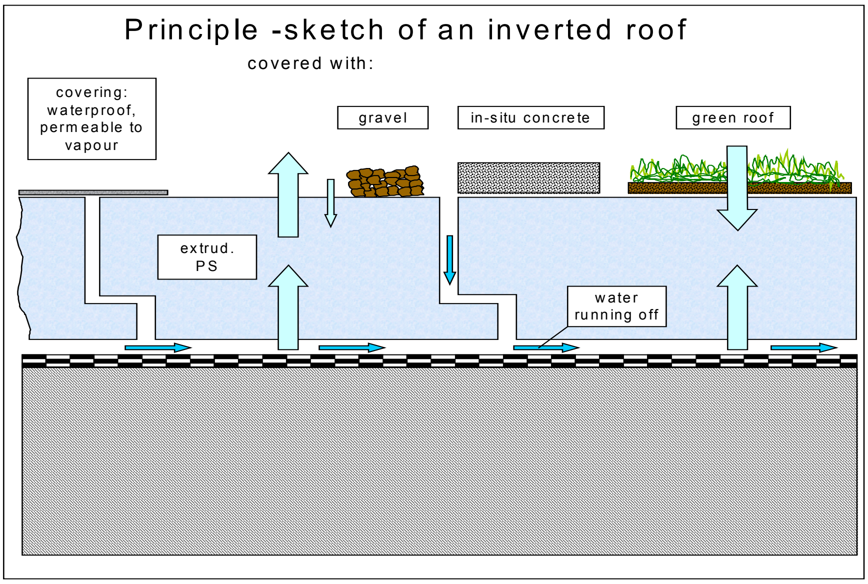

Figure 17 - Cross-section of an inverted roof , principle sketch.

Currently the standard workgroups discuss this type of flat roof concerning the increasing of the U-value caused by the enthalpy losses due to the precipitation running off between the waterproofing membrane and the thermal insulation layer. The proposal of the final draft is

$$\Delta U = p \cdot f \cdot x \cdot (Ri/Rt),$$

where:

p: the average rate of precipitation per day during the heating season in mm/day

f: factor of dewatering (only a portion of “p” reaches the membrane).

x: coefficient estimated either by experiment or analytically; in case of a gravel packing above of a finish layer x = 0.04 W-day/m^2-K-mm.

Ri: thermal resistance of the layer of XPS insulation above the waterproofing membrane.

Rt: total thermal resistance of the roof construction.

At the test stand of the FHL investigations were carried out with regard to the dewatering factor. In case of a specific, diffusion open covering underneath of the gravel the factor f tends to zero. Thus, the additional enthalpy effect by precipitation running away is eliminated. Fig. 17 demonstrates the effect of dewatering owing to the retention of precipitation by the storage of a green roof.

