

Saimaa University of Applied Sciences
Faculty of Technology, Lappeenranta
Double Degree Programme in Civil and Construction Engineering
Civil Engineering

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**Thermal and humidity conditions inside
enclosing structures made of thin-walled
galvanized steel profiles**

Bachelor's Thesis 2015

Abstract

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The purpose of the thesis was to study the possibility of application of thin-walled galvanized steel profiles produced by Ruukki Rus LLC as a part of enclosing structure in the climatic conditions of St. Petersburg. The main tasks of the work were: to develop the structure of external wall with the use of thin-walled galvanized steel profiles, to develop a program for automatic calculation of the thermal and humidity parameters, to study thermal and humidity regime inside the wall in the climatic conditions of St. Petersburg, to check that operating conditions of thin-walled galvanized steel profiles correspond to recommendations of N.P. Melnikova Research and Design Institute of steel building structures within humidity parameter. The study was requested by Ruukki Rus LLC because of the need to prove that thin-walled galvanized steel profiles inside the external wall structure are allowed to use in St. Petersburg and to prepare the data for the State expertise's permission.

Data for this study was gathered from scientific literature. Calculations were made by manual methods.

The results of the study demonstrate the applicability of this kind of structures in the climatic conditions of St. Petersburg. Further, the results can be used for obtaining the State expertise's permission and can simplify the process of legalisation of steel profiles use. The data obtained can be included in the base of documents for the design, calculation and operation of building structures with the use of light thin-walled steel structures. This base will help to decrease the number of emergency cases in construction and increase the reliance of consumers.

Keywords: relative humidity, light thin-walled steel structures, corrosion.

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1 Introduction

One of the barriers to the widespread use of light steel thin-walled structures as a part of enclosing building structures in St. Petersburg is high air humidity, which can lead to wetting of insulation and as a result corrosion of the steel profile.

Therefore, the purpose of the thesis was to study the possibility of application of thin-walled galvanized steel profiles produced by Ruukki Rus LLC as a part of enclosing structure in the climatic conditions of St. Petersburg.

The main tasks of the work were:

- to develop the structure of external wall with the use of thin-walled galvanized steel profiles,
- to develop a program for automatic calculation of the thermal and humidity parameters,
- to study thermal and humidity regime inside the wall in the climatic conditions of St. Petersburg,
- to check that the operating conditions of thin-walled galvanized steel profiles correspond to recommendations of N.P. Melnikova Research and Design Institute of steel building structures within humidity parameter.

The study was requested by Ruukki Rus LLC because of the need to prove that thin-walled galvanized steel profiles inside the external wall structure are allowed to use in St. Petersburg and to prepare the data for the State expertise's permission. The required program for automatic calculation will allow the company and its customers to set the initial parameters like thickness of the layers, their sequence, building height, outside temperature and relative humidity, and to get curves of relative humidity across the width of the wall, and then to check if the use of these profiles is allowed and in which part of the wall it is allowed.

All the calculations performed in the work are one-dimensional calculations. Change of parameters over time is not considered. The subject of two-dimensional calculation can be studied in future research.

2 Background

2.1 Current market situation in Russia

Nowadays, due to the rapidly expanding metallurgical industry and the growing demand for metal products, lightweight steel thin-walled structures offer a promising direction of development of civil engineering in Russia and worldwide. There are hundreds of manufacturing plants and design organizations in different regions of the country, which produce a wide range of products for various purposes, such as cold-formed galvanized steel thin-walled profiles, wall and roof panels, sets of prefabricated metal buildings, metal tiling, seam roofing, etc.

One of the main reasons why construction technology with the use of light steel thin-walled structures appeared in Russia is a need for rapid construction of buildings corresponding to the climatic conditions of the country. This technology became very popular rather quickly. It has reduced the application of wooden frames which are susceptible to rotting, attractive to insects, have low fire resistance and high cost.

The fundamental normative documents for metal engineering in Russia are SNIP II-23-81* "Steel Structures" and its actualized edition SP 16.13330.2011. These documents do not take into account specific features of design and operation of thin-walled steel structures.

Application of light steel thin-walled structures in Russia is constrained due to the lack of national and interstate regulatory and methodological basis for their design, construction and operation. In order to make the application of material legal, it has to be examined by the State expertise and the company producing it should get permission. Currently, without the development of special technical conditions the State expertise can not be passed.

During the last years the number of accidents has grown on construction sites because of the absence of the basic documents for the design, calculation and maintenance of building structures using light steel thin-walled structures. Consumer's confidence in such buildings and structures is getting lower.

Thus, the issue of development and continuous improvement of the regulatory and methodological basis for light steel thin-walled structures is an important step in the development of the market in the Russian Federation.

One of the companies that support the development of light steel thin-walled structures in Russia is Ruukki Rus LCC.

2.2 The Rautaruukki group

Rautaruukki has started its work in Raahе, Finland and was founded by the Finnish government. Here the steel plants were built in the 1960s. These plants were the first ones in the West that used a new cost effective continuous casting method. (2.)

In the 1970s operations were expanded into steel processing, a cold rolling mill was built and pipe and sheet production began in Hämeenlinna.

In the 1980s the company began to find new opportunities for development in Western Europe organizing sales offices and making purchases. The contacts were set with Denmark, Norway, Germany.

In the 1990s Ruukki gained Finnish steel roof manufacturer Rannila and joined the construction business. The company has expanded markets on Eastern Europe: first in the Baltics and Poland, and later in Russia, Ukraine, the Czech Republic and Hungary.

In the 2000s Rautaruukki Corporation name was shortened to Ruukki. The main focus of Ruukki was on solutions for construction and the engineering industry. The company's steel business was intended for special steel products. Markets were expanded on Asia. (2.)

Since July 2014 Ruukki is part of SSAB and the new company has five divisions:

SSAB Special Steels –value added Advanced High Strength Steels (AHSS) and Quenched & Tempered steels (Q&T);

SSAB Europe –high quality strip, heavy plate and tubes;

SSAB Americas –heavy plate;

Tibnor –steel distribution partner;

Ruukki Construction –provider of energy efficient building and construction solutions. (1.)

Ruukki Construction provides solutions for lifecycle and energy-efficient steel structures in the construction industry. Ruukki Construction's products are used in commercial, office and industrial construction, as well as in the construction of single-family houses, ports, wind turbines and infrastructure construction. Ruukki is now the largest steel constructor on the Russian market to the west of Urals. (1.)

Today, Ruukki has a strong foothold on the Nordic markets and is searching for growth opportunities in Russia, Central Eastern Europe and also China (1). In these regions, Ruukki has built a strong manufacturing and sales network to serve construction and engineering industry customers.

The main office and production of Ruukki Rus LCC is situated in Obninsk. There are also departments in Saint Petersburg and Moscow.

2.3 About light thin-walled steel structures

Metal structures made of light steel profiles are used in:

- the frames of industrial buildings
- the floor structures, that are supported by walls, columns or pillars;
- the frames of special buildings (hangars, pavilions, etc.), the main structure of which is beam, arched or domed covering;
- the construction of high-rise civil buildings;
- the construction of facilities that serve for storage of granular materials, liquids or gases (reservoirs, gas tanks, hydraulic structures, etc.).
- the construction of towers and masts
- bridges and crane structures;

Frame building of light metal structures is a constructive solution that allows rapid construction of industrial, commercial and warehouse buildings. The period of construction of the steel frame building is 2-3 times less than for the same building made of reinforced concrete (3). The cost of prefabricated building is on average 10-15% lower, due to economy of labor force and equipment (mounting crane is enough), as well as a simple construction of foundations (usually columnar).

The main element is a cold-formed steel profile made of thin galvanized sheet, which can be used for construction of the whole frame of the building and its individual elements: external and internal walls, partitions, storey slabs, trusses, roofs and etc.

Wall filling is mineral wool, sandwich panels or double glazing, roofing is profiled steel flooring or metal tiles. Fixing of the structural elements is done without welding by means of self-tapping screws of high strength steel.

