THERMAL AND HYDROTHERMAL INVESTIGATIONS OF THE EXTERNAL WALLS OF MODERN APARTMENT HOUSES IN SAINT-PETERSBURG

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ABSTRACT

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Thermal and hydrothermal investigations of the external walls of modern apartment houses in Saint-Petersburg, 120 pages, 6 appendixes.

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The purpose of this work was to investigate properties of modern multi-layered external walls implemented in modern multi-storey apartment houses in Saint-Petersburg (Russia). Long cold winters prevail in northern regions of Russia. Good thermal and hydrothermal properties of the building mantle help to achieve high energy efficiency of buildings and to decrease energy consumption by heating system. Therefore, construction of modern widespread types of external walls must be thoroughly investigated. The study projects observed in this work are multi-storey houses of residential complexes Swedish Krona and Ȯland erected by NCC Housing in Saint-Petersburg. Multi-layered walls are used in Swedish Krona project, whereas houses of Ȯland project have concrete sandwich panel walls. These types of external walls are both used in Russian multi-storey housing. In Finland panel walling is widespread. Therefore, comparison of multi-layered walls and panel walls was executed in this work. Thermal properties of the studied wall structures were calculated according to Finnish and Russian norms. Hydrothermal properties were investigated with the help of computer programs. Some construction specialities of the studied wall structures were described. The conclusion about expediency of using multi-layered walls in multi-storey housing in Finland was made.

Keywords: external walls, multi-layered walls, panel walls, energy efficiency

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1. INTRODUCTION

House construction includes a lot of stages, which should satisfy many demands stated by government norms. These demands concern the designing stage as well as the process of building mounting. Along with critical demands to the safety of the structure energy efficiency requirements are very important. Energy consumption of the building must be as low as possible. In northern regions of Russia and in Finland where long winters prevail, system of air heating consume a lot of energy to maintain required internal climate conditions. Saint-Petersburg (Russia) is the northest megalopolis in the world. The period of air heating system functioning is about seven months in a year (220 days). Chart 1 shows fluctuations of the month average temperatures, average relative humidity of the external air and heating period. Its duration is more than half a year.
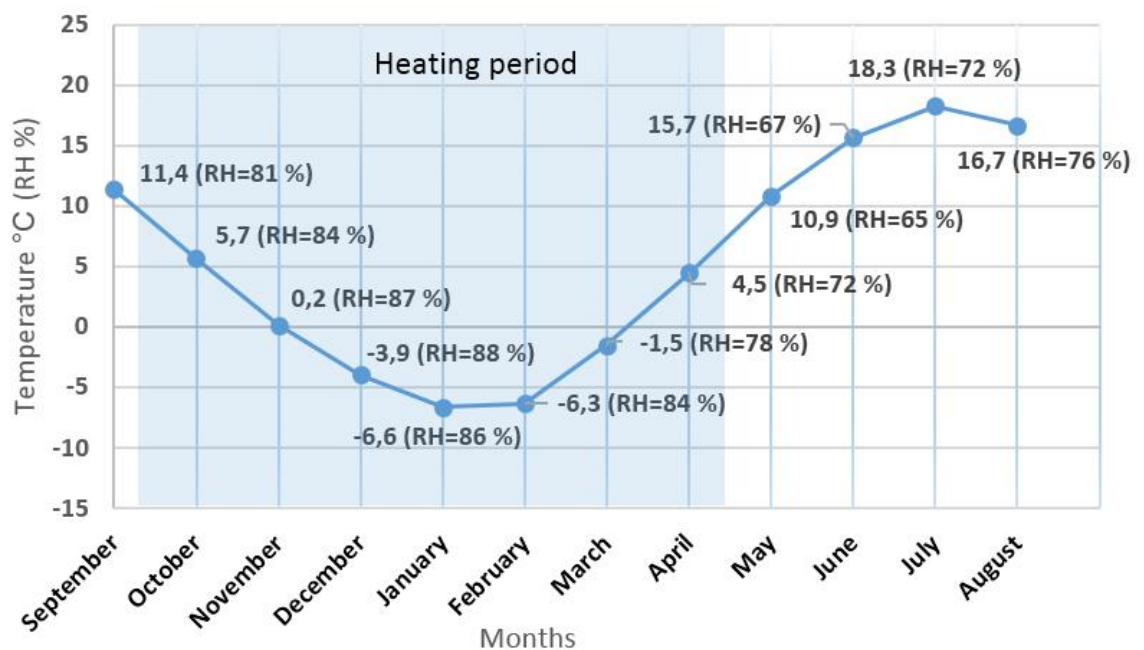

Chart 1. Distribution of average month temperatures and relative humidity in Saint-Petersburg.

Chart 2 shows distribution of the average month wind speeds during a year. The fastest wind speeds are in the months that belong to the heating period.
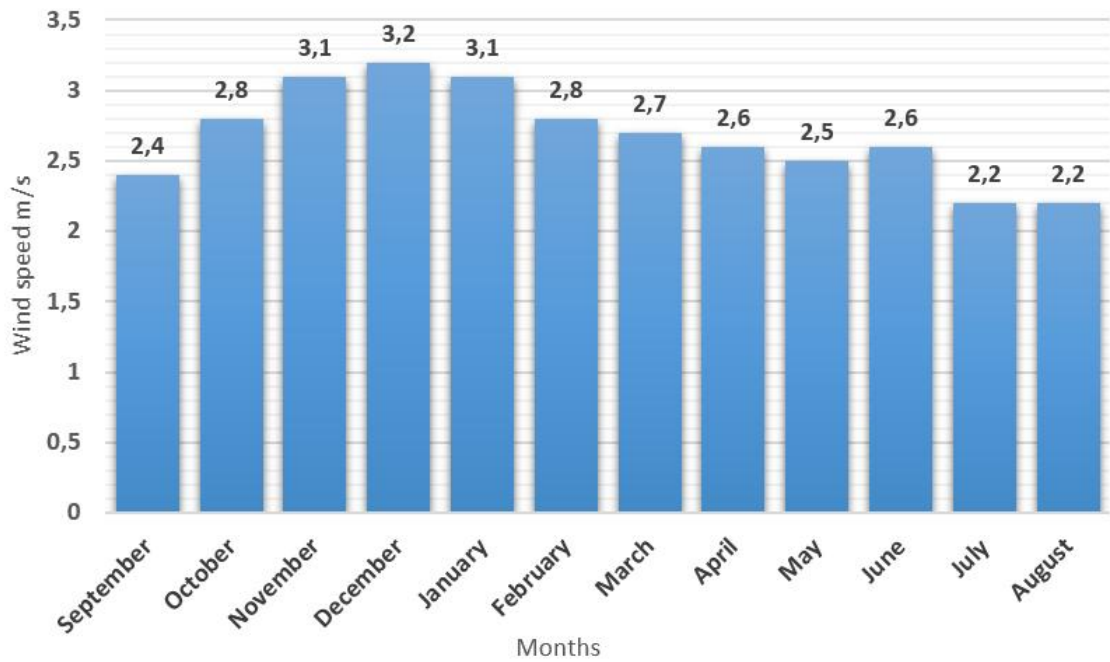
Chart 2. Distribution of average month wind speeds in Saint-Petersburg.

Design climatic conditions of the cold period of the year are presented in table 1.

Table 1. Design climatic conditions of the cold period of the year.

Design external temperature (°C)	-26
Average external temperature (°C)	-1,8
Relative humidity (%)	86
Wind speed (m/s)	4,2
Average fluctuation of the temperature during twenty-four hours period (°C)	5,3
Amount of precipitations (mm)	202

To decrease the heating energy consumption of the building modern energy lowering measures should be implemented. However, some of these measures can seriously increase initial investments to the project. As a result, the price of the house or apartments in a multi-storey house can be increased for a client. This circumstance may negatively influence the payback of the project. Apart

from technical aspects of the construction process demands of the market should be taken into account to improve the payback of the project. The developer should take into account preferences of the potential client. Such factors as apartment layout, location of the building, developed infrastructure, quality of construction and finishing strongly influence on the potential client and increase sales. Also the exterior and architecture of the building have strong influence on the target client's impression and should always correspond his expectance.

Such part of the building structure as exterior walls influences all factors listed above. The load bearing capacity and quality of the bearing parts of the external wall structure determine the safety of the building. Outer walls are the part of the building mantle, which consists of different elements separating the interior of the building from the outside atmosphere and its exterior surroundings. All parts of the building mantle (outer walls, roof, base-floor, windows and doors) protect interior from low temperatures and other weather impacts (3). Heat losses through external walls take a great part among all losses through other parts of the building mantle (Fig.1)
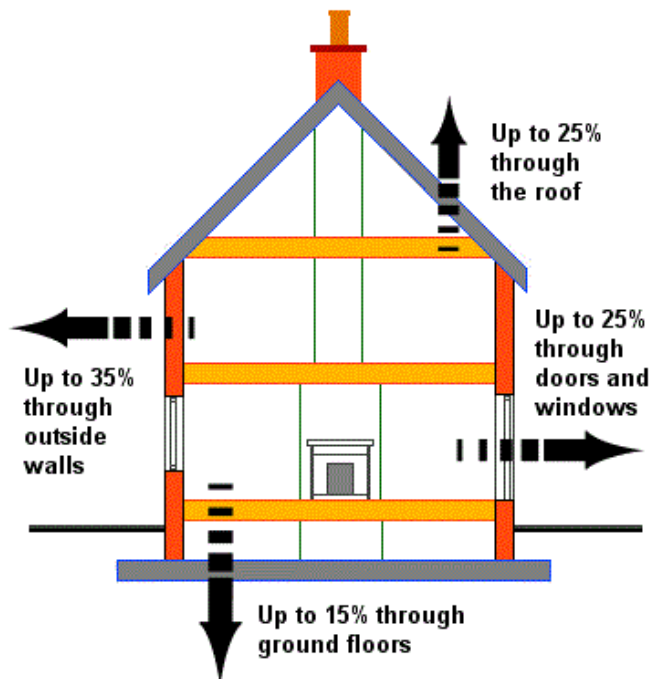

Figure 1. Heat losses through building mantle

Therefore, good thermal resistance and physical characteristics of the external walls help to decrease total heat losses and increase energy efficiency of the whole building. Often the type of the external wall determines architecture and the exterior design of the building. There are many different types of external walls. For multi-storey houses concrete panel walls and curtain walls are the most commonly used as long as they provide sufficient load-bearing capacity (1).

Not long ago some Finnish and Swedish construction companies such as YIT and NCC have started their projects in Saint-Petersburg. These companies faced the fact that Russian consumers prefer to live in multi-storey houses with curtain walls. This circumstance is connected with the fact that "panel" houses with concrete panel outer walls are associated with the common type of Soviet Union "mass" housing. Those houses are not comfortable and do not satisfy modern thermal resistance demands. Also, after several years of exploitation become they bad-looking. (Fig.2)

Figure 2.Typical old "panel" houses in Russia

New apartment buildings are erected in all parts of Saint-Petersburg. However, height of the buildings in central part of the city is strictly limited according to architectural planning. In remote districts of the Saint-Petersburg where apartment housing prevails construction of high buildings is not restricted. Figure 3 shows the map of the buildings height in Saint-Petersburg.

● < 15 meters ≈ 5 floors and less   ● 28-36 meters ≈ 10-12 floors   ● 52-63 meters ≈ 18-21 floors
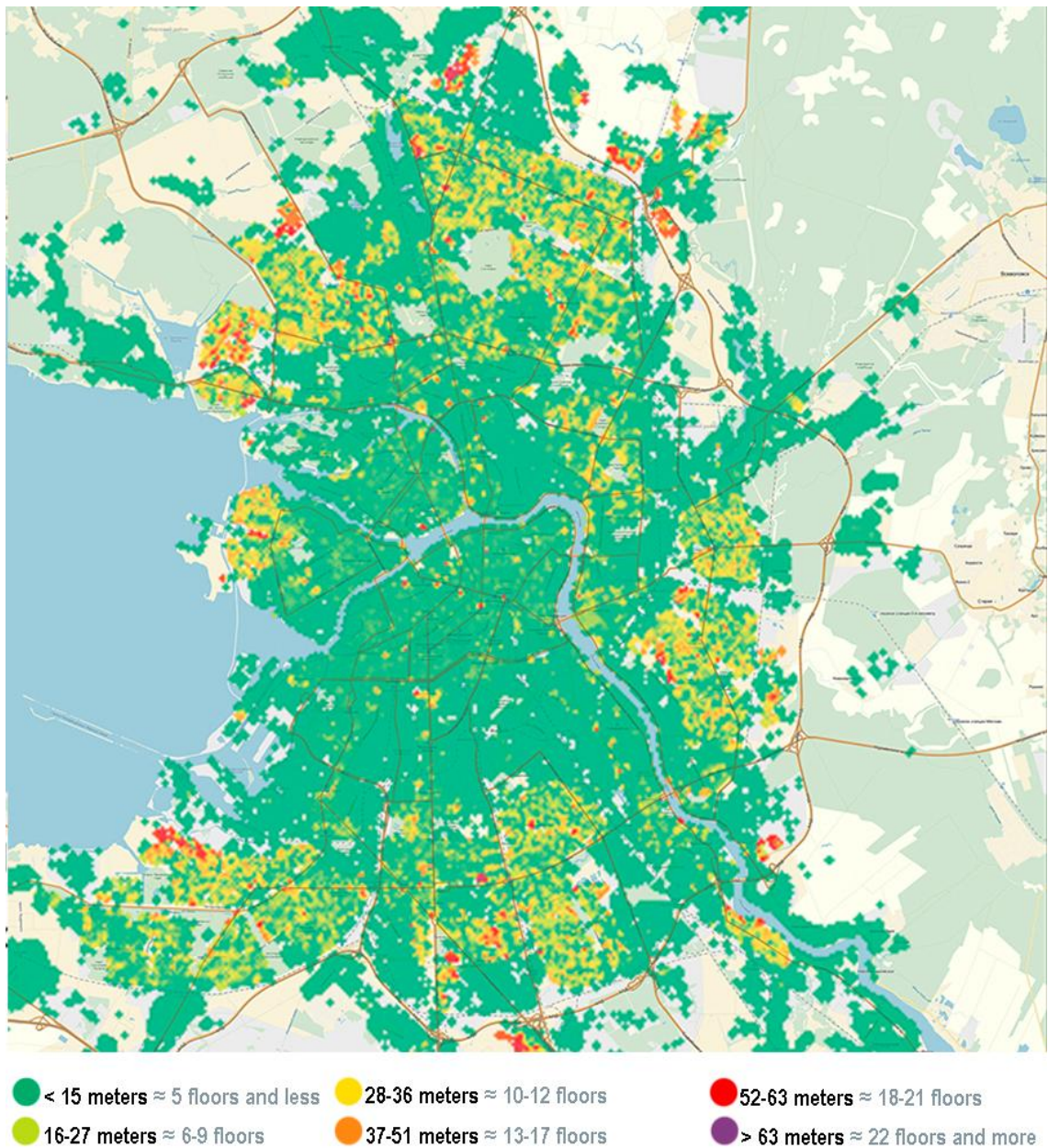● 16-27 meters ≈ 6-9 floors   ● 37-51 meters ≈ 13-17 floors   ● > 63 meters ≈ 22 floors and more

Figure 3. Map of the buildings height in Saint-Petersburg

The height of the modern multi-storey houses in Saint-Petersburg reaches up to 20-30 stories and houses with curtain walls are widely spread among them.

Using of the cast-in situ concrete frame elements for such type of buildings allows making houses of different shapes. Each house is architecturally unique (Fig 4).
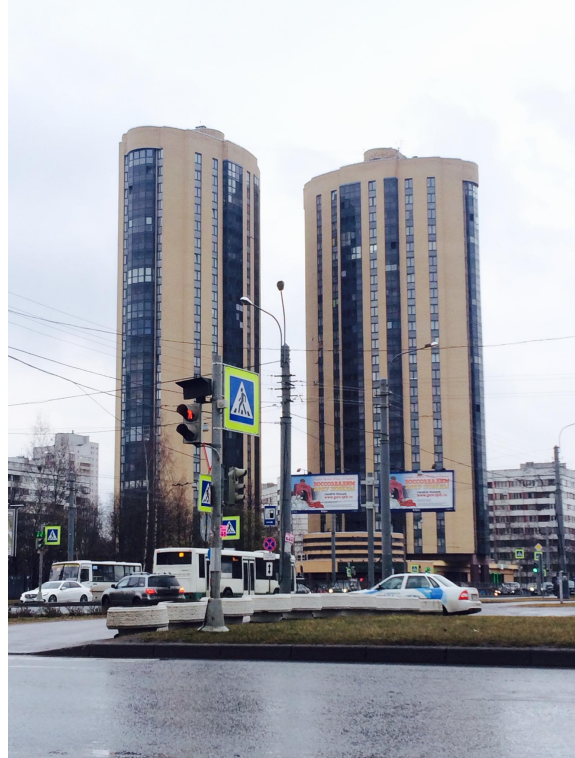

Figure 4. Modern houses in Saint-Petersburg

The most popular type of multi-layered walls has an external layer made of the façade brick. Using of the façade brick in such structures creates the illusion of "brick building". This illusion helps to attract customers and therefore to increase sales (2).

In Finland multi-layered external walls with façade brick are not common for multi-storey houses. Concrete panels with the layer of thermal insulation are mostly used for such type of residential buildings. Using the prefabricated elements helps to decrease the cost of construction but does not allow making architecturally expressive and unique buildings (Fig 5).

Figure 5. Old panel houses in Finland. Imatra, Kouvola.

In Finland residential buildings should satisfy many requirements to energy and economic efficiency. Finnish climate performs long winters with low temperatures as well. However, energy consumption for heating must be minimized (3). Regulations limiting the energy consumption by buildings in Finland are stricter than in Russia. State construction rules (SNiP) 23-02-2003 "Thermal performance of the buildings" determine reference thermal resistance

of the building mantle and limit of the building energy consumption within its energy class. In Finland the main document is D3 Code of Building Regulations "Energy Efficiency of Buildings Regulations and Guidelines 2010" which determines demands to energy efficiency that must be satisfied in modern residential buildings. The main part of the D3 Code demands concern thermal resistance characteristics of the building mantle, air tightness of the building envelope and heat recovery of the ventilation system of the building (3). As long as outer walls are the major part of the building mantle, they should demonstrate very good thermal resistance characteristics. In Finland potential using of the multi-layered curtain walls with façade brick for multi-stored houses instead of the concrete panels is possible if this type of walls satisfy Eurocodes and Finnish norms requirements. External walls must be reliable and durable.

In this work comparison of the concrete panel and multi-layered external walls is made to present benefits of using multi-layered external walls in residential buildings. Two different residential building projects of NCC in Saint-Petersburg are studied. In these projects different types of wall structures are used. Physical and thermal resistance characteristics of concrete panel and multi-layered walls with façade brick are analysed according to Russian and Finnish norms with the help of computer program calculations. Typical problems and specific characteristics of the mounting process of the multi-layered walls with façade brick are described. The conclusion about expediency of using multi-layered walls with façade brick in Finland is made.

2. DESCRIPTION OF THE WORKING PROJECTS

Swedish construction company NCC started its work in Saint-Petersburg in 2008 as both a developer and a contractor. The main working field of NCC is a construction of the multi-stored residential houses. Its first projects are Swedish Krona and Öland. Both these projects are a complex of block of flats with kindergarten and parking. (Fig. 6)

Figure 6. Swedish Krona (top) and Ȯland (bottom) projects

NCC separated these projects in different classes according internal classification system. Swedish Krona is a project of B class and Ȯland is a project of C class. Generally B class buildings are located in a prestigious district of the city, flats in the buildings have big rooms, in the whole complex intelligent ground environment is installed, the complex has underground parking. C class is a "mass" class which means smaller and cheaper flats and the location of the complex in the remote district of the city. Many design decisions aim to reduce the cost of the building. Therefore, in Ȯland project concrete panels are used whereas in Swedish Krona project multi-layered walls with façade brick are used. Using concrete panels in Ȯland helps to reduce cost of construction and using multi-layered walls with façade brick in Swedish Krona helps to attract customers. The wall types are illustrated below (Fig. 7)
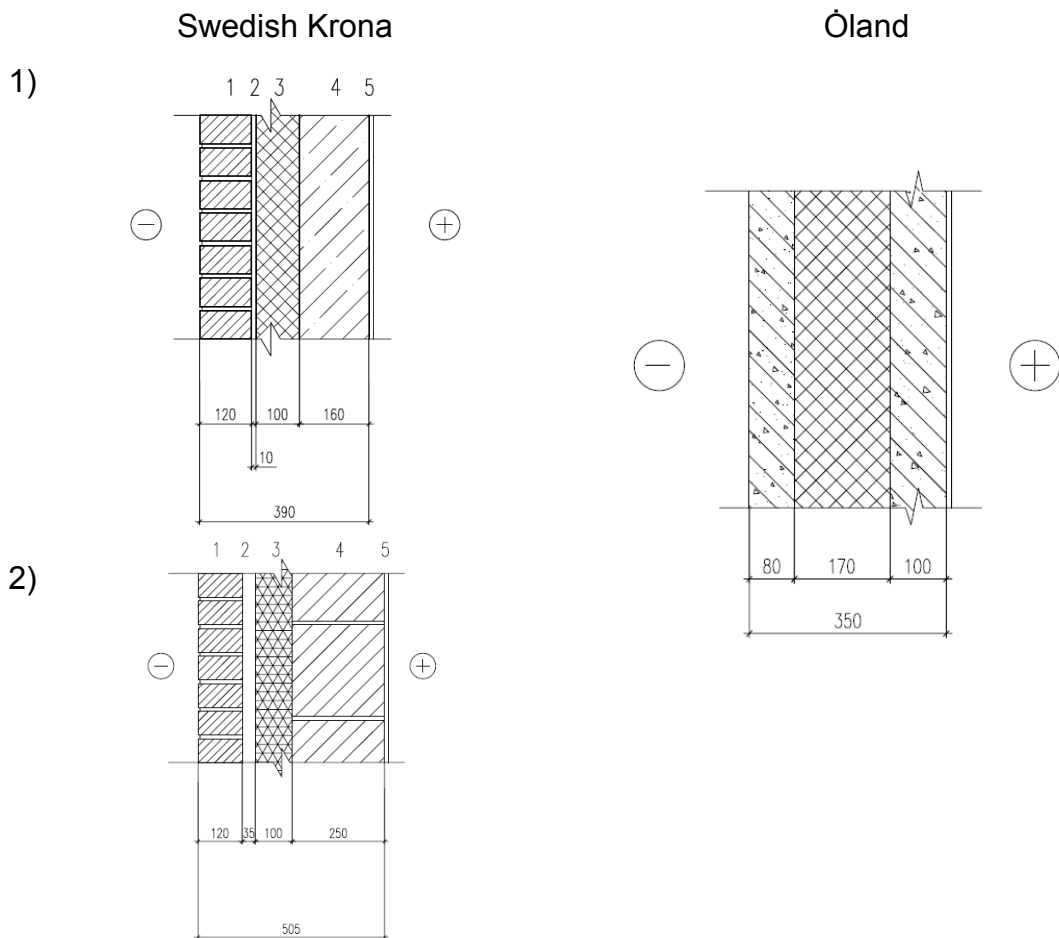
Swedish Krona   Ôland

1)

2)

Figure 7. Wall types of Swedish Krona and Ôland projects

Two types of multilayered external made in situ walls are used on Swedish Krona.

1) Reinforced concrete core 160 mm, XPS thermal insulation 100 mm, unventilated tolerances gap 10 mm and façade brick cladding 120 mm.

2) Lightweight concrete blocks cladding 250 mm, mineral wool insulation 100 mm, ventilated gap 35 mm, façade brick cladding 120 mm.

The first type of wall (with concrete core) is load-bearing. The second type of wall (with lightweight concrete) is a no-load bearing curtain wall. In Ôland project concrete sandwich panels consist of internal load-bearing and non-loadbearing layer of concrete 160, 120, 100 mm, EPS insulation 170 mm and external protective concrete layer 80 mm.

3. FINNISH NORMS AND DEMANDS

The main normative document in Finland, which describes demands to energy efficiency of the buildings, is D3 Code of Building Regulations of Finland "Energy Efficiency of Buildings Regulations and Guidelines 2010".

This document considers suitable room temperature, the demanded quality of the indoor air, lighting, hot service water and other services which presume energy consumption for functioning. To achieve a good level of energy efficiency of the building unnecessary use of energy and loss of energy must be limited. There are several ways to manage energy consumption of the building. (3)

One of the ways to make a building more energy efficient is to recover heating energy of the building's outgoing ventilation air and to utilize internal heat loads. For that purpose, recuperation equipment and internal heat pumps can be applied. Also external energy sources such as solar, wind energy, external air and underground water heating energy can be utilized to reduce a building's consumption of the purchased energy. For that purpose solar collectors can be applied to produce electrical energy and to heat water. Rational planning solutions of the building and windows orientation help effectively to utilize solar radiation heat and natural light. This leads to reduction of the heating system energy consumption and consumption of electrical lighting. (3)

Also automatic adjustment and control of the service systems help to avoid unnecessary energy use. To limit heating energy consumption automatic temperature regulation can be executed with the help of special thermoregulation valves set on heating devices. Also external and internal temperature sensors can be used to regulate the power of the whole heating system. Special sensors help to detect presence of people and to control the work of the lighting system. Temperature sensors and sensors of the carbon dioxide can adjust energy consumption of the ventilation system by managing air heating device and ventilators' productivity. (4)

One of the most important issues concerning improvement of the energy efficiency is a reduction of the building's heat loss. Therefore, building norms strictly limit its value. Heat loss of a building is the combined heat loss, which occurs because of *heat transfer through the building mantle, air leakage through the building envelope and via ventilation system*. D3 Code set the following reference values, which are used in the calculation of the total building's reference heat loss (3):

-value of the coefficient of the thermal transmittance of the building part,
-combined window area of the building
-annual efficiency of heat recovery from a building's outgoing air
-the air-leakage coefficient of a building

According to D3 Code the conformity to regulations regarding the heat loss of the building is demonstrated by means of an equalizing calculation. The equalizing of a building's heat losses is a calculatory procedure for fulfilling the requirements set for heat loss. The heat loss of one of the factors (building mantle, air leakage, ventilation) when it exceeds reference heat loss demands at least a corresponding reduction of some other factor's heat loss. (3) Parts C4 "Thermal insulation of the building", D2 "Indoor climate and ventilation of buildings" and D3 "Energy efficiency of buildings" presets restrictions within which the equalizing of heat losses is allowed.

1. Calculation of heat loss from the mantle of a building

The heat loss of the mantle of a building is calculated using equation:

$$\sum H_{conduct} = \sum (U_{outer\text{-}wall} \cdot A_{outer\ wall}) + \sum (U_{roof} \cdot A_{roof}) + \qquad (1)$$
$$\sum (U_{base\text{-}floor} \cdot A_{base\text{-}floor}) + \sum (U_{window} \cdot A_{window}) + \sum (U_{door} \cdot A_{door})$$

where: $\sum H_{conduct}$ – combined specific heat loss of building's parts, (W/K);

U – coefficient of thermal transmittance of a part of a building, $(W/(m^2 K))$;

A – floor area of a part of a building, (m^2).

The coefficient of thermal transmittance presented in Section 3.2 of part C3 of the National Code of Building Regulations of Finland as well as reference value of the window area are used in calculating the total reference heat loss of the building.

