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SPECIAL MOBILITY STRAND

BUILDING PHYSICS FOR ENERGY EFFICIENCY
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The content of the lecture

1. Introduction: Why building physics?

2. Physical processes through the building components

- *Heat transfer*
- *Water vapor diffusion and condensation*

3. Measurements of the thermal performance of building elements

4. Conclusions

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1. Why building physics?

“What is the medicine for a human, it is a building physics for buildings, because the building is like a living being – it was born, it gets old, ill, and in the end it dies. Failure to meet the basic requirements of building physics causes lasting consequences for the ecology of the living space built for a life.“

***Build** no. 7, September 2008*

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1. Why building physics?

EE of buildings became an important issue in the time of the world's energy crisis in 1970s.

As the consequence energy price was higher what caused a reduction in energy consumption for heating and cooling of buildings.

In 21th century the largest amount of total energy consumption in the world is still used in buildings for heating and cooling (EU countries 40%, B&H ~50%).

Furthermore, the energy required to maintain a comfortable temperature inside the building accounts for 40-50% of global CO_2 emissions.

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1. *Why building physics?*

The physical processes which continually take place in the building envelope are hygrothermal loads due to heat, air and moisture transport.

If the building structures are exposed to large temperature differences and accumulated moisture its impact on the building, user's health and the environment will be hazardous.

Buildings which don't have adequate thermal protection have increased energy consumption for the heating and cooling, which further leads to increased CO_2 *emissions, causing significant economic maintenance costs and thermal discomfort.*

1. Why building physics?

For EE and healthy buildings it is important to use adequate thermal insulation, thermal mass in the building envelope and optimize airtightness.

Applying building physics the processes can be explained and the performance of the building constructions predicted.

In case of insufficient building documentation or in case of old buildings the measurement of building physics quantities must be performed.

Building physics becomes an imperative not only on the engineering task list, but on the global world agenda.

2. Physical processes through building elements

The differences in the interior and exterior air temperatures at the boundary elements of the building lead to an uninterrupted process of heat transfer through the building envelope from higher to lower temperature.

In the winter, when the outside air temperature is lower than the air temperature inside the building, there is a continuous heat transfer through the envelope and in this way heat losses occur.

In the summer, when the temperature of the outside air is higher than the temperature of the interior air due to increased solar radiation, significant heat gains can occur within the building.

Heat transfer through the envelope occurs via:

- *Conduction,*
- *Convection,*
- *Thermal radiation.*

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2.1.1. Heat transfer mechanisms

Thermal conduction is facilitated by microscopic particles without bulk movement of particles.Occurs in a solid (vibrating atoms collide and free electrons move), liquid and gas.

The density of conductive heat flow rate is proportional to the negative temperature gradient according to ***I Fourier's law:***

Steady heat transfer $\vec{q} = -\lambda \vec{\nabla} t$

$$\vec{\nabla} = \frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\vec{k}$$

For 1D: $q = -\lambda \cdot \frac{dt}{dx}$

Proportionality coefficient is the thermal conductivity λ[W/mK], depends on the density and the content of moisture in the material

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2.1.1. Heat transfer mechanisms

***The specific thermal capacity** (specific heat) c[J/kg·K] is the measure of heat accumulation capability/storage of thermal energy.*

The larger are the specific thermal capacity and density more thermal energy Q can be stored in the material:

$$Q = c \cdot \rho \cdot V \cdot \Delta t$$

where ρ*[kg/m*^{3} *]is density, V[m*^{3}*] volume and* Δt*[℃] temperature difference.*

There are two material characteristics which depend on heat capacity: diffusivity (how fast material reacts to temperature changes) and effusivity.

