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Comparison of Thermal Insulation Materials

for Building Envelopes of Multi-storey Buildings

in Saint-Petersburg

Bachelor Thesis

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Abstract

This thesis is about comparing of different thermal insulation materials of different manufactures. In our days there are a lot of different thermal insulation materials which properties are very close to each other, but prices can be vary a lot. As a result, using of incorrect thermal insulation material in building envelope can provoke lower cost efficient and low energy efficient of the project. With a help of this work it is possible to choose most energy-efficient and cost-efficient thermal insulation material for building envelope with ventilated air cavity.

Comparing of thermal insulation material made for outdoor walls of multi-storey building in region of Saint-Petersburg Russia. But way of calculations in this thesis is multipurpose and can be used also for another regions, and constructions of building envelopes.

Subject headings (keywords)

thermal insulation, building envelope, thermal resistance, heat transfer, manufacturing of thermal insulation, mineral wool, foam plastic, expanded polystyrene, extruded polystyrene

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LIST OF SYMBOLS USED

λ - thermal conductivity	$[W/(m \cdot K)]$
λ_0 - thermal conductivity at the temperature 273K	$[W/(m \cdot K)]$
R_i - thermal resistance	$[\frac{m^2 \cdot {}^0C}{W}]$
γ - specific weight of air	$[\frac{N}{m^3}]$
e - partial pressure	[Pa]
E - maximum partial pressure	[Pa]
α - coefficient of heat transfer	$[\frac{W}{m^2 \cdot {}^0C}]$
R_{des} – air tightness	$[\frac{kg}{m^2 \cdot h}]$
Ω - resistance of the water vapor permeability	$[\frac{m^2 \cdot h \cdot Pa}{kg}]$

1 INTRODUCTION

In northern countries, builders have been forced to fight with low temperatures, cold winds, high humidity, and many other adverse weather conditions. For good work and comfortable life, human need buildings with a good indoor climate, which does not depend on weather conditions during the year. In our days it is impossible to build walls from brick or stone which thickness is close to one meter, because it will cost a lot of money and nobody will pay for such heavy and expensive building. That’s why the best way to save heat in winter time, and not let in warm in summer time it is to use modern thermal insulation materials in building envelope.

It will be very easy to build “warm” walls, if we have such material, which is so strong as stone, so warm as fluff, and so cheap as air. In modern structures, builders never use only one type of material in building envelope, because one material can prevent air leakage, other one protect from weather conditions and another one can bearing loads. But only one layer, which consists of thermal insulation material, can prevent heat transfer effectively.

Thermal insulation is the main layer of building envelope, which can reduce heat losses and make building more energy efficient. So, the main question is to choose correct thermal insulation material which will help to satisfy requirements of building codes at the lowest cost. In my work I take most common design of building envelope and check, with which thermal insulation material, properties of the building envelope becomes mostly close to requirements of building codes. As a result I have found the answer on a question: Which thermal insulation material is mostly energy-efficient and cost-efficient.

Some manufactures of thermal insulation materials have made comparison of their products, but in most cases they make a comparing using one or two parameters. Also, usually manufactures comparing only their products, for example mineral wool, or polystyrene, but never a complete building envelope with many layers. Builders are talking about comparing of different thermal insulation materials on special forums in the internet, but usually, these disputes are ended without any results, because each person try to make a comparing by their own way. As a result, nobody can answer, what combination of what thermal insulation materials in building envelope are mostly energy-efficient and cost-efficient /2/.

2 INVESTIGATION OF THE PROPERTIES OF THERMAL INSULATION MATERIALS

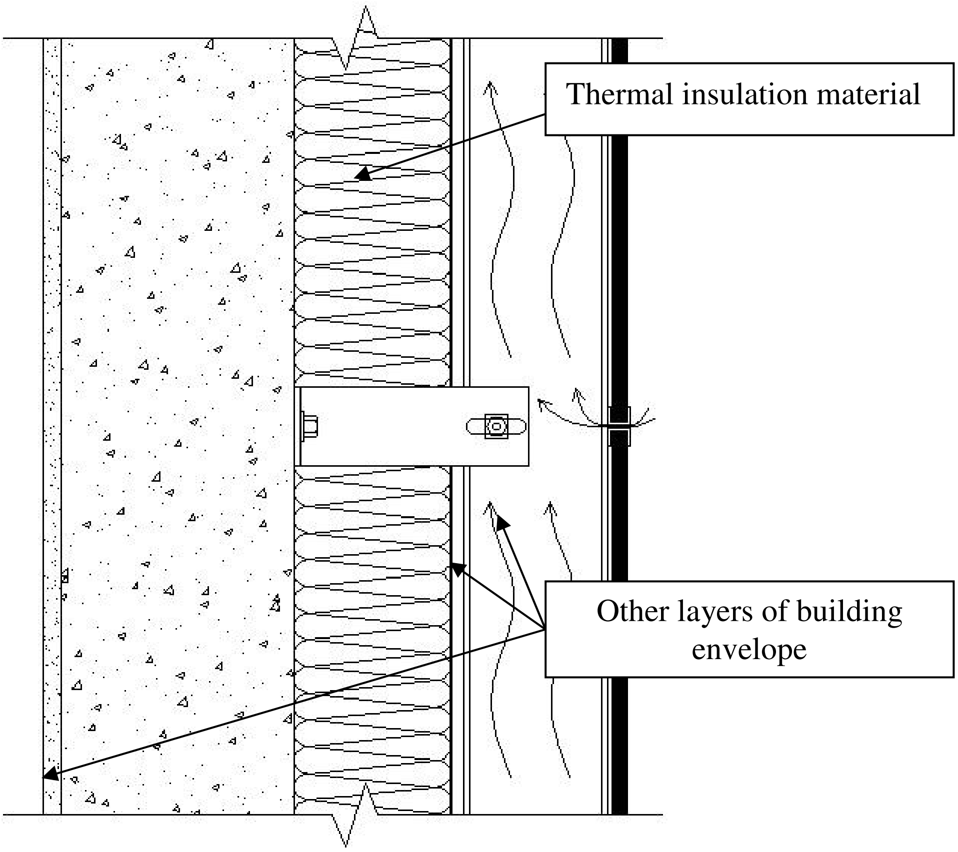
At first I will talk about object of investigation. And I will justify, that this object is real interesting to be investigated.

Next I will distinguish the main groups of the thermal insulation materials which are will be investigated in my work.

Then I will explain processes of manufacturing of the main thermal insulation materials, to explain the reason of differences in properties of thermal insulation materials, which are manufactured from the same raw materials.

After that I will talk about main requirements for thermal insulation materials, which are used in building envelope. With a help of information from previous paragraphs I will explain, how different properties of the thermal insulation materials help to achieve the requirements.

2.1 Problem statement



Picture 1. Principle design of outdoor wall (with ventilated façade) of the building envelope of multi-storey building /8/

In Picture 1 it's possible to see that the layer of the building envelope, which consists of thermal insulation material isn't so thick as other layers (about them I will talk in future paragraphs) but it's the most important layer in a question of energy-efficiency and cost-efficiency. For example, price of thermal insulation materials can vary from 50,4 euro/m^3
to 105,3 euro/m^3 (prices in Saint-Petersburg, Table 2). And the V_{tim} - volume of thermal insulation material in a simple multi-storey building can be calculated by the Formula 2.1.1.

$$V_{tim} = (a \cdot 2 + b \cdot 2) \cdot h \cdot t \tag{2.1.1}$$

where: a – length of the building, a = 20 m (for example);

b – length of the building, b = 50 m (for example);

h – height of the building, h = 50 m (for example);

t – thickness of the thermal insulation, t = 0,1 m (for example).

$$V_{tim} = (20 \cdot 2 + 50 \cdot 2) \cdot 50 \cdot 0{,}1 = 700\,\mathrm{m}^3$$

And now, if we multiply volume of the thermal insulation material with different prices we will see, that price of the construction may differ on 38500 euro depending on which thermal insulation material will be selected for the building envelope. That's why in my work I want to find the most energy-efficient and cost-efficient thermal insulation material.

The main idea is to prove that so big price of the thermal insulation materials of some manufactures is not a result of great technology, or best properties of the thermal insulation materials, just an advertisement and PR. At the same time I will prove that it's possible to build energy efficient building and archive the requirements of building codes with a help of low price thermal insulation materials. For this purpose I should look at all thermal insulation materials from different perspectives. And I will start from manufacture.

2.2 Process of manufacturing of the main thermal insulation materials

In this chapter I will talk about manufacturing of the main thermal insulation materials like as:

1. foam plastic with open pore;
2. foam plastic with closed pore;
3. mineral wool from slag;
4. mineral wool natural rock.

Manufacturing process is interesting, because main properties of those materials are formed during manufacturing stage. Be familiar with it, is very useful for understanding how will material work and what processes will take place in it, and also which material should be used in different situations.

2.2.1 The manufacture of the mineral wool

There are two main types of mineral wool:

1. mineral wool from slag;
2. mineral wool from rock.

This classification is based on the type of raw material.

Most mineral wool produced today is produced from slag or a mixture of slag and rock. Most of the slag used by the industry is generated by integrated iron and steel plants as a blast furnace byproduct from cast iron production. Other sources of slag include the copper, lead, and phosphate industries./3/ Also, different countries always use slag as a raw material, but sources of this slag can be different. For example:

1. USA use slag which is stay from blast furnace;
2. French, Sweden and Yugoslavia use slag which is stay from blast furnace and add to it basalt or diabase;
3. Germany use slag which is stay from blast furnace, but add to it marl;
4. Russia use slag , which is a waste of iron industry. /5, p. 64./

But using the slag from iron industry is a heritage of economic policy of the USSR. Because using of this slag give a positive effect for iron industry (because they can make profit from producing mineral wool from this slag), but at the same time using of such slag have a harmful influence on mineral wool. Because, it is very hard to keep properties of slag (from iron industry) constant. As a result properties of mineral wool can be different.

The following process description are based on the description given on the EPA website /3/.

The production process has three primary components: molten mineral generation in the cupola, fiber formation and collection, and final product formation.

The first step in the process involves melting the mineral feed. The raw material (slag and

rock) is loaded into a cupola in alternating layers with coke at weight ratios of about 5 to 6 parts
mineral to 1 part coke. As the coke is ignited and burned, the mineral charge is heated to the molten state at a temperature of 1300 to 1650°C (2400 to 3000°F).

The molten mineral charge exits the bottom of the cupola in a water-cooled trough and falls
onto a fiberization device. Most of the mineral wool produced is made by variations of 2 fiberization methods. The Powell process uses groups of rotors revolving at a high rate of speed to form the fibers. Molten material is distributed in a thin film on the surfaces of the rotors and then is thrown off by centrifugal force. As the material is discharged from the rotor, small globules develop on the rotors and form long, fibrous tails as they travel horizontally. Air or steam may be blown around the rotors to assist in fiberizing the material. A second fiberization method, the Downey process, uses a spinning concave rotor with air or steam attenuation. Molten material is distributed over the surface of the rotor, from which it flows up and over the edge and is captured and directed by a high-velocity stream of air or steam.

During the spinning process, not all globules that develop are converted into fiber. The nonfiberized globules that remain are referred to as "shot." In raw mineral wool, as much as half of the mass of the product may consist of shot. Shot is usually separated from the wool by gravity immediately following fiberization.

After formation and chemical treatment, the fiber is collected in a blowchamber. Resin- and/or
oil-coated fibers are drawn down on a wire mesh conveyor by fans located beneath the collector. The speed of the conveyor is set so that a wool blanket of desired thickness can be obtained.
Mineral wool containing the binding agent is carried by conveyor to a curing oven, where the
wool blanket is compressed to the appropriate density and the binder is baked. Hot air, at a
temperature of 150 to 320°C (300 to 600°F), is forced through the blanket until the binder has set.

Curing time and temperature depend on the type of binder used and the mass rate through the oven. A cooling section follows the oven, where blowers force air at ambient temperatures through the wool blanket.

To make batts and industrial felt products, the cooled wool blanket is cut longitudinally and
transversely to the desired size./3/

So, basing on information about manufacturing it is possible to make some findings:

1. The main difference between properties of mineral wool is fire safety. If as raw materials slag and rock, fire safety becomes higher up to 1000 ^{0}C and if raw material is just a slag, fire safety is decrease to 600^{0}C;
2. The price of mineral wool from slag and rock is higher because it needs higher temperatures during the production (as a result more energy), and more expensive raw material as basalt, than mineral wool from slag (Table 2);
3. The possible harmful influence of the binder which is used to put together fibers. Because, usually as a binder use formaldehyde, which can have a harmful influence on human during the process of exploitation. But this harmful effect is decrease close to zero with a help of hot air, at a temperature of 150 to 320°C (300 to 600°F), is forced through the blanket until the binder has set. Such heat treatment destroy all free particles of formaldehyde which can become free during the operation of the building, and make a bad influence for human

2.2.2 Process of manufacturing of the foam plastic

There are two main types of foam plastic:

3. foam plastic with open pore (in following paragraphs – expanded polystyrene)
4. foam plastic with closed pore (in following paragraphs – extruded polystyrene)

This classification is based on the way of manufacturing

The raw material for this two types of materials is the same, they are thermosetting polymer, aeration component, hardeners and different types of supplements to correct properties of product. But there are two different technologies of processing of the raw material and as a result there are two different thermal insulation materials with different properties.

The following process description are based on the description given in a book "thermal insulation materials and constructions /5/. The first one is expanded polystyrene. Method of manufacturing of this material at first was invented by "Badisclie Anilin und Soda Fabrik A. Ci." BASF. The main idea of this method is that at first, from a single mass of polymer, manufacturing the prefabricated material which is called expandable polystyrene, it is consist of particles of "milk" color, and have a form of little balls like beads. This particles contains aeration component, usually it is easy boiling liquid. Process of transformation of this particles to the final product consist of the heat treatment of particles which is invoke soften of polymer and derivation of little sticky, then starts widening of particles out of the evaporation of aeration component, and then gluing of the particles with each other. As a result we have material which is consist of a big number of separate particles, which structure is open.

The second one is extruded polystyrene which is manufacturing by extrusion method. This method was opened by American company "Dow Chemical Company", the main idea is that polymer with a help of high temperature becomes in liquid fluid state and stay under the pressure. After this, aeration component added to it and this two components mixing with each other. On the next stage this mixture pushed through the extruder (something like nozzles which have a form of future product). While material coming through extruder pressure is decrease very fast and aeration component start to foam and in a structure of material little pore start to form. This pore has closed structure. The next stage of the manufacturing process is cooling of the product. And during this process material becomes hard /5/.

The main value of such manufacturing process is that subject of transformation is not separate pellets, but single mass of aeration component and polypropylene in fluid stage. And as a result, future material has closed pores and more homogeneous structure, than foam plastic with open pores.

The quality of foam plastic is regulated by the number of residual monomer sterol, molecular weight and a content of aeration material:

1. Increasing of amount of monomer sterol decrease thermal resistance, increase ability to aging and also increase harmful influence on human;
2. Molecular weight has big influence on strength and acoustic characteristics. So the increasing of molecular weight has good influence on strength and acoustic characteristics;

3. Content of aeration material is connect with molecular weight. Because when manufacture try to get material with high molecular weight (to get better strength and acoustic properties) it should increase the number of aeration material, because the possibility to foam of the material with high molecular weight should be the same as material with low molecular weight. At the same time big number of aeration material leads to a rapid evaporation of it from the material. Some of materials which are used as aeration materials (that which contain phenol) has a harmful influence on human

Also properties of the foam plastics can be improved by using different polymers as raw material:

1. Foam plastics based on polypropylene. Disadvantages of this kind of foam plastic is, low fire safety, instability of benzene and materials which are based on solvents. But question of fire safety can be solved by adding flame retardants.
2. Foam plastics based on polyvinylchloride. Polyvinylchloride is thermoplastic polymer which contain 56,8% of combined chlorine, it is provide high fire safety properties.
3. Foam plastics based on polyurethane. Such foam plastics have very high flexibility, density (at the same time high thermal resistance),

So, basing on information about manufacturing it is possible to make some findings:

1. Extruded polystyrene is more water resistant than foam plastic with open pore (which is produce by method of foam pellet). Because structure of closed pore prevented hit of water into the material and as a result prevent decreases of thermal resistance.
2. Extruded polystyrene increase air tightness of the construction thanks to closed structure of pores;
3. Extruded polystyrene is more human safety. Monomer sterol and aeration component content in both types on foam plastics, but in extruded polystyrene, the possibility of evaporation of this component during the manufacturing process and the process of exploitation is decreased due to closed structure of the material. All free particles of monomer sterol, and aeration component are stay closed in pores;
4. Extruded polystyrene is more strength then expanded polystyrene, because extruded polystyrene is more homogeneous, and the contact area between particles is higher, then in foam plastic with open pore. The reason is that extruded polystyrene manufactured from a single liquid mass of polymer, and expanded polystyrene is manufactured from separate pellets.

2.3 Requirements for the thermal insulation materials

To find best solution for the construction of building envelope, it is important to choose thermal insulation materials which match requirements. The most important requirements are:

1. Low and constant, during all the period of exploitation, thermal conductivity;
2. Possibility not to break down under different weather conditions and temperature of insulated object;
3. Not to cause the corrosion and breaking down of the insulated object;
4. Not to prevent temperature deformations of the insulated object (it means to be flexible);
5. Life cycle of the thermal insulation material shouldn't be lower then the life cycle of the insulated object;
6. Sound proofing should guarantee the allowable sound level for human.

To have an understanding of choosing the correct thermal insulation material, which will match to these requirements, it is important to know how to determine main properties of different thermal insulation materials.

2.3.1 Main properties of thermal insulation materials

Density. Knowing of the density of the material, gives a lot of information about it's thermal insulation and strength characteristics. The lower is the density of the material, the lower is the thermal conductivity. But as low density, as low possibility of installing of the material, and usually high water absorption, and as a result life of the material will be decrease. For determining of the properties of the thermal insulation material, uses average density.

Porosity. As was said before, the lower density, the lower thermal conductivity. Density depends on porosity. So, low density means high porosity (it's mean a big amount of air in the material, which have very low thermal conductivity 0,027 W/($m \cdot k$) at temperature 20^0C /6, t. D1./) and low thermal conductivity. Thermal insulation properties don't depend only on porosity, but also on kind of the material, structure of pore, there size and form, uniform of the distribution of pores in the material and also are pores closed or open, can they communicate with surroundings air. So, the best thermal insulation properties have materials with a big amount of little closed pores which are have uniform distribution in the volume of the material.