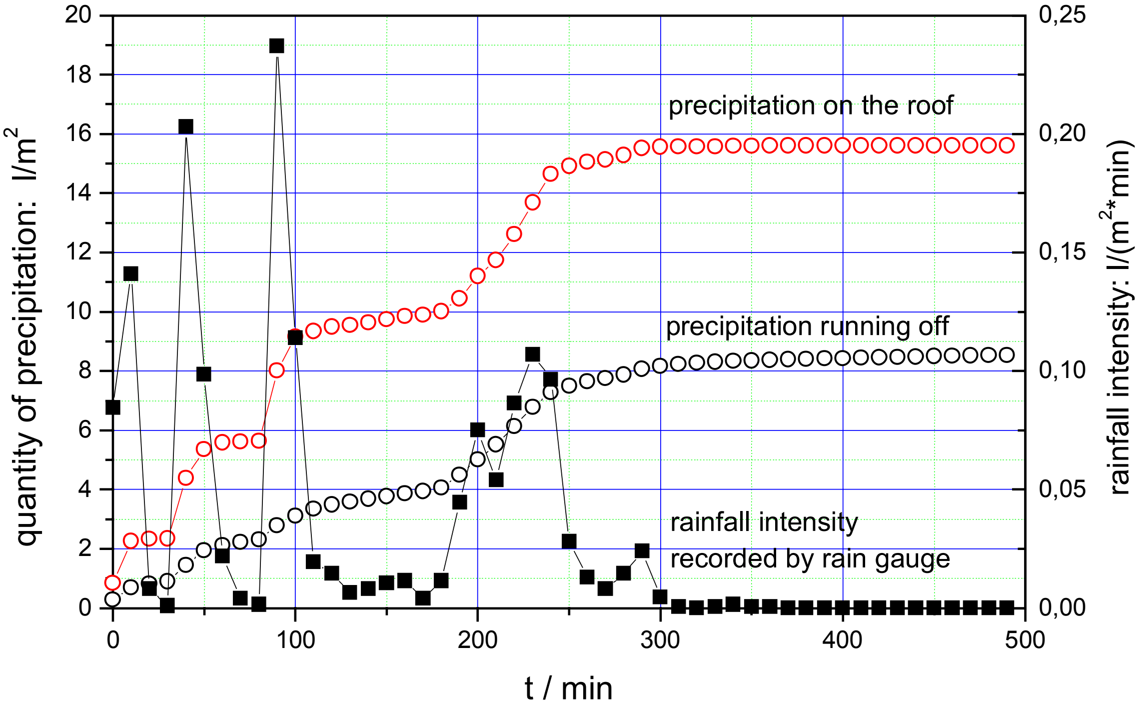

Figure 18 - Storage of rainfall by green roof.

In Fig. 19, the total moisture content of the thermal insulation layer of different types of inverted roof structures is represented under climate boundary conditions of Middle Europe. The results show, that some profiles of inverted roofs can be a very risk structure.

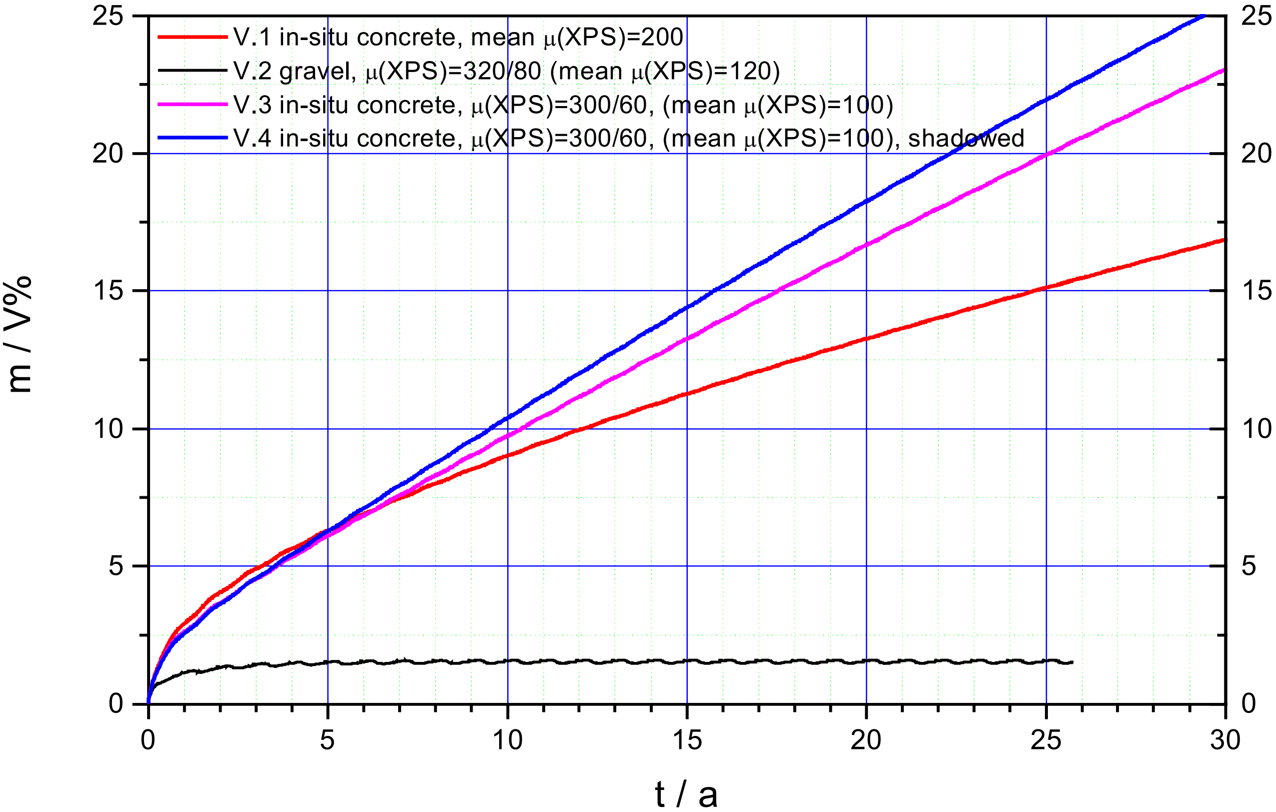

Figure 19 - total moisture content of the insulation layer of inverted roofs, TRY Middle Europe.

