UNIVERSITY of DEBRECEN

Thermophysics of materials

Editor:

Dr. Lakatos Ákos

The course material/work/publication is supported by the EFOP-3.4.3-16-2016-00021 "Development of the University of Debrecen for the Simultaneous Improvement of Higher Education and its Accessibility" project. The project is supported by the European Union and co-financed by the European Social Fund.

Editor:

Dr. Lakatos Ákos

Authors:
Dr. Lakatos Ákos (1-7 chapter(s))

Proofreading:
Dr. Tünde Kalmár PhD

Manuscript closed: 30/June/2018

ISBN: 978-963-490-012-2

Published by: DE Műszaki Kar

Table of Contents

Content

1. INTRODUCTION TO MATERIALS PHYSICS

1.1. Basics of thermodynamics

In this section the book will presented an overview of the basics of thermodynamics from the literature.

1.1.1. Intensive and extensive Properties

Thermodynamic properties can be divided into two general classes: intensive and extensive properties. An intensive property is independent of the amount of mass. The value of an extensive property varies directly with the mass. Thus, if a quantity of matter in a given state is divided into two equal parts, each part will have the same value of intensive property as the original and half the value of the extensive property. Temperature, pressure, specific volume, and density are examples of intensive properties. Mass and total volume are examples of extensive properties.

1.2. Temperature

Temperature is a measure of the molecular activity of a substance. The greater the movement of molecules, the higher the temperature is. It is a relative measure of how "hot" or "cold" a substance is and can be used to predict the direction of heat transfer. *(Lakatos, 2014)*

1.2.1. Temperature scales

The three temperature scales normally employed for measurement purposes are the Kelvin (K), Fahrenheit (F) and Celsius (C) scales. These scales are based on a specification of the number of increments between the freezing point and boiling point of water at standard atmospheric pressure. The Kelvin and Celsius scale has 100 units between these points, and the Fahrenheit scale has 180 units. The zero points on the scales are arbitrary. The freezing point of water was selected as the zero point of the Celsius scale and the 273.16th point of the Kelvin scale. The coldest temperature achievable with a mixture of ice and salt water was selected as the zero point of the Fahrenheit scale. The temperature at which water boils was set at 100 on the Celsius, moreover 373.16 on the Kelvin's scale and 212 on the Fahrenheit scale. The relationship between the scales is represented by the following equations:

- $°F = 32.0 + (9/5)°C$
- $°C = (°F - 32.0)(5/9)$
- $°R = °F + 460$

- °K = °C + 273

1.3. Heat

Heat is energy in transit. The transfer of energy as heat, however, occurs at the molecular level as a result of a temperature difference, from the warmest system, body or field to the coldest system, body or field. The symbol Q is used to define heat and its unit is Joule [J]. It is important to make a distinction between heat added to a system from its surroundings and heat removed from a system to its surroundings. A positive value for heat indicates that heat is added to the system by its surroundings. It equals the total heat (Q) added or removed divided by the mass (m). The term "specific heat" is not used for q since specific heat is used for another parameter. The quantity represented by q is referred to simply as the heat transferred per unit mass. *(Lakatos, 2014)*

1.4. Specific heat

Signed with “c” gives to amount of the heat in Joules what should be supplied to a body or system with 1 kg mass to increase its temperature with 1 ^{o}C or 1 ^{o}K. Since this is the measure for the change of the internal energy. Its unit is J/kg ^{o}K, J/kg ^{o}C. For water it is 4180 J/kgK. *(Lakatos, 2014)*

1.5. Heat transfer

The purpose of the use of the insulation is two: once, to retard the flow of heat from one place to another, and to maintain temperatures such that condensation does not occur on inside surfaces. The function is once, to increase the temperature of the internal surface of the wall. In the winter, insulation retards the flow of heat from inside of the building to the outside, and in the summer retards the flow of heat from the outside to the inside. Also in the winter it helps keep the inside surface warm enough that condensation will not occur. Insulation should be installed in the walls and ceiling of all confinement-type buildings for better control of temperature and moisture. The function of the insulation twice in winter time is to further decrease the surface temperature of the wall outside.

Heat can be transferred to or from a building by three methods: conduction, convection, and radiation.

Conduction: This is the method by which heat is transferred through a solid material, from molecules to molecules. It can happen both in liquids and in gases also.

Convection: This is the main method by which heat is transferred within fluids motion (gases and liquids). The motion of the fluid carries the heat from the warm area to a cooler area through their kinetic energy. Natural convection occurs when warm air rises, cool air settles, etc. Forced-air convection is when fans move air, like in a warm air furnace where heat is transferred from the furnace to the rooms.

Radiation: Radiation is the method by which heat is transferred from hot objects to cooler objects through space by electromagnetic waves without heating the air it mainly happens in vacuum.

Insulation acts to reduce the rate of heat transfer by all three of these methods. The insulation conducts heat at a slower rate than common building materials, thus heat transfer by conduction through the walls is reduced. By filling the open spaces and sealing the cracks in the walls, the rate of heat transfer by convection is reduced. The insulation keeps the inside surface of the walls more nearly equal to the inside air temperature and thus reduces the rate of heat transfer by radiation (hot or cold walls, ceilings, etc., "radiate" to objects or animals in the room). *(Lakatos, 2014)*

1.6. Thermal conductivity

The thermal conductivity λ of homogenous solid materials can be defined easily by the measurement of the equilibrium heat flow passing through the material resulted by the dT/dx temperature gradient:

$$q = \lambda \frac{\partial T}{\partial x} \qquad \text{(Eq. 1)}$$

where q is thermal energy flow. From this equation one can see that the transport of the heat in a material is a stochastic (randomized) process. It means that the way of the energy through the material is not linear, but it diffuses through the sample suffering collisions. It can be easily accepted by understanding the meaning of the temperature gradient. For the thermal conductivity of the materials from the kinetic gas-model the following equation can be reached:

$$\lambda = \frac{1}{3} C \times u \times \Lambda \qquad \text{(Eq. 2)}$$

where C is the specific heat capacity, u is the average velocity of the particles and Λ is the average free path. This equation was first presented by Debye applied for solid dielectrics. Where C is the specific heat capacity of the phonons (collective crystal

vibrations), u is the speed of the sound and Λ is the average free path of the phonons. (in solid crystals 10^{-8}-10^{-9} m). *(Lakatos, 2017)*

1.7. The effective thermal conductivity

We cannot apply the above mentioned theory for bulk, regular insulation materials with 10^{1}-10^{-2} m thicknesses, because we cannot speak about homogenous materials in those cases, resulted by this new definition for thermal conductivity should be given:

$$\lambda_T = \lambda_{c,s}+\lambda_{c,g}+\lambda_r+\lambda_{conv} + \lambda_{coupling} + \lambda_{leak} \qquad \text{(Eq. 3)}$$

where ($\lambda_{c,g}$), (λ_r), ($\lambda_{c,s}$) and (λ_{conv}) are the conductive part of the gas filling ($\lambda_{c,g}$), and the solid material ($\lambda_{c,s}$), the radiation part (λ_r), and the convective part of the gas filling (λ_{conv}) (if there is enough place). Moreover, $\lambda_{coupling}$ and λ_{leak} can be defined as the followings: $\lambda_{coupling}$ = thermal conductivity term accounting for second order effects between the various thermal conductivities in Eq.(3), λ_{leak} = leakage thermal conductivity. In order to reach a thermal conductivity as low as possible, each of the above thermal contributions have to be minimized. Normally, the leakage thermal conductivity λ_{leak}, representing an air and moisture leakage driven by a pressure difference, is not considered as insulation materials and solutions are supposed to be without any holes enabling such a thermal leakage transport. The coupling term $\lambda_{coupling}$ can be included to account for second order effects between the various thermal conductivities in Eq. (3). This coupling effect can be quite complex and will be neglected in the rest of this article. This λ_T is called to effective thermal conductivity. *(Lakatos, 2017)*

1.8. Bulk Density

The density or more precisely, the volumetric mass density of a substance is its mass per unit volume. The symbol most often used for density is ρ (the lower case Greek letter rho). Mathematically density is defined as mass divided by volume. For measuring the bulk density of a given solid material (Eq., 1) can be used.

$$\rho = \frac{m}{V} \text{ (Eq. 4)}$$

1.9. Heat absorption and thermal inertia

The heat absorption of a material (b) can be calculated as the square root of the multiplication of thermal conductivity, density and specific heat capacity see in *Fekete I. (edited), 1985*:

$$b = \sqrt{\lambda \times C \times \rho} \qquad \text{(Eq. 5)}$$

The thermal inertia of a material is the multiplication of its resistance and heat absorption coefficient.

$$D = R \times b \qquad \text{(Eq. 6)}$$

1.10. Compressive resistance

Compressive resistance is defined as the compressive load per unit of area at a specified deformation. When the specified deformation is the start of complete failure, the property is called to compressive strength. Compressive strength is measured in kg/m^2 and is important where the insulation material must support a load without crushing (e.g. insulation inserts used in pipe hangers and supports). When insulation is used in an expansion or contraction joint to take up a dimensional change, lower values of compressive resistance are desirable.

1.11. Porosity

Porosity is a measure of the empty fraction in a material. Voids can be in closed or in open from. Porosity can also be defined the as the ratio of the volume of the empty spaces (V_b) and the total volume of the body (V_T). (*Fekete I. (edited), 1985)*

$$\phi = \frac{V_b}{V_T} \qquad \text{(Eq. 7)}$$

-Macroporosity

In solids, where the sizes of the pores are greater than 50 nm in diameter. Transport through the macropores is described by bulk diffusion of water in the solid material.

-Mesoporosity

In solids, where the sizes of the pores are greater than 2 nm and less than 50 nm in diameter. Transport through mesopores is described by Knudsen diffusion effect.