Thermal conductivity it is a property of the material to transfer the heat flow, which is come from temperature difference between opposite surfaces. Different materials provide the heat flow with different speed (iron do it faster, and thermal insulation material do it slower). Thermal conductivity depends on average density of the material (if average density increase, thermal conductivity starts to decrease) , it's structure, porosity, humidity (if of the material start to increase, thermal conductivity start to decrease very fast) and temperature of the material of the layer. That's why all thermal insulation materials should be storaged in dry conditions.

Dependence between thermal conductivity - λ, and average temperature of the material layer can be express by formula 4.1.1.

$$\lambda = \lambda_0 + b \cdot t_{average} \tag{4.1.1}$$

where: λ - thermal conductivity, $W/(m \cdot K)$;

λ_0 - thermal conductivity at the temperature 273 K, $W/(m \cdot K)$;

b - constant value for each material, which shows the change of thermal conductivity during the change of temperature on 1K;

$t_{average}$ - average temperature of the material, K.

From formula 4.1.1 we can see, that while the average temperature of the material and b increase, thermal conductivity of the material is increases too. So, materials with high density, have higher b.

Heat capacity it is a property of the material to absorb heat

Humidity. Thermal insulation materials can't be always dry, because they absorb the moisture from surroundings air (sorption humidity), or during the contact with it (with a help of water absorption). During the humidification of thermal insulation materials, there thermal conductivity rises very fast. Because when thermal insulation material is dry it's pores and free area in the structure are field by the air with a low thermal conductivity (0,027 W/($m \cdot k$) at temperature 20^0C), and after humidification this pores and free areas start to be filled by water which thermal conductivity is rather high (0,6 W/($m \cdot k$) at temperature 20^0C /6, t. D1./).

Water vapor permeability it is a property of the materials to skip water vapor, which air contains, because of differences of partial pressures on opposite surfaces of the material. Partial pressure is a part of full pressure of mixture of gases, from which air consists. Partial pressure of water vapor is equal to the pressure of water vapor if it will occupy all volume of air at the temperature of air.

Partial pressure of water vapor increases while temperature is increases. So, water vapor is seeking to the area of lower pressure, in another words, on a side of material with lower pressure. That's why it's very important to prevent the contact of thermal insulation material with moistening surfaces or water vapor.

Sound absorption and sound proofing are two very important characteristics for thermal insulation materials, which are used in a building envelope (most of all for such case, which is considered in this work, building envelope for multi-storey building)

Sound is a mixture of different noises which are interfere to perceive helpful and needed sound information, or it can give a harmful influence on a human.

Sound absorption is a degree of sound intake of the material.
Sound proofing is a weakening of sound energy which is coming through the building envelope.

The greater the porosity then the greater sound absorption properties of the material. Materials with open and communicated with each other pores are better for sound absorption, than materials with low porosity, and closed pores.

Sound absorption materials include materials with hard fiber structure (for example hard mineral wool) or cellular structure (for example cellular concrete). Sound proofing materials (for example soft mineral wool). Sound absorption materials are used for insulation from different noises (noise from cars, streets). Sound proofing materials are used for insulation from different vibrations which are coming through building structure (vibrations from trams, trains, heavy cars, shock vibrations in different flats or other buildings). That's why sound proofing materials are don't used in such part of building envelope as outdoor walls. Because the main goal of outdoor walls to insulate human from different noises.

2.3.2 Determining the values of the properties

Density – value equal to the ratio of mass of substance to it's volume (pores and voids don't take into account).

Units of density are: g/cm^3, kg/m^3, tn/m^3.
Density is calculating using the formula 4.2.1:

$$\rho = m / V \quad (4.2.1)$$

where: ρ - is a density of substance, (kg/m^3);

m – is a mass of substance, (kg);

V – is a volume of substance, (m^3)

Average density – value equal to the ratio of the mass of substance to whole volume of the substance (including pores and voids).
Units of density are: g/cm^3, kg/m^3, tn/m^3.
Average density is calculating by formula 4.2.2:

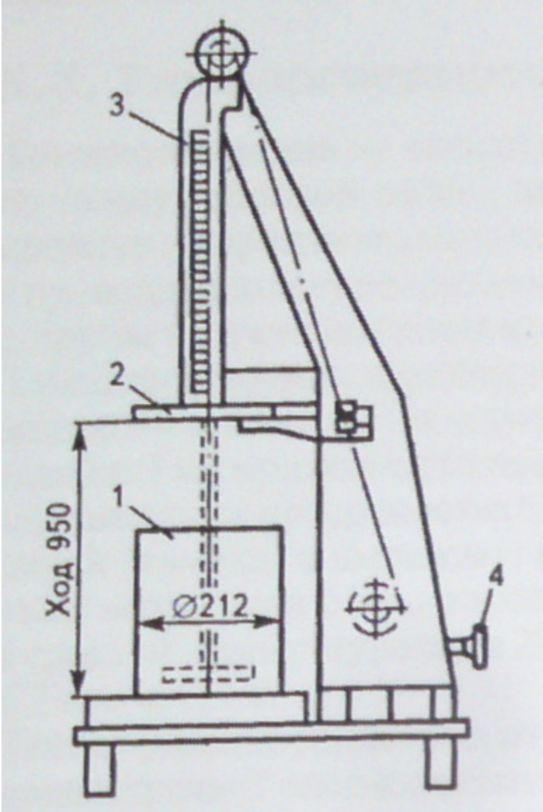
$$\rho = m / [V \cdot (1 + 0{,}01 \cdot W)] \quad (4.2.2)$$

where: W – is a mass humidity of the material, (%)

To calculate an average density we need to know m, V, W. Mass can be find by weighing. Humidity can be find by drying of the material with temperature 105 ± 5^0C. But determining of the volume of the material is not very easy, because mineral wool can change it's volume according to the surroundings conditions. That's why for determining of the volume of mineral wool using special measuring unit Picture 2. Principle of working: follower plate 2 press on the material which is put in cylinder 1 with strength 0,002 MPa /5, p.39./, and after 5 minutes, using the scale of the rod we measuring h and using Formula 4.2.3 we can calculate volume V.

$$V = \pi \cdot R^2 \cdot h \quad (4.2.3)$$

where: R – is radius of the cylinder 1, (mm)



Picture 2. Measuring unit for determining of the average density of loose, fiber materials /5, p. 40./

1 - cylinder; 2 - follower plate; 3 – rod with a scale; 4 – lifting mechanism

Porosity - is the degree of filling of the material by pores. Total porosity P_t, (%) is a ratio between the volume of pores V_{por}, to whole volume of the material V. For the calculation of the total porosity, using Formula 4.2.4.

$$P_t = (\frac{V_{por}}{V}) \cdot 100 \qquad (4.2.4)$$

In another way we can calculate total porosity by formula 4.2.5.

$$P_t = (1 - \frac{\rho_{vm}}{\rho}) \cdot 100 \qquad (4.2.5)$$

where: ρ_{vm} - bulk density of the product, g/cm^3;

Thermal conductivity. Thermal conductivity characterized by the amount of heat (J), which is comes through the layer of the material which thickness is 1 meter and surface area 1 m^2, during 1 hour. Material can be using as thermal insulation material if it's thermal conductivity is less than 0,175 $W/(m \cdot K)$ at temperature 298 K and normal humidity.

Thermal conductivity can be calculated by the Formula 4.2.6.

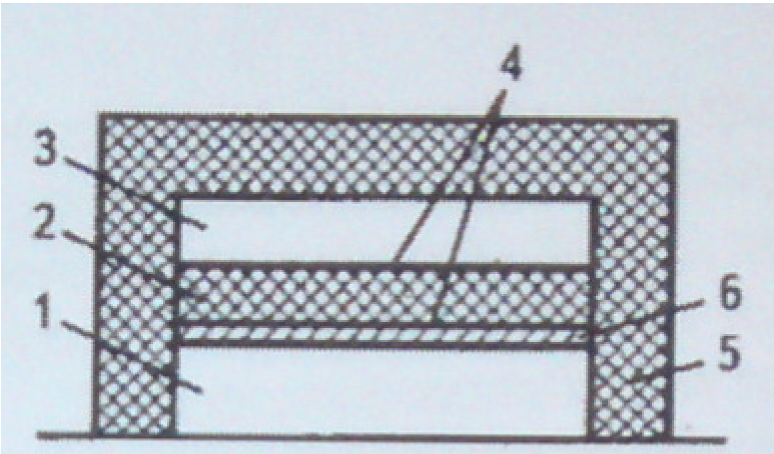
$$\lambda = \frac{q \cdot \delta}{t_1 - t_2} \tag{4.2.6}$$

where: q – heat flow, which is coming through the material with area 1 m^2, W/m^2;

δ - thin of the sample of the material, m;

t_1,t_2 – temperature of the upper and lower surfaces of the sample, K.

Heat flow can't be calculated by any formulas, it can be just measuring by special measuring unit, as on Picture 3. Principle of working is that between two thermostatically plates 1 and 3, with a help of which create and support needed temperature differences, putting a sample of the material 2 (size is 250*250 mm., thickness is 10 - 50 mm.) Between the lower plate 1 and the sample, putting calorimeter 6 (which is measuring the heat flow). Temperature on the surfaces of the sample, changing by two thermocouples 4. Heat flow creating from up to down.



Picture 3. Measuring unit for determining of the heat flow /6, p.43./

1,3 – thermostatically plates; 2 – sample of the material; 4 – thermocouple; 5 – thermal insulating cover; 6 – calorimeter.

Heat capacity determining as an ratio between amount of heat, which is given to the material, and an appropriate changing of the temperature. So heat capacity can be calculated using Formula 4.2.7

$$C = \frac{Q}{T} \tag{4.2.7}$$

where: C – heat capacity of the material, J/K;

Q – amount of heat which is given to material, J;

T – changing of temperature during the heating of it, K.

Humidity - content of the moisture in the material, it can be calculated by the Formula 4.2.8

$$W = [\frac{(m - m_i)}{m_i}] \cdot 100 \quad (4.2.8)$$

where: m – mass of the material in natural conditions, g;

m_i – mass of the material, which is drying to a constant mass;

W – humidity, %.

Sorption humidity W_{sorp} is depends on humidity and temperature of the ambient air, and also of structure of the material. Sorption humidity can be calculated by the Formula 4.2.9

$$W_{sorp} = [\frac{m_1 - m_2}{m_2 - m_3}] \cdot 100 \quad (4.2.9)$$

where: m_1 – mass of the container with the sample of the material after keeping above the water, g;

m_2 – mass of the container with dry sample of the material, which is drying up to constant temperature, g;

m_3 – mass of the dry container, g.

Water absorption of thermal insulation materials is characterize by the amount of water, which can be absorb by the material, divided by mass of the dry material. Water absorption can be calculated by the Formula 4.2.10

$$W_{abs} = [\frac{m_2 - m_1}{m_1}] \cdot 100 \quad (4.2.10)$$

where: m_1 – mass of the material in dry conditions, g;

m_2 – mass of the material in full of water conditions, g.

Water vapor permeability is characterized by the coefficient of water vapor permeability, which is determining by the amount of water vapor (mg), which is going through the layer of the material, which area is 1 m^2, during 1 hour, at the pressure difference on opposite surfaces is 133,3 Pa (one millimeter of mercury) /5, p.39./.

2.3.3 Dependence between requirements and properties of the thermal insulation materials (foam plastic, and mineral wool)

In previous paragraph I write the main requirements which are offered for thermal insulation materials which are used in building envelope. These requirements are:

1. Low and constant, during the all period of exploitation, thermal conductivity;

2. Possibility not to break down under different weather conditions and temperature of insulated object;
3. Not to cause the corrosion and breaking down of the insulated object;
4. Not to prevent temperature deformations of the insulated object (it's mean be flexible);
5. Life cycle of the thermal insulation material shouldn't be lower then the life cycle of the insulated object;
6. Sound proofing should guarantee the allowable sound level for human.

Also, in previous paragraphs I identified main groups of the thermal insulation materials, based on the technology of manufacturing. This groups are:

1. expanded polystyrene;
2. extruded polystyrene;
3. mineral wool from slag;
4. mineral wool from rock.

Now with a help of knowledge about technology of manufacturing thermal insulation materials, and their properties, it will be useful, to make a conclusion about dependence between requirements and properties of the thermal insulation materials. It will help to compare the constructions of the building envelopes in following paragraphs.

Influence of the main properties on the main requirements, for the main groups of the thermal insulation materials are shown in the Table 1. Table show an influence of properties of the thermal insulation materials (Density, porosity, thermal conductivity, humidity, water vapor permeability, sound absorption and sound proofing) on each of the main requirements.

Table 1, Influence of the main properties on the main requirements, for the main groups of the thermal insulation materials

Name of the group of the thermal insulation material	Properties of the thermal insulation materials					
	Low and constant thermal conductivity	Resistance to different weather conditions	Prevent corrosion and breaking down of the insulated object	Flexibility	Long life cycle	Sound proofing
Expanded polystyrene	Can be decreased due to absorbing the water due to open structure of the pore, and a lot of free space in structure	Should be protect from water, due to open structure of pore. Also from high temperatures (higher than $+75^0$C) due to raw material, which can't withstand high temperatures. Material can't be used as air barrier.	Should be insulated from different kinds of iron structures, because, material can provide water and cause the corrosion of the steel structures.	Has a low opportunities to flexibility, due to during the manufacturing process, object of the heat treatment are separate particles of polystyrene. So, the contact between particles of polystyrene isn't very strong	Live cycle can be decreased due to contact with water, deformation of the construction, or contact with different substances which are based on solvents	Can't be used as sound proofing, but it's sound proofing properties are better than extruded polystyrene. Because pore are open, and they are big (0,3-0,4 mm). But structure of the material is too hard to absorb the energy of sound wave
Extruded polystyrene	Can save it's thermal conductivity on a constant level during the life cycle of the insulated object, due to closed structure of pore and absent of free space inside the material.	Have a high level of the resistance to weather conditions due to closed pores and absent of free space in inside. Also can be used as air barrier, due to possibility of sealing between the lists of the material. But, also should be protect from temperatures higher than $+75^0$C	Can protect insulated structure from corrosion, because, this material don't absorb water. Also can protect different kinds of insulated structures from outdoor impacts.	Has a high opportunities to flexibility, due to during the manufacturing process, object of heat treatment is a single mass of polystyrene. So, the contact between particles of structure is very strong, and can withstand deformations.	Live cycle can be decreased due to contact with different substances which are based on solvents	Can't be used as sound proofing, because pore are closed, and they are too small (0,1-0,2 mm). And the structure of the material is too hard to absorb the energy of sound wave

Mineral wool from slag	Can be decreased due to absorbing the water due to spongy structure. Because during the manufacturing process many fibers are glue with each other and form structure with a lot of big and communicated with each other pore, with a lot of free space with each other.	Can't prevent harmful influence of weather conditions, so it should be protect from wind, snow and water by other protecting materials. Application temperature is up to +400^{0}C.	Can't prevent the corrosion of iron structure, due to absorbing the water. So it should be separate from iron structures. Also this material can have a harmful influence for other surrounding materials. Because it can keep absorbing water for a long time, and harm other constructions.	Has a high opportunity to flexibility, because it consist of fibers, which a flexible. But Flexibility increases while density increases.	Life cycle can be decreased due to absorbing water. Also if mineral wool with low density (<100 kg/m^3) will put into walls, it will clod.	Mineral wool with low density (<100 kg/m^3) is very good material for sound proofing, because it has structure, which is consist of fibers, which connections with each other is soft. So, when sound wave contact with it, it can absorb energy of the wave. Also, a lot of big (1-5 mm) pore, communicated with each other, give a good effect. It's good to insulate from impact noise, and vibrations.
Mineral wool from rock	Can be decreased due to absorbing the water due to spongy structure. Because during the manufacturing process many fibers are glue with each other and form structure with a lot of big and communicated with each other pore, with a lot of free space with each other.	Can't prevent harmful influence of weather conditions, so it should be protect from wind, snow and water by other protecting materials. Application temperature is up to +800^{0}C.	Can't prevent the corrosion of iron structure, due to absorbing the water. So it should be separate from iron structures. Also this material can have a harmful influence for other surrounding materials. Because it can keep absorbing water for a long time, and harm other constructions.	Has a low opportunity to flexibility, because it consist of fibers, which a not flexible (raw material is rocks). Also density of such materials are usually high (>100 kg/m^3), which is not good for flexibility.	Life cycle can be decreased due to absorbing water. But this kind of material isn't clod, because fibers are thicker, and density is high enough (>100 kg/m^3)	Such mineral wool with high density (>100 kg/m^3) is very good material for sound absorption, because it has structure, which consist of fibers, which connections with each other is harder than in mineral wool from slag. So this material is better to use for insulation from noise.

2.4 Results of the theoretical part

As a result of theoretical part I identified the main group of the thermal insulation materials which are mostly common during the construction of the building envelope of the multi-storey buildings in our days. These groups are:

1. expanded polystyrene;
2. extruded polystyrene;
3. mineral wool from slag;
4. mineral wool from rock.

I have explained the meanings of the main properties of the thermal insulation materials for reader. And I have been explain the processes of determining the values of properties, because, reader should understand the meaning of the properties before he start to read practical part of the thesis.

And, based on the whole information from theoretical part I have formed Table 1, to explain the dependence between properties of the main groups of the thermal insulation materials and the main requirements. Table 1 help to understand, which properties of any thermal insulation materials helps it to achieve the requirements.

3 CALCULATION OF THE BUILDING ENVELOPE

In this part of the work I will talk about comparing of one, mostly common in Saint-Petersburg, design of building envelope, but with different thermal insulation materials (from main groups of thermal insulation materials which were identified in previous chapter).

I will make calculations of building envelope based on Russian building codes. The main requirements, which are offered to building envelope are /7/:

1. Thermal resistance;
2. Temperature difference between indoor air temperature and temperature of the surface temperature;
3. Air tightness of the wall;
4. Water vapor permeability.

As I said before, in my work I'm looking for not all parts of building envelope, such as (roof, walls of underground floors, floors, etc.), but only for outdoor walls of multi-storey buildings.

3.1 List of the thermal insulation materials

In Table 2 there is a list of the thermal insulation materials, of different mostly common on a market of Saint-Petersburg manufactures, which will be comparing with each other.

