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BUILDING PHYSICS FOR ENERGY EFFICIENCY

Abstract: In the 21th century, the energy efficiency is one of the most important topics on the global world agenda since the largest amount of total energy consumption is used for heating and cooling of buildings. The engineers have to design energy efficient and sustainable buildings with the user's health and comfort in the central place while minimizing environmental impact. The application of building physics, therefore, plays an important role in the explanation of the physical processes and prediction of performance of the building constructions. 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.

Key words: building physics, energy efficiency, thermal performance, occupant comfort

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1. WHY BUILDING PHYSICS?

The importance of building physics describes the best the following statement: „*What is the medicine for a human, that is a building physics for buildings because the building is like a living being – it was born, it gets old, it gets 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.*“ [1].

The energy efficiency of buildings became an important issue in the time of the world's energy crisis in the 1970s. As the consequence energy price was higher what caused a reduction in energy consumption of buildings. In the 21th century, the energy efficiency is still one of the most important topics on the global world agenda since the largest amount of total energy consumption in the world is used in buildings (EU countries ~40%, and Bosnia and Hercegovina ~50%). In Bosnia and Hercegovina most of this energy is used for heating and cooling due to the poor thermal performance of building envelopes and inadequate thermal insulation, as at the time of their construction, not the same energy efficiency principles applied as of today or deterioration of the building envelope over time [2]. Furthermore, most conventional buildings use fossil fuels for heating instead of the application of renewable energy sources. The energy required to maintain a comfortable temperature inside the building accounts for 40-50% of the global carbon dioxide emissions. Buildings that do not have adequate thermal protection have increased the energy consumption for heating and cooling, which further leads to increased CO_2 emissions, causing significant economic maintenance costs and resulting in the thermal discomfort. Furthermore, in boundary cases of penetration and retention of moisture in the building envelope, materials and constructions are damaged, which significantly affects the function of the building and the health and comfort of users.

Winter heat losses and summer heat gains occur due to heat transfer via transmission and air ventilation/infiltration. Both can be reduced and buildings protected from hazardous events using adequate thermal insulation and thermal mass in the building envelope. Furthermore, this results in lower CO_2 emission in the atmosphere and high thermal comfort and air quality. An important role plays the choice of building materials. The correct choice, dimensioning, ordering and installation of building materials corresponding to the type of building, the climate of the area and use of the building, reduce the loss of heat from the building in the winter and heat gain in the summer, thus ensuring the conditions of the user's thermal comfort at all times.

The quality of the building envelope will determine the quality of the indoor environment and protect it from external hazards due to weather loads. Physical processes that continually take place in the building envelope are hydrothermal 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.

Applying building physics the processes can be explained and the performance of the building constructions predicted. Furthermore, in case of insufficient building documentation or in case of old buildings the measurement of building physics quantities must be performed in real conditions. The environment is adequate if at least 80% of users are satisfied with it. The parameters of users' comfort: thermal, air quality, acoustic, and light might be measured as well.

Therefore, building physics becomes important not only for engineers, but even more it is an imperative on the global world agenda.

2. PHYSICAL PROCESSES THROUGH BUILDING ELEMENTS

2.1. Heat transfer through building components

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 until the state of the thermodynamic equilibrium is established [2]. In winter, when the temperature of the outside air is lower than the temperature of the air inside the building, there is a continuous heat transfer through the envelope causing the heat loss. Due to solar radiation heat gains occur within the building, especially in summer.

2.1.1. Heat transfer mechanisms

Heat can be transferred through the envelope via three mechanisms: conduction, convection, and thermal radiation.