2.4 Advantages of frames made of light thin-walled steel structures

1) Easiness of installation

Complete factory readiness, lightness and speed of installation, the possibility of dismantling, no welding and "wet" processes allow working all year round (3). This is particularly important for investors and during the construction of low-cost housing when the return of investments is the determining factor. Reduced construction time depends on the degree of optimization of the construction process in which with the use of light steel thin-walled structures for series construction (e.g. cottage villages with the typical buildings or townhouses) it is possible to use enlarged assembly of prefabricated factory elements.

2) Wide area of application

Frame technology provides an individual approach, the optimum use of space, a variety of possible solutions and types of wall panels.

Structures made of lightweight steel structures can be used:

- for construction of low-rise buildings up to 4 floors.
- to create modular homes in the frames of special programs, such as the creation of a reserve fund in case of emergencies.
- to create outdoor warm envelope in multi-storey buildings with a heavy reinforced concrete frame.
- during the reconstruction of buildings.
- during insulation of roofing and facades.

3) Light weight

Weight of 1 m² of load-bearing steel frame is within the 20-25 kg, and the weight of 1 m² of a ready building is on average 150 kg (3). This advantage allows the opportunity of construction on the bad soils, the use of light steel thin-walled structures in reconstruction of buildings, carrying out construction in cramped urban areas without the use of heavy lifting equipment

4) High heat-saving indicators

The use of effective insulation allows reducing the operating costs of a building. High heat performance allows the use of light steel thin-walled structures for economical construction even in the Far North.

Gypsum board and insulation - rock wool or ecowool – are usually used as covering for walls made with the use of light steel thin-walled structures. These materials are environmentally friendly and can be 100% recycled. Manufacturing, transportation, installation and operation have much lower energy costs than for traditional materials.

5) Resistance to seismic and other dynamic loads

Buildings, in which light steel thin-walled profiles are used as load-bearing structures can withstand seismic loads up to 9 on the Richter scale (3). This is due to the elasticity of the steel frame.

6) Fire resistance

The fire resistance of the design is provided by the plate material of covering, in which the number of layers can be optimally matched to the specific fire protection requirements.

7) Exact preparation of design specifications

The use of modern CAD systems and engineering design techniques allows automatically generate a list of materials in an electronic form. Getting specification in electronic form ensures the accuracy of the mechanical engineering.

3 Thermal and relative humidity regime inside the wall

3.1 Initial data

All the calculations are done in accordance with Russian normative documents: GOST 30494-96, SP 131.13330.2012 (actualized edition of SNiP 23-01-99), SP 50.13330.2012 (actualized edition of SNiP 23-02-2003).

The U-shape cold-formed steel profile produced by Ruukki is taken as the design thin-walled galvanized steel profile. These profiles are suitable for practically any kind of steel structure, whether for commercial or residential building (1).

In this work the operating conditions of thin-walled galvanized steel profiles are studied in a 2-storey public building situated in St. Petersburg.

At the beginning the layers shown in Figure 1 are taken as a wall structure:

- 1) gypsum board;
- 2) vapour barrier;
- 3) insulation and U-shape steel profile;
- 4) gypsum board;
- 5) ventilated cavity;
- 6) ceramic granite plates.

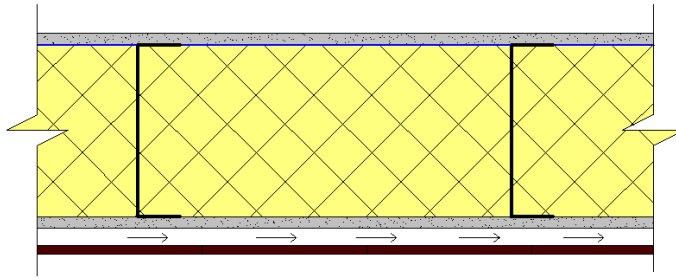


Figure 1. Initial wall structure

Characteristics of materials of enclosing structure are presented in Table 1.

| Material | Density γ_0 , kg/m^3 | Thick-ness δ , mm | Coefficient of thermal conductivity λ , $\text{W}/(\text{m}\cdot^\circ\text{C})$ | Coefficient of wa-ter vapor per-meability μ , $\text{mg}/\text{m}\cdot\text{h}\cdot\text{Pa}$ |
|-------------------------|--------------------------------------|--------------------------|--|---|
| Gypsum board | 704 | 12,5 | 0,21 | 0,075 |
| Vapour barrier | 171 | 0,42 | - | 0,00005 |
| Insulation ISOVER Light | 38 | 200 | 0,04 | 0,3 |
| U-shape steel profile | 7850 | | 58 | - |
| Gypsum board | 716 | 9,5 | 0,21 | 0,075 |
| Ventilated cavity | - | 30 | - | - |
| Ceramic granite plates | 2600 | 10 | 0,67 | 0,11 |

Table 1. Characteristics of materials

Climatic parameters of St. Petersburg are as follows:

- the average design temperature of indoor air: $t_{int} = 20^\circ\text{C}$ (4);
- design relative humidity of the air inside the building is 60%;
- design temperature of outdoor air in the cold season (the temperature of the coldest five-day week): $t_{ext} = -28^\circ\text{C}$;
- design relative humidity of the air outside the building is 86%;
- duration of the heating period (duration of a period when the average daily temperature is less than or equal to 8°C): $z_{ht} = 213$ days;
- the average outdoor temperature during the heating period:
 $t_{ht} = -1,3^\circ\text{C}$;

- St. Petersburg is located in the 1st moisture zone. Operating conditions of enclosing structures in this moisture zone - B.

3.2 Requirements for the thermal protection of the building

Three conditions should be taken into account during the design of thermal protection of residential and public buildings:

1. The total thermal resistance of individual elements of enclosing structures R_0 should not be lower than the normative value R_{req} .

$$R_0 \geq R_{req}$$

2. The calculated difference between the inside air temperature and the temperature of inner surface of the wall must not exceed normative value Δt_n .

$$\Delta t_0 \leq \Delta t_n$$

3. The temperature of the inner surface of the wall τ_{int} should not be lower the dew point of the indoor air t_{dp} at the design temperature of outside air in winter.

$$\tau_{int} > t_{dp}$$

The first condition is established for the reason of energy saving, the second and third conditions are based on the sanitary and comfortable conditions in the building.

3.3 Thermal resistance of external walls

The total thermal resistance R_0 of enclosing structure is determined by the formula:

$$R_0 = \frac{1}{\alpha_{int}} + R_1 + R_2 + \dots + R_n + \frac{1}{\alpha_{ext}} \quad (1)$$

where α_{int} – coefficient of heat transfer of the inner surface of enclosing structure, $W/(m^2 \cdot ^\circ C)$. For walls $\alpha_{int} = 8,7 W/(m^2 \cdot ^\circ C)$ (5);

α_{ext} – coefficient of heat transfer of the outer surface of enclosing structure, $W/(m^2 \cdot ^\circ C)$. For external walls with air cavity $\alpha_{ext} = 12 W/(m^2 \cdot ^\circ C)$;

R_1, R_2, \dots, R_n – thermal resistance of separate layers;

When determining R_0 the layers disposed between the air layer and the outer surface of the wall are not considered (5).

The calculation results of the thermal resistance of separate layers are presented in Table 2.

| No | Materials | Thermal resistance R, ($m^2 \cdot ^\circ C/W$) | |
|----|-------------------------|--|------|
| 1 | Gypsum board | 0,0595 | |
| 2 | Vapour barrier | - | |
| 3 | Insulation ISOVER Light | 5 | 0,86 |
| | U-shape steel profile | 0,0034 | |
| 4 | Gypsum board | 0,0452 | |

Table 2. Thermal resistance of the layers

Calculation example:

$$R_1 = \frac{0,0125}{0,21} = 0,0595 m^2 \cdot ^\circ C/W$$

Thermal resistance of the third layer is determined differently.

