Effectiveness Evaluation of Cellar Application with Controlled Temperature Mode in Low-Rise Buildings with Pile Foundations

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Abstract. Low-rise buildings made of light steel thin-walled structures (LSTS below) in the Arctic regions are considered by thermal protection destruction due to many heat-conducting elements and high air infiltration. Constructive measures have been recommended to increase thermal protection for buildings made of LSTS including thermally insulated cellar with a controlled temperature mode. A comparative assessment of the energy efficiency of the proposed measures has been carried out. A significant temperature improvement on the inner surface of the basement slab was obtained. The energy characteristics improvement of a building made of LSTS is shown in comparison with the indicators of a standard solution.

1. Introduction

The permafrost soils distribution area within Russia is 55% to 65% of the territory according to various sources. Almost the whole Yakutia is located in the continuous permafrost zone. The topsoil melts to a depth of only 3.5 m. during the summer. The permafrost thickness in the central part of Yakutia reaches from 100 to 200 m, in the northern part from 700 m or more. The permafrost soils temperature at a depth of 20 m varies from -2°C to -5°C in the region prevailing area and only in its northern part decreases to -6°C ÷ -9°C. The standard depth of soils seasonal melting varies from 0.5 to 1.5 m in the northern part and from 1.5 m to 3.0 m in the southern part depending on the relief, lithology and exposure of the area. [1-3]. There are prognostic data on changes in the permafrost zone in Russia based on monitoring and the results of numerical modeling [4,5].

Bases and foundations on permafrost soils in accordance with SP 25.13330.2012. The updated version of SNiP 2.02.04-88 one of the basic principles of buildings construction in the permafrost zone is the preservation of the base soils in the frozen state during their operation (principle I) ensuring stability, reliability and increases the service life of objects. Therefore, the most common type of buildings foundations on permafrost soils are pile foundations [6]. Meanwhile, the buildings operating experience on pile foundations in the extreme climatic conditions of Yakutia shows that significant heat losses occur through the basement floor and the internal temperature mode of buildings worsens if there is a ventilated cellar through the basement floor [7].
In recent years, the prefabricated buildings construction volume with LSTS use on screw steel or drilling reinforced concrete piles has increased in the Arctic regions. The basement part of such buildings is characterized by the heat-conducting elements and a significant area of external fences. In addition, during the stable low outside air temperature \((t_{\text{on}} \leq -40^\circ\text{C})\), there is an intense penetration of cold air through the joints of structural elements due to high air infiltration [8]. For example, the difference in pressure between outdoor and indoor air in low-rise buildings on the coldest days can reach 50 Pa in the Arctic regions of Yakutia. It is proposed to use a heat-insulated cellar with a controlled temperature mode in order to improve the temperature mode of the internal premises of buildings and reduce the effect of air infiltration in the extreme conditions of the North.

The currently adopted methods for buildings foundations constructing on permafrost soils are based on the research results of G.V. Porkhaev. [9], Tsytovich N.A. [10] and others which give some overestimated values of thawing depths of soils under buildings. In recent years, it has become possible to calculate more accurately the soils temperature field in the buildings foundations using mathematical modeling methods and increased computing power [11, 12]. The article [13] presents the main mathematical modeling principles of the interaction of a building on pile foundations with a heat-insulated cellar. As a result of the numerical experiment, the regularities of the formation of the soils temperature mode of the low-rise buildings base with heat-insulated cellar application depending on the configuration and the building dimensions in plan, the cellar height, the basement thermal resistance and the cellar fencing were obtained. Monitoring of the foundation soils condition of the operated buildings from the LSTS carried out for 5 years showed that with a heat-insulated cellar and correct temperature regulation in the cellar, a soil stable low temperature remains below the active layer and there is no thawing under the building [14].

Based on the above, it is recommended to use a cellar with a controlled temperature mode for low-rise buildings with a width of 15 m and less with pile foundations on permafrost soils and average annual outdoor air temperatures below minus 2°C. At the same time, the reduced resistance to heat transfer of the buildings basement overlap should be no less than the standardized values specified in SP 50.13330.2012 Thermal protection of buildings. Updated edition of SNiP 23-02-2003. Air temperature control in the cellar is carried out to maintain a stable position of the permafrost boundary upper part and ensure the bearing capacity of pile foundations. The regulation of the air temperature in the buildings cellar is due to the heat-insulated fence device around the perimeter of the entire pile field with a heat transfer resistance of about 1.2 m²·°C / W and air ventilation in the cellar through vents depending on the outside air temperature.