The design coefficient of thermal transmittance as well as window area per building part are used in calculation of the total design heat loss of a building.

2. Calculation of a building's air leakage

The heat loss of a building's air leakage is calculated using the following equation:

$$H_{air\ leakage}=\rho_i \cdot c_{pi} \cdot q_{v,air\ leakage} \qquad (2)$$

where: $H_{air\ leakage}$ – specific heat loss of air leakage, (W/K);

ρ_i – air density (1,2 (kg/m^3));

c_{pi} – specific heat capacity of air, 1000 (Ws/(kg·K));

$q_{v,\ air\ leakage}$ – flow of air leakage, (m^3/s),

The flow of air leakage $q_{v,\ air\ leakage}$ is calculated using equation:

$$q_{v,\ air\ leakage} = n_{air\ leakage} \cdot V/3600 \qquad (3)$$

where: $q_{v,\ air\ leakage}$ – flow of air leakage, (m^3/s),

$n_{air\ leakage}$ – air leakage coefficient of a building, times per hour (1/h);

V – air volume of a building (m^3);

3600 – coefficient used in perfoming quality transformation m^3/h => m^3/s, unit is s/h.

The value $n_{air\ leakage}$ = 0,8 (1/h) corresponds to air leakage value n_{50} = 2,0 (1/h). It used as the air leakage coefficient of a building in calculation the total building reference heat loss.

3. Calculation of the heat loss from ventilation

The heat loss of a building from ventilation is calculated using equation:

$$H_{iv} = \rho_i \cdot c_{pi} \cdot q_{v,exhaust} \cdot t_d \cdot r \cdot t_v \cdot (1-\eta_a) \qquad (4)$$

where: H_{iv} – specific heat loss of ventilation, (W/K),

ρ_i – air density, 1.2 (kg/m^3);

c_{pi} – specific heat capacity of air, 1000 (Ws/(kg·K));

$q_{v,exhaust}$ – flow of exhaust air, (m^3/s);

t_d – ventilation system's average diurnal running time ratio, (h/24h);

t_v – ventilation system's weekly running time ratio, days/7 days (with day=24 h);

r – reduction factor (or transformation factor) which takes into account the diurnal running time of the ventilation system; the coefficient r gets the value 1.00 in around the clock operation, the value 0.93 in day-time operation, and the value 1.07 in night-time operation;

η_a – the annual efficiency rate of the heat recovery of the ventilation system. It is the ratio of the energy which is recovered per year by means of heat recovery equipment and the energy that is made use of as compared to the energy required by the heating of the supplied air when there is no heat recovery.

The same flows of air are used in calculation of the reference heat loss and design heat loss. The value 50% is used as the annual efficiency rate of heat recovery of ventilation system in calculation of the reference heat loss.

As determined, heat loss from a mantle takes a great part of the overall heat loss of a building. Therefore, insulation ability of building envelope structures is very important. In the multistory houses, external walls make up the biggest part of the building envelope. Low coefficient of thermal transmittance of the external wall $U_{outer-wall}$ leads to lower heat loss from a mantle of a building and therefore to higher energy efficiency of a building. According to D3 and C3 Codes of Finland reference value of the thermal transmittance of the external wall $U_{outer-wall}$=0,17 (W/(m2·K)).

Calculation procedure of the design value of thermal transmittance of the building's elements is presented in SFS-EN ISO 6946 "Building components

and building elements. Thermal resistance and thermal transmittance. Calculation method". Hydrothermal properties of materials used in building elements are determined using calculation methods and tabulated information presented in SFS-EN ISO 10456 "Building materials and products-Hydrothermal properties-Tabulated design values and procedures for determining declared and design thermal values". Regulations determine the calculatory procedure where heat loss from building mantle depends on U-value of the components composing it. However, U-value of the component can be changed influenced by physical processes such as moistening. U-value of the component depends on the thermal (heat) conductivity of the materials composing it, according to following equations:

$$U = \frac{1}{R} \tag{5}$$

$$R = R_{si} + \Sigma R_i + R_{se} \tag{6}$$

$$R_i = \frac{d_i}{\lambda} \tag{7}$$

where: R – thermal resistance of the building component (m$^2\cdot$K/W);

R_{si} – the internal surface resistance (m$^2\cdot$K/W);

R_i – the design thermal resistance of each layer composing building element (m$^2\cdot$K/W);

R_{se} – the external surface resistance (m$^2\cdot$K/W);

d_i – thickness of the material layer in the component (m);

λ_i – thermal conductivity of the material (W/(m$\cdot$°C));

Whereas, thermal (heat) conductivity depends on moisture content in the material. Increase of moisture leads to the growth of the thermal conductivity value and U-value, which leads to deterioration of the thermal insulation properties of construction. Figure 8 shows the increase of the heat conductivity value of different insulation materials as dependent on their moisture content (5)
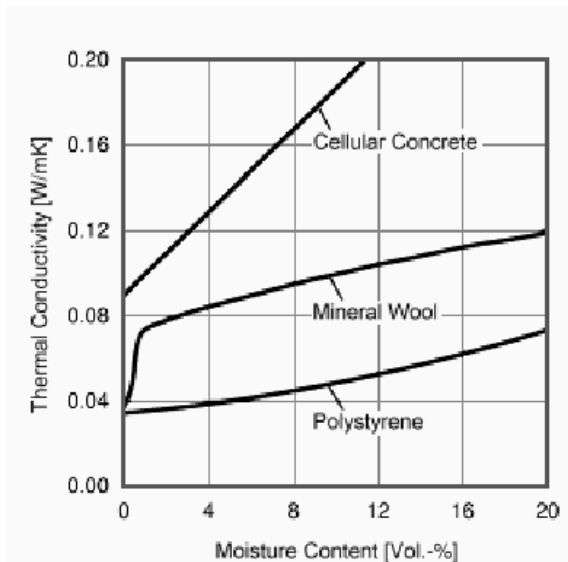
Figure 8. The effect of the moisture on the measured thermal conductivity ofbuilding materials

Other effects of moistening on building components are mold or algae growth, swelling and shrinking caused by salt crystallization or humidity changes, damages caused by frost, corrosion or rotting, etc.

One of the most significant problems in moisture accumulation in materials of the wall structure. During the winter season in cold regions the moisture content of the air within building is considerably higher than that of the outdoor air. As a result, moisture permeates into walls and becomes absorbed within the wall materials. A significant accumulation of moisture within these materials may have a negative effect on their durability and insulating properties (6).

In some cases there exists the risk of a dew point within the wall structure. It occurs under curtain external and internal climate conditions (usually in cold period of the year). Practically, condensation happens when temperature in some point of the wall structure is equal of lower than dew point temperature. Or, equally, when partial pressure of the water vapor in some point of the wall structure reaches the value of the partial pressure of the saturated water vapor. Prolonged exposure to the conditions that result in a dew point inside wall structure (especially in soft material of the insulation) will lead to accumulation of moisture. Too much accumulation for too long a duration could eventually

increase U-value of the wall structure and damage the surrounding wall components.

Exterior conditions exposing the building construction are air temperature, precipitations, relative humidity and solar radiation. Interior climate conditions influence are presented by values of the indoor temperature and relative humidity, which fluctuate during year period. (7)

Processes of vapor diffusion, surface diffusion and capillary conduction are predominant in description of moisture transport mechanism in porous building materials. The combined effect of these processes is illustrated in figure 9. (7)
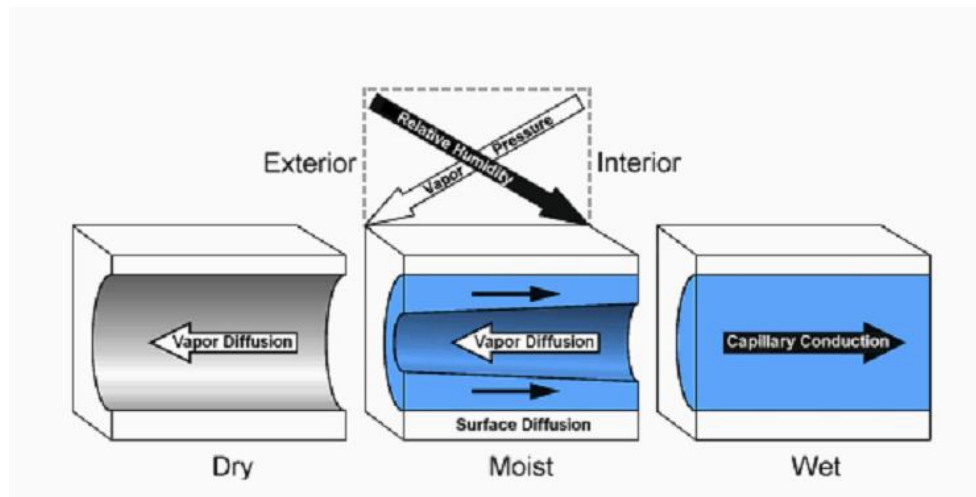

Figure 9. Moisture transport phenomena in the pores of a massive exterior wall in winter, for different levels of moisture content

The moisture transport phenomena in porous materials is illustrated with the help of building material cylindrical capillary. Boundary conditions presume excess of vapor pressure on the interior surface compared to vapor pressure on exterior surface and oppositely relative humidity is higher on exterior surface. This presumption corresponds well to real conditions. (7)

If building material is sufficiently dry, then diffusion of the water vapor takes place in direction from interior surface to interior surface. The direction of the vapor diffusion is explained by the difference of vapor pressure on surfaces.

Under conditions of relative humidity ca. 60% sorption film on the walls of the pore becomes mobile. The direction of the moisture transport in this film follows the direction of the relative humidity digression, i.e. moisture flows in direction from exterior surface to interior surface. If capillary is filled with moisture then the force of capillary conduction determines the direction of the moisture transport. In phenomena of capillary conduction the capillary tension (tension of the water surface is meniscus) is a driving force for moisture movement. As long as capillary tension is functionally related to equilibrium humidity of the air under the meniscus, the relative humidity can be used as a condition for moisture transport description in case of capillary conduction. Thus, relative humidity and vapor pressure can be used as driving potentials for the moisture transport process in a building material. (8)

Standard EN ISO 13788 "Hygrothermal performance of building components and building elements — Internal surface temperature to avoid critical surface humidity and interstitial condensation — Calculation methods" describes the simplified moisture calculation methods. It uses monthly climate data and assumes vapor diffusion as the only moisture transport process inside the building component. The standard gives the calculation method for determining temperature of the internal surface, which is critical for mould growth under given conditions of internal relative humidity and temperature. Also the standard gives the calculation method for determining the possibility and position of interstitial vapor condensation within the building component. It deals both with heating and cooling periods. Moreover, the standard gives calculation method to determine the time required for drying out the condensed vapor within the building material and the risk of the vapor condensation in other parts of the component during this period. Unfortunately, calculation methods presented in the standard do not take into account changes of the building materials physical properties caused by moistening process. Also liquid moisture transfer and capillary suction, hydroscopic properties of materials are not taken in account. (9)

There are several programs, which help to calculate steady-state models to determine the risk of dew point within the building construction. For example,

DofTherm program uses the database of internal and external conditions and physical properties of different building materials to build up monthly humidity and temperature curves. However, it consider only vapor diffusion as a moisture transport within the material and temperature and humidity as exposing conditions. To assess a more real moistening situation (moisture accumulation and changes of thermal insulation properties of the component due to moistening) non steady-state models should be applied. Changes of the building material's physical properties caused by moistening process, surface diffusion and capillary conduction processes and hydroscopic properties of materials should be taken into account. In addition, such external conditions as precipitations and solar radiation should be taken in an account as well. Such non steady-state models are simulated with the help of computer programs such as WUFI. (7)

Calculation procedure of the building element thermal resistance value according SFS-EN ISO 6946 is presented in Appendix 1. U-value calculations of the studied wall structures are presented in Appendix 3. Calculation of the dew point possibility in the wall structures and temperature of the internal surface are executed in DofTherm program with the help of steady-state model. Results of calculation are presented in Appendix 4. Calculation of the moisture situation using non-steady model is executed in Wufi program. The results of calculation are presented in Appendix 5.

4. RUSSIAN NORMS AND DEMANDS

Generally, there are several norms in Russia, which determine demands to physical and thermal resistance characteristics of outer walls. These norms have a lot of equal and never incompatible information. State construction norms and rules (SNiP) 23-02-2003 "Thermal performance of the buildings" mostly give general information about demanded values of thermal resistance, general demands to outer walls. State construction rules (SP) 23-101-2004 "Design of thermal performance of the buildings" mostly describe calculation methods, GOST 30434 "Residential and Public Buildings. Indoor climate

parameters" and SNiP 23-01-99 "Construction climatology" give information about the demanded indoor and external climate parameters respectively. SNiP II-3-79* "Construction thermotechnics" gives information about the physical characteristics of different construction materials.

According to Russian norms characteristics of the indoor climate must be kept on certain level. Energy consumption must be minimized. These demands can be satisfied by designing good thermal protection (performance) of the buildings. Thermal performance of the building depends on the good level of the thermal resistance of the outer walls, their physical characteristics, reliability and durability of the outer walls. To increase thermal resistance of the outer walls effective insulation must be used in the wall structure. Water should not condensate inside the soft material of the thermal insulation. Layers must be designed in the correct sequence between cold and warm surfaces of the wall structure. (10)

According to Russian norms the design thermal resistance coefficient R_0 ($m^2 \cdot °C/W$) of the external walls should not be lower than the demanded value R_{req}. This value depends on the purpose of the building and climate parameters of the region. Moreover external walls have to satisfy several demands such as:

1) Difference between the temperature of indoor air of the building and internal surface of the wall should be higher than the maximal value. Moreover temperature of the internal wall surface should not be lower than dew point for the internal air otherwise moistening of the wall occurs.

2) Outer walls should perform thermal stability. The wall structure should suppress swings of the external temperature changing during day and night period. The ability of the suppression is characterized by the difference between the daily maximum and minimum values of the temperature of the internal wall surface (at the summer period) and indoor temperature (at the winter period).

3) Air should not penetrate the wall structure more than on certain value.

4) Water vapour should not penetrate the wall structure more than on certain value otherwise soft thermal insulation material starts to

accumulate water. This leads to the decrease of thermal resistance characteristic of the thermal insulation layer and as a result of the whole wall structure. (4)

5) Optionally, verification of the dew point possibility in wall structure can be considered.

The sequence of the external wall physical characteristics calculation according to Russian norms is presented in Appendix 2. The results of the calculation of physical and thermal resistance characteristics of the studied outer walls are presented in Appendix 6.

5. SPECIALITIES OF CONSTRUCTION PROCESS

Each of the studied wall structures has its own construction specialities which must be attentively considered during the construction process. The quality of mounting process and junctions assembly determine the reability and design thermal parametrs of construction.

5.1. Multilayered walls with facade brick

Mounting of multilayered walls with facade brick is a labor-consuming process. Human reliability plays a big role during the construction process. This speciality leads to high probability of construction mistakes and deviations from design decisions which strongly influence on the durability, thermal properties and safety of the wall construction. (11).

One of the grossest mistakes is incorrect calculation of the amount of flexible fasteners which are fixing external masonry layer. Moreover, only fiberglass or corrosion-resistant steel could be used for that purpose as long as corrosion effect is very intensive. For example, fasteners made of zinc-coated or aluminized steel corrode till complete destruction in several years of exploitation. Therefore, design decisions must be very precise and changes of fasteners material during construction process should not be accepted. In

Russia gross design and construction mistakes connected with a bad masonry fastening took place in the period between 2005 and 2009 years. These mistakes led to masonry collapse (Fig.10) .(12)

Bad quality of the masonry works may lead to filling of the ventilation space by plaster. Closing of the ventilation gap by plaster prevents a free movement of the air between masonry and thermal insulation layer. Thus, excess moisture does not dry out from the surface of the insulation layer and accumulates inside the material. This leads to the deterioration of the thermal insulating ability of the walling.

Figure 10. External masonry collapse.

Another important factor which influences safety of the wall construction is an accuracy of reinforced concrete and lightweight mounting works. Deviations of the slab edge or concrete wall surface from horizontal or vertical directions lead to problems with external masonry support and sizes of the air gap. Figure 11 shows the junction of the external not load bearing wall (including external facade brick layer) and the slab.
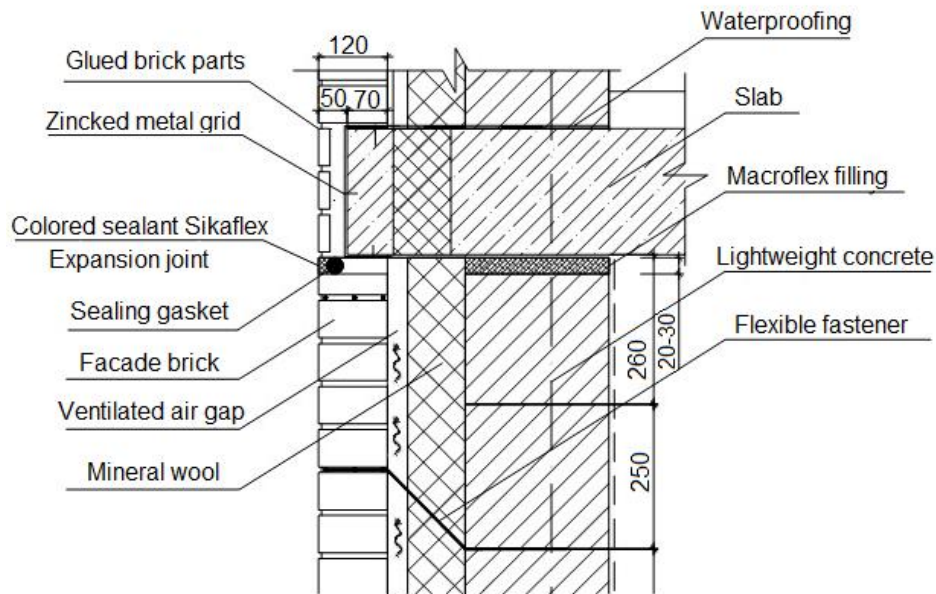
Figure 11. Junction of the external not load bearing multilayered wall and slab

It is obvious that slab supports only part of the façade brick layer. If reinforced concrete slabs are executed with deviations of the edges, then the brick layer might be unsupported. This is one of the most widespread reasons of façade brick layer damages or even collapse.

The sealing of the slot between the bottom surface of the slab and the upper part of the masonry must be executed very accurately. The slot must be wide enough to prevent damages of the masonry caused by the loads which slab may transfer on it (especially after settling of the building). On the other hand, slot must be sealed very well. Poor quality of the sealing may cause penetration of the precipitations into the air gap and moistening of the thermal insulation layer and even ice formation (11).

Multilayer walls with facace brick are used in buildings with reinforced concrete load-bearing core. The cost of reinforced concrete structures execution is considerably higher than the cost of «panel» buildings execution. Moreover, the process of the multilayered walls mounting itself is costly because it presumes use of a lot of qualified labor work. For high buildings the process of walls mounting becomes a very demanding task.

5.2. Concrete sandwich panels

The mounting process of the concrete sandwich walling elements is less labor-demanding, faster and therefore considerably cheaper. The most important issue of mounting a process is a good quality of panel connection with other panels and parts of a building. Poor quality of junctions considerably decreases thermal insulating properties of the whole construction.

Good design decisions and using of mostly typical junctions reduces the risk of construction errors and deterioration of thermal properties of construction. One of typical junction decisions is presented in figure 12.
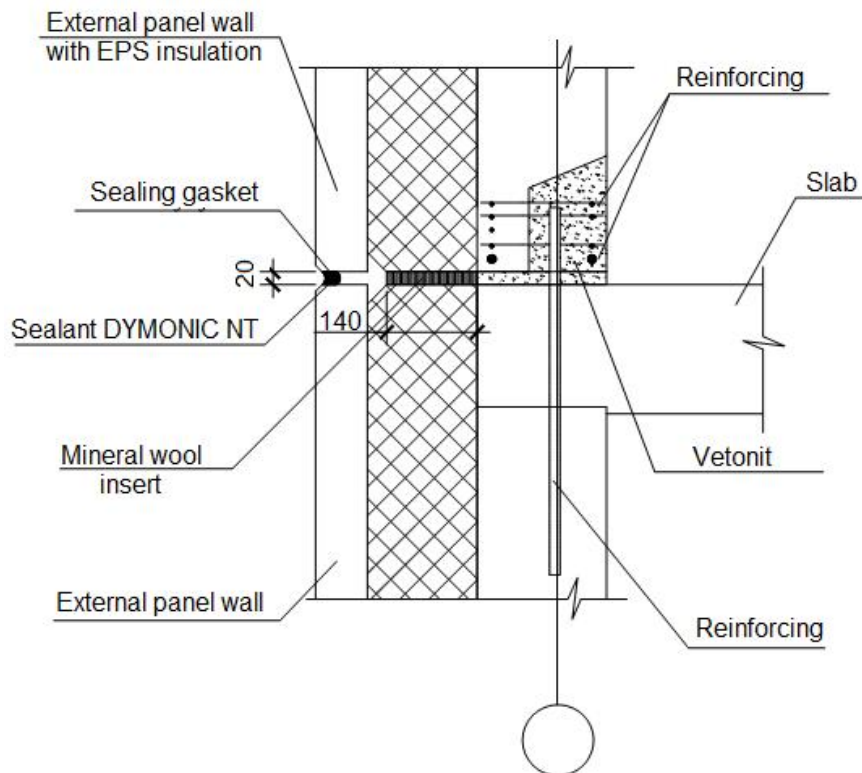
Figure 12. Junction of the external load bearing panel wall and slab

Good quality of junctions sealing and using of durable sealing materials ensure good thermal properties of construction as well.

Nevertheless, panel construction has its flaw. Most external panels join to each other and with the internal panel at the same place. That leads to limitation of

the room sizes by the lenght of the external panel. Whereas construction made of cast in-situ concrete allows to design big spaces inside the building.

CONCLUSIONS

In the executed study of the Swedish Krona and Òland external walls, thermal and hydrothermal properties were analysed. Calculations were made according to Finnish and Russian norms which determine demands to thermal and hydrothermal properties of the external walls. The most important factor is U-value (or R-value as R=1/U) of the wall structure as long as it shows the level of thermal resistance of the structure. External walls with low U-value have better thermal resistance property which is strongly influences on thermal resistance of the whole building mantle. This factor helps to decrease heat losses and heating energy consumption of the building. Comparison of the calculated properties is presented in table 2.

Table 2. Calculated properties of the studied external walls

Wall type	U-value (Finnish norms satisfaction)[*]	R-value/ U-value (Russian norms satisfaction)	Dew-point risk	Moisture accumulation
Curtain wall with lightweight concrete and mineral wool insulation	0,251 **(no)**	4,140/0,242 (yes)	no	no
Curtain wall with reinforced concrete core and XPS insulation	0,305 **(no)**	3,160/0,316 (yes)	no	no
Panel wall with EPS insulation	0,291 **(no)**	3,309/0,302 (yes)	**yes**	no

(* reference value)

U-value calculations shows that none of the studied walls satisfy Finnish norms demands (reference value $U_{outer-wall}$=0,17 (W/(m^2·K)). However, wall structures do satisfy the demands of the Russian norms to R-value as long as the studied projects are presumed to be mounted in Saint-Petersburg. The best thermal resistance properties have curtain wall with lightweight concrete and mineral wool insulation (the lowes U-value).

Required U-value (or R-value) is regulated by norms and strongly influenced by general demands to energy performance and energy consumption of the buildings. National Building Code of Finland determines demands to energy class of the building and maximum allowable annual energy consumption within the established energy class. Requirements of the National Code depend on European Energy Performance Directive (EPBD). Due to recast EPBD revised regulations for new buildings in Finland came into force in July 2012. According revised requirements value of the total energy consumption per year by apartment buildings should not exceed 130 (kW/m^2·year). Thus, the lowest acceptable energy class of the new apartment building is C. (13)

Russian regulations also determine demands to energy performance of the buildings in compliance with European Energy Performance Directive. However, the similar revision of allowable maximum value of the annual energy consumption by apartment building will take force only in January 2016. Tightening of the demands to energy consumption in Russia will lead to revision of requirements to thermal resistance of the building components.

Another important factor affecting durability of wall structure is its hydrothermal properties. Walling with good hydrothermal properties does not accumulate moisture and the risk of dew point within the wall structure is excluded. Therefore, thermal insulation properties of construction remains stable. Also such problems as mold or algae growth, swelling and shrinking caused by salt crystallization or humidity changes, damages caused by frost, corrosion or rotting are avoided.

In studied case the worst hydrothermal properties has concrete not load-bearing panel wall as long there is the risk of a dew point within the wall structure. Results of the manual and computer calculations of the temperature and humidity curves are presented in figure 13. In the left picture curves of the design temperature inside the wall structure and a dew point temperature are shown. In the right picture curves of the design and maximum water vapor content are shown. Intersection of the curves reveals dew point risk within the wall structure. In this case condensed water freezes into ice and expands. This leads to corruption of the material and deterioration of the thermal resistance ability of the walling.
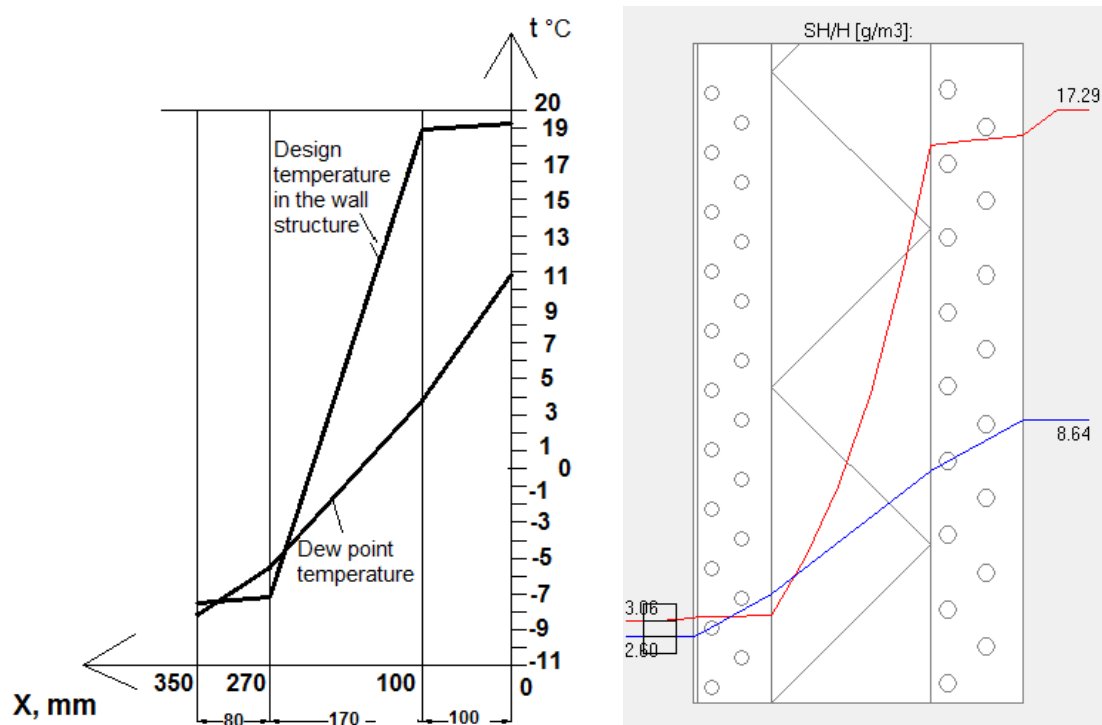
Figure 13. Thermal and humidity curves within structure of the panel wall

During short and cold summer in Saint-Petersburg moisture inside the wall structure may not dry out completely. Thereby, walling may accumulate moisture. During life cycle with repeating processes of freezing and thawing moisture disrupts insulation material inside the wall structure. In several years the wall structure may loose the most of its insulating properties and repair of the corrupted parts of the insulation material would be inevitable. In case of the panel sandwich walling the whole panel element must be replaced which is very demanding task.