Thermal conduction is the transfer of internal energy (as heat), which occurs between neighboring molecules of a solid, liquid or gas and between different materials in close contact. It can be described by the first Fourier's law of thermal conduction: the rate of heat transfer is proportional to the negative temperature gradient:

$$\vec{q} = -\lambda \vec{\nabla} t \qquad (1)$$

Since the gradient of temperature in y (the height) and z direction (the length) is negligible with respect to x direction (the thickness of the element) the density of heat flow rate can be written for 1D:

$$q = -\lambda \cdot \frac{dt}{dx} \qquad (2)$$

The proportionality coefficient is called thermal conductivity λ[W/mK]. It is the quantity of heat Q, transmitted during time interval Δt through a material of thickness dx, in a direction normal to a surface of area S, per unit area of S, due to a temperature difference ΔT, under steady state conditions. It is material dependent, but it also depends on the content of moisture in the material. The larger is the density of the material and the content of the moisture the thermal conductivity is higher. For example, for asbestos cement (ρ=1600-1900 kg/m^3) for dry material λ=0,35 to 0,7 W/mK and for moistured 0,9-1,2 W/mK.

Another important thermal property of the building materials is **the specific thermal capacity** (specific heat) c[J/kg·K] which represents the amount of heat required to heat 1 kg of a substance by 1 K. It is the measure of heat accumulation capability/storage of thermal energy and determines the energy performance of a building to store and release heat (TES). The larger is the specific thermal capacity and density more thermal energy Q can be stored in a material:

$$Q = c \cdot \rho \cdot V \cdot \Delta t \tag{3}$$

where c[J/kgK] is the specific thermal capacity, ρ[kg/m^3] raw density, V[m^3] volume and Δt [°C] temperature difference.

There are two material characteristics which depend on heat capacity: diffusivity and effusivity.

Thermal diffusivity of the material α[m^2/s] indicates how fast material reacts to temperature changes [3]. The higher is thermal diffusivity the faster is the change of temperature. It is calculated as the ratio of of the thermal conductivity to the volumetric heat capacity:

$$\alpha = \frac{\lambda}{\rho \cdot c} \tag{4}$$

Thermal effusivity[2] β[W/m^{2}Ks^{0,5}] is calculated from the square root of the product of thermal conductivity and volumetric heat capacity:

$$\beta = \sqrt{\lambda \cdot \rho \cdot c} \tag{5}$$

The larger the thermal effusivity the material is more active in the heat storage.

In engineering practice, stationary boundary conditions are presumed, however in nature prevail, non-stationary boundary conditions.

Convection is the heat transfer by moving groups of molecules of the fluid. It can be caused by the temperature difference of parts of the fluid (natural convection) or by an external force (forced convection). It can be described by Newton's law of convection (cooling): the density of heat flow rate between surrounding air and building component is proportional to their temperature difference:

$$q = \alpha_c \cdot (t_z - t) \tag{6}$$

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[2] Contact coefficient

where t[°C] temperature of the air, t_z[°C] the wall surface temperature, α_c[W/m^{2}K] convective surface film coefficient which depends on geometry (shape and orientation of surface), material properties (surface roughness), fluid properties (viscosity), fluid free stream velocity (speed and direction) and the temperature of the bulk fluid and the surface.

Thermal radiation is the transfer of heat by electromagnetic waves. It is emitted by all objects with the temperature above absolute zero. According to the Stefan-Boltzmann's law the density of heat flow rate emitted from the surface of absolute temperature T law is proportional to the fourth power of the surface temperature:

$$q = \varepsilon \cdot \sigma \cdot T^4 \tag{7}$$

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

According to the Kirchoff’s law the amount of radiative energy emitted by a surface is equal to the amount of radiative energy absorbed by that surface provided it is measured at the same temperature as the radiating source for the same wavelength. Absorptivity is important at wavelengths of solar radiation and emissivity for far-infra-red wavelength radiation that is emitted by terrestrial objects. For most materials, these two are not the same[3].

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

$$q = \alpha_r \cdot (t_z - t) \tag{8}$$

where α_r[W/m^{2}K] radiative surface film coefficient, t[°C] temperature of the air and t_z[°C] temperature of the wall surface.

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

$$q = \alpha \cdot (t - t_z) \tag{9}$$

where $\alpha = \alpha_r + \alpha_c$ is different for the internal and external air and depends on the direction of heat transfer.

