Formation of thermal-insulating building envelopes of dome constructions for the far north regions

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Abstract. The Far North territories development is carried out in most cases by the rotation-based work, with frequent deployment. Therefore, special conditions are imposed on the shift workers constructions. In particular, high insulating properties, resistance to wind and snow loads, multiple assembly and disassembly possibility, compactness in the traveling condition are presented to them. These requirements correspond to the dome prefabricated constructions. To calculate the thermal-insulating properties of building envelopes, climatic conditions were adopted for the city of Verkhoyansk, as the coldest settlement. The main task for such buildings is to provide the required thermal insolation with the minimum sizes of the building envelope. For this purpose, the prefabricated elements structure of dome-shaped constructions consisting of a timber frame shaped like a triangle 200 mm thick, filled with polyisocyanurate foam, a closed air space on both sides of the prefabricated elements, an OSB inner panel covered with thermal-insulating paint, an outer slab of cement-bonded particleboard, covered with bitumen tile was developed. Moisture protection of thermal-insulating materials is provided from the inside with aluminum foil, and from the external with wind-moisture-proof membrane. In the research process it was found that the thermal resistance of the building envelope without applying thermal insulating paint is $R = 6.7 \text{ m}^2\text{K}/\text{W}$ that is not enough for Verkhoyansk conditions. The treatment with liquid thermal-insulating paint increased the thermal resistance to $R = 7.94 \text{ m}^2\text{K}/\text{W}$ that exceeds the standard values.

Introduction
Until recently, the Far North regions especially the Arctic Ocean territory have been little studied as geographic features and in mineral exploration. At the end of the 20th and the beginning of the 21st century, with the advent of progressive transportation means, exploration and navigation, it became possible not only to study geographic features, but also to explore mineral deposits. First of all, these are energy commodities reserves. According to the American researchers’ estimates [1], approximately 22% of world oil and gas reserves are located in the Arctic zone. These are the coastal Alaska zones, the Barents Sea shelf and the Russian coast of the Arctic Ocean. These areas are rich in other minerals. Therefore, Norway mines coal on the island of Svalbard, where the richest mine in Europe is located [2]. Gold, nickel, diamonds, zinc, lead, iron and other minerals are mined in the Arctic and the Far North. Intensive exploration of new deposits is carried out.
Due to the climatic conditions severity, mineral exploration in the Far North regions is carried out on a rotational basis. The shifts camps are constructed at the unequipped places, in the permafrost zone. Therefore, one of the requirements for these buildings is the multiple assembly and dismantling possibility and assembly elements transportation. As noted in [3], for the Far North regions it is advisable to use the dome shaped modular prefabricated buildings. Such buildings use will provide high resistance to wind loads, heat distribution equitability indoors, rational consumption of building materials and interior space. The frame structure design of the dome constructions is quite simple and is based on the spherical geometry laws. To calculate the structural elements, a special calculator [4] is used which calculated the whole structure, assembly elements and assembly units, as well as individual components. Assembly elements are made in form of triangles of several nominal sizes that allows unifying the design and simplifying the frame structure assembly.

Building envelopes of dome constructions should provide sufficient strength and premises protection from heat loss. At present, heat-insulating materials in the form of plates, rolls, and film coatings are widely represented on the building materials market [5–11]. Thermotechnical characteristics of these materials are separately presented in reference sources. But when forming building envelopes with the combined use of various types of thermal-insulating and building materials, information on thermotechnical indicators or their calculation method is not presented in the reference sources.

The purpose and objectives of the study
The purpose of this work is to substantiate and select thermal-insulating materials for building envelope elements of dome constructs for the Far North regions and the Arctic zone and to evaluate their thermophysical properties.

Scientific novelty of the results
The paper proposes a method for assessing the thermal conductivity of precast building envelopes and laboratory equipment for evaluating thermal conductivity and thermal resistance of precast building envelopes. The reduced resistance calculation of heat transfer was carried out according to the method described in Building codes and regulations 23-02-2003 "Thermal protection of buildings". Thermal conductivity evaluation of individual materials was carried out using an ITS-1 thermal conductivity meter (refer with Fig. 1). Thermal resistance of prefabricated building envelopes was evaluated by climatic tests using the KRK-400 ILKA climatic chamber (refer with Fig. 2). To assess the thermally conductive properties of prefabricated panels, a laboratory chamber with high heat-protective properties was developed. The chamber front is replaceable where samples with prefabricated heat-protective properties materials were installed. Thermal resistance evaluation of the building envelope was carried out by determining the temperature difference inside the KRK-400 ILKA climatic installation and inside the laboratory chamber. The thermal conductivity and heat capacity of the laboratory chamber are determined in advance. Experimental panels samples were made in such a way that they were placed in the laboratory chamber opening.