To prevent such problems measures limiting water vapor penetration inside the wall structure should be taken. Additional water vapor resistant materials should be used on the internal surface of the walling. Water vapor resistant plaster or painting could be used for that purpose. Another way to avoid water vapor penetration is to use special additives to improve water vapor resistance ability of the concrete layer.

 Curtain walls have satisfactory hydrothermal properties. Moisture accumulation within wall structure and dew point phenomena are excluded.

Thus, multi-layered curtain walls (as implemented in Swedish Krona project) can be used in Finland under circumstance of increasing thickness of the insulation layer. Mineral wool layer thickness should be increased at least to d=250 mm. XPS insulation layer should be increased at least to d=200 mm.

Apart from costliness, there are several benefits of construction of multi-storey houses with multi-layered walls:

1) Possibility to construct architecturally unique and expressive multi-storey houses with facade brick
2) It is possible to design big rooms and open spaces in the houses with cast-in-situ concrete load-bearing core (unlike panel houses)
3) Good hydrothermal properties of multi-layered walls
4) Good level of the construction quality in Finland allows to execute multi-layered walls without mistakes which leads to durability of construction

In Saint-Petersburg housing market is developing rapidly. In 2014 1055 new houses (including apartment houses) were put into operation. About a half of the new multistory apartment houses have reinforced concrete core and curtain walls. Another part of the new buildings in Saint-Petersburg are made of the concrete sandwich panels. Decision about the type of the building and its mantle structures takes customer according to the budget of the project, principle design and necessity to fit into the architectural style of the area. In Saint-Petersburg NCC erects both types of the multistory houses. Òland and Skandi Klubb projects are multistorey concrete panel houses. Swedish Krona and future project Meltzer Håll have reinforced concrete core and curtain walls. To improve quality of construction at both stages of designing and mounting the

Platform was developed in NCC-Russia. This system allows collecting, analysing, changing and saving good design decisions based on experience of completed projects. Relevant information about specialities of designing and mounting of the structures is included into documents and drawings which are saved in the Platform. Designers and constructors inside company can use these files free. This system helps to share experiences, avoid mistakes and significantly improve final quality of the construction.

FIGURES

CHARTS

Chart 2. Distribution of average month wind speeds in Saint-Petersburg

TABLES

Table 1. Design climatic conditions of the cold period of the year

Table 2. Calculated properties of the studied external walls

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Calculation procedure of the building element thermal resistance value according to SFS-EN ISO 6946

According to SFS-EN ISO 6946 principle of the calculation of the building element thermal resistance value is:

-to determine the thermal resistance of each thermally homogeneous part of the element

-to combine these individual resistances so as to determine the total thermal resistance of the component, including the effect of surface resistances

Design thermal values can be given as design thermal conductivity. Otherwise, it is given as design value of thermal resistance. If thermal conductivity is given then thermal resistance of the homogeneous layer is obtained by equation:

$$R = \frac{d}{\lambda} \qquad (1.1)$$

where: d – thickness of the material layer in the component (m);

λ – the design thermal conductivity of the material, either calculated in accordance with ISO 10456 or obtained from tabulated values, $(W/(m \cdot K))$.

The total thermal resistance of a plane building component consisting of homogeneous layers and set perpendicular to the heat flow shall be calculated by the following expression:

$$R_{T,f} = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se} \qquad (1.2)$$

where: R_{si} – the internal surface resistance $(m^2 \cdot K/W)$;

R_1, R_2…R_n – the design thermal resistances of each layer (m²·K/W);

R_{se} – the external surface resistance (m²·K/W);

For building elements where direction of heat flow is horizontal (vertical walls), values of thermal resistances are tabulated and determined according to Table 1 ISO 6496. R_{si}=0,13 (m²·K/W) and R_{se}=0,04 (m²·K/W).

The influence of the air layer, which is the part of the building element, depends on the type of the air layer. Unventilated air layer is one which no airflow take place. Design values of thermal resistance are tabulated and determined according Table 2 ISO 6496. A well-ventilated air layer allows disregarding in the total thermal resistance calculation the air layer and all other layers between the air layer and external environment. The value of the external surface resistance can be determined according to Table 1 ISO 6496.

A wall structure may have air voids in the insulation layer in form of gaps between insulation units (boards or mats) or between insulation and construction elements in direction of the heat flow. Also air voids may be in form of cavities in the insulation layer or between the insulation and the construction, perpendicular of the direction of the heat flow. Often construction of the wall structure may include mechanical fasters, which penetrate the insulation layer. Air voids and mechanical fasteners influence on the total thermal resistance of the wall structure, which may be decreased. Therefore ISO 6496 presume correction of the thermal transmittance of the layers by adding a correction term ΔU. The corrected thermal transmittance U_c is determined as:

$$U_c = U + \Delta U \qquad (1.3)$$

where U – thermal transmittance of the layer without air voids and mechanical fasteners.

ΔU for wall structure is given by equation:

$$\Delta U = \Delta U_g + \Delta U_f \qquad (1.4)$$

where ΔU_g – correction for air voids;

ΔU_f – correction for mechanical fasteners.

Correction for air voids is obtained by equation:

$$\Delta U_g = \Delta U'' \cdot \left(\frac{R_1}{R_{T,h}}\right)^2 \qquad (1.5)$$

where R_1 – thermal resistance of the layer containing gaps, determined by equation (5), (m²·K/W);

$R_{T,h}$ – the total thermal resistance of the component ignoring any thermal bridging, determined by equation (1.2) (m²·K/W);

$\Delta U''$ – correction factor depending on the intensity (level) of air voids spreading in the the insulation layer, given by table D.1 ISO 6946.

The influence of mechanical fasteners such as wall ties between masonry leaves or fasteners in composite panel system is determined by the correction to the thermal transmittance using the following equation:

$$\Delta U_f = \alpha \cdot \frac{\lambda_f \cdot A_f \cdot n_f}{d_0} \cdot \left(\frac{R_1}{R_{T,h}}\right)^2 \qquad (1.6)$$

where λ_f – thermal conductivity of the fastener (W/(m·K));

n_f – number of fasteners per square meter;

A_f – the cross-sectional area of the fastener (m²);

d_0 – thickness of the insulation layer containing the fasteners (m);

R_1 – thermal resistance of the insulation layer penetrated by the fasteners (m²·K/W);

$R_{T,h}$ – the total thermal resistance of the component ignoring any thermal bridging, determined by equation (1.2) (m²·K/W);

α – coefficient obtained by following:

$\alpha = 0,8$ if the fastener fully penetrates the insulation layer or

$$\alpha = 0,8 \cdot \frac{d_1}{d_0} \tag{1.7}$$

if fastener is recessed

d_1 – length of fastener that penetrates the insulation layer (m).

Sequence of the external wall physical characteristics calculation according to Russian norms

1. Calculation of the required thermal resistance of the external wall $R_{req.}$

1.1. Initial information about climatic parameters.

Internal temperature of the residential building is determined according to SP 23-101-2004 as $t_{int}=20°C$. Design external temperature t_{ext} for certain region is taken according to SNiP 23-01-99 as an average temperature of the 5 coldest days in a year. For Saint-Petersburg $t_{ext}=-26°C$. Also SNiP 23-01-99 gives information about the duration of the heating season z_{ht} (days) in each region and the average external temperature during the heating season t_{ht}. For Saint-Petersburg $z_{ht}=220$ days and $t_{ht}= - 1,8°C$

1.2. Calculation of the R_{req}.

To determine R_{req} equation (2.1) is used:

$$R_{req} =a·G_d+b, \tag{2.1}$$

where G_d is "degree-days" (°C·days) determined by equation (2.2):

$$G_d =(t_{int} - t_{ht})·z_{ht} \tag{2.2}$$

a and *b* are the coefficients taken according SNiP23-02-2003 depending on the type of buildings and value of G_d. For Saint-Petersburg
$G_d =(20 + 1,8)·220 = 4796$ (°C·days).
For residential buildings and $G_d =4796$ (°C·days), coefficients *a* and *b* are equal 0,00035 and 1,4 respectively. Thus,
$R_{req} = 0,00035· 4796+ 1,4 = 3,079$ (m²·°C/W)

2. Calculation of the design thermal resistance coefficient R_0

To determine the design thermal resistance of the wall equation (2.3) is used:

$$R_0 = 1/\alpha_{int} + R^r_1 + R^r_2 + ... + R^r_n + 1/\alpha_{ext} \qquad (2.3)$$

where α_{int} – coefficient of the heat transfer of the internal surface of the wall, $(W/(m^2 \cdot {^oC}))$;

α_{ext} – coefficient of the heat transfer of the external surface of the wall, $(W/(m^2 \cdot {^oC}))$.

R^r_1, R^r_2, ...,R^r_n – design thermal resistance of each material layer composing the wall structure $(m^2 \cdot {^oC}/W)$;

α_{int} and α_{ext} are taken according to SNiP 23-02-2003 for walls as $\alpha_{int} = 8,7$ $(W/(m2 \cdot {^oC}))$ and $\alpha_{ext} = 23$ $(W/(m2 \cdot {^oC}))$.

The design thermal resistance of the material is determined using equation (2.4):

$$R = \frac{\delta}{\lambda} \qquad (2.4)$$

where δ - thickness of the material (thickness of the material), (m);

λ – design coefficient of the heat transfer of the material, $(W/(m \cdot {^\circ C}))$.

Value of λ for each material is provided by the producer or can be specified using information presented in the SNiP II-3-79*about physical characteristics of the different materials.

After calculating R_0 and R_{req}, these values are compared and conclusion about conformity of the wall structure to norms is made. Wherein design value R_0 should always be higher or equal to R_{req}.

3. Verification of the internal surface temperature level

The procedure of the verification of the internal surface temperature of the wall is obligatory but is rarely held. Usually this requirement is satisfied automatically due to the high level of the thermal resistance of the external wall. But for several types of buildings the temperature of the internal surface of the wall must be checked. It is connected with the fact that demanded (and therefore

design) value of thermal resistance of the walls depends on internal climatic parameters. According to equations (2.1) and (2.2) R_{req} linearly depends on the internal temperature of the building t_{int}. For some types of building (for example manufacturing and industrial buildings) the demanded t_{int} can be much lower than for residential and commercial buildings. Therefore R_{req} and R_0 are lower and the internal surface of such a wall can be too cold and even vapor condensation may occur. The procedure of the internal surface temperature verification consists of the two calculations. The first calculation helps to determine difference Δt_0 between the temperature of the internal surface of the wall and internal air temperature. The value of the difference is compared with the maximum reference value set for different types of the buildings in the SP 23-101-2004. To determine the difference equation (2.5) is used:

$$\Delta t_0 = \frac{n \cdot (t_{int} - t_{ext})}{R_0 \cdot \alpha_{int}} \qquad (2.5)$$

where n is a coefficient which depends on the type and position of the building envelope part (horizontal, vertical or inclined) and taken according SNiP 23-02-2003. For vertical walls n=1.

t_{int} - internal air temperature, t_{ext} – design external temperature, R_0 - design thermal resistance of the wall, α_{int} – coefficient of the heat transfer of the internal surface of the wall. For residential buildings Δt_0 of the external wall must not be higher than 4 °C.

The second calculation verifies the possibility of the vapor condensation on the internal surface of the wall. The temperature of the internal surface of the wall is determined by the equation (2.6):

$$T_{int} = t_{int} - \Delta t_0 \qquad (2.6)$$

This temperature is compared with dew point of the internal air. T_{int} must always be higher than dew point t_{rp} ($T_{int} > t_{rp}$). For example for residential buildings with internal air humidity ϕ=55% and t_{int}=20°C dew point t_{rp}=10,69°C. Therefore T_{int} should always be higher than t_{rp}=10,69°C to avoid condensation.

4. Verification of the thermal stability of the wall.

Wall structure ability to suppress swings of the external temperature changing during day and night periods is verified. This requirement is connected with the demand to maximum possible swings of the indoor temperature (for winter time) which is stated by SNiP 23-02-2003 as $A_t^{req}=1,5^oC$.

The calculation sequnce is presented below.

1) For each material composing the wall structure coefficient of the heat absorption ability is determined by the equation (2.7):

$$s = \sqrt{\frac{2 \cdot \pi \cdot \lambda \cdot c \cdot \gamma_0}{Z}} \qquad (2.7)$$

where λ – heat transfer of the material (W/(m·°C));

      c – specific heat capacity (kJ/(kg·°C));

      γ_0 – density of the material (kg/m^3);

      Z – calculation period of the temperature swings (24 houts).

If layer of the wall (material) is inhomogeneous then coefficient of the heat absorption ability is stated as average value using equation (2.8);

$$s = \frac{\sum_{i=1}^{i=n} m_i s_i}{\sum_{i=1}^{i=n} m_i} \qquad (2.8)$$

where «s_i» is a coefficient of the heat absorption ability of the part composing inhomogeneous layer and «m_i» is a mass of this part.

2) Index of the heat lag of each material composing the wall structure is determined by the equation (2.9)

$$D^r = R^r s \qquad (2.9)$$

where R^r– thermal resistance of the layer material.

The total heat lag of the wall structure is determined as:

$$D = \sum_{n}^{1} D_i^r \qquad (2.10)$$

where D^r_i – heat lag of each material composing wall structure.
Ventilated air gap is not taken into accont in the calculation of the heat lag. Material between external surface of the wall structure and ventilated air gap is not taken into account as well.

3) For the wall structure coefficient of the internal surface heat assimilation ability Y_{int} must be determined.

Y_{int} (W/m$^2 \cdot$°C) is depending on physical characteristics of the zone of sharp temperature fluctuations (Fig.2.1). Temperature fluctuations on the internal surface of the wall cause retarding damping temperature fluctuations inside the wall material. Line (τ_{int} -τ_{int}) shows the average temperature change into the material of the wall. A_τ − is an internal surface temperature range during 24 hours. The range of temperature fluctuations inside the material is decreasing along the thickness (δ) of the wall. In the zone of sharp fluctuations the range of the temperature fluctuations is not less than ($A_\tau/2$). For materials of this zone D=1.
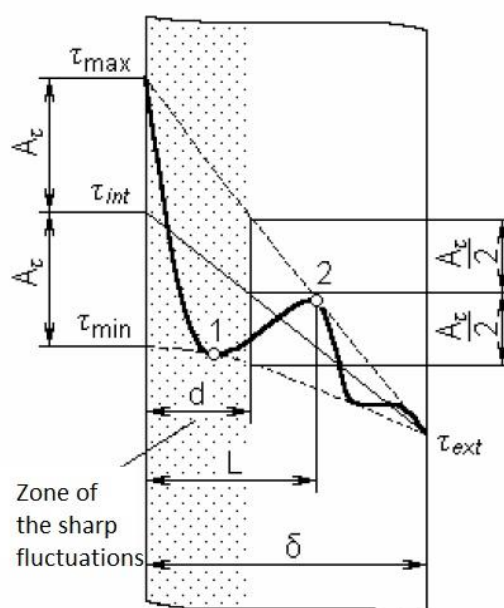
Figure 2.1. Temperature fluctuations in the wall structure

For the multilayered wall D is determined for each material starting from the internal layer.

- If for the first layer $D_1 \geq 1$ then $Y_{int} = s_1$
- If D1<1, but $D_1 + D_2 \geq 1$ then Y_{int} is determined by the equation:

$$Y_{int} = \frac{R_1 \cdot s_1^2 + s_2}{1 + R_1 \cdot s_2}$$ (2.11)

4) The index of the internal surface heat absorption ability B (W/m²·°C) is determined by the equation:

$$B = \frac{1}{\dfrac{1}{\alpha'_{int}} + \dfrac{1}{Y_{int}}}$$ (2.12)

where α'_{int} — coefficient of the heat transfer of the internal surface of the wall, (W/(m²·°C)), taken 4,5 + α_k;

α_k — coefficient of the convective heat transfer of the internal surface of the wall, (W/(m²·°C)) taken 1,2.

5) Finally the design swings of the indoor temperature A_t^{des} are determined by equation:

$$A_t^{des} = m \cdot (t_{int} - t_{ext})/BR_0 \qquad (2.13)$$

where m — index of the irregularity of the heater work (depending on swings of its heat transfer value during 24 hours), for casual heating systems taken 0,1

t_{int} —average internal temperature during 24 hours;

t_{ext} —average external temperature during 24 hours.

5. Verification of the air penetration resistance ability.

Design air penetration resistance value (J^{des}) of the external wall should not be lower than demanded value J^{req} ($m^2 \cdot h \cdot Pa/kg$), where J^{req} is determined by the equation:

$$J^{req} = \Delta p/G_n \qquad (2.14)$$

where Δp — difference of air pressure on external and internal surfaces of the wall structure (Pa);

G_n— demanded air penetration resistance of the external wall, slabs and roofs structures in commercial buildings and houses, stated by SNiP 23-02-2003 as 0,5 ($kg/(m^2 \cdot h)$).

Requirement to air penetration resistance applies especially to not load-bearing external walls consisting mostly of porous thermal insulation materials without wind barriers.

The difference of air pressure on external and internal surfaces of the wall structure is determined by the equation:

$$p = 0,55H \cdot (\gamma_{ext} - \gamma_{int}) + 0,03\, \gamma_{ext} v^2_0 \qquad (2.15)$$

where H – height of the building (from the level of the first floor to the upper edge of the ventilation shaft), meters;

v – maximal of the average wind speeds (along the rumbs) in January which friquency is 16% and more. Taken for different regions according to SNiP 23-01-99, (m/h);

γ_{ext}, γ_{int} – specific weight of the external and internal air respectively, (N/m^3). Determined by equation:

$$\gamma_{ext} = 3463/(273 + t_{ext}) \qquad (2.16)$$

$$\gamma_{int} = 3463/(273 + t_{int}) \qquad (2.17)$$

Design value of the air penetration resistance of the wall strucrure J^{des}, (m^2·h·Pa/kg) is determined by the equotion:

$$J^{des} = J_1 + J_2 + J_3 + \ldots + J_n \qquad (2.18)$$

where $J_1, J_2, J_3, \ldots, J_n$, – value of the air penetration resistance of the materials composind layers of the external wall structure. Values are taken from the table presented in SP 23-101-2004.

Air penetration resistance of the air gaps and fibred thermal insulation materials (mineral wool or shavings) is not taken into account.

6. Verification of the water vapor penetration resistance.

Demanded ability of the wall structure to resist water vapor penetration is stated by SNiP 23-02-2003. According these demands design value of the water vapor penetration resistance of the wall structure Ω (m^2·h·Pa/mg) is determined for the layers between internal surface of the wall and external surface of the thermal insulation (external surface of the thermal insulation is considered as a plane where dew point is possible to appear). According to SNiP 23-02-2003 the total design water vapor penetration resistance Ω_{rp} of these parts of the wall structure must not be lower than:

a) required water vapor resistance Ω_{req}^{*} determined by equation:

$$\Omega_{req}^{*} = \frac{(e_{int} - E)\Omega_e}{(E - e_{ext}^{av})} \qquad (2.19)$$

(exclusion of the moisture accumulation during one year period of the exploitation)

b) required water vapor resistance Ω_{req}^{**} determined by equation:

$$\Omega_{req}^{**} = \frac{0,0024z_0\left(e_{int} - E_0\right)}{\gamma\delta_W\Delta W_{av} + \eta} \qquad (2.20)$$

(exclusion of moisture accumulation during period with month average temperatures below 0°C)

In the equations (2.19) and (2.20) e_{int} is a water vapor partial pressure on conditions of design internal parametrs (design internal temperature and humidity), determined by equation:

$$e_{int} = (\varphi_{int}/100) \cdot E_{int} \qquad (2.21)$$

where E_{int} – partial pressure of the saturated water vapor on conditions of design internal temperature t_{int};

φ_{int} – design internal air humidity, taken 55% for living premises according to SNiP 23-02-2003.

Ω_e – water vapor penetration resistance of the layers between external surface of the wall structure and plane where dew point is possible to appear;

e_{ext}^{av} – average external air water vapor partial pressure during one year (Pa). Determined according to SNiP 23-01-99.

z_0 – amount of days in the period of possible moisure accumulation in the wall structure. Duration of this period is equal to the period with month average temperatures below 0°C. Determined according to SNiP 23-01-99.

E_0 – saturated water vapor partial pressure in a plane of its possible condensation. Determined under condition of average temperature on this plane τ_0 (τ_0 is an average temperature of the period z_0. Determined according fo tables of water vapor partial pressure given in SP 23-101-2004).

Value of τ_0 is determined by equation:

$$\tau_0 = t_{int} - (t_{int} - t_0) \cdot (R_{si}+R_e)/R_o, \qquad (2.22)$$

where t_0 – month average external air temperature during period z_0 (^{0}C);

$R_{si}=1/\alpha_{int}$ – thermal resistance of the internal surface of the wall ($m^2 \cdot$°C/W);

R_e – thermal resistance of layers between the external surface of the wall structure and the plane where dew point is possible to appear, ($m^2 \cdot$°C/W);

R_o – thermal resistance of the whole wall structure, ($m^2 \cdot$°C/W);

δ_W – thickness of the wall part where moistening occurs, taken equal to 2/3 of the thermal insulation layer thickness (in the multilayered wall structure);

γ– density of the thermal insulation material;

ΔW_{av} – the maximum allowable increment of the material moisure content (%) in the zone δ_W during the period z_0, determined according to SNiP 23-02-2003. For rock wool plates ΔW_{av}=3 %, for foamed polymer insulations ΔW_{av}=25 %.

E – water vapor partial pressure in the plane where dew point is possible to appear during one year period of exploitation. Determined by equation:

$$E=(E_1 \cdot z_1+E_2 \cdot z_2+E_3 \cdot z_3)/12 \qquad (2.23)$$

where E_1, E_2, E_3 – saturated water vapor partial pressures if the plane where dew point is possible to appear under condition of the temperatures of this plane τ_1, τ_2, τ_3, (winter (index 1), autumn and spring (index 2) and summer (index 3) periods). Determined accoring tables of water vapor partial pressure given in SP 23-101-2004.

Value of τ_i is determined by equation:

$$\tau_i = t_{int} - (t_{int} - t_i) \cdot (R_{si} + R_e)/R_o, \quad i=1, 2, 3 \qquad (2.24)$$

where t_i — average temperature of the external air of the «i» period determined by equation:

$$t_i = \sum_{j=1}^{n} t_j^{av} / n \qquad (2.25)$$

where t_j^{av} — average month temperature («j» month in the «i» period);

n — total amount of months if the «i» period;

z_1, z_2, z_3 – amount of months in the winter, autumn-spring and summer periods relatively. Determined according to SNiP 23-01-99 (temperature of the external air in months of the winter period is less than -5 °C; temperature of the external air in months of the autumn-spring period is from -5 to +5 °C; temperature of the external air in months of the summer period is more than +5 °C);

η– coefficient, determined by equation:

$$\eta = 0{,}0024 \cdot (E_0 - e_0^{ext}) \cdot z_0/\Omega_e, \qquad (2.26)$$

where e_0^{ext} – external air water vapor average partial pressure (Pa) during period with external air temperature below zero (possible to determine e_0^{ext} as average value of external air water vapor partial pressure under condition of negative value of the average month external air temperature t_0);

To determine *design* value of the water vapor penetration resistance of the wall structure Ω_{rp} (for the layers between internal surface of the wall and external surface of the thermal insulation) Ω of each layer must be found using equation:

$$\Omega = \delta/\mu \qquad (2.27)$$

where μ– water vapor permeability ratio of the layer material (mg/m·hour·Pa);

δ – thickness of the layer (m).

Water vapor penetration resistance of the whole wall structure Ω_o and Ω_{rp} can be determined by equation:

$$\Omega_{rp} = \Omega_o = \Omega_{int} + \Omega_1 + \Omega_2 + \ldots + \Omega_n + \Omega_{ext} = \Omega_{int} + \delta_1/\mu_1 + \delta_2/\mu_2 + \ldots + \delta_n/\mu_n + \Omega_{ext} \quad (2.28)$$

where Ω_1, Ω_2,… – the water vapor penetration resistance of each layer,

n – amount of all layers;

Ω_{int} и Ω_{ext} – moisture transfer resistance of internal and external surfaces of the wall structure. For calculation procedures can be taken Ω_{int} = $26,6 \cdot 10^{-3}$ (Pa·hour·m^2/g) and Ω_{ext} = $13,3 \cdot 10^{-3}$ (Pa·hour·m^2/g).

If the wall structure has ventilated air gap then Ω_{ext} is not taken into account in calculation of the $\Omega_{rp.}$ In Ω_o calculation all layers between internal surface of the ventilated gap and external surface of the wall structure can be presumed as $\Omega_{ext.}$

7. Verification of the dew point possibility in wall structure

The process of of the water vapor condensation is not possible when temperature in each point of the wall structure (τ_i) is higher than dew point (t_i^{rp}). Equally, partial pressure of the water vapor in each point of the wall structure (e_i) does not reach value of the partial pressure of the saturated water vapor (E_i.), i.e. following conditions are satisfied:

$$\tau_i > t_i^{rp} \text{ or } e_i < E_i.$$

To determine temperature τ_i of surfaces between layers equation (2.24) can be used:

$$\tau_i = t_{int} - (t_{int} - t_{ext}) \cdot (R_{si} + \Sigma R_i)/R_o$$

where i – number of the layer taken from the internal surface of the wall structure;

τ_i – temperature of the external surface of each layer;

$R_{sj}=1/\alpha_{int}$ – thermal resistance of the internal surface of the wall structure;

ΣR_i – total thermal resistance of the layers between internal surface of the wall structure and external surface of the «i» layer;

R_o – total thermal resistance of the whole wall structure.

Saturated water vapor partial pressure on each surface E_i is determined under condition of the temperature τ_i.

To determine design water vapor partial pressure e_i on each surface the following equation can be used:

$$e_i= e_{int}– (e_{int}– e_{ext})\cdot(\Omega_{int}+\Sigma\Omega_i)/\Omega_0 \qquad (2.29)$$

where Ω_i – total water vapor resistance of the layers between internal surface of the wall structure and external surface of the of the «i» layer.

Evaluated e_i and E_i. should be compared.

To determine air humidity in plane of the external surface of the «i» layer the following equation should be used:

$$\varphi = \frac{e_i}{E_i}\cdot 100\% \qquad (2.30)$$

Dew point temperature t_i^{dp} can be determined useing «i-d» diagram. Evaluated τ_i and t_i^{dp} should be compared.

