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Stavebně fyzikální chování dvouplášťových konstrukcí

The hygrothermal behaviour of building constructions with a ventilated air layer

SUMMARY

The first part of the presented publication briefly describes principles of the hygrothermal function of building constructions with a ventilated air layer. Typical defects of these cold deck constructions are also briefly discussed.

In the main body of the text, the most important sources of hygrothermal defects of the cold deck constructions are described. The first cause being discussed is the influence of higher requirements on thermal protection of buildings, which lead to lower air temperatures in the ventilated air layer and subsequently to the lower ability of this air to absorb water vapour and dissipate it out of the construction. The second cause of defects is the permeable inner deck of the cold deck constructions. Any leakage, imperfection, crack or absence of water vapour or wind barrier leads to considerable increase of heat and water vapour transport through the inner deck. This higher transport is caused mainly by the air convection – either by infiltration (external air flowing into construction) or by exfiltration (internal air flowing to exterior). In both cases, the results are higher heat loss of the adjacent room, discomfort of dwellers and extremely high risk of water vapour condensation either on the outer deck of the cold deck construction (exfiltration) or on the internal surface of the construction (infiltration). Generally, the air exfiltration is more risky than infiltration but in both cases, the condensation rate may be even many times higher than in the case of tight construction. The presented publication shows some case studies, which clearly document the importance of convective heat and water vapour transport through the permeable inner deck. The third discussed cause of defects is the insufficiently ventilated air layer (due to small openings, insufficient vertical distance between openings or due to blocked air layer), which leads again to problems with water vapour condensation on the outer deck. The last discussed cause of defects is the design of the outer deck with insignificant thermal inertia and resistance, such as corrugated steel sheets. The water vapour condensation occurs on such decks occasionally even if the rest of the construction is excellently designed. The reason for this phenomenon is the long-wave radiant heat exchange between the outer deck and the sky vault, especially during clear nights with a very humid outside air.

The third part of the publication contains a brief overview of the calculation procedures for the evaluation of the cold deck constructions (methods from the technical standards and more precise CFD models).

The last part is focused on the recommended solutions for the design of the cold deck constructions. The most important rules are recapitulated – from the importance of inner deck's impermeability to the recommended thermal resistance of the outer deck.

SOUHRN

V první části předložené práce jsou stručně popsány principy tepelně-vlhkostní funkce dvouplášťových konstrukcí s větranou vzduchovou vrstvou. Stručně komentovány jsou i typické poruchy těchto konstrukcí.

V hlavní části textu jsou popsány nejdůležitější příčiny tepelně-vlhkostních poruch dvouplášťových konstrukcí. První popsanou příčinou poruch jsou vyšší požadavky na tepelnou ochranu budov, které způsobily snížení teploty vzduchu ve větrané vrstvě oproti minulosti a následně vedly k nižší schopnosti větracího vzduchu absorbovat vodní páru a bezpečně ji odvádět do exteriéru. Druhou diskutovanou příčinou poruch je netěsný vnitřní plášť. Každá netěsnost, trhlina nebo absence parozábrany či vzduchotěsné vrstvy vede k významnému nárůstu transportu vodní páry a tepla vnitřním pláštěm. Tento vyšší transport je způsoben hlavně prouděním vzduchu – ať už infiltrací (vnější vzduch proniká do konstrukce), nebo exfiltrací (vnitřní vzduch proniká do exteriéru). V obou případech je výsledkem vyšší tepelná ztráta přilehlé místnosti, diskomfort obyvatel a extrémně vysoké riziko kondenzace vodní páry – a to buď na vnějším plášti (při exfiltraci), nebo na vnitřním povrchu konstrukce (při infiltraci). Obecně je exfiltrace rizikovější než infiltrace, ale v obou případech může být míra kondenzace vodní páry v konstrukci i řádově vyšší než v případě těsné konstrukce. Předložená publikace obsahuje několik modelových výpočtů, které jasně dokumentují význam konvektivního přenosu tepla a vodní páry propustným vnitřním pláštěm. Třetí diskutovanou příčinou poruch je nedostatečně větraná vzduchová vrstva (kvůli malým větracím otvorům, malému převýšení mezi větracími otvory či kvůli ucpané vzduchové vrstvě), což může opět způsobovat kondenzaci vodní páry na vnějším plášti. Poslední diskutovanou příčinou poruch je návrh vnějšího pláště se zanedbatelnou tepelnou setrvačností a tepelným odporem (například trapézové plechy). Na těchto pláštích se kondenzace vodní páry vyskytuje příležitostně v průběhu roku, a to i tehdy, když jsou zbylé části dvouplášťové konstrukce navrženy bez chyb. Příčinou tohoto jevu je totiž dlouhovlnná výměna tepla sáláním mezi vnějším pláštěm a oblohou, která je nebezpečná zvláště za jasných nocí s velmi vlhkým vnějším vzduchem.

Ve třetí části práce je uveden stručný přehled výpočetních postupů pro ověření návrhu a chování dvouplášťových konstrukcí (metody z technických norem a přesnější CFD modely).

Poslední část práce je zaměřena na doporučená řešení návrhu dvouplášťových konstrukcí. Jsou zde zrekapitulovány nejdůležitější pravidla návrhu – od významu zajištění těsnosti vnitřního pláště po doporučené tepelné odpory pláště vnějšího.

Klíčová slova: stavební fyzika, dvouplášťové konstrukce, šíření tepla, šíření vodní páry, kondenzace vodní páry, numerické modelování

Keywords: building physics, constructions with ventilated air layer, heat transport, water vapour transport, water vapour condensation, numerical modelling

ISBN

CONTENTS

1. INTRODUCTION

The building constructions with a ventilated air layer between the inner and the outer decks (layers) of the construction (Fig. 1) are usually designed in order to prevent the water vapour condensation in the external cold parts of the construction during the wintertime. The expected function of these constructions is based on the use of the external air, the current of which is used to dissipate water vapour migrating through the internal deck.