2.1.2. U-value of walls and windows

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[3] The colour of a surface is a good indicator of absorptivity but not of emissivity, which depends only upon the material’s surface.

In everyday practice, all three types of heat transfer occur together (**Error! Reference source not found.**):

- 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 heat flow rate through the multi-layered composite flat wall can be calculated combining expressions describing above listed processes:

$$q=\frac{t_u-t_s}{\frac{1}{\alpha_u}+\sum_{i=1}^{n=3}\frac{d_i}{\lambda_i}+\frac{1}{\alpha_s}} \qquad (10)$$

where to t_u[°C] and t_s[°C] are the temperatures of the indoor and outdoor air, respectively.

The denominator in this expression represents the thermal resistance of the multilayered flat wall R. Its reciprocal value is the thermal transmittance (U-value [W/m^{2}K]) which is 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:

$$U=\frac{1}{R}=\frac{1}{\frac{1}{\alpha_u}+\sum_{i=1}^{n}\frac{d_i}{\lambda_i}+\frac{1}{\alpha_s}} \qquad (11)$$

Finally, the density of heat flow rate can be calculated using the U-value:

$$q=\frac{t_u-t_s}{R}=U(t_u-t_s) \qquad (12)$$

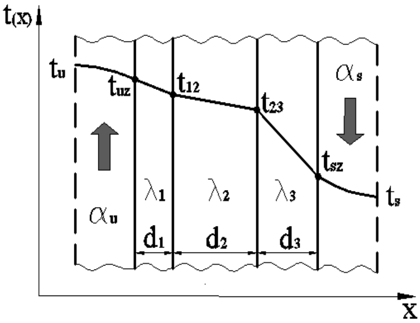

Figure 1 - Heat transfer through the composite flat wall

The lower is the U-value, i.e.the higher the resistance, the lower is the heat lost due to transmission which means that the wall is better insulated. The calculation of the heat transfer coefficient of building elements is the first and unavoidable step in determining the thermal protection of a building, because it represents a measure of the quality of its thermal characteristics. In addition, the U-value is the starting point for the calculation of the required energy consumption. Permitted values of the heat transfer coefficient of building elements, depending on the purpose of the building, climate, etc., are prescribed by appropriate regulations related to the energy efficiency. If these values are not met, the building needs to be additionally insulated in order to improve the thermal performance of its elements, and thus the entire envelope [2].

The U-value of the structural element is calculated depending on the type of the building element according to the international standards EN ISO 6946:2006 [5], EN ISO 13370:2007 [6] etc.

Windows

Transparent elements of the envelope such as windows transmit natural light into the interior and provide contact with the outside environment. However, the heat loss of the building through the transparent elements represents a significant share in the total heat loss in the winter and might cause overheating in the summer. Some studies have shown that there are almost half of the total heat lost from the building envelope through these elements.

The heat transfer coefficient of the transparent building element (windows and balcony doors) is calculated in accordance to standard EN ISO 10077-1 [7]:

$$U_W = \frac{U_f A_f + U_g A_g + \psi_g l_g}{A_f + A_g} \tag{13}$$

As it can be seen the thermal transmittance of the glazing depends on: $A_g[m^2]$ glazing and A_f $[m^2]$ frame surface, $U_g[W/m^2K]$ the thermal transmittance of the glazing without the influence of the thermal bridge (depends on the width of the slot, the slit height and the gas in the slot, the emissivity of the surface of the glass in the slot), $U_f[W/m^2K]$ the thermal transmittance of the frame without the influence of a thermal bridge, $l_g[m]$ length and $\psi_g[W/mK]$ linear thermal transmittance of the junction between the frame and glazing.

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

Glass has high absorption and emissivity for the IR radiation. Also, the IR radiation from the interior space radiates to the outer space. If the emisivity (and absorption) of glass is decreased it will not absorb the heat and therefore will not convect or radiate it to the indoor space. Therefore, low-E glazing is useful in winter due to reduced heat loss (the heat is reflected back into the room for wavelengths more than a micron) and in summer due to reduced heat gains (the reflection of IR emitted by warm surfaces outside the building and near-IR from the Sun). Low-E windows transmit light and reflect IR (long-wave radiation). However, the Sun produces considerable energy in the near-IR at wavelengths shorter than one micron.