U-value calculation

1. Multi-layered wall with lightweight concrete.

In figure 3.1 multi-layered wall with lightweight concrete is presented. The sequence of layers from internal to external is as follows:

1) Vetonit TT – leveling gypsum insulating plaster (d=0,002 m);

2) Lightweight concrete block (d=0,25 m; λ_d=0,14 (W/(m·K)); ρ=500 (kg/m^3));

3) Mineral wool insulation venti-batts (λ_d=0,04 (W/(m·K)); d=0,1 m);

4) Ventilated air gap (d=0,035 m);

5) Cilica facade brick (d=0,12 m)
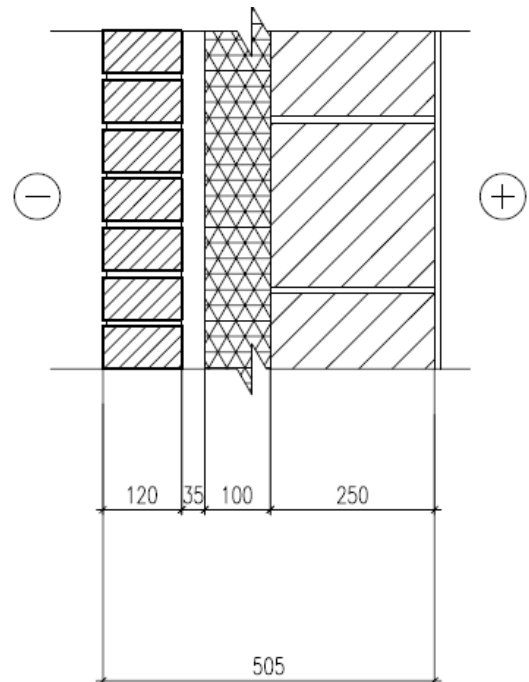
Figure 3.1. Structure of multi-layered wall with lightweight concrete

As long as air gap is ventilated its thermal resistance is not taken into account. Thermal resistance of the external facade brick layer is not taken into account as well.

For external masonry fastening corrosion-resistant steel bars are used. Diameter of rods is d=8 mm. Amount of bars is 4 pieces per 1,668 m^2 (2,4 pieces per 1 m^2) of the wall structure. Sheme of the masonry fastening is presented in figure 3.2. Fasteners are inclined on the average angle 45° in the mineral wool layer and penetrate lightweight concrete layer on 0,2 m.
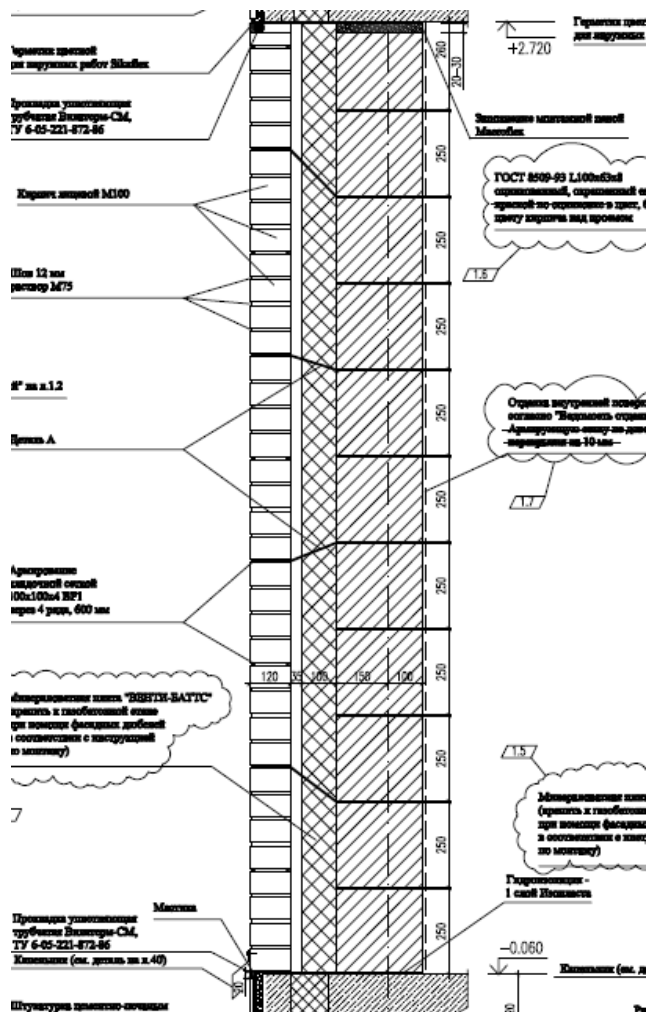
Figure 3.2 Sheme of the external masonry fastening.

Properties of fasteners are as follows:

λ_f – 58 (W/(m·K));

n_f – 2,4 pieces;

A_f – 5,024·10^{-5} (m^2);

The total thermal resistance of the wall without thermal bridging:

$$R_{T,f} = 0,13 + \frac{0,1}{0,04} + \frac{0,25}{0,14} + 0,04 = 4,456 \quad (\frac{m^2 \cdot K}{W})$$

U-value of the wall without thermal bridging:

$$U = \frac{1}{4,456} = 0,2244 \quad (\frac{W}{m^2 \cdot K})$$

Thermal transmittance correction for fasteners in the mineral wool layer

$$\alpha = 0,8 \cdot \frac{0,1 \cdot \sqrt{2}}{0,1} = 1,13$$

$$R_1 = \frac{0,1}{0,04} = 2,5 \quad (\frac{m^2 \cdot K}{W})$$

$$\Delta U_f = 1,13 \cdot \frac{58 \cdot 5,024 \cdot 10^{-5} \cdot 2,4}{0,1} \cdot (\frac{2,5}{4,456})^2 = 0,02487 \quad (\frac{m^2 \cdot K}{W})$$

Thermal transmittance correction for fasteners in the lightweight concrete layer

$$\alpha = 0,8 \cdot \frac{0,2}{0,25} = 0,64$$

$$R_1 = \frac{0,2}{0,14} = 1,43 \quad (\frac{m^2 \cdot K}{W})$$

$$\Delta U_f = 0,64 \cdot \frac{58 \cdot 5,024 \cdot 10^{-5} \cdot 2,4}{0,25} \cdot (\frac{1,43}{4,456})^2 = 0,00184 \quad (\frac{m^2 \cdot K}{W})$$

Thermal transmittance correction for air voids:

$$\Delta U_g = \Delta U'' \cdot (\frac{R_1}{R_{T,h}})^2 = 0$$

($\Delta U'' = 0$ of the level 0 according to table D.1 ISO 6946)

Design U_d-value of the wall with thermal bridging:

$$U_d = 0,2244 + 0,02487 + 0,00184 = 0,2511 \quad (\frac{W}{m^2 \cdot K})$$

2. Multi-layered wall with reinforced concrete core.

In figure 3.3 multi-layered wall with reinforced concrete core is presented.

Sequence of layers from internal to external is as follows:

1) Reinforced concrete layer (d=0,16 m, λ_d=2,04 (W/(m·K)));

2) Thermal insulation XPS (d=0,1 m, λ_d=0,032 (W/(m·K)))

3) Unventilated air gap (d=0,01 m, R=0,15 (m^2·K/W) according to table 2 ISO 6496);
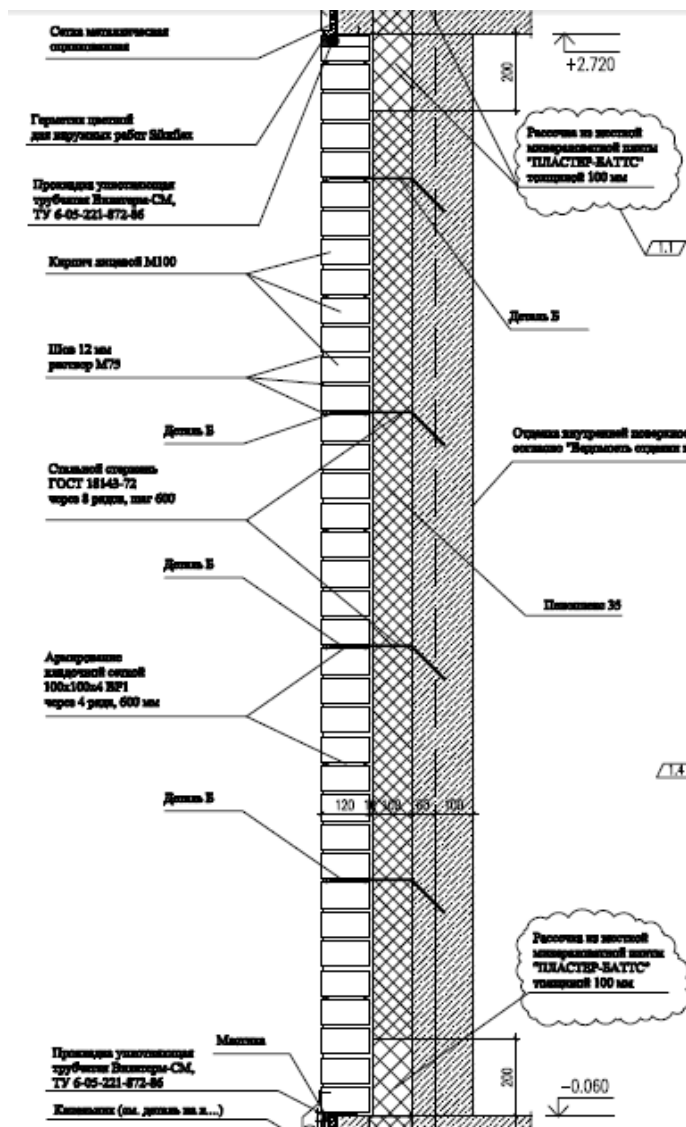
4) Cilica facade brick (d=0,12 m, λ_d=0,52 (W/(m·K)))
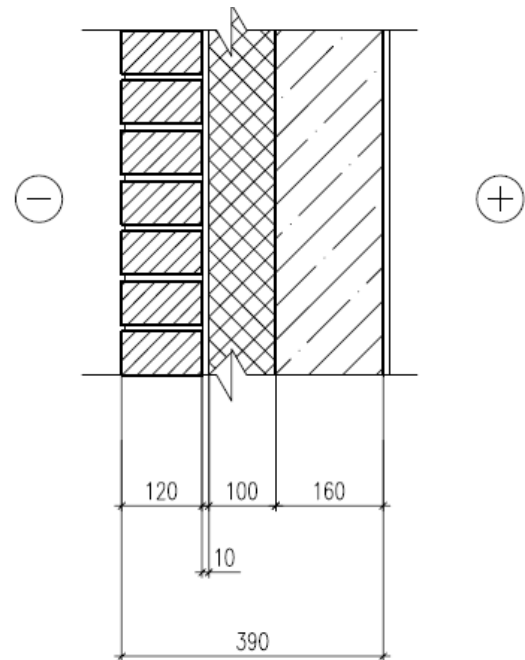
Figure 3.3. Structure of multi-layered wall with reinforced concrete

For external masonry fastening corrosion-resistant steel bars are used. Diameter of rods is d=8 mm. Amount of bars is 4 pieces per 1,668 m^2 (2,4 pieces per 1 m^2) of the wall structure. Sheme of the masonry fastening is presented in figure 3.4.

Figure 3.4. Sheme of the external masonry fastening.

Properties of fasteners are as follows:

λ_f – 58 (W/(m·K));

n_f – 2,4 pieces;

A_f – 5,024·10^{-5} (m^2);

The total thermal resistance of the wall without thermal bridging:

$$R_{T,f} = 0,13 + \frac{0,12}{0,52} + 0,15 + \frac{0,1}{0,032} + \frac{0,16}{2,04} + 0,04 = 3,754 \quad (\frac{m^2 \cdot K}{W})$$

U-value of the wall without thermal bridging:

$$U = \frac{1}{3,754} = 0,2664 \quad (\frac{W}{m^2 \cdot K})$$

Thermal transmittance correction for fasteners in the XPS insulation layer

$$\alpha = 0,8$$

$$R_1 = \frac{0,1}{0,032} = 3,125 \quad (\frac{m^2 \cdot K}{W})$$

$$\Delta U_f = 0,8 \cdot \frac{58 \cdot 5,024 \cdot 10^{-5} \cdot 2,4}{0,1} \cdot (\frac{3,125}{3,754})^2 = 0,0388 \quad (\frac{m^2 \cdot K}{W})$$

Thermal transmittance correction for air voids:

$$\Delta U_g = \Delta U'' \cdot (\frac{R_1}{R_{T,h}})^2 = 0$$

($\Delta U'' = 0$ of the level 0 according table D.1 ISO 6946)

Design U_d-value of the wall with thermal bridging:

$$U_d = 0,2664 + 0,0388 = 0,3052 \quad (\frac{W}{m^2 \cdot K})$$

3. Panel wall with EPS insulation.

In figure 3.5. panel wall with EPS insulation is presented. Sequence of layers from internal to external is as follows:

1) Reinforced concrete (d=0,1 m,
   λ_d=2,04 (W/(m·K)));
2) EPS insulation (d=0,17 m,
   λ_d=0,0513 (W/(m·K)));
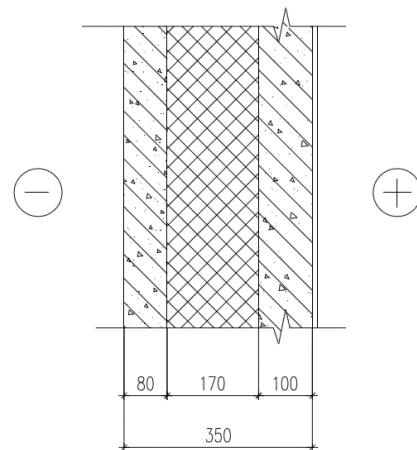3) Reinforced concrete (d=0,08 m,
   λ_d=2,04 (W/(m·K))).

Figure 3.5. Structure of panel wall

Panel wall structure presumes using of the diagonal metal ties and connection rods Peikko between concrete layers as presented in figure 3.6. The total amount of rods in the panel penetrating insulation layer is 40 pieces (2,9 pieces per 1 m^2). The diameter of the rods is d=4 mm. Inclination 45°.
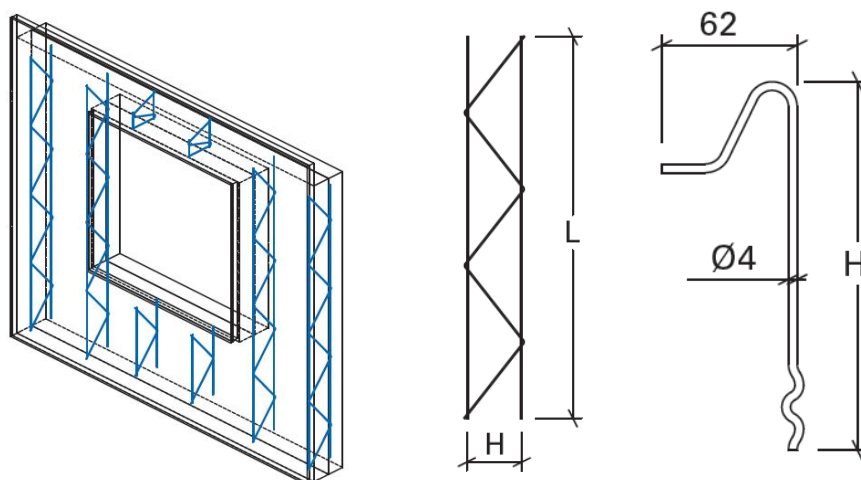

Figure 3.6. Sheme of the diagonal ties and connection rods

Properties of rods are as follows:

λ_f – 58 (W/(m·K));

n_f – 2,9 pieces;

A_f – 1,257·10⁻⁵ (m²);

Total thermal resistance of the wall without thermal bridging:

$$R_{T,f} = 0,13 + \frac{0,08}{2,04} + \frac{0,17}{0,0513} + \frac{0,1}{2,04} + 0,04 = 3,585 \quad (\frac{m^2 \cdot K}{W})$$

U-value of the wall without thermal bridging:

$$U = \frac{1}{3,585} = 0,2789 \quad (\frac{W}{m^2 \cdot K})$$

<u>Thermal transmittance correction for fasteners in the EPS insulation layer</u>

$$\alpha = 0,8 \cdot \frac{0,17 \cdot \sqrt{2}}{0,17} = 1,13$$

$$R_1 = \frac{0,17}{0,0513} = 3,314 \quad (\frac{m^2 \cdot K}{W})$$

$$\Delta U_f = 1,13 \cdot \frac{58 \cdot 1,257 \cdot 10^{-5} \cdot 2,9}{0,17} \cdot (\frac{3,314}{3,585})^2 = 0,012 \quad (\frac{m^2 \cdot K}{W})$$

<u>Thermal transmittance correction for air voids</u>:

$$\Delta U_g = \Delta U'' \cdot (\frac{R_1}{R_{T,h}})^2 = 0$$

($\Delta U''$ = 0 of the level 0 according table D.1 ISO 6946)

Design U_d-value of the wall with thermal bridging:

$$U_d = 0,2789 + 0,012 = 0,2909 \quad (\frac{W}{m^2 \cdot K})$$

DofTherm calculations

The aim of calculations in DofTherm software is to determine internal surface temperature and to analyse the risk of dew point within the wall structure. Internal and external climatic parameters are taken from Helsinki climatic databases (table 4.1).

Table 4.1. Monthly internal and external climatic parametrs

No.:	Period:	External T [c]	Internal T [c]	External RH [%]	Internal RH [%]	Duration [h]
1	January	-5.70	20.00	85.00	50.00	744.00
2	February	-5.70	20.00	84.00	50.00	672.00
3	March	-2.10	20.00	82.00	50.00	744.00
4	April	3.10	20.00	75.00	50.00	720.00
5	May	9.70	20.00	67.00	50.00	744.00
6	June	15.00	20.00	68.00	50.00	720.00
7	July	17.00	20.00	73.00	50.00	744.00
8	August	15.70	20.00	78.00	50.00	744.00
9	September	11.10	20.00	82.00	50.00	720.00
10	October	6.40	20.00	83.00	50.00	744.00
11	November	1.40	20.00	86.00	50.00	720.00
12	December	-2.90	20.00	86.00	50.00	744.00

Calculation of the internal surface temperature and analysis of the dew point risk is executed for one of the coldest months of the year (January).

1. Multi-layered wall with lightweight concrete.

Initial data

Structure of the wall and physical properties of the layer materials are presented in figure 4.1.
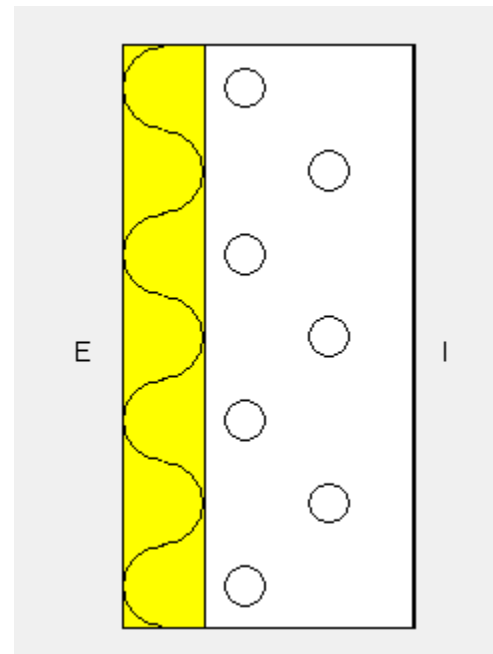
No.:	Layer:	T [mm]:	TC [W/mK]:	SR [-]	Price [euro/m3]:	Mass [kg/m3]:	Thermal bridge:	Used in calculation:
1	Mineral wool RockWool Venti-Batts	100.00	0.0400	2.175000e+00	0.00	90.00	ON	ON
2	Lightweight concrete	250.00	0.1400	3.480000e+00	0.00	500.00	ON	ON
3	Gypsum insulating plaster (Vetonit TT)	2.00	0.1800	6.000000e+00	0.00	600.00	OFF	ON

Figure 4.1. Wall structure and physical properties of the layer materials

Water vapor permeability factor SR (μ) is determined as follows:

$$\mu = \frac{\delta_{p,air}}{\delta_{p,material}}$$

(4.1)

Where $\delta_{p,\,air}$ – water vapor permeability ratio of the air, taken $\delta_{p,\,air}$ =1,74·10^{-10} (kg/(Pa·S·m))

$\delta_{p,\,material}$ – water vapor permeability ratio of the material

For mineral wool $\delta_{p,\,l.c.}$ = 0,8·10^{-10} (kg/(Pa·S·m)):

$$\mu_{m,w,} = \frac{1,74 \cdot 10^{-10}}{0,8 \cdot 10^{-10}} = 2,175$$

For lightweight concrete $\delta_{p,\,l.c.}$ = 0,5·10^{-10} (kg/(Pa·S·m)):

$$\mu_{l.c.} = \frac{1,74 \cdot 10^{-10}}{0,5 \cdot 10^{-10}} = 3,48$$

For gypsum insulating plaster $\delta_{p,\,g.p.}$ = 0,29·10^{-10} (kg/(Pa·S·m)):

$$\mu_{l.c.} = \frac{1,74 \cdot 10^{-10}}{0,29 \cdot 10^{-10}} = 6,0$$

The physical characteristics of the wall structure are presented in table 4.2

Table 4.2. Physical characteristics of the wall structure

Information:	Value:
Thermal transmittance:	0.257 W/m2K
External surface resistance:	0.040 m2K/W
Internal surface resistance:	0.130 m2K/W
Angle (0-90) deg. :	90.000
Area:	1.00 m2
Thickness:	352.000 mm
Steam resistance:	1.527e+03 m2hPa/g
Steam transmittance:	6.548e-04 g/m2hPa
Thermal resistance:	3.885 m2K/W
Mass:	135.48 kg

Results of dew point risk analysis are presented as a distribution of the water vapor content within the wall structure. Figure 4.2 shows humidity curves. One of the curves relates to real water vapor distribution (g/m^3) within the wall structure. Another curve shows distribution of the maximal water vapor content (g/m^3). As long as curves do not intersect, there is no risk of dew point within the wall structure. In addition, figure 2.2 shows the temperature curve that indicates temperature distribution. Temperature of the internal surface (in point 4) is close to internal air temperature; therefore, there is no risk of mold growth.
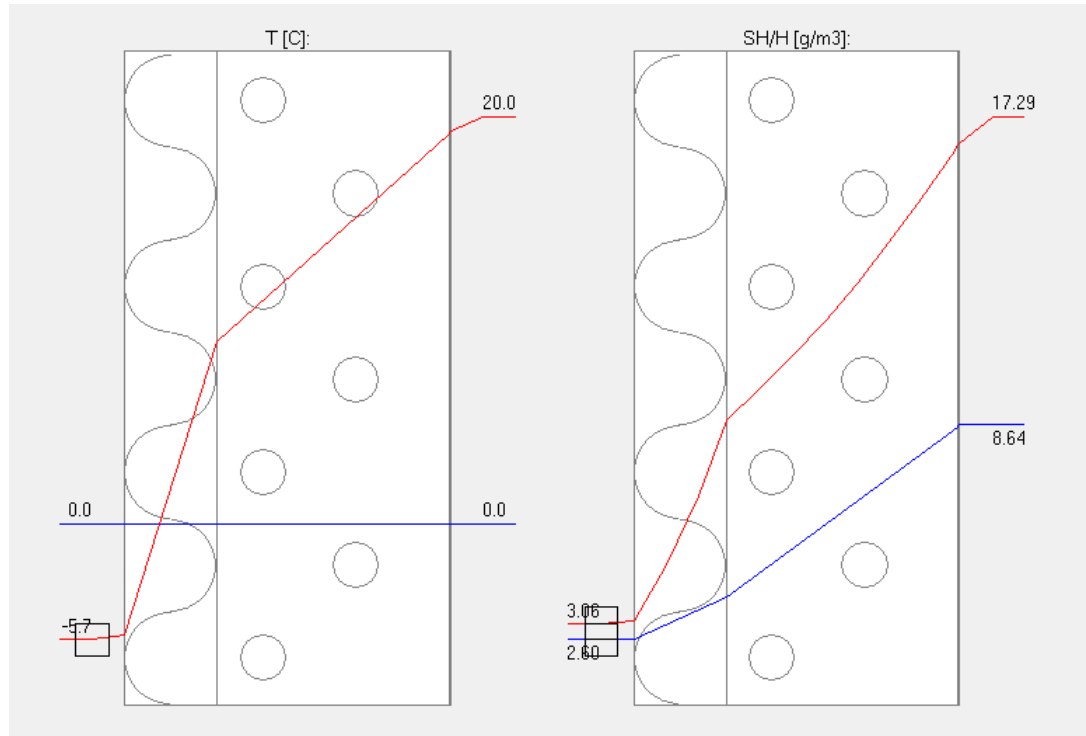
Temperature, water vapor content and humidity in the points of layers boundaries:

Point:	T(c):	SH [g/m3]:	H [g/m3]:	RH [%]:
E	-5.70	3.06	2.60	85.0
1	-5.47	3.12	2.60	83.4
2	8.91	8.77	3.80	43.3
3	19.19	16.48	8.58	52.0
4	19.25	16.54	8.64	52.2
I	20.00	17.29	8.64	50.0

T (°C) – temperature curve

SH (g/m^3) – maximal water vapor content

H (g/m^3) – real water vapor content

RH (%) – relative humidity within the wall structure

Figure 4.2. Temperature and humidity curves within the wall structure

2. Multi-layered wall with reinforced concrete core.

Initial data

The structure of the wall and physical properties of the layer materials are presented in figure 4.3.
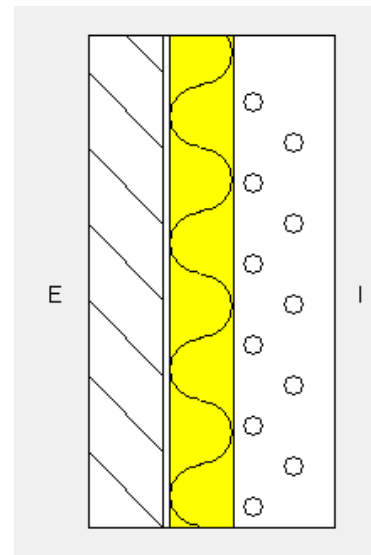
No.:	Layer:	T [mm]:	TC [W/mK]:	SR [-]	Price [euro/m	Mass [kg/m3]:	Thermal bridge:	Used in calculation:
1	Facade brick	120.00	0.5200	3.670000e+00	1.00	1200.00	ON	ON
2	Unventilated air layer 10 mm	10.00	0.0667	1.000000e+00	0.00	0.00	ON	ON
3	Penoplex 35 XPS	100.00	0.0320	3.480000e+01	0.00	35.00	ON	ON
4	Concrete B25	160.00	2.0400	2.096000e+01	0.00	2500.00	OFF	ON

Figure 4.3. Wall structure and physical properties of the layer materials

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Water vapor permeability factor SR (μ)

For facade brick $\delta_{p, f.b.}$ = 0,472·10^{-10} (kg/(Pa·S·m)):

$$\mu_{m,w,} = \frac{1,74 \cdot 10^{-10}}{0,472 \cdot 10^{-10}} = 3,67$$

For air layer $\delta_{p, air.}$ = 1,74·10^{-10} (kg/(Pa·S·m)):

$$\mu_{l.c.} = \frac{1,74 \cdot 10^{-10}}{1,74 \cdot 10^{-10}} = 1$$

For XPS insulation $\delta_{p, XPS}$ = 0,05·10^{-10} (kg/(Pa·S·m)):

$$\mu_{l.c.} = \frac{1,74 \cdot 10^{-10}}{0,05 \cdot 10^{-10}} = 34,8$$

For reinforced concrete $\delta_{p, r.c.}$ = 0,083·10^{-10} (kg/(Pa·S·m)):

$$\mu_{l.c.} = \frac{1,74 \cdot 10^{-10}}{0,083 \cdot 10^{-10}} = 20,96$$

The physical characteristics of the wall structure are presented in table 4.3.