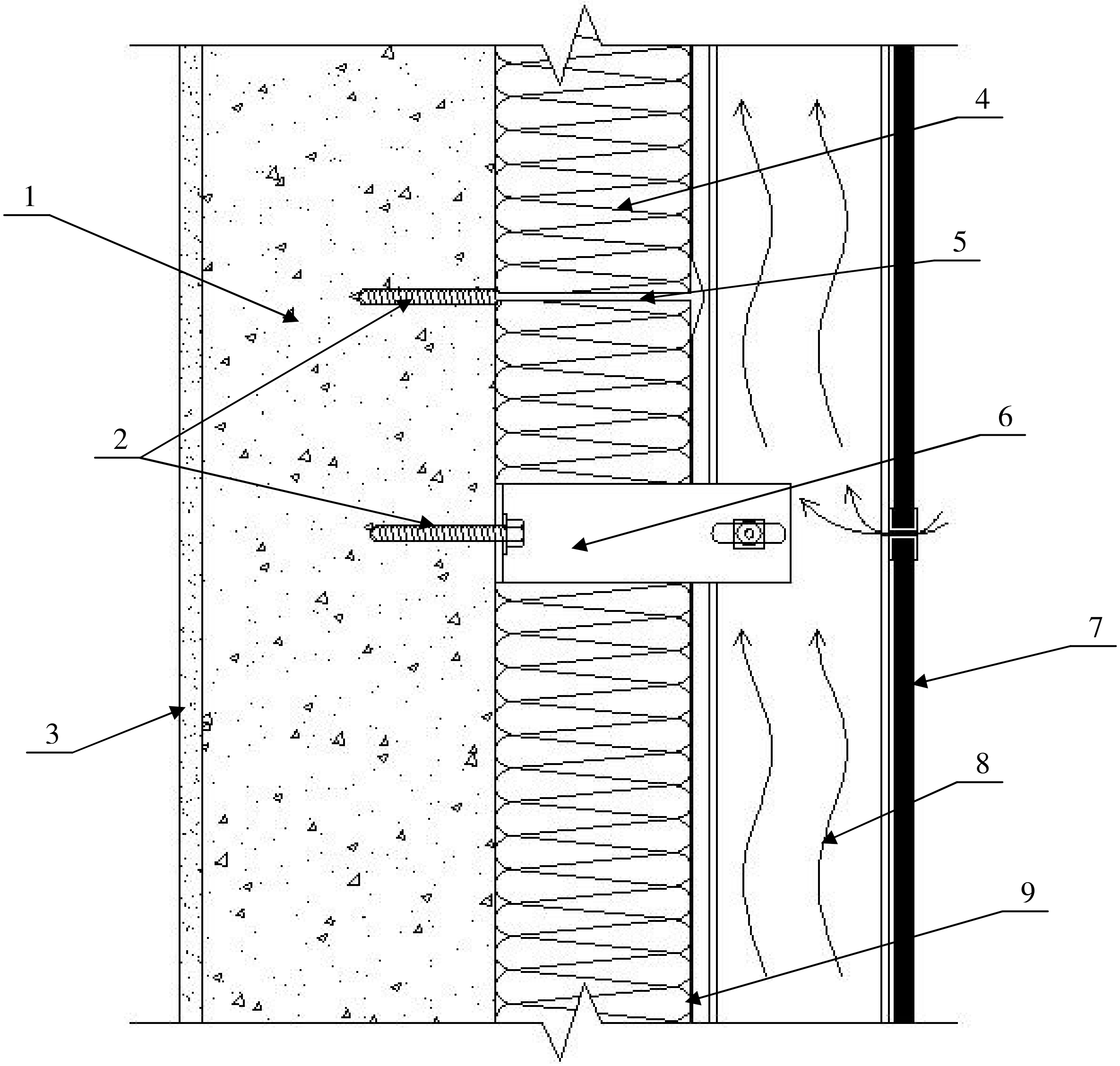
Table 2 List of the properties of the thermal insulation materials

№	Name of the material	Name of the manufacture	Thermal conductivity λ, $\frac{W}{m \cdot K}$	Specific heat capacity c, $\frac{kJ}{kg \cdot K}$	Density ρ, $\frac{kg}{m^3}$	Water vapor permeability μ, $\frac{mg}{m \cdot h \cdot Pa}$	Price of the 1 m^3 euro
1	Mineral wool from slag – *Fasad termo plita 032*	KNAUFINSULATION	0,040 /12/	0,72 /13/	50 /13/	0,5 /13/	50,6 /13/
2	Mineral wool from rock – *Raroc WAS35*	PAROC	0,043 /14/	0,78 /15/	85 /15/	0,45 /15/	115 /15/
3	Mineral wool from rock – *Venti bats*	ROCKWOOL	0,045 /16/	0,82 /18/	90 /16/	0,3 /16/	83,4 /17/
4	Mineral wool from rock – *FRE75*	KNAUFINSULATION	0,048 /19/	0,81 /21/	85 /21/	0,5 /19/	105,3 /20/
5	Mineral wool from rock – *Technovent optima*	TechnoNICOL	0,047 /22/	0,79 /24/	81-99 /22/	0,3 /22/	83,4 /23/
6	Extruded polystyrene - *30-250*	TechnoNICOL	0,031 /25/	1,45 /25/	25-30 /25/	0,011 /25/	87,6 /26/
7	Extruded polystyrene – *Penoplex - 31*	PENOPLEX	0,032 /27/	1,45 /27/	30,5 /27/	0,008 /27/	79,6 /28/
8	Expanded polystyrene – *Knauf Therm Facade*	KNAUF-PENOPLAST	0,036 /29/	0,98 /30/	30 /30/	0,05 /30/	50,4 /29/

All prices were calculated according to 42,7 rub. by 1 euro at 31.10.2010

3.2 The computational model

As the estimated construction of outdoor wall I have been taken mostly common for Saint-Petersburg type of it’s construction, Picture 3:



Picture 3. Principle design of outdoor wall (with ventilated façade) of the building envelope of multi-storey building /8/

1 – aerated concrete; 2 – plugs; 3 – cement-sand plaster; 4 – thermal insulation; 5 – guides; 6 – fixing elements; 7 – facing material; 8 – air cavity; 9 – air barrier

3.2.1 Operation conditions of the building envelope.

Outside conditions:

Study area – Saint-Petersburg;

Air temperature - -26^{0}C (it's a temperature of the coldest five days with probability 92%) /9, t.1*/;

Air humidity – φ_{ext} = 86% (it's an average level of air humidity during the coldest month) /9, t.1*/.

Inside conditions:

Air temperature - +22^{0}C (it's a temperature for residential buildings) /6, t.1/;

Air humidity – φ_{int} = 55% (it's an air humidity for residential buildings) /6, t.1/;

Humidity indoor mode – normal /7, t.1/;

Operation conditions of the building envelope – normal /7, t.2/.

3.2.2 Parameters of the building envelope

In Table 3 there are all thermal insulation materials which are used in taken into account building envelope.

Air cavity number 8, and facing material don't have any influence on a thermal resistance of the building envelope, because air cavity is ventilated /10, p.19/, so I can make a decision that the last layer of building envelope, which should be taken into account it is Air barrier. But I will come back to the role of ventilated air cavity and facing material in future paragraphs.

Table 3 Properties of the materials of the building envelope

№	Name of the material	Thickness of the layer δ, m	Thermal conductivity λ, $\frac{W}{m \cdot K}$	Specific heat capacity c, $\frac{kJ}{kg \cdot K}$	Density ρ, $\frac{kg}{m^3}$	Water vapor permeability μ, $\frac{mg}{m^2 \cdot h \cdot Pa}$
1	Cement-sand plaster	0,012	0,93	0,84	1800	0,09
2	Blocks of aerated concrete	0,15	0,15	0,84	400	0,23
3	Thermal insulation material					
4	Air barrier TYVEK	0,001	0,27	1,08	600	0,01

Also, in the construction we have some iron elements, such us fixing elements, and guides. They will be calculated as thermal bridges, $\lambda = 62 \dfrac{W}{m \cdot K}$.

Information in rows 1,2 and 4 in Table 3 will be constant for our calculations, but information in row 3 will be taken from Table 2. In such a way I will make calculations for each type of thermal insulation material from 1 to 9, from Table 2.

3.3 Way of the calculations

3.3.1 Calculation of the thermal resistance

All formulas which were using in calculations are taken from Russian building codes /6/, /7/, /9/.Calculations are starting from calculating of degree days of heating season. D_d is calculating using the Formula 3.3.1.1:

$$D_d = (t_{\text{int}} - t_{ht}) \cdot z_{ht} \qquad (3.3.1.1)$$

where: t_{int} – the internal temperature, $t_{int} = +22^0$C;

t_{ht} – the average temperature during the heating season, $t_{ht} = -1{,}8^0$C;

z_{ht} – the time length of heating season (number of days with average temperature less than $+8^0$C) $z_{ht} = 220$ /9, t.1*/

Thermal resistance R_0 should be the same or higher than R_{req}, which value is calculating depending on D_d, by using the Formula 3.3.1.2:

$$R_{req} = a \cdot D_d + b \qquad (3.3.1.2)$$

where: a – coefficient which is choosing by /7, t.4/, a=0,00035;

D_d – degree days of heating season;

b – coefficient which is choosing by /7, t.4/, b=1,4.

Now, I know the normative level of thermal resistance R_{req}, according to SNIP 23-02-2003. “Thermal protection of the building”

R_i - Thermal resistance of the material layer is calculating, using the Formula 3.3.1.3:

$$R_i = \frac{\delta_i}{\lambda_i} \qquad (3.3.1.3)$$

where: δ_i, λ_I – this values are taken from Table 3

Thermal resistance of the layers, which consist of different materials which have different values of thermal conductivity - λ_i, λ_j are calculating by the Formula 3.3.1.4:

$$R_{i,j} = R_i - (A_j \cdot 100) \cdot R_j \qquad (3.2.1.4)$$

where: A_j – square of the material (metal plates) on 1 square meter of the building envelope.

After this I should calculate R_T - total thermal resistance of the building envelope using Formula 3.3.1.5:

$$R_T = R_{si} + R_1 + R_2 + ... + R_n + R_{se} \qquad (3.3.1.5)$$

where: R_{si} + R_{se} – the sum of the internal and external surface resistance, $R_{si} + R_{se}$=0,16 $\frac{m^2 \cdot {}^0C}{W}$

R_1, R_2,… R_n - thermal resistance of the inhomogeneous material layer 1, 2, ... n, $\frac{m^2 \cdot {}^0C}{W}$

Now it's necessary to satisfy the condition, that $R_T \geq R_{req}$

If this condition is satisfied, it's mean that thermal resistance level of the building envelop is satisfy, according to SNIP 23-02-2003. "Thermal protection of the building"

3.3.2 Calculation of the temperature difference between the indoor air temperature and temperature of the internal surface of the wall

Design value of the Δt_0 - temperature difference between the indoor air temperature and temperature of the internal surface of the wall shouldn't be higher than the normative value, Δt_n = 4^0C /7, t.5/. It's important to satisfy this rule to create comfortable conditions for future occupants of the building. Δt_0 can be calculated using the Formula 3.3.2.1:

$$\Delta t_0 = \frac{n \cdot (t_{int} - t_{ext})}{R_T \cdot \alpha_{int}} \qquad (3.3.2.1)$$

where: n – coefficient which is depending on orientation of the building envelope to outdoor air

n=1 /7, t.6/

α_{int} - coefficient of heat transfer of the internal surface of the building envelope

α_{int} =8,7 $\frac{W}{m^2 \cdot {}^0C}$ /7, t.7/

Now it's necessary to satisfy the condition, that $\Delta t_0 \leq \Delta t_n$

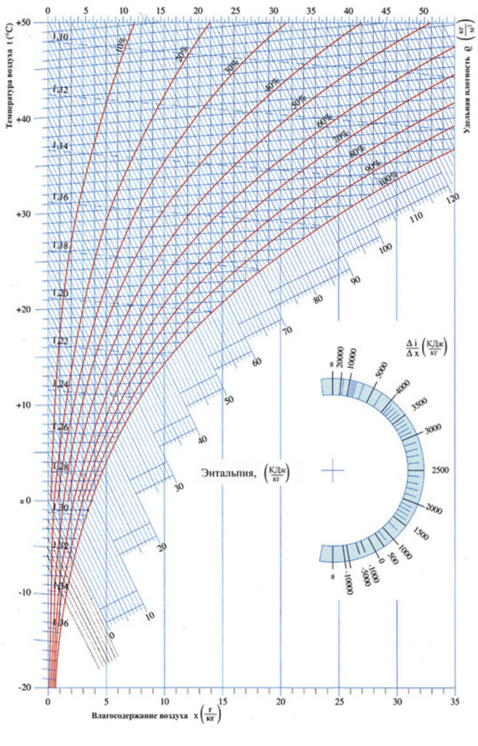
If this condition is satisfied, it’s mean that temperature difference between the indoor air temperature and temperature of the internal surface of the wall is satisfy, according to SNIP 23-02-2003. “Thermal protection of the building”.

3.3.3 Calculation of the temperature of the internal surface of the building envelope

The next one important step it is the calculation of the t_{si} – temperature of the internal surface of the building envelope. This temperature should be higher than t_{dp} – dew point temperature, to prevent the condensation of the water vapor on the internal surface of the building envelope.
t_{si} can be calculated by the Formula 3.3.3.1:

$$t_{si} = t_{\text{int}} - \Delta t_0 \qquad (3.3.3.1)$$

After the calculation of the t_{si} it is possible to find t_{dp}, by using the Mollier chart, Picture 4.



Picture 4. The Mollier psychrometric chart.

Now it’s necessary to satisfy the condition, that $t_{si} \geq t_{dp}$
If this condition is satisfied, it’s mean, that the condition of preventing the condensation of the water vapor on the internal surface of the building envelope is satisfied according to SNIP 23-02-2003. “Thermal protection of the building”.

3.3.4 Calculations of the air tightness of the building envelope

To calculate the air tightness of the building envelope, it's important to know air tightness properties of each material of the building envelope, Table 4. And after this table, values of the air tightness should be summarized. Properties of the thermal insulation materials will be change.

Table 4. Air tightness properties of the materials of the building envelope /6, t.17/

№	Name of the material	Thickness of the layer δ, m	Density ρ, $\frac{kg}{m^3}$	Air tightness R^{des}, $\frac{m^2 \cdot h \cdot Pa}{kg}$
1	Cement-sand plaster	0,012	1800	373
2	Blocks of aerated concrete	0,15	400	21
3	Thermal insulation material			
4	Air barrier TYVEK	0,001	600	10

Σ 404

At first should be calculated the specific weight of the interior and exterior air can be calculated by the Formula 3.3.4.1:

$$\gamma_{ext} = \frac{3463}{273 + t_{ext}}$$
$$\gamma_{int} = \frac{3463}{273 + t_{int}} \qquad (3.3.4.1)$$

Moving of the air through the building envelope is due to pressure differences on the opposite surfaces of the building envelope. The pressure difference on the interior and exterior surfaces of the building envelope - Δp can be calculated by the Formula 3.3.4.2:

$$\Delta p = 0,55 \cdot H \cdot (\gamma_{ext} - \gamma_{int}) + 0,03 \cdot \gamma_{ext} \cdot V^2 \qquad (3.3.4.2)$$

where: H – height of the building, H = 50 m;

$\gamma_{ext}, \gamma_{int}$ - specific weight of the interior and exterior air, $\frac{N}{m^3}$;

V – maximum of the average values of the wind speed, during the January,

V = 5,5 r /6, t.12/

Air tightness of the building envelope of the residential buildings – R^{des}, shouldn't be lower than the normative value R^{req}, which can be calculated by Formula 3.3.4.1:

$$R^{req} = \frac{\Delta p}{G_n} \tag{3.3.4.1}$$

where: Δp - the pressure difference between interior and exterior surfaces of the building envelope;

G_n – normative value of the air tightness of the building envelope, G_n=0,5 $\frac{kg}{m^2 \cdot h}$ /7, t.11/.

Now it's necessary to satisfy the condition, that $R_{des} \geq R_{req}$

If this condition is satisfied, it's mean, that the condition of the air tightness of the building envelope is satisfied according to SNIP 23-02-2003. "Thermal protection of the building".

3.3.5 Calculation of the possibility of condensation in building envelope

When air is coming through the building envelope (in winter time) it's temperature decreases and it can reach the dew point temperature and provoke the condensation. Condensation of the water vapor is very harmful for the thermal insulation material, about it I have been wrote in previous paragraphs.

At first it is important to calculate the partial pressure of the saturation water vapor on the internal and external surfaces of the building envelope by the Formula 3.3.5.1:

$$\begin{aligned} e_{\text{int}} &= \frac{\varphi_{\text{int}}}{100} \cdot E_{\text{int}} \\ e_{ext} &= \frac{\varphi_{ext}}{100} \cdot E_{ext} \end{aligned} \tag{3.3.5.1}$$

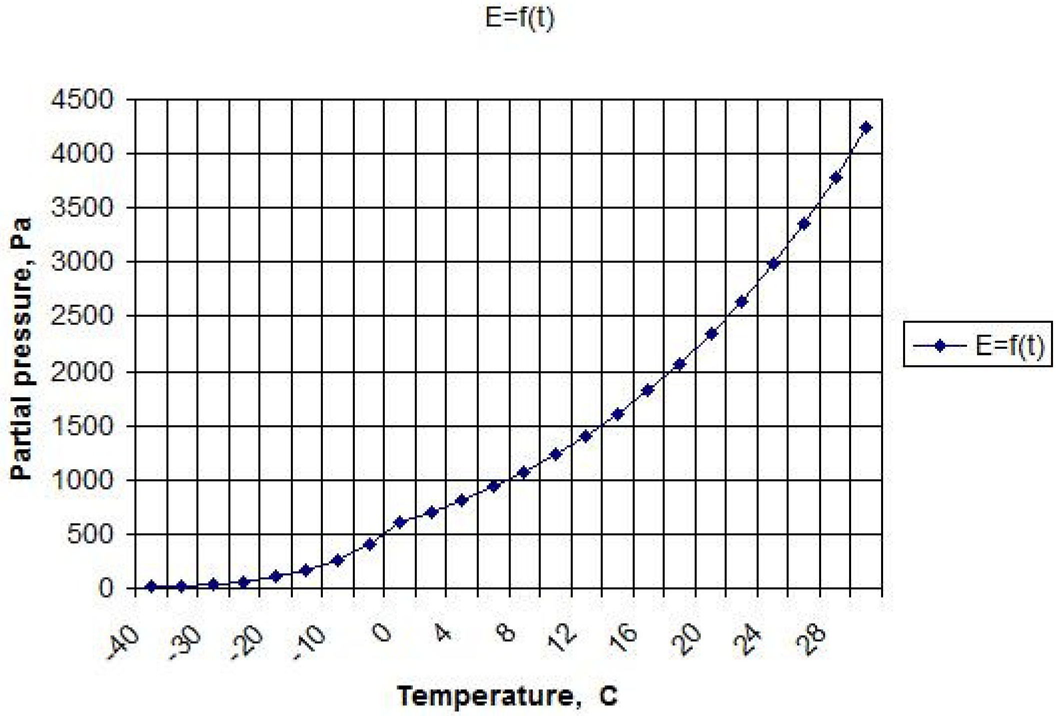
where: e_{int}, e_{ext} - partial pressure of the water vapor on the internal and external surfaces of the building envelop;

E_{int}, E_{ext} - maximum partial pressure of the water vapor on the internal and external surfaces of the building envelope.