As there is a heat transfer q from inner surface to the outer one, some part of heat goes through a steel profile q_{st} and the other part goes through the insulation q_{ins} .

$$Q_{st} = q_{st} \cdot A_{st} \quad (2)$$

where Q_{st} – total heat flow through a steel profile;

q_{st} – amount of heat that goes through a 1 unit of square of steel profile;

A_{st} – square of steel profile through which heat flow goes;

$$Q_{ins} = q_{ins} \cdot A_{ins} \quad (3)$$

where Q_{ins} – total heat flow through an insulation;

q_{ins} – amount of heat that goes through a 1 unit of square of insulation;

A_{ins} – square of insulation through which heat flow goes;

$$Q_{tot} = Q_{st} + Q_{ins} \quad (4)$$

where Q_{tot} – total heat flow through a layer;

$$q = \frac{t_1 - t_2}{R} \quad (5)$$

where R – thermal resistance of a material;

According to (4) and (5),

$$\frac{t_1 - t_2}{R_3} A_{tot} = \frac{t_1 - t_2}{R_{st}} A_{st} + \frac{t_1 - t_2}{R_{ins}} A_{ins} \quad (6)$$

$$\frac{A_{tot}}{R_3} = \frac{A_{st}}{R_{st}} + \frac{A_{ins}}{R_{ins}} \quad (7)$$

$$R_3 = \frac{A_{tot} R_{st} R_{ins}}{A_{ins} R_{st} + A_{st} R_{ins}} \quad (8)$$

where R_3 - thermal resistance of a third layer;

R_{st} - thermal resistance of steel profile;

R_{ins} - thermal resistance of insulation;

A_{ins} - square of insulation, that can be calculated by formula:

$$A_{ins} = h \cdot s \quad (9)$$

where s – distance between steel profiles;

h - storey height;

$$A_{\text{ins}} = 4,2 \cdot 0,6 = 2,52 \text{ m}^2$$

A_{st} - square of steel, that can be calculated by formula:

$$A_{\text{st}} = h \cdot t \quad (10)$$

where t – thickness of steel profile;

$$A_{\text{st}} = 4,2 \cdot 0,002 = 0,0084 \text{ m}^2$$

A_{tot} - total square of steel profile and insulation;

$$A_{\text{tot}} = A_{\text{ins}} + A_{\text{st}} \quad (11)$$

$$A_{\text{tot}} = 2,52 + 0,0084 = 2,5284 \text{ m}^2$$

$$R_3 = \frac{2,5284 \cdot 0,0034 \cdot 5}{2,52 \cdot 0,0034 + 0,0084 \cdot 5} = 0,86 \text{ m}^2 \cdot \text{°C/W},$$

The total thermal resistance of enclosing structure will be:

$$R_0 = \frac{1}{8,7} + 0,0595 + 0,86 + 0,0452 + \frac{1}{12} = 1,17 \text{ m}^2 \cdot \text{°C/W}.$$

Normative value R_{req} depends on the degree-days of the construction area G_d that are defined by the formula:

$$G_d = (t_{\text{int}} - t_{\text{ht}}) \cdot z_{\text{ht}} \quad (12)$$

where t_{ht} – average temperature of outside air during heating period;

z_{ht} – duration of heating period.

$$G_d = (20 + 1,3) \cdot 213 = 4537 \text{ °C} \cdot \text{days}$$

Normative value R_{req} :

$$R_{req} = a \cdot G_d + b \quad (13)$$

where a and b – coefficients (5). For public buildings $a=0,0003$, $b=1,2$.

$$R_{req} = 0,0003 \cdot 4537 + 1,2 = 2,561 \text{ m}^2 \cdot \text{°C/W}$$

As a result, it is seen that the value of total thermal resistance of enclosing structure is lower than the normative value.

$$1,17 \text{ m}^2 \cdot \text{°C/W} < 2,561 \text{ m}^2 \cdot \text{°C/W}$$

$$R_o < R_{req}$$

So the structure does not meet the thermal resistance requirements.

The following solution can be offered: the extra layer of rigid insulation can be added. The required thickness of this insulation can be calculated from the required thermal resistance of the wall:

$$R_5 = R_{req} - \frac{1}{8,7} - R_1 - R_2 - R_3 - R_4 - \frac{1}{12} \quad (14)$$

$$R_5 = 2,561 - \frac{1}{8,7} - 0,0595 - 0,86 - 0,0452 - \frac{1}{12} = 1,40 \text{ m}^2 \cdot \text{°C/W}$$

Angle brackets are used to fasten ventilated façade to bearing steel profiles. As the thicknesses of insulation and steel brackets are the same, the required thickness of insulation can be defined:

$$R_5 = \frac{A_{tot} \cdot \frac{\delta_5}{\lambda_{st}} \cdot \frac{\delta_5}{\lambda_{ins}}}{A_{ins} \cdot \frac{\delta_5}{\lambda_{st}} + A_{st} \cdot \frac{\delta_5}{\lambda_{ins}}} \quad (15)$$

$$\delta_5 = \frac{R_5 \cdot (A_{ins} \cdot \lambda_{ins} + A_{st} \cdot \lambda_{st})}{A_{tot}} \quad (16)$$

$$A_{st} = h_{br} \cdot t \cdot n \quad (17)$$

where n - the number of brackets,

t – the width of a bracket;

h_{br} – the thickness of a bracket;

$$A_{st} = 0,002 \cdot 0,05 \cdot 7 = 0,0007m^2$$

$$A_{ins} = 4,2 \cdot 0,6 = 2,52m^2$$

$$\delta_s = \frac{1,40 \cdot (2,52 \cdot 0,039 + 0,0007 \cdot 58)}{2,5207} = 0,077m$$

In this case the required thickness of extra insulation is 0,077 m. Choosing among different types of insulation, Isover Venti seems the most suitable, because of its characteristics:

- it can be used as in both single-layer and multi-layer structure – as an external layer of insulation;
- it is used in buildings of all types, without height restrictions;
- it has a property of effective moisture removal from the structure due to the high vapor permeability.

The standard thickness of Isover Venti is 50 mm and 100 mm, so the thickness 100 mm is chosen according to requirements of thermal protection.

As an air barrier, a gypsum board, 9,5 mm in thickness, can be added between two layers of insulation (7). In order to protect external insulation from getting wet, a waterproofing membrane will cover the Isover Venti.

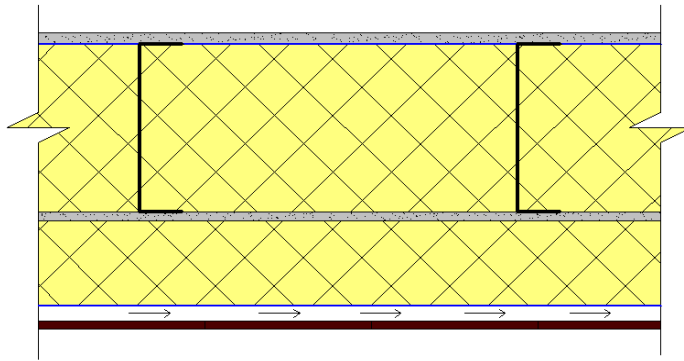


Figure 2. Layers of the wall structure

Thermal resistances of waterproofing membrane and vapour barrier are very low, that is why they are not considered in calculations.

Thermal resistances of the new structure layers are presented in Table 3.

| Material | Density γ_0 , kg/m ³ | Thick-ness δ , mm | Coefficient of thermal conductivity λ , W/(m·°C) | Coefficient of water vapor permeability μ , mg/m·h·Pa |
|-----------------------------------|--|--------------------------|--|---|
| Gypsum board | 704 | 12,5 | 0,21 | 0,075 |
| Vapor barrier | 171 | 0,42 | - | 0,00005 |
| Insulation ISOVER Light | 38 | 200 | 0,04 | 0,3 |
| U-shape steel profile | 7850 | | 58 | - |
| Gypsum board | 716 | 9,5 | 0,21 | 0,075 |
| Insulation ISOVER Venti | 80 | 100 | 0,039 | 0,3 |
| Angle bracket | 7850 | | 58 | - |
| Waterproofing membrane Tyvek Soft | 333 | 0,00018 | - | 0,002 |
| Ventilated cavity | - | 30 | - | - |
| Ceramic granite plates | 2600 | 10 | 0,67 | 0,11 |

Table 3. Thermal resistance of the new structure layers

Then the thermal resistance of the wall is:

$$R_0 = \frac{1}{8,7} + 0,0595 + 0,86 + 0,0452 + 1,815 + \frac{1}{12} = 2,978 \text{ m}^2 \cdot \text{°C/W}$$

$$2,978 \text{ m}^2 \cdot \text{°C/W} > 2,561 \text{ m}^2 \cdot \text{°C/W}$$

$$R_0 > R_{\text{req}}$$

Finally, the structure meets the requirements of the thermal resistance of enclosing structures.