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2.1.1. Heat transfer mechanisms

Convection *is the heat transfer by moving groups of molecules of fluid from the region of higher temperature to the region at the lower temperature.*

According to ***Newton's law of convection*** *(cooling): the density of convective heat flow rate (between fluid and surface of solid body) is proportional to the difference in the temperature of the solid body (building component) and the surrounding fluid (surrounding air):*

$$q = \alpha_c \cdot (t_f - t_z)$$

where t_f*[℃] is temperature of the air,* t_z*[℃] the wall surface temperature,* α_c*[W/m²·K] convective surface coefficient, which depends on fluid thermo-physical properties and geometric arrangements of the system.*

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2.1.1. Heat transfer mechanisms

Thermal radiation *is the transfer of heat by electromagnetic waves emitted by all objects with the temperature above absolute.*

According to the ***Stefan-Boltzmann's law*** *the density of heat flow rate emitted from the surface at absolute temperature is proportional to the fourth power of the temperature:*

$$q = \varepsilon \cdot \sigma \cdot T^4$$

where $\sigma = 5.67 \cdot 10^{-8}$ *[W/*$m^2 \cdot K^4$*] is the Stefan-Boltzmann's constant,* ε *the emissivity of the substance or radiating surface (the ratio of the energy emitted from a certain material to the energy of an ideal emitter (a black body) at the same temperature) and T[K] temperature of the surface which radiates heat.*

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2.1.1. Heat transfer mechanisms

The density of the heat flow rate transferred by radiation between the air surrounding the building element and the surface of the element is:

$$q = \alpha_r \cdot \left(t_f - t_z\right)$$

where α_r[W/m^{2}K] convective surface film coefficient, t_f[℃] temperature of the air, t_z[℃] the wall surface temperature, α_c[W/m^{2}K] convective surface film coefficient.

The total density of the heat flow rate due to radiation and convection is:

$$q = \alpha(t_f - t_z)$$

where $\alpha = \alpha_r + \alpha_c$ is $_{the}$ surface film coefficient.

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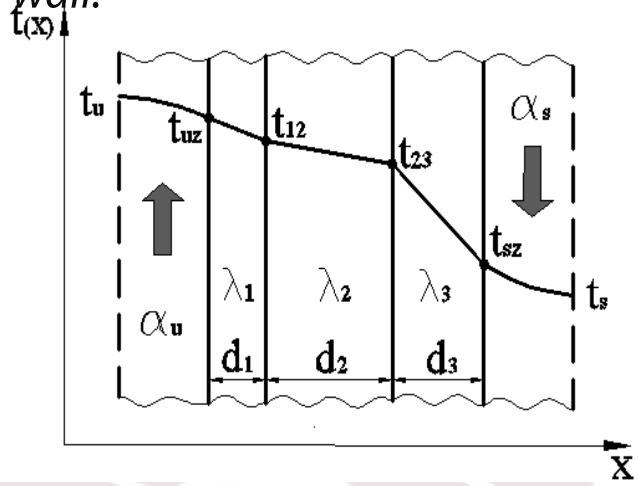
2.1.2. The U-value of walls and windows

In everyday practice, all three types of heat transfer occur together:

- *Convection and radiation occur from the internal air in the room to the internal surface of the wall,*
- *From the internal surface to the external surface of the wall heat is transferred by the conduction*
- *Convection and radiation from the external wall to the external air of the wall.*

The density of the heat flow rate *trough the composite flat wall:*



$$q = \frac{t_u - t_s}{\frac{1}{\alpha_u} + \sum_{i=1}^{n=3} \frac{d_i}{\lambda_i} + \frac{1}{\alpha_s}}$$

The total thermal resistance*:*

$$R = \frac{1}{\alpha_u} + \sum_{i=1}^{n=3} \frac{d_i}{\lambda_i} + \frac{1}{\alpha_s} = R_u + R_z + R_s \left[\frac{m^2 K}{W} \right]$$

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2.1.2. The U-value of walls and windows

The U - value *W/m²K] represents the reciprocal value of the thermal resistance of the multilayer flat wall is called the thermal transmittance:*

$$U = \frac{1}{R} = \frac{1}{\frac{1}{\alpha_u} + \sum_{i=1}^{n} \frac{d_i}{\lambda_i} + \frac{1}{\alpha_s}}$$

U-value - the amount of heat transferred through the unit of surface in a unit of time through the building construction element from the side of the warmer to the side of the cooler air, when the difference of their temperatures is 1 K.