Many researchers dealt with the thermal protective properties improving of enclosing structures of buildings from LSTS [15-19]. This article authors have developed the basic design principles and new solutions for external fences of low-rise buildings from the LSTS based on buildings field monitoring in the Arctic regions [20]. The buildings thermal protection made of LSTS must be solved in a complex way with the use of heat-efficient external fences and a heat-insulated cellar with a controlled temperature mode in extremely low outside air temperature conditions. This article provides an assessment of the effectiveness of fences new types use and heat-insulated cellar in buildings from the LSTS in the Arctic regions of Yakutia.

2. Methods
The energy efficiency assessment of low-rise buildings from the LSTS was carried out using the example of a paramedic-obstetric center (FAP) in the village Zhigansk of the Republic of Sakha (Yakutia) according to the methodology adopted in SP 50.13330.2012. Thermal protection of buildings. Updated edition of SNiP 23-02-2003. The building is one-story, G-shaped in plan with overall dimensions of 14.8×10.2 m. The foundation is screw piles. External and internal walls made of thin-walled bent profiles. Floor insulation - expanded polystyrene plates PSB-S-35 300 mm thick. Wall insulation - Rockwool LIGHT BATT S SCANDIC thermal insulation boards and Venti Butts Rockwool insulation boards 250 mm thick. Insulation in the coating - mineral wool boards "Rockwool" 350 mm thick. The total area is 128.83 m². The heated volume is 396.81 m³.
According to SP 50.13330.2012 and GOST 30494-96, the calculated average temperature of the internal air is taken as $t_v = +20 \, ^\circ C$. According to SP 131.13330.2012. Construction climatology. Updated edition of SNiP 23-01-99* the calculated outside air temperature of the coldest five-day period with 0.92 for Zhigansk settlement $t_{out} = -52 \, ^\circ C$, duration $Z_{out} = 288$ days and average outside air temperature $t_{tot} = -18.7 \, ^\circ C$ for the heating period. Degree-days of the heating period of the GSOP are determined by the formula:

$$GSOP = (t_v - t_{tot}) \cdot Z_{tot} = (20 - (-18.7)) \cdot 288 = 11145 \, ^\circ C \cdot \text{days}.$$ 

According to the rules for these degree-days, the normalized resistance to heat transfer for external walls is $R_{reqw} = 5.3 \, m^2 \cdot ^\circ C / W$, coatings $R_{reqc} = 7.77 \, m^2 \cdot ^\circ C \cdot W$, overlapping over the technical cellar $R_{reqf} = 6.92 \, m^2 \cdot ^\circ C / W$, windows and other translucent structures $R_{reqf} = 0.78 \, m^2 \cdot ^\circ C / W$. According to table 14 of SP 50.13330.2012, the standardized specific consumption of heat energy for building heating and ventilation is $q_{ot}^{req} = 0.394 \, W / m^3 \cdot ^\circ C$.

Thermal and energy characteristics have been determined to assess the effectiveness of new constructive solutions use for external enclosing structures and a heat-insulated cellar in the present building. For comparison, the characteristics of a typical FAP building developed according to the Technical Certificate No. 4661-15 of the Ministry of Construction of the Russian Federation - "Album of standard design solutions SNK 001-06-2015 AMK LLC" were also determined. The main constructive solutions for walls and basement floors of typical and proposed buildings made of LSTS are shown in Fig. 1.

**Figure 1.** Wall-to-basement conjunction:
a - typical solution; b - energy efficient solution

1 - monolithic reinforced concrete slab ($\lambda = 1.92 \, W/(m \cdot ^\circ C)$); 2 - polystyrene foam plates PSB-S-35 ($\lambda = 0.04 \, W/(m \cdot ^\circ C)$); 3 - cement-sand screed M150 ($\lambda = 0.76 \, W/(m \cdot ^\circ C)$); 4 - gypsum plasterboard gypsum board ($\lambda = 0.21 \, W/(m \cdot ^\circ C)$); 5 - heat-insulating plates Rockwool "LIGHT BATTs SCANDIC" ($\lambda = 0.039 \, W/(m \cdot ^\circ C)$); 6 - rack steel profiles with 1.8 mm wall thickness with a step of 600 mm ($\lambda = 58 \, W/(m \cdot ^\circ C)$); 7 - rough strand board OSB ($\lambda = 0.34 \, W/(m \cdot ^\circ C)$); 8 - heat-insulating plates Rockwool "Venti Butts" ($\lambda = 0.04 \, W/(m \cdot ^\circ C)$); 9 - thermal liner made of lightweight concrete ($\lambda = 0.16 \, W/(m \cdot ^\circ C)$)