-Microporosity

In solids where the sizes of the pores are smaller than 2 nm in diameter. Transport through the micropores is activated by diffusion. (*Fekete I. (edited), 1985)*

1.12. Moisture in materials

The building materials are mainly porous materials. Since the presence of the moisture can easily cause problems inside the materials, and in the whole building structure. In the vapor technique the effects of the two phases of the moisture can be divided. The

vapor phase what transports through the pores inside the materials due to the pressure difference, the movement of it can be hardly influenced. After condensation inside the material the moisture in liquid phase appears. The buildings are usually in contact with humid environment during its lifetime. But, the materials are containing moisture in normal quantity. This amount can be determined by laboratory measurements (see later). If the amount of the water exceeds the normal quantity undesirable changes can occur. Three different phases can be defined inside the building material: solid phase – the solid skeleton of the building material, the moisture connected to the surface of, the solid body with adsorption, and the gas phase over the liquid phase inside the material. The phases of the water can be separated to three parts: - vapor phase, liquid phase and the solid phase (ice). The vapor phase causes the smallest effects by only increasing the thermal conductivity of the materials, while the liquid phase can cause very harmful changes: increasing the thermal conductivity, has chemical effects, and it is undesirable from the point of view of esthetics. It has the greatest effect if it fills the pores. The ice can cause changes in the materials through the volume changing. The building materials can be separated to three types: 1) tight materials where only chemical bonds can be formed (e.g.: metals), here the water up-taking only goes with adsorption at the solid surface. 2) Materials with closed cells: they can take up water only with adsorption (e.g. extruded polystyrene). 3) Materials with open cells show different behavior. One type of them does not let the moisture be up-taken by adsorption, only with diffusion (wool materials). Other types do not let the moisture in with adsorption, but it lets with capillarity and with diffusion. Most of the materials show capillarity, adsorption and diffusion water uptake. The connection between the materials and moisture shows three different effects. The first is the Chemical bonds which can only be broken by thermal annealing. Physical-chemical bonds where adsorption on the surface of the solid can happen. Here besides the adsorption, desorption can be found also it is derived by the temperature and pressure difference. Mechanical bonds are dependent from the sized of the pores. In macrocapillars ($r>10^{-5}$ cm) the moisture fills the place only if it is in direct contact with the water. In microcapillars ($r<10^{-5}$ cm) sorption can happen also and the third form is if the volume is filled totally. (*Fekete I. (edited), 1985)*

1.12.1.The effect of the moisture in the building materials

The moisture effects can be separated to the following groups:

-liquid moisture and its effects,

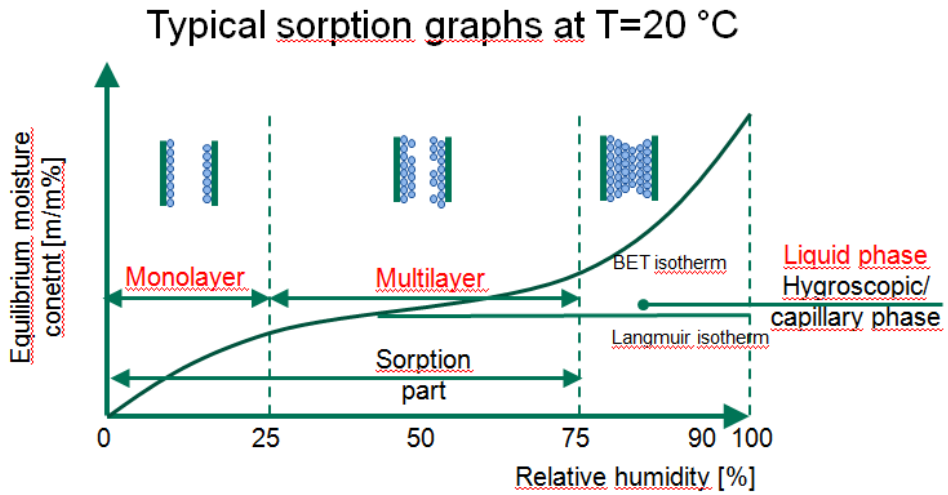
- vapor phase and its effects.

The presence of the water in liquid phase causes the most harmful effects. It can be happen if the building structures get into direct contact with water. Some of the building materials reach water during the manufacture (concrete). Since, it has water content in normal case. Or it can take up water from the indoor or outdoor environment. The

ground-water can appear inside the structure through capillary water up-take. Meteorological water occurs from the driving rain or from the environment with high humidity. Moistures from the operation can happen by the wrong maintenance of the buildings. Water vapor diffusion happens derived by the pressure/concentration gradient of the water/vapor. The condensation is a phenomenon too, it occurs usually on the internal surface of the structure. It can cause mold/mildew growth. (*Fekete I. (edited), 1985)*

1.12.2. Sorption isotherms

Sorption characteristics of building materials are key point from the rating and from performance durability point of view. As above mentioned water my cause unwanted changes in physical, mechanical and chemical properties of the materials.



1. Figure: Typical sorption isotherm graphs

Typical sorption graphs

On the picture the two mostly applied sorption isotherm graphs can be found: the Langmuir and the BET, ones. These two sorption characteristics are the most important ones, however other shapes are happen but here only these two will be presented and analyzed. Till about 40 % of the relative humidity both shows a square root type function, this means that firstly during the water up-taking the adsorption process at the surface take place, however after this with increasing relative humidity value the Bet isotherm shows a continuously increase while the Langmuir ones showing a constant equilibrium moisture content independently from the relative humidity. Through the BET isotherms one can follow the sorption phenomena, at first only the surface

contacts, than the multilayer part will occur. At high humidity region the diffusion of the liquid water happens too. *(Brunauer et. al. ,1940, Brunauer, 1943, Lakatos, 2011)*

1.12.3. Moisture absorption

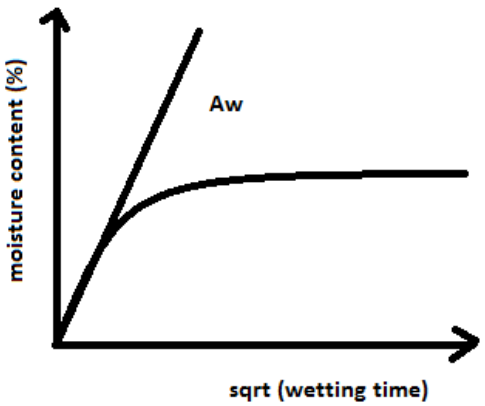
Water absorption coefficient "A_w" value of a material manages the capillary transport of the liquid moisture. "A_w" values is defined as the moisture absorption coefficient as the ratio of the water content (m_{wet}-m_{dry}) in kg, taken up through a given area (A) over the square root of the wetting time (t).

$$A_w = \frac{m_{wet} - m_{dry}}{A\sqrt{t}} \qquad \text{(Eq. 8)}$$

where m_{wet} and m_{dry} are the moist and dry masses of the samples,

1.12.4. Moisture kinetic curves

By applying long time wetting of the materials at a given humidity value and under a certain temperature, from the downer showed figure one can find the moisture absorption coefficient.



2. Figure: The kinetic curve

Hygroscopic moisture absorption can be further measured by Nuclear magnetic resonance (NMR) method, or through water immersion test. The A_w value can also be measured by using the ISO 15148:2002. Hygrothermal performance of building materials and products -- Determination of water absorption coefficient by partial immersion standard.

1.13. Effect of the moisture in the thermal conductivity

Most of the building and insulation materials have porous or fibrous structure, which holes can be present by up to 90% of the total volume of the material. These holes are containing air, or can contain other gases (e.g.: pentane). The above mentioned total/effective thermal conductivity mainly depends from the specific properties of the materials: from the density of the material (ρ), from the temperature (T), from the moisture content (ω) and from its age. On microscopic level it depends from the size and distribution of pores and fibers. Since the total/effective thermal conductivity can be given by:

$$\lambda_{eff} = f\,(\omega, \rho, T, p, other) \quad \text{(Eq. 9)}$$

In a normal temperature range (-10 ^{o}C - 25^{o}C) it can be easily showed that the pressure and the temperature of the ambient air has not effect in the thermal conductivity of a dry material, however in moist materials it has.

In moist materials with great pores (macroporous materials) the equation of the thermal conductivity is different. The air in the pores is superseded by the water absorbed from the air, or from the direct contact with the water. Because the thermal conductivity value of the water is greater than the air's the conductive, moreover the convective parts of the thermal conductivities will be increased, since the total thermal conductivity of the material will be raised up.

In literature for describing the relationship between the thermal conductivity and water content several models are used.

$$\lambda_{wet} = f(\lambda_{dry}, \omega) \qquad \text{(Eq. 10)}$$

where ω is the moisture content (kg/kg) and can be given as follows:

$$\omega = \frac{m_{water}}{m_{dry}} = \frac{m_{wet} - m_{dry}}{m_{dry}} \qquad \text{(Eq. 11)}$$

1.13.1. Linear model

The first model shows a pure and simple model to make a relationship between the thermal conductivity and the moisture content:

$$\lambda_{wet} = \lambda_{dry} \cdot \left(1 + \frac{\omega \cdot Z}{100}\right) \qquad \text{(Eq. 12)}$$

where λ_{wet}, λ_{dry}, are the thermal conductivities of the wet and dry materials respectively, while ω is the moisture content. Z is a constant and called to the moisture supplement of the thermal conductivity.

1.13.2. The polynomial model

The second model to describe the relationship between the moisture content and the thermal conductivity is a polynomial model, and it can be written as follows:

$$\lambda_{wet} = \lambda_{dry} \pm A\omega \pm B\omega^2 \pm C\omega^3 \pm \cdots \text{(Eq. 13)}$$

Where A, B, and C are material constants and can be reached from experiments.

1.13.3. Exponential model

For the correct understanding of the relationship between the thermal conductivity and moisture content an exponential model is used:

$$\lambda_{wet} = \lambda_{dry} + A \cdot T \cdot \omega \cdot e^{-B\omega} \qquad \text{(Eq. 14)}$$

(*Fekete I. (edited) 1985)*

1.14. Fire and heat resistance

The effect of the temperature in the physical properties and mechanical stability of the insulation and building materials is very important from applicability point of view. If the material is combustible it's behavior against the fire is significant. The highest temperature value for their use should be given for their applicability. The materials have fire classifications due to the MSZ EN 13501-1:2007+A1:2010 standard. They are classified to be A1, A2, B, C, D, E and F, category.