The lower U-value is (the greater the resistance), the lower the density of heat flow rate that passes through the wall (i.e. the wall is better insulated)

$$q = \frac{t_u - t_s}{R} = U \cdot \left(t_u - t_s\right)$$

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2.1.2. The U-value of walls and windows

The heat losses of the building through the transparent elements represent a significant share in the total heat losses in the winter and might cause overheating in the summer. The U-value of a window:

$$U_W = \frac{U_f A_f + U_g A_g + \psi_g l_g}{A_g + A_f}$$

It depends on the thermal transmittance and surface of glazing and the frame, as well as the linear thermal transmittance of the junction between the frame and glazing ψ_g *[W/mK]*

The heat loss can be reduced using windows with multiple low-E glazing filled with an air/gas gap between the glass panes and using frames with multiple chambers.

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2.1.3. Heat loss

The heat loss from the building is proportional to the temperature difference of the internal t_u and external t_s air:

$$Q_g = Q_T + Q_V = (H_T + H_V)(t_u - t_s)$$

where the proportionality coefficient is the sum of the transmission H_T[W/K] and the ventilation heat loss coefficient H_T[W/K] .

Ventilation heat losses constitute a significant share in total heat losses and occur due to infiltration and ventilation.

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2.1.3. Heat loss

The coefficient of ventilation heat loss of a building:

$$H_V = \rho_a \cdot c \cdot_p V \cdot n$$

where V[m^3]is the volume of the heated part of the building, n[1/h]number of air changes (the number of changes in the volume of the heated part of the building with the outside air in one hour), $\rho_a c_p$=1200 J/m^{3}K.

The transmission heat loss occurs due to heat transfer via: conduction, convection and radiation.

The coefficient of transmission heat loss:

$$H_T = \sum_i U_i \cdot A_i \cdot F_i + \Delta H_{TM}$$

Where U_i[W/m^{2}K] U-value of the building component i, A_i[m^2] its corresponding surface and F_i-temperature correction factor, ΔH_{TM}[W/K] correction of the thermal transmission loss coefficient due to the existence of thermal bridge.

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2.1.4. Thermal mass

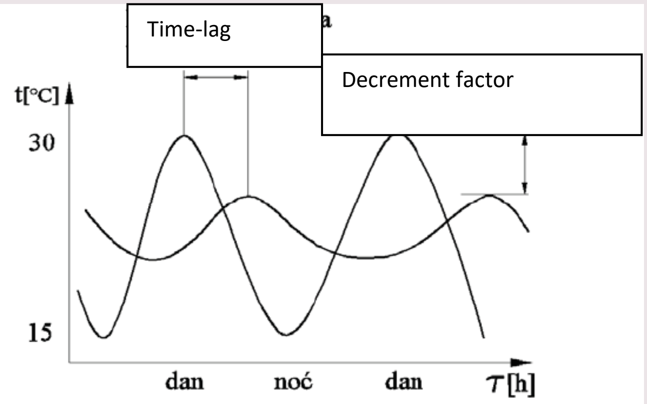
Heat accumulation is the property of an element of a building structure to accumulate (store) the heat.

The time lag *(difference in hours between occurrence of the amplitude of the internal and the amplitude of external temperature)*

Decrement factor *(the ratio of the amplitude of the internal to the amplitude of the external air temperature).*

Massive building elements (brick) have a large time lag and lower decrement factor than thinner elements of lightweight materials.

Therefore, placing the thermal insulation on the outside part of the wall.



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2.2. Moisture in building elements

*The moisture has **the greatest impact on the quality of buildings and building components** (70% of damage of buildings)*

The moisture transfers into building constructions if they are in direct contact with water or water vapor depending on: the climatic conditions, the type and characteristics of the materials from which the construction is made, such as porosity, but also the order of the layers of the construction, the facility usage etc.

Physical mechanisms of water transfer in building constructions: condensation of the water vapor diffusing through construction, physical adsorption, capillary absorption.