The calculated specific characteristic of the thermal energy consumption for the building heating and ventilation $q_{ot}^{req}$, $W/(m^3 \cdot ^\circ C)$ is determined according to SP 50.13330.2012 by the formula:

$$q_{ot}^{req} = [k_{ob} + k_{vent} - (k_{by} + k_{rad}) \cdot v \cdot \zeta] \cdot (1 - \xi) \cdot \beta_h$$
where: $k_{ab}$ is the specific heat-protective characteristic of the building, W / (m$^3$ · °C), is determined in accordance with Appendix G SP 50.13330.2012;

$k_{vent}$ is specific ventilation characteristics of the building, W / (m$^3$ · °C);

$k_{oat}$ is the specific characteristic of the building's household heat emission, W / (m$^3$ · °C);

$k_{rad}$ – specific characteristic of heat input into the building from solar radiation, W / (m$^3$ · °C);

$\xi$ is a coefficient taking into account reduction of heat consumption when heat energy for heating is taken into account, it is taken $\xi = 0.1$;

$\beta_h$ is a coefficient taking into account the additional heat consumption of the heating system associated with the nominal heat flow discreteness of the heating devices range, their additional heat losses through the radiator sections of the fences, the increased air temperature in the corner rooms, the heat losses of pipelines passing through unheated rooms, $\beta_h = 1.13$;

$\nu$ – coefficient of heat input reduction due to thermal inertia of the enclosing structures $\nu = 0.95$;

$\zeta$ – efficiency coefficient of automatic regulation of heat supply in heating systems; recommended value is 0.95.

The specific heat-protective characteristic of the building is calculated according to the formula G.1 SP 50.13330.2012:

$$k_{ab} = \frac{1}{V_{ot}} \sum_i \left( n_{ij} \cdot \frac{A_{f,i}}{R_{o,i}^{pr}} \right) = K_{comp} \cdot K_{tot},$$

where: $R_{o,i}^{pr}$ – reduced resistance to heat transfer of the i-th fragment of the building's heat-shielding envelope, (m$^2$ · °C) / W;

$A_{f,i}$ – area of the corresponding fragment of the building's heat-shielding envelope, m$^2$;

$V_{ot}$ – heated building volume, m$^3$;

$n_{ij}$ – coefficient that takes into account the difference between the internal or external temperature of the structure from those adopted in the calculation of the GSPC, is determined by the formula (5.3 SP 50.13330.2012).

For the building in question, this formula will look like this

$$k_{ab} = \frac{1}{V_{ot}} \cdot \left( \frac{A_{wall}}{R_{wall}} + \frac{A_{win}}{R_{win}} + \frac{A_{door}}{R_{door}} + \frac{A_{af}}{R_{af}} + \frac{A_{bf}}{R_{bf}} + n_b \cdot \frac{A_{ junction}}{R_{ junction}} \right),$$

where: $A_{wall}$ and $R_{wall}$ – the area and resistance to heat transfer of the external walls;

$A_{win}$ and $R_{win}$ – the area and resistance to heat transfer of windows;

$A_{door}$ and $R_{door}$ – the area and resistance to heat transfer of the doors;

$A_{af}$ and $R_{af}$ – the area and resistance to heat transfer of the coating;

$A_{bf}$ and $R_{bf}$ – the area and heat transfer resistance of the basement floor;

$A_{ junction}$ and $R_{ junction}$ – the area and resistance to heat transfer of the basement slab junction.

If there is a cellar as for an unheated basement, a coefficient taking into account the difference between the internal temperature of the basement and the outside air temperature is additionally introduced and determined by the formula:

$$n_b = \frac{t_{c} - t_{b}}{t_{c} - t_{ot}} = \frac{20 - (-5.69)}{20 - (-18.7)} = 0.664,$$

where: $t_b$ – the average air temperature in the basement during the heating period, $t_b = -5.69^\circ$C.

The specific building ventilation characteristic is determined by the formula (G.2 SP 50.13330.2012):

$$k_{vent} = 0.28 \cdot c \cdot n_v \cdot \beta_v \cdot \rho_v^{vent} \cdot \left(1 - k_{eff} \right) = 0.28 \cdot 1 \cdot 0.48 \cdot 0.85 \cdot 1.21 \cdot (1 - 0) = 0.14 \text{ W / m}^3 \cdot ^\circ\text{C},$$

where: $c = 1$ kJ / (kg · °C) – specific heat capacity of air;

$\beta_v$ – coefficient of air volume reduction in the building taking into account the internal enclosing structures, $\beta_v = 0.85$;