2. ATOMIC AND THERMAL DIFFUSION PROCESSES

2.1. The diffusion of atoms

In this section the comparison of the mathematics of the atomic diffusion with the heat and moisture diffusion will be presented. In order to fully understand the atomic flux, firstly the diffusion must be defined. Diffusion is caused by random molecular motion that leads to complete mixing. It follows then that flux can be described as "the rate per unit area at which mass moves. *(Lakatos et. al., 2015, Lakatos 2016a, b, Lakatos, 2017)*

$$J = -D \times grad(X) \quad \text{(Eq. 15)}$$

where J is the flux of an extensive property (eg.: atomic flux, heat flux etc.) and X is the intensive physical property (eg.: atomic concentration, temperature). By using Eq, 15 we can make a connection between the first (Eq. 16) and the second law of Fick (Eq. 17) with the thermal conductivity equations (Eq. 18. (Fourier) and 19.):

$$J_A = -D_A \times grad(C) \qquad \text{(Eq. 16)}$$

where J_A is the diffusion flux of the atoms in a given substance, D_A is the atomic diffusion coefficient and grad C is the concentration gradient of the diffusing atoms. Representing the 2nd law of Fick in one dimension and assuming that there are no sources and D_A is constant, the following equation can be reached:

$$\frac{\partial C}{\partial t} = D_A \times \frac{\partial^2 C}{\partial x^2} \qquad \text{(Eq. 17)}$$

where t is the time. *(Lakatos et. al., 2015, Lakatos 2016a, b, Lakatos, 2017)*

2.2. The heat diffusion

If we represent now the main equation of the thermal conduction which is the modified Fourier's law, a form of the equation is similar to the above mentioned ones (Eq. 15-17) can be found:

$$q = -D_T \times grad(T) \qquad \text{(Eq. 18)}$$

where J_q is the heat flux and grad T is the temperature (T) gradient, however,

$$D_T = \frac{\lambda_T}{\rho \times c_p} \qquad \text{(Eq. 19)}$$

is the thermal diffusion coefficient, λ_{eff} is the above mentioned thermal conductivity, ρ is the mass density and cp is the specific heat of the material. If we represent the modified Fourier's law (Eq. 18) in one dimension the following equation can be reached by using the following assumptions: the sample is free from heat sources and D_T is constant:

$$\frac{\partial T}{\partial t} = D_T \times \frac{\partial^2 T}{\partial x^2} \qquad \text{(Eq. 20)}$$

2.2.3 Calculation methods for the retardation time

There are some cases, when the atomic diffusion between pure two A and B materials cannot be represented as a Gaussian function, since the concentration profiles have a complementary error function dependence on depth near the interface and can be modeled as:

$$C(z,t) = \frac{C_0}{2} \times erfc\left(\frac{z}{2\times\sqrt{D_A t}}\right) \qquad \text{(Eq. 21)}$$

If one is measuring the rate of flow of a gas through a membrane in which the gas dissolves there will be an interval from the moment the gas comes into contact with the membrane until it emerges at a constant rate at the other side. In atomic diffusion is called to delay, time lag or retardation time of the diffusion barrier. *(Lakatos et. al., 2015, Lakatos 2016a, b, Lakatos, 2017)*

From (Eq. 22) the t (in h) as the time lag can be reached as:

$$t(h) = \frac{1}{4\times const^2 \times D_A} : 3600 \qquad \text{(Eq. 22)}$$

Similarly to Eq. 21 and 22 the temperature profiles can also be modeled as a complementary error function:

$$T(z,t) = \frac{T_0}{2} \times erfc\left(\frac{z}{2\times\sqrt{D_T t}}\right) \text{ (Eq. 23)}$$

From (Eq. 24) the t (in h) as the time lag can be reached as:

$$t(h) = \frac{1}{4\times const^2 \times D_T} : 3600 \qquad \text{(Eq. 24)}$$

Here has to be mentioned that equations 21 and 22 are well known equations for the diffusion profiles in nanodiffusion and it was presented earlier that they can be applied

with good approximations for thermal diffusions. *(Lakatos et. al., 2015, Lakatos 2016a, b, Lakatos, 2017)*

2.3. Liquid diffusivity

According to the above mentioned Fick's Law for isotropic materials the rate of the transfer measured perpendicular to the section of diffusing moisture through a unit area of a section is proportional to the gradient of moisture concentration. Hence, the liquid moisture transport phenomenon through isotropic building materials can be written, with the following:

$$J_m = -D_w \times grad(C_m) = -D_w \times \frac{\partial C_m}{\partial x} \qquad \text{(Eq. 25)}$$

where J_m is the rate of a liquid transfer per unit area of section (kg/m^{2}s), D_w is a material specific liquid diffusion coefficient (m^2/s), C_m is the volumetric moisture concentration. In the above mentioned equation C_m (the volumetric moisture concentration) can be substituted with the multiplication of the dry density of the material with the ω (kg/kg) moisture content. *(Mukhopadhyaya et al., 2002)*

$$J_m = -(\rho_{dry} \times D_w) \times grad(\omega) = -(\rho_{dry} \times D_w) \times \frac{\partial \omega}{\partial x} \quad \text{(Eq. 26)}$$

2.3.1. Water absorption and liquid diffusivity

A literature published by P. Mukhopadyaya in 2002 gives a simplification to reach an average liquid diffusivity from the water absorption coefficient. With the downer equation from the saturated volumetric moisture content of the material (w_c) one can evaluate an average liquid diffusivity coefficient:

$$D_w = \frac{\Pi}{4} \times \left(\frac{A_w}{W_c}\right)^2 \approx \left(\frac{A_w}{W_c}\right)^2 \qquad \text{(Eq. 27)}$$

(Mukhopadhyaya et al., 2002)

2.3.2. Water vapor diffusion resistance factor, μ-value

Diffusion of water vapor in air can be described by the equation:

$$J_v = -\delta \times grad(p) = -\delta \times \frac{\partial p}{\partial x} \qquad \text{(Eq. 28)}$$

where: Jv [kg/m²s]: water vapor flux density

p [Pa]: water vapor partial pressure

δ [kg/(msPa)]: water vapor diffusion through the pore spaces), but it is impeded by the reduction of the accessible cross-section, adsorption effects at the pore walls and the tortuosity of the pore paths. In the context of building physics, it is admissible to allow for this by simply introducing a diffusion resistance factor μ:

$$J_v = -\frac{\delta}{\mu} \times \frac{\partial p}{\partial x} \text{ (Eq. 29)}$$

μ [-]: water vapor diffusion resistance factor.

Retaining δ as a separate coefficient in the above equation has the advantage that it already describes the temperature and pressure dependence of water vapor diffusion , moreover μ is therefore practically independent of temperature and pressure, i.e. it is a constant which only depends on the material in question.

However, measurements of μ which are performed at different levels of relative humidity (dry-cup and wet-cup) may result in different values for one and the same material. This is due to surface diffusion which becomes noticeable once at a certain temperature and at higher humidity but would be more properly treated as liquid transport. The μ-value represents the ratio of the diffusion coefficients of water vapor in air and in the building material and has therefore a simple interpretation: it is the factor by which the vapor diffusion in the material is impeded, as compared to diffusion in stagnant air. *(Krus, 1996, Mukhopadhyaya et al., 2002)*

2.3.3. Freeze-thaw cycles

All materials are subjected to temperature dilatation or contraction, which can occur mechanical and physical failures; and generates internal stresses inside with about 9% when it freezes (ice forms), since the repeated freeze-thaw cycles may cause measureable changes in the system or structure of the building material. For example,

frost weathering due to water freezing has shown several issues in composite materials or bricks due to ice volume expansion and the related pressure increase. Therefore, testing the resilience of materials towards freeze-thaw cycles is important especially in those climates that experience frequent freeze-thaw conditions *(Jelle, 2012)*

2.3.4. Elevated temperature

High temperatures can increase the kinetic reaction rates within the molecules of the materials and enhance the chemical, moreover the physical degradation phenomenon. The effect of the change in the temperature of the environment (ageing) can be modeled with thermal annealing at higher temperatures. Certainly, thermal annealing of the samples at high temperatures would never be experienced in typical outdoor climate conditions; it can happen that it will generate unrealistic aging issues. For these reasons, thermal annealing processes for modeling the ageing phenomena of the building materials are usually executed below $70\ ^{o}C$. *(Jelle, 2012)*

3. measurement methods of the thermal properties of materials

3.1. Thermal conductivity measurements

The thermal conductivity measurements should be executed as the rules of the EN ISO 12664:2001 standard (Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Dry and moist products of medium and low thermal resistance). *(Lakatos et. al., 2015, Lakatos et al., 2013)*

3.1.1. Thermal conductivity measurements of the building and insulation materials with Holometrix lambda 2000

For measuring the thermal conductivity of each sample, Lambda 2000 Heat flow meter (HFM) is used. This equipment is designed to determine the thermal conductivity of materials in accordance with standard ASTM C518 and ISO 8301 protocols. A sample with 30 cm x 30 cm x 1-10 cm geometry is placed in the test section between two plates which are maintained at different temperatures (T_1=285 K and T_2=295 K, with T_{mean}=290 K) during the test. After achieving thermal equilibrium and establishing a uniform temperature gradient throughout the sample, thermal conductivity is determined. To determine the thermal conductivity of a sample, three independent measurements should be carried out. The thermal conductivity of analyzed material is the mean value of the three measured results.

For understanding the measurement method of Holometrix Lambda equipment the following comments are indispensable. The magnitude of the heat flow (Q) depends on several factors:

a) thermal conductivity of samples (λ=k)

b) the thickness of the specimen (Δx)

c) the temperature difference across the specimen (ΔT)

d) area through which the heat flows (A).

The Fourier heat flow equation gives the relationship between these parameters when the test section reaches thermal equilibrium.

$$Q = \lambda \times A \times \frac{\partial T}{\partial x} \qquad \text{(Eq. 30)}$$

One or two heat flow transducers measure the heat flow through the specimen. The signal of a heat flow transducer (in Volts (V)) is proportional to the heat flow through the transducer. In the Lambda 2000 HFM instrument, the area of the heat flow transducer represents the area through which the heat conduction is realized and it is the same for all specimens, therefore the heat flow will be:

$$Q = N \times V \qquad \text{(Eq. 31)}$$

Where N is the calibration factor, that relates the voltage signal of the heat flow transducer to the heat flux through the specimen. For calibration of apparatus a fibrous glass board standard sample with λ= 0.035 W/mK is used. Using the above mentioned equations the heat conductivity can be determined:

$$\lambda = N \times V \times \frac{\Delta X}{A \Delta T} \qquad \text{(Eq. 32)}$$

The term reproducibility indicates the variation of the test results of one specimen from test to test. Factors such as how well the specimen makes contact with the plates and the temperature stability affect the reproducibility. If the thermal resistance of the test specimen is commensurable with the reference standard's ± 5% or better accuracy can be obtained. *(Lakatos et. al., 2015, Lakatos et al., 2013)*

3. Figure: The Holometrix apparatus

Measurement steps:

1. Measure the geometry of the sample, sides, thickness and the mass.
2. Calculate the density.
3. Switch on the apparatus.
4. Place the specimen to the measuring field of the equipment.

3. Run Qlab program on the computer.

4. Press Test button.

5. Give in the details to the Qlab program:

-Calibration file, file name, density and thickness.