For the energy efficient and high thermal performance windows with double glazing-window it is important to use at least one low-E glass.

2.1.3. Heat loss

The heat loss from the building can be evaluated using two building physics quantities: **the transmission heat loss coefficient** and **the ventilation heat loss coefficient**.

The heat loss due to transmission is determined by the transmission heat loss coefficient in W/mK is calculated using the formula [9]:

$$H_T = \sum_i U_i \cdot A_i \cdot F_i + \Delta H_{TM} \tag{14}$$

where U_i[W/mK] is U-value of the building element that covers total area A_i[m^2] of the building envelope, F_i is the temperature correction factor and ΔH_{TM}[W/K] correction due to the existence of thermal bridges.

Thermal bridges are localized parts of the building envelope where an increased heat loss occurs due to the change in material, thickness or geometry of the building element - both within the construction and on its surface.

- Structural, thermal bridges occur at the places where construction elements consist of heterogeneous materials which have different thermal properties such as thermal conductivity, raw density and specific heat capacity (joints of balcony with walls, reinforced concrete etc.).
- Geometric thermal bridges occur when the construction element deviates from a certain geometry (corner angles, parts around the window).
- Mixed forms formed by combination geometric and structural bridges.

The thermal bridges have multiple consequences: Increased heat loss (temperature drops at the site of the thermal bridge), the appearance of the mold and surface condensation on the inside of the structure, the appearance of condensation on the surface and within the construction, disruption of user comfort and health impact, mechanical damage and heat stresses of the structures. Structural solutions for reducing the impact of thermal bridges are avoiding it in the design phase, solving the details.

Air tightness and ventilation heat loss

An important aspect of energy efficiency is air tightness since the ventilation heat loss constitutes a significant share in the total heat loss. However, in order to have an adequate indoor air quality it is necessary to supply a sufficient amount of fresh air (via natural ventilation through dedicated vent openings or mechanical ventilation system etc.). This might be a very challenging issue in existing buildings.

The physical quantity used to define the amount of fresh air is the number of air changes n n[1/h] which is a measure of air volume exchanged in one hour in the volume of space.

The heat loss due to ventilation can be quantified calculating the ventilation heat loss coefficient:

$$H_V = \rho_a \cdot c \cdot_p V \cdot n \tag{15}$$

where V[m^3] is volume of the heated part of the building, n[1/h] number of air changes (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 energy certification of buildingd is based on the energy need for heating determined from the energy balance heat losses and gains and represents the amount of heat that should be brought to the building for maintenance of the designed internal temperature during one year:

$$Q_{h,nd} = Q_g - \eta Q_d \tag{16}$$

where Q_d[kWh/a] is total heat gains of the building, η efficiency of heat gains and Q_g[kWh/a] is total heat losses of the building due to transmission and ventilation which can be calculated in the following way:

$$Q_g = Q_T + Q_V = (H_T + H_V)(t_u - t_s) \tag{17}$$

2.1.4. Thermal mass

Heat accumulation is the property of an element of a building structure to accumulate (store) the heat. The thermal mass plays an important role in energy efficiency and the higher it is, the lower is an energy need for heating and cooling.

According to Kamal when building elements are subjected to temperature fluctuations, not only the heat transmitted by the element but also the time taken for heat to travel through the element becomes important [8]. There are two physical quantities used to describe thermal mass: the time-lag (difference in hours between occurrence of the amplitude of the internal and the amplitude of the external temperature) and decrement factor (the ratio of the amplitude of the internal of the amplitude of the external temperature). Massive building elements such as brick have a large time-lag and lower decrement factor than thinner elements of lightweight materials. Time-lag depends upon the thermal diffusivity, and thickness of the building element. Due to relatively low specific heat capacity of most materials TES is obtained by using elements of high surface mass or so/called heavy weight constructions (stone, concrete, brick) of moderate conductance and density and a high emissivity.