The calculated difference between the inside air temperature and the temperature of inner surface Δt_0 (8) is defined by the formula:

$$\Delta t_0 = \frac{n(t_{\text{int}} - t_{\text{ext}})}{R_0 \alpha_{\text{int}}} \quad (18)$$

where n - coefficient taking into account conditions on the outer surface of the wall (5);

t_{int} – design temperature of inside air;

t_{ext} - design temperature of outside air, that is equal to the temperature of the coldest five-day week (5).

$$\Delta t_0 = \frac{1(20 + 28)}{2,978 \cdot 8,7} = 1,85 \text{ °C}$$

The normative value is 4,5°C for public buildings (5).

$$\Delta t_0 < \Delta t_n$$

The condition 2 is met.

The temperature of inner surface of the wall τ_{int} is determined by the formula:

$$\tau_{\text{int}} = t_{\text{int}} - \Delta t_0 \quad (19)$$

$$\tau_{\text{int}} = 20 - 1,85 = 18,15 \text{ °C}$$

The actual water vapor pressure in the room e_{int} is determined by the formula:

$$e_{int} = \frac{\varphi_{int} E}{100} \quad (20)$$

where φ_{int} – relative humidity in the room;

E – partial pressure of saturated water vapor that is determined depending on the air temperature by a graph $E=f(t)$.

The data for getting the graph is shown in Table 4.

| t, °C | E, Pa | t, °C | E, Pa | t, °C | E, Pa | t, °C | E, Pa |
|-------|--------|-------|-------|-------|-------|-------|-------|
| -40,0 | 12,40 | -10,0 | 260,0 | 8,0 | 1073 | 20,0 | 2338 |
| -35,0 | 22,26 | -5,0 | 401,3 | 10,0 | 1228 | 22,0 | 2644 |
| -30,0 | 37,33 | 0,0 | 610,6 | 12,0 | 1403 | 24,0 | 2984 |
| -25,0 | 62,66 | 2,0 | 705,3 | 14,0 | 1599 | 26,0 | 3361 |
| -20,0 | 102,70 | 4,0 | 813,3 | 16,0 | 1817 | 28,0 | 3780 |
| -15,0 | 165,30 | 6,0 | 934,6 | 18,0 | 2064 | 30,0 | 4242 |

Table 4. Partial pressure of saturated water vapor depending on temperature

The graph of partial pressure of saturated water vapor depending on temperature is presented in Figure 3.

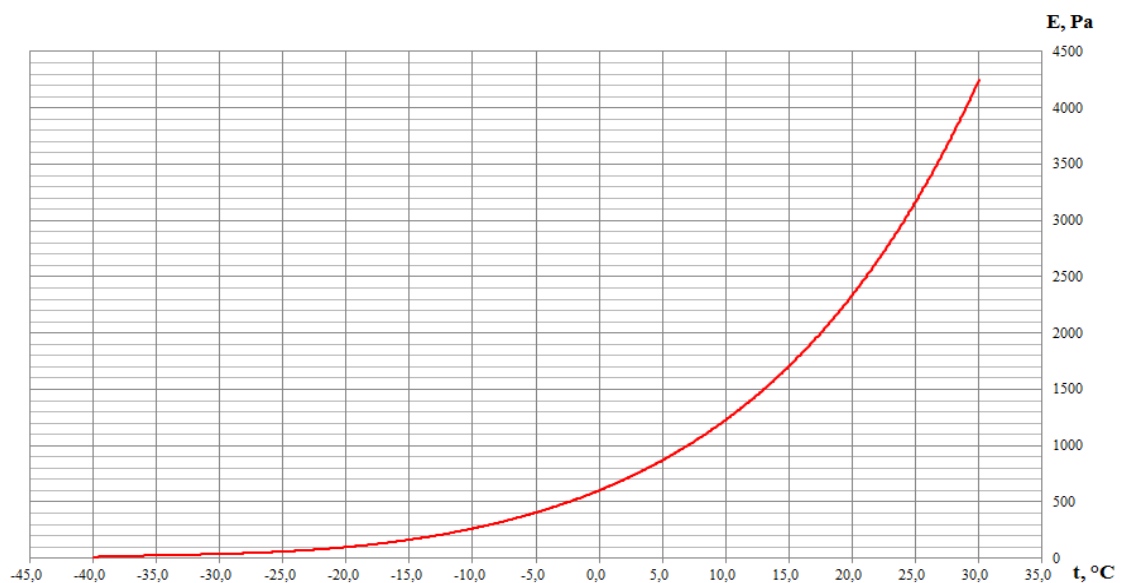


Figure 3. Partial pressure of saturated water vapor depending on temperature

According to the graph t_{dp} is determined, at this temperature vapor is saturated and has pressure of e_{int} .

$$e_{int} = \frac{60 \cdot 2185}{100} = 1311 \text{ Pa}$$

$$t_{dp} = 11^\circ\text{C}$$

$$18,15^\circ\text{C} > 11^\circ\text{C}$$

As $t_{int} > t_{dp}$, the condition of absence of vapor condensation on the inner surface of external wall is met.

3.4 Thermal stability of walls

3.4.1 Determining coefficients of heat absorption of material

The design amplitude of daily fluctuations of resulting temperature of indoor air in public buildings should not exceed the normative value A_t^{req}

$$A_t^{des} \leq A_t^{req}$$

As there is a central heating system in the building A_t^{req} is assumed to be $1,5^\circ\text{C}$ (5).

1) Determining coefficients of heat absorption of material. For each homogeneous layer heat absorption coefficient of the material s is determined by the formula:

$$s = \sqrt{\frac{2\pi\lambda_w c \gamma_0}{Z}} \quad (21)$$

where λ_w – coefficient of thermal conductivity of the material at the design humidity value;

c – specific heat capacity of material;

γ_0 – density of material;

Z – period of temperature fluctuations, that is taken equal to 24 hours.

If the layer is not homogeneous, the coefficient of heat absorption s_r is determined as a weighed average value.

$$s_r = \frac{\sum_{i=1}^{i=n} m_i s_i}{\sum_{i=1}^{i=n} m_i} \quad (22)$$

where s_i and m_i – coefficients of heat absorption and masses of each homogeneous part of the layer.

The calculation results are presented in Table 5.

| Material | Density γ_0 , kg/m ³ | Coefficient of thermal conductivity λ , W/(m·°C) | Specific heat capacity c , J/(kg·°C) | Coefficient of heat absorption s , W/(m ² ·°C) |
|--------------------------------------|---|--|--|---|
| Gypsum board | 704 | 0,21 | 0,84 | 5,70 |
| Vapour barrier | 171 | - | - | - |
| Insulation ISOVER Light | 38 | 0,04 | 0,93 | 122,05 |
| U-shape steel profile | 7850 | 58 | 0,482 | |
| Gypsum board | 716 | 0,21 | 0,84 | 5,75 |
| Insulation ISOVER Venti | 80 | 0,039 | 0,93 | 13,17 |
| Angle bracket | 7850 | 58 | 0,482 | |
| Waterproofing membrane Tyvek Soft | 333 | - | - | - |

Table 5. Coefficients of heat absorption

Calculation example:

For the third layer coefficient of heat absorption is determined in the following way.