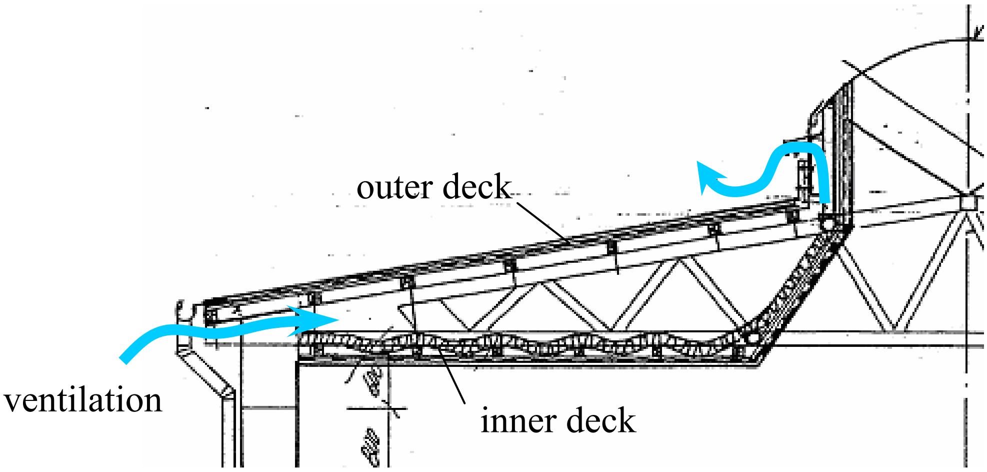


Fig. 1 Scheme of a roof with a ventilated air layer

The inner deck of the construction ensures the thermal protection (it has to fulfil the requirements on the thermal transmittance expressed usually as the required U-value), the outer deck ensures the protection against climatic impacts, mainly the rain and the snow. The ventilated air layer ensures that no water vapour condensation occurs in the construction – or at least it should ensure that.

This concept is on the first sight very simple and functional. The cold deck constructions (another commonly used nomenclature for the constructions with a ventilated air layer) are therefore frequently recommended for the buildings with a moist internal climate in many publications and even technical standards.

In spite of the prevailing technical opinions, the cold deck constructions are in fact very difficult to design. Every fault in their design leads very quickly to the fatal defects in their hygrothermal behaviour. The speed of condensation defects can be really astounding – it is not exceptional that the water vapour condensation in the ventilated air layer and on the surfaces of the external deck is detected during only several months after completion of the building. In the case of the roofs, the water droplets then fall back on the thermal insulation in the inner deck and then even through the inner deck to interior. The damage from such water dripping can be very serious.

2. SOURCES OF DEFECTS

2.1 Higher requirements on thermal protection of buildings

The first cause of such hygrothermal defects of cold deck constructions is rather surprising. The continuously increasing requirements on the thermal protection of buildings lead to the reduction of the temperatures in the ventilated air layer and the still colder air is able to absorb less and less water vapour before it becomes saturated. The result is much more higher risk of water vapour condensation in the recent cold deck constructions than in the older ones.

Let us see some informative values. In the period from 1983 to 1994, the required U-value for the light-weight roof in the Czech Republic was 0,50 W/(m^2.K). This value was guaranteed by the dimension of the thermal insulation in the inner deck of the construction (typically 80 mm). The mean air temperature in the ventilated air layer of a typical roof was in that period around 5 °C above the outside air temperature. The revision of requirements in 1994 changed the required U-value of the light-weight roof to 0,27 W/(m^2.K). This change caused the decrease of a typical mean temperature in the ventilated air layer approximately by 2 °C in comparison with the previous period. At present time, the required U-value of the light-weight roof is 0,24 W/(m^2.K) and a typical mean temperature of the air in the ventilated air layer is only approximately 2 °C above the external air temperature.

The presented rough changes in the mean temperature of the ventilated air layer show how much the ability of the air to absorb the water vapour had decreased. While the air with temperature of -10 °C (typical mean temperature in the ventilated air layer in winter with outside temperature -15 °C in the period prior to 1994) can absorb almost 2 g of water vapour per 1 kg of dry air until it becomes saturated, the air with temperature of -13 °C can absorb only a little above 1 g of water vapour.

The risk of water vapour condensation in the ventilated air layer and on the internal surface of the outer deck is therefore much more higher in the case of recent cold deck constructions than it used to be in the case of older ones.

2.2 Permeable inner deck

The cracks, leakages, openings, absenting water vapour and/or wind barriers or other imperfections in the inner deck of the construction with a ventilated air layer make the inner deck permeable both for the air and the water vapour transport (Fig. 2) – especially in the case when the permeable thermal insulation as rock wool is used. This permeability is a highly serious problem because the heat and water vapour transport caused by convection through the leakages can considerably increase the amount of water vapour migration through the construction and subsequently lead to severe damages.

Fig. 2 Leakages in the wind barrier

The air convection through the permeable construction can be oriented towards the interior (infiltration) or towards the exterior (exfiltration). In both cases, the air convection leads to a higher heat loss of adjacent room, discomfort of occupants and even more seriously also to a high condensation risk. In the case of exfiltration, the condensation risk is especially extreme – the most threatened parts of the construction are located on the external side (internal surface of the outer deck, external layers of the inner deck). In the case of infiltration, the internal surface of the inner deck is most in danger from the point of view of the water vapour condensation (Fig. 3).

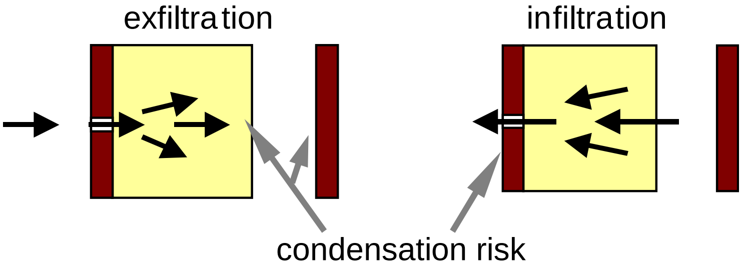


Fig. 3 Infiltration and exfiltration through the cold deck wall

Let us discuss some problems of the **combined heat and moisture transport caused by coupled conduction (diffusion) and convection** through the permeable inner deck more in detail.

The heat transfer caused by conduction and convection is governed by the so-called convective-diffusion equation, which can be expressed for the case of the two-dimensional steady-state heat transport in a porous medium as

$$\lambda \cdot \nabla^2 \theta - \rho_a c_a \vec{v} \cdot \nabla \theta = 0 \qquad (1),$$

where λ is thermal conductivity in W/(m.K), θ is temperature in °C, ρ_a is the air density in kg/m^3, c_a is thermal capacity of the air in J/(kg.K) and $\vec{v}$ is vector of air flow velocity in m/s.