Table 4.3. Physical characteristics of the wall structure

Information:	Value:
Thermal transmittance:	0.363 W/m2K
External surface resistance:	0.040 m2K/W
Internal surface resistance:	0.130 m2K/W
Angle (0-90) deg. :	90.000
Area:	1.00 m2
Thickness:	390.000 mm
Steam resistance:	1.012e+04 m2hPa/g
Steam transmittance:	9.885e-05 g/m2hPa
Thermal resistance:	2.753 m2K/W
Mass:	547.68 kg

The results of dew point risk analysis are presented as a distribution of the water vapor content within the wall structure. Figure 4.4 shows humidity curves. One of the curves relates to real water vapor distribution (g/m^3) within the wall structure. Another curve shows the distribution of the maximal water vapor content (g/m^3). As long as curves do not intersect, there is no risk of dew point within the wall structure. In addition, figure 2.4 shows temperature curve that indicates temperature distribution. The temperature of the internal surface (in point 4) is close to internal air temperature; therefore, there is no risk of mold growth.

Figure 4.4. Temperature and humidity curves within the wall structure
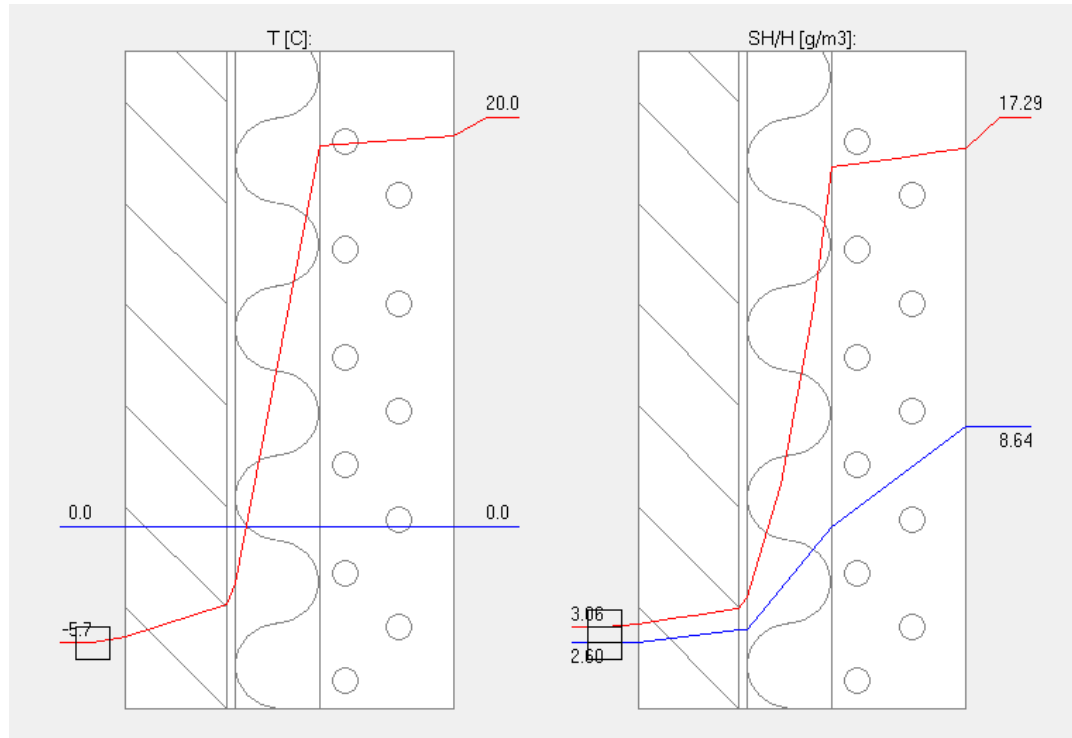
Temperature, water vapor content and humidity in the points of layers boundaries:

Point:	T(c):	SH [g/m3]	H [g/m3]:	RH [%]:	C [g/m2]:
E	-5.70	3.06	2.60	85.0	0.00
1	-5.43	3.13	2.60	83.1	0.00
2	-3.85	3.56	2.97	83.3	0.00
3	-2.82	3.87	2.98	76.9	0.00
4	18.57	15.89	5.86	36.9	0.00
5	19.11	16.41	8.64	52.7	0.00
I	20.00	17.29	8.64	50.0	0.00

T (°C) – temperature curve

SH (g/m^3) – maximal water vapor content

H (g/m^3) – real water vapor content

RH (%) – relative humidity within the wall structure

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3. Panel wall

<u>Initial data</u>

The structure of the panel wall and physical properties of the layer materials are presented in figure 4.5.
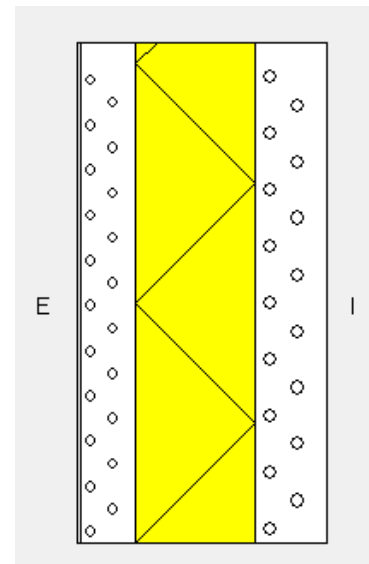
No.:	Layer:	T [mm]:	TC [W/mK]:	SR [-]	Price [euro/m3]:	Mass [kg/m3]:	Thermal bridge:	Used in calculation:
1	External plastering	5.00	0.1800	2.100000e+01	0.00	600.00	OFF	ON
2	Concrete B25	80.00	2.0400	2.096000e+01	0.00	2500.00	OFF	ON
3	EPS	170.00	0.0390	3.000000e+01	0.00	35.00	OFF	ON
4	Concrete B25	100.00	2.0400	2.096000e+01	0.00	2500.00	OFF	ON

Figure 4.5. Wall structure and physical properties of the layer materials

Water vapor permeability factor SR (μ)

For external plastering $\delta_{p, e.p.} = 0{,}0829 \cdot 10^{-10}$ (kg/(Pa·S·m)):

$$\mu_{m,w,} = \frac{1{,}74 \cdot 10^{-10}}{0{,}0829 \cdot 10^{-10}} = 21{,}0$$

For reinforced concrete $\delta_{p, c.l.} = 0{,}083 \cdot 10^{-10}$ (kg/(Pa·S·m)):

$$\mu_{l.c.} = \frac{1{,}74 \cdot 10^{-10}}{0{,}083 \cdot 10^{-10}} = 20{,}96$$

For EPS insulation $\delta_{p, EPS} = 0{,}058 \cdot 10^{-10}$ (kg/(Pa·S·m)):

$$\mu_{l.c.} = \frac{1{,}74 \cdot 10^{-10}}{0{,}058 \cdot 10^{-10}} = 30{,}0$$

The physical characteristics of the wall structure are presented in table 2.3.

Table 4.4. Physical characteristics of the wall structure

Information:	Value:
Thermal transmittance:	0.215 W/m2K
External surface resistance:	0.040 m2K/W
Internal surface resistance:	0.130 m2K/W
Angle (0-90) deg. :	90.000
Area:	1.00 m2
Thickness:	355.000 mm
Steam resistance:	1.247e+04 m2hPa/g
Steam transmittance:	8.020e-05 g/m2hPa
Thermal resistance:	4.645 m2K/W
Mass:	458.95 kg

The results of dew point risk analysis are presented as a distribution of the water vapor content within the wall structure. Figure 4.6 shows humidity curves. One of the curves relates to real water vapor distribution (g/m^3) within the wall structure. Another curve shows the distribution of the maximal water vapor content (g/m^3). Curves intersects inside the EPS insulation material, which means the risk of dew point within the wall structure and possibility of the deterioration of the wall insulating properties. In addition, figure 2.6 shows temperature curve that indicates temperature distribution. The temperature of the internal surface (in point 4) is close to internal air temperature; therefore, there is no risk of mold growth.

Figure 4.6. Temperature and humidity curves within the wall structure
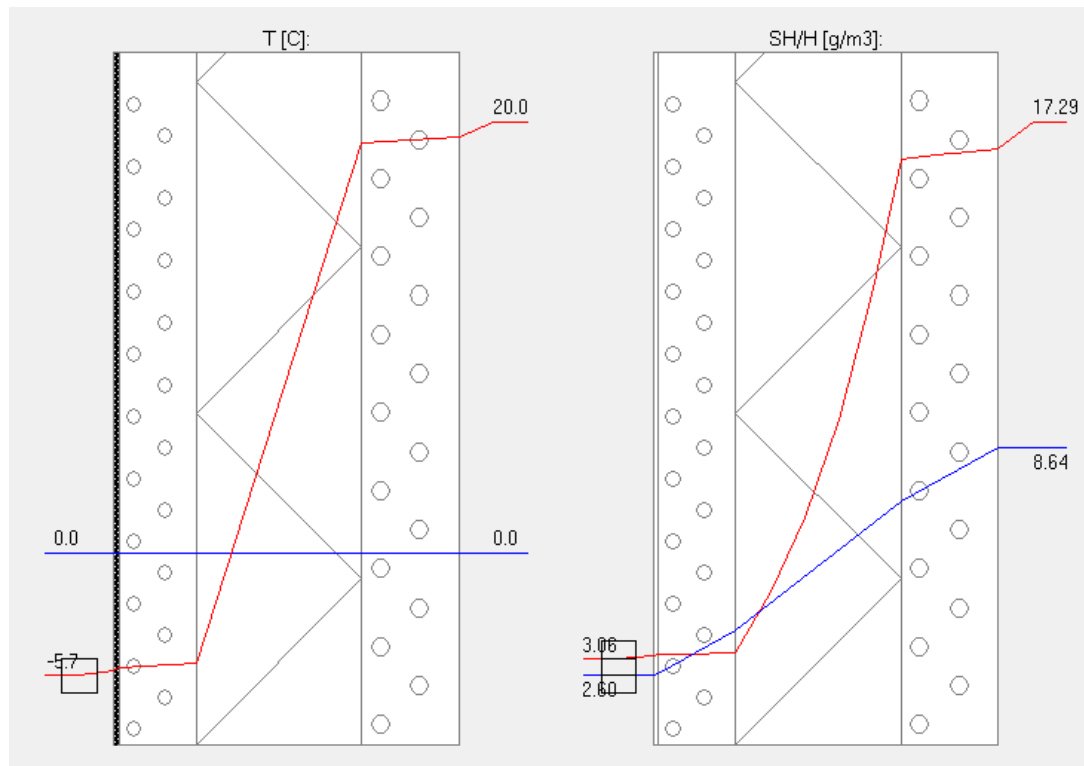
Temperature, water vapor content and humidity in the points of layers boundaries:

Point:	T(c):	SH [g/m3]	H [g/m3]:	RH [%]:	C [g/m2]:
E	-5.70	3.06	2.60	85.0	0.00
1	-5.48	3.12	2.60	83.5	0.00
2	-5.32	3.16	2.67	84.7	0.00
3	-5.11	3.22	3.80	100.0	34.44
4	19.01	16.31	7.23	44.3	0.00
5	19.28	16.57	8.64	52.2	0.00
I	20.00	17.29	8.64	50.0	0.00

T (°C) – temperature curve

SH (g/m^3) – maximal water vapor content

H (g/m^3) – real water vapor content

RH (%) – relative humidity within the wall structure

WuFi calculations

WuFi calculations allow analyzing water content within the wall structure during any period. It helps to access the risk of water accumulation within wall materials. Analysis of the water accumulation risk within the studied wall structures is accomplished for a 10-year period. Investigation of the temperature and relative humidity is produced for the borders of the layers. Fluctuations of the water content during investigation period are presented for individual materials and the whole wall structure. Properties of the materials are taken from WuFi material database.

1. Multi-layered wall with lightweight concrete.

Initial data

The structure of the wall and numbers of the observing positions (cameras) on the borders of the layers are presented in figure 5.1.
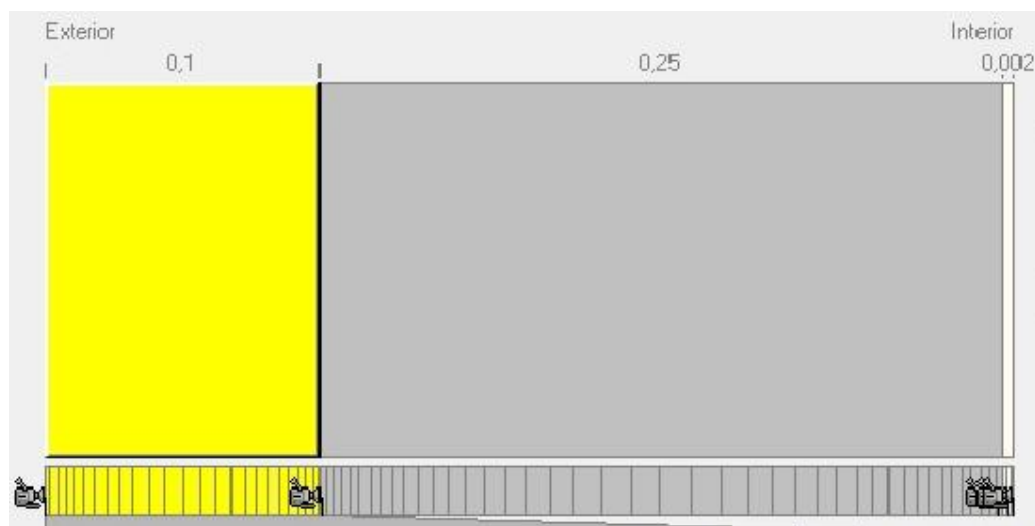
Figure 5.1. Structure of multi-layered wall with lightweight concrete

Position 1 – exterior surface;

Position 2 – mineral wool and lightweight concrete border;

Position 3 – lightweight concrete and gypsum insulating plaster border;

Position 4 – interior surface.

Here exterior surface of the element coincides with external surface of the mineral wool insulation layer. Ventilated air gap and façade brick layer are not taken into account during WuFi calculations. However, impact of precipitations on the insulation layer material is excluded.

Temperature and relative humidity calculations

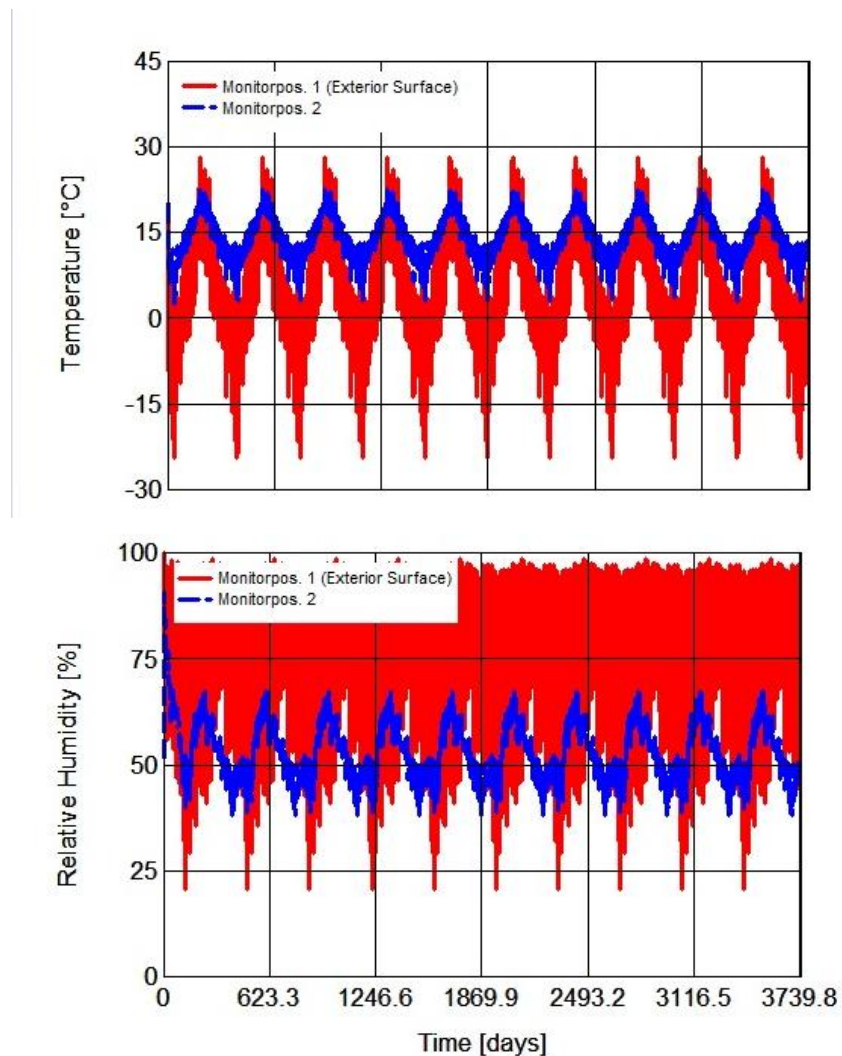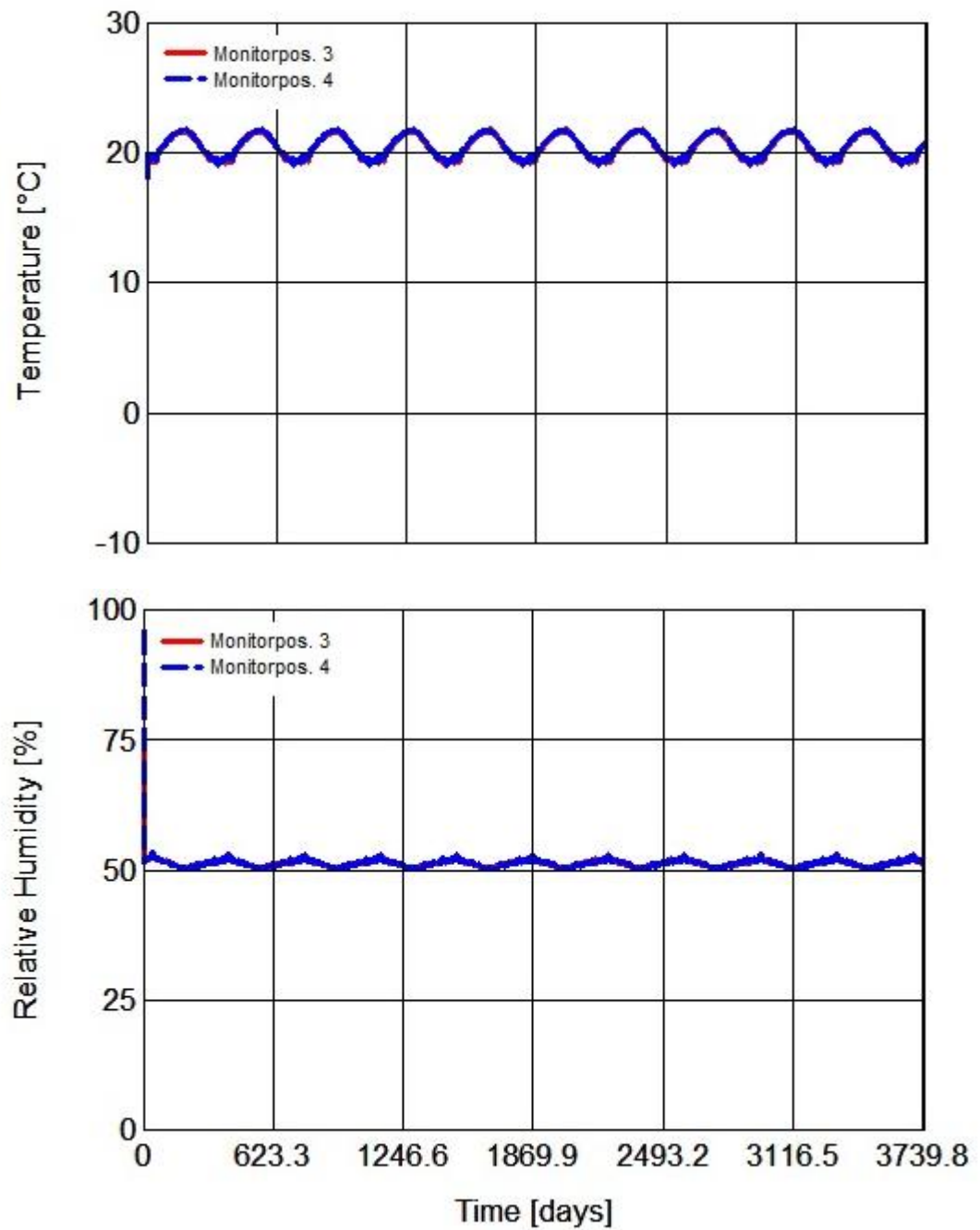Temperature and relative humidity curves for position 1 and position 2 are presented in figure 5.2.

Figure 5.2. Temperature and relative humidity curves for position 1 and position 2

Temperature and relative humidity curves for position 3 and position 4 are presented in figure 5.3.

Figure 5.3. Temperature and relative humidity curves for position 3 and position 4

Water content calculations

Water content curves and values for the individual materials are presented in figure 5.4.
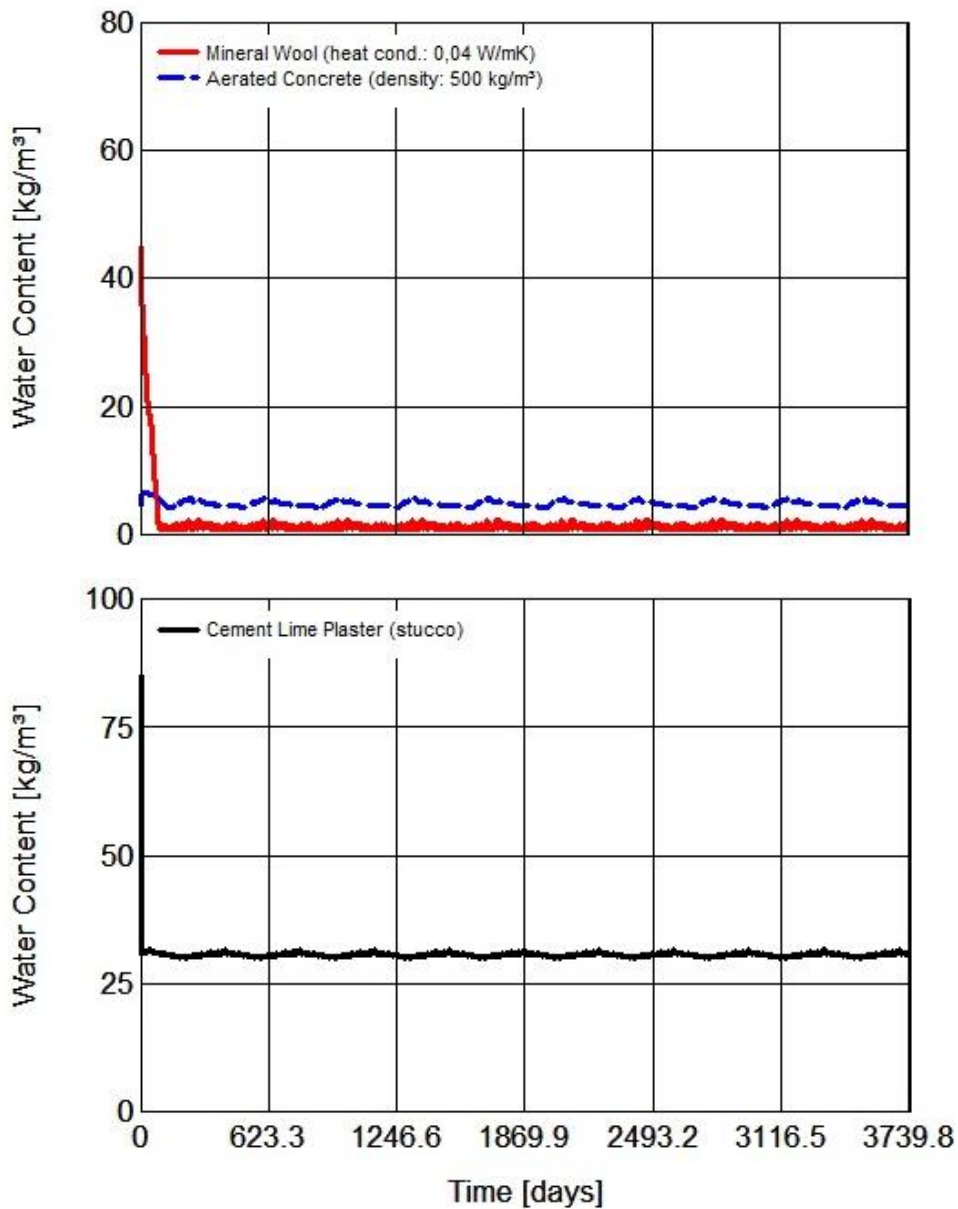
Water Content [kg/m³]				
Layer/Material	Start of Calc.	End of Calc.	Min.	Max.
Mineral Wool (heat cond.: 0,04 W/mK)	45,00	0,54	0,26	45,00
Aerated Concrete (density: 500 kg/m³)	4,50	4,42	4,09	6,55
Cement Lime Plaster (stucco)	85,00	30,81	30,04	85,00

Figure 5.4. Water content curves and values for the individual materials

The total water content curve for the wall structure is presented in figure 5.5.
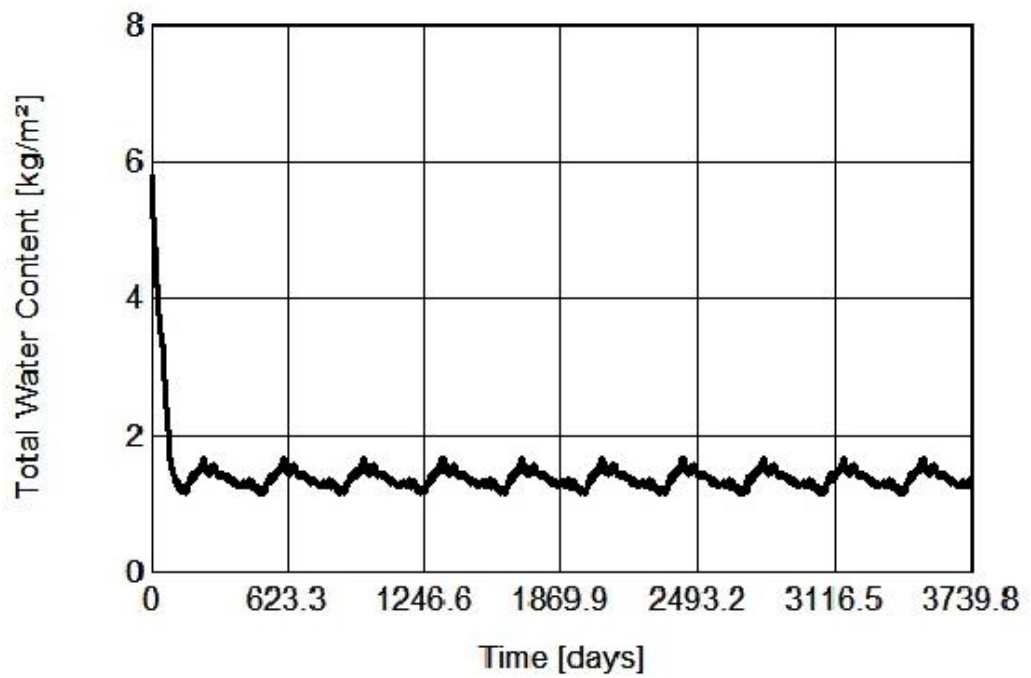
Figure 5.5. Total water content curve for the wall structure

Water content calculations show that there is no water accumulation within individual materials and the whole wall structure. Water content curves do not upraise during the calculation period.