The Results of experimental studies
In accordance with the climate map of the Russian Federation, areas where the heating degree-day exceeds the value of 6000 are the Far North areas. Heat transfer resistance rates for the main Far North regions are presented in Table. 1. As can be seen from the presented data, Verkhoyansk is in the most difficult conditions according the temperature condition. Therefore, the calculations will be carried out for this settlement.
Figure 1. General view of ITS-1 thermal conductivity meter.

Figure 2. KRK-400 ILKA climatic chamber.

Table 1. Heat-transfer resistance standards of the main structural buildings elements for some Far North regions.

| Region               | heating degree day | Heat-transfer resistance standards R, m² K/W |
|----------------------|--------------------|---------------------------------------------|
|                      |                    | walls | partitions | windows | lights |
| Arkhangelsk          | 6200               | 3.6   | 4.7        | 0.61    | 0.41   |
| Ulan-Ude             | 7200               | 4.1   | 5.3        | 0.7     | 0.45   |
| Khanty-Mansisk       | 7200               | 4.1   | 5.3        | 0.7     | 0.45   |
| Chita                | 7600               | 4.2   | 5.5        | 0.7     | 0.45   |
| Surgut               | 7700               | 4.28  | 5.53       | 0.7     | 0.45   |
| Magadan              | 7800               | 4.3   | 5.55       | 0.7     | 0.45   |
| Naryan-Mar           | 7888               | 4.31  | 5.56       | 0.7     | 0.45   |
| Yekutka              | 8900               | 4.6   | 6.1        | 0.73    | 0.475  |
| Anadyr               | 9500               | 4.9   | 6.4        | 0.75    | 0.5    |
| Urengoy              | 9500               | 4.9   | 6.4        | 0.75    | 0.5    |
| Yakutsk              | 10400              | 5.1   | 6.8        | 0.79    | 0.54   |
| Dudinka              | 10400              | 5.1   | 6.8        | 0.79    | 0.54   |
| Verkhoyansk          | 12300              | 5.7   | 7.4        | 0.81    | 0.56   |

The city of Verkhoyansk is located on the border of the temperate and subarctic belts. Winter is extremely cold, dry and long, summer is short, but warm and relatively dry (there are also hot periods), often cold snaps and frosts are possible. It is established that there is the biggest difference of maximum and minimum temperatures in Verkhoyansk. Precipitation is very small, about 150-200 mm per year, which is comparable to the precipitation amount in deserts. The average annual temperature is -14.5 °C, and the average annual wind speed is up to 1.4 m/s. The average annual humidity is 69%. The temperature of the cold five-day period reliability of 92% is -58 °C. The duration of the heating period is 272 days.

The average air temperature during the heating period is -25 °C. The relative humidity of the coldest month is 74%. The number of degree-days during the heating period is 12512 °C days.

Method for the thermal resistance calculation of multilayer building envelopes is given in the code specification 50.13330.2012. The inverse calculation method determined the values of the rated
thermal resistance for walls in the Verkhoyansk conditions. As a result of the calculations it was established that the heat-transfer resistance standart should be at least 5.7 m²K/W. We accept that the reduced thermal resistance will be equal to the specified value. In this case, the total wall panels resistance will be equal to:

\[ R_{R} = R_{\text{ded}} + \frac{1}{\alpha_{h}} + \frac{1}{\alpha_{f}} = 7.4 + \frac{1}{8.7} + \frac{1}{23} = 7.56, \text{ m}^2 \text{K}/\text{Vt} \]  

(1)

where \( R_{\text{ded}} \) is the deduced thermal resistance of the wall building envelopes in this case equal to the permissible in accordance with the standards;
- \( \alpha_{h} \) is a heat transfer coefficient of the internal surface of the building envelope, \( \alpha_{h} = 8.7 \text{ W/m}^2\text{K} \);
- \( \alpha_{f} \) is a heat transfer coefficient of the outer surface, \( \alpha_{f} = 23 \text{ W/m}^2\text{K} \).