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2.2. Moisture in building elements

The consequences of transport and retaining moisture in buildings are different:

- ***Increased thermal conductivity** of building materials, and thus greater heat losses through the components of the envelope in which the moisture occurs,*
- *The appearance of salt in the walls, which directly affects the durability of buildings,*
- *The consequences on the health of users due to the development of micro-organisms, fungi and mold,*
- *Additional mechanical strain on the structure,*
- *Disturbed user comfort.*

By knowing the physical laws describing the mechanisms of moistening the building component, the waterproofing properties of the building materials, advantages and disadvantages, the most optimal ways of protection against moisture can be chosen.

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2.2.1. Water vapor diffusion

Water vapor diffusion *is a spontaneous process of moving water vapor molecules from the region of the larger to the region of the lower mass concentration. It can be expressed using the gradient of water vapor pressure and the first Fick's law which states that the density of water (vapor) is proportional to the negative partial pressure gradient:*

$$\vec{j} = -D_{DV}\vec{\nabla}p$$

for 1D

$$j = -D_{DV}\frac{\partial p_x}{\partial x}$$

D_{DV}[m^2/s] is the water vapor diffusion coefficient of the air layer.

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2.2.1. Water vapor diffusion

The water vapor resistance factor μ represents the ratio of the diffusion coefficient of the air layer and the diffusion coefficient of the construction material of the same thickness at the same temperature:

$$\mu = \frac{D_{DV}}{D_D}$$

It determines the hydro-insulating properties of the material and depends on the structure of the material (number, size, layout and position of the pores and channels in the material).

For the air is μ = 1, and for any building material μ> 1!

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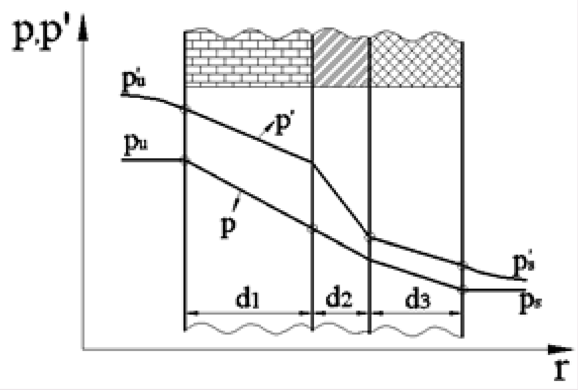
2.2.1. Water vapor diffusion

During water vapor diffusion through the wall, we consider:

- *Water vapor transfer from the interior air to the layer along the surface of the wall;*
- *Conducting water vapor through the wall;*
- *Water vapor transfer from the outer surface to the air.*

The density of water vapor flow rate through the multi-layered flat wall:

$$j = \delta_{DV} \frac{p_u - p_s}{\sum_{i=1}^{n} r_i}$$



where r[m] the water vapor diffusion-equivalent air layer thickness is the product of thickness and water vapor resistance factor:

$$r = d \cdot \mu$$

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2.2. Moisture in building elements

Condensation usually occurs in the winter period in structures where the sequence of layers of embedded materials, taking into account their thickness and conductivity of the water vapor, is not adequately chosen as for example, the thermal insulation material is on the inner part of the wall.

If it is determined by calculation that the water accumulated during the humidification period of the structure (in winter) will dry out during the summer condensation is considered as allowed. In case this is not the case design measured have to be considered and the element protected from moisture.

Therefore, building components should have good thermal protection, thermal insulation on the outside part of the wall and the surface temperature should be higher than the temperature of the dew point.

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2.2. Moisture in building elements

*Condensation occurs when the water vapor temperature is below its saturation temperature (**dew point**) with moist air at the moment it becomes saturated.*

The temperature of the dew point corresponds to the relative humidity φ=100%, i.e. when the partial pressure of the water vapor is equal to the saturation pressure ($p = p'$).

Condensation of water vapor might occur inside the building construction element (interstitial) or on its surface.