The value of the maximum partial pressure can be determined by the diagram which is show the dependence between E and t, E=f(t) Picture 5. Such diagram can be drawn using the values from Table 5.

Table 5. Dependence between maximum value of the partial pressure of the water vapor and temperature of the air

t, °C	E, Pa	t, °C	E, Pa	t, °C	E, Pa	t, °C	E, Pa
-40,0	12,40	-10,0	260,0	8,0	1073	20,0	2338
-35,0	22,26	-5,0	401,3	10,0	1228	22,0	2644
-30,0	37,33	0,0	610,6	12,0	1403	24,0	2984
-25,0	62,66	2,0	705,3	14,0	1599	26,0	3361
-20,0	102,7	4,0	813,3	16,0	1817	28,0	3780
-15,0	165,3	6,0	934,6	18,0	2064	30,0	4242



Picture 5. Dependence between partial pressure of the water vapor and temperature.

The main idea is to determine the Maximum values of the partial pressure of the water vapor and the real values of partial pressure of the water vapor (with a help of temperature in the plane of possible condensation in the building envelope, and Picture 5), and after this draw it on a one diagram, and find spaces where real values of the partial pressure becomes higher than maximum value. In this zone the condensation of the water vapor becomes possible/11, p. 138/

The temperature in the plane of possible condensation in the building envelope - τ_i can be calculated by the Formula 3.3.5.2. We should numbered layers of the material from inside to outside.

$$\tau_i = t_{\text{int}} - \frac{(t_{\text{int}} - t_i) \cdot (R_{si} + R_i)}{R_T} \tag{3.3.5.2}$$

where: t_i – the average air temperature of the coldest period of the year, t_i = -6,1^{0}C /9, t.8/;

R_i – thermal resistance of the layer of the material before the layer of the possible condensation.

Now, by using Picture 5, it's possible to determine the maximum values of the partial pressure of the water vapor – E, and put this values to the Table 6.

Resistance of the water vapor permeability of the material layer of the building envelope - Ω_i $\frac{m^2 \cdot h \cdot Pa}{kg}$, can be calculated by the Formula 3.3.5.3.

$$\Omega_i = \frac{\delta}{\mu} \tag{3.3.5.3}$$

Total resistance of the water vapor permeability of the material layer of the building envelope - Ω_T $\frac{m^2 \cdot h \cdot Pa}{kg}$, can be calculated by the Formula 3.3.5.4.

$$\Omega_T = \Omega_{\text{int}} + \Omega_1 + \Omega_2 + ... + \Omega_n + \Omega_{ext} \tag{3.3.5.4}$$

where: $\Omega_{\text{int}}, \Omega_{ext}$ - resistance of the water vapor permeability of the internal surface,

Ω_{int} =0,0266 $\frac{m^2 \cdot h \cdot Pa}{kg}$ /6, t.18/;

Ω_{ext} =0,0133 $\frac{m^2 \cdot h \cdot Pa}{kg}$/6, t.18/.

The real partial pressure of the water vapor between the layers of the building envelope – e_i can be calculated by the Formula 3.3.5.4.

$$e_i = e_{\text{int}} - \frac{(e_{\text{int}} - e_{ext}) \cdot (\Omega_{\text{int}} + \Sigma\Omega_i)}{\Omega_T} \tag{3.3.5.4}$$

where: $\Sigma\Omega_i$ - sum of the resistance of the water vapor permeability of the layers of the materials of the building envelope between the internal surface and the plane of the possible condensation.

Now the values of the real partial pressure of the water vapor should be put in Table 6.

Table 6. Results, of the possibility of the condensation of the water vapor in a building envelope

Border of the layers	x, m	ΣR_i, $\frac{m^2 \cdot {}^0C}{W}$	τ_i, ℃	E, Pa	$\Sigma\Omega_i$, $\frac{m^2 \cdot h \cdot Pa}{kg}$	e_i, Pa
int-1	0,0					
1-2	0,012					
2-3	0,162					
3-4	0,262					
4-ext	0,263					

x – distance from inside surface of the building envelope to the layer of possible condensation;

ΣR_i - it's the sum of thermal resistance of the layers of building envelope from inside to the layer of possible condensation (end of each next layer);

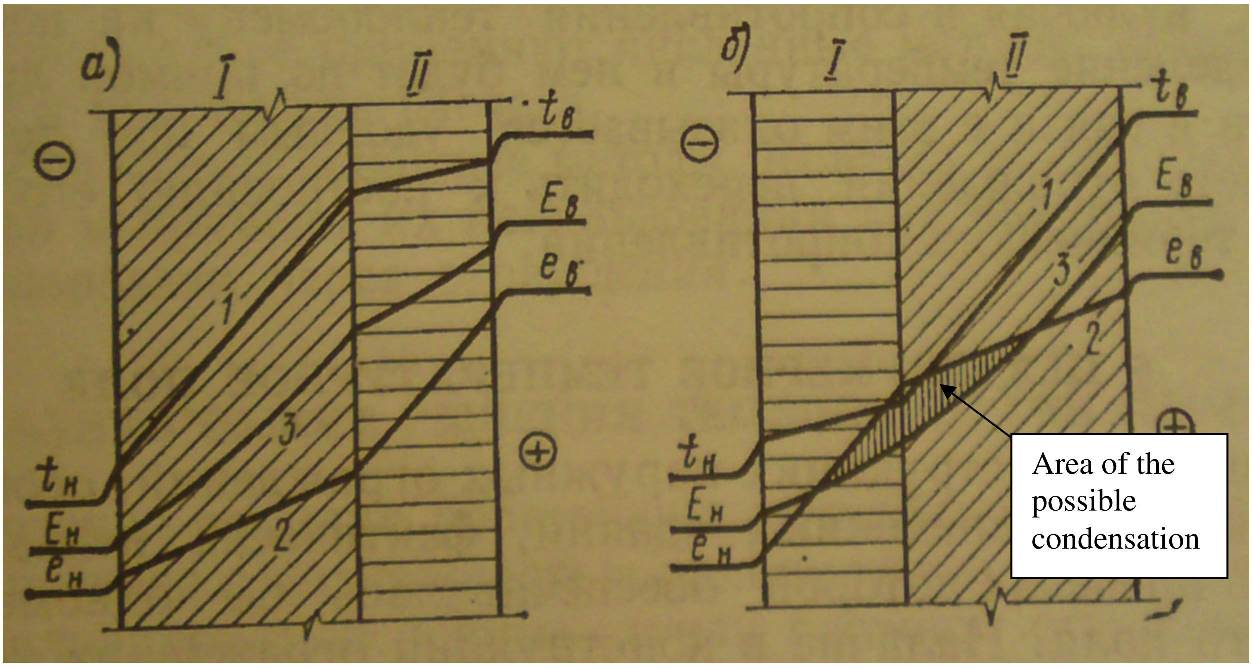
τ_i, - it's the temperature between layers of building envelope;

E - maximum partial pressure of the water vapor between layers of building envelope;

$\Sigma\Omega_i$ - it's the sum of water vapor resistance of the layers of building envelope from inside to the layer of possible condensation (end of each next layer);

e_i - the real values of partial pressure of the water vapor between layers of building envelope;

To make a final conclusion about the possibility of the condensation of the water vapor in a building envelope I should draw a diagram according to the Table 6, with values of maximum partial pressure of the water vapor and the real values of partial pressure of the water vapor. And find the area of the possible condensation. But in systems of building envelopes with ventilated air cavity the main idea is that condensation is possible in the thermal insulation material, but this moisture is deleted by the air flow in the air cavity. So, building envelope should be design in such way, that resistance of the water vapor permeability should be as low as possible, to don't prevent the deleted of the moisture from the building envelope.



Picture 6. Curves of distribution of the maximum values of the water vapor permeability, and real values through the thickness of the building envelope /11, p.139/.

3.4 Results of calculations

After all calculations I should put the results to the Table 7.

I have been calculate in Appendix 3,4, that reasonable thickness of the thermal insulation from extruded and expanded polystyrene is 80 mm. According to this, price of the 1 m^3 of the extruded and expanded polystyrene should be less on 20%.

Table 7. Results of the calculations of the building envelope with different types of thermal insulation materials

№	Name of the material	Requirements for the building envelope						Price of the one square meter, euro
		Thermal resistance of the building envelope	Temperature of the internal surfaces	Possibility of the condensation on the internal surfaces	Air tightness of the building envelope	Possibility of the condensation in the building envelope	Possibility of freezing in the building envelope	
1	Mineral wool from slag – *Fasad termo plita 032*	Satisfy	Satisfy	Satisfy	Satisfy	Small possibility of the condensation	Freezing is possible to a depth of 8,31 mm.	50,6 /13/
2	Mineral wool from rock – *Raroc WAS35*	Satisfy	Satisfy	Satisfy	Satisfy	Small possibility of the condensation	Freezing is possible to a depth of 8,61 mm.	115 /15/
3	Mineral wool from rock– *Venti bats*	Satisfy	Satisfy	Satisfy	Satisfy	Small possibility of the condensation	Freezing is possible to a depth of 8,61 mm.	83,4 /17/
4	Mineral wool from rock–*FRE75*	Satisfy	Satisfy	Satisfy	Satisfy	Small possibility of the condensation	Freezing is possible to a depth of 8,61 mm.	105,3 /20/
5	Mineral wool from rock– *Technovent optima*	Satisfy	Satisfy	Satisfy	Satisfy	Small possibility of the condensation	Freezing is possible to a depth of 8,61 mm.	83,4 /23/
6	Extruded polystyrene - *30-250*	Satisfy	Satisfy	Satisfy	Satisfy	No condensation	No possibility for freezing	70,1 /26/
7	Extruded polystyrene – *Penoplex - 31*	Satisfy	Satisfy	Satisfy	Satisfy	No condensation	No possibility for freezing	63,7 /28/
8	Expanded polystyrene – *Knauf Therm Facade*	Satisfy	Satisfy	Satisfy	Satisfy	Small possibility of the condensation	Freezing is possible to a depth of 2,77 mm.	50,3 /29/

4 CONCLUSION

According to the results of the practical part, the best energy efficient and cost efficient thermal insulation material for building envelope with ventilated air cavity is Expanded polystyrene – *Knauf Therm Façade*, by KNAUFPENOPLAST, or Mineral wool from slag – *Fasad termo plita 032*, by KNAUFINSULATION. Because, building envelope with this thermal insulation materials satisfy all requirements of building codes, which were used in calculations, and the price of 1 m^3 is the lowest.

But, if this materials will be compared with the requirements of theoretical part, it is became possible to see, that this two materials can't be used as thermal insulation material in a building envelope with ventilated air cavity, because they can't satisfy fire safety norms /31/. In a case of fire, such easy flammable material will contribute to the spread of fire. In this way expanded polystyrene or mineral wool from slag can be used in building envelope, but with another structure, which can protect thermal insulation material from fire. Also, expanded polystyrene don't satisfy sound protection norms. Mineral wool from slag can be used as sound protection material, but it can prevent, mostly, different vibrations. While, building envelope should protect from different noises, better material for this purpose is mineral wool from rock.

So, I can choose only that group of materials which are not flammable. This is mineral wool from rock. In such a way most energy efficient and cost efficient thermal insulation material for the building envelope with ventilated air cavity of the multi-storey building, is Mineral wool from rock – *Venti bats*, by ROCKWOOL or Mineral wool from rock – *Technovent optima*, by TECHNONICOL. As a result builders can choose between these two materials, because they have the same properties and prices.

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Appendix 1. Calculation of the building envelope with the layer of thermal insulation material №1

Table 1 Properties of the materials of the building envelope

№	Name of the material	Thickness of the layer δ, m	Thermal conductivity $\lambda,\ \frac{W}{m\cdot K}$	Specific heat capacity c, $\frac{kJ}{kg\cdot K}$	Density $\rho,\ \frac{kg}{m^3}$	Water vapor permeability $\mu,\ \frac{mg}{m\cdot h\cdot Pa}$
1	Cement-sand plaster	0,012	0,93	0,84	1800	0,09
2	Blocks of aerated concrete	0,15	0,15	0,84	400	0,23
3	Thermal insulation material. *KNAUFINSULATION Fasad termo plita 032*	0,1	0,040	0,72	50	0,5
4	Air barrier TYVEK	0,001	0,27	1,08	600	0,01

Also, in the construction we have some iron elements, such us fixing elements, and guides.

They will be calculated as thermal bridges, $\lambda = 62\frac{W}{m\cdot K}$.

$$D_d = (t_{\text{int}} - t_{ext})\cdot z_{ht} \tag{3.3.1.1}$$

$$D_d = (22-(-1,8))\cdot 220 = 5236 \text{ degree days}$$

$$R_{req} = a\cdot D_d + b \tag{3.3.1.2}$$

$$R_{req} = 0,00035\cdot 5236 + 1,4 = 3,23\ \frac{m^2\cdot^0 C}{W}$$

$$R_i = \frac{\delta_i}{\lambda_i} \tag{3.3.1.3}$$

$$R_1 = \frac{0,012}{0,93} = 0,01\ \frac{m^2\cdot^0 C}{W}$$

$$R_2 = \frac{0,15}{0,15} = 1,0\ \frac{m^2\cdot^0 C}{W}$$

$$R_3 = \frac{0,1}{0,04} = 2,5\ \frac{m^2\cdot^0 C}{W}$$

$$R_4 = \frac{0,001}{0,27} = 0,004\ \frac{m^2\cdot^0 C}{W}$$

$$R_{i,j} = R_i - (A_j\cdot 100)\cdot R_j \tag{3.2.1.4}$$

$$R_{i,j} = 2,5 - (0,00072 \cdot 100) \cdot 0,0096 = 2,49 \ \frac{m^2 \cdot {}^0 C}{W}$$

Influence of metal elements on thermal resistance of the layers is not so much, so it’s not necessary to calculate it.

$$R_T = R_{si} + R_1 + R_2 + ... + R_n + R_{se} \qquad (3.3.1.5)$$

$$R_T = 0,16 + 0,01 + 1,0 + 2,5 + 0,004 = 3,67 \ \frac{m^2 \cdot {}^0 C}{W}$$

$R_T \geq R_{req}$

$$3,67 > 3,23 \ \frac{m^2 \cdot {}^0 C}{W}$$

$$\Delta t_0 = \frac{n \cdot (t_{int} - t_{ext})}{R_T \cdot \alpha_{int}} \qquad (3.3.2.1)$$

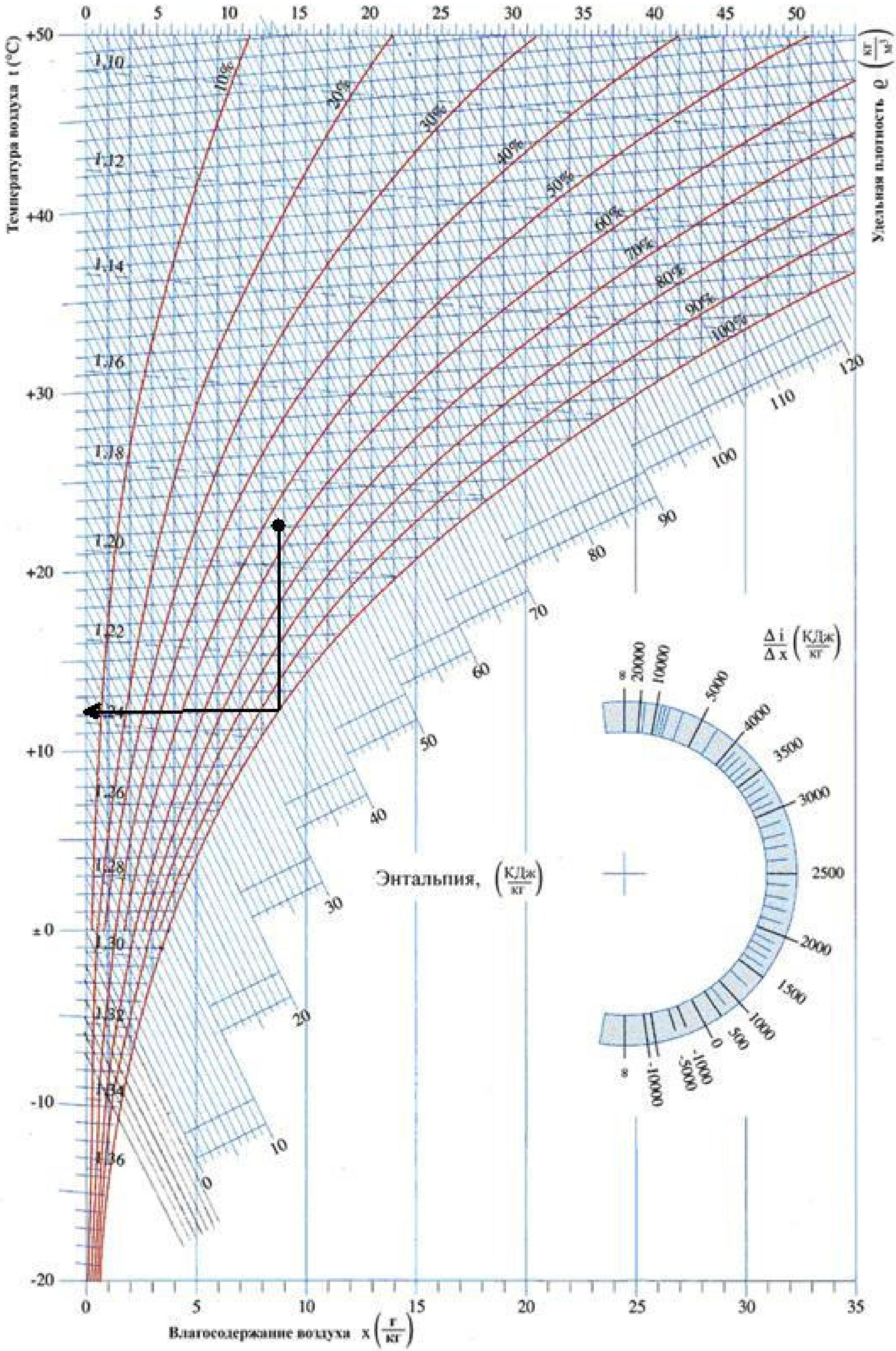
$$\Delta t_0 = \frac{1 \cdot (22 - (-26))}{3,67 \cdot 8,7} = 1,5$$

$\Delta t_0 \leq \Delta t_n$

$1,5 < 4,0\ {}^0$C

$$t_{si} = t_{int} - \Delta t_0 \qquad (3.3.3.1)$$

$t_{si} = 22 - 1,5 = 20,5\ {}^0$C



Picture 1. The Mollier psychrometric chart.