The Newton type boundary condition connected to equation (1) is defined as

$$-\lambda\frac{\partial\theta}{\partial n}+v_n\rho_a c_a\left(\theta-\bar{\theta}\right)=h\left(\theta-\bar{\theta}\right) \quad (2),$$

where v_n is velocity component normal to the boundary in m/s, $\bar{\theta}$ is known temperature in the environment adjacent to the boundary in °C and h is heat transfer coefficient in W/(m^2.K).

The combined water vapour transport through the permeable inner deck caused by diffusion and convection can be similarly described by another type of convective-diffusion equation

$$\frac{D}{\mu}\nabla^2\rho_v-\vec{v}\cdot\nabla\rho_v=0 \quad (3),$$

where D is water vapour diffusion coefficient in air in m^2/s, μ is water vapour resistance factor, ρ_v is partial water vapour density in kg/m^3.

The Newton boundary condition for the equation (3) can be defined as

$$-\frac{D}{\mu}\frac{\partial\rho_v}{\partial n}+v_n\rho_v=\beta\left(\rho_v-\bar{\rho}_v\right) \quad (4),$$

where β is water vapour boundary transfer coefficient in m/s and $\bar{\rho}_v$ is known partial water vapour density at element boundary in kg/m^3.

The numerical solution of the equations (1) and (3) with the boundary conditions (2) and (4) can be derived using the following assumptions:

- water vapour and heat transport is steady-state and two-dimensional
- convection of air through the building construction is caused only by pressure difference
- air is incompressible
- flow of air is linear according to Darcy´s Law

  $$\vec{v}=-\frac{k}{\eta}\vec{\nabla}P \quad (5),$$

  where k is permeability of the porous medium in m^2, η is dynamic viscosity of the air in Pa.s and P is air pressure in Pa.
- pressure distribution is governed by Laplace equation

  $$k\cdot\nabla^2P=0 \quad (6).$$

The equations (1) and (3) belong to the family of convective-diffusion equations. It is always more complicated to find the numerical solution of such equations than to find the solution of the related usual diffusion equation. The main cause is the convective transport term, which can - under certain conditions - produce instabilities in the numerical solution.

If the finite element method (FEM) is used to obtain **the numerical solution** of the equations (1) and (3), the general finite element formulation must be derived by means of the Petrov-Galerkin process, which is one of the weighted residuals methods. Therefore, the derivations of the finite element formulations start with the following conditions

$$\int_{\Omega^{(e)}} \left[\lambda \nabla^2 \theta - \rho_a c_a \vec{v} \cdot \nabla \theta\right] \cdot W \, \mathrm{d}\Omega = 0 \qquad (7)$$

$$\int_{\Omega^{(e)}} \left[\frac{D}{\mu} \nabla^2 \rho_v - \vec{v} \cdot \nabla \rho_v\right] \cdot W \, \mathrm{d}\Omega = 0 \qquad (8)$$

which are also the mathematical expressions of the requirement that the residuals of the numerical solutions of the equations (1) and (3) must be orthogonal to the weighting functions *W*.

The unknown functions ρ_v and θ in equations (7) and (8) are taken as approximations

$$\rho_v = N_i^T \cdot \rho_{v,i} \text{ and } \theta = N_i^T \cdot \theta_i \qquad (9).$$

While interpolation functions N_i are known functions depending on the type of the chosen finite elements, weighting functions W_i must be derived from the following equation recommended by Zienkiewicz in [19]

$$W_i = N_i + \varepsilon \frac{b}{2} \frac{v_x \frac{\partial N_i}{\partial x} + v_y \frac{\partial N_i}{\partial y}}{|v|} \qquad (10),$$

where b is size of a finite element in the velocity direction in m and v_x and v_y are velocity components in the x-axis and y-axis directions in m/s.

Now, if the value of ε is chosen as

$$\varepsilon = \coth Pe - \frac{1}{Pe} \qquad (11),$$

where Pe is Peclet number, then according to Zienkiewicz numerical oscillations do not arise for any possible rate between convective and diffusive water vapour transport. The general finite element formulations can be finally derived from the equations (7) and (8) by means of integration by parts and by means of introduction of the boundary conditions (2) and (4). The final general FEM formulations are

- for the case of heat transfer:

$$\left(K_\lambda + K_v + K_\alpha\right)\cdot \theta_i = q_\alpha \qquad (12)$$

- for the case of water vapour transfer:

$$\left(K_D + K_v + K_\beta\right)\cdot \rho_{v,i} = q_\beta \qquad (13).$$

The diffusion matrices K_λ and K_D are defined as

$$K_\lambda = \int_{\Omega^{(e)}} \lambda\left(\frac{\partial W_i}{\partial x}\frac{\partial N_i^T}{\partial x} + \frac{\partial W_i}{\partial y}\frac{\partial N_i^T}{\partial y}\right)\mathrm{d}\Omega \text{ and } K_D = \int_{\Omega^{(e)}} \frac{D}{\mu}\left(\frac{\partial W_i}{\partial x}\frac{\partial N_i^T}{\partial x} + \frac{\partial W_i}{\partial y}\frac{\partial N_i^T}{\partial y}\right)\mathrm{d}\Omega$$

the convective transport matrices K_v as

$$K_v = \int_{\Omega^{(e)}} \rho_a c_a\left(v_x W_i \frac{\partial N_i^T}{\partial x} + v_y W_i \frac{\partial N_i^T}{\partial y}\right)\mathrm{d}\Omega \text{ and } K_v = \int_{\Omega^{(e)}}\left(v_x \cdot W_i \frac{\partial N_i^T}{\partial x} + v_y \cdot W_i \frac{\partial N_i^T}{\partial y}\right)\mathrm{d}\Omega,$$

the boundary conditions matrices K_α and K_β as

$$K_\alpha = \int_{\Gamma^{(e)}} \left(h - v_n \rho_a c_a\right) W_i N_i^T \,\mathrm{d}\Gamma \text{ and } K_\beta = \int_{\Gamma^{(e)}} \left(\beta - v_n\right) W_i N_i^T \,\mathrm{d}\Gamma$$

and the boundary conditions vectors q_β and q_β as

$$q_\alpha = \int_{\Gamma^{(e)}} \left(h - v_n \rho_a c_a\right) W_i \bar{\theta} \,\mathrm{d}\Gamma \text{ and } q_\beta = \int_{\Gamma^{(e)}} \beta \cdot W_i \cdot \bar{\rho}_v \,\mathrm{d}\Gamma .$$

Note that the convective transport matrices K_v are asymmetrical, which leads to the asymmetrical matrices of the linear equations system for unknown nodal values $\rho_{v,j}$ and θ_j.