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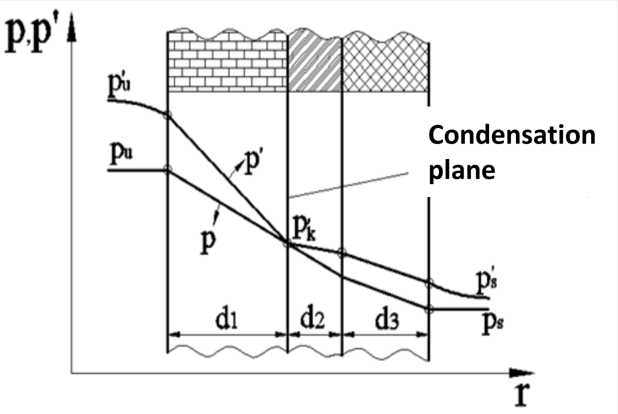
2.2.2. Condensation of water vapor

Interstitial condensation occurs when the saturation pressure line and the partial pressure line intersect at one point (condensation in plane) or more points (condensation in zone).

The condensation site and the amount of condensed water vapor inside the building component can be determined using the ***Glazer's*** *analytically-graphical method.*



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2.2.2. Condensation of water vapor

Surface condensation *occurs on the surface of the building component when the warm air in the room collides with the cold wall surface.*

At places in a room where there is a sufficiently low surface temperature (dew point), surface water condensation may occur.

The temperature of ***the dew point*** *indicates the temperature at which the maximum saturation of air is achieved by steam or relative air humidity is 100%.*

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2.2.2. Condensation of water vapor

Condensation on the surface of the building component occurs when the surface temperature of the building component t_{uz} is below the dew point of the boundary air in the room.

The condition of minimum thermal resistance R of the building component:

$$R_{\min} \geq R_u \cdot \frac{t_u - t_s}{t_u - t_r} - (R_u - R_s)$$

where t_r[°C] is the dew point, t_u[°C] internal air temperature, t_s[°C] external air temperature, R_u[$W/m^2 \cdot K$] resistance to the passage of heat of indoor air, R_c[$W/m^2 \cdot K$] resistance to heat transfer of external air.

The requirement of a minimum value of the thermal resistance of a building component should always be maintained independently of other energy requirements

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3. *Measurement* of the thermal characteristics of the building envelope

The thermal performance of the envelope has a large impact on the total energy consumption, the economy of the building, and the environmental protection.

The methods recommended for calculation of physical quantities given in standards and used in the national regulations are largely based on the assumption of an ideal construction, although some minor corrections of the value are predicted for certain cases.

The problem that engineers face is missing or incomplete design documentation.

The construction materials might change their properties with time: for example, due to the moisture present in porous material. Therefore, measurements of thermal characteristics of the envelope should be performed.

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3.1. Thermal imaging

Thermal imaging is the qualitative, contactless and non-destructive method measuring the surface temperature of the object by measurement in the invisible (infrared) part of the electromagnetic radiation spectrum.

Used to detect thermal defects and air leakage in buildings envelopes.
The result is thermal image which shows the temperature distribution on the building's surface is obtained based on the intensity of electromagnetic radiation.

The measurements of two buildings were performed:
old and new (energy efficient).

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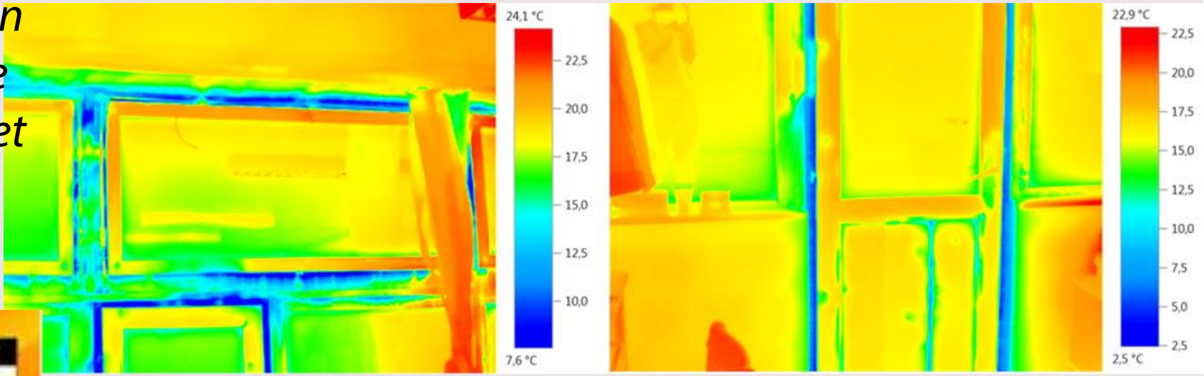
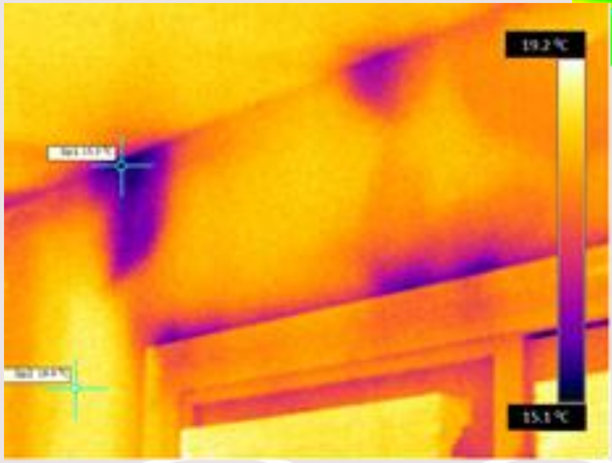
3.1. Thermal imaging