20,5 ≥ 12,5 ^{0}C

Table 2. Air tightness properties of the materials of the building envelope

№	Name of the material	Thickness of the layer δ, m	Density ρ, $\frac{kg}{m^3}$	Air tightness R^{des}, $\frac{m^2 \cdot h \cdot Pa}{kg}$
1	Cement-sand plaster	0,012	1800	373
2	Blocks of aerated concrete	0,15	400	21
3	Thermal insulation material. <u>*KNAUFINSULATION Fasad termo plita 032*</u>	0,1	50	4 /6, t.17/
4	Air barrier TYVEK	0,001	600	10

Σ 408

$$\gamma_{ext} = \frac{3463}{273 + t_{ext}}$$
$$\gamma_{\text{int}} = \frac{3463}{273 + t_{\text{int}}} \qquad (3.3.4.1)$$

$$\gamma_{ext} = \frac{3463}{273 + (-26)} = 14,0 \frac{N}{m^3}$$
$$\gamma_{\text{int}} = \frac{3463}{273 + 22} = 11,7 \frac{N}{m^3}$$

$$\Delta p = 0,55 \cdot H \cdot (\gamma_{ext} - \gamma_{\text{int}}) + 0,03 \cdot \gamma_{ext} \cdot V^2 \qquad (3.3.4.2)$$

$$\Delta p = 0,55 \cdot 50 \cdot (14,0 - 11,7) + 0,03 \cdot 14,0 \cdot 5,5^2 = 75,9 \text{ Pa.}$$

$$R^{req} = \frac{\Delta p}{G_n} \qquad (3.3.4.1)$$

$$R^{req} = \frac{75,9}{0,5} = 151,8 \frac{m^2 \cdot h \cdot Pa}{kg}$$

$R_{des} \geq R_{req}$

$408 > 151,8 \ \frac{m^2 \cdot h \cdot Pa}{kg}$

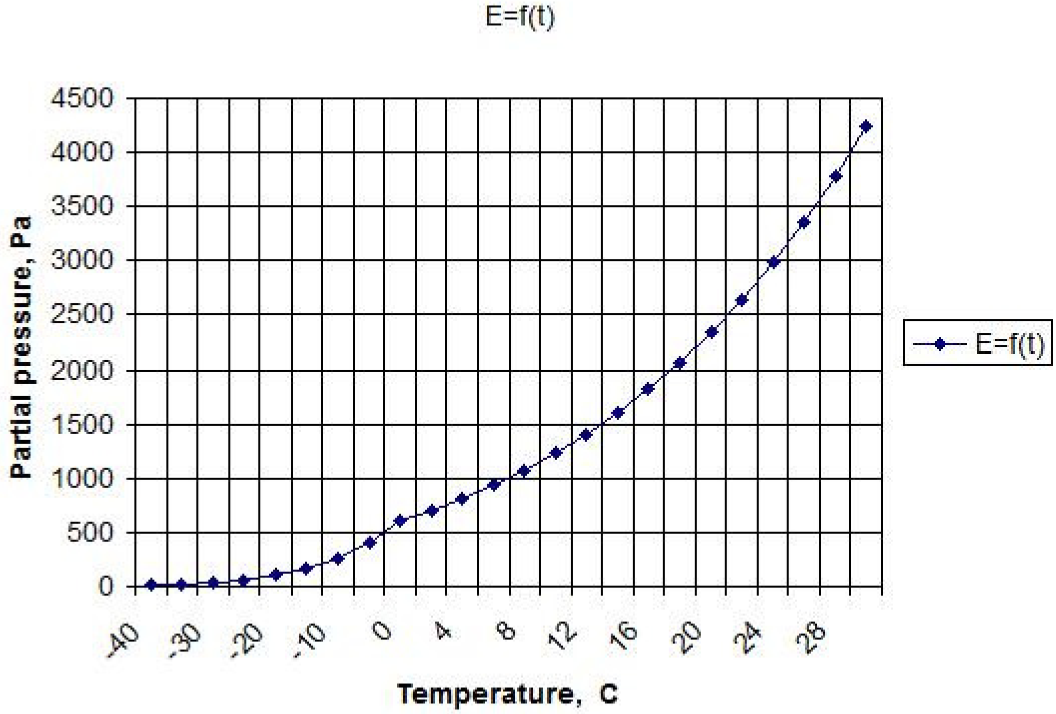
$$e_{\text{int}} = \frac{\varphi_{\text{int}}}{100} \cdot E_{\text{int}}$$
$$e_{ext} = \frac{\varphi_{ext}}{100} \cdot E_{ext} \qquad (3.3.5.1)$$

$$e_{\text{int}} = \frac{55}{100} \cdot 2500 = 1375 Pa$$

$$e_{ext} = \frac{86}{100} \cdot 300 = 258 Pa$$

Table 3. Dependence between maximum value of the partial pressure of the water vapor and temperature of the air

t, °C	E, Pa	t, °C	E, Pa	t, °C	E, Pa	t, °C	E, Pa
-40,0	12,40	-10,0	260,0	8,0	1073	20,0	2338
-35,0	22,26	-5,0	401,3	10,0	1228	22,0	2644
-30,0	37,33	0,0	610,6	12,0	1403	24,0	2984
-25,0	62,66	2,0	705,3	14,0	1599	26,0	3361
-20,0	102,7	4,0	813,3	16,0	1817	28,0	3780
-15,0	165,3	6,0	934,6	18,0	2064	30,0	4242



Picture 2. Dependence between partial pressure of the water vapor and temperature.

$$\tau_i = t_{\text{int}} - \frac{(t_{\text{int}} - t_i) \cdot (R_{si} + R_i)}{R_T} \qquad (3.3.5.2)$$

$$\tau_{\text{int}-1} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 0)}{3,67} = 21,2\,^0\text{C}$$

$$\tau_{1-2} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 0,01)}{3,67} = 21,1\,^0\text{C}$$

$$\tau_{2-3} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 1,01)}{3,67} = 13,4\,^0\text{C}$$

$$\tau_{3-4} = 22 - \frac{(22-(-6,1))\cdot(0,11+3,51)}{3,67} = -5,7\ ^0\mathrm{C}$$

$$\tau_{4-ext} = 22 - \frac{(22-(-6,1))\cdot(0,11+3,56)}{3,67} = -6,1\ ^0\mathrm{C}$$

$$\Omega_i = \frac{\delta}{\mu} \qquad (3.3.5.3)$$

$$\Omega_1 = \frac{0,012}{0,09} = 0,1\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_2 = \frac{0,15}{0,23} = 0,7\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_3 = \frac{0,1}{0,5} = 0,2\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_4 = \frac{0,001}{0,00024} = 0,1\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_T = \Omega_{\mathrm{int}} + \Omega_1 + \Omega_2 + \ldots + \Omega_n + \Omega_{ext} \qquad (3.3.5.4)$$

$$\Omega_T = 0,0266 + 0,1 + 0,7 + 0,2 + 0,1 + 0,0133 = 1,14\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$e_i = e_{\mathrm{int}} - \frac{(e_{\mathrm{int}} - e_{ext})\cdot(\Omega_{\mathrm{int}} + \Sigma\Omega_i)}{\Omega_T} \qquad (3.3.5.4)$$

$$e_{\mathrm{int}-1} = 1375 - \frac{(1375-258)\cdot(0,0266+0)}{1,14} = 1345\,\mathrm{Pa}$$

$$e_{1-2} = 1375 - \frac{(1375-258)\cdot(0,0266+0,1)}{1,14} = 1247\,\mathrm{Pa}$$

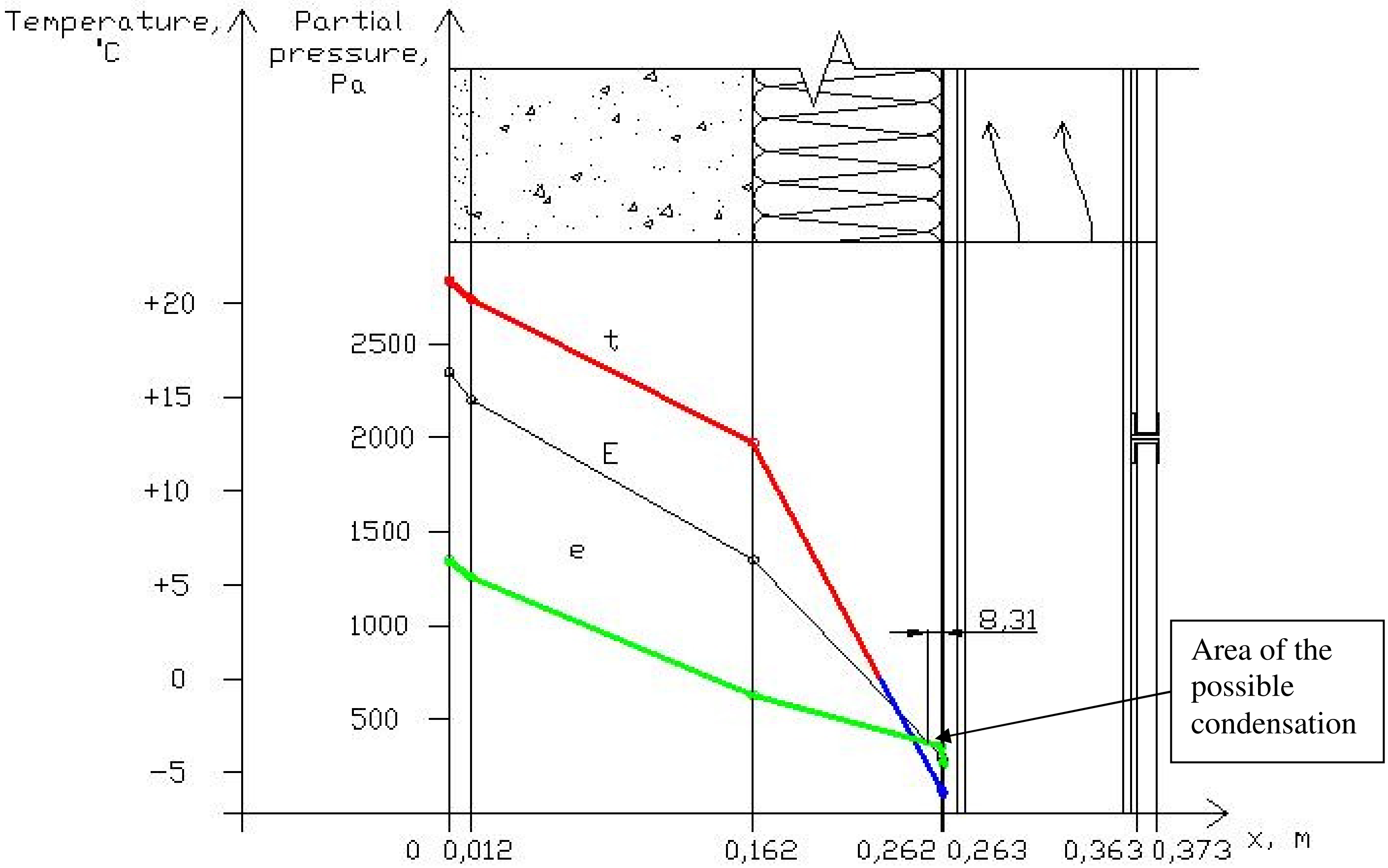
$$e_{2-3} = 1375 - \frac{(1375-258)\cdot(0,0266+0,8)}{1,14} = 561\,\mathrm{Pa}$$

$$e_{3-4} = 1375 - \frac{(1375-258)\cdot(0,0266+1,0)}{1,14} = 365\,\mathrm{Pa}$$

$$e_{4-ext} = 1375 - \frac{(1375-258)\cdot(0,0266+1,11)}{1,14} = 258\,\mathrm{Pa}$$

Table 4. Results, of the possibility of the condensation of the water vapor in a building envelope

Border of the layers	x, m	ΣR_i, $\frac{m^2 \cdot {}^0C}{W}$	τ_i, ℃	E, Pa	$\Sigma \Omega_i$, $\frac{m^2 \cdot h \cdot Pa}{kg}$	e_i, Pa
int-1	0,0	0,0	21,2	2350	0	1345
1-2	0,012	0,01	20,2	2200	0,1	1247
2-3	0,162	1,01	12,6	1350	0,8	561
3-4	0,262	3,51	-5,9	300	1,0	365
4-ext	0,263	3,56	-6,1	280	1,11	258



Picture 3. Determining of the area of the possible condensation and freezing of the water vapor in building envelope.

Appendix 2. Calculation of the building envelope with the layer of thermal insulation material №3

Table 1 Properties of the materials of the building envelope

№	Name of the material	Thickness of the layer δ, m	Thermal conductivity λ, $\frac{W}{m \cdot K}$	Specific heat capacity c, $\frac{kJ}{kg \cdot K}$	Density ρ, $\frac{kg}{m^3}$	Water vapor permeability μ, $\frac{mg}{m \cdot h \cdot Pa}$
1	Cement-sand plaster	0,012	0,93	0,84	1800	0,09
2	Blocks of aerated concrete	0,15	0,15	0,84	400	0,23
3	Thermal insulation material *ROCKWOOL Venti bats*	0,1	0,045	0,82	90	0,3
4	Air barrier TYVEK	0,001	0,27	1,08	600	0,01

Also, in the construction we have some iron elements, such us fixing elements, and guides. They will be calculated as thermal bridges, $\lambda = 62 \frac{W}{m \cdot K}$.

$$D_d = (t_{\text{int}} - t_{ext}) \cdot z_{ht} \tag{3.3.1.1}$$

$$D_d = (22 - (-1,8)) \cdot 220 = 5236 \text{ degree days}$$

$$R_{req} = a \cdot D_d + b \tag{3.3.1.2}$$

$$R_{req} = 0,00035 \cdot 5236 + 1,4 = 3,23 \ \frac{m^2 \cdot {}^0C}{W}$$

$$R_i = \frac{\delta_i}{\lambda_i} \tag{3.3.1.3}$$

$$R_1 = \frac{0,012}{0,93} = 0,01 \ \frac{m^2 \cdot {}^0C}{W}$$

$$R_2 = \frac{0,15}{0,15} = 1,0 \ \frac{m^2 \cdot {}^0C}{W}$$

$$R_3 = \frac{0,1}{0,04} = 2,2 \ \frac{m^2 \cdot {}^0C}{W}$$

$$R_4 = \frac{0,001}{0,27} = 0,004 \ \frac{m^2 \cdot {}^0C}{W}$$

$$R_{i,j} = R_i - (A_j \cdot 100) \cdot R_j \tag{3.2.1.4}$$

$$R_{i,j} = 2,2 - (0,00072 \cdot 100) \cdot 0,0096 = 2,19 \ \frac{m^2 \cdot {}^0C}{W}$$

Influence of metal elements on thermal resistance of the layers is not so much, so it’s not necessary to calculate it.

$$R_T = R_{si} + R_1 + R_2 + ... + R_n + R_{se} \tag{3.3.1.5}$$

$$R_T = 0,16 + 0,01 + 1,0 + 2,2 + 0,004 = 3,37 \ \frac{m^2 \cdot {}^0C}{W}$$

$R_T \geq R_{req}$

$$3,37 > 3,23 \ \frac{m^2 \cdot {}^0C}{W}$$

$$\Delta t_0 = \frac{n \cdot (t_{int} - t_{ext})}{R_T \cdot \alpha_{int}} \tag{3.3.2.1}$$

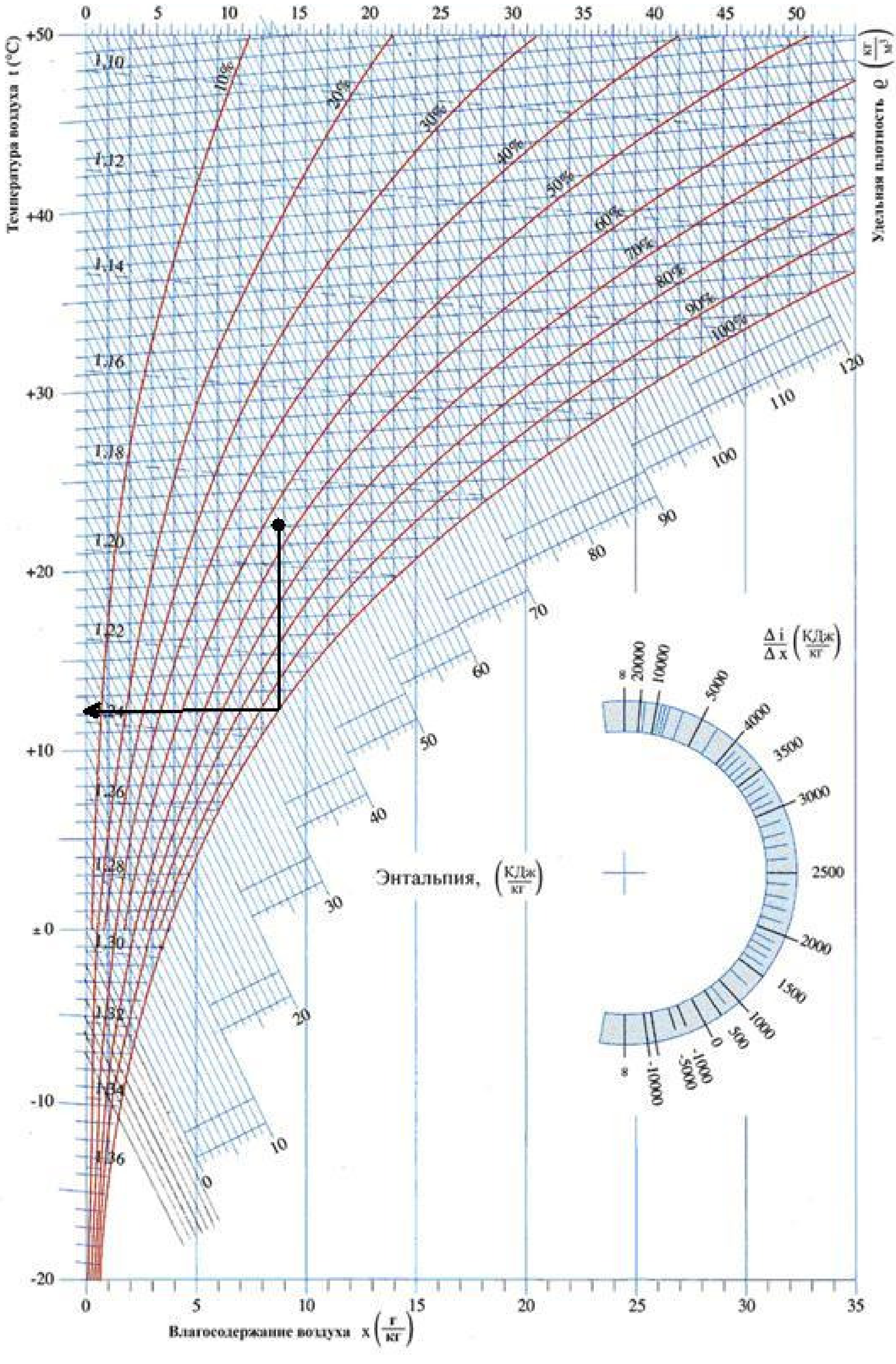
$$\Delta t_0 = \frac{1 \cdot (22 - (-26))}{3,37 \cdot 8,7} = 1,63$$

$\Delta t_0 \leq \Delta t_n$

$1,63 < 4,0\ {}^0C$

$$t_{si} = t_{int} - \Delta t_0 \tag{3.3.3.1}$$

$t_{si} = 22 - 1,63 = 20,37\ {}^0C$



Picture 1. The Mollier psychrometric chart.