5.5 Basement masonry wall

In this chapter the correlation between rising moisture within an outside masonry wall and energy losses is investigated. It is a question of comfort and a matter of energy saving too. In case of a missing or a destroyed horizontal barrier moisture of the ground rises –depending on the climate boundary conditions- up to a height of about 2m versus the basement floor, Fig. 20. Due to an increased thermal conductivity the thermal resistance of the masonry wall decreases.

Fig. 21 shows the dynamic effect of the drying out process by built in of a barrier 0.5m above the floor. The basement is situated 1m below the ground surface. At the fundamental basis the contact moisture is 20 V%. We have to distinguish two thermal transmission coefficients due to the different external boundary conditions. Both U-values of the wall above the built in barrier tend in laps of time against the U-values of the dry areas of the wall. Below the barrier the state of moisture and heat transfer keeps unchanged.

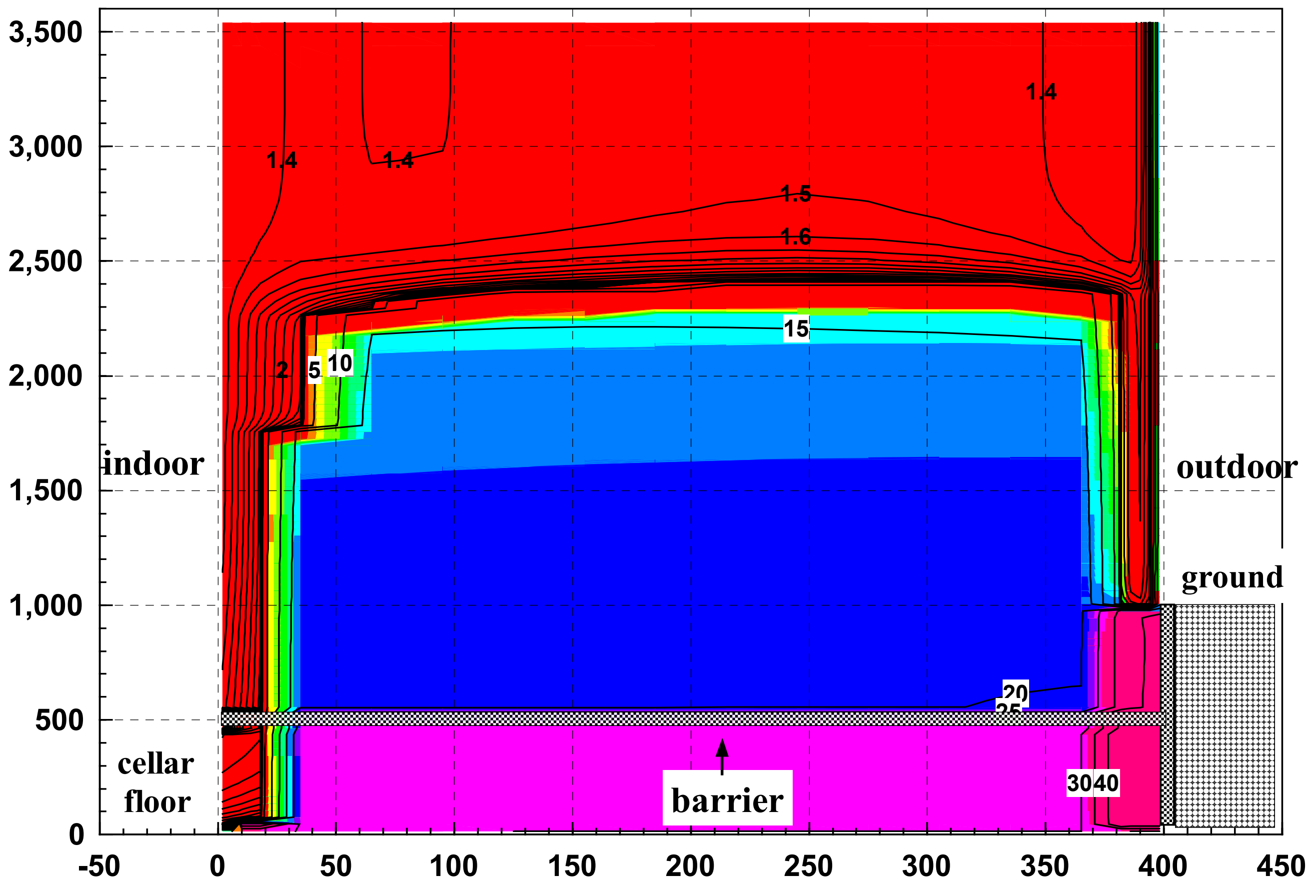

Figure 20 - Cross section of the basement wall: moisture field a half year after the installation of the horizontal barrier. Outdoor climate: TRY Middle Europe. Indoor climate: 15°C; 60%..

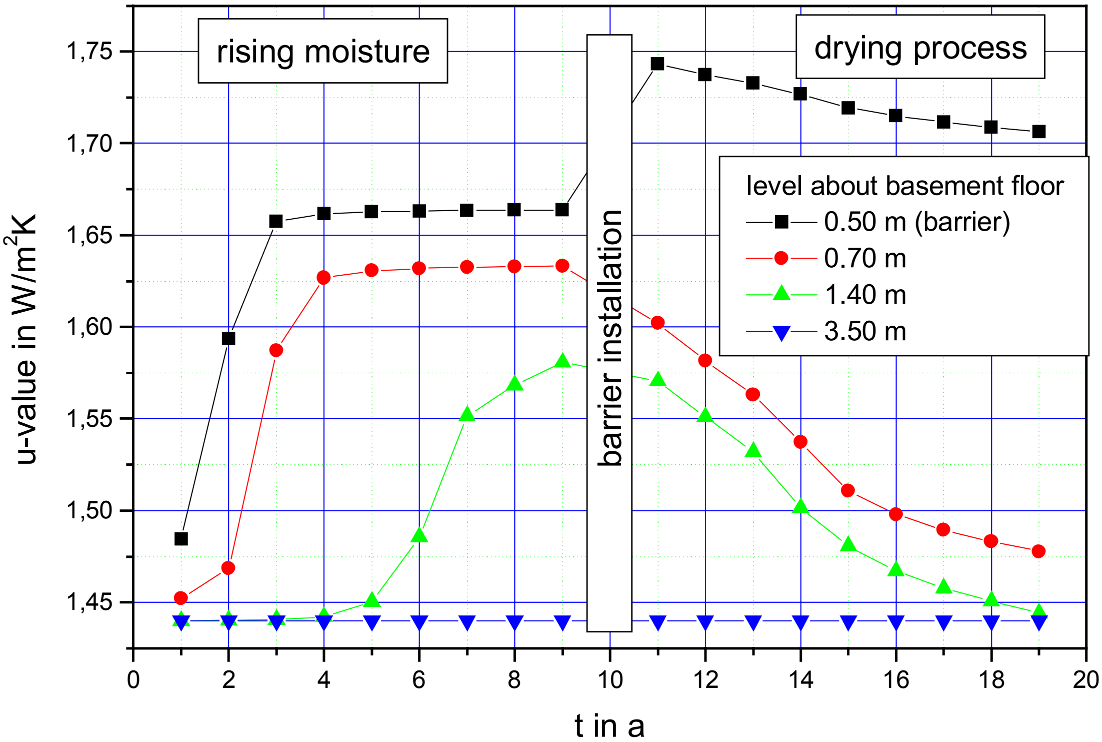

Figure 21 - Course of the U-values of the outside wall acc. Fig. 19 at different levels against the floor.

6. EFFECTIVENESS CONTROLL

6.1 Certificates of the Energy Saving

Improved building envelopes concerning energy saving and hygrothermal performance are to realize by means of the competition on the markets and by directives of the institutions and administrations. For this reason the European energy saving directive provides certificates that represent energy and heating use of a building to the clients. The German government has fulfilled already this requirement in connection with its energy ordinance published in 2002 and a better transparency for building owners and users is reached.