6. Hit Enter button.

7. Press reset on the back of the computer.

3.1.2. Thermal insulation – Determination of steady-state thermal transmission properties – Calibrated and guarded hot box

a. Calibrated chamber method *(Lakatos et. al., 2015, Lakatos et al., 2013)*

The determination of steady-state thermal transmission and thermal insulation of wall structures by calibrated hot box can be executed on the basis of to the MSZ EN ISO:8990 standard. The box should be made of 0.1 m thick EPS 200 enclosed between two sheets of wood with 0.02 m thickness. The temperature outside the box must be kept by basic portable electric radiator to constant. Measurement of temperatures both of the air and on the wall surfaces, at both sides should be done by Pt-100 type thermocouples, or other thermocouples. The temperatures of the walls on the surfaces both on the cold and the warm sides are measured at 9 points and the results are stored on data storage. The average value of surface temperatures should be calculated from the unique values of the Pt-100 thermocouples. Inside the box a small fan is used for circulating air, and is heated by two bulbs, moreover their electric power is measured too. It is done outside the box with two calibrated electricity meters separately. At the cold side one fan as well as two air baffles are used in order to reach a good air average temperature. From the measured surface temperatures of the wall the temperature difference can be calculated (ΔT^{cc} in K) in steady-state stage. From the measured electric power and the operating time (t in h) an average power (P^{cc} in W) can be found. For achieving the thermal resistance of the layer structure, with A^{cc}=1.44 m^2 surface area, the following equation can be used:

$$R^{cc} = \frac{T^{cc}}{A^{cc} \times P^{CC}} \qquad \text{(Eq. 33)}$$

b. Hukseflux apparatus *(Lakatos et. al., 2015, Lakatos et al., 2013)*

Hukseflux HFP01 heat flux sensors serve the reason to measure the density of heat flow rate that flows through the object in which it is incorporated or on which it is mounted. This instrument can measure the density of heat flow rate, and air temperature, so the R-value of building envelopes can be calculated according to ISO 9869, ASTM C1046 and ASTM C1155 standards. The measurements are carried out by using two HF sensors with 5.024×10^{-2} m^2 rounded surface. For good spatial averaging they were fixed up at different points on the wall. For measuring the air temperatures at both warm and cold sides 2 pairs of thermo-couples belong to this apparatus. By using this apparatus one can reach an accurate value for the thermal resistance (R-value) measured by using the following equation, similarly to the above mentioned:

$$R^{hf} = \frac{T^{hf}}{q^{hf}} \qquad \text{(Eq. 34)}$$

3.1.3. Thermal conductivity measurement with guarded hot plate method (GHP)

The GHP process is based on an absolute test method and therefore requires no calibration standards opposite to the measurements with a heat flow meter. It offers good accuracy regardless of the temperature range of test interest. The measurement method is the following. The hot plate and the guard ring are sandwiched between two samples of the same test material and with approximately the same thickness (Δx). Auxiliary heaters (cold plates) are placed above and below both samples. The cold plates are heated such that a well-defined, user selectable temperature difference (ΔT) is established between the hot and the cold plates (over the sample thickness). The power input in the hot plate with area A is then measured as soon as thermal equilibrium is reached. Using the measured sample thicknesses, temperatures and power inputs, the thermal conductivity can be determined from the steady-state heat transfer equation.

3.2. Measurement of the specific heat of the materials with differential scanning calorimeter

Differential scanning calorimeter, (DSC), is a thermo-analytical method in which the difference in the quantity of heat is needed to change the temperature of a specimen and reference is measured as a function of temperature degree. Both the sample and reference are kept to nearly equal temperature during the test. Generally, the temperature change of the equipment is designed such that the temperature of the specimen holder increases as a linear function of time. The reference specimen should have a known specific heat capacity in the range of temperatures to be tested.

The measurement method was developed by E. S. Watson and M. J. O'Neill in 1962, and introduced commercially at the 1963 Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy. The first adiabatic differential scanning calorimeter that could be used was showed by P. L. Privalov and D. R. Monaselidze in 1964 at Institute of Physics in Tbilisi, Georgia. The DSC method was coined to describe this equipment, which measures heat energy directly and allows proper investigation of specific heat capacity. (*Wunderlich, 1987, Wunderlich, 1993, Dean, 1995, Pungor, 1995, Skoog, 1998)*

Types of DSC:

-Power-compensated DSC, (keeps power supply constant)

-Heat-flux DSC, (keeps heat flux constant)

-Detection of phase transitions

The basic principle of this method is that when the sample undergoes a physical state transition such as phase transition, more or less heat will need to flow to it than the reference to maintain both at the same temperature. If less or more heat should flow in to the specimen depends on whether the procedure is exo- or endothermic. If a solid specimen forms to a liquid (melting), it will require more heat flowing to in; to change its temperature at the same rate as the temperature of the reference specimen. This is due to the amount of absorbed heat by the sample as it undergoes the endothermic phase change from solid to liquid (melting). Likewise, as the specimen suffers exothermic change, (e.g.: crystallization) smaller heat is needed to change the temperature of the specimen. By registering the difference in the heat flow among the sample and reference specimen, this type of calorimeter is capable to measure the quantity of heat absorbed, or released under such change. Differential scanning calorimeter can also be used to observe more subtle physical transitions, for example as glass transitions. It is widely used in industrial circumstances as a quality controlling instrument due to its applicability in characterize sample purity and for studying polymer curing.

Differential thermal analysis

A possible technique, which shares much in common with DSC, is differential thermal analysis (DTA). In this technique the heat flowing to the specimen and reference sample that remains equal rather than their temperature degree. If the test sample and reference specimen are heated together, phase changing and other thermal processes cause a measurable difference in their temperature value (test and reference sample). Both the DSC method and DTA procedure provide comparable and similar information. Differential scanning calorimeter measures the heat energy needed to keep both the reference specimen and the test sample at the equal temperature, whereas DTA

measures the difference in the temperature among the test specimen and the reference sample when the same quantity of energy has been supplied to both.

Applications of DSC and DTA

DS calorimeter is used to measure some thermal characteristic properties of materials. Using this equipment it is possible to detect fusion and crystallization phenomenon as well as glass transition temperatures etc. DSC can also be used to study oxidation, as well as several chemical reactions.

Glass transitions occur, when the temperature of an amorphous solid is increased. The glass transition happens if the sample undergoes a change in its heat capacity; no formal phase change occurs.

As the temperature increases, the viscosity of the amorphous solid will be less. At some point the molecules may obtain enough freedom of motion to spontaneously arrange themselves into a crystalline form. This is known as the crystallization temperature (T_c). This transform from amorphous to crystalline solid is exothermic process, moreover it results in a peak in the DSC curve. (*Wunderlich, 1987, Wunderlich, 1993, Dean 1995, Pungor 1995, Skoog 1998)*

3.3. Bomb calorimeter

Bomb calorimeter is a procedure to determine the heat of combustion or calorific value of solid and liquid materials which are combusted. It has relevance in a primary test of great importance to: coal production, power stations, fuel analysis, animal feed research, educational institutes, commercial analytical laboratories, by-product analysis, building materials sector, etc. The CV (Calorific Value)/combustion heat of a substance is measured by burning it in a controlled environment. The resulting heat released by this combustion, i.e. the net temperature rise is proportional to the calorific value. Measurement of the calorific value of insulation materials is very important from fire safety point of view. The combustion is carried out in high pressured very clean oxygen (30 bar), in an adiabatic chamber, since no heat loss can be expected during the burning. With this apparatus liquids (oil fuels) can be tested too, which are not evaporate at room temperature. The apparatus measures the heat of combustion what is the total heat energy released from the material if a substance undergoes total combustion in pure oxygen under fixed conditions. A chemical reaction takes place typically as hydrocarbon reacting with oxygen to form carbon dioxide and water and release heat. It may be expressed with the quantities:

energy/mole of fuel (kJ/mol)

energy/mass of fuel

energy/volume of the fuel

Heating value unit conversions:

MJ/kg= kcal/kg × 238.846

Btu/lb = kJ/kg× 2.326

Btu/lb = kcals/kg x 0.5556

Measurement steps:

1. Measure the thickness of the sample with a milligram preciseness balance.
2. Put the sample in the combustion tower, with the firing kit.
3. Close the tower.
4. Open gas vessel.
5. Fill the can with Oxigen gas.
6. Put it into the calorimeter.
7. Close the top of the calorimeter.
8. Type in the mass with the keyboard, MA=.

4. Figure: The bomb calorimeter apparatus

3.4. Sorption measurements

For the measurement of the sorption/water up-taking properties of solid materials three equipments should be combined. A drying oven, a climatic chamber and a (milligram preciseness) balance. At first the samples should be dried to changeless weight in a drying oven, in this context in a Venticell 111 apparatus. The Venticell 111 apparatus has internal volume with 111 liter. It works between 10°C to 250 °C. With this device materials can be dried by setting different air temperatures. It works with hot air circulation using an inbuilt ventilator, and a homogenous dry environment forms. After drying the materials in the Venticell apparatus to changeless weight, their masses should be measured with the balance. Than the materials should be placed in a climatic chamber in this example its a Climacell 111 equipment. This apparatus is a laboratory incubator where homogenous environment can be created. The apparatus works in a 0 °C to 100 °C temperature range without humidity and from 10 °C to 95 °C with humidity. The relative humidity can be fixed from 10% to 90%. The sorption measurement should be separated to two parts. The first part is the determination of the sorption isotherms of building materials the other one is the determination of the kinetic curves.

3.4.1. Sorption isotherms

The sorption isotherm measurements should be carried out by using the ISO 12571: 2013 standard (Hygrothermal performance of building materials and products -- Determination of hygroscopic sorption properties, Part B- climatic chamber method). The standard defines the measurement's order (e.g.: the number and size of the samples). The sorption isotherms (SI curve) of the materials were presented above. By the combination of the above mentioned three apparatus (venticell, climacell and milligram preciseness balance) the SI curves can be reached. At first the materials should be dried to changeless weight, and then they should be wetted to equilibrium state in the climacell apparatus at fixed temperature (usually 20 °C) under at least 5 relative humidity values between 20 and 90 %. By the measurements of the wetted and dried weights and using the following equation:

$$\omega\left(\frac{kg}{kg}\%\right) = \frac{m_{wet} - m_{dry}}{m_{dry}} \times 100 \quad \text{(Eq. 35)}$$

the equilibrium moisture content can be reached.

3.4.2. Kinetic curves

If one fixes not only the temperature but the relative humidity in the climatic chamber and wets the samples for different times (e.g.: 20 min to 48 h) the so-called square-root of the time type kinetic curves can be found, from initially increasing moisture content to reaching the equilibrium.

5. Figure: The Venticell 111, Climacell 111 equipments and the milligram preciseness balance.

Measurement steps:

1. Switch on the Venticell apparatus

2. Set the temperature to the relevant temperature.

3. Put in the samples to the drying oven.

Wait for the equilibrium(to changeless weight).