$\rho_v^{vent}$ – average density of the supply air for the heating period, kg / m$^3$;

$$\rho_v^{vent} = \frac{353}{273 + t_{ot}} = \frac{353}{273 + 18.7} = 1.21 \text{ kg / m}^3.$$
The specific characteristic of the building’s household heat emission $k_{hyt}$, W / (m³ · °C) is determined by the formula (G.6. SP 50.13330.2012):

$$k_{hyt} = \frac{q_{tot} \cdot A_c}{V_{tot} \cdot (t_{in} - t_{out})} = \frac{10.39 \cdot 74.21}{396.81 \cdot (20 - (-18.7))} = 0.05 \text{ W} / (\text{m}^3 \cdot \degree \text{C})$$

where: $q_{tot}$ - the value of household heat emission is taken equal to 10.39 W / m²;

$A_c$ – the estimated area of a public building is 74.21 m².

The specific characteristic of heat input into the building from solar radiation $k_{rad}$, W / (m³ · °C) is taken as a reserve equal to 0.

The specific consumption of heat energy for heating and ventilation of the building during the heating period $q$ is determined by the formula (G.9a SP50.13330.2012):

$$q = 0.024 \cdot GSOP \cdot q_{tot}^r \cdot h, \text{ kWh} / \text{m}^3 \cdot \text{year}$$

where: $h$ - average building floor height, m, equal to 3.05 m.

The consumption of heat energy for heating and ventilation of the building during the heating period $Q_{tot}^\text{year}$, kW · h / year, is determined by the formula (G.10 SP50.13330.2012):

$$Q_{tot}^\text{year} = 0.024 \cdot GSOP \cdot V_{tot} \cdot q_{tot}^r$$

The building total heat loss for the heating period $Q_{tot}^\text{year}$, kWh / year, is determined by the formula (G.11 SP50.13330.2012):

$$Q_{tot}^\text{year} = 0.024 \cdot GSOP \cdot V_{tot} \cdot (k_{ob} + k_{vent}).$$

3. Results

Thermotechnical calculations were carried out using the Heat2 / Heat3 software and calculation complex. All calculations were performed for structures fragments in 3D format (Fig. 2). The thermotechnical characteristics for a typical solution with a ventilated cellar and an energy-efficient solution of a wall junction with a building basement with a heat-insulated cellar were determined for comparison. The spacing of the upright profiles in the walls is 600 mm. A junction fragment of the wall with the basement floor is considered with dimensions 3000 × 2000 × 1450 mm (L × W × H) (Fig. 2). When carrying out thermotechnical calculation for the proposed solution for a building with a heat-insulated cellar, the outside air temperature was taken to be -52°C, the air temperature in the cellar was -13°C, and the indoor air temperature was +20°C. Also, calculations of the heat engineering indicators of fragments of the basement floor, wall, and attic floor have been performed.
Figure 2. 3D temperature field junction of the basement:

a - a typical solution;  b - energy efficient solution.

The line from zero temperature passes almost through the inner corner of the wall joints with the basement close to the fence inner surface in a typical solution. The minimum temperature on the inner surface in the fragment under consideration is +5.7°C which is lower than the condensation temperature. Experience shows that moisture and icing are often observed in these zones. This situation is due to the cold bridge: reinforced concrete floor - steel rack profile (Fig. 3).

Figure 3. Temperature distribution in the corner joint along the vertical section in steel rack-mount wall profile: a - typical solution $t_{out}=-52$°C; b- energy efficient solution $t_{out}=-52$°C и $t_{in}=-13$°C.

The temperature distribution over the unit section is much more positive than in a typical solution with thermal inserts made of lightweight concrete blocks and a cellar with a controlled temperature mode in a building made of LST. In this case, all steel rack profiles are in a zone with a positive temperature. The minimum temperature on the inner surface of the fragment under consideration is +14.2°C which is higher than the temperature of condensation. It should be noted that the gradual light blocks location prevents of cold air during the shrinkage of expanded polystyrene plates of the lower layer (Fig. 3).

It has been established that a cellar with a controlled temperature mode can significantly reduce heat losses through the corner joint of the wall with the basement ceiling as a result of two options comparing: the specific heat losses for the standard and proposed solutions are, respectively, $\Psi =$
0.143 W / (m · °C) and \( \Psi = 0.121 \) W / (m · °C). The reduced resistance to heat transfer of the proposed design of the base unit is 8.29 m\(^2\) · °C / W, and for a typical solution - 6.97 m\(^2\) · °C / W.

The results of the thermal performance calculating other elements of the enclosing structures for a typical building and a building with a controlled cellar are shown in Table 1.