6.2 Measuring Technique

The European directive requires certificates of energy savings for new erected buildings and in case of retrofitting. But there are tools necessary too for checking the quality of building envelopes in an objective way. A measuring technique should be available. Above all things measuring devices are necessary for an in-situ checking concerning thermal insulation and drying out processes.

On the one hand, numerous techniques are available to determine the parameters of materials by use of laboratory methods. For instance a lot of instruments and instructions and international rules exist for the measurement of the thermal conductivity in laboratories. In opposite to this, there are no possibilities to investigate the hygrothermal state of the envelopes in-situ. That’s why we have developed a so-called λ-needle probe [25]. It enables to check the thermal conductivity and the moisture content of insulation layers of envelope parts and thermal insulated pipes. By means of such a needle it is possible to determine the time depending change of this thermal parameter in-situ and in a quasi non-destructive way, see Fig. 22.

Figure 22 - Measuring device: λ - needle probe detecting the hygrothermal performance of an inverted roof structure in-situ.

In case of a pointshaped and uniformly heated source with a radius R the temperature at the surface of the sphere tends to a simple limit. We get a relation between the overtemperature $\Delta T = T(t) - T_o(0)$ and the thermal conductivity λ: $\Delta T = q_0 \,.\, R/\lambda$; (q_0 is the heat flow density running off into the sample). However the practice requires a limited heating and measuring time. Moreover there are a contact resistance and a deviation from the spherical shape. So a calibration curve is necessary. The technological transfer of the theoretical idea is realized by means of prefabricated sensors. For example, it is possible to use double wire sheathed thermocouples. One couple is used for the heating circle, the other couple for the measuring of the overtemperature. Nowadays a miniature platin resistance is used as a heating source and temperature sensor.

Owing to the correlation between λ and the moisture content of the material, it is possible to detect and control moistening and drying out processes. Above all things it is a reliable monitoring also in masonry with salt ions too. In case of absolute values of moisture this measuring method requires admittedly a well-known calibration curve for each material. If there are samples with a certain hardness a bore hole is to prepare and by means of an injection spray an emulsion is pressed into the hole as a contact material before the needle is inserted.

6.3 Measuring Results

Fig. 23 represents the course of the thermal conductivity of a XPS thermal insulation layer of an inverted roof and covered with gravel. In such a roof structure the water tight membrane is below the thermal insulation acc. Fig. 17. Due to this arrangement within the structure a comprehensive coupled heat and moisture transfer takes place influenced by the fluctuation of precipitation and sunshine. Fig. 23 demonstrates clearly the influence of the outdoor climate periods on the effect of the thermal insulation of an inverted roof construction.