2. Multi-layered wall with XPS insulation.

Initial data

The structure of the wall and numbers of the observing positions (cameras) on the borders of the layers are presented in figure 5.6.

Figure 5.6. Structure of multi-layered wall with XPS insulation

Position 1 – exterior surface;

Position 2 – facade brick and XPS insulation border;

Position 3 – XPS insulation and reinforced concrete core border;

Position 4 – interior surface.

Temperature and relative humidity calculations

The temperature and relative humidity curves for position 1 and position 2 are presented in figure 5.7.
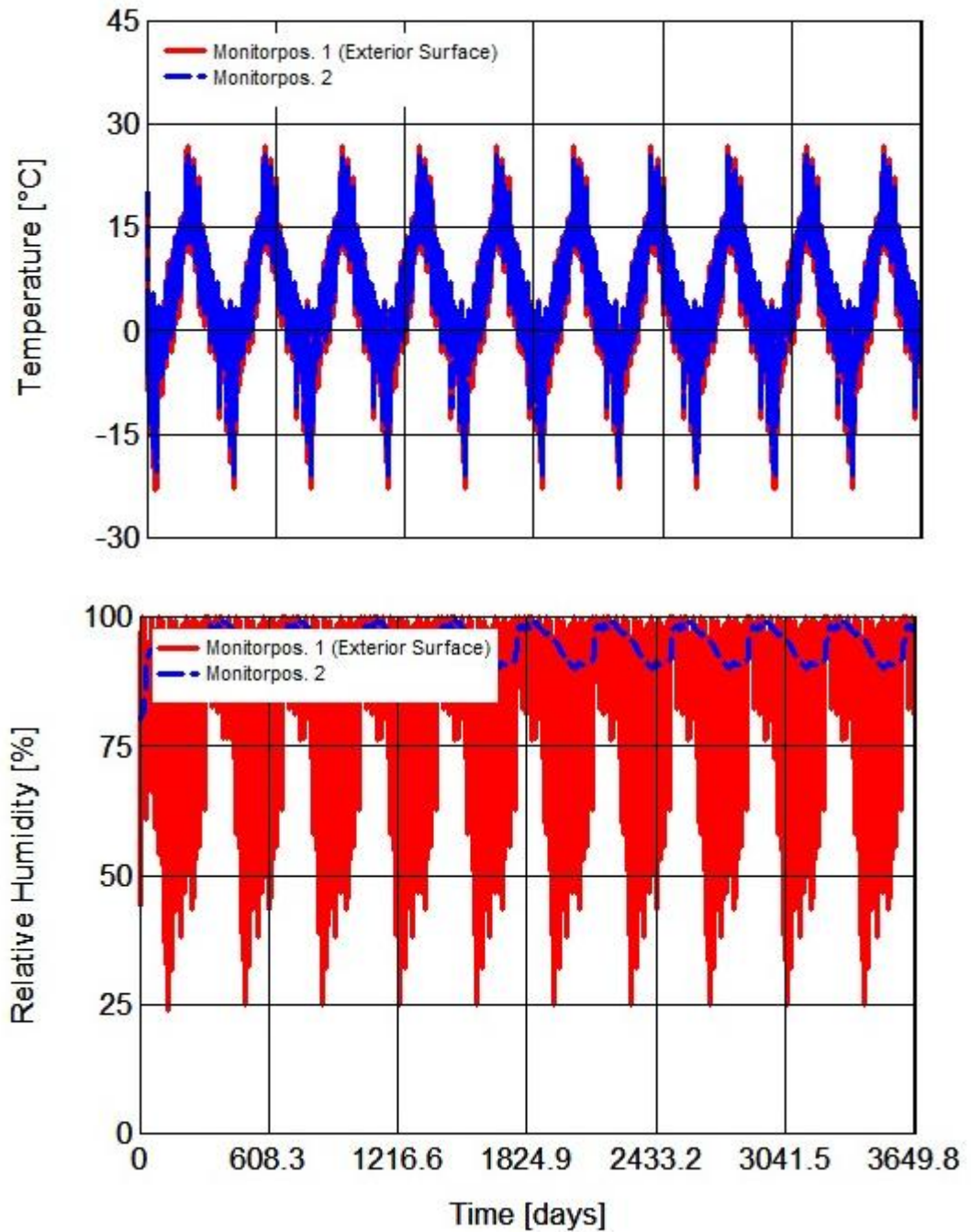
Figure 5.7. Temperature and relative humidity curves for position 1 and position 2

The temperature and relative humidity curves for position 3 and position 4 are presented in figure 5.8.
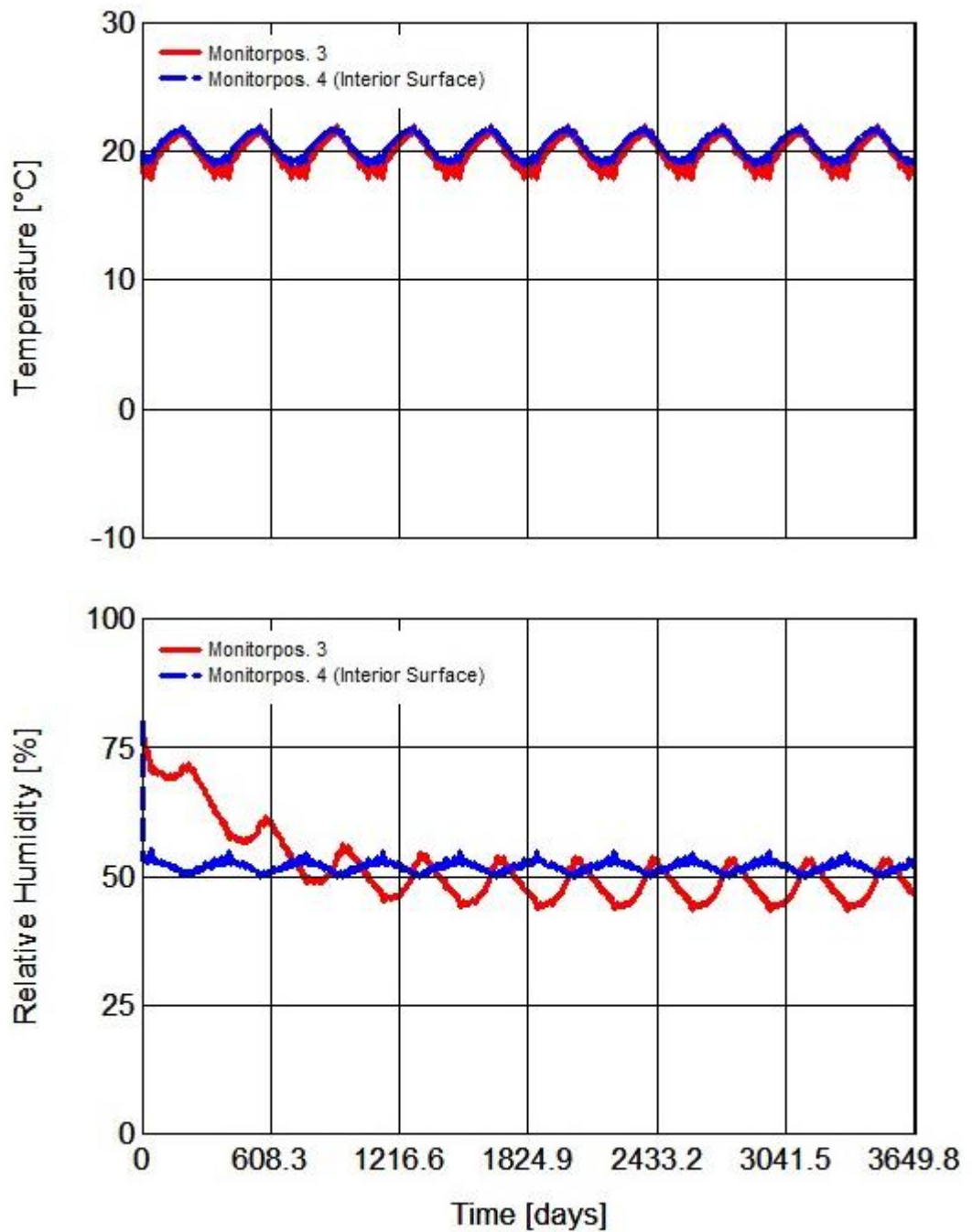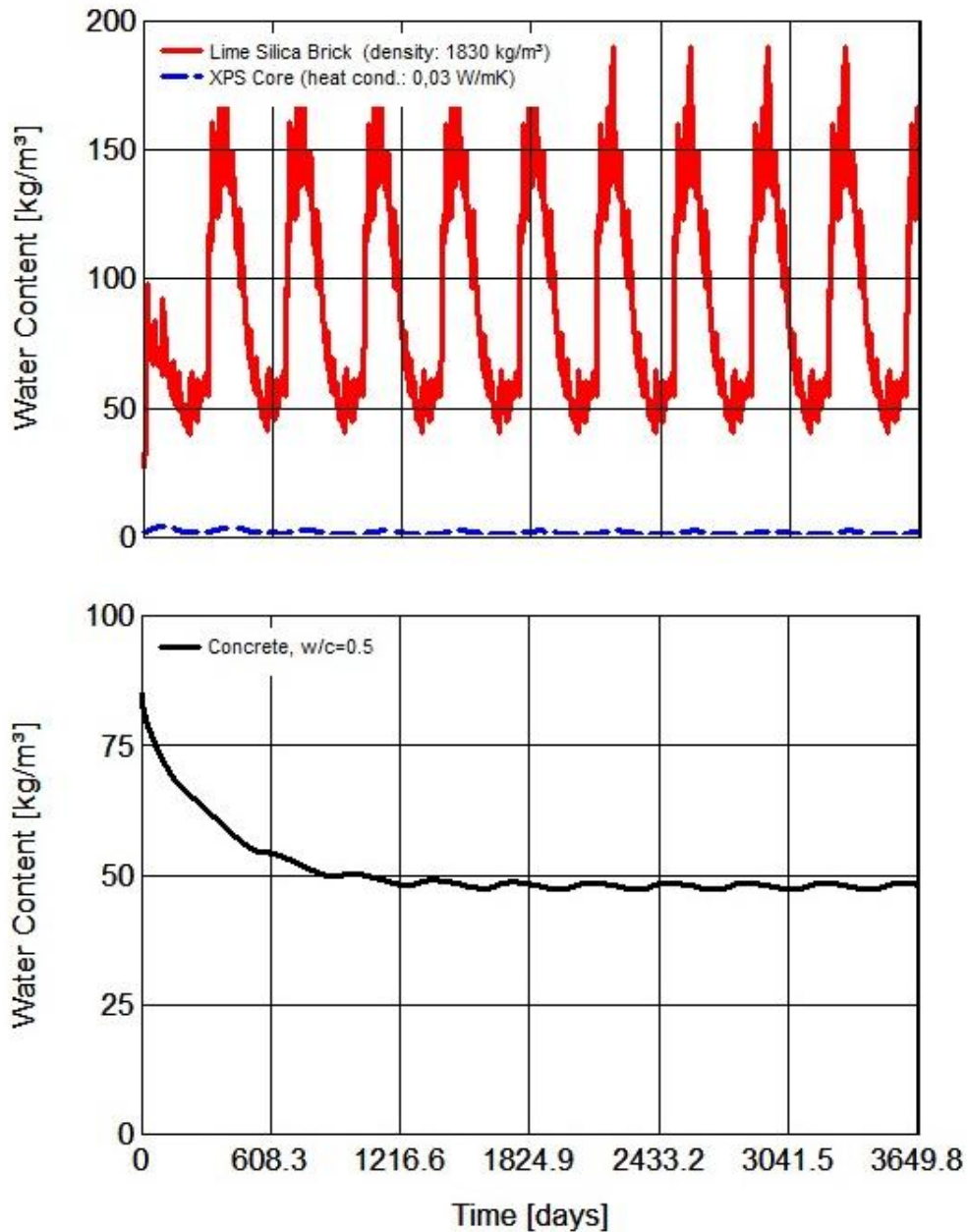

Figure 5.8. Temperature and relative humidity curves for position 3 and position 4

<u>Water content calculations</u>

The water content curves and values for the individual materials are presented in figure 5.9.

Water Content [kg/m³]				
Layer/Material	Start of Calc.	End of Calc.	Min.	Max.
Lime Silica Brick (density: 1830 kg/m³)	27,47	139,28	27,11	190,76
XPS Core (heat cond.: 0,03 W/mK)	1,79	2,11	1,32	4,01
Concrete, w/c=0.5	85,00	48,20	47,22	85,00

Figure 5.9. Water content curves and values for the individual materials

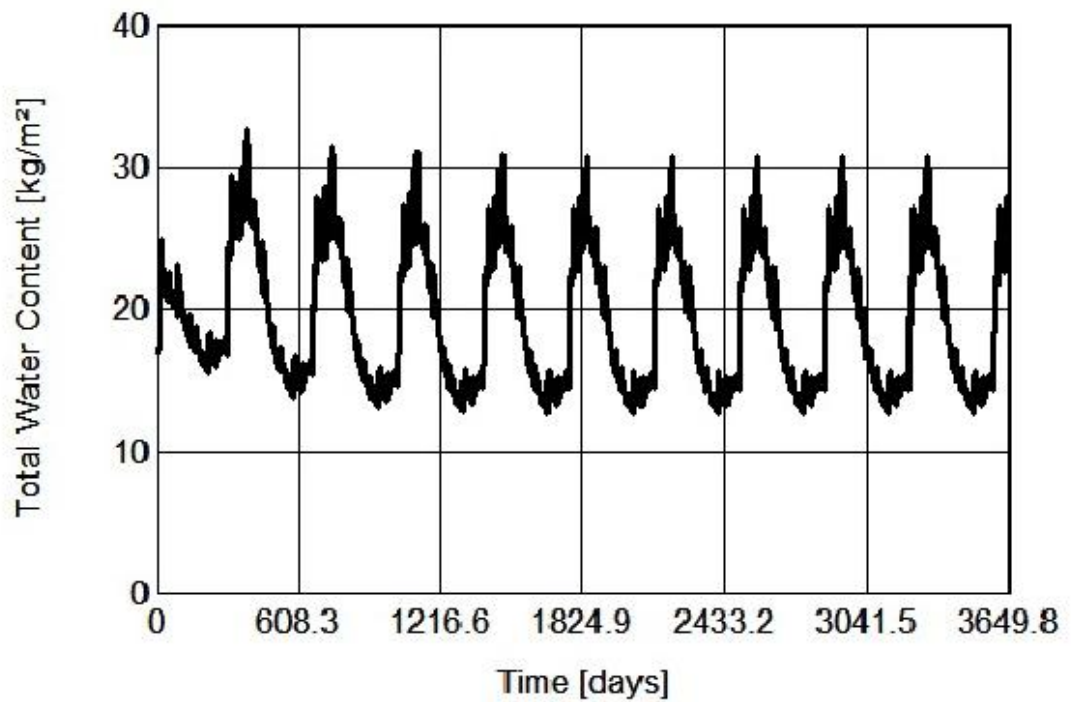The total water content curve for the wall structure is presented in figure 5.10.

Figure 5.10. Total water content curve for the wall structure

Water content calculations show that there is no water accumulation within individual materials and the whole wall structure. Water content curves do not upraise during the calculation period.

3. Panel wall.

<u>Initial data</u>

The structure of the wall and numbers of the observing positions (cameras) on the borders of the layers are presented in figure 5.11.
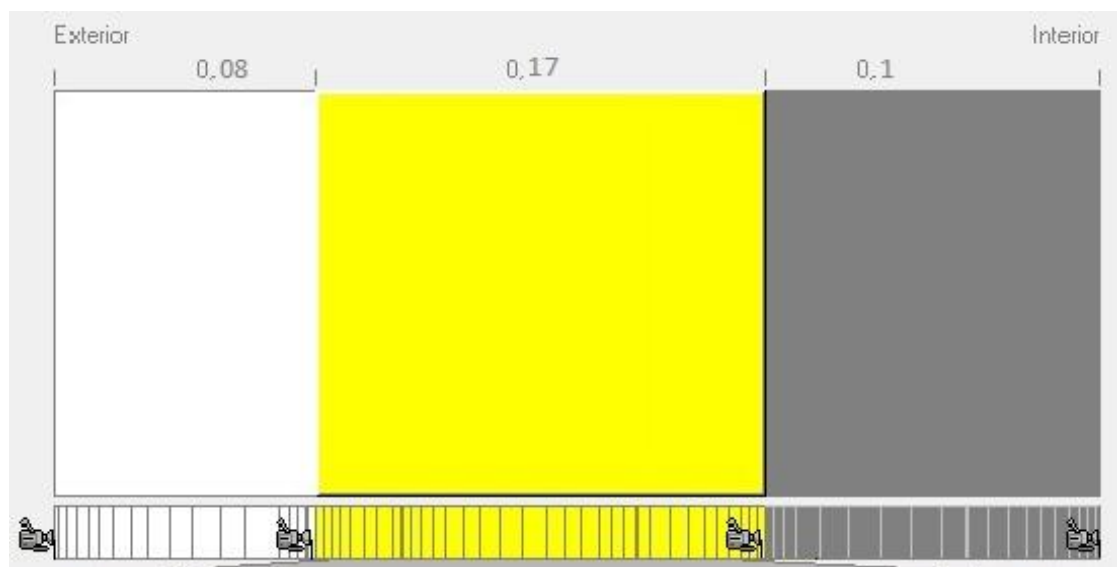

Figure 5.11. Structure of the panel wall

Position 1 – exterior surface;

Position 2 – protective concrete layer and EPS insulation border;

Position 3 – EPS insulation and concrete core border;

Position 4 – interior surface.

Temperature and relative humidity calculations

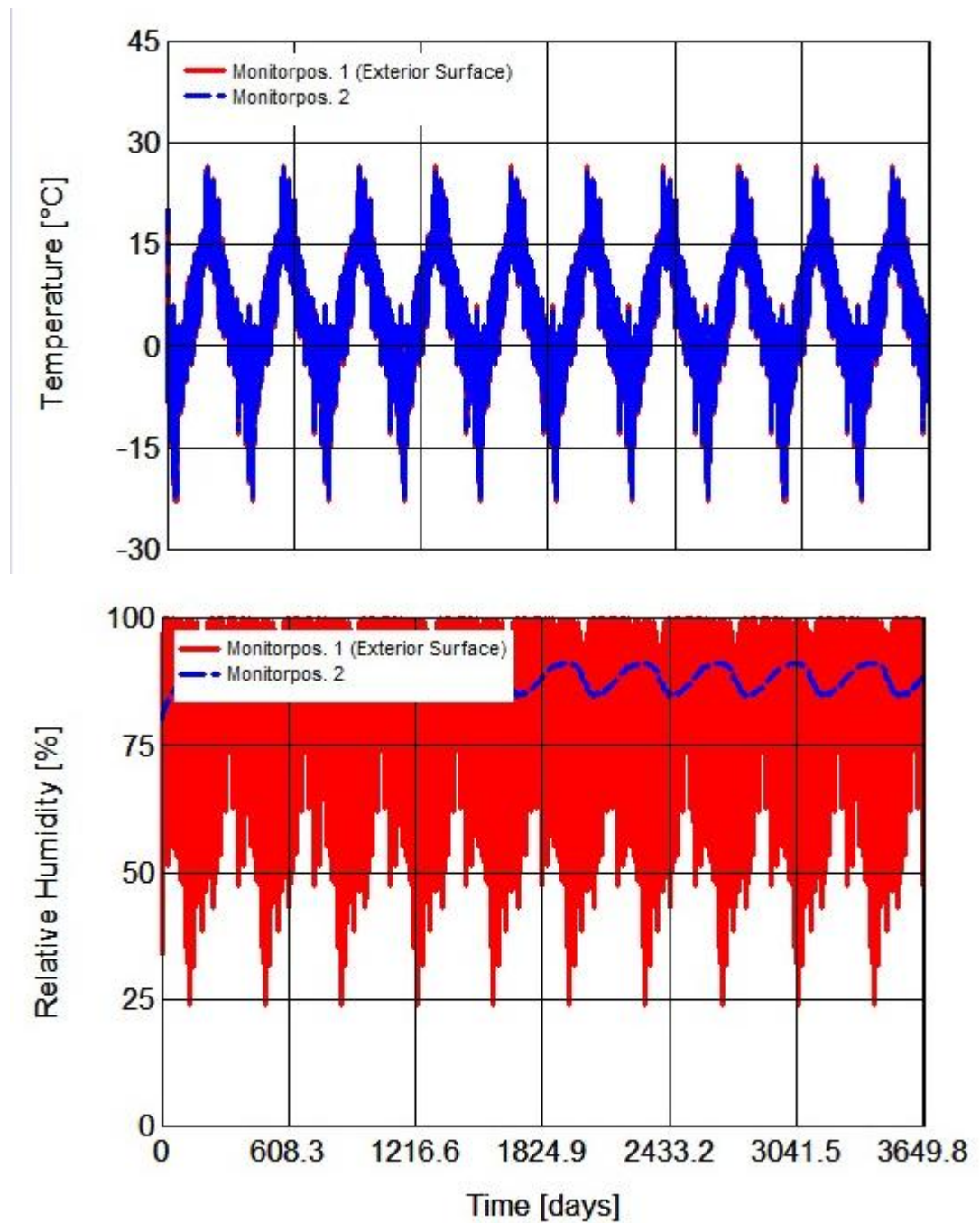The temperature and relative humidity curves for position 1 and position 2 are presented in figure 5.12.

Figure 5.12. Temperature and relative humidity curves for position 1 and position 2

The temperature and relative humidity curves for position 3 and position 4 are presented in figure 5.13.
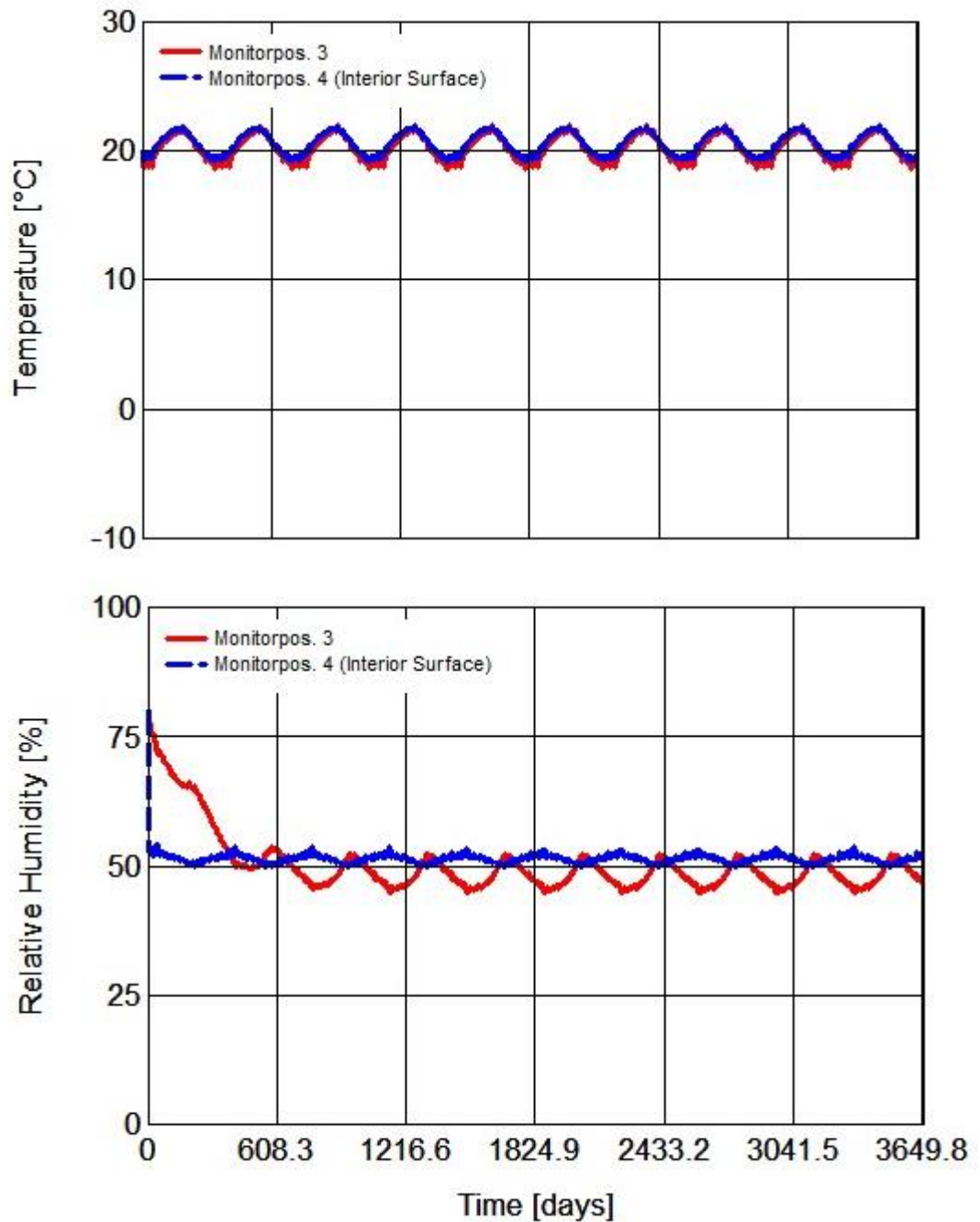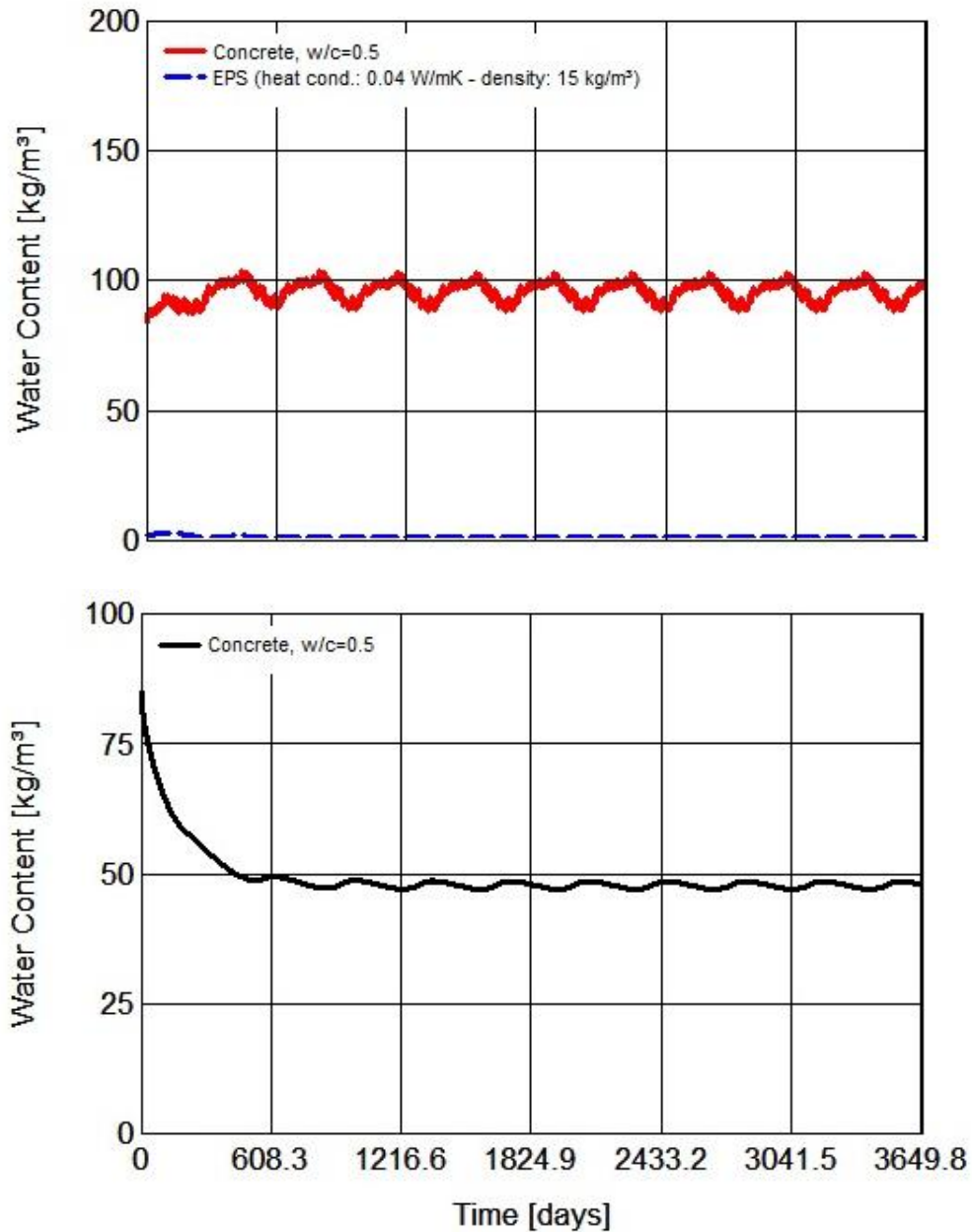

Figure 5.13. Temperature and relative humidity curves for position 3 and position 4

<u>Water content calculations</u>

The water content curves and values for the individual materials are presented in figure 5.14.