Special attention must be paid to the **calculation of the final values of the partial water vapour densities**. The field of partial water vapour densities $\rho_{v,i}$ calculated from the equation (13) is correct only in the case with no interstitial condensation – in other words, when the following condition is met in any part of the solved area

$$\rho_v < \rho_{v,sat} \qquad (14),$$

where $\rho_{v,sat}$ is saturated partial water vapour density in kg/m^3. Otherwise, the water vapour condensation occurs in the building construction and the calculated field of partial water vapour densities is deformed according to this fact. The simplified iteration process can be used to obtain the area of water vapour condensation and the final field of partial water vapour densities. This iteration process is based on the condition

$$\rho_v \le \rho_{v,sat} \qquad (15)$$

which can be expressed also as requirement that the partial water vapour density cannot in any part of the construction exceed the saturated partial water vapour density. The iteration process itself can be programmed in the following steps:

- at first, the field of partial water vapour densities and the field of saturated partial water vapour densities are calculated separately and compared – the result of comparison shows if the water vapour condensation occurs in the construction
- if there is condensation, the maximum difference between partial water vapour density and the saturated partial water vapour density is found
- the value of saturated partial water vapour density is then introduced as Dirichlet type of boundary condition in the mesh node with this maximum difference and the whole calculation of partial water vapour density field is repeated
- the newly calculated field of partial water vapour densities is afterwards compared with known field of saturated partial water vapour densities in order to find out if there are still mesh nodes where the partial water vapour density exceeds the maximum limit
- if yes, the maximum difference is found again and the calculation of partial water vapour density field is repeated with all the existing and new Dirichlet conditions.

The iteration process continues until the condition (15) is fulfilled with chosen accuracy in all mesh nodes. Convergence of this iteration is reliable and quite rapid. The result of the iteration process is the field of partial water vapour densities in the construction with interstitial water vapour condensation. More common field of relative humidities can be calculated from

$$\varphi = \frac{\rho_v}{\rho_{v,sat}} \cdot 100 \qquad (16).$$

It can be seen from the already described methods and equations that the temperature field must be determined at first because the saturated partial water vapour density is calculated using equation

$$\rho_{v,sat} = \frac{p_{sat}}{461{,}9 \cdot (273{,}15 + \theta)} \qquad (17),$$

where p_{sat} is saturated partial water vapour pressure in Pa (function of the temperature).

After necessary introduction to numerical modelling, it is possible to discuss the effects of combined convective-conductive heat and water vapour transport in permeable inner decks of the constructions with a ventilated air layer using some **case studies**. Let us consider a typical slope roof construction with a thermal insulation between the rafters (Tab. 2) and let us take a closer look on the hygrothermal behaviour of its inner deck.

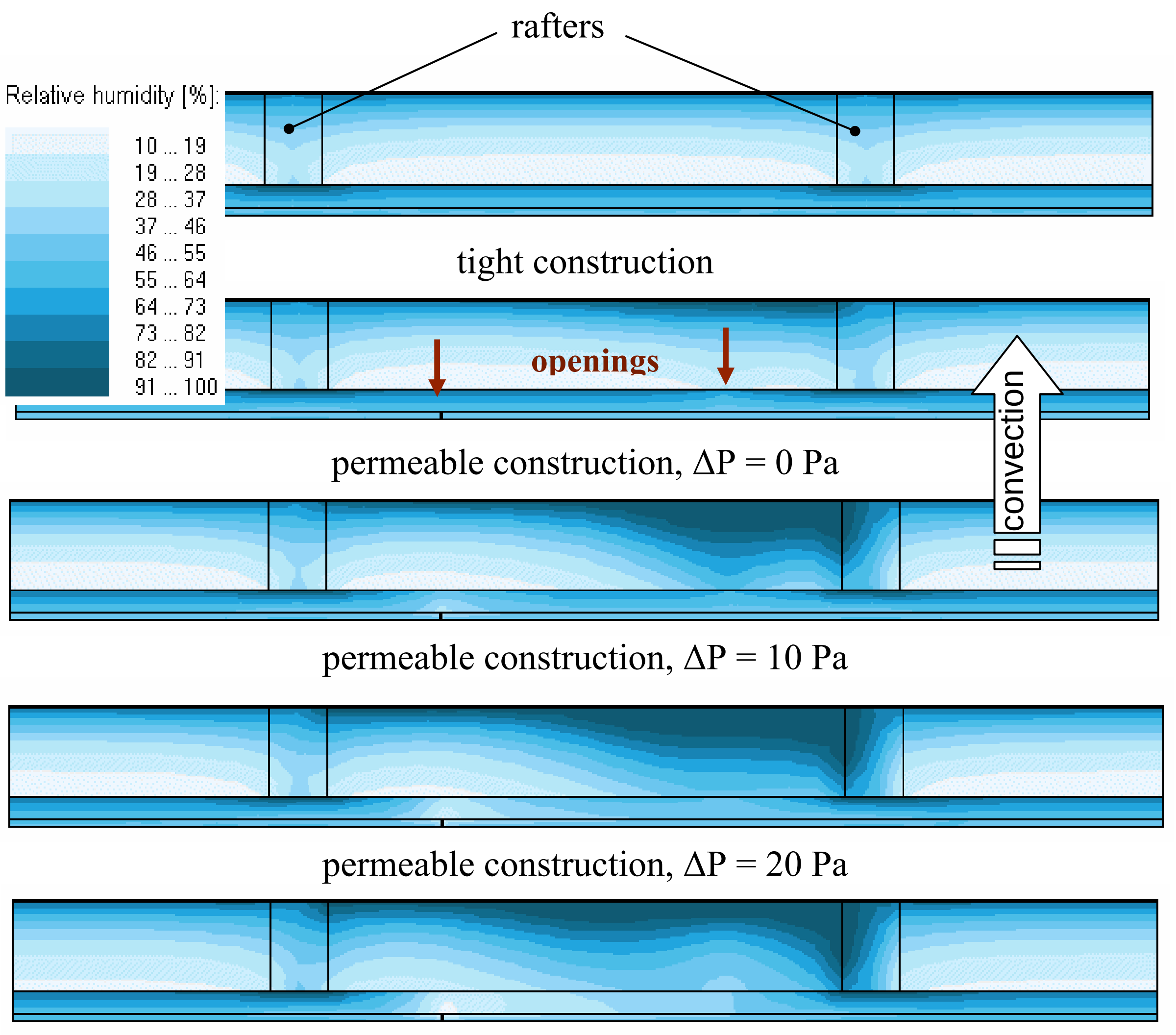
Table 2 Layers of the analyzed construction