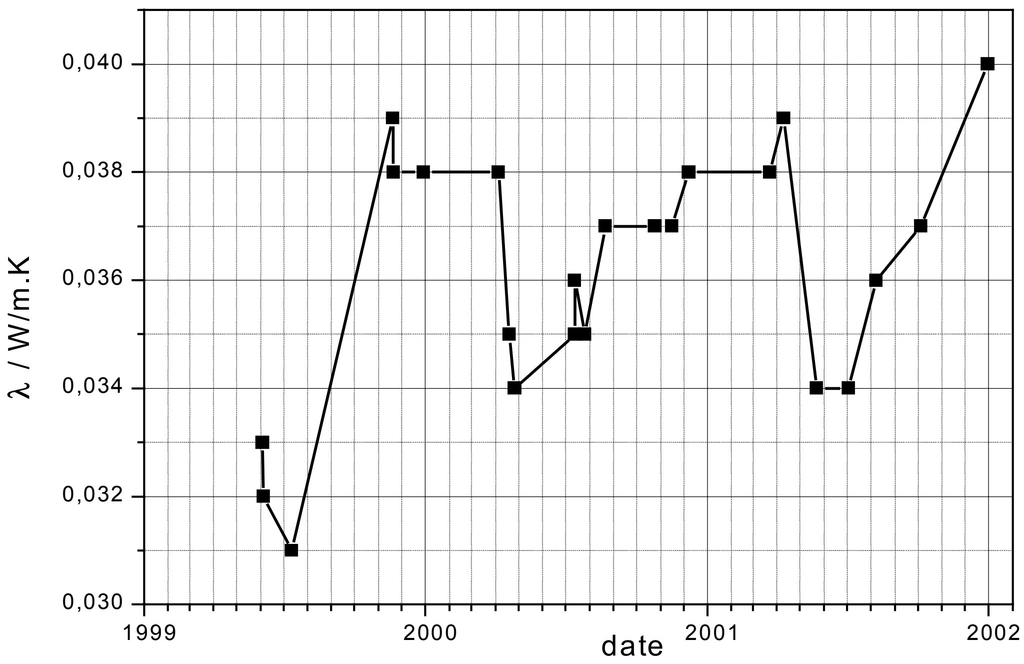

Figure 23 - Inverted roof: course of the thermal conductivity of the insulation layer.

Fig. 24 shows the influence of climate periods on the course of moisture content of wooden beam heads. Some years are necessary to dry out the built-in moisture caused by the activities of retrofitting.

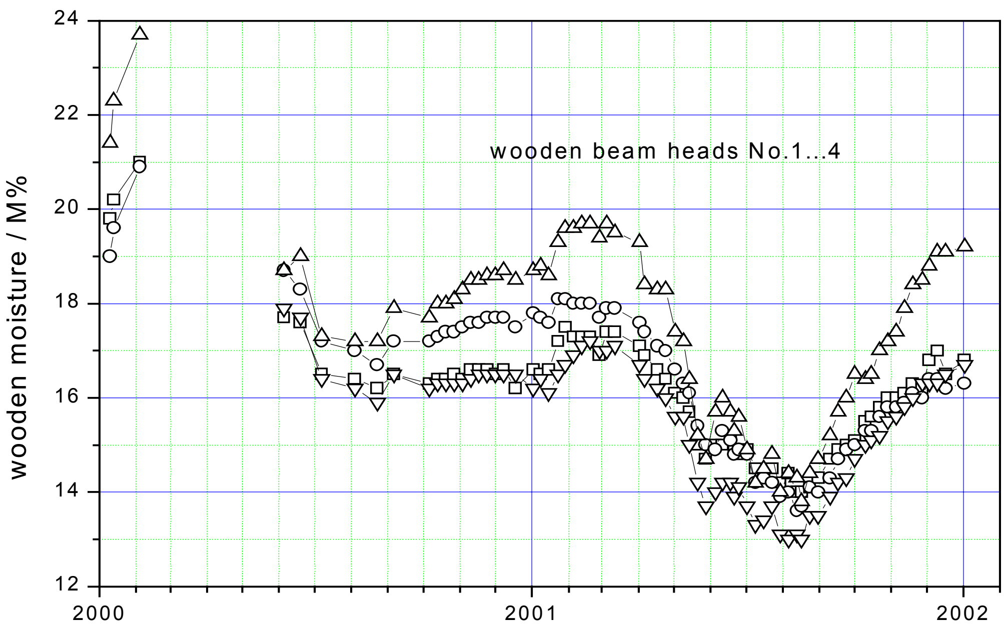

Figure 24 - Wooden beam heads: course of moisture content after renovation.

An example of progress review of a drying out process is demonstrated in Fig. 25. After the installation of a horizontal barrier against rising moisture within an outside wall, the neutron probe and the lambda-needle probe indicate insignificant effects. But a new plastering is to recognize clearly due to the added moisture the overtemperature decreases and the rate of absorbed impulses increases at the same time.