$20{,}37 \geq 12{,}5\ ^{0}C$

Table 2. Air tightness properties of the materials of the building envelope

№	Name of the material	Thickness of the layer δ, m	Density ρ, $\frac{kg}{m^3}$	Air tightness R^{des}, $\frac{m^2 \cdot h \cdot Pa}{kg}$
1	Cement-sand plaster	0,012	1800	373
2	Blocks of aerated concrete	0,15	400	21
3	Thermal insulation material. <u>*ROCKWOOL Venti bats*</u>	0,1	90	4 /6, t.17/
4	Air barrier TYVEC	0,001	600	10

Σ 408

$$\gamma_{ext} = \frac{3463}{273 + t_{ext}} \qquad \gamma_{\text{int}} = \frac{3463}{273 + t_{\text{int}}} \tag{3.3.4.1}$$

$$\gamma_{ext} = \frac{3463}{273 + (-26)} = 14,0 \frac{N}{m^3}$$

$$\gamma_{\text{int}} = \frac{3463}{273 + 22} = 11,7 \frac{N}{m^3}$$

$$\Delta p = 0,55 \cdot H \cdot (\gamma_{ext} - \gamma_{\text{int}}) + 0,03 \cdot \gamma_{ext} \cdot V^2 \tag{3.3.4.2}$$

$$\Delta p = 0,55 \cdot 50 \cdot (14,0 - 11,7) + 0,03 \cdot 14,0 \cdot 5,5^2 = 75,9 \text{ Pa.}$$

$$R^{req} = \frac{\Delta p}{G_n} \tag{3.3.4.1}$$

$$R^{req} = \frac{75,9}{0,5} = 151,8 \frac{m^2 \cdot h \cdot Pa}{kg}$$

$R_{des} \geq R_{req}$

$$408 > 151,8 \ \frac{m^2 \cdot h \cdot Pa}{kg}$$

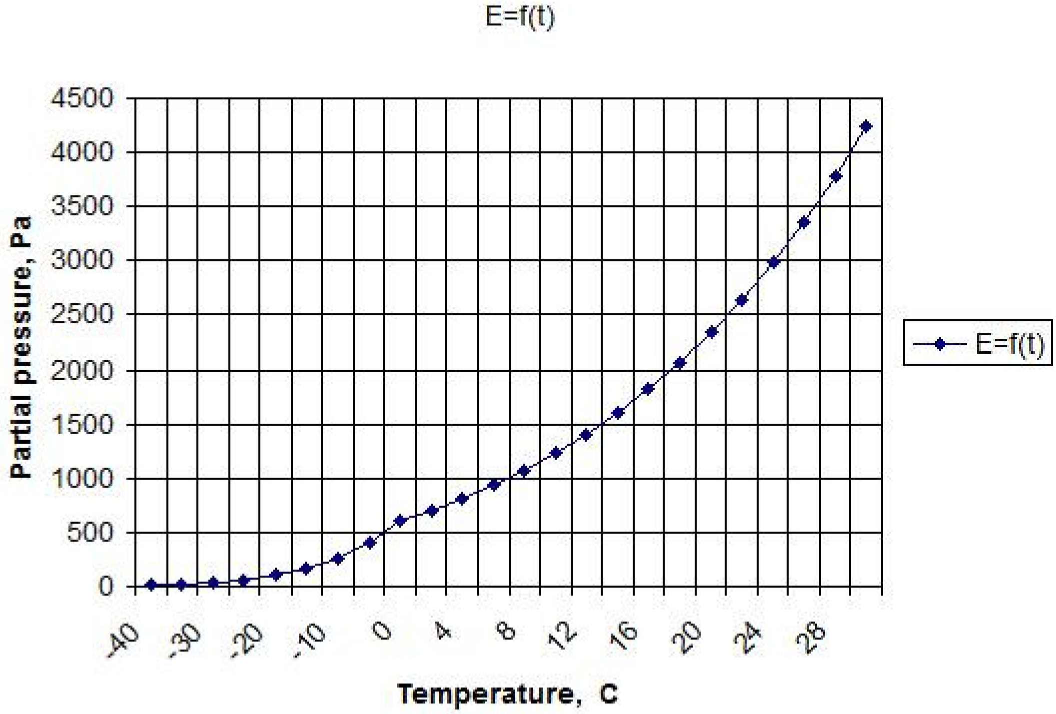
$$e_{\text{int}} = \frac{\varphi_{\text{int}}}{100} \cdot E_{\text{int}} \qquad e_{ext} = \frac{\varphi_{ext}}{100} \cdot E_{ext} \tag{3.3.5.1}$$

$$e_{\text{int}} = \frac{55}{100} \cdot 2500 = 1375 Pa$$

$$e_{ext} = \frac{86}{100} \cdot 300 = 258 Pa$$

Table 3. Dependence between maximum value of the partial pressure of the water vapor and temperature of the air

t, ^{o}C	E, Pa	t, ^{o}C	E, Pa	t, ^{o}C	E, Pa	t, ^{o}C	E, Pa
-40,0	12,40	-10,0	260,0	8,0	1073	20,0	2338
-35,0	22,26	-5,0	401,3	10,0	1228	22,0	2644
-30,0	37,33	0,0	610,6	12,0	1403	24,0	2984
-25,0	62,66	2,0	705,3	14,0	1599	26,0	3361
-20,0	102,7	4,0	813,3	16,0	1817	28,0	3780
-15,0	165,3	6,0	934,6	18,0	2064	30,0	4242



Picture 2. Dependence between partial pressure of the water vapor and temperature.

$$\tau_i = t_{\text{int}} - \frac{(t_{\text{int}} - t_i) \cdot (R_{si} + R_i)}{R_T} \tag{3.3.5.2}$$

$$\tau_{\text{int}-1} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 0)}{3,37} = 21,9\ ^{0}\text{C}$$

$$\tau_{1-2} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 0,01)}{3,37} = 20,9\ ^{0}\text{C}$$

$$\tau_{2-3} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 1,01)}{3,37} = 12,6\ ^{0}\text{C}$$

$$\tau_{3-4} = 22 - \frac{(22-(-6,1))\cdot(0,11+3,21)}{3,37} = -5,7\,^{0}\mathrm{C}$$

$$\tau_{4-ext} = 22 - \frac{(22-(-6,1))\cdot(0,11+3,36)}{3,37} = -6,1\,^{0}\mathrm{C}$$

$$\Omega_i = \frac{\delta}{\mu} \tag{3.3.5.3}$$

$$\Omega_1 = \frac{0,012}{0,09} = 0,1\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_2 = \frac{0,15}{0,23} = 0,7\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_3 = \frac{0,1}{0,3} = 0,3\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_4 = \frac{0,001}{0,01} = 0,1\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_T = \Omega_{\text{int}} + \Omega_1 + \Omega_2 + \ldots + \Omega_n + \Omega_{ext} \tag{3.3.5.4}$$

$$\Omega_T = 0,0266 + 0,1 + 0,7 + 0,3 + 0,1 + 0,0133 = 1,24\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$e_i = e_{\text{int}} - \frac{(e_{\text{int}} - e_{ext})\cdot(\Omega_{\text{int}} + \Sigma\Omega_i)}{\Omega_T} \tag{3.3.5.4}$$

$$e_{\text{int}-1} = 1375 - \frac{(1375-258)\cdot(0,0266+0)}{1,24} = 1347\ \mathrm{Pa}$$

$$e_{1-2} = 1375 - \frac{(1375-258)\cdot(0,0266+0,1)}{1,24} = 1257\ \mathrm{Pa}$$

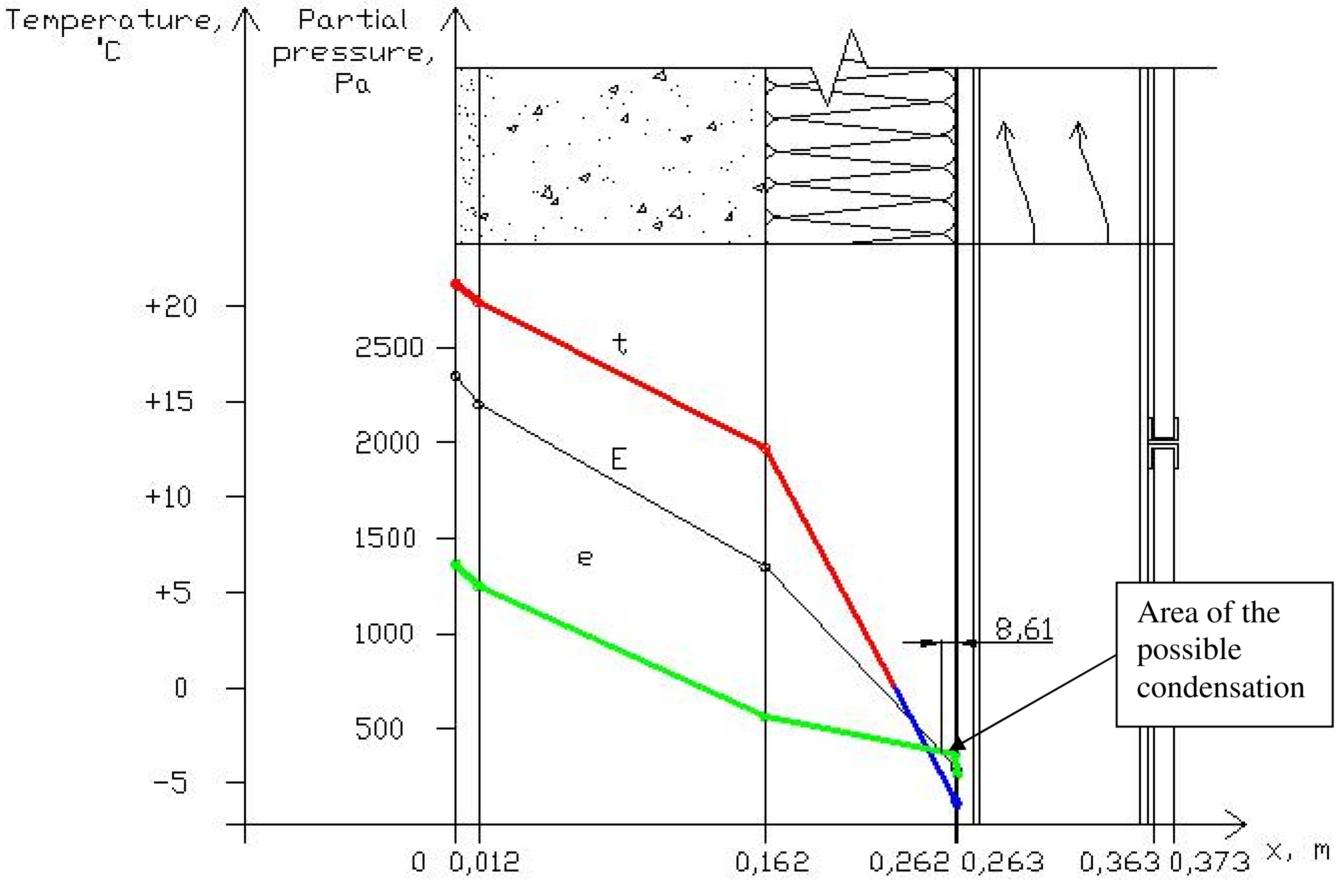
$$e_{2-3} = 1375 - \frac{(1375-258)\cdot(0,0266+0,8)}{1,24} = 627\ \mathrm{Pa}$$

$$e_{3-4} = 1375 - \frac{(1375-258)\cdot(0,0266+1,1)}{1,24} = 357\ \mathrm{Pa}$$

$$e_{4-ext} = 1375 - \frac{(1375-258)\cdot(0,0266+1,21)}{1,24} = 258\ \mathrm{Pa}$$

Table 4. Results, of the possibility of the condensation of the water vapor in a building envelope

Border of the layers	x, m	ΣR_i, $\frac{m^2 \cdot {}^0 C}{W}$	τ_i, ℃	E, Pa	$\Sigma \Omega_i$, $\frac{m^2 \cdot h \cdot Pa}{kg}$	e_i, Pa
int-1	0,0	0,0	21,2	2350	0	1347
1-2	0,012	0,01	20,2	2200	0,1	1257
2-3	0,162	1,01	12,6	1350	0,8	627
3-4	0,262	3,21	-5,9	300	1,1	357
4-ext	0,263	3,26	-6,1	280	1,21	258



Picture 3. Determining of the area of the possible condensation and freezing of the water vapor in building envelope.

Properties of all another kinds of mineral wall from rock are very close to each other, so, results of calculations will be quite the same. According to this reason I will use this results for all kinds of mineral wool from slag.

Appendix 3. Calculation of the building envelope with the layer of thermal insulation material №7

Table 1 Properties of the materials of the building envelope

№	Name of the material	Thickness of the layer δ, m	Thermal conductivity λ, $\frac{W}{m \cdot K}$	Specific heat capacity c, $\frac{kJ}{kg \cdot K}$	Density ρ, $\frac{kg}{m^3}$	Water vapor permeability μ, $\frac{mg}{m \cdot h \cdot Pa}$
1	Cement-sand plaster	0,012	0,93	0,84	1800	0,09
2	Blocks of aerated concrete	0,15	0,15	0,84	400	0,23
3	Thermal insulation material. *PENOPLEX Penoplex - 31*	0,1	0,032	1,45	30,5	0,008
4	Air barrier TYVEK	0,001	0,27	1,08	600	0,01

Also, in the construction we have some iron elements, such us fixing elements, and guides. They will be calculated as thermal bridges, $\lambda = 62 \frac{W}{m \cdot K}$.

$$D_d = (t_{\text{int}} - t_{ext}) \cdot z_{ht} \quad (3.3.1.1)$$

$$D_d = (22 - (-1,8)) \cdot 220 = 5236 \text{ degree days}$$

$$R_{req} = a \cdot D_d + b \quad (3.3.1.2)$$

$$R_{req} = 0,00035 \cdot 5236 + 1,4 = 3,23 \frac{m^2 \cdot {}^0 C}{W}$$

$$R_i = \frac{\delta_i}{\lambda_i} \quad (3.3.1.3)$$

$$R_1 = \frac{0,012}{0,93} = 0,01 \frac{m^2 \cdot {}^0 C}{W}$$

$$R_2 = \frac{0,15}{0,15} = 1,0 \frac{m^2 \cdot {}^0 C}{W}$$

$$R_3 = \frac{0,1}{0,032} = 3,1 \frac{m^2 \cdot {}^0 C}{W}$$

$$R_4 = \frac{0,001}{0,27} = 0,004 \frac{m^2 \cdot {}^0 C}{W}$$

$$R_{i,j} = R_i - (A_j \cdot 100) \cdot R_j \quad (3.2.1.4)$$

$$R_{i,j} = 3,1-(0,00072\cdot 100)\cdot 0,0096 = 3,0\ \frac{m^2\cdot{}^0C}{W}$$

Influence of metal elements on thermal resistance of the layers is not so much, so it's not necessary to calculate it.

$$R_T = R_{si} + R_1 + R_2 + ... + R_n + R_{se} \qquad (3.3.1.5)$$

$$R_T = 0,16+0,01+1,0+3,1+0,004 = 4,27\ \frac{m^2\cdot{}^0C}{W}$$

$R_T \geq R_{req}$

$$4,27 >> 3,23\ \frac{m^2\cdot{}^0C}{W}$$

The thermal resistance of building envelope with such thermal insulation material as <u>*Penoplex – 31*</u> is to much, so, the sickness of the thermal insulation material layer can be decrease to the less manufacturing size δ = 80 mm.

$$R_3 = \frac{0,08}{0,032} = 2,5\ \frac{m^2\cdot{}^0C}{W}$$

$$R_T = 0,16+0,01+1,0+2,5+0,004 = 3,67\ \frac{m^2\cdot{}^0C}{W}$$

$$3,67 > 3,23\ \frac{m^2\cdot{}^0C}{W}$$

$$\Delta t_0 = \frac{n\cdot(t_{int} - t_{ext})}{R_T\cdot\alpha_{int}} \qquad (3.3.2.1)$$