Defects in the distribution of the surface temperature caused by the presence of moisture within the envelope. The temperature difference between dry and wet areas of the envelope is 3.6 ^{0}C

Old building





Increased infiltration occurs in the lines along which the windows and the doors are closed where the maximum and minimum temperatures at the window are 22.0 ^{o}C and 6.5 ^{o}C, respectively while at the door 19.3 ^{o}C and 2.9 ^{o}C, respectively

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3.2. U-value measurement

In accordance with ISO 6946, the U-value can be calculated under the assumption that the sequence, thickness and structure of used materials are known and that construction is ideal.

The measurement of the U-value on-site and under actual conditions in which building is used takes into account different irregularities and the degradation of the structural elements.

For some older buildings the problems are thickness and thermal characteristics of embedded materials are incomplete or the properties of the material characteristics have changed over time.

3.2. U-value measurement

The limit U-values as prescribed for this climate zone $U=0.30\ W/m^2K$

The measurements of U-value were performed for two different buildings the old and the new one which is energy efficient.

Old:

$U_{wall\text{-}design}=1.423/1.241\ W/m^2K$

$U_{wall\text{-}measured}=1.025\pm0.202\ W/m^2K$

Measured U-value of the old building is approximately 28% higher.

The reasons are: The age of the building and the completeness of the information stated in the design documentation.

New:

$U_{wall\text{-}design} = 0.272\ W/m^2K$

$U_{wall\text{-}measured} = 0.281 \pm0.035\ W/m^2K$

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3.3. The Blower door test

Testing the air tightness of the building – has been performed using the Blower door test.

The methodology is defined by the standard ISO 13829.

The Blower Door test examines the object's tightness and reveals imperfections in a thermal envelope, such as poor installation or poor quality of built-in windows and doors.

The device achieves a difference in pressure internal and external air of 50 Pa and by measuring the volume flow of air determines the number of air changes $n_{50}[h^{-1}]$.

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3.3. The Blower door test

In accordance with the Rulebook requirements the highest permitted value for buildings with natural ventilation $n_{50} = 3.0\ h^{-1}$

The air infiltration measurements :

For the old building (unsatisfactory airtightness) $n_{50}=8.78\ h^{-1}$
For the energy efficient building (satisfactory airtightness) $n_{50}= 2.72\ h^{-1}$

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4. CONCLUSIONS

In order to have an energy efficient building, increase comfort of users and protect the environment by lowering CO_2 emission building physics plays an important role.

Applying building physics calculations and performing building physics measurements in real conditions while using new technologies and materials the most optimal solutions for energy efficient and sustainable buildings, excluding hazardous to the health of users, building materials and environment can be found.

In the 21th century the energy efficiency of buildings can be improved using modern materials which meet building physics requirements with significantly lower thermal conductivities and thermal mass in order to reduce energy consumption.

In case of old buildings and incomplete design documentation measurement of building physics quantities must be performed.

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