Layer	Thickness [mm]	Thermal conductivity [W/(m.K)]	Equivalent diffusion thickness [m]	Permeability [m^2]
Roof tiles	Not considered in calculation			
Ventilated air layer				
Waterproof barrier	0.1	0.21	0.02	10^{-12}
Mineral wool	160	0.04	0.18	10^{-9}
Vapour barrier	0.1	0.21	1.44	10^{-17}
Mineral wool	40	0.04	0.04	10^{-9}
Plasterboard	12.5	0.22	0.11	10^{-12}

There is no major risk of huge interstitial condensation in this model construction if the water vapour barrier is tight. On the other hand, if the water vapour barrier is perforated, the situation can be quite different. Let us suppose that in the plasterboard and in the water vapour barrier are relatively small openings 1 mm wide – and to be more realistic – these openings are located in the distance of 500 mm. The safety waterproof barrier is considered tight (with loosely overlapped partial layers).

The calculated relative humidity fields in this model construction for the air exfiltration caused by various pressure gradients are shown on Fig. 4. The results are valid for the external air with temperature -15 ˚C and relative humidity 84% and for internal air with temperature 21 ˚C and relative humidity 50%. The water vapour condensation zone for the pressure difference of 40 Pa is very interesting. The apparent reduction of this zone in comparison with the zones for the lower pressure gradients is caused by higher heat transport through the leaky construction (Fig. 5). However, this higher heat transport does not lead to analogous reduction of water vapour condensation rate as can be seen in Fig. 7 – the only effect is the displacement of the condensation zone to colder parts of the construction. While the air exfiltration causes obvious enlargement of the water vapour condensation zone, the air infiltration leads to more subtle changes in the extent of the condensation zone (Fig. 6). Nevertheless, the water vapour condensation rate rises up in both cases as the pressure difference gradually moves to higher levels (Fig. 7).

Although the increase of the water vapour condensation rate is substantial mainly in the case of air exfiltration (e.g. for the pressure difference of 40 Pa, the condensation rate is about 15-times higher than for the case of tight construction), it is not negligible also in the case of air infiltration.