4. Measure the mass of the materials.

4. Switch on the climacell apparatus.

5. Set a relevant temperature.

6. Set a relevant relative humidity.

7. Place in the samples.

8. Wait for a certain time, or the equilibrium.

4. CONVENTIONAL INSULATION MATERIALS

In the European Union buildings take about the 20–40% of the total final energy consumption *(Perez-Lombard 2008).* Because no one of the member states is independent from energy point of view, in the building sector the main goals are to increase the energy efficiency and the utilization of renewable energy sources. This is part of the 20-20-20 EU target. To fulfill the fixed goals several Directives were prepared. One of the Directives is the 2002/91/EC Directive dealing with energy performance of buildings. *(Directive 1)* This Directive in 2010 was revised and adopted as 2010/31/EU Directive *(Directive 2).* According to this Directive as of 31 December 2020 new buildings in the EU will have to consume 'nearly zero' energy and the used energy will be 'to a very large extent' from renewable sources. Public authorities that own or occupy a new building should set an example by building, buying or renting such 'nearly zero energy building' as of 31 December 2018. In this context proper insulation of buildings envelope is one of the leading challenges of the building industry. One of the most important actions is the thermal insulation of buildings. For this several types of insulation materials are available (e.g.: expanded polystyrene, extruded polystyrene, mineral wool, foam glass, poly-urethane, poly-iso-cyanurate etc. In this book only the mainly used insulation materials will be presented. It was above mentioned that all materials has thermal resistance in function of its thermal conductivity and thickness, since the materials has insulating capability. In the building physics the materials are grouped from their thermal conductivity value point of view. Materials have lower than 0.15 W/mK thermal conductivity, determined at 10 ^{o}C average temperature are called to insulation materials. In practice those materials are called to insulation materials, which have lower than 0.06 W/mK thermal conductivity. They are also called to effective insulation materials. *(Bozsaky, 2017)* The insulation materials can be further grouped whether they are natural or artificial, organic or inorganic, moreover from their structure point of view (foamy or fibrous.)

In this section a review will be given about different insulation materials available on the market.

4.1. Requirements for the insulation materials

The insulation materials should meet several requirements what will give their performance. These requirements are the followings:

- low thermal conductivity,

- resistance to mechanical impact,

- volume and dimensional stability,

- physical and chemical stability,

- fire, heat and frost resistant,

- un-hygroscopic,

- breathable.

4.1.1. Acoustic requirements

The insulations materials should meet requirements from acoustic point of view. It is the ability to contrast sound transmission and to absorb impinging sound waves. Sound absorption once defines the part of the acoustic energy dissipated inside a material because of friction or thermal loss inside the porous materials or of resonance. While, the porous sound insulation materials are good thermal insulators, vice versa is not always true. The sound insulation of the construction mainly depends on the performance of the heaviest components e.g.: brick or concrete.

4.1.2. Life Cycle Assessment

Life Cycle Assessment (LCA) is a known procedure to assess the environmental impact of any services or products. The methodology to performed the evaluation is clearly written in ISO standards 14040 *International Organization for Standardization, ISO 14040: 2006 Environmental management – Life cycle assessment – principles and framework* and *14044 International Organization for Standardization, ISO 14044: 2006 Environmental management – life cycle assessment – requirements and guidelines.* LCA allows measuring the environmental weight through number of indicators; the most used methods are the Cumulative Energy Demand (CED) and the Global Warming Potential (GWP). Cumulative Energy Demand is the primary energy consumed directly and indirectly through the considered life cycle of the evaluated product. Global warming up potential is used to measure or assess the impact in the global warming of a product under its life cycle; for the evaluation it uses all the gas emissions, which are calculated in terms of kg of CO_2 equivalent. The indicator can be expressed in milestone years: 20, 50 and 100. Another methodology applied in life cycle studies is the Eco-indicator, that allows measuring the damage caused during the life cycle of a product. Each environmental impact is normalized to a functional unit, f.u. *(Schiavoni et al. 2016)*

4.2. Plastic foam materials

The foamy materials can be divided to two groups from their cell structure point of view whether they have closed or open cells. These materials are manufactured from organic monomers (e.g. styrene, ethylene etc.) by polymerization or by addition polymerization. They are foamed by pentane gas or air and the locked amount of gas in the cells will give their insulation capability. *(Bozsaky, 2017)*

4.2.1. Expanded polystyrene

The expanded polystyrene (EPS) has open cell structure. Its density and compressive strength is in the range of 30-200. It means that it can be mainly used in the frontage of the buildings. Its resistance to the moisture transport is low. They are available with different densities 10-40 kg/m^3 with different thermal conductivities λ=0.32-0.044 W/mK. Their melting point can be found at about 80 ^{o}C. Their main physical parameter is their density. It characterizes their main thermal properties. The manufacturing of the EPS materials are carried out by expanding the styrene grains in a pre-foamer with pentane gas. During the expanding water vapor is given to the poly-styrene and the grains are expanding to 20-50 times to their initial volume. From these product blocks will be manufactured. During the cooling down of the blocks their surface will be hardened and the pentane in the cells will be replaced by air. *(Bozsaky, 2017)*

4.2.2. Extruded polystyrene

The extruded polystyrene materials (XPS) are manufactured by melting the styrene grains in extruders. Their cell structure is closed and much more rigid than the above mentioned type. They are watertight since they are mainly used as roof or plinth insulations. Their stability and strength are greater than the above mentioned one, however their density and thermal conductivity is higher than the (EPS). Their mechanical properties are good, their compressive strength value can be up to 700. Their cost is about 20-30% greater than the EPS's. *(Bozsaky, 2017)*

4.2.3. Poly-urethane

It (PUR) is used in the building sector since 1970 due its excellent thermal insulation capability. They are mainly used as sandwich panels. They have two important types: the ether and the ester based. They have differences between their strength or density and thermal insulation capability. It is produced during an exothermic reaction between di- or poly-iso-cyanate with ether or ester. Their thermal conductivity is at about 0.025-0.035 W/mK and their density is ranging between 15-130 kg/m^3. They are mainly use as roof insulation with bitumen type bonding. *(Bozsaky, 2017)*

4.2.4. Poly-iso-cyanurate

Poly-iso-cyanurate (PIR) is produced through a chemical reaction similar to the process of above mentioned ones, polyurethane, by using a polyester-derived polyol and higher pieces of methylene diphenyl diiso-cyanate. PIR materials are typified by their higher resistance against fire compared to PUR ones (classification B, is better than the E of PUR's). Moreover, compared to the other plastic foams, PIR materials have the best fire resistance capability. In compared to PUR insulation, they have lower thermal

conductivity ranging between 0.018 and 0.027 W/mK, and with nearly the same values of density 15-45 kg/m^3 and specific heat with about 1400 J/kgK. They are also used as roof insulations and as external structure manufactured as in sandwich panels with thicknesses 15-20 cm. *(Schiavoni et al., 2016)*

4.2.5. Phenolic foam

Phenolic foam insulation materials have low thermal conductivity in a range between 0.018-0.025 W/mK. They are organic insulation materials. Their density is relatively higher than the other presented plastic foam insulation (150 kg/m^3). Their specific heat capacity is in the same range than the others however they have good reaction to fire.

4.3. Fibrous materials

These types of insulation materials are mainly produced in blanket or rolls. They have fibrous structure since they are poor water insulators, but the air can transport through the samples well, since they can be dried out easily. But water vapor can cause undesirable changes in its thermal properties. They are not water proof; however they can be manufactured in hydrophobic form.

4.3.1. Mineral wool

Mineral wool is the mainly used fibrous insulation material. Its base material is the vulcanized rock, and formed by rolling, spinning or drawing molten minerals. They are used both as pipe and thermal insulations. They have high fire resistance. They are good sound insulators. It can be either manufactured from molten rocks, at relatively high temperature at about 1600 ^{o} C. Better production techniques are based on spinning molten rock in high-speed spinning heads. The final product is a mass of fine, intertwined fibers with a typical diameter of 2 to 6 micrometers. Mineral wool may contain a binder, often a terpolymer, and an oil to reduce dusting. They are timeless, their mass density is ranging between 30-200 kg/m^3 and their thermal conductivity is ranging between 0,032-0,040 W/mK. *(Schiavoni et al., 2016)*

4.3.2 Stone wool

This type of insulation material is made by melting at about 1500-1700 ^{o}C different types of rocks (basalt, dolostone, etc.). From these fibers will be obtained and bound together with binders (resin). They are commercialized mainly as panels or blanket rolls. Their density is widely ranging from about 50-200 kg/m^3. Their thermal conductivity is between about 0.032-0.044 W/mK. They are good sound absorber and tcan be recycled.

4.3.3 Foam glass

A Pittsburgh Corning Corporation (settled: 1937) is producing foam glass materials since 1938. They are producing these materials in porous form since 1942. The reason for the manufacturing of their porous form is their use as thermal insulation. Due to their composition they have relatively high compressive strength. It is produced from 66% of recycled glass. They are fire proof, incombustible resist against acids and most of the solvents, they are water and corrosion proofs. Its capillary water up-taking is negligible, completely hydrophobic. Due to their strength they are used mainly in cryo-technique as cool-insulators. But nowadays they are also used as roof insulators. Their manufacture process is the following: Sand and other additives are mixed with carbon particles and with recycled glass and crushed to dust together. These mass is melted at about 1000 ^{o}C in furnace. Due to the high temperature the carbon particles will burn to carbon-dioxide bubbles what will expand. This is the foaming process of the material and due to this, it will have porous structure with expanding to the 20 times of the initial volume. The samples will be thermal annealed at a fix temperature for several hours (relaxation). The additive carbon will give the black color of the foam glass. Their thermal conductivity is about 0.05 W/mK, while their density is ranging between 100-160 kg/m^3. Their compressive strength is about 500-1700 kN/m^2.They can also used where driving rain happens.

4.3.4. Glass wool

Glass wools are mainly produced from recycled glass or waste glasses mixed and melt with natural sand at about 1400 ^{o}C. In a blower centrifuge fibers will be produced, by adding resins to the melt they will be bounded. Their thermal and sound insulation capability is nearly the same to the stone wool.

4.3.5 Expanded perlite

The name of this material originates from the word pearl. From mineralogy point of view perlites are meta-stable and amorphous volcanic rock containing aluminum-silicates, which has hollow structure and contain chemically bonded water. The bonded water content of the expanded perlite is between 2.5 and 4%. From Tokaj region of Hungary good quality perlites can be mined. The broken and dried perlites are milled to 1.6 mm size and expanded at about 100 ^{o}C. Their maximal density is about 100 kg/m^3 and their thermal conductivity is about 0.04-0.047 W/mK. They can be used as additive to concretes with cement forming a lightweight concrete.