Although the U-value is unaffected by the position of the thermal insulation that is not the case for admittance and decrement factor. External insulation gives high admittance in contrary to the internal insulation. The rule is to place thermal mass inside the insulated building envelope. During the heating season it can store solar and internal gains by day and release the heat by night. During the cooling season it gains heat from interior sources during occupied periods and can be flushed of heat at night. A masonry wall that is insulated on the interior is thermally isolated from internal gains and solar gains that enter the building through the glazing (Figure 2).

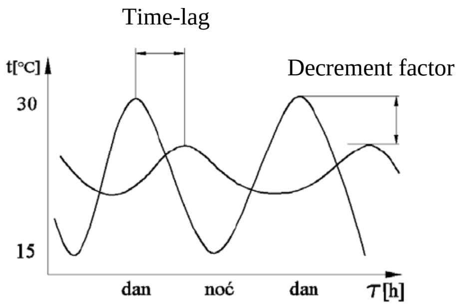

Figure 2 – Time-lag and decrement factor

2.2. Moisture in building components

The moisture is one of the factors that has the greatest impact on the quality of buildings and building components. Every occupied room contains a certain amount of water vapor depending on its usage. The moisture in building constructions occurs 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 materials in the construction element, the facility usage, etc. 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 microorganisms, fungi and mold,
- Disturbed user comfort,
- Additional mechanical strain on the structure.

The moisture penetrates through the wall through porous building materials. From the building physics point of view the moisture due to condensation of the water vapor diffusing through construction is the most important. In order to identify the place of condensation and calculate the amount of condensated water vapor Glaser method is used.

A moisture problem in buildings is closely related to the number of air changes per hour. A building must be able to accommodate various types of water induced loads without incurring damage by water, vapor and bulking (increase in volume) due to ice formation, and without creating an uncomfortable indoor climate.

2.2.1. Water vapor diffusion

The water vapor diffusion is a spontaneous process of moving water vapor molecules from the region of the higher to the region of the lower mass concentration. It can be expressed using the first Fick's law which states that the density of water vapor flow rate is proportional to the negative partial pressure gradient:

$$\vec{j} = -D_{DV}\vec{\nabla}p \tag{18}$$

or for 1 D (only for direction normal to the building element):

$$j = -D_{DV}\frac{\partial p_x}{\partial x} \tag{19}$$

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

The ratio of the water vapor diffusion coefficient of stagnant air and the water vapor diffusion coefficient of the material of the same thickness at the same temperature is called the water vapor resistance factor μ:

$$\mu = \frac{D_{DV}}{D_D} \tag{20}$$

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 $\mu = 1$, and for any building material $\mu > 1$.

Water vapor diffusion-equivalent air layer thickness r shows resistance the layer of the building material component of thickness d provides to the diffusion of water vapor.

$$r = d \cdot \mu \tag{21}$$

It is important to realize that thermal and water vapor resistance diverges with the exception of foam glass. During water vapor diffusion through the wall, we consider: Water vapor moves from the interior air to the layer along the surface of the wall, Conducting water vapor through the wall, Water vapor moves from the outer surface to the air. The density of water (vapor) flow through the flat multi-layered wall:

$$g = \delta_{DV} \frac{p_u - p_s}{\sum_{i=1}^{n} r_i} \tag{22}$$

2.2.2. Condensation of water vapor

At low temperatures and high pressures, interactions between molecules are no longer negligible, molecules of the substance are approaching, and the volume of a gas decreases, the substance changes its state, passes from the gas into the liquid phase, and condenses. 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'). The amount of moisture that the air can absorb depends on the temperature. The higher the temperature air can receive more water vapor and vice versa. Condensation of water vapor might occur inside the building construction element (interstitial) or on its surface.