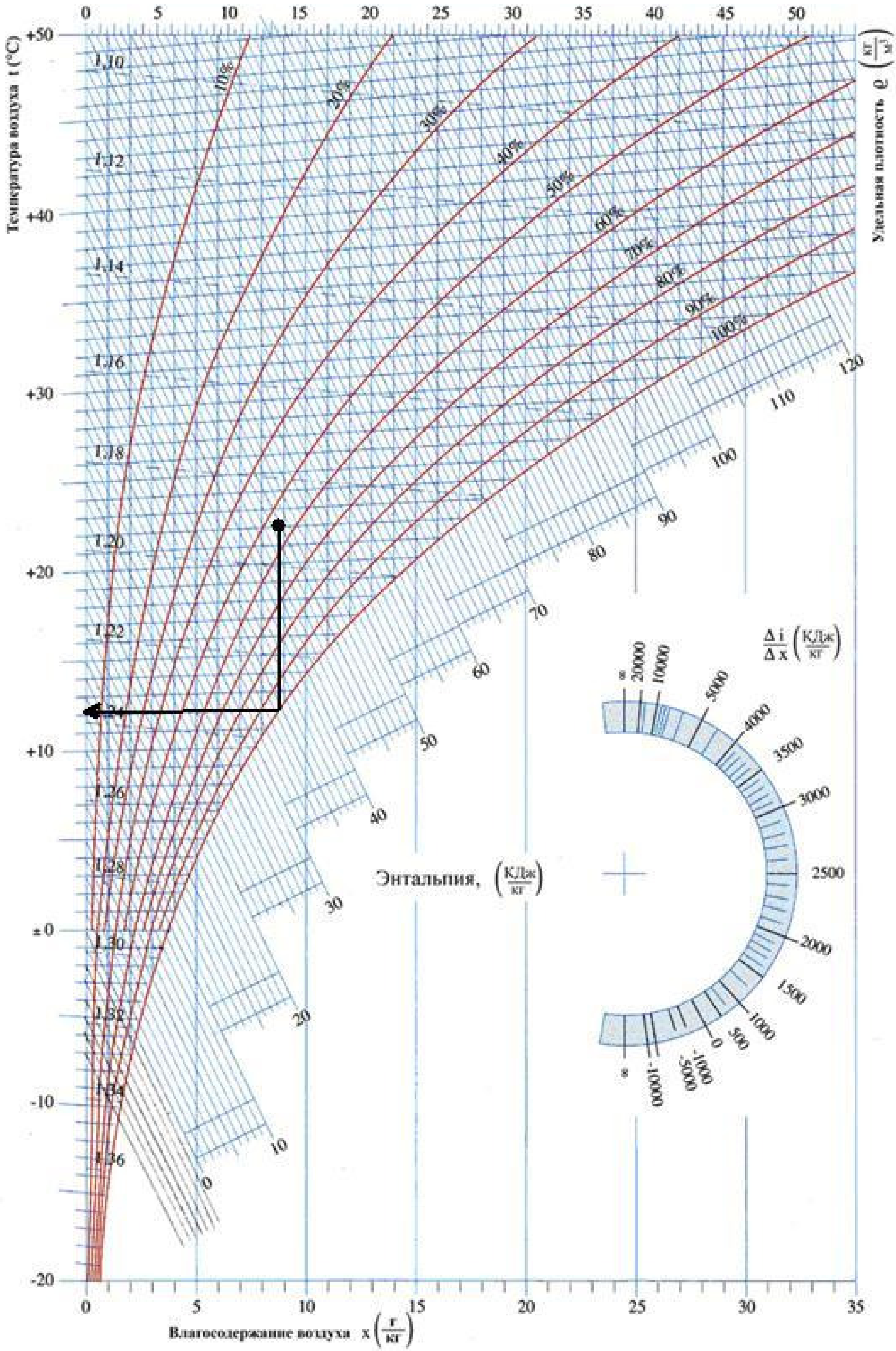
$$\Delta t_0 = \frac{1\cdot(22-(-26))}{3,67\cdot 8,7} = 1,5$$

$\Delta t_0 \leq \Delta t_n$

$1,5 < 4,0\ {}^0C$

$$t_{si} = t_{int} - \Delta t_0 \qquad (3.3.3.1)$$

$t_{si} = 22 - 1,5 = 20,5\ {}^0C$



Picture 1. The Mollier psychrometric chart.

$20{,}5 \geq 12{,}5\ ^0C$

Table 2. Air tightness properties of the materials of the building envelope

№	Name of the material	Thickness of the layer δ, m	Density ρ, $\frac{kg}{m^3}$	Air tightness R^{des}, $\frac{m^2 \cdot h \cdot Pa}{kg}$
1	Cement-sand plaster	0,012	1800	373
2	Blocks of aerated concrete	0,15	400	21
3	Thermal insulation material. <u>*PENOPLEX Penoplex - 31*</u>	0,08	50	79 /6, t.17/
4	Air barrier TYVEC	0,001	600	10
				Σ 483

$$\gamma_{ext} = \frac{3463}{273 + t_{ext}}$$
$$\gamma_{\text{int}} = \frac{3463}{273 + t_{\text{int}}} \qquad (3.3.4.1)$$

$$\gamma_{ext} = \frac{3463}{273 + (-26)} = 14,0 \frac{N}{m^3}$$

$$\gamma_{\text{int}} = \frac{3463}{273 + 22} = 11,7 \frac{N}{m^3}$$

$$\Delta p = 0,55 \cdot H \cdot (\gamma_{ext} - \gamma_{\text{int}}) + 0,03 \cdot \gamma_{ext} \cdot V^2 \qquad (3.3.4.2)$$

$$\Delta p = 0,55 \cdot 50 \cdot (14,0 - 11,7) + 0,03 \cdot 14,0 \cdot 5,5^2 = 75,9 \text{ Pa.}$$

$$R^{req} = \frac{\Delta p}{G_n} \qquad (3.3.4.1)$$

$$R^{req} = \frac{75,9}{0,5} = 151,8 \frac{m^2 \cdot h \cdot Pa}{kg}$$

$R_{des} \geq R_{req}$

$$483 > 151,8 \frac{m^2 \cdot h \cdot Pa}{kg}$$

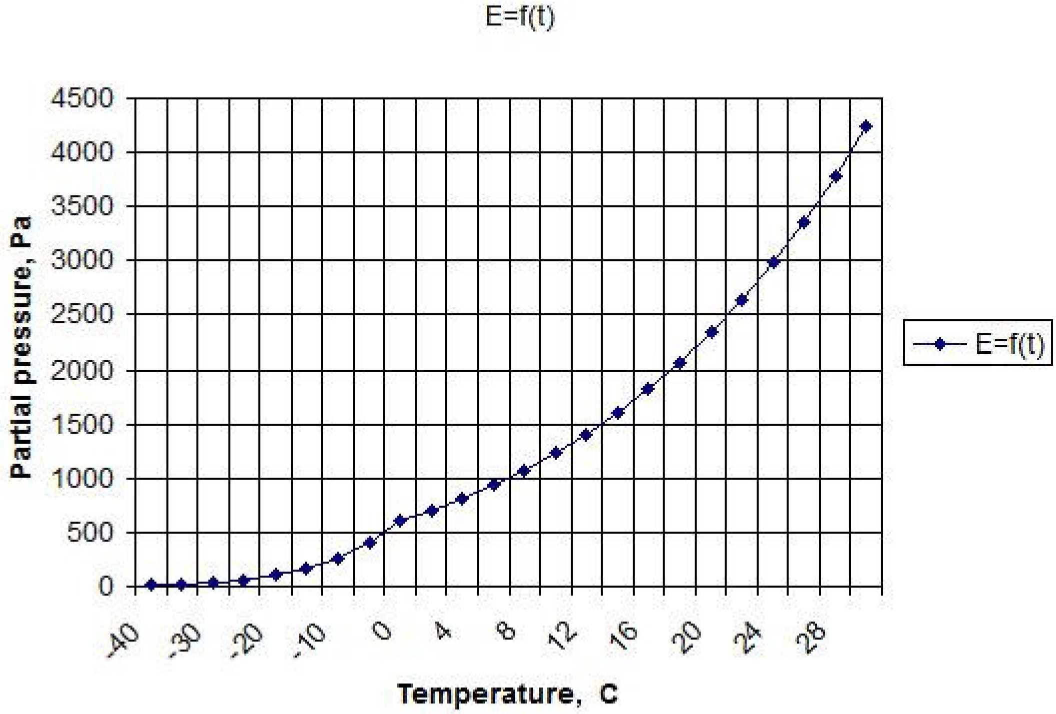
$$e_{\text{int}} = \frac{\varphi_{\text{int}}}{100} \cdot E_{\text{int}}$$
$$e_{ext} = \frac{\varphi_{ext}}{100} \cdot E_{ext} \qquad (3.3.5.1)$$

$$e_{int} = \frac{55}{100} \cdot 2500 = 1375 Pa$$

$$e_{ext} = \frac{86}{100} \cdot 300 = 258 Pa$$

Table 3. Dependence between maximum value of the partial pressure of the water vapor and temperature of the air

t, °C	E, Pa	t, °C	E, Pa	t, °C	E, Pa	t, °C	E, Pa
-40,0	12,40	-10,0	260,0	8,0	1073	20,0	2338
-35,0	22,26	-5,0	401,3	10,0	1228	22,0	2644
-30,0	37,33	0,0	610,6	12,0	1403	24,0	2984
-25,0	62,66	2,0	705,3	14,0	1599	26,0	3361
-20,0	102,7	4,0	813,3	16,0	1817	28,0	3780
-15,0	165,3	6,0	934,6	18,0	2064	30,0	4242



Picture 2. Dependence between partial pressure of the water vapor and temperature.

$$\tau_i = t_{int} - \frac{(t_{int} - t_i) \cdot (R_{si} + R_i)}{R_T} \qquad (3.3.5.2)$$

$$\tau_{int-1} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 0)}{3,67} = 21,2\,^0\text{C}$$

$$\tau_{1-2} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 0,01)}{3,67} = 21,1\,^0\text{C}$$

$$\tau_{2-3} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 1,01)}{3,67} = 13,4\,^0\text{C}$$

$$\tau_{3-4} = 22 - \frac{(22-(-6,1))\cdot(0,11+3,51)}{3,67} = -5,7\ {}^{0}\mathrm{C}$$

$$\tau_{4-ext} = 22 - \frac{(22-(-6,1))\cdot(0,11+3,56)}{3,67} = -6,1\,{}^{0}\mathrm{C}$$

$$\Omega_i = \frac{\delta}{\mu} \tag{3.3.5.3}$$

$$\Omega_1 = \frac{0,012}{0,09} = 0,1\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_2 = \frac{0,15}{0,23} = 0,7\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_3 = \frac{0,08}{0,008} = 10\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_4 = \frac{0,001}{0,01} = 0,1\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$\Omega_T = \Omega_{\mathrm{int}} + \Omega_1 + \Omega_2 + \ldots + \Omega_n + \Omega_{ext} \tag{3.3.5.4}$$

$$\Omega_T = 0,0266 + 0,1 + 0,7 + 10 + 0,1 + 0,0133 = 10,94\ \frac{m^2\cdot h\cdot Pa}{kg}$$

$$e_i = e_{\mathrm{int}} - \frac{(e_{\mathrm{int}} - e_{ext})\cdot(\Omega_{\mathrm{int}} + \Sigma\Omega_i)}{\Omega_T} \tag{3.3.5.4}$$

$$e_{\mathrm{int}-1} = 1375 - \frac{(1375-258)\cdot(0,0266+0)}{10,94} = 1372\,\mathrm{Pa}$$

$$e_{1-2} = 1375 - \frac{(1375-258)\cdot(0,0266+0,1)}{10,94} = 1361\,\mathrm{Pa}$$

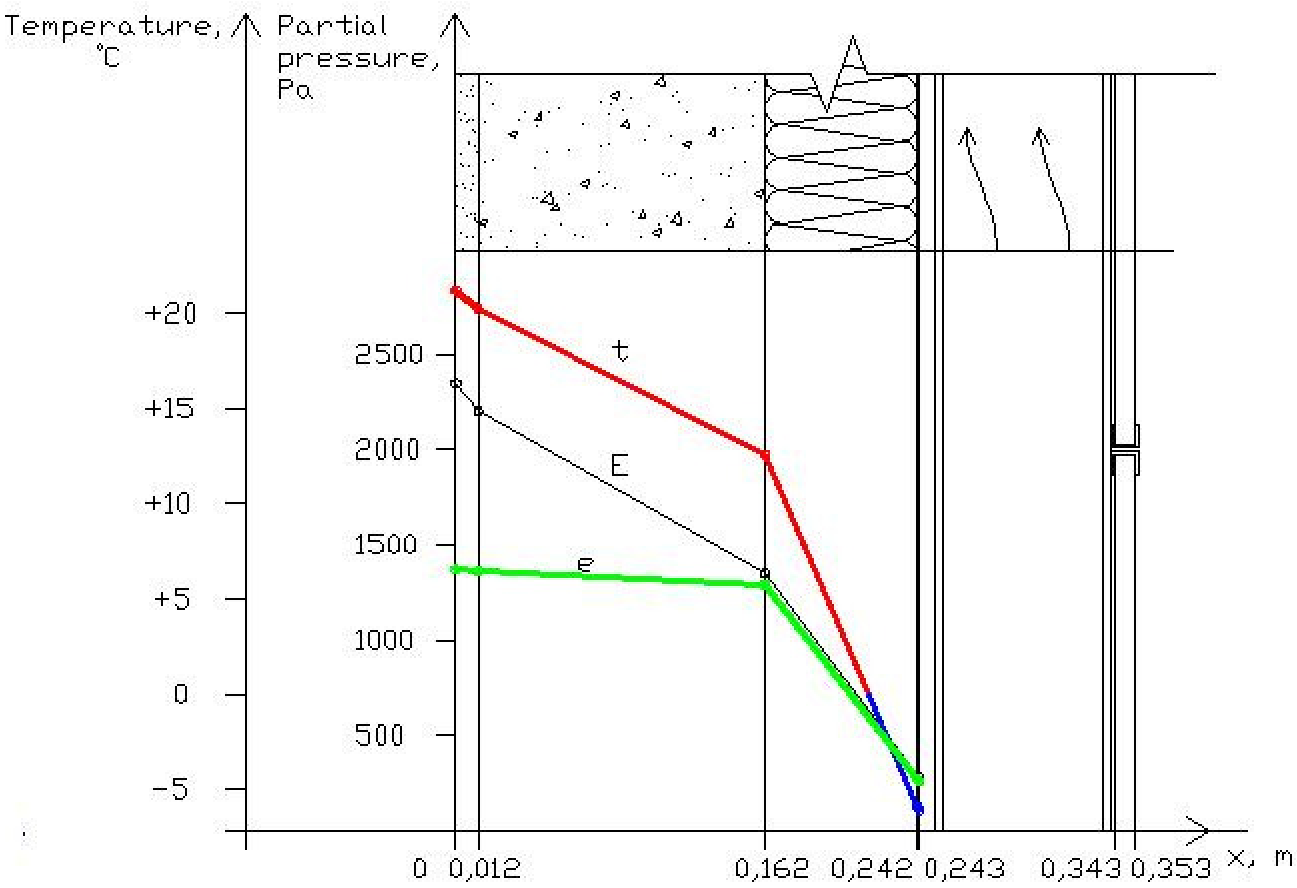
$$e_{2-3} = 1375 - \frac{(1375-258)\cdot(0,0266+0,8)}{10,94} = 1290\,\mathrm{Pa}$$

$$e_{3-4} = 1375 - \frac{(1375-258)\cdot(0,0266+10,8)}{10,94} = 269\,\mathrm{Pa}$$

$$e_{4-ext} = 1375 - \frac{(1375-258)\cdot(0,0266+10,91)}{10,94} = 258\,\mathrm{Pa}$$

Table 4. Results, of the possibility of the condensation of the water vapor in a building envelope

Border of the layers	x, m	ΣR_i, $\frac{m^2 \cdot {}^0 C}{W}$	τ_i, ℃	E, Pa	$\Sigma \Omega_i$, $\frac{m^2 \cdot h \cdot Pa}{kg}$	e_i, Pa
int-1	0,0	0,0	21,2	2350	0	1372
1-2	0,012	0,01	20,2	2200	0,1	1361
2-3	0,162	1,01	12,6	1350	0,8	1290
3-4	0,242	3,51	-5,9	300	10,8	269
4-ext	0,243	3,56	-6,1	280	10,91	258



Picture 3. Determining of the area of the possible condensation and freezing of the water vapor in building envelope.

Appendix 4. Calculation of the building envelope with the layer of thermal insulation material №8

Table 1 Properties of the materials of the building envelope

№	Name of the material	Thickness of the layer δ, m	Thermal conductivity λ, $\frac{W}{m \cdot K}$	Specific heat capacity c, $\frac{kJ}{kg \cdot K}$	Density ρ, $\frac{kg}{m^3}$	Water vapor permeability μ, $\frac{mg}{m \cdot h \cdot Pa}$
1	Cement-sand plaster	0,012	0,93	0,84	1800	0,09
2	Blocks of aerated concrete	0,15	0,15	0,84	400	0,23
3	Thermal insulation material. *KNAUFPENOPLAST Knauf Therm Facade*	0,1	0,036	0,98	30	0,05
4	Air barrier TYVEK	0,001	0,27	1,08	600	0,01

Also, in the construction we have some iron elements, such us fixing elements, and guides.