4.4. Alternative materials

(Schiavoni et al. 2016)

4.4.1. Corkwood

Cork can be used for many applications. Cork oak materials are commonly used also in the building technique, due to their good thermal and acoustic properties. The lambda value of these materials is changing between 0.04 and 0.06 W/mK, their density goes from 100 to 150 kg/m^3 while the specific heat is about 1600 J/kgK. This material is manufactured in panels, stripes, loose or added to plaster, and it can be easily recycled. It is made from the crust of the cork oak tree. These trees can be found in the Mediterranean countries. They have very good fire resistant property since they are also used in rocket technique. They have containing air bubbles in elastic cells.

4.4.2. Hemp

Hemp is a fibrous material produced from cannabis sativa (Latin name) that is used also for building application mixed with poly-ester fiber and fire retardant additives. One of hemp's most innovative and applicable uses today is in building materials sector. Their thermal conductivity is ranging between 0.04 and 0.06 W/mK, their density is between 20-90 kg/m^3, moreover their specific heat capacity is about 1500 j/KgK. Due to their natural and fibrous originate they can absorb water easily from air, with a measurable increase in the thermal conductivity. They are usually produce with hydrophobic additives (e.g.: waxes pasta) to be water proof. They are also used as additives at lightweight concretes (hempcrete). Containing lack of proteins makes it highly resistant to mold growth, dust, and other pollutants. By adding soda the fire resistant properties can be maintained. *(Schiavoni et al., 2016)*

4.4.3. Wood fiber

The use of wood fiber insulation goes back to the last 20 years. The mainly used particles are the timber wood particles. Their thermal conductivity is ranging between 0.038 to 0.045 W/mK and their density is about 50 to 250 kg/m^3. Aluminum sulfate binder can be added to it to activate the lignin of wood. Due their natural and fibrous origin they can take up moisture easily from the air. But it is also breathable and helps the moisture content being regulated. Their thermal conductivity strongly depends from the temperature and from the moisture content. They are used both for wall and for roof insulation. *(Schiavoni et al., 2016)*

4.4.1. Cellulose

Cellulose insulation blankets are produced from 100% recycled paper. Since, they have little environmental impact. They are good thermal and sound insulators, too. They are produced from paper and newspaper wastes collected selectively, moreover from wood fibers. The collected wastes are granulated and then they are flocked with adding boron and borax. Since, it will be a fire resistant thermal insulation material. Their thermal conductivity is about 0.039 W/mK. It has high heat storing capacity and also protects from the summer overheating. It fills the available places well. Their density is between 30-40 kg/m^3. They are elastic so can be applied well as insulation of floating floors. The wastes of this insulation material cannot be further recycled due to the boron and borax content. *(Schiavoni et al., 2016)*

4.5. Classification of building insulation materials

4.5.1. According to heat exchange properties

Insulations can be grouped into two classes regarding the purpose of the use by manipulating the heat transfer through itself: 1) mass insulations, 2) reflective insulations. Mass insulations are those having high density, and can retard the heat flow by conduction, whereas the reflective insulations are those ones which reduce the amount of heat transfer by radiation or reflection. *(Aditya et al. 2017)*

4.5.2. Mass insulation

Objects with high thermal mass, density as well specific heat capacity absorb and retain heat, slowing the rate at which the sun heats a space and the rate at which space loses heat when the sun is gone. Without thermal mass, heat that has entered a space will simply re-radiate back out quickly, making the space overly hot with sunlight and overly cold without. Mass insulations are those having high density, high specific heat capacity, that can retard the heat flow through itself by conduction. Insulations should be particularly valuable in preventing direct heat gain from being conducted to the ground or outside air, where it is lost. In hot climate where direct heat gain is not desirable, it can even be beneficial for exterior finishing to have low thermal mass, as well as low conductivity, to increase the effectiveness of insulation. Regarded as the most commonly used type of thermal insulation, mass insulation diminishes heat flow rate by conduction at the case where practically no convection and radiation occur by heat transfer. Due to this, the effectiveness of mass insulations is highly depending on insulation material thickness. Moreover depends in its specific heat and density.

Increasing the thickness proportionally increases the thermal performance of the mass insulation, and these materials usually have low rate of heat conduction. Apart from that, the thermal performance of thermal insulation material is also depending on the condition of subdivision or density of material. As previously mentioned, mass insulation usually contains a huge number of tiny air trapped pockets, which reduces conductive heat transfer. These tiny pockets of trapped air act as barriers for heat flow. Therefore, any attempt to condense or compress the mass insulation will reduce its effectiveness. *(Aditya et al. 2017)*

4.1.3. Reflective insulations

Reflective insulations are thermal insulation which reflects or absorbing radiation heat, preventing transfer from one side to another due to a reflective (or low emittance) surface. This concurrently decreases the amount of heat transferred or solar heat gain impacting the building and improves interior temperatures and air quality. The amount of energy radiated depends on the surface temperature and a property called emissivity; the higher the emissivity, the greater the emitted radiation at that wavelength. Reflective insulation utilizes one or more low-emittance reflective surfaces that enclose air spaces, which is usually used in home attics, roofing and wall systems. The reflective insulation has at least one reflective surface that faces an airspace by this application. The reflective insulation contributions on the thermal performance detailed were investigated in a number of publications. *(Aditya et al. 2017)*

5. NANOTECHNOLOGICAL INSULATION MATERIALS

The nano word origins from Greek work “nanos” meaning “dwarf”. Nanotechnology is the technology to investigate the matters at an atomic and molecular scale, with dimensions less than 100 nm. Nano insulation materials are containing nano-particles or nano-pores.

1) Vacuum insulation materials are homogenous material with a closed small pore structure filled with vacuum (evacuated air) with an overall thermal conductivity of less than 4 mW/mK.

2) Gas filled insulation materials are homogenous materials too with a closed small pore structure filled, in this case, with a gas with low thermal conductivity, achieving very low thermal conductivity. These gases are enclosed between two layers their thickness is small, since their convective heat transport property is negligible.

3) Nano insulating materials are homogeneous materials with a closed or open small nano pore structure with an overall thermal conductivity of less than 4 mW/mK.

4) Dynamic insulation material is a material where thermal conductivity may be controlled within a desirable range. The thermal conductivity control may be achieved by:

-Inner pore gas content or concentration including the mean free path of the gas molecules and the gas-surface interaction

-The emissivity of the inner surfaces of the pores

-The thermal conductivity of the solid skeleton (lattice, crystal etc.)

(Bozic, 2015)

Nano insulating materials are based on the impartiality of change of energy through the collision of molecules of a gas. If the pore size in a certain material is reduced to a naometric scale, on the principle of Knudsen effect when the molecules mostly collide with the walls of the pores (cells), and not with the other molecules of gas. This elimination of intermolecular collisions is basically in reduction of thermal conductivity and efficiency of nano insulation materials. Nowadays, commercially available state-of-the-art nano/advanced-insulations e.g.: aerogels, ceramic insulations, graphite doped EPS, VIP, etc, have been reported to have thermal conductivities lower than 0.02 W/(mK), in ambient circumstances. However, these days their high production cost goes against their applications. Aerogels have relatively high compression strength, but they are very fragile due to their very low tensile strength, moreover, the blanket/fibrous ones are very dusty and it is hard to fix them on the wall. A very interesting aspect of aerogels is that they can be produced as either opaque (in a blanket), translucent or transparent materials, they can be used as windows too. Thus it

is enabling a wide range of possible building applications. For aerogels to become a widespread thermal insulation material for opaque applications, the costs have to be lowered substantially. However, their thermal properties are much lower than those of the transparent ones (windows). These blankets were developed as an insulation material based on silica-aerogels. “HY-TECH” or advanced ceramic insulating paint additive is a fine, white powder blend of high strength ceramic "micro/nanospheres". Each single ceramic microsphere is so small that it looks to the naked eye as if it is a single grain of flour, (slightly thicker than a human hair). Nano-technological graphite doped materials are added to expanded polystyrene for enhancing its heat transfer, increasing the reflectance of the radative heat. Because nano-graphite reduces the huge amount of heat that moving through the EPS by radiation. The result is that it can cut the heat transfer through the material by 9 to 21%, depending on density. The construction industry has much to gain from nanotechnology. Solutions in the offing range from materials with better insulating properties, to solar cells that power your house more economically, and siding that is protected from the effects of weather. Driven by updated building energy codes and green building initiatives across the world, vacuum insulation panel, also known as VIP, has become a perfect insulation product for building envelope constructions. VIP has initial center-of-panel thermal conductivity of 0.004 W/mK or lower, and integration of VIP in building envelopes can reduce CO_2 emissions and contribute towards ‘net-zero’ or ‘near-net-zero’ building constructions.

5.1. Aerogel

Silica aerogel fibrous insulation material is one of the advanced and state-of-the-art insulation materials. They are dried gels with very porous structure. The application of aerogel products in building science is not very common due to the their relatively high cost. Aerogel blankets/panels have already been used at all parts of the building envelopes except by the moisture loaded parts. Commercially available and affordable state-of-the-art aerogels have been reported to have excellent thermal conductivities between 0.014-0.022 W/mK thermal conductivity. Aerogels have acceptable compression strength, but the samples are very fragile due to their very low tensile strength, as well as the fibrous types are very dusty. A remarkable property of the aerogels is that they can be produced as either opaque (in a blanket), translucent or transparent materials, thus enabling a wide range of possible building applications (window, external coating etc.). The main reason and advantage for their use as thermal insulation can be found in their space-saving benefit, which has been proved also using aerogel insulation films. Due to their low thermal conductivity they can be used in thinner layers than the above mentioned insulation materials. Couple of decades earlier they were used as glazing systems, in both monolithic and granular form for space

filling. Monolithic silica-aerogel has good solar transmittance than the granular ones but they are very fragile. They are produced through sol-gel process as the following: It starts with the sol-gel preparation, when the gel is produced with a sol-gel process through the dissolution of the solid components of the gel in a liquid agglomerate forming a uniform 3D network structure throughout the solution. Then the process is followed by the gel ageing, when the fragile gel is aged in its base-solution to become stiffer and stronger, till a relatively strong porous solid body is formed by trapping the solvents into the pores; and the preparation process finishes with the drying of the gel, when the liquid inside the pores will be replaced by air *(Lakatos, 2017. Aegerter et al., 2011, Berardi, 2018, Nosrati et. al., 2018)*