Coefficient of heat absorption of steel s_{st} :

$$s_{st} = \sqrt{\frac{2 \cdot 3,14 \cdot 58 \cdot 0,482 \cdot 7850}{24}} = 239,63 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$$

Coefficient of heat absorption of insulation s_{ins} :

$$s_{ins} = \sqrt{\frac{2 \cdot 3,14 \cdot 0,04 \cdot 0,93 \cdot 38}{24}} = 0,61 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$$

Mass of insulation:

$$m_{ins} = \rho_{ins} \cdot V_{ins} \quad (23)$$

$$m_{ins} = 38 \cdot (4,2 \cdot 0,6 \cdot 0,2) = 19,15 \text{ kg}$$

Mass of steel:

$$m_{st} = \rho_{st} \cdot V_{st} \quad (24)$$

$$m_{st} = 7850 \cdot 4,2 \cdot 0,002 \cdot (0,2 + 0,05 \cdot 2) = 19,78 \text{ kg}$$

Coefficient of heat absorption of third layer:

$$s_{r3} = \frac{m_{ins} \cdot s_{ins} + m_{st} \cdot s_{st}}{m_{ins} + m_{st}} \quad (25)$$

$$s_{r3} = \frac{19,15 \cdot 0,61 + 19,78 \cdot 239,63}{19,15 + 19,78} = 122,05 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$$

For the 5th layer coefficient of heat absorption is determined in the same way as for the third layer.

$$s_{r5} = \frac{20,16 \cdot 0,81 + 1,1 \cdot 239,63}{20,16 + 1,1} = 13,17 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C})$$

3.4.2 Determination of thermal inertia of enclosing structure

For each layer thermal inertia is calculated by the formula:

$$D=R \cdot s, \quad (26)$$

where R – thermal resistance of a layer;

s – the design coefficient of material heat absorption of a separate layer.

For a multi-layer wall:

$$D = D_1 + D_2 + \dots + D_n, \quad (27)$$

where D_1, D_2, \dots, D_n – the design values of the thermal inertia of the separate layers.

The results are shown in Table 6.

| Materials | Thermal resistance R, (m ² ·°C)/W | Coefficient of heat absorption s, W/(m ² ·°C) | Thermal inertia D |
|--|--|--|-------------------|
| Gypsum board | 0,0595 | 5,70 | 0,34 |
| Vapour barrier | - | - | - |
| Insulation ISOVER Light U-shape steel profile | 0,86 | 122,05 | 104,96 |
| Gypsum board | 0,0452 | 6,15 | 0,28 |
| Insulation ISOVER Venti Angle bracket | 1,82 | 13,17 | 23,97 |
| Waterproofing membrane Tyvek Soft | - | - | - |

Table 6. Thermal inertia

Thermal inertia of the wall:

$$D = 0,34+104,96+0,28+23,97=129,55$$

When a total thermal inertia of the building envelope is $D \geq 4$, the calculation on thermal stability is not required (5).

Determination of heat stability of a wall in the warm season is required if the construction site is located in an area with the average July temperature of 21°C and above. The average monthly temperature in July in St. Petersburg is 18,3°C, so in this case determination of heat stability of a wall is not necessary.

3.5 Air permeability of external walls

Resistance to air permeability of walls of residential and public buildings J_{des} should be less than the normative resistance to air permeability J_{req} , $m^2 \cdot h \cdot Pa/kg$. It is determined by the formula:

$$J_{req} = \frac{\Delta p}{G_n} \quad (28)$$

where Δp - difference in air pressure on the external and internal surfaces of a wall;

G_n – normative lateral resistance to air permeability of enclosing structures (5).
For external walls: 0,5 kg/($m^2 \cdot h$).

Difference in air pressure on the external and internal surfaces of a wall is determined by the formula:

$$\Delta p = 0,55H(\gamma_{ext} - \gamma_{int}) + 0,03 \gamma_{ext} v^2, \quad (29)$$

where H – building height, m;

v – maximum of the average wind speeds in January (6).

γ_{ext} , γ_{int} – specific weight of external and internal air that is determined by the formulas:

$$\gamma_{ext} = \frac{3463}{273 + t_{ext}} \quad (30)$$

$$\gamma_{\text{ext}} = \frac{3463}{273 - 26} = 14,02 \text{ N/m}^3$$

$$\gamma_{\text{int}} = \frac{3463}{273 + t_{\text{int}}} \quad (31)$$

$$\gamma_{\text{int}} = \frac{3463}{273 + 20} = 11,82 \text{ N/m}^3$$

$$\Delta p = 0,55 \cdot 8,6 \cdot (14,02 - 11,82) + 0,03 \cdot 14,02 \cdot 3,3^2 = 14,99 \text{ Pa}$$

$$J_{\text{req}} = \frac{14,99}{0,5} = 29,98 \text{ m}^2 \cdot \text{h} \cdot \text{Pa/kg}$$

Resistance to air permeability of a multi-layer wall J_{des} is determined by the formula:

$$J_{\text{des}} = J_1 + J_2 + J_3 + \dots + J_n \quad (32)$$

where $J_1, J_2, J_3, \dots, J_n$, – Resistance to air permeability of a separate layer (8).

| Material | Thickness, mm | Resistance to air permeability, $\text{m}^2 \cdot \text{h} \cdot \text{Pa/kg}$ |
|--|-----------------|--|
| Gypsum board | 12,5 | 25 |
| | 9,5 | 19 |
| Insulation | 200 | 8 |
| | 100 | 4 |
| Vapor barrier and Waterproofing membrane | 0,42 0,00018 | 2000 |

Table 7. Resistance to air permeability of materials

$$J_{\text{des}} = 25 + 2000 + 8 + 19 + 4 + 2000 = 4056 \text{ m}^2 \cdot \text{h} \cdot \text{Pa/kg}$$

The calculation shows that the requirement of the air permeability to the wall structure is satisfied, $J_{des} > J_{req}$. It will also be satisfied in the absence of a vapor barrier, J_{des} will be equal to 2056 $m^2 \cdot h \cdot Pa/kg$, therefore further calculations are done without the layer of vapor barrier.

3.6 Protection from excessive moisture inside the wall

3.6.1 Resistance to water vapor transmission

Resistance to water vapor transmission is defined by the formula:

$$\Omega = \frac{\delta}{\mu} \quad (33)$$

where δ – layer thickness, m;

μ – coefficient of water vapor transmission, $mg/(m \cdot h \cdot Pa)$;

Calculation example:

$$\Omega_1 = \frac{0,0125}{0,075} = 0,17 \text{ Pa} \cdot h \cdot m^2/mg$$

The calculation results are presented in Table 8.

| Material | Thickness δ , m | Coefficient of water vapor transmission μ , $mg/(m \cdot h \cdot Pa)$ | Resistance to water vapor transmission Ω , $Pa \cdot h \cdot m^2/mg$ |
|-------------------------|------------------------|---|---|
| Gypsum board | 0,0125 | 0,0750 | 0,17 |
| Insulation ISOVER Light | 0,2 | 0,3000 | 0,67 |
| U-shape steel profile | | - | - |
| Gypsum board | 0,0095 | 0,0750 | 0,13 |
| Insulation ISOVER Venti | 0,1 | 0,3000 | 0,33 |
| Angle bracket | | - | - |

| | | | |
|-----------------------------------|---------|------|------|
| Waterproofing membrane Tyvek Soft | 0,00018 | 0,02 | 0,09 |
|-----------------------------------|---------|------|------|

Table 8. Resistance to water vapor transmission of a layer

Resistance to water vapor transmission of a wall Ω_o is determined considering resistance to moisture exchange at the inside and outside surfaces by the formula:

$$\Omega_o = \Omega_{int} + \Omega_1 + \Omega_2 + \dots + \Omega_n + \Omega_{ext} \quad (34)$$

Ω_{int} - resistance to the moisture exchange at the inside surface of the wall;

$$\Omega_{int} = 0,03 \text{ Pa}\cdot\text{h}\cdot\text{m}^2/\text{mg}$$

Ω_{ext} - resistance to the moisture exchange at the outside surface of the wall;

$$\Omega_{ext} = 0,01 \text{ Pa}\cdot\text{h}\cdot\text{m}^2/\text{mg}$$

$$\Omega_o = 0,03 + 1,39 + 0,01 = 1,43 \text{ Pa}\cdot\text{h}\cdot\text{m}^2/\text{mg}.$$

Resistance to water vapor transmission of the wall (ranging from the inside surface to the possible condensation plane) must not be less than the highest of the following normative values:

a) normative resistance to water vapor transmission Ω_{req}^* (considering that accumulation of moisture inside the wall during the year is not allowed), that is defined by the formula:

$$\Omega_{req}^* = \frac{(e_{int} - E) \cdot \Omega_e}{(E - e_{ext}^{av})} \quad (35)$$

where e_{int} –vapor pressure at the design temperature and relative humidity of indoor air, that is determined by the formula:

$$e_{\text{int}} = \left(\frac{\varphi_{\text{int}}}{100}\right) \cdot E_{\text{int}} \quad (36)$$

where E_{int} – saturated vapor pressure at the reference temperature t_{int} ;

φ_{int} – relative humidity of the internal air, equal to 60%;

E - partial pressure of saturated water vapor in the plane of maximum moisture during the year of operation, that is determined by the formula:

$$E = \frac{(E_1 z_1 + E_2 z_2 + E_3 z_3)}{12} \quad (37)$$

where E_1, E_2, E_3 – partial pressure of saturated water vapor, respectively in winter, spring and autumn period, that are defined by the temperature in a plane of maximum moisture, at the average outdoor temperature of the corresponding period;

z_1, z_2, z_3 - duration of winter, spring and autumn and summer periods (6).