Calculation was made for the partition over a cold basement that communicates with the outside air that corresponds to the buildings on the pile foundation. Based on the requirements for the envelope elements of the dome constructures, it is assumed that the frame structure of the assembly elements will be made of pine or deal board with a section of 50x150 mm. It is proposed to use polyurethane foam (PUF) as a filler for the internal space, since this material has the lowest thermal conductivity coefficient, \( \lambda = 0.02 \text{ W/m}^2\text{K} \) and is not affected by rot and insects. The PUF thickness is equal to the frame beam thickness and is 150 mm.

The initial composition of the assembly elements was adopted as follows:
1. OSB-3 plate 12 mm thick, that will ensure the room protection against the air flow and the frame stability from the tangential forces affect the building;
2. Closed air gap 25 mm thick, provided with wood rolls of the same thickness. The closed air gap use will provide a gap between the warmth-keeping jacket and the inner panel, since moisture may accumulate at the contact point that will help to reduce the thermal-insulating properties of the warmth-keeping jacket. Closed air gap is also a good heat insulator because the layer thickness is small and the air is stagnant inside [14].
3. Vapor-protective membrane that will protect the heat-insulating materials from the moisture vapor penetration and their accumulation in the heat insulator represented by dew drops. Aluminum foil 0.1 mm. thick is proposed to use as a membrane.
4. The assembly elements of the dome construction are triangular. The elements frame is made of softwood boards with a section of 50x150 mm. Polyurethane foam 150 mm. thick is used as a filler and heat insulator.
5. Closed air gap 25 mm. thick designed to prevent insulation contact with surfaces contacting with outside air. This will reduce the condensate formation in the insulation that can lead to deterioration or complete thermal-insulating properties loss. Air gap also acts as a heat insulator.
6. The moisture-windproof membrane that will protect the structural element from the external moisture ingress from the environment and the steam removal and moisture generated in a closed layer.
7. Cement bonded particle board CBPB 12 mm thick that will ensure the structural element strength and rigidity on the outside of the frame.
8. Bitumen tile 3 mm. thick to protect the construction from external precipitation in the form of rain, snow and dew.

According to the calculated data, the thermal resistance of the assembly elements timber frame will be \( R_{f} = 1.07 \text{ m}^2\text{K}/\text{Vt} \), the insulation \( R_{i} = 6.25 \text{ m}^2\text{K}/\text{Vt} \), the total heat transfer resistance of the whole structure will be \( R = 5.37 \text{ m}^2\text{K}/\text{Vt} \) that is significantly less than the standard values of elementwise requirements \( (R_{R} = 7.56 \text{ m}^2\text{K}/\text{Vt}) \). According to the obtained data, it can be concluded that this frame structure will not provide the structure thermal protection.

To improve the thermal insulation properties, it was proposed to increase the panel frame thickness together with the warmth-keeping jacket up to 200 mm. In this case, the total thermal resistance is \( R = 6.87 \text{ m}^2\text{K}/\text{Vt} \). Tests have shown that the building envelope satisfies sanitary and hygienic standards for
thermal protection and the normalized value of elementwise requirements, but not sufficient for the basic value of elementwise requirements \( R_e \).

Further thickness frame increase will significantly complicate the construction assembly and increase the elements volume during transportation and storage. Therefore, it was proposed to use liquid thermal insulation for increasing thermal resistance. Based on the market review of liquid thermal insulation materials Corundum thermal insulation paint was chosen [12]. Corundum thermal insulation has low consumption and is quite economical. The filler contains microscopic hollow spheres - ceramic, polymer, composite, glass balls, which are filled with expanded air. Such microparticles can differ not only in composition, but also in microgranules size, percentage, component homogeneity, etc.

Water-acrylic solution is in the liquid insulation basis. Its properties make it possible to ensure uniform distribution of thermal-insulating components on the worksurface. In addition, the paint composition contributes to better fixing of liquid ceramics. Composition includes special fixatives, catalytic substances, anti-corrosion additives, as well as a bonding base on high-strength acrylic to do this. The paint is easy to apply and spread over the entire surface, providing good energy savings and thermal insulation. The binder contains various kinds of additives that improve the performance parameters of thermal paint, in particular, natural and artificial rubbers, silicone, etc. Additives provide good paint adhesion to the base, sealing seams and joints. The temperature operation range varies from -65 °C to +260 °C that corresponds to the Far North conditions.