They will be calculated as thermal bridges, $\lambda = 62 \frac{W}{m \cdot K}$.

$$D_d = (t_{\text{int}} - t_{ext}) \cdot z_{ht} \qquad (3.3.1.1)$$

$$D_d = (22 - (-1,8)) \cdot 220 = 5236 \text{ degree days}$$

$$R_{req} = a \cdot D_d + b \qquad (3.3.1.2)$$

$$R_{req} = 0,00035 \cdot 5236 + 1,4 = 3,23 \frac{m^2 \cdot {}^0C}{W}$$

$$R_i = \frac{\delta_i}{\lambda_i} \qquad (3.3.1.3)$$

$$R_1 = \frac{0,012}{0,93} = 0,01 \frac{m^2 \cdot {}^0C}{W}$$

$$R_2 = \frac{0,15}{0,15} = 1,0 \frac{m^2 \cdot {}^0C}{W}$$

$$R_3 = \frac{0,1}{0,036} = 2,8 \frac{m^2 \cdot {}^0C}{W}$$

$$R_4 = \frac{0,001}{0,27} = 0,004 \frac{m^2 \cdot {}^0C}{W}$$

$$R_{i,j} = R_i - (A_j \cdot 100) \cdot R_j \qquad (3.2.1.4)$$

$$R_{i,j} = 3{,}1 - (0{,}00072 \cdot 100) \cdot 0{,}0096 = 2{,}79 \ \frac{m^2 \cdot {}^0C}{W}$$

Influence of metal elements on thermal resistance of the layers is not so much, so it's not necessary to calculate it.

$$R_T = R_{si} + R_1 + R_2 + ... + R_n + R_{se} \tag{3.3.1.5}$$

$$R_T = 0{,}16 + 0{,}01 + 1{,}0 + 2{,}8 + 0{,}004 = 4{,}07 \ \frac{m^2 \cdot {}^0C}{W}$$

$R_T \geq R_{req}$

$$4{,}07 >> 3{,}23 \ \frac{m^2 \cdot {}^0C}{W}$$

The thermal resistance of building envelope with such thermal insulation material as *Knauf Therm Facade* is to much, so, the sickness of the thermal insulation material layer can be decrease to the less manufacturing size $\delta = 80$ mm.

$$R_3 = \frac{0{,}08}{0{,}036} = 2{,}2 \ \frac{m^2 \cdot {}^0C}{W}$$

$$R_T = 0{,}16 + 0{,}01 + 1{,}0 + 2{,}2 + 0{,}004 = 3{,}37 \ \frac{m^2 \cdot {}^0C}{W}$$

$$3{,}37 > 3{,}23 \ \frac{m^2 \cdot {}^0C}{W}$$

$$\Delta t_0 = \frac{n \cdot (t_{int} - t_{ext})}{R_T \cdot \alpha_{int}} \tag{3.3.2.1}$$

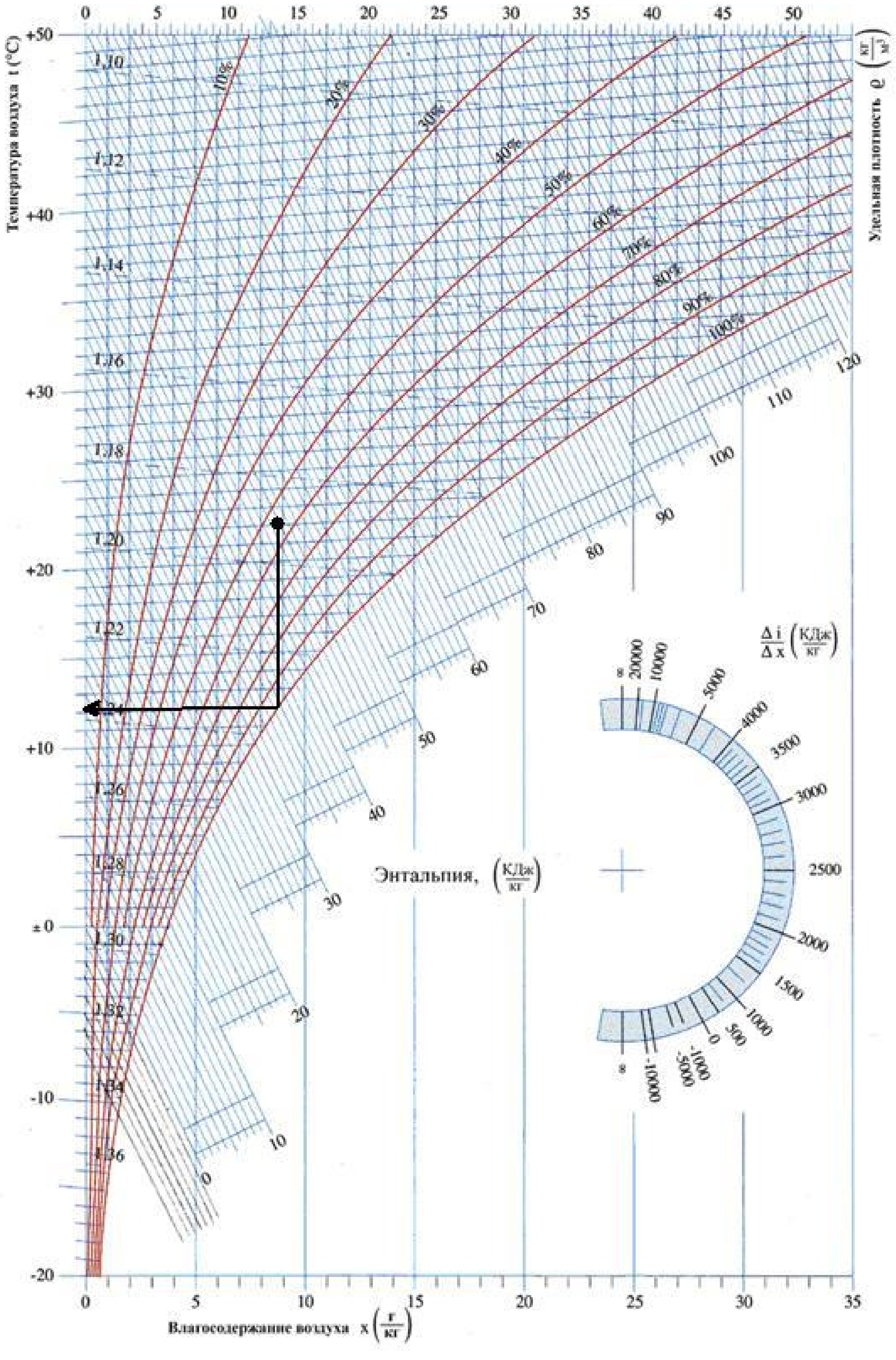
$$\Delta t_0 = \frac{1 \cdot (22 - (-26))}{3{,}37 \cdot 8{,}7} = 1{,}6$$

$\Delta t_0 \leq \Delta t_n$

$1{,}6 < 4{,}0\ {}^0C$

$$t_{si} = t_{int} - \Delta t_0 \tag{3.3.3.1}$$

$$t_{si} = 22 - 1{,}6 = 20{,}4\ {}^0C$$



Picture 1. The Mollier psychrometric chart.

$20{,}4 \geq 12{,}5\ ^0C$

Table 2. Air tightness properties of the materials of the building envelope

№	Name of the material	Thickness of the layer δ, m	Density ρ, $\frac{kg}{m^3}$	Air tightness R^{des}, $\frac{m^2 \cdot h \cdot Pa}{kg}$
1	Cement-sand plaster	0,012	1800	373
2	Blocks of aerated concrete	0,15	400	21
3	Thermal insulation material. *KNAUFPENOPLAST Knauf Therm Facade*	0,08	30	79 /6, t.17/
4	Air barrier TYVEC	0,001	600	10
				Σ 483

$$\gamma_{ext} = \frac{3463}{273 + t_{ext}}$$
$$\gamma_{\text{int}} = \frac{3463}{273 + t_{\text{int}}} \qquad (3.3.4.1)$$

$$\gamma_{ext} = \frac{3463}{273 + (-26)} = 14,0 \frac{N}{m^3}$$

$$\gamma_{\text{int}} = \frac{3463}{273 + 22} = 11,7 \frac{N}{m^3}$$

$$\Delta p = 0,55 \cdot H \cdot (\gamma_{ext} - \gamma_{\text{int}}) + 0,03 \cdot \gamma_{ext} \cdot V^2 \qquad (3.3.4.2)$$

$$\Delta p = 0,55 \cdot 50 \cdot (14,0 - 11,7) + 0,03 \cdot 14,0 \cdot 5,5^2 = 75,9 \text{ Pa.}$$

$$R^{req} = \frac{\Delta p}{G_n} \qquad (3.3.4.1)$$

$$R^{req} = \frac{75,9}{0,5} = 151,8 \frac{m^2 \cdot h \cdot Pa}{kg}$$

$R_{des} \geq R_{req}$

$483 > 151,8 \ \frac{m^2 \cdot h \cdot Pa}{kg}$

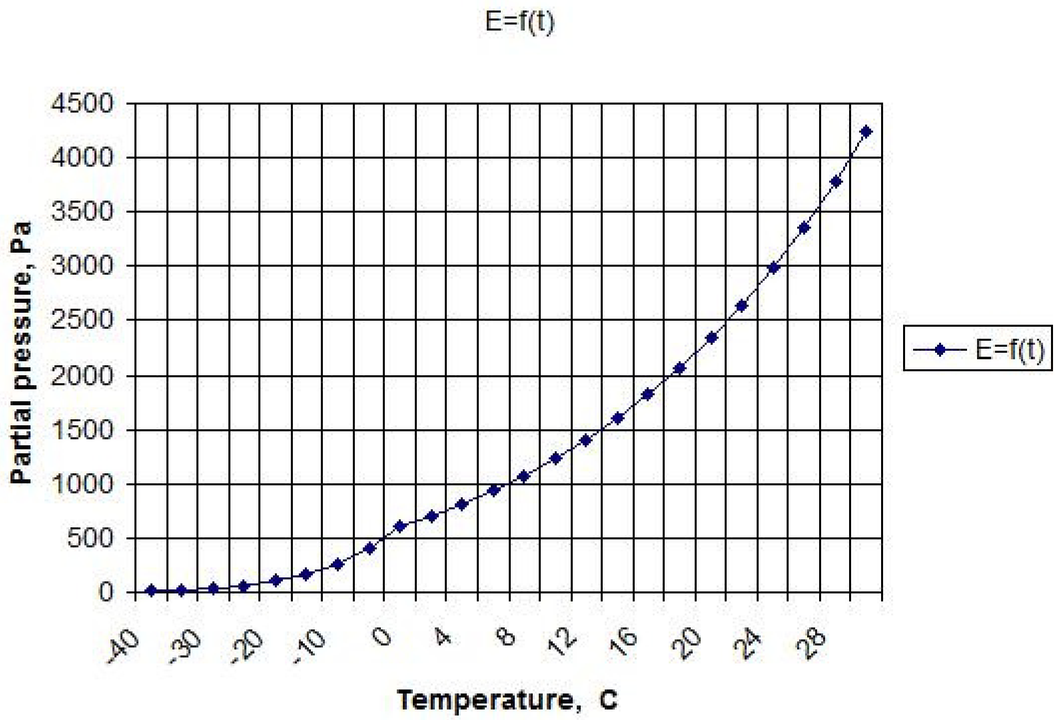
$$e_{\text{int}} = \frac{\varphi_{\text{int}}}{100} \cdot E_{\text{int}}$$
$$e_{ext} = \frac{\varphi_{ext}}{100} \cdot E_{ext} \qquad (3.3.5.1)$$

$$e_{int} = \frac{55}{100} \cdot 2500 = 1375 Pa$$

$$e_{ext} = \frac{86}{100} \cdot 300 = 258 Pa$$

Table 3. Dependence between maximum value of the partial pressure of the water vapor and temperature of the air

t, ^oC	E, Pa	t, ^oC	E, Pa	t, ^oC	E, Pa	t, ^oC	E, Pa
-40,0	12,40	-10,0	260,0	8,0	1073	20,0	2338
-35,0	22,26	-5,0	401,3	10,0	1228	22,0	2644
-30,0	37,33	0,0	610,6	12,0	1403	24,0	2984
-25,0	62,66	2,0	705,3	14,0	1599	26,0	3361
-20,0	102,7	4,0	813,3	16,0	1817	28,0	3780
-15,0	165,3	6,0	934,6	18,0	2064	30,0	4242



Picture 2. Dependence between partial pressure of the water vapor and temperature.

$$\tau_i = t_{int} - \frac{(t_{int} - t_i) \cdot (R_{si} + R_i)}{R_T} \qquad (3.3.5.2)$$

$$\tau_{int-1} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 0)}{3,37} = 21,9\,^0\text{C}$$

$$\tau_{1-2} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 0,01)}{3,37} = 20,9\,^0\text{C}$$

$$\tau_{2-3} = 22 - \frac{(22 - (-6,1)) \cdot (0,11 + 1,01)}{3,37} = 12,6\,^0\text{C}$$

$$\tau_{3-4} = 22 - \frac{(22-(-6,1)) \cdot (0,11+3,21)}{3,37} = -5,7\ ^0\text{C}$$

$$\tau_{4-ext} = 22 - \frac{(22-(-6,1)) \cdot (0,11+3,36)}{3,37} = -6,1\ ^0\text{C}$$

$$\Omega_i = \frac{\delta}{\mu} \tag{3.3.5.3}$$

$$\Omega_1 = \frac{0,012}{0,09} = 0,1\ \frac{m^2 \cdot h \cdot Pa}{kg}$$

$$\Omega_2 = \frac{0,15}{0,23} = 0,7\ \frac{m^2 \cdot h \cdot Pa}{kg}$$

$$\Omega_3 = \frac{0,08}{0,05} = 1,6\ \frac{m^2 \cdot h \cdot Pa}{kg}$$

$$\Omega_4 = \frac{0,001}{0,01} = 0,1\ \frac{m^2 \cdot h \cdot Pa}{kg}$$

$$\Omega_T = \Omega_{\text{int}} + \Omega_1 + \Omega_2 + \ldots + \Omega_n + \Omega_{ext} \tag{3.3.5.4}$$

$$\Omega_T = 0,0266 + 0,1 + 0,7 + 1,6 + 0,1 + 0,0133 = 2,54\ \frac{m^2 \cdot h \cdot Pa}{kg}$$

$$e_i = e_{\text{int}} - \frac{(e_{\text{int}} - e_{ext}) \cdot (\Omega_{\text{int}} + \Sigma\Omega_i)}{\Omega_T} \tag{3.3.5.4}$$

$$e_{\text{int}-1} = 1375 - \frac{(1375-258) \cdot (0,0266+0)}{2,54} = 1362\ \text{Pa}$$

$$e_{1-2} = 1375 - \frac{(1375-258) \cdot (0,0266+0,1)}{2,54} = 1317\ \text{Pa}$$

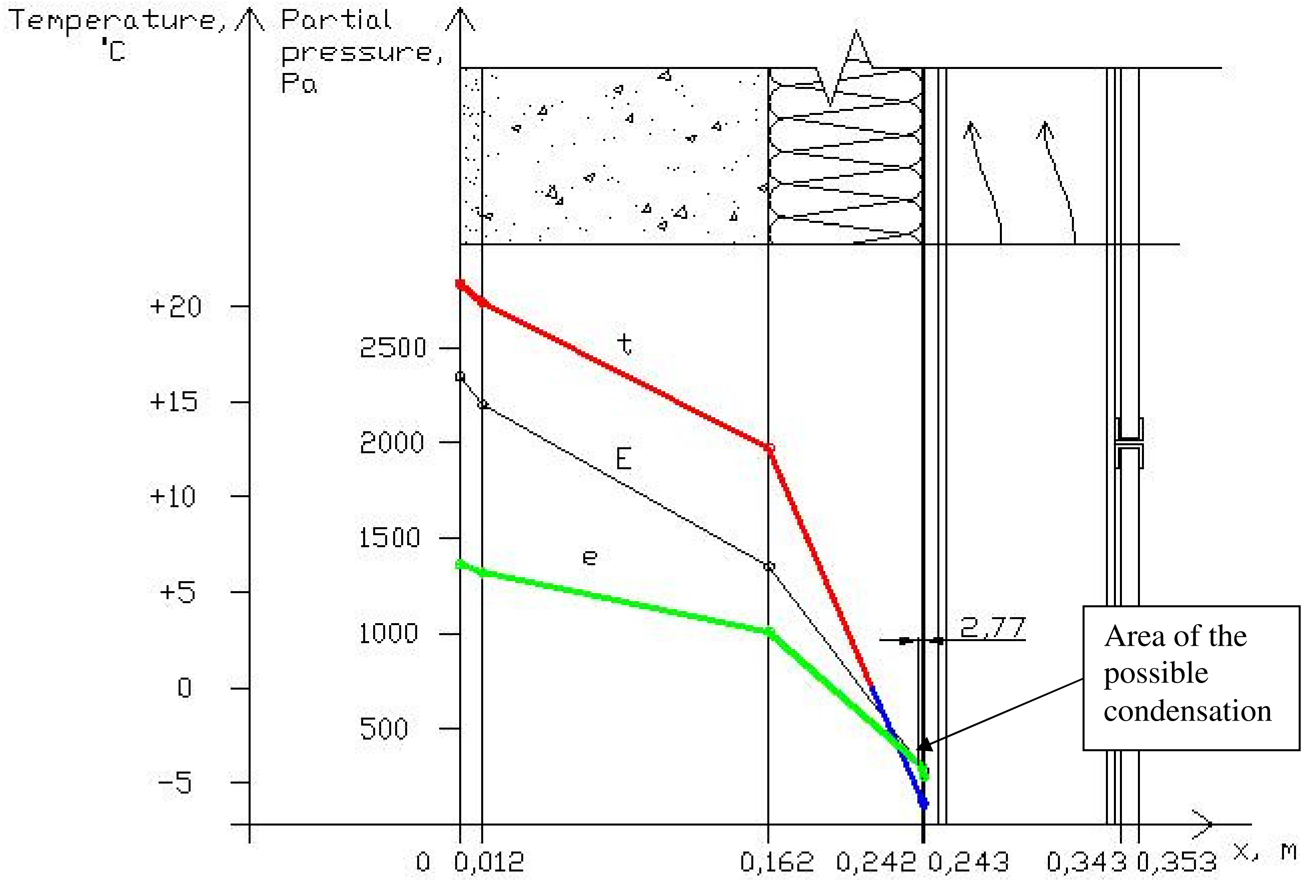
$$e_{2-3} = 1375 - \frac{(1375-258) \cdot (0,0266+0,8)}{2,54} = 1009\ \text{Pa}$$

$$e_{3-4} = 1375 - \frac{(1375-258) \cdot (0,0266+2,41)}{2,54} = 302\ \text{Pa}$$

$$e_{4-ext} = 1375 - \frac{(1375-258) \cdot (0,0266+2,51)}{2,54} = 258\ \text{Pa}$$

Table 4. Results, of the possibility of the condensation of the water vapor in a building envelope

Border of the layers	x, m	ΣR_i, $\frac{m^2 \cdot {}^0 C}{W}$	τ_i, ℃	E, Pa	$\Sigma \Omega_i$, $\frac{m^2 \cdot h \cdot Pa}{kg}$	e_i, Pa
int-1	0,0	0,0	21,2	2350	0	1362
1-2	0,012	0,01	20,2	2200	0,1	1317
2-3	0,162	1,01	12,6	1350	0,8	1009
3-4	0,242	3,21	-5,9	300	2,41	302
4-ext	0,243	3,26	-6,1	280	2,51	258



Picture 3. Determining of the area of the possible condensation and freezing of the water vapor in building envelope.