### Table 1. Thermotechnical parameters of the enclosing structures made of LSTS

| Enclosing structures element | Total area of a structural element, m\(^2\) | Standard solution option | Proposed solution option |
|-----------------------------|---------------------------------------------|--------------------------|--------------------------|
|                             | Provided resistance to heat transfer, m\(^2\) · °C / W | Specific heat loss \( \Psi \), W / (m · °C) | Reduced resistance to heat transfer, m\(^2\) · °C / W | Specific heat loss \( \Psi \), W/(m · °C) |
| Exterior walls              | 134,3 (96,8)*                                  | 4,77                     | 0,21                      | 4,77                     | 0,21                      |
| Windows                     | 11,99                                        | 0,79                     | 1,265                     | 0,79                     | 1,265                     |
| Doors                       | 6,51                                         | 1,12                     | 0,893                     | 1,12                     | 0,893                     |
| Attic slab                  | 130,1                                        | 6,88                     | 0,145                     | 6,88                     | 0,145                     |
| Basement slab               | 130,1 (45,9)*                                | 7,84                     | 0,128                     | 7,84                     | 0,128                     |
| Wall junction with basement slab | 154,4                                      | 6,97                     | 0,143                     | 8,29                     | 0,121                     |

*area minus the basement slab is in brackets

The external enclosing structures areas, the heated area and the building volume required for calculating the energy passport, and the thermal characteristics of the building were determined according to the project in accordance with SP 50.13330.2012. The energy characteristics calculating results of the typical building and a building with a controlled cellar are shown in Table 2. The energy characteristics of a building made of LSTS with a heat-insulated cellar in combination with a new junction are improved in comparison with the standard solution from 7.2 to 12.1%. The Arctic regions of Yakutia are characterized by high tariffs for electricity and heat due to the difficulty of the delivery of fuel (diesel fuel, coal). In these circumstances, improving the buildings energy efficiency is of great importance and leads to significant financial savings.

### Table 2. Energy characteristics.

| Energy indicators                                                                 | Typical building | Building with regulated cellar | Improving efficiency, % |
|-----------------------------------------------------------------------------------|------------------|--------------------------------|--------------------------|
| Specific heat insulation characteristic \( k_{\text{sol,}} \), W/m\(^2\) · °C     | 0,208            | 0,183                          | 12,1                     |
| Estimated specific characteristic of heat energy consumption for heating and ventilation of the building \( q_{\text{p.et}} \), W/(m\(^2\) · °C) | 0,308            | 0,282                          | 8,5                      |
| Specific consumption of heat energy for heating and ventilation of the building during the heating period \( q \), kW·h/(m\(^2\) · year) | 82,4             | 75,4                           | 8,5                      |
| Specific consumption of heat energy for heating and ventilation of the building during the heating period \( q \), kW·h/(m\(^2\) · year) | 251,3            | 230,0                          | 8,5                      |
| Heat consumption for heating and ventilation of the building during the heating period \( Q_{\text{tot}} \), kW·h/year | 32689,9          | 29930,4                        | 8,5                      |
| Total heat loss of the building during the heating period \( Q_{\text{tot}} \), kW·h/year | 36936,3          | 34282,8                        | 7,2                      |
4. Conclusion
1. It is suggested to use a cellar with a controlled temperature mode to improve the temperature mode of the interior of low-rise buildings made of LSTs with a width of 15 m and less with pile foundations on permafrost soils and average annual outdoor temperatures below minus 2 °C. The regulation of the air temperature in the buildings’ cellar is due to a heat-insulated fence in the basement part and air ventilation through the vents in the fence.

2. The temperature mode of the building interiors is significantly improved and air infiltration effect on the coldest days is reduced with a heat-insulated cellar application in combination with a new junction of a wall with a basement in buildings made of LSTs. Specific heat loss through a fragment of the recommended interface is reduced by 15.4%, the reduced heat transfer resistance is increased by 16.0% compared to the standard solution.

3. An assessment of the cellar effectiveness application with a controlled temperature mode for a paramedic-obstetric center (FAP) built in Zhigansk of the Republic of Sakha (Yakutia) from an LST with a total area of 128.8 m² was carried out. According to the assessment, the calculated specific characteristic of the heat energy consumption for heating and ventilation for a typical building is 0.208 W / (m² · °C), while, for a building with a heat-insulated cellar, it is 0.183 W / (m² · °C). Heat consumption for heating and ventilation during the heating period and the total heat losses of the building during the heating period for the FAP building with a heat-insulated cellar are reduced by 8.5% and 7.2% in comparison with the standard solution.

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