Ω_e - resistance to water vapor transmission of a part of the wall between the outer surface and the maximum moisture plane;

$e_{\text{ext}}^{\text{av}}$ – average partial water vapor pressure of outside air during the year (6).

$$e_{\text{ext}}^{\text{av}} = 780 \text{ Pa.}$$

For each layer of the multi-layer structure the value of the complex $f_i(t_{\text{m.y.}})$ is calculated, it characterizes the temperature in the plane of the maximum moisture.

$$f_i(t_{\text{m.y.}}) = 5330 \cdot \frac{\Omega_0 (t_{\text{int}} - t_0)}{R_0 (e_{\text{int}} - e_0^{\text{ext}})} \cdot \frac{\mu_i}{\lambda_i} \quad (38)$$

where Ω_0 – total resistance to water vapor transmission of the wall, $\text{Pa} \cdot \text{h} \cdot \text{m}^2 / \text{mg}$;

R_0 – total thermal resistance of the wall, $(m^2 \cdot ^\circ C)/W$;

t_0 – average temperature of outside air during the period with temperatures below zero; $t_0 = -4,6^\circ C$;

e_0^{ext} – average water vapor pressure of outside air during the period with temperatures below zero, Pa;

λ_i, μ_i – estimated coefficients of thermal conductivity, $W/(m \cdot ^\circ C)$, and water vapor transmission, $mg/(m \cdot h \cdot Pa)$, of a material.

Calculation example:

$$f_i(t_{m.y.}) = 5330 \cdot \frac{1,43 \cdot (20 + 4,6)}{2,978 \cdot (1311 - 420)} \cdot \frac{0,075}{0,21} = 25,24 \text{ } (^\circ C)^2/Pa$$

Temperature in the plane of the maximum moisture for the 1st layer $t_{m.y.}$ is higher than $18^\circ C$ (5).

Temperature at the layer boundaries is determined by the formula:

$$\tau_i = t_{int} - (t_{int} - t_0)(R_{si} + R_e)/R_o, \quad i = 1, 2, 3 \quad (39)$$

where R_e – thermal resistance of the layers between the inside surface and the plane that is x mm far from the inside surface, $m^2 \cdot ^\circ C/W$;

R_o – thermal resistance of the wall, $m^2 \cdot ^\circ C/W$;

R_{sj} – thermal resistance of the inside surface of the wall, $m^2 \cdot ^\circ C/W$;

$$\tau_{int} = 20 - (20+4,6)(0,115)/2,978=19,05^\circ C$$

$$\tau_{1-2} = 20 - (20+4,6) \cdot (0,115+0,06)/2,978=18,56^\circ C$$

| No | $f_i(t_{m.y.}),$ (°C) ² /Pa | Temperature in the plane of the maximum moisture $t_{m.y.}, °C$ | Temperature on the layer boundaries, °C |
|----|---|--|--|
| 1 | 25,24 | >18 | 19,05 18,56 |
| 2 | 92,17 | 4 | 18,56 11,45 |
| 3 | 25,24 | >18 | 11,45 11,08 |
| 4 | 353,32 | -16 | 11,08 -3,99 |

Table 9. Results

Since the temperature $t_{m.y.}$ in any of the layers is not disposed in the temperature range of the boundaries of this layer, it is impossible to determine in which layer the plane of maximum moisture is.

Since the third layer is colder layer than the second one and $t_{m.y.}$ of the third layer is above its temperature, and $t_{m.y.}$ of the second layer is lower than its temperature, it can be concluded that the plane of maximum moisture is between layers 2 and 3 (5).

The partial pressure of saturated water vapor in the plane of maximum moisture in winter, spring, autumn and summer periods is determined by the temperature at the plane of maximum moisture.

The duration and the temperature of winter, spring and autumn and summer periods in climatic conditions of St. Petersburg are defined as follows:

$$t_i = \frac{\sum t_j^{av}}{n} \quad (40)$$

where t_i – average temperature of outside air during i period, °C

t_j^{av} average temperature of outside air during j month, °C;

n – number of months of i period;

1) winter period (December, January, February, March):

$z_1 = 4$ months;

$$t_1 = [(-3,9) + (-6,6) + (-6,3) + (-1,5)] / 4 = -4,58^\circ\text{C};$$

$$\tau_1 = 20 - (20 + 4,58) \cdot (0,115 + 0,92) / 2,978 = 11,46^\circ\text{C};$$

$$E_1 = 1355,8 \text{ Pa};$$

2) spring and autumn period (April, October, November):

$z_2 = 3$ months;

$$t_2 = (4,5 + 5,7 + 0,2) / 3 = 3,47^\circ\text{C};$$

$$\tau_2 = 20 - (20 - 3,47) \cdot (0,115 + 0,92) / 2,978 = 14,26^\circ\text{C};$$

$$E_2 = 1628 \text{ Pa};$$

3) summer period (May, June, July, August, September):

$z_3 = 5$ months;

$$t_3 = (10,9 + 15,7 + 18,3 + 16,7 + 11,4) / 5 = 14,6^\circ\text{C};$$

$$\tau_3 = 20 - (20 - 14,6) \cdot (0,115 + 0,92) / 2,978 = 18,12^\circ\text{C}.$$

$$E_3 = 2080,3 \text{ Pa}.$$

$$E = \frac{1355,8 \cdot 4 + 1628 \cdot 3 + 2080,3 \cdot 5}{12} = 1725,73 \text{ Pa}$$

Resistance to water vapor transmission of a part of the wall between the outer surface and the maximum moisture plane is defined by the formula:

$$\Omega_e = \Omega_3 + \Omega_4 + \Omega_5 \quad (41)$$

$$\Omega_e = 0,13 + 0,33 + 0,09 = 0,55 \text{ Pa} \cdot \text{h} \cdot \text{m}^2 / \text{mg}$$

When $\varphi_{\text{int}} = 60\%$, $E_{\text{int}} = 2185 \text{ Pa}$.

$$e_{\text{int}} = \left(\frac{60}{100}\right) \cdot 2185 = 1311 \text{ Pa}$$

Then normative resistance to water vapor transmission Ω_{req}^* during the year of operation:

$$\Omega_{\text{req}}^* = \frac{(1311 - 1725,73) \cdot 0,55}{(1725,73 - 780)} = -0,024 \text{ Pa} \cdot \text{h} \cdot \text{m}^2 / \text{mg}$$

b) normative resistance to water vapor transmission Ω_{req}^{**} (considering that accumulation of moisture inside the wall during the period with temperatures below zero is not allowed), that is defined by the formula:

$$\Omega_{\text{req}}^{**} = \frac{0,0024 z_0 (e_{\text{int}} + E_0)}{\gamma \cdot \delta_w \cdot \Delta W_{av} + \eta} \quad (42)$$

where z_0 – period of moisture accumulation taken equal to the period with negative average monthly temperatures of outdoor air (6); $z_0 = 131$ days

E_0 - partial pressure of saturated water vapor in the plane of maximum moisture, that is determined at an average temperature of outdoor air during the period of moisture accumulation, Pa;

γ - material density of moistened layer, kg/m^3 ;

ΔW_{av} – maximum allowable increment of moisture content (%) in the condensation zone during the period of accumulation of moisture z_0 . For mineral wool $\Delta W_{av} = 3\%$;

$\delta_w \cdot \Delta W_{av}$ - the plane of maximum moisture is on the boundaries between two layers, this value shall be equal to the sum $\delta_{w1} \Delta w_1 + \delta_{w2} \Delta w_2$, where δ_{w1} и δ_{w2} is a half of thickness of a layer;

η – coefficient that is defined by the formula:

$$\eta = \frac{0,0024(E_0 - e_0^{ext})z_0}{\Omega_e} \quad (43)$$

where e_0^{ext} – average water vapor pressure of outside air during the period of months with negative average monthly temperatures, Pa.