Water Content [kg/m³]				
Layer/Material	Start of Calc.	End of Calc.	Min.	Max.
Concrete, w/c=0.5	85,00	97,57	84,03	103,78
EPS (heat cond.: 0.04 W/mK - density: 15 kg/m³)	1,79	1,16	1,05	2,86
Concrete, w/c=0.5	85,00	47,99	47,09	85,00

Figure 5.14. Water content curves and values for the individual materials

The total water content curve for the wall structure is presented in figure 5.15.
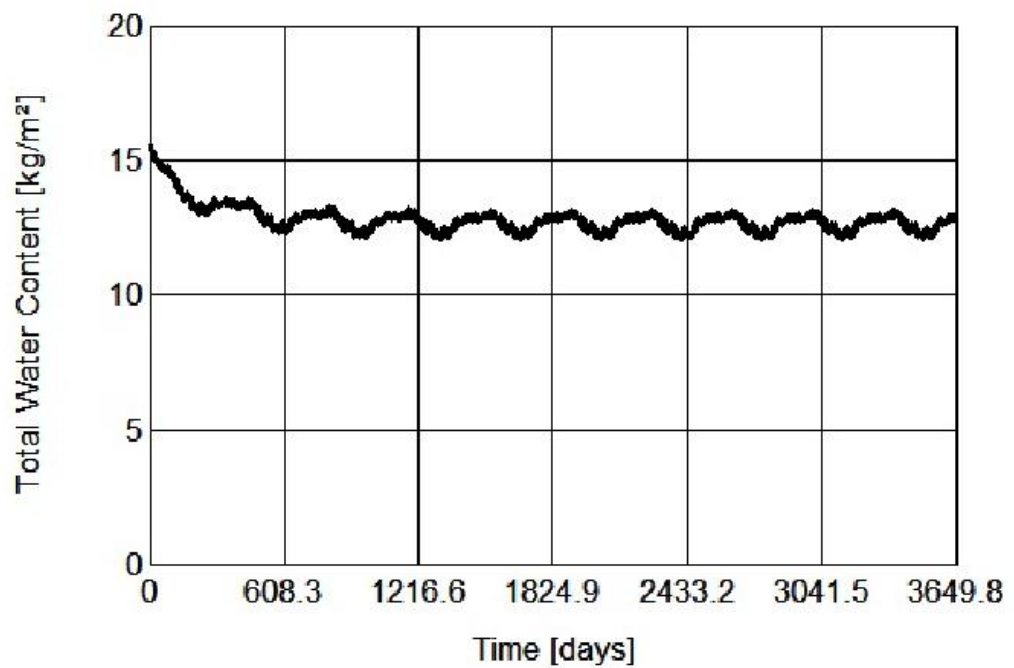
Figure 5.15. Total water content curve for the wall structure

Water content calculations show that there is no water accumulation within individual materials and the whole wall structure. Water content curves do not upraise during the calculation period.

Thermal resistance and physical properties calculations according to Russian norms

Climatic parameters

Design average interior temperature is taken t_{int} = 20 °C.

Design average exterior temperature of the 5 coldest days is taken t_{ext} = -26°C.

Duration of the heating season is taken z_{ht} = 220 days.

Design average exterior temperature during heating season is taken t_{ht} = -1,8°C.

Coefficients of the surface heat transfer

Coefficient of the heat transfer of the internal surface α_{int} = 8,7 (W/(m^2·°C)).

Coefficient of the heat transfer of the external surface α_{ext} =23 (W/(m^2·°C)).

Reference value of the thermal resistance

«Degree-days» G_d = (20 + 1,8)·220 = 4796 (°C·days).

Reference value of the thermal resistance:
R_{req} = 0,00035· 4796+ 1,4 = *3,079* (m^2·°C/W).

1. Multi-layered wall with lightweight concrete.

Wall structure, layers properties and scheme of fastening see Appendix 3. Physical properties of the materials are presented in table 6.1. Façade brick and air gap properties are not taken into account as long as air gap is ventilated.

Table 6.1. Physical properties of the materials

Material	Layer thickness δ, (m)	Coefficient of the heat transfer of the dry material. λ_0, (W/(m·°C))	Design coefficient of the heat transfer of the material. λ_W, (W/(m·°C))	Density γ_0, (kg/m³)	Water vapor permeability ratio, μ (mg/m·hour· Pa).
Mineral wool insulation Rockwool	0,1	0,036	0,045	100	0,3
Lightweight concrete	0,25	0,14	0,12	500	0,2
Gypsum plaster VetonitTT	0,004	0,41	0,64	1400	0,11

Fastening steel bars:

Coefficient of the heat transfer λ_w = 58 (W/(m·°C))

Heat capacity C=0,482 (kJ/(kg·°C));

Density γ_0=7850 (kg/m³).

The ratio of the fasteners containment (in 1 m² of the wall structure) for:

-Insulation 0,012%

-Lightweight concrete 0,008%

Design thermal resistance

Thermal resistance of the insulation layer:

$$R_y = \frac{\delta_y}{\lambda_y} = \frac{0,1}{0,045} = 2,2222 (\frac{m^2 \cdot {}^\circ C}{W})$$

Thermal resistance of the fasteners penetrating insulation layer:

$$R_{My} = \frac{\delta_{My}}{\lambda_M} = \frac{0,1}{58} = 0,0017 (\frac{m^2 \cdot {}^\circ C}{W})$$

Total area of the fasteners per 1 m² of the wall structure is determined by equation:

$$A_2 = n \cdot \pi \cdot r^2 \qquad (6.1)$$

where A_2 – total area of the fasteners per 1 m² of the wall structure (m²);

n – amount of fasteners per 1 m² of the wall structure, 2,4 (pieces);

r – radius of the bars, 0,004 (m).

$$A_2 = 2,4 \cdot 3,14 \cdot 0,004^2 = 1,2 \cdot 10^{-4} (m^2)$$

Area of the homogeneous part of the insulation layer:

$$A_1 = 1 - 0,00012 = 0,999888 (m^2)$$

Design thermal resistance of the inhomogeneous layer is determined by equation:

$$R_0^{\,r} = A / \sum_{i=1}^{i=m} (A_i / R^r_{0,i}), \qquad (6.2)$$

where A – total area of the inhomogeneous layer, taken 1 (m²);

A_i – area of the homogeneous parts of the wall (m²);

$R^r_{0,I}$ – thermal resistance of the homogeneous parts of the wall ((m²·°C)/W)

Design thermal resistance of the inhomogeneous insulation layer:

$$R_1^{\,r} = \frac{1}{\dfrac{0,99988}{2,2222} + \dfrac{0,00012}{0,0017}} = 1,9211 (\frac{m^2 \cdot {}^\circ C}{W})$$

Steel fasteners penetrate lightweight concrete layer only for 160 mm. Therefore, we can separate layer to homogeneous part without fasteners (90 mm) and inhomogeneous part with fasteners (160 mm).

For inhomogeneous part thermal resistance of the lightweight concrete:

$$R_{e1} = \frac{\delta_{e1}}{\lambda_e} = \frac{0,16}{0,12} = 1,3333 (\frac{m^2 \cdot °C}{W});$$

Thermal resistance of the steel fasteners:

$$R_{\text{м}e1} = \frac{\delta_{\text{м}e1}}{\lambda_{\text{м}}} = \frac{0,16}{58} = 0,0028 (\frac{m^2 \cdot °C}{W})$$

Design thermal resistance of the inhomogeneous lightweight concrete layer:

$$R_2^r = \frac{1}{\dfrac{0,99988}{1,3333} + \dfrac{0,00012}{0,0028}} = 1,2614 (\frac{m^2 \cdot °C}{W}).$$

Design thermal resistance of the homogeneous lightweight concrete layer:

$$R_3^r = \frac{0,09}{0,12} = 0,75 (\frac{m^2 \cdot °C}{W})$$

Desigh thermal resistance of the wall:

$R_0 = 1/\alpha_{int} + R_1^r + R_2^r + R_3^r + 1/\alpha_{ext} =$
$= 1/8,7 + 1,9211 + 1,2614 + 0,75 + 1/10,8 = 4,14$ (m²·°C/W).

Design thermal resistance of the wall structure is higher than reference thermal resistance (4,14>3,079). Requirement is satisfied.

<u>Verification of the internal surface temperature level</u>

Difference between internal air temperature and temperature of the internal surface of the wall:

$$\Delta t_0 = \frac{1 \cdot (20 + 26)}{4,146 \cdot 8,7} = 1,28 \ (°C).$$

Maximum demaded value is 4°C. Therefore, requirement is satisfied.

Temperature of the internal surface:

t_{int}=20-1,28=18,72 (°C).

Temperature of the dew point for internal conditions is t_{dp}=10,69 (°C).

t_{int}> t_{dp}, therefore, there is no risk of the internal surface moistening.

<u>Verification of the thermal stability of the wall</u>

Results of the coefficients of the heat absorption ability (s), indexes of the heat lag (D) and design thermal resistances (R) calculations of the wall layers are presented in table 6.2

Table 6.2. Coefficients of the heat absorption ability (s), indexes of the heat lag (D) and thermal resistances of the wall layers

N	Material	Layer thickness δ, (m)	Density γ_0, (kg/m³)	Coefficient of heat absorption ability s, (W/(m²·°C))	Design thermal resistance R, (m²·°C/W)	Index of the heat lag D
1	Mineral wool insulation Rockwool	0,1	100	6,47	0,00625	0,04
2	Lightweight concrete	0,25	500	2,03	2,0114	3,62
3	Gypsum plaster VetonitTT	0,004	1400	1,72	1,9211	3,30
						Sum:6,96

$D_1<1$, $D_1+D_2\geq1$. Therefore, zone of sharp fluctuations is situated in layer 1 and 2.

Coefficient of the internal surface heat assimilation ability:

$$Y_{int}=\frac{0,00625\cdot6,47^2+2,03}{1+0,00625\cdot2,03}=2,26(\frac{W}{m^2\cdot°C})$$

Index of the internal surface heat absorption ability:

$$B=\frac{1}{\frac{1}{5,7}+\frac{1}{2,26}}=1,62\ (W/(m^2\cdot°C)).$$

Design swings of the indoor temperature:

$A_t^{des}=0,1\cdot(20+26)/(1,62\cdot4,146)=0,685\ (°C)$

$A_t^{des}=0,685\ (°C) < A_t^{req}=1,5\ (°C)$. Therefore, wall structure satisfies the demand to thermal stability during cold period of the year.

Verification of the air penetration resistance ability.

Specific weight of the external and internal air:

$\gamma_{ext}=3463/(273-26)=14,02\ (N/m^3)$;

$\gamma_{int}=3463/(273+20)=11,82\ (N/m^3)$.

Difference of air pressure on external and internal surfaces of the wall structure:

$\Delta p=0,55\cdot26\cdot(14,02-11,82)+0,03\cdot14,02\cdot4,2^2=38,88\ (Pa)$.

Demanded air penetration resistance:

$J^{req}=38,88/0,5=77,76\ (m^2\cdot hour\cdot Pa/kg)$.

Design values of the air penetration resistance ability of the wall layers are presented in table 6.3

Table 4.3. Design values of the air penetration resistance ability of the wall layers

Material	Layer thickness δ, (m)	Density Y_0, (kg/m³)	Design air penetration resistance J^{des}, (m²·hour·Pa/kg).
Gypsum plaster VetonitTT	0,004	1400	373
Lightweight concrete	0,25	500	1960
			Sum:2333

$J^{des} > J^{req}$ (2333>77,76). Therefore, demand is satisfied.

<u>Verification of the water vapor penetration resistance</u>

Partial pressure of the saturated water vapor on conditions of the design internal temperature (t_{int}=20°C) is E_{int}=2338 (Pa).

Water vapor partial pressure on conditions of design internal parameters:

e_{int}=(55/100)·2338=1285,9 (Pa).

Parameters of the year periods for Saint-Petersburg region:

1) Winter period (January and February).

Amount of months z_1 = 2 (months);

Average temperature of the external air t_1 = (-7,8-7,8)/2=-7,8 (°C);

Temperature in the plane of the possible condensation

τ_1 = 20 - (20 + 7,8)·(0,115 + 3,939) / 4,146= -7,2 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation

E_1 = 332 (Pa).

2) Autumn-spring season (October, November, December, March, April).

Amount of months z_2 = 5 (months);

Average temperature of the external air

t_2 = (-3,9+3,1+4,9+(-0,3)+(-5)) /5 = -0,24 (°C);

Temperature in the plane of the possible condensation

τ_2 = 20 - (20+0,24)·(0,115 + 3,939) / 4,146 = 0,2 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation E_2 =620 (Pa).

3) Summer period (May, June, July, August, September).

Amount of months z_3 = 5 (months);

Average temperature of the external air

t_3 = (9,8 + 15+ 17,8+16 + 10,9) / 5 = 13,9 (°C);

Temperature in the plane of the possible condensation

τ_3 = 20 - (20 -13,9)·(0,115 + 3,939) / 4,146 = 14,03 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation E_3 =1629 (Pa).

Water vapor partial pressure in the plane where dew point is possible to appear during one year period of expluatation:

E = (332·2 + 620·5 + 1629·5) / 12 = 992,42 (Pa).

External surface of the wall is taken as an external surface of the insulation layer. Water vapor penetration resistance of the layers between external surface of the wall structure and plane where dew point is possible to appear can be taken as Ω_{ext}=13,3·10^{-3} (m2·hour·Pa /mg). Average external air water vapor partial pressure during one year of the exploitation e_{ext}^{av}=600 (Pa).

Required water vapor resistance Ω_{req}^{*}:

$$\Omega_{req}^{*} = \frac{(1285{,}9 - 992{,}42) \cdot 0{,}013}{(992{,}42 - 600)} = 0{,}0097(Pa \cdot hour \cdot m^2 / g).$$

To determine Ω_{req}^{**} consider period with month average temperatures below 0°C.

Duration of the period z_0 = 151 days (January, February, March, November, December).

Average temperature of the external air t_0 = -4,96 (°C).

Temperature in the plane of the possible condensation

τ_0 = 20 - (20 + 4,96)·(0,115 + 3,939) / 4,146=-4,4 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation E_0 =423 (Pa).

External air water vapor average partial pressure during period with external air temperature below zero e_0^{ext}=300 (Pa).

Coefficient η:

η = 0,0024·(423–300)·151/0,013 = 3429

$$\Omega_{req}^{**} = \frac{0{,}0024 \cdot 151 \cdot (1285{,}9 - 423)}{100 \cdot 0{,}0667 \cdot 3 + 3489} = 0{,}089(Pa \cdot hour \cdot m^2 / g)$$

Design values of the water vapor permeability ratio and water vapor penetration resistance of the wall layers are presented in table 6.4.

Table 6.4. Design values of the of the water vapor permeability ratio and water vapor penetration resistance of the wall layers

N	Material	Layer thickness δ, (m)	Water vapor permeability ratio μ, (mg/m·hour·Pa)	Design water vapor penetration resistance Ω, (m2·hour·Pa /mg)
1	Gypsum plaster VetonitTT	0,004	0,11	0,036
2	Lightweight concrete	0,25	0,2	1,25
3	Mineral wool insulation Rockwool	0,1	0,3	0,333
			Sum	1,619

Design water vapor penetration resistance of the wall Ω_o:

$\Omega_o = 26{,}6 \cdot 10^{-3} + 1{,}619 + 13{,}3 \cdot 10^{-3} = 1{,}659$ (m^2·hour·Pa /mg).

Design water vapor penetration resistance of the layers between internal surface of the wall and external surface of the insulation layer :

$\Omega_{rp} = 26{,}6 \cdot 10^{-3} + 1{,}619 = 1{,}646$ (m^2·hour·Pa /mg).

$\Omega_{rp} > \Omega_{req}^{*}$ and $\Omega_{rp} > \Omega_{req}^{**}$. Requirement is satisfied.

Verification of the dew point possibility in wall structure

For design internal parametrs (t_{int} = 20 (°C), φ_{int} = 55%), partial pressure of the saturated water vapor E_{int} = 2338 (Pa). Partial pressure of the water vapor on the internal surface of the wall:

e_{int} = (55 / 100)2338 = 1285,9 (Pa)

Design external parametrs are taken for the coldest month (January). Average month temperature t_{ext} = -7,8 (°C) , humidity φ_{int} = 86 %. Partial pressure of the

saturated water vapor E_{int} = 315 (Pa). Partial pressure of the water vapor on the external surface of the wall:

e_{ext} = (86/100)·315 = 271 (Pa).

Determine parameters (τ_i and E_i) on the layers borders starting from internal surface of the wall to external.

1) τ_{int} = 20 - (20 + 7,8)·0,115 / 4,146 = 19,23 (°C);

   E^{τ}_{int} = 2226 (Pa);

2) τ_{1-2} = 20 - (20 + 7,8)·(0,115 + 0,00625) / 4,146= 19,2 (°C);

   E_{1-2} = 2225 (Pa);

3) τ_{2-3} = 20 - (20 + 7,8)·(0,115 + 0,00625+2,0114) / 4,146= 5,7 (°C);

   E_{2-3} = 916 (Pa);

4) τ_{ext} = 20 - (20 + 7,8)·(0,115 + 0,00625+2,0114+1,9211) /4,146=-7,18 (°C);

   E^{τ}_{ext} = 332 (Pa).

Partial pressure of the water vapor on layers borders:

e_i= 1285,9– (1285,9–271)(0,0266+ΣΩ$_i$)/1,619=1285,9-626,87(0,0266+ΣΩ$_i$).

Dew point calculations are executed with the help of the "I-d" diagram. Results of the dew point calculation are presented in table 6.5.

Table 6.5. Results of the dew point calculation

Layers border	x, (m)	ΣR_i, (m²·°C/W)	τ_i, (°C)	E_i, (Pa)	$\Sigma \Omega_i$, (m²·hour· Pa/mg)	e_i, (Pa)	t^{dp}, (°C)
int-1	0	0	19,23	2226	0	1269,22	10,5
1-2	0,004	0,00625	19,2	2225	0,036	1246,66	10,1
2-3	0,254	2,018	5,7	916	1,286	463,07	-3,5
3- *ext*	0,354	3,939	-7,2	332	1,619	254,32	-10,7

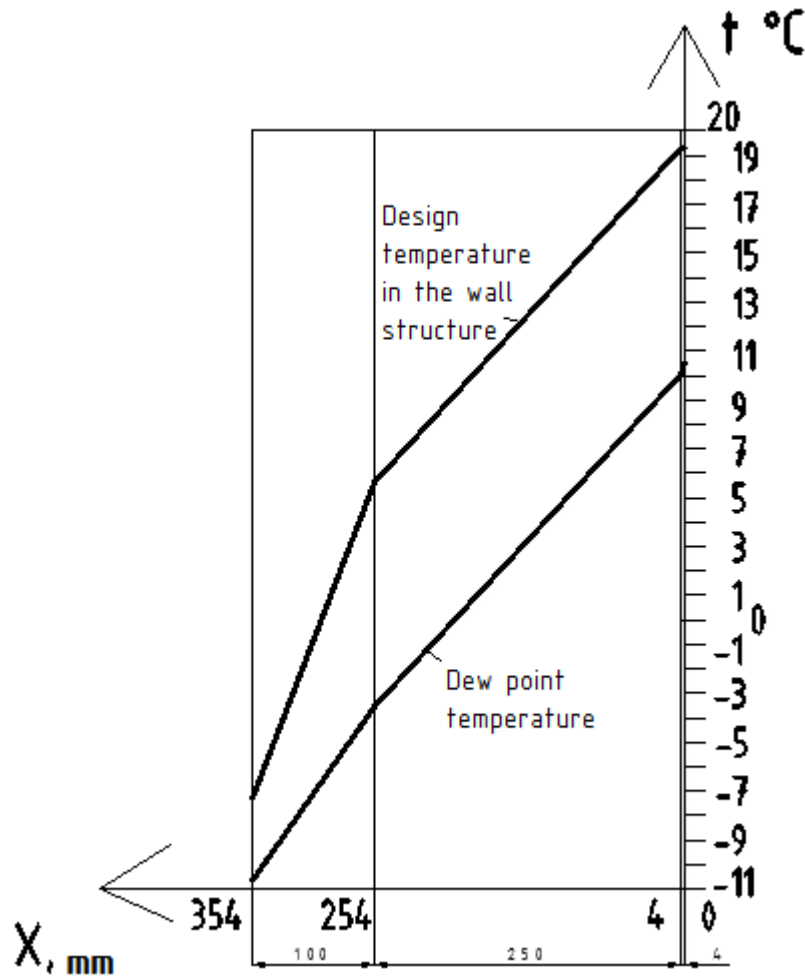Figure 6.1 presents temperature curves inside the wall structure.

Figure 6.1. Temperature curves inside the wall structure.

As long as curves do not intersect there in no risk of the dew point inside the wall structure.

2. Multi-layered wall with XPS insulation

Wall structure, layers properties and scheme of fastening see Appendix 3. Physical properties of the materials are presented in table 6.6.

Table 6.6. Physical properties of the materials

Material	Layer thickness δ, (m)	Coefficient of the heat transfer of the dry material. λ_0, (W/(m·°C))	Design coefficient of the heat transfer of the material. λ_W, (W/(m·°C))	Density γ_0, (kg/m³)	Water vapor permeability ratio, μ (mg/m·hour·Pa).
Silica facade brick	0,12	0,35	0,52	1200	0,16
Unventilated air gap	0,01	-	-	-	-
XPS insulation	0,1	0,03	0,032	35	0,018
Reinforced concrete	0,16	1,69	2,04	2500	0,03

Fastening steel bars:

Coefficient of the heat transfer λ_w = 58 (W/(m·°C))

Heat capacity C=0,482 (kJ/(kg·°C));

Density γ_0=7850 (kg/m³).

The ratio of the fasteners containment (in 1 m² of the wall structure) for:

-Insulation 0,012%

-Air gap 0,012

-Facade brick 0,01%

<u>Design thermal resistance</u>

Thermal resistance of the façade brick layer:

$$R_1 = \frac{0,12}{0,52} = 0,2308(\frac{m^2 \cdot °C}{W})$$

Thermal resistance of the air gap:

$$R_y = 0{,}15(\frac{m^2 \cdot {}^\circ C}{W})$$

Thermal resistance of the fasteners penetrating air gap:

$$R_{My} = \frac{\delta_{My}}{\lambda_M} = \frac{0{,}01}{58} = 0{,}00017(\frac{m^2 \cdot {}^\circ C}{W})$$

Total area of the fasteners per 1 m² of the wall structure (m²):

$$A_2 = 2{,}4 \cdot 3{,}14 \cdot 0{,}004^2 = 1{,}2 \cdot 10^{-4}(m^2)$$

Area of the homogeneous part of the air gap:

$$A_1 = 1 - 0{,}00012 = 0{,}999888(m^2)$$

Design thermal resistance of the inhomogeneous air gap:

$$R_2{}^r = \frac{1}{\dfrac{0{,}99988}{0{,}15} + \dfrac{0{,}00012}{0{,}00017}} = 1{,}9211(\frac{m^2 \cdot {}^\circ C}{W})$$

Thermal resistance of the insulation layer:

$$R_y = \frac{\delta_{My}}{\lambda_M} = \frac{0{,}1}{0{,}032} = 3{,}125(\frac{m^2 \cdot {}^\circ C}{W})$$

Thermal resistance of the fasteners penetrating insulation layer:

$$R_{My} = \frac{\delta_{My}}{\lambda_M} = \frac{0{,}1}{58} = 0{,}0017(\frac{m^2 \cdot {}^\circ C}{W})$$

Design thermal resistance of the inhomogeneous insulation layer:

$$R_3{}^r = \frac{1}{\dfrac{0{,}99988}{3{,}125} + \dfrac{0{,}00012}{0{,}0017}} = 2{,}5605(\frac{m^2 \cdot {}^\circ C}{W})$$

Thermal resistance of the reinforced concrete layer:

$$R_1 = \frac{0,16}{2,04} = 0,0784(\frac{m^2 \cdot {}^{\circ}C}{W})$$

Design thermal resistance of the wall:

$R_0 = 1/\alpha_{int} + R_1 + R^r_2 + R^r_3 + R_{3+} \, 1/\alpha_{ext} =$

$= 1/8,7 + 0,2308 + 0,1357 + 2,5605 + 0,0784 + 1/10,8 = 3,1601 \, (m^2 \cdot {}^{\circ}C/W).$

Design thermal resistance of the wall structure is higher than reference thermal resistance (3,1601>3,079). Requirement is satisfied.

<u>Verification of the internal surface temperature level</u>

Difference between internal air temperature and temperature of the internal surface of the wall:

$$\Delta t_0 = \frac{1 \cdot (20 + 26)}{3,1601 \cdot 8,7} = 1,67 \, ({}^{\circ}C).$$

Maximum demanded value is 4°C. Therefore, requirement is satisfied.