Interstitial condensation occurs when the partial pressure at the boundary of the two layers is equal to the saturation pressure (graphically, the saturation pressure line and the partial pressure lines are cut at one point (p = p' in the area x = x_1). It can occur in the plane and in the zone (Figure 3).

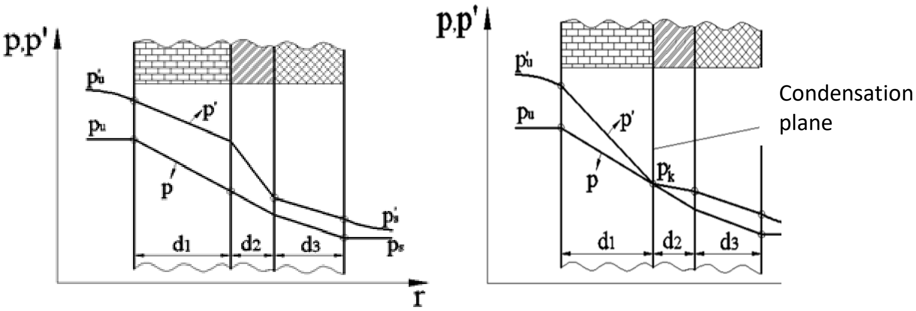

Figure 3 - Water vapor diffusion without condensation (left) and condensation in plane (right)

The amount of condensed water vapor (mass of water vapor) in a plane or zone in unit time per unit of the wall surface is the difference between the density of water vapor flow rate entering the plane/zone of condensation and the one leaving the plane/zone of condensation. For instance, for the condensation in plane:

$$j = j_1 - j_2 = \delta_{DV} \cdot \left(\frac{p_u - p_k^{'}}{r_1} - \frac{p_k^{'} - p_s}{r_2} \right) \tag{23}$$

where p_u[Pa], p_s[Pa] is the partial pressure of the internal and external air, respectively, p'_k[Pa] the pressure of saturation of water vapor in the plane, r_1[m] the sum of the water vapor diffusion-equivalent air layer thickness of the layers of the construction between the inner surface and the condensation layer, r_2[m] the sum of the water vapor diffusion-equivalent air layer thickness of the layers of the wall between the condensation layer and the outer surface of the structure.

Surface condensation occurs on the surface of the building component when the warm air in the room collides with the cold surface of the wall. At places in a room where there is a sufficiently low surface temperature (dew point), surface water vapor condensation may occur. The temperature of the dew point indicates the temperature at which the maximum saturation of air is achieved by water vapor or relative air humidity is 100%. Therefore, the condition of minimum thermal resistance R of the building component must be always kept independently of other energy requirements:

$$R_{\min} \geq R_u \cdot \frac{t_u - t_s}{t_u - t_r} - (R_u - R_s) \tag{24}$$

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

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 placed 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 evaporation (summer) condensation is considered as allowed. In case this is not the case design measures have to be considered and the element protected from the 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.

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, of course, 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. Another problem that engineers face is missing or incomplete design documentation. Finally, 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 [2].

3.1. Thermal imaging

Thermography is a contactless and non-destructive method of measuring the surface temperature of the object using a thermal imager (Figure 4) by measurement in the invisible (infrared) part of the electromagnetic radiation spectrum. It is used to detect thermal defects and air leakage in building envelopes.

Figure 4 – FLIR b60 (left) and TESTO 435-2 for U-value mesurement with fluxmeter and temperature sensor (last 3 images on the right)

The result is a thermal image on which the temperature distribution on the building's surface is obtained based on the intensity of electromagnetic radiation. An example is shown in figure (Figure 5). As it can be seen the increased infiltration occurs on the lines along which the windows and the doors are closed where the maximum and minimum temperatures at the window are 22.0 °C and 6.5 °C, respectively (Figure 5 left) while at the door 19.3 °C and 2.9 °C, respectively (Figure 5 right).