5.1.1. Aerogel windows

The windows are mainly responsible for about 25-30% of the total energy loss of the buildings. Both the monolithic and the granule based aerogel samples can be used as windows/glazing systems by applying them between two glass panels. Aerogel has good thermal insulation property and high visible transmittance. Monolithic silica aerogels have higher solar transmittance than the grain ones. But their disadvantage can be found in their mechanical stability; they are fragile. Aerogel incorporated windows are usually triple-multilayered glazing systems. *(Berardi, 2018, Nosrati et. al., 2018)*

5.1.2 Aerogel incorporated products

Aerogels can be used as additives to lightweight concretes. Lightweight concretes have low density and better thermal conductivity moreover less compressive strength compared to the conventional concretes. They are mainly used as floors or roofs too. The different types of lightweight concretes are made from different additives (e.g. polystyrene grains, mineral or wood fibers. Lightweight concretes are prepared by substituting partially the cement aggregates of concrete with insulation materials. In the scientific research one can found novel solutions for manufacturing Aerogel based cements, mortars and plasters by adding aerogel granules to the core material. *(Berardi, 2018, Nosrati et. al., 2018)*

5.2. Vacuum insulation panels (VIP)

Vacuum insulation panels (VIP) said to be as one of the most picking up thermal insulation solutions with high performance. The thermal conductivity of the VIP samples is ranging between 0.002 and 0.004 W/mK depending from the type of the material. Vacuum insulation panels high insulation capability enables their use both for

reducing the thermal loss in buildings and for industrial application (hot and cold). At the beginning they were used as thermal packaging materials, but nowadays their use by passive houses, nearly zero energy buildings or internal insulation for historical buildings is spreading over too. Due to their very low thermal conductivity they can be used also where the available space for the insulation is limited. The technology for the manufacturing of the VIPs is very complicated however, it is based on the evacuation of the air from a panel, and vacuum (P<5 mbar) will be formed instead of air. The main contents of this type of materials are once the core material and the surrounding environment, barrier envelope. The core material of the first VIPs was fibrous mineral or glass wool, but nowadays for being core material is fumed silica. They are often covered with metallic coating (e.g.: alumina) for mechanical protection. Their lifetime is shorter due to the diffusion of the gas molecules or water vapor into the panel with increasing the pressure inside. For reducing the in-diffusion of the gases getter materials are often used inside the panels. The above mentioned aerogel is often used as core material of the VIPs. *(Song et. al., 2016, Bozsaky, 2017)* However, vacuum insulation panel is one of the most promising insulation materials, their usage and applicability is limited, due to its very vulnerable property. Its packaging, transporting, handling and installation need extraordinary circumspections, because they are very fragile. Any mechanical shock can break the panels, since they will lose their nearly perfect thermal insulation capability. Their fixing procedure should also be carried out with care, mechanical fastenings cannot be used (e.g.: steel, plastic anchors). The panels will become more accessible to consumers, when the installation method of the panels will be much safer and easier. *(Bozic, 2015)*

5.3. Graphite enhanced expanded polystyrene

Graphite Polystyrene (GPS) is highly efficient, rigid foam insulation used in various remodeling and new construction applications, such as behind new siding, below grade, and below slab. This material can provide up to 20% more energy savings than traditional white expanded polystyrene (EPS) insulation. To convert the material into rigid insulation boards, the graphite beads are injected into a mold then hit with steam, which causes them to expand until they fill the mold. Depending on the shape of the mold, the pieces are either ejected from the mold and packaged, or cut to their finished shape with hot wires. *(Web 1)*

To further reduce the thermal conductivity of the expanded insulation materials, graphite nanotubes or carbon particles are added to the polystyrene grains during the manufacturing procedure. Since these materials will have much lower thermal conductivity (0.03-0.035 W/mK) than the above mentioned EPS materials. As above mentioned the heat is transferred in three ways (conduction, convection, radiation). It should be mentioned that during a heat transfer process the entire three phenomenon occur, but one of them is dominant. Graphite has very good thermal radiation absorbing

capability; moreover it has beam scatter property too. This material works in the very same way as traditional insulation, with one primary difference – the high-purity graphite particles give the insulation a reflective property which increases the energy efficiency of the material.Their color will be grey due to the colors of the graphite particles. Their other properties (compressive strength, density etc.) are similar to the above mentioned conventional EPS ones. The graphite component of this type of insulation causes the heat to be reflected hundreds of times as it moves through the insulation. This significantly slows the transfer of heat, making this material more energy efficient than traditional EPS insulation. This type of insulation material has better sound insulation property compared to the above mentioned EPS materials. The advantage of adding graphite to the polystyrene grains with respect to vibroacoustic characteristics can cause a reduction in dynamic stiffness. The fire resistance class of this material is E. *(Lakatos et. al., 2013)*

6. PHASE CHANGE MATERIALS (PCM)

These materials are not insulation materials, but they are often used as reducing the energy loss of the buildings. Phase change materials (PCMs) used for the storage of thermal energy. The thermal energy storing capability can be understood through their phase change behavior. They have the capability to store (keep inside) and release (give down) energy in the form of latent heat or sensible heat during phase change methods. They do it between a solid-liquid (melting)/liquid-solid (freezing) phase changes at their melting point temperature. PCMs are used as thermal storage systems in order to store excessive heat from inside the building. Several types of these materials e.g.: inorganic systems (salt and salt hydrates), organic compounds such as paraffin or fatty acids and polymeric materials and poly(ethylene glycol called to PEGs). The applicability of the PCMs depends on several factor e.g.: the structure of the building, the external temperature (climate), indoor environmental parameters and from the melting/freezing point of the PCM. When the PCM is at a temperature under its melting point is solid and its physical behavior is the same as other normal bulk material. After increasing its temperature it absorbs and transfers heat according to their thermal conductivity, density, and heat capacity (heat absorption coefficient and thermal diffusion coefficient). If the temperature of the environment reaches the melting point of the materials, it starts the phase change (melting) at an almost constant temperature keeping the heat inside till the material is completely melts. The amount of this heat energy is called to melting heat. Nowadays, on the market one can find a solid-solid PCM also. The heat storing and releasing capacity can be found in their crystallization processes. They can store and release heat during their phase transitions between crystalline and amorphous change or in their re-crystallization at room temperature. *(Konoklu, 2015, Berardi, 2017)*

7. EXAMPLES FOR THE MEASUREMENTS

7.1. Thermal conductivity measurements and calculations with Holometrix apparatus

1. Table: Example of the results of the thermal conductivity measurements with holometrix apparatus 1.

ID of the specimen	A (m)	B (m)	C (m)	Mass (kg)	Density (kg/m^3)	Average temperature (^{o}C)
XY201X/Y	0.294	0.296	0.05	0.0732	16.82	32

Thermal conductivity (W/mK)						
1	2	3	4	5		Average
0.029075	0.028562	0.028767	0.028664	0.02887		0.028788
0.000287	0.000226	2.06E-05	0.000124	8.24E-05	±	7.4E-05
8.26E-08	5.09E-08	4.24E-10	1.53E-08	6.79E-09	St. dev.	0.000279

1. Table: Example of the results of the thermal conductivity measurements with Holometrix apparatus 2.

7.2. Thermal resistance measurements with Hukseflux apparatus

Time (h)	Heat flux	DT	Twarm	Tcold
0,000	28,935	32,020	20,690	-11,330
0,167	27,285	32,420	20,540	-11,880
0,333	26,375	32,570	20,445	-12,125
0,500	25,660	31,505	20,370	-11,135
0,667	25,050	32,555	20,285	-12,270
0,833	24,560	32,070	20,215	-11,855
1,000	24,040	31,250	20,150	-11,100
1,167	23,685	32,495	20,090	-12,405
1,333	23,310	31,585	20,025	-11,560
1,500	37,555	31,175	20,895	-10,280
1,667	26,810	32,060	20,425	-11,635
1,833	32,800	32,895	21,080	-11,815
2,000	28,490	31,730	20,645	-11,085
10,000	24,430	31,425	20,135	-11,290
Time (h)	Heat flux	DT	Twarm	Tcold
	27,137	32,115	20,411	-11,704
	R (m^2K/W)	1,183		
	R_o (m^2K/W)	0,601		
	Lambda (W/mK)	0,017		

2. Table: Example of the results of thermal resistance measurements with Hukseflux equipment

7.3. Thermal resistance measurements with calibrated chamber method

Time [h]	Warm wall	Warm air	Cold wall	Cold air
0.00	19.59	21.23	-11.10	-14.93
0.02	19.63	21.29	-11.26	-15.13
0.03	19.75	21.27	-12.30	-17.35
0.05	19.76	21.38	-13.45	-18.83
0.07	19.71	21.20	-14.10	-18.79
0.08	19.66	21.02	-14.23	-18.86
0.10	19.63	21.03	-14.09	-18.63
0.12	19.54	21.18	-13.95	-18.14
0.13	19.50	20.82	-13.74	-17.73
0.15	19.55	21.39	-13.38	-17.64
0.17	19.78	21.49	-13.28	-17.05
0.18	19.74	21.50	-13.04	-16.79
0.20	19.72	21.35	-12.81	-16.88
0.22	19.77	21.18	-12.62	-16.56
0.23	19.70	21.27	-12.49	-16.52
0.25	19.66	21.11	-12.28	-16.28
0.27	19.70	21.39	-12.15	-16.25
0.28	19.83	21.38	-12.08	-15.85

0.30	19.86	21.97	-11.98	-15.61

3. Table: Example of the results of thermal resistance measurements with hot box method 1.

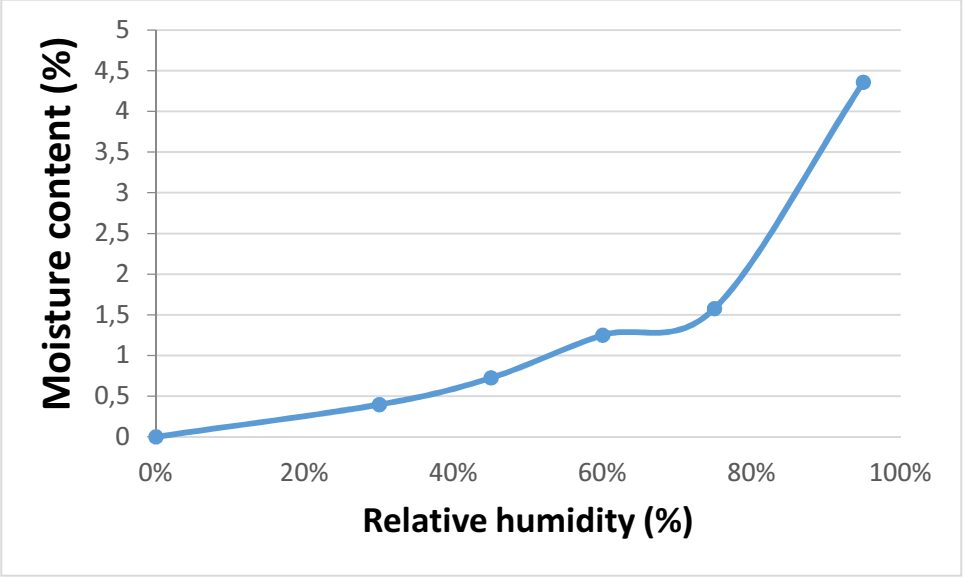
	p1	p2			
Start	83.700	57.140	Time (h)	25.000	
Stop	84.400	57.750	Wall area (m^2)	1.440	
diff.	0.700	0.610		1.120	
DT_{wall}	32.289	44.800		$R_{energowall\_fal}$=	1.038
DT_{air}	37.952			$U_{energowall\_fal}$=	0.964
U_{air} [W/m^2K]	0.820	R_{air} [m^2K/W]	1.220	R_{01} [m^2K/W]	0.420
		R_{air}-R_{wall}	0.182	R_{02} [m^2K/W]	0.590
		Alfa: [W/m^2K]	5.493	lambda, air [W/mK]	0.021
				lamda, wall [W/mK]	0.021