Average water vapor pressure of outside air during the period of months with negative average monthly temperatures e_0^{ext} is taken equal to saturated water vapor pressure at the temperature $t_0 = -4,6^\circ\text{C}$:

$$e_0^{ext} = 420 \text{ Pa};$$

The temperature τ_0 in the plane of maximum moisture during a period z_0 :

$$\tau_0 = 11,45^\circ\text{C}$$

Partial water vapor pressure E_0 in the plane of maximum moisture when $\tau_0 = 11,45^\circ\text{C}$ is $E_0 = 1355 \text{ Па}$.

$$\eta = \frac{0,0024 \cdot (1355 - 420) \cdot 131}{0,55} = 534,48$$

$$\Omega_{req}^{**} = \frac{0,0024 \cdot 131 \cdot (1311 - 1355)}{0,03 \cdot (0,3 + 3,4) + 534,48} = -0,026 \text{ Pa} \cdot \text{h} \cdot \text{m}^2 / \text{mg}$$

Comparing Ω_0 with required values it is seen that:

$$\Omega_0 > \Omega_{req}^* > \Omega_{req}^{**} \quad (1,43 > -0,024 > -0,026)$$

The walls satisfy the requirements in regard to resistance against water vapor transmission.

3.6.2 Determination of possible formation of condensation in the wall

Design temperature t_{ext}'' and relative humidity of outside air φ_{ext} are equal to the average monthly temperature and average relative humidity of the coldest month.

$$t_{ext}'' = -6,6^{\circ}\text{C}; \varphi_{ext} = 86 \%; e_{ext} = 305,7 \text{ Pa}$$

$$t_{int} = 20^{\circ}\text{C}, \varphi_{int} = 60 \%; e_{int} = 1311 \text{ Pa}$$

Temperatures on the layers boundaries τ_i are defined as follows. The numbers are from the inside to outside surface.

$$\tau_{int} = 20 - (20+4,6)(0,115)/2,978 = 19,05^{\circ}\text{C}$$

$$\tau_{1-2} = 20 - (20+4,6)(0,115+0,06)/2,978 = 18,56^{\circ}\text{C}$$

$$\tau_{2-3} = 20 - (20+4,6)(0,115+0,06+0,86)/2,978 = 11,45^{\circ}\text{C}$$

$$\tau_{3-4} = 20 - (20+4,6)(0,115+0,06+0,86+0,05)/2,978 = 11,08^{\circ}\text{C}$$

$$\tau_{4-5} = 20 - (20+4,6)(0,115+0,06+0,86+0,05+1,815)/2,978 = - 3,91^{\circ}\text{C}$$

$$\tau_{ext} = 20 - (20+4,6)(0,115+0,06+0,86+0,05+1,815+0,083)/2,978 = - 4,6^{\circ}\text{C}$$

Due to the material's resistance to water vapor transmission, water vapor pressure will reduce from e_{int} to e_{ext} . The values of water vapor pressure at the layers boundaries are determined by the formula:

$$e_i = e_{int} - (e_{int} - e_{ext})(\Omega_{int} + \sum \Omega_i)/\Omega_0 \quad (44)$$

where e_i – water vapor pressure at the outside surface of i layer;

$\sum \Omega_i$ – sum of resistances to water vapor transmission of the layers, counting from the inside surface.

The partial pressure of saturated water vapor at the boundaries of layers E_i is determined according to the graph in Figure 3 by the values τ_i .

The calculation results are presented in Table 10.

| Layer boundary | Temperature on the boundaries τ , °C | Partial pressure of saturated water vapor E_i , Pa | Partial pressure of water vapor e_i , Pa |
|----------------|---|--|--|
| int | 19,05 | 2204,54 | 1322,73 |
| 1-2 | 18,56 | 2138,11 | 1192,16 |
| 2-3 | 11,45 | 1355,34 | 741,76 |
| 3-4 | 11,08 | 1322,17 | 656,18 |
| 4-5 | -3,91 | 444,20 | 430,98 |
| ext | -4,60 | 419,99 | 361,19 |

Table 10. Results of the possibility assessment of vapor condensation inside the wall

It is seen in the Figure 4 that the graph of water vapor pressure e along the axis t (the thickness of the wall) does not intersect with the line of saturated water vapor pressure E , so no condensation is formed inside the wall.

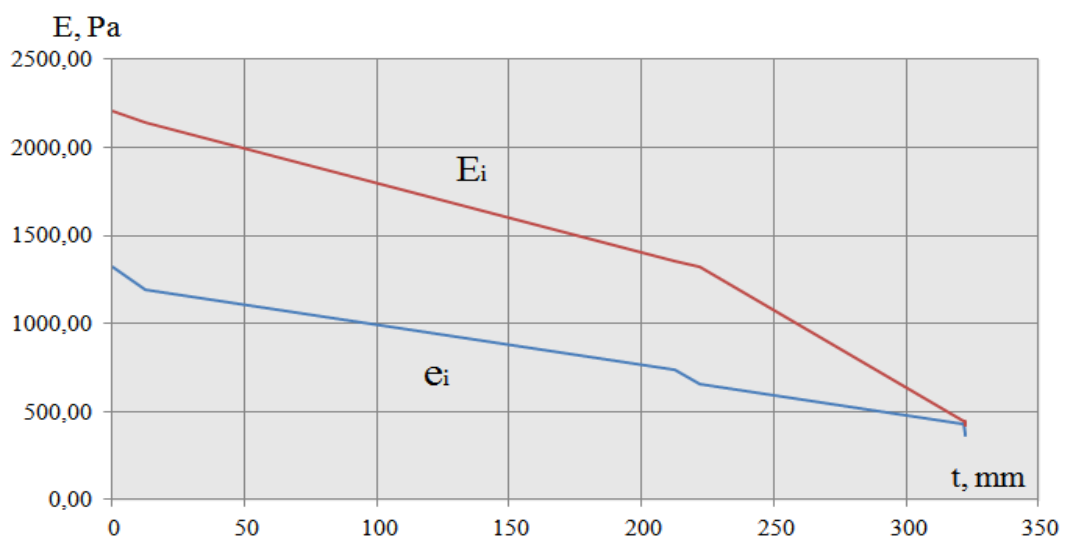


Figure 4. The graph of water vapor pressure and saturated water vapor pressure inside the wall

Relative humidity on the layers boundaries is defined by the formula:

$$\varphi_i = \frac{100 \cdot e_i}{E_i} \quad (45)$$

The results of determination of moisture on the layers boundaries are presented in Table 11.

| Layers boundaries | Relative humidity φ , % |
|-------------------|---------------------------------|
| int | 60,00 |
| 1...2 | 55,76 |
| 2...3 | 54,73 |
| 3...4 | 49,63 |
| 4...5 | 97,02 |
| ext | 86,00 |

Table 11. Relative humidity at the layers boundaries

Moisture distribution in the thickness of the wall is shown in Figure 5.