Temperature of the internal surface:
$t_{int} = 20 - 1,67 = 18,33 \, ({}^{\circ}C).$

Temperature of the dew point for internal conditions is $t_{dp} = 10,69 \, ({}^{\circ}C).$
$t_{int} > t_{dp}$, therefore, there is no risk of the internal surface moistening.

<u>Verification of the thermal stability of the wall</u>

Results of the coefficients of the heat absorption ability (s), indexes of the heat lag (D) and design thermal resistances (R) calculations of the wall layers are presented in table 6.7

Table 6.7. Coefficients of the heat absorption ability (s), indexes of the heat lag (D) and thermal resistances of the wall layers

N	Material	Layer thickness δ, (m)	Density γ_0, (kg/m³)	Coefficient of heat absorption ability s, (W/(m²·°C))	Design thermal resistance R, (m²·°C/W)	Index of the heat lag D
1	Reinforced concrete	0,16	2500	17,65	0,078	1,38
2	Insulation XPS	0,1	35	3,65	2,5605	9,33
3	Silica facade brick	0,12	1200	6,37	0,2308	1,45
						Sum:12,66

$D_1 > 1$. Therefore, zone of sharp fluctuations is situated in the layer 1.

Coefficient of the internal surface heat assimilation ability $Y_{int} = s_1$:

$$Y_{int} = 17,65(\frac{W}{m^2 \cdot °C})$$

Index of the internal surface heat absorption ability:

$$B = \frac{1}{\frac{1}{5,7} + \frac{1}{17,65}} = 4,31 \ (W/(m^2 \cdot °C)).$$

Design swings of the indoor temperature:

$A_t^{des} = 0,1 \cdot (20+26)/(4,31 \cdot 3,1601) = 0,338 \ (°C)$

$A_t^{des} = 0,338 \ (°C) < A_t^{req} = 1,5 \ (°C)$. Therefore, wall structure satisfy demand to thermal stability during cold period of the year.

APPENDIX 6

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Verification of the air penetration resistance ability.

Specific weight of the external and internal air:

γ_{ext} =3463/(273-26)=14,02 (N/m^3);

γ_{int}=3463/(273+20)=11,82 (N/m^3).

Difference of air pressure on external and internal surfaces of the wall structure:

Δp=0,55·26·(14,02-11,82)+0,03·14,02·4,2^2=38,88 (Pa).

Demanded air penetration resistance:

J^{req}= 38,88/0,5=77,76 (m^2·hour·Pa/kg).

Design values of the air penetration resistance ability of the wall layers are presented in table 6.8

Table 6.8. Design values of the air penetration resistance ability of the wall layers

Material	Layer thickness δ, (m)	Density γ_0, (kg/m^3)	Design air penetration resistance J^{des}, (m^2·hour·Pa/kg).
Reinforced concrete	0,16	2500	19620
Insulation XPS	0,25	35	79
Silica facade brick	0,12	1200	22
			Sum:19721

J^{des}>J^{req} (1972>77,76). Therefore, demand is satisfied.

Verification of the water vapor penetration resistance

Partial pressure of the saturated water vapor on conditions of the design internal temperature (t_{int}=20°C) is E_{int}=2338 (Pa).

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Water vapor partial pressure on conditions of design internal parameters:

$e_{int}=(55/100)\cdot2338=1285,9$ (Pa).

Parameters of the year periods for Saint-Petersburg region:

1) Winter period (January and February).

Amount of months z_1 = 2 (months);

Average temperature of the external air t_1 = (-7,8-7,8)/2=-7,8 (°C);

Temperature in the plane of the possible condensation

τ_1 = 20 - (20 + 7,8)·(0,115 + 2,6389) / 3,1601= -4,2 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation

E_1 = 429 (Pa).

3) Autumn-spring season (October, November, December, March, April).

Amount of months z_2 = 5 (months);

Average temperature of the external air

 t_2 = (-3,9+3,1+4,9+(-0,3)+(-5)) /5 = -0,24 (°C);

Temperature in the plane of the possible condensation

τ_2 = 20 - (20+0,24)·(0,115 + 2,6389) / 3,1601 = 3,36 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation

E_2 =778 (Pa).

3) Summer period (May, June, July, August, September).

Amount of months z_3 = 5 (months);

Average temperature of the external air

t_3 = (9,8 + 15+ 17,8+16 + 10,9) / 5 = 13,9 (°C);

Temperature in the plane of the possible condensation

τ_3 = 20 - (20 -13,9)·(0,115 + 2,6389) / 3,1601 = 14,7 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation E_3 =1672 (Pa).

Water vapor partial pressure in the plane where dew point is possible to appear during one year period of exploitation:

E = (429·2 + 778·5 + 1672·5) / 12 = 1092,3 (Pa).

External surface of the wall is taken as an external surface of the facade brick layer. Water vapor penetration resistance of the layers between external surface of the wall structure and plane where dew point is possible to appear is taken as a water vapor penetration resistance of the brick layer.

$\Omega_e = \Omega_\kappa = 0,12 / 0,16 = 0,75$ (m2·hour·Pa /mg)

Average external air water vapor partial pressure during one year of the exploitation e_{ext}^{av}=600 (Pa).

Required water vapor resistance Ω_{req}^{*}:

$$\Omega_{req}^{*} = \frac{(1285,9 - 1092,3) \cdot 0,75}{(1092,3 - 600)} = 0,29 (Pa \cdot hour \cdot m^2 / g).$$

To determine Ω_{req}^{**} consider period with month average temperatures below 0°C.

Duration of the period z_0 = 151 days (January, February, March, November, December).

Average temperature of the external air t_0 = -4,96 (°C).

Temperature in the plane of the possible condensation

τ_0 = 20 - (20 + 4,96)·(0,115 + 2,6389) / 3,1601=-1,75 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation

E_0 =528 (Pa).

External air water vapor average partial pressure during period with external air temperature below zero e_0^{ext}=300 (Pa).

Coefficient η:

η = 0,0024·(528–300)·151/0,75 = 110,17

$$\Omega_{req}^{**} = \frac{0,0024 \cdot 151 \cdot (1285,9 - 528)}{35 \cdot 0,0667 \cdot 25 + 110,7} = 1,63 (Pa \cdot hour \cdot m^2 / g)$$

Design values of the of the water vapor permeability ratio and water vapor penetration resistance of the wall layers are presented in table 6.9.

Table 6.9. Design values of the of the water vapor permeability ratio and water vapor penetration resistance of the wall layers

N	Material	Layer thickness δ, (m)	Water vapor permrability ratio μ, (mg/m·hour·Pa)	Design water vapor penetration resistance Ω, (m²·hour·Pa /mg)
1	Reinforced concrete	0,16	0,03	5,33
2	Insulation XPS	0,1	0,018	5,56
3	Silica facade brick	0,12	0,16	0,75
			Sum	11,64

Design water vapor penetration resistance of the wall Ω_o:

Ω_o = 26,6·10⁻³+11,64+13,3·10⁻³=11,679 (m²·hour·Pa /mg).

Design water vapor penetration resistance of the layers between internal surface of the wall and external surface of the insulation layer :

Ω_{rp}=26,6·10⁻³+5,33+5,56=10,56 (m²·hour·Pa /mg).

Ω_{rp}>Ω_{req}^{*} and Ω_{rp}>Ω_{req}^{**}. Requirement is satisfied.

Verification of the dew point possibility in wall structure

For design internal parametrs (t_{int} = 20 (°C), φ_{int} = 55%), partial pressure of the saturated water vapor E_{int} = 2338 (Pa). Partial pressure of the water vapor on the internal surface of the wall:

e_{int} = (55 / 100)2338 = 1285,9 (Pa)

Design external parameters are taken for the coldest month (January). Average month temperature t_{ext} = -7,8 (°C) , humidity φ_{int} = 86 %. Partial pressure of the saturated water vapor E_{int} = 315 (Pa). Partial pressure of the water vapor on the external surface of the wall:

e_{ext} = (86/100)·315 = 271 (Pa).

Determine parameters (τ_i and E_i) on the layers borders starting from internal surface of the wall to external.

1) τ_{int} = 20 - (20 + 7,8)·0,115 / 3,16 = 19 (°C);

   E^{τ}_{int} = 2197 (Pa);

2) τ_{1-2} = 20 - (20 + 7,8)·(0,115 + 0,0784) / 3,16= 18,3 (°C);

   E_{1-2} = 2102 (Pa);

3) τ_{2-3} = 20 - (20 + 7,8)·(0,115 + 0,0784+2,5605) / 3,16= -4,2 (°C);

   E_{2-3} = 429 (Pa);

4) τ_{3-4} = 20 - (20 + 7,8)·(0,115 + 0,0784+2,5605+0,1357) / 3,16= -5,4 (°C);

   E_{3-4} = 388 (Pa);

5) τ_{ext} = 20 - (20 + 7,8) · (0,115 + 0,0784 + 2,5605 + 0,1357 + 0,2308) /3,16 = -7,4 (°C);

   E^{τ}_{ext} = 327 (Pa).

Partial pressure of the water vapor on layers borders:

e_i= 1285,9 – (1285,9–271)·(0,0266+$\Sigma\Omega_i$)/11,679=1285,9-86,9·(0,0266+$\Sigma\Omega_i$).

Dew point calculations are executed with the help of the "I-d" diagram. Results of the dew point calculation are presented in table 6.10.

Table 6.10. Results of the dew point calculation

Layers border	x, (m)	ΣR_i, (m²·°C/W)	τ_i, (°C)	E_i, (Pa)	$\Sigma\Omega_i$, (m²·hour· Pa/mg)	e_i, (Pa)	t^{dp}, (°C)
int-1	0	0	19	2197	0	1289,59	10,9
1-2	0,16	0,0784	18,3	2102	5,33	820,41	4,5
2-3	0,26	2,6389	-4,2	429	10,89	337,25	-6,7
3-4	0,27	2,7746	-5,4	388	10,89	337,25	-7,1
4 - ext	0,39	3,0017	-7,4	327	11,64	272,07	-9,8

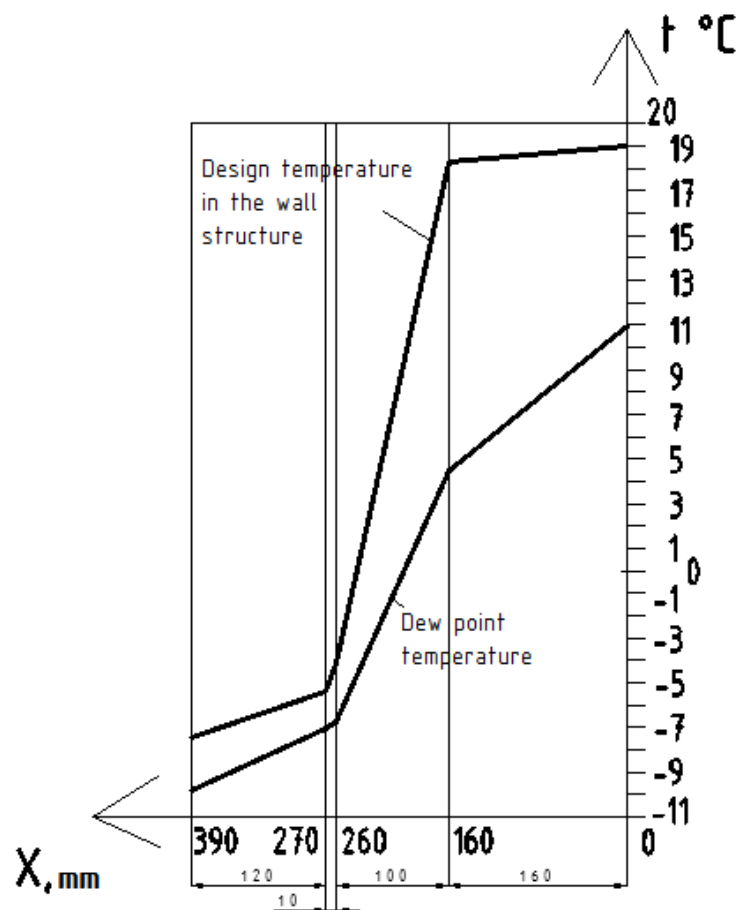Figure 6.2 presents temperature curves inside the wall structure.

Figure 6.2. Temperature curves inside the wall structure.

As long as curves do not intersect there in no risk of the dew point inside the wall structure.

3. Panel wall

Wall structure, layers properties and scheme of fastening see Appendix 3. The physical properties of the materials are presented in table 6.11.

Table 6.11. Physical properties of the materials

Material	Layer thickness δ, (m)	Coefficient of the heat transfer of the dry material. λ_0, (W/(m·°C))	Design coefficient of the heat transfer of the material. λ_W, (W/(m·°C))	Density γ_0, (kg/m³)	Water vapor permeability ratio, μ (mg/m·hour·Pa).
Reinforced concrete	0,1	1,69	2,04	2500	0,03
EPS insulation	0,17	0,038	0,0513	35	0,025
Reinforced concrete	0,08	1,69	2,04	2500	0,03

Fastening steel bars:

Coefficient of the heat transfer λ_w = 58 (W/(m·°C))

Heat capacity C=0,482 (kJ/(kg·°C));

Density γ_0=7850 (kg/m³).

<u>Design thermal resistance</u>

Thermal resistance of the panel wall is determined be equation:

$$R_o^r = R_o^{con} \cdot r \qquad (6.3)$$

where R_o^{con} – thermal resistance of the homogeneous part of the wall

r – coefficient of the inhomogeneity which is determined by equation:

$$r = [1 + (1/A)\sum_{i=1}^{m}(A_i f_i)]^{-1},$$

(6.4)

where A_i, f_i – area (m^2) and coefficient of the mechanical fasteners effectum. A_i is determined by equation:

$$A_i = 4 \cdot \delta_e^2.$$

(6.5)

where δ_e – thikness of the panel wall (m).

f_i is determined according to table data of the SP 23-101-2004. For flexible fasteners $f_i = 0,05$.

40 fastening rods penetrate insulation layer.

$A_i = 40 \cdot 4 \cdot 0,35^2 = 19,6$ (m^2)

$r = 1/[1 + (1/10,5) \cdot 19,6 \cdot 0,05] = 0,929$

$R_o^{con} = 1/\alpha_{int} + R_1 + R_2 + R_{3} + 1/\alpha_{ext} =$

$= 1/8,7 + (0,1/2,04) + (0,17/0,0513) + (0,08/2,04) + 1/10,8 = 3,56$ (m$^2 \cdot$°C/W).

$R_o,^r = 3,56 \cdot 0,929 = 3,309$ (m$^2 \cdot$°C/W).

Design thermal resistance of the wall structure is higher than reference thermal resistance (3,309>3,079). Requirement is satisfied.

Verification of the internal surface temperature level

Difference between internal air temperature and temperature of the internal surface of the wall:

$$\Delta t_0 = \frac{1 \cdot (20 + 26)}{3,309 \cdot 8,7} = 1,60 \ (°C).$$

Maximum demanded value is 4°C. Therefore, requirement is satisfied.

Temperature of the internal surface:

t_{int}=20-1,60=18,40 (°C).

Temperature of the dew point for internal conditions is t_{dp}=10,69 (°C).

t_{int}> t_{dp}, therefore, there is no risk of the internal surface moistening.

Verification of the thermal stability of the wall

Results of the coefficients of the heat absorption ability (s), indexes of the heat lag (D) and design thermal resistances (R) calculations of the wall layers are presented in table 6.12

Table 6.12. Coefficients of the heat absorption ability (s), indexes of the heat lag (D) and thermal resistances of the wall layers

N	Material	Layer thickness δ, (m)	Density γ_0, (kg/m³)	Coefficient of heat absorption ability s, (W/(m²·°C))	Design thermal resistance R, (m²·°C/W)	Index of the heat lag D
1	Reinforced concrete	0,1	2500	17,65	0,049	0,8651
2	EPS insulation	0,17	35	0,7618	3,314	2,525
3	Reinforced concrete	0,08	2500	17,65	0,039	0,6920
						Sum:4,0821

D_1<1, D_1+ D_2≥1. Therefore, zone of sharp fluctuations is situated in the layer 1 and 2.

Coefficient of the internal surface heat assimilation ability:

$$Y_{int} = \frac{0,049 \cdot 17,65^2 + 0,7618}{1 + 0,049 \cdot 17,65} = 8,597 (\frac{W}{m^2 \cdot °C})$$

Index of the internal surface heat absorption ability:

$$B = \cfrac{1}{\cfrac{1}{5,7}+\cfrac{1}{8,597}} = 3,43 \ (W/(m^2 \cdot °C)).$$

Design swings of the indoor temperature:

A_t^{des} =0,1·(20+26)/(3,43·3,19)=0,420 (°C)

A_t^{des} =0,420 (°C) < A_t^{req}=1,5 (ºC). Therefore, wall structure satisfies the demand to thermal stability during cold period of the year.

Verification of the air penetration resistance ability.

Specific weight of the external and internal air:

γ_{ext} =3463/(273-26)=14,02 (N/m³);

γ_{int}=3463/(273+20)=11,82 (N/m³).

Difference of air pressure on external and internal surfaces of the wall structure:

Δp=0,55·78,45·(14,02-11,82)+0,03·14,02·4,2²=102,34 (Pa).

Demanded air penetration resistance:

J^{req}= 102,34/0,5=204,68 (m²·hour·Pa/kg).

Design value of the air penetration resistance of the reinforced concrete layer (which is enough to satisfy demand) is presented in table 6.13.

Table 6.13. Design values of the air penetration resistance ability of the wall layers

Material	Layer thickness δ, (m)	Density Y_0, (kg/m³)	Design air penetration resistance J^{des}, (m²·hour·Pa/kg).
Reinforced concrete	0,1	2500	19620

$J^{des} > J^{req}$ (19620>204,68). Therefore, demand is satisfied.

Verification of the water vapor penetration resistance

Partial pressure of the saturated water vapor on conditions of the design internal temperature (t_{int}=20°C) is E_{int}=2338 (Pa).

Water vapor partial pressure on conditions of design internal parameters:

e_{int}=(55/100)·2338=1285,9 (Pa).

Parameters of the year periods for Saint-Petersburg region:

1) Winter period (January and February).

Amount of months z_1 = 2 (months);

Average temperature of the external air t_1 = (-7,8-7,8)/2=-7,8 (°C);

Temperature in the plane of the possible condensation

τ_1 = 20 - (20 + 7,8)·(0,115 + 3,363) / 3,560= -7,16 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation

E_1 = 332 (Pa).

4) Autumn-spring season (October, November, December, March, April).

Amount of months z_2 = 5 (months);

Average temperature of the external air

t_2 = (-3,9+3,1+4,9+(-0,3)+(-5)) /5 = -0,24 (°C);

Temperature in the plane of the possible condensation

τ_2 = 20 - (20+0,24)·(0,115 + 3,363) / 3,56= 0,2 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation

E_2 =620 (Pa).

3) Summer period (May, June, July, August, September).

Amount of months z_3 = 5 (months);

Average temperature of the external air

t_3 = (9,8 + 15+ 17,8+16 + 10,9) / 5 = 13,9 (°C);

Temperature in the plane of the possible condensation

τ_3 = 20 - (20 -13,9)·(0,115 + 3,363) / 3,560 = 14,0 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation

E_3 =1629 (Pa).

Water vapor partial pressure in the plane where dew point is possible to appear during one year period of exploitation:

E = (332·2 + 620·5 + 1629·5) / 12 = 992,4 (Pa).

External surface of the wall is taken as an external surface of the protective concrete layer. Water vapor penetration resistance of the layers between external surface of the wall structure and plane where dew point is possible to appear is taken as a water vapor penetration resistance of the concrete layer.

Ω_e=$\Omega_к$=0,08 / 0,03 =2,667 (m2·hour·Pa /mg)

Average external air water vapor partial pressure during one year of the expluatation e_{ext}^{av}=600 (Pa).

Required water vapor resistance Ω_{req}^{*}:

$$\Omega_{req}^{*} = \frac{(1285,9 - 992,42) \cdot 2,667}{(992,42 - 600)} = 1,9946(Pa \cdot hour \cdot m^2 / g).$$

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To determine Ω_{req}^{**} consider period with month average temperatures below 0°C.

Duration of the period z_0 = 151 days (January, February, March, November, December).

Average temperature of the external air t_0 = -4,96 (°C).

Temperature in the plane of the possible condensation

τ_0 = 20 - (20 + 4,96)·(0,115 + 3,363) / 3,560=-4,4 (°C);

Saturated water vapor partial pressure in the plane of the possible condensation E_0 =423 (Pa).

External air water vapor average partial pressure during period with external air temperature below zero e_0^{ext}=300 (Pa).

Coefficient η:

η = 0,0024·(423–300)·151/2,667 = 16,71

$$\Omega_{req}^{**} = \frac{0,0024 \cdot 151 \cdot (1285,9 - 423)}{35 \cdot 0,1333 \cdot 25 + 16,71} = 2,345 (Pa \cdot hour \cdot m^2 / g)$$

Design values of the of the water vapor permeability ratio and water vapor penetration resistance of the wall layers are presented in table 6.14.

Table 6.14. Design values of the of the water vapor permeability ratio and water vapor penetration resistance of the wall layers

N	Material	Layer thickness δ, (m)	Water vapor permeability ratio μ, (mg/m·hour·Pa)	Design water vapor penetration resistance Ω, (m²·hour·Pa /mg)
1	Reinforced concrete	0,1	0,03	3,333
2	EPS insulation	0,17	0,025	6,8
3	Silica facade brick	0,08	0,03	2,667
			Sum	12,8

Design water vapor penetration resistance of the wall Ω_o:

$\Omega_o = 26{,}6 \cdot 10^{-3} + 12{,}8 + 13{,}3 \cdot 10^{-3} = 12{,}839$ (m²·hour·Pa /mg).

Design water vapor penetration resistance of the layers between internal surface of the wall and external surface of the insulation layer :

$\Omega_{rp} = 26{,}6 \cdot 10^{-3} + 3{,}333 + 6{,}8 = 10{,}157$ (m²·hour·Pa /mg).

$\Omega_{rp} > \Omega_{req}{}^{*}$ and $\Omega_{rp} > \Omega_{req}{}^{**}$. Requirement is satisfied.

Verification of the dew point possibility in wall structure

For design internal parametrs (t_{int} = 20 (°C), φ_{int} = 55%), partial pressure of the saturated water vapor E_{int} = 2338 (Pa). Partial pressure of the water vapor on the internal surface of the wall:

e_{int} = (55 / 100)2338 = 1285,9 (Pa)

Design external parametrs are taken for the coldest month (January). Average month temperature t_{ext} = -7,8 (°C) , humidity φ_{int} = 86 %. Partial pressure of the saturated water vapor E_{int} = 315 (Pa). Partial pressure of the water vapor on the external surface of the wall:

e_{ext} = (86/100)·315 = 271 (Pa).

Determine parameters (τ_i and E_i) on the layers borders starting from internal surface of the wall to external.

6) τ_{int} = 20 - (20 + 7,8)·0,115 / 3,56 = 19,1 (°C);

   E^{τ}_{int} = 2210 (Pa);

7) τ_{1-2} = 20 - (20 + 7,8)·(0,115 + 0,049) / 3,56= 18,7 (°C);

   E_{1-2} = 2156 (Pa);

8) τ_{2-3} = 20 - (20 + 7,8)·(0,115 + 0,049+3,314) / 3,56= -7,2 (°C);

   E_{2-3} = 332 (Pa);

9) τ_{ext} = 20 - (20 + 7,8) · (0,115 + 0,049 + 3,314+ 0,039) /3,56 = -7,5 (°C);

E^{τ}_{ext} = 324 (Pa).

Partial pressure of the water vapor on layers borders:

e_i= 1285,9 – (1285,9–271)·(0,0266+$\Sigma\Omega_i$)/12,839=1285,9-79,05·(0,0266+$\Sigma\Omega_i$).

Dew point calculations are executed with the help of the "I-d" diagram. Results of the dew point calculation are presented in table 6.15.

Table 6.15. Results of the dew point calculation

Layers border	x, (m)	ΣR_i, (m²·°C/W)	τ_i, (°C)	E_i, (Pa)	$\Sigma\Omega_i$, (m²·hour· Pa/mg)	e_i, (Pa)	t^{dp}, (°C)
int-1	0	0	19,1	2210	0	1283,8	10,8
1-2	0,1	0,049	18,7	2156	3,333	1221,9	10,2
2-3	0,27	3,363	-7,2	332	10,133	482,78	-5,5
3 - ext	0,35	3,402	-7,5	324	12,8	271,36	-9,9

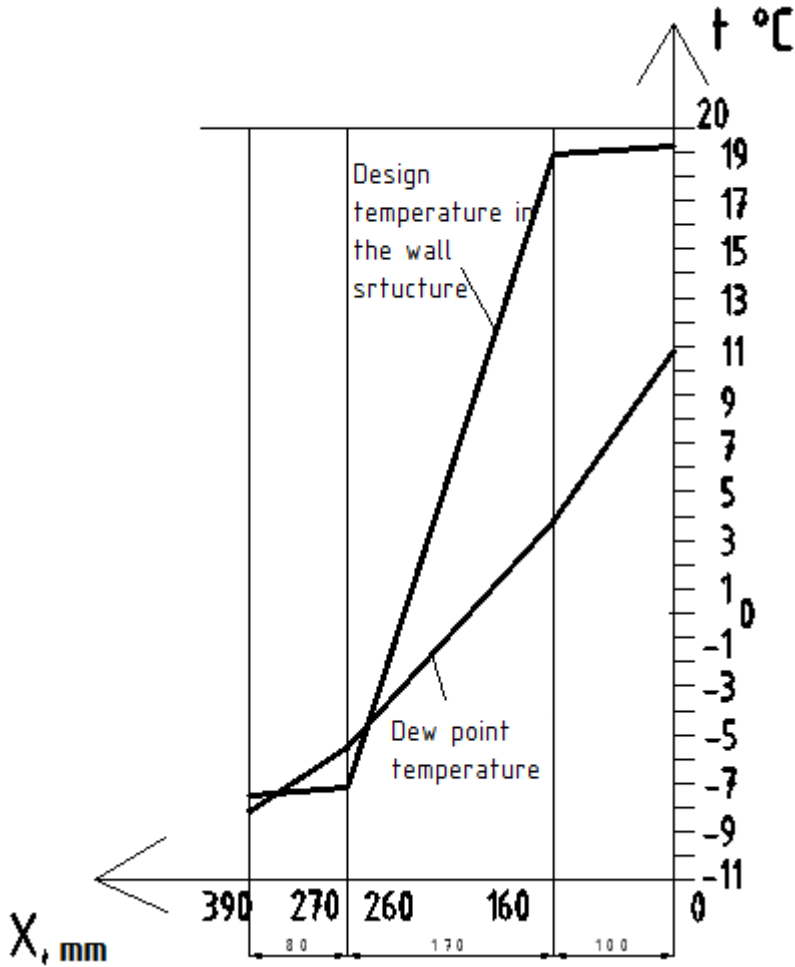Figure 6.3 presents temperature curves inside the wall structure.

Figure 6.3. Temperature curves inside the wall structure.

As long as curves have intersection there is the risk of the dew point inside the wall structure.