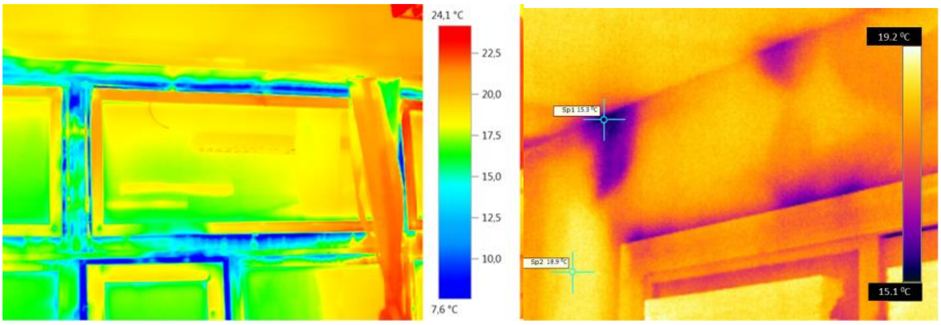

Figure 5 - Thermal images of the window with air infiltration (left) and moisture on the surface of the element (right)

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. However, the measurement of the U-value on-site and in actual conditions of use of the building take into account different irregularities and the degradation of the structural elements (change of the characteristics of the material over time, increased thermal conductivity due to the penetration of moisture etc.) [10]. For some older buildings the problems are thickness and thermal characteristics of embedded materials are incomplete, missing or there has been a change in the properties of the material over time. The methods for the calculation defined in the standard are based on the assumption of an ideal construction and do not take into account the various irregularities in terms of the uneven quality of the applied material, inadequate installation and the effects of degradation of the thermal characteristics of the built-in materials during the period of use of the facility. The most reliable method of estimating the heat transfer coefficient of the element is by measuring on-site and under the actual conditions in which the building is used (defined by the ISO 98691:2014 standard) [9]. The heat transfer coefficient is determined on the basis of the ratio of the measured the density of heat flow rate and the temperature difference (Figure 4):

$$U = \frac{\sum_{i=1}^{N} q_i}{\sum_{i=1}^{N} (t_u - t_s)_i} \tag{25}$$

In this way, the real values of the coefficient of heat transfer are obtained and the errors in the estimation of thermal losses are minimized.

The measurements were performed for two different buildings the old one and the new one which is energy efficient. The measured U-value of the old building is approximately 28% higher than the design value ($U_{wall\text{-}design}$=1.423 W/m^{2}K, $U_{wall\text{-}measured}$=1.025 W/m^{2}K). The reasons for such a large discrepancy may lie in the fact the project documentation provides no specific information about the thermal characteristics of the used materials, merely stating the wall was built from hollow bricks plastered with a layer of lime cement mortar on both sides. Two types of hollow bricks were used at the time the kindergarten was built, as well as various kinds of lime cement mortar. Therefore, the possible thermal transmittance values considered ranged from $U = 1.241$ W/m^{2}K to $U = 1.423$ W/m^{2}K. The U-value of the dominant layer of external wall at the new kindergarten has approximately the same value (the design value of $U_{wall\text{-}design} = 0.272$ W/m^{2}K is approximately 3% lower than the measured $U_{wall\text{-}measured} = 0.281$ W/m^{2}K). This could be expected, considering the age of the building and the completeness of the information stated in the design documentation. Although the new kindergarten was designed in 2008, the materials used to build its main wall show that its thermal characteristics correspond to the limit U-values as prescribed for this climate zone in Annex 3, Table 5, of the Rulebook on Minimum

Energy Requirements for buildings in the Republic of Srpska, which has been in effect since 2016 [12].

3.3. The Blower door test

Testing the air tightness of the building can be done using the Blower door test (Figure 6). The methodology of measurement 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 of the internal and external air of 50 Pa and by measuring the volume flow of air determines the number of air changes $n_{50}[h^{-1}]$.