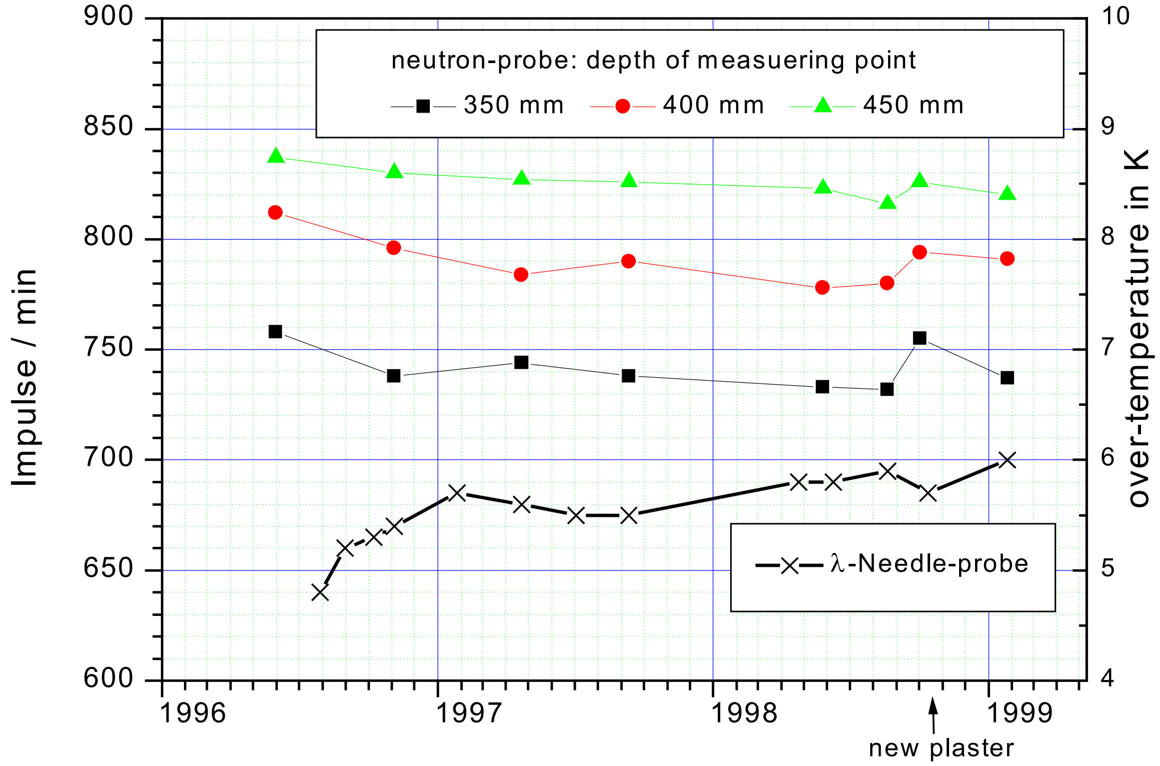

Figure. 25 - Basement wall: progress review of the drying out process.

7. CONCLUSIONS

Directives for energy saving and limited raw materials require an enhancement of the building's envelopes of new and existing buildings worth preserving facades included. From the building physics point of view the coupled heat and moisture transfer is to consider and the hygrothermal performance of the envelope parts should be quantified. The presentation describes the energy ordinances in Europe and the physico-mathematical situation of the coupled heat and mass transfer in capillary porous materials of building structures. The calculations are supported by modern numerical simulation methods as effective tools discussed in this paper. Besides it represents numerous examples with regard to the capillary active inside insulation, alga problems, infrared reflecting coatings, inverted roofs and damp proof membranes quantifying the hygrothermal effects. Finally an effectiveness control of the hygrothermal performance of envelope parts by means of a developed λ-needle probe is demonstrated.

8. REFERENCES

1 - Commission of the European Communities. Proposal for a directive of the European Parliament and of the Council on the energy performance of buildings. Brussels, 11.May 2001.

2 - Directive 2002/91/EC. Official Journal of the European Communities, 16.December 2002.

3 - Standard DIN EN 832. Thermal performance of buildings – Calculation of energy use for heating - Residential buildings (includes corrigenda AC:2002); German Version EN 832:1998 + AC:2002.

4 - The Energy Saving Ordinance - EnEV. Official Journal of the Government, Germany, November 2001.

5 - CUNNINGHAM. M. J., The moisture performance of framed structures: a mathematical model, Building and Environment (23) (1988) 123–135.

6 - KERESTECIOGLU A. and GU L., Incorporation of the effective penetration depth theory into TRNSYS, Draft Report, Florida Solar Energy Center, Cape Canaveral, Fl, 1989.

7 - BURCH D.M. and THOMAS W.C., An analysis of moisture accumulation in wood frame wall subjected to winter climate, NISTIR 4674, National Institute of Standards and Technology, Gaithersburg, 1991.

8 - El DIASTY R., FAZIO P. and BUDAIWI I., Dynamic modeling of moisture absorption and desorption in buildings, Building and Environment (28) (1993) 21-32.