4. Table: Example of the results of thermal resistance measurements with hot box method 2.

7.4. Sorption isotherm measurements results

ω	AD	±
0%	0	
30%	0,39653	0,13218
45%	0,72541	0,00942
60%	1,24977	0,00392
75%	1,5761511	7,40149E-17
95%	4,35963371	0,033640891

5. Table: Example of the results of sorption isotherm measurements 1

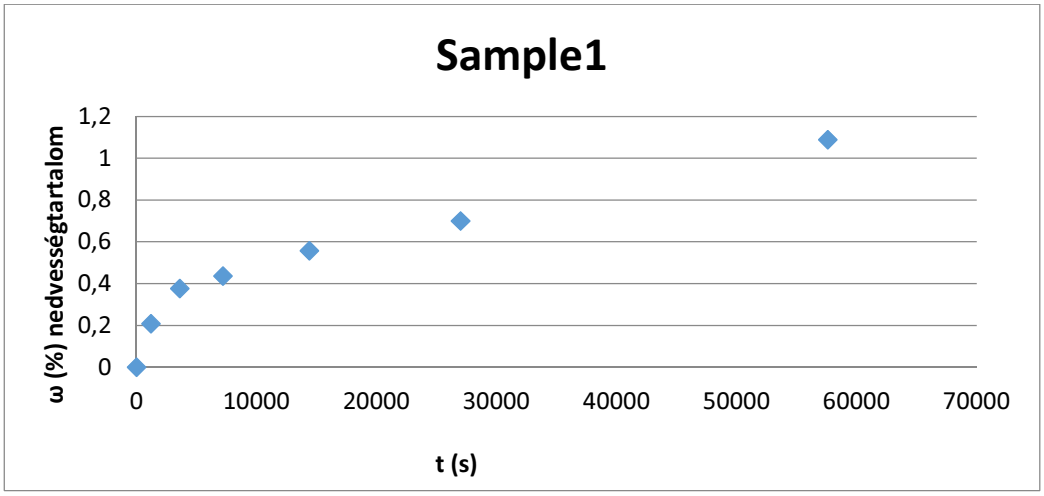


6. Table: Example of the results of sorption isotherm measurements 2

7.5. Water absorption measurement result

Time (h)	Time (s)	Sqrt time (sqrt s)	Sample1	Error
0	0	0	0	0
0.333333	1200	34.64101615	0.208	0.0213
1	3600	60	0.3762	0.0125
2	7200	84.85281374	0.436	0.0527
4	14400	120	0.5575	0.053
7.5	27000	164.3167673	0.7	0.0833
16	57600	240	1.089	0.0517

7. Table: Example for the measurement results of the water absorption test



6. Figure: Example for the result of a water absorption test

TABLES

FIGURES

LITERATURE

ADITYA Lisa, MAHLIA Teuku Meurah Indra, RISMANCHI, Behzad, NG H. M., HASAN, M. H., METSELAAR Hendrik Simon Cornells, MURAZA Oki: *A review on insulation materials for energy conservation in buildings.* In: Renewable and Sustainable Energy Reviews, 2017., vol. 73. pp. 1352-1365.

AEGERTER Michel, LEVENTIS Nicholas, KOEBEL Matthias M. (Eds.): *Aerogels Handbook*. New York: New York Springer, 2011. pp. 537–564.

BERARDI Umberto, MANCA Mauro: *The energy saving and indoor comfort improvements with latent thermal energy storage in building retrofits in Canada.* In: Energy Procedia, 2017., vol. 111. pp. 462 – 471.

BERARDI Umberto: *Aerogel-enhanced systems for building energy retrofits: Insights froma case study*. In: Energy and Buildings, 2018., vol. 159. pp. 370–381.

BOZIC Jelena: *Nano insulation materials for energy efficient buildings.* In: Contemporary Materials (Renewable energy sources), 2015., vol VI. no. 2. pp. 150-159.

BOZSAKY Dávid: Építési hőszigetelő anyagok (Thermal insulation materials for buildings). Budapest: Budapest, Terc Kft. 2017. ISBN 978 615 5445 446

BRUNAUER Stephen, DEMING Lola, DEMING Edwards, TELLER Edward: *On a theory of the van der Waals adsorption of gases.* In: Journal of American Chemical Society, 1940. 62. vol. pp. 1723–1732

BRUNAUER Stephen: *The Absorption of the Gases and Vapors. I. Physical Adsorption.* Princeton, Princeton University Press, 1943. ISBN 978-1406750300

DEAN John A: *The Analytical Chemistry Handbook.* New York: McGraw Hill, Inc. pp. 1995- ISBN 0-07-016197-6.

Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. Official Journal of the European Communities, L 1/65, 4.1.2003

Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official Journal of the European Union, L 153/13, 18.6.2010.

FEKETE Iván (edited): *Épületfizika kézikönyv*. *(Handbook of Building Physics).*

JELLE Peter: *Accelerated climate ageing of building materials, components and structures in the laboratory*. In: J Mater Sci. 2012., vol. 47. pp. 6475–6496.

KONOKLU Yeliz: *Review on using microencapsulated phase change materials (PCM) in building applications.* In: Energy and Buildings, 2015., vol. 106 pp. 134–155.

KRUS Martin: *Moisture Transport and Storage Coefficients of Porous Mineral Building Materials*. *Theoretical Principles and New Test Methods*. Stuttgart: Stuttgart Fraunhofer IRB Verlag. 1996. –ISBN 3-8167-4535

LAKATOS Á: *Investigation of the moisture induced degradation of the thermal properties of aerogel blankets: Measurements, calculations, simulations.* In. Energy and Buildings, 2017., vol. 139. pp. 506-516.

LAKATOS Ákos, CSÁKY Imre, KALMÁR Ferenc: *Thermal Conductivity Measurements with Different Methods: A Procedure for the Estimation of the Retardation Time. In:* Materials and Structures, 2015., 48. vol. 5. no. pp. 1343-1353.

LAKATOS Ákos, KALMÁR Ferenc: *Investigation of thickness and density dependence of thermal conductivity of expanded polystyrene insulation materials.* In: Materials and Structures, 2013., 46. vol. 7. no. pp. 1101-105.

LAKATOS Ákos: *A Theoretical Approach to Estimate the Time Lag of Building Envelopes* In: & (ed.) 16th International Multidisciplinary Scientific Geoconference SGEM 2016: Book 6: Nano, Bio and Green - Technologies for a Sustainable Future Conference Procedings Vol III. 692 p. STEF92 Technology Ltd., 2016. pp. 403-410. ISBN 978-619-7105-79-7

LAKATOS Ákos: *Basics of heat transfer and fluid mechanics*. Debrecen: University of Debrecen, 2014. ISBN 978-963-473-798-8

LAKATOS Ákos: *Method for the determination of sorption isotherms of materials demonstrated through soil samples.* In: International Review of Applied Sciences and Engineering, 2011., 2. vol. 2. no. pp. 117-121.

LAKATOS Ákos: *Nanotechnológiás hőszigetelőanyagok vizsgálata tömör tégla falazaton.* In: Energiagazdálkodás, 2016., 57. vol. 3-4. no. pp. 21-25.

LAKATOS Ákos: *Thermophysical investigations of nanotechnological insulation materials*. In: AIP Conference Proceedings, 2017., 1866. vol. 030003. pp. 1-6.

MUKHOPADHYAYA Phalguni, Goudreau Partrick, KUMARAN Kumar, NORMANDIN Nicole: *Effect of surface temperature on water absorption coefficient of building materials*. In: Journal of Thermal Envelope and Building Science, 2002. 26. vol. no. 2. pp. 179-195.

NOSRATI Roya Hamideh Nosrati, BERARDI Umberto: *Hygrothermal characteristics of aerogel-enhanced insulatingmaterials under different humidity and temperature conditions*. In: Energy and Buildings, 2018., vol. 158. pp. 698–711

PE´REZ-LOMBARD Luis, ORTIZ José, POUT, Christine: *A Review on buildings energy consumption information.* In: Energy and Buildings, 2008., 40. vol. pp. 394–398

PUNGOR Ernő: *A Practical Guide to Instrumental Analysis.* Florida: Boca Raton. 1995. pp. 181–191.- ISBN - 9780849386817

SCHIAVONI Samuel, ALESSANDRO Francesco, BIANCHI Francesco, ASDRUBALI Francesco: *Insulation materials for the building sector: A review and comparative analysis. In:* Renewable and Sustainable Energy Reviews. 2016., Vol. 62. pp. 988-1011.

SKOOG Douglas, HOLLER James Holler, NIEMAN Timothy: *Principles of Instrumental Analysis* 1998 (5 ed.). New York. pp. 805–808. ISBN 0-03-002078-6.

SONG Kuo, MUKHOPADHYAYA Phalguni: *Vacuum insulation panels (vips) in building envelope constructions: an overview.* In: International Review of Applied Sciences and Engineering 2016., vol. 7. no. 2. pp. 113–119.

WEB Reference 1: https://www.progressivefoam.com/neopor-graphite-polystyrene-what-it-is-and-how-it-works/ Downloaded: 2018.05.29.

WUNDERLICH Bernhard: *Development towards a single-run DSC for heat capacity measurements*. In: Journal of Thermal Analysis, 1987., 32. vol. 6. no. pp. 1949-1955.

WUNDERLICH Bernhard: *Single-run heat capacity measurement by DSC: principle, experimental and data analysis*. In: Thermochimica Acta, 1993., 226. vol. pp. 155-161