tight construction

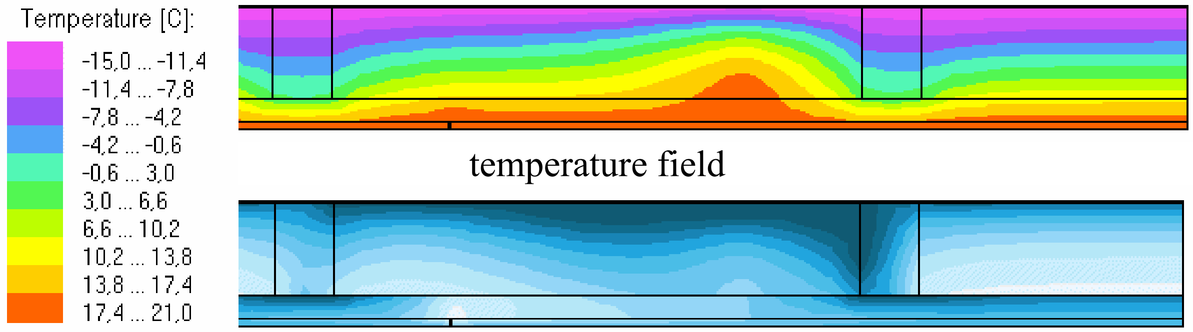
permeable construction, ΔP = 0 Pa

permeable construction, ΔP = 10 Pa

permeable construction, ΔP = 20 Pa

permeable construction, ΔP = 40 Pa

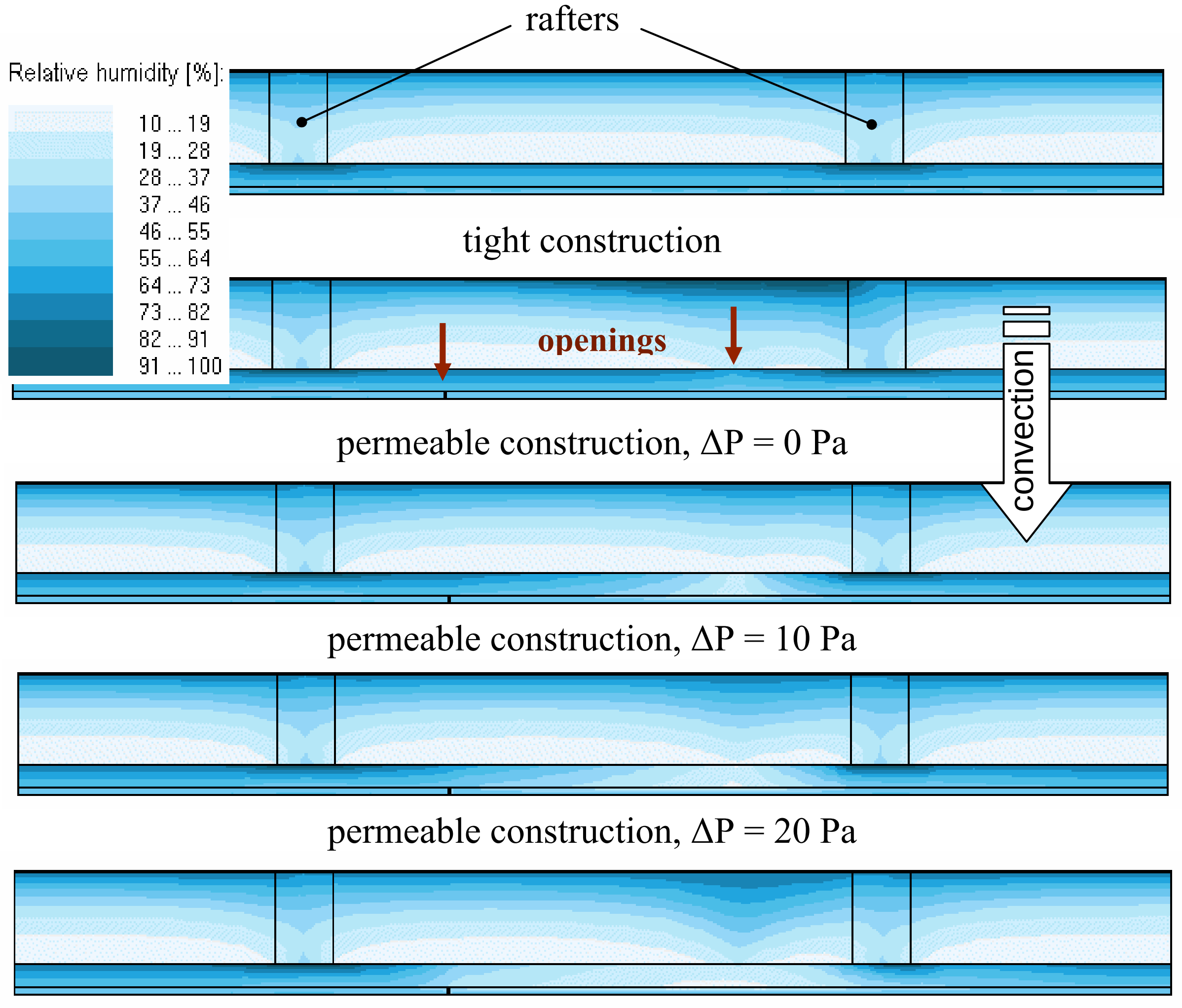
Fig. 4 Relative humidity field in the slope roof construction – the case of air exfiltration



temperature field

relative humidity field

Fig. 5 Various fields for exfiltration through the slope roof caused by pressure gradient of 40 Pa



tight construction

permeable construction, ΔP = 0 Pa

permeable construction, ΔP = 10 Pa

permeable construction, ΔP = 20 Pa

permeable construction, ΔP = 40 Pa

Fig. 6 Relative humidity field in the slope roof construction – the case of air infiltration

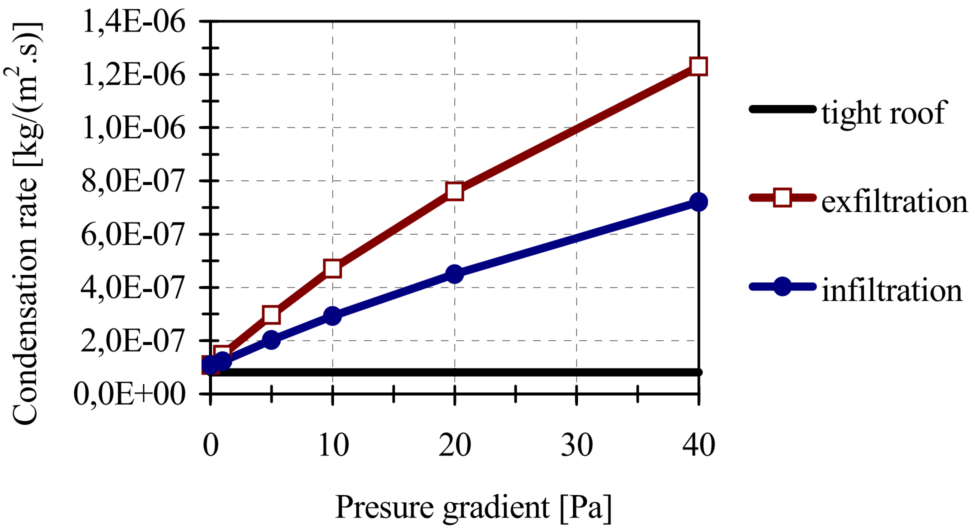


Fig. 7 Water vapour condensation rate

These effects are caused almost exclusively by convection because the increased diffusion through the openings leads itself to the increase of condensation rate only around 33% (Fig. 7).

Let us take a look also on the effects of the convection on the **increase of the U-value** of the inner deck. The model construction has no water vapour or wind barrier this time. It is a simple slope roof with thermal insulation from 160 mm thick rock wool placed between the rafters and covered from inside by a plasterboard. Material characteristics of this construction are the same as in the case of previous model construction. Fig. 8 shows the dependency of this construction's U-value on the loading pressure gradient during infiltration. It can be seen that even in the case of tight construction, the air convection through the permeable thermal insulation causes the increase of U-value (approximately 10% for the pressure difference of 20 Pa). This increase is much more higher in the case of permeable plasterboard. If the area of leakages reaches 0.2% from the total construction area, the U-value of such un-tight construction can be higher by 170% (!) in comparison with the same tight construction.