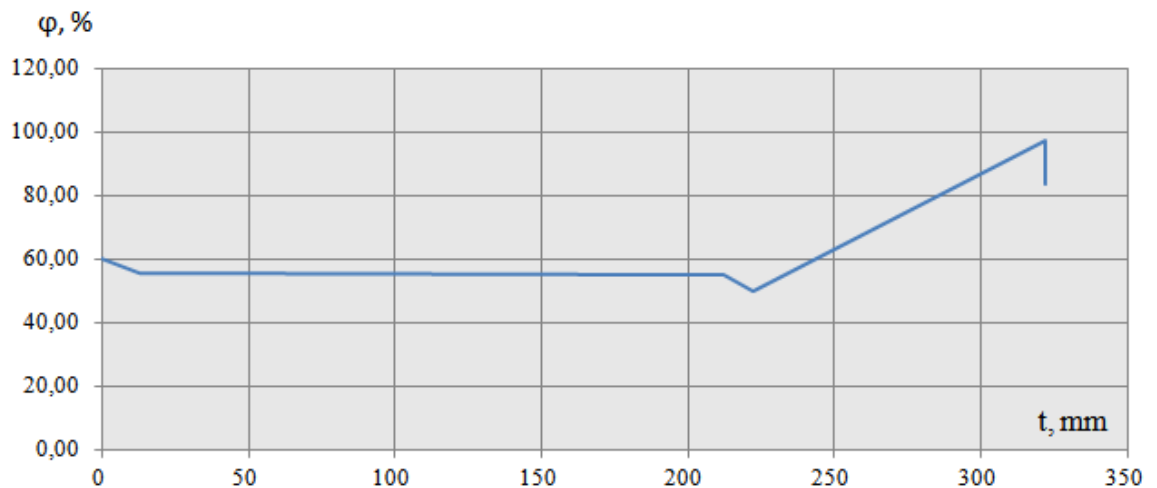


Figure 5. Moisture distribution in the thickness of the wall structure

It can be concluded that the moisture in the area of the U-shaped thin-walled galvanized steel profile is not more than 65%. This value is the allowable value, set in recommendations of N.P. Melnikova Research and Design Institute of steel building structures (9).

The final set of layers of external walls:

- 1) gypsum board 12.5 mm;
- 2) insulation Isover Light + U-shaped galvanized steel profile 200 mm;
- 3) gypsum board 9.5 mm;
- 4) insulation Isover Venti + angle bracket 100 mm;
- 5) waterproofing membrane 0,18 mm.

The presented set of layers is selected in accordance with theoretical calculation, however practically the layer of vapor barrier would be added between the gypsum board 12.5 mm and the layer of insulation Isover Light with steel profile. In real life conditions there is no guarantee that there will be no seams or cracks in the wall, the real relative humidity inside the building can also be higher than the design value. In order to save required air permeability of walls the layer of vapor barrier is needed.

4 Program for the automated calculation of the heat and humidity regime

In order to define operating conditions of thin-walled galvanized steel profiles inside the wall structure quickly the program based on Microsoft Excel was developed.

The first step is entering initial data in the program: temperature and relative humidity of inside and outside air, dimensions of steel elements, thicknesses of layers, location and building type.

| Initial data | | |
|---------------------------------|------|----|
| Outside air temperature | -4,6 | °C |
| Outside air relative humidity | 86 | % |
| Inside air temperature | 20 | °C |
| Inside air relative humidity | 60 | % |
| Floor height | 4,2 | m |
| Distance between steel profiles | 0,6 | m |
| Profile thickness | 2 | mm |
| Building height | 7,8 | m |
| Bracket thickness | 2 | mm |
| Distance between steel brackets | 0,8 | m |
| Width of the bracket | 0,05 | m |

| | |
|---------------|------------------|
| Building type | public |
| Location | Saint-Petersburg |

| Materials | Thickness, m | Coefficient of thermal conductivity λ | Thermal resistance of a layer R_i , $m^2 \cdot ^\circ C / W$ | Coefficient of water vapor permeability μ , $mg / (m \cdot h \cdot Pa)$ | Resistance to water vapor permeability C |
|---|--------------|---|--|---|--|
| 1 Gypsum board | 0,01250 | 0,21 | 0,06 | 0,0750 | 0,17 |
| 2 Insulation Isover Light + Steel profile | 0,20000 | 0,23 | 0,86 | 0,3000 | 0,67 |
| 3 Gypsum board | 0,00950 | 0,21 | 0,05 | 0,0750 | 0,13 |
| 4 Insulation Isover Venti + Steel bracket | 0,10000 | 0,06 | 1,82 | 0,3000 | 0,33 |
| 5 Waterproofing membrane Tyvek Soft | 0,00018 | - | 0 | 0,0020 | 0,09 |
| 6 Gypsum board Vapor barrier | | - | 0 | - | 0,00 |
| 7 Insulation Isover Light + Steel profile Insulation Isover Venti + Steel bracket Waterproofing membrane Tyvek Soft | | - | 0 | - | 0,00 |
| 8 | | - | 0 | - | 0,00 |
| 9 | | - | 0 | - | 0,00 |

| | | | | |
|---|---------|-----------------------------|----|--|
| Required thickness of external insulation | 0,0817 | m | OK | OK - thickness of external insulation corresponds to requirements; !!! - it is necessary to increase the thickness of external insulation; #H/Д - there is no layer of external insulation. |
| Thermal resistance of a wall | 2,9781 | $m^2 \cdot ^\circ C / W$ | OK | |
| Required thermal resistance of a wall | 2,5611 | $m^2 \cdot ^\circ C / W$ | OK | |
| Resistance to water vapor permeability | 1,4232 | $Pa \cdot h \cdot m^2 / mg$ | OK | |
| Required resistance to water vapor permeability | -0,0196 | $Pa \cdot h \cdot m^2 / mg$ | | |

Figure 6. Fragments of the program in Microsoft Excel. Initial data

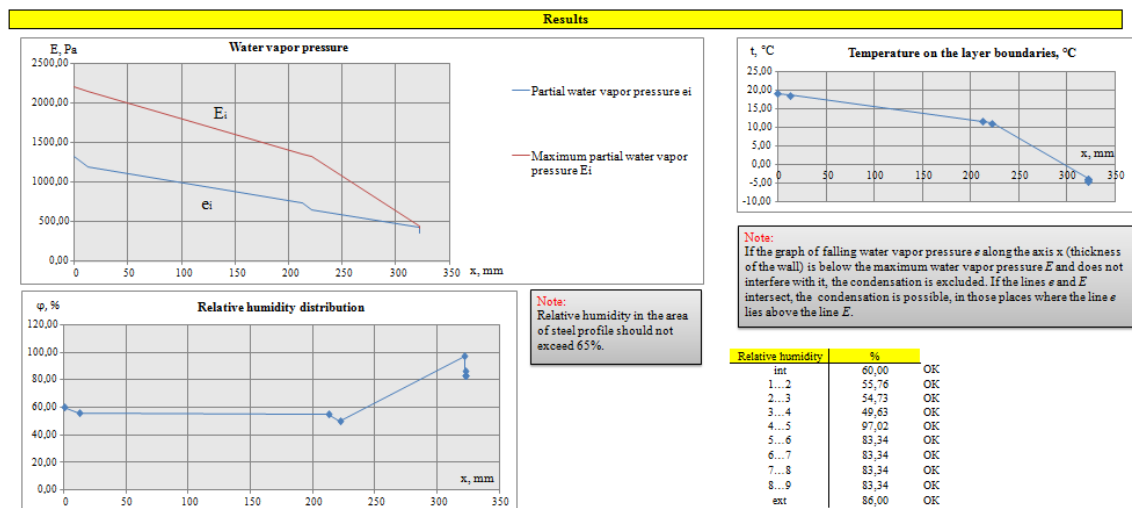


Figure 7. Fragments of the program in Microsoft Excel. Results

The program allows checking whether the structure meet the requirements of SP 50.13330.2012 "Thermal protection of buildings", checking a possibility of condensation, to obtain humidity distribution curve and in accordance with this curve to decide in which part of the wall it is allowed to use of steel thin-walled galvanized profiles.

5 Summary

In this work the possibility of using a thin-walled galvanized steel profile as part of enclosing structure in the climatic conditions of St. Petersburg is studied.

As a result of the work:

- 1) structure of the wall with the use of U-shaped thin-walled galvanized steel profile is designed;
- 2) a program for automatic calculation of the heat and humidity conditions is developed;
- 3) heat and humidity conditions inside the wall are calculated for the climatic conditions of St. Petersburg;
- 4) it is found that the operating conditions of a U-shaped thin-walled galvanized steel profile comply with the recommendations of N.P. Melnikova Research and Design Institute of steel building structures in humidity parameter.

The developed program for automated calculation of heat and humidity conditions allows identifying the possibility of condensation formation inside the wall structure. On the basis of the automatically drawn graph of distribution of the relative humidity inside the structure it is easy to draw a conclusion as in what part of the structure thin-walled galvanized steel profiles can be used without the threat of corrosion.

As the calculations performed in the work are one-dimensional calculations, there is a need for further research. The change of temperature and other parameters over time and the influence of thermal bridges on the heat transfer can be studied more deeply.

6 References

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