9 - LIESEN R. J., Development of a response factor approach for modeling the energy effects of combined heat and mass transfer with vapor adsorption in building elements, Ph.D. thesis, Mechanical Engineering Department, University of Illinois, Chicago, Il, 1994.

10 - YIK F. W. H., UNDERWOOD C. P. and CHOW W. K., Simultaneous modeling of heat and moisture transfer and air-conditioning systems in buildings, Proceedings of 4th IBPSA – International Building Performance Simulation Association - Conference, Madison, WI, 1995.

11 - BUENO, A. D. Transferência de Calor e Umidade em Telhas de Cerâmica Vermelha: Simulação e Experimentação. Dissertação de Mestrado, Florianópolis, Brasil, 1994.

12 - MENDES N., WINKELMANN F. C., LAMBERTS R., PHILIPPI P.C. and CUNHA NETO J.A.B., Dynamic Analysis of Moisture Transport through Walls and Associated Cooling Loads in the Hot/Humid Climate of Florianópolis, Brazil, 10th Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth - Texas, USA, 1996.

13 - MENDES, N.; WINKELMANN, F. C.; LAMBERTS, R., Moisture Effects on Conduction Loads. Energy and Buildings, v. 35, n. 7, p. 631-644, 2003.

14 - IEA (International Energy Agency) Annex 24 Final Report, Heat, Air, and Moisture Transfer in Insulated Envelope Parts, Vol 1, Task 1: Modelling, Belgium, 1996.

15 - MENDES, N., PHILIPPI, P. C., LAMBERTS, R. A new Mathematical Method to Solve Highly Coupled Equations of Heat and Mass Transfer in Porous Media. International Journal of Heat and Mass Transfer, V. 45, p. 509-518, 2002.

16 - MENDES, N. and PHILIPPI, P. C., MultiTriDiagonal Matrix Algorithm for Coupled Heat Transfer in Porous Media: Stability Analysis and Computational Performance, Journal of Porous Media, 2003. (In press)

17 - GRUNEWALD, J.; HÄUPL, P.; STOPP, H.: Modelling of the coupled heat, air and moisture transfer in porous building materials – Application to building structures. Proceedings of the Building Physics Conference in the Nordic Countries, Helsinki 1996.

18 - GRUNEWALD, J: Diffusiver und konvektiver Stoff- und Energietransport in kapillarporösen Baustoffen. Ph.D. thesis, TU Dresden 1997, Germany.

19 - HÄUPL, P.;PLAGGE,R.; FECHNER,H.: "Hygrische Materialfunktionen von porösen Baustoffen". Gesundheitsingenieur 122(2001), H6, page 305-315.

20 - PHILIP J. R. and DE VRIES D. A., Moisture movement in porous materials under temperature gradients, Transactions of the American Geophysical Union 38, n.2, 222-232, 1957.

21 - MENDES N., RIDLEY I., LAMBERTS R., PHILPPI P.C. and BUDAG K., UMIDUS: A PC Program for the Prediction of Heat and Moisture Transfer in Porous Building Elements, Building Simulation Conference – IBPSA 99, p. 277-283,Kyoto, Japan, 1999.

22 - PERRIN B., Etude des Transferts Couplés de Chaleur et de Masse dans des Matériaux Poreux Consolidés non-Saturés Utilisés en Génie Civil", Thèse Docteur d'Etat, Université Paul Sabatier de Toulouse, Toulouse, France, 1985.

23 - HÄUPL, P.; STOPP, H; STRANGFELD, P : Internat. Energy Agency, Annex 32. Integral Building Envelope Performance Assement. Retrofitting, Internal Report STB – D –99/1.

24 - STOPP, H.; STRANGFELD, P. and FECHNER, H.; HÄUPL,P.: The hygrothermic performance of external walls with inside insulation systems. Proceedings of the Performance of exterior envelopes of whole buildings VIII conference, Clearwater Beach, Dec. 2 – 7, 2001, FL. USA.

25 - STOPP, H.; STRANGFELD, P., HÄUPL, P.; FECHNER, H.: In-situ Measurement of Moist Materials by means of λ-Needle Probe, Proceedings of the 5th Asian Thermophysical Conference, Seoul 98.