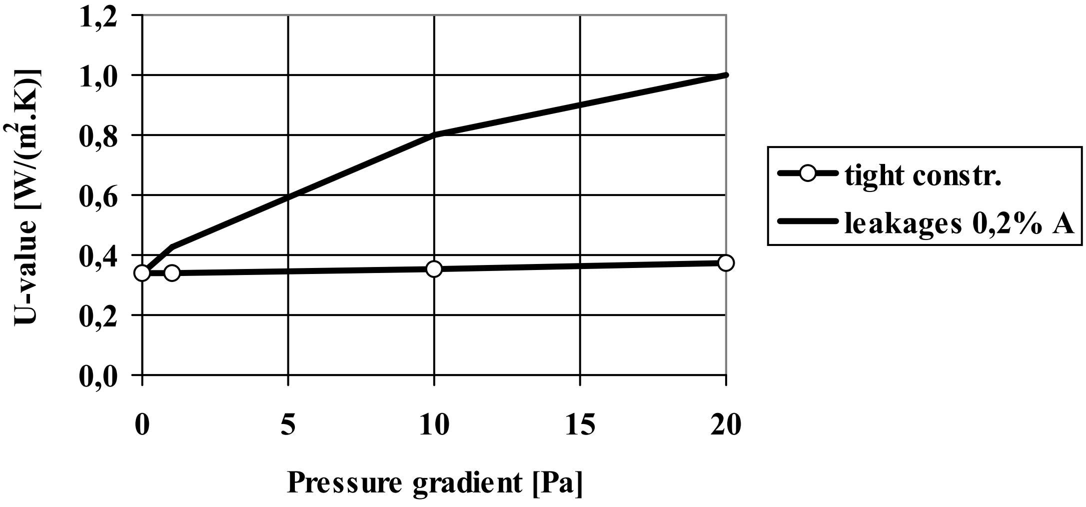


Fig. 8 The U-value of the model construction

2.3 Insufficiently ventilated air layer

Another cause of the defects is insufficiently ventilated air layer – either due to inadequately small openings to the ventilated layer, unsatisfactorily small vertical distance between the openings or due to blocked air layer by incorrectly placed thermal insulation. The results are again very serious – the originally designed cold deck construction with a ventilated air layer acts in fact as warm deck construction with closed air layer, which is exposed to a high risk of water vapour condensation on the internal surface of the outer deck.

2.4 Outer deck with insignificant thermal inertia and resistance

If the outer deck of a cold deck construction is made of material with a low thermal inertia and resistance (such as corrugated steel sheets) the water vapour condensation occasionally occurs on this part of the construction regardless on the quality of the design and realisation of the rest of the construction. This problem concerns mainly the cold deck roofs.

The reason for this condensation appearance is the long-wave radiant heat transfer between the construction and the sky vault – especially during unclouded nights when the outside air humidity is very high. The radiant heat flow from the construction to the sky and back is not in balance as is in principle in the case of the radiant heat exchange between the construction and the other buildings and objects on the Earth's surface. The heat flow, which the sky vault takes away from the construction, can be - according to several published measurements [8], [11] - up to 80 W/m^2. This heat loss can cause the decrease of the outer deck temperature by more than 2 °C. Moreover, this decrease is in some conditions (humid external air) high enough to cause the condensation of the water vapour contained in the external air on both sides of the outer deck.

3. CALCULATION PROCEDURES

The basic technical calculation procedures for the evaluation of the cold deck constructions can be found in Czech and Slovak standards ČSN 730540-4 and STN 730540-4 (it is interesting in this context that no similar European standard concerning this subject exists and so far is also not under preparation). These procedures were derived from the simple principles of pressure, heat and moisture balances in the differential part of the construction with a ventilated air layer. They can be used for the basic evaluation without problems and they are usually sufficient for the purposes of the common design process.

For the more ambitious evaluation, the CFD (computational fluid dynamics) programs can be used. It is possible to calculate more precisely the temperature distribution and also the heat flows (and subsequently the U-value) of the cold deck constructions by means of such software tools. The CFD modelling is even irreplaceable in the case of evaluation of the special types of cold deck constructions such are the double facades.

One example of the U-value calculation for the special ventilated window construction using CFD modelling is presented on Fig. 9. The window on this figure is a model of a window with intentionally ventilated air layer designed for the refurbishment of the Bata skyscraper in Zlín, which has been evaluated using CFD modelling from several points of view. The calculated U-value of this window reaches from 0.9 W/(m^2.K) in the case of only naturally ventilated air layer to 1.4 W/(m^2.K) in the case of very heavy ventilation.

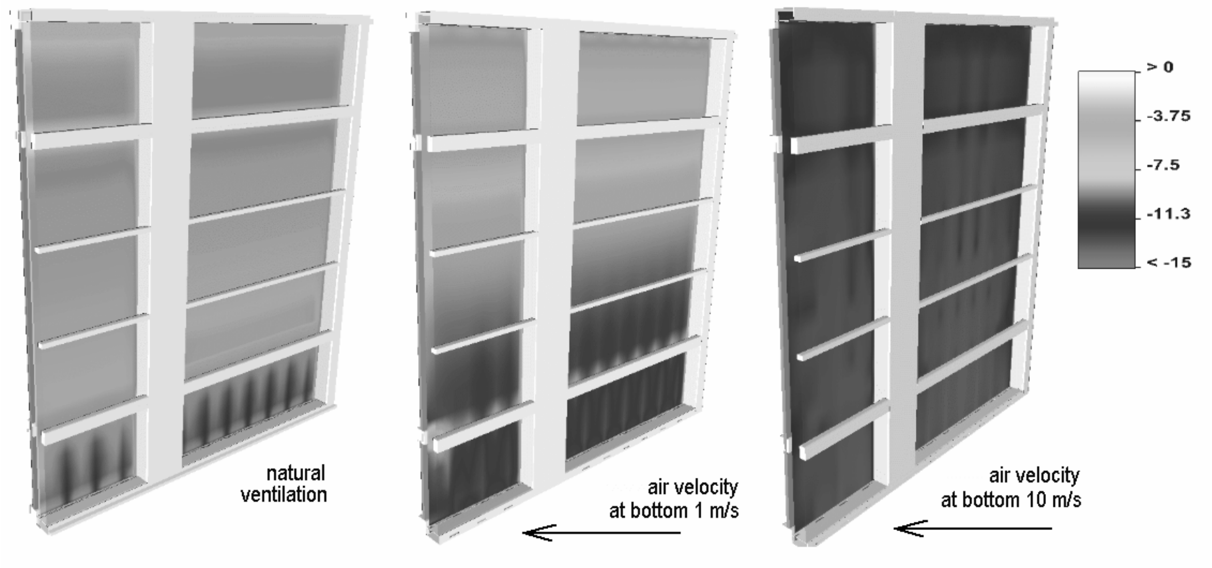


Fig. 9 Temperature field in the centre of a ventilated air space

4. RECOMMENDED SOLUTIONS

The most important issue during the design process of the construction with a ventilated air layer is to ensure that the inner deck of the construction will be air-tight and water vapour-tight after completion of the building.