Figure 6 – Blower door test measurement

The measurements of air infiltration were also performed for two buildings and the following results have been obtained: for the old kindergarten n_{50}=8.78 h^{-1} and for the new (energy efficient) n_{50}=2.72 h^{-1}. Comparing the experimentally obtained values with the highest permitted value for buildings with natural ventilation n_{50} = 3.0 h^{-1}, as prescribed in in the Rulebook, it can be concluded that the tightness of the old building is unsatisfactory, and satisfactory in the case of the new kindergarten, as expected, fulfilling the criteria, i.e., in accordance with the Rulebook requirements. However, when calculating ventilation losses, air infiltration in both kindergartens should be 0.5 h^{-1}, in order to ensure the necessary supply of fresh air [13].

4. CONCLUSIONS

In the 21th century the energy efficiency of buildings can be improved using different modern materials which meet building physics requirements:

- Thermal insulation. Using new types of insulation materials with significantly lower thermal conductivities: Vacuum insulation panels (VIP), structural insulated panels (SIP) which are fire resistant, Plant-based polyurethane foam (bamboo, hemp and kelp) which are moisture resistant, aerogels, graphite doped products and recycled steel which is useful in areas where there are earthquakes and high winds.

- Thermal mass. Phase Change Materials (PCM) are used to absorb and store external heat during the day and release it through the phase transition during the night when air temperatures have gone down or vice versa.
- Thermal bridges. With lower heat transmission through the plane surfaces of the building envelope, there is an ever increasing relevance of minimizing the thermal bridges of buildings, e.g. at foundations, at window joints, etc.
- Low-E windows with multi-layers of glass with filling of noble gas and frames made of fiber reinforced composites have warmer edges than traditional windows. Heat mirror window panes can be used with enhanced durability and very low U-values.
- Overheating in summer. Shading systems with smart control might be used to improve thermal comfort in the summer. It can be combined with some daylight directing techniques to ensure that the indoor lighting conditions are suitable.
- Preventing buildings against moisture and durability is an important task of sustainability. In order to have a healthy and comfortable environment a proper ventilation of space needs to be used. In that way fresh and cooler air comes into the building and warm and moist dries out.

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 achieved.

Modern buildings with very good thermal insulation and optimal airtightness require detailed planning of the thermal and moisture protection to prevent water vapor condensation, mold formation and energy loss due to thermal bridges while ensuring high thermal comfort and indoor air quality.

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Knowledge FOr Resilient soCiEty

Guest lecture on topic:
BUILDING PHYSICS FOR ENERGY EFFICIENCY

Lecturer: Biljana Antunović, Associate Professor, PhD
University of Banja Luka, Faculty of Architecture, Civil Engineering and Geodesy

Place: Faculty of Technical Sciences, University of Novi Sad
Date: 25.02.2020.

Student:

Student’s identification number:

QUESTIONS

1. Why is building physcis important for the energy efficiency of buildings?

   Answer:

   Applying building physics the physical processes through the building envelope can be explanied and the performance of the building constructions predicted.

   In case of need to know building thermal performance under real conditions the measuremetns of physical quantities can be performed.

2. Which hygrothermal physical processes occur through the building envelope and why are they important?

   Answer:

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

   They are important because if they are not controled will cause: increased energy consumption for the heating and cooling (inefficient building), which further leads to the increased CO_2 emissions, significant economic maintenance costs, thermal discomfort and poor air quality.

3. What are the main hazards caused by the heat and moisture transport through the building envelope? What is their impact on building, users and environment?

   Answer:

The main hazards caused by the heat and moisture transport through the building envelope are:changed characteristics od material such as material damage, higher thermal condcution, increased heat loss during winter, overheating during summer.

They could have Impact on the building, user's health and environment

4. When measurements of the thermal performance of the building envelope shall be performed?

   Answer:
   In order to evaluate thermal performance of the building envelope the measurements should be perfomered: when there is missing or incomplete design documentation and in case of odl buildings.

5. Which types of heat losses occur through the building envelope? How they can be minimized?

   Answer:
   Heat losses through the building envelope occur due to: heat transmission and ventilation.
   They can be reduced and buildings protected from hazardous events: using adequate choice and position of thermal insulation materials, thermal mass and airtightness.