The insulating coating properties of thermal insulating paint are achieved in several ways:
- by convection, i.e. heat transfer by the heat insulating paint layer. Due to the fact that most of the liquid insulation specific weight consists of hollow balls, the losses for convection in the composition are completely insignificant;
- thermal material conductivity, when heat is transferred from the more heated surface part to the colder place. In liquid insulation, only 20% of the binder component has the thermal conductivity properties;
- radiation - a phenomenon whereby heat transfer occurs through the internal suspension energy. In internal suspension energy. Microscopic spheres are endowed with reflection and heat dissipation properties in energy-saving paint. Almost 90% of the reflected radiation turns the processed wall worksurface into a thermos analogue.

The main disadvantage of insulating paints, in particular Corundum, is the high cost that hinders their use.

Externally, ceramic ultrafine paint is practically no different from the usual acrylic paint. The composition must be applied in three layers, while the flow rate should be about 1 l/m². The layer thermal conductivity 1 mm. thick is 0.0011 W/m K.

The structural elements composition of the building envelope with regard to the heat-insulating paint Corundum use, their thermophysical properties are presented in table 2.

As a result of experimental studies, it was found that when applying thermal insulating paint Corundum on the room inside over the OSB surface, thermal resistance will be \( R = 7.94 \text{ m}^2\text{K}/\text{W} \), and when applied on the outside CBPB surface under bitumen tile, thermal resistance will be \( R = 7.87 \text{ m}^2\text{K}/\text{W} \). In the event of the closed air gap leakage on the frame elements outside and the occurrence of airflow through this space, when applying thermal insulation paint Corundum on the inner OSB surface will provide thermal resistance within \( R = 7.69 \text{ m}^2\text{K}/\text{W} \), which is higher than the standard values. Thus, it can be concluded that with an insignificant deficit of heat-protective properties of building envelopes, it is possible to achieve standard values of heat-shielding properties when using heat-insulating liquid coatings.

**Table 2.** The elements construction composition of dome structures and their thermophysical properties.

| layer № | Material      | Thickness, mm | Thermal conductivity | Heat-transfer resistance |
|---------|---------------|---------------|----------------------|-------------------------|
|         |               |               |                      |                         |
|                     | coefficient, W/mK | standards R, m²·K/W |
|---------------------|--------------------|---------------------|
| Temperature inside +20°C |                    |                     |
| 1. Thermal paint Corund | 1.0011             | 0.91                |
| 2. Oriented strand board OSB-2 (OSB-3) | 0.13               | 0.09                |
| 3. Closed air gap      | 0.30               |                     |
| 4. Aluminum foil       | 0.1                |                     |
| 5. Frame element: fat wood, aggregate - polyisocyanurate foam (PIR) | 5.94               |                     |
| 6. Closed air gap      | 0.19               |                     |
| 7. Moisture wind-proof membrane | 0.1           |                     |
| 8. Cement bonded particle board (CBPB) | 0.23              | 0.02                |
| 9. Bitumen tile        | 0.17               | 0.02                |
| the temperature outside -10°C |                |                     |

The calculation of overwetting protection was made on the basis of the dimensionless quantities method. As a result of the calculation, it has been established that the building envelope satisfies the protection regulations against overwetting. In particular, the resistance to vapor permeation from the inner structure surface to the maximum moisture plane is \( R_v(1) = 110 \text{ m}^2 \cdot \text{h} \cdot \text{Pa}/\text{mg} \) at a rate of \( R_v.tr(1) = 5 \text{ m}^2 \cdot \text{h} \cdot \text{Pa}/\text{mg} \). Wood structures must be protected from damage by fungi, insects and fire [13]. For this purpose, it was proposed to use antiseptics and Senezh antipyrines.

**Summary**

1. According to the climatic data, hethermotechnical calculations were carried out for the Verkhoyansk conditions, the Sokh Republic, as a generally recognized cold pole. The normative values of thermal resistance were calculated for this area: according to sanitary and hygienic requirements - 4.09 \( (\text{m}^2 \cdot \text{˚C})/\text{W} \), according to the normalized value of element requirements - 6.02 \( (\text{m}^2 \cdot \text{˚C})/\text{W} \), on basic value of element requirements - 7.53 \( (\text{m}^2 \cdot \text{˚C})/\text{W} \).

2. Heat-protective panel structure of structural elements of dome structures for the Verkhoyansk conditions has been developed, consisting of the following elements: Corundum heat-insulating paint 1 mm thick; OSB 12 mm; air gap 25 mm; steam moisture-proof aluminum foil; wooden frame 200 mm thick filled with PIR 20 mm thick; air gap 25 mm; moisture-windproof membrane; cement bonded particle board 400 kg/m3 density and 12 mm thick; bitumen tile 3 mm thick.

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