The openings to the ventilated air layer must be at the same time sufficiently large – their area have to be at least 1/100 of the area of the ventilated construction. Highly recommended is the design of the vertical difference between openings so the natural ventilation will be possible due to stack effect.

The ventilated air layer itself must be open in its whole length, with no obstacles and sufficiently thick (40-50 mm at least).

The thermal resistance of the outer deck should not be irrelevant – the value of 0.2 m^2.K/W is commonly recommended as a minimum measure which can lower the risk of water vapour condensation caused by long-wave radiation exchange between the construction and the sky vault. Still, even in the case of thermally insulated outer decks, the use of safety waterproof barrier is recommended.

If the above-mentioned rules cannot be fulfilled, it is extremely risky to continue with the design of the cold deck construction. The warm deck construction without air layer is in that case usually better solution.

REFERENCES

[1] Bittnar, Z.: Metody numerické analýzy stavebních konstrukcí. ČVUT Praha 1983.

[2] Bittnar, Z. – Šejnoha, J.: Metoda konečných prvků I. ČVUT Praha 1991.

[3] Claesson, J.: Forced Convective-Diffusive Heat Flow in Insulations, A New Analytical Technique. In: Proc. of the 3rd Symposium Building Physics in the Nordic Countries, Vol. 1, TU of Denmark, Copenhagen 1993, pp.137-144.

[4] Hagentoft, C.E.: Thermal Effects Due to Air Flows in Cracks. In: Proc. of the 3rd Symposium Building Physics in the Nordic Countries, Vol. 1, TU of Denmark, Copenhagen 1993, pp. 153 - 160.

[5] Hagentoft, C.E. – Blomberg, T.: 1D-HAM – Coupled Heat, Air and Moisture Transport in Multi-layered Wall Structures – Manual with brief theory and an example, Lund-Gothenburg Group for Computational Building Physics, Lund 2000.

[6] Halahyja, M. – Chmúrny, I. – Sternová, Z.: Stavebná tepelná technika – Tepelná ochrana budov. Jaga Bratislava 1998.

[7] Huebner, K.H. – Thornton, E.A.: The Finite Element Method for Engineers. John Wiley & Sons, New York 1982.

[8] Chyský, J. – Hemzal, K. a kol.: Větrání a klimatizace. Bolit - B Press Brno 1993.

[9] Janák, M.: Simulácia transparentnej dvojplášťovej vetranej fasády. In: Sborník 2. národní konference IBPSA-CZ „Simulace budov a techniky prostředí“, Praha 2002, str. 59-64.

[10] Kolektiv: Technicko – fyzikální analýza staveb – Pomůcka pro cvičení. ČVUT Praha 1991.

[11] Künzel, H.M. – Schmidt, T. – Holm, A.: Exterior Surface Temperature of Different Wall Constructions - Comparison of Numerical Simulation and Experiment. In: Proceedings of the 11th Symposium of Building Physics, pp. 441-449, Dresden 2002.

[12] Mrlík, F.: Vlhkostné problémy stavebných materiálov a konštrukcií. Alfa SNTL Bratislava 1985.

[13] Svoboda, Z.: Aplikační programy pro stavební fyziku. Svoboda Software Kladno 1991-2005.

[14] Svoboda, Z.: The Analysis of the Convective-Condutive Heat Transfer in the Building Constructions, In: Proceedings of the 6th IBPSA Building Simulation Conference, Vol. I, Kyoto 1999, pp. 329-335.

[15] Svoboda, Z.: The Convective-Diffusion Equation and Its Use in Building Physics. In: International Journal on Architectural Science. Vol. 1, No. 2 (2000), pp. 68-79.

[16] Svoboda, Z.: Využití CFD výpočtů pro stanovení součinitele prostupu tepla dvojitého okna. In: Tepelná ochrana budov. 6, č. 4 (2003), s. 20-22.

[17] Svoboda, Z. - Tywoniak, J.: Refurbishment of BATA-Skyscraper in Zlín, Czech Republic - Building Physics Analysis as a Design Supporting Tool, In: CISBAT 2003 Proceedings - Innovation in Building Envelopes and Environmental Systems, pp. 125-130, Laussanne 2003.

[18] Svoboda, Z.: Vliv šíření vzduchu prouděním na tepelně vlhkostní chování konstrukcí, In: Sborník materiálů 11. mezinárodní konference Tepelná ochrana budov 2004, pp. 27-32, Praha 2004.

[19] Zienkiewicz, O.C. - Taylor, R.L.: The Finite Element Method, Fourth Edition, Vol. 1 & 2. McGraw - Hill Book Company, London 1991.

[20] Technical standards cited in the text.

Curriculum vitae

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Education:

- MSc. (Ing.) 1991, Czech Technical University in Prague, Faculty of Civil Engineering
- PhD. (Dr.) 1997, Czech Technical University in Prague, Faculty of Civil Engineering

Professional Positions:

- since 1991: development and distribution of building physics programs, consultation activities, building physics calculations and evaluations
- 1991 – 1993: postgraduate student at the Department of Building Structures, Faculty of Civil Engineering, CTU Prague
- 1993 – 2004: lecturer at the Department of Building Structures, Faculty of Civil Engineering, CTU Prague
- since 2004: senior lecturer at the Department of Building Structures, Faculty of Civil Engineering, CTU Prague

Technical Interests:

- Building physics, mainly thermal protection of buildings; development of specialised software; consultations; expert evaluations and calculations; technical standardisation

Teaching Activities:

- Building physics, building constructions, project design

Visiting Positions:

- 1992: study stay at the Department of Building Structures of the Technical University of Denmark at Lyngby
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Research projects:

- Cooperation on the research projects No. 1 MSM 210 000 001 and No. 5 MSM 210 000 005.

Cooperation with practice:

- Long-term cooperation with various architectural and building design offices (e.g. VPÚ DECO a.s., HELIKA a.s., STOPRO s.r.o., Ateliér Lábus, Arch. studio GAMA s.r.o., LZ Atelier s.r.o., METROSTAV a.s., SIPRAL a.s.)
- Cooperation with distributors and producers of building materials and products on the numerical evaluations (e.g. SCHÜCO International CZ,

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Publications:

- more than 70 papers in technical journals and proceedings of conferences
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