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RESEARCH OF ENERGY EFFICIENT SOLUTIONS FOR HEAT INSULATION OF CONSTRUCTIONS AND PIPELINES WITH AEROGEL

Ways of energy saving in buildings, namely compliance with the regulatory framework of European standards, possibilities to reduce heat losses during energy transportation through pipelines on the example of heating systems and reducing heat losses during the operation of buildings and structures are studied in the article. It was found that, despite the regular updates of the State Construction Norms of Ukraine, the coefficient of thermal conductivity of insulation materials is not brought into line with generally accepted European standards. The second part of the article presents the results of analytical studies of various thermal insulation materials that are widely used in the territory of Ukraine. After comparing the results, we concluded that the most common at this stage of development of insulation materials will not fully satisfy all the requirements, which must meet all the materials for insulation of structures. The use of some materials is impossible of thermal insulation of structures and pipelines with complex configuration. The solution of energy efficiency along with increasing soundproofing properties, reducing the fire hazard, reducing the load on the bearing structures of buildings and structures is possible through the use of aerogel as a thermal insulation material. The material is characterized by low dependence of the thermal conductivity coefficient on changes in ambient temperature, which makes it the best option for use in harsh operating conditions. After analytical studies of various insulating materials, it was found that aerogel in roll in addition to low coefficient of heat transfer is characterized by better operating properties, namely, non-combustibility of the material, environmental safety, light weight, which reduces the burden on the structure, ease of installation, the possibility of using the structures with high rate of sound insulation.

Keywords: thermal insulation technologies, thermal insulation materials, energy saving, thermal conductivity, energy-efficient solutions, aerogel, pipelines, reducing heat loss, structures

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1. Introduction

In 2019, a national database of energy and performance characteristics of buildings was introduced in Ukraine at the initiative of the Ministry of Community and Territory Development of Ukraine. One of the objectives of the Ministry of Regional Development was the planning of energy efficiency measures through the formation of medium-term plans for the implementation of energy efficiency measures to ensure the maximum use of the available potential to improve the energy efficiency of buildings and avoid repeated repairs, wrong sequence of measures, etc. [1].

The problem of energy efficiency of residential buildings, their maintenance, repair and thermo-modernization should be considered, first of all, from the position that the building should provide the creation of artificial environment for life and activity of people, since the natural environment does not meet the requirements of the vital processes of people, their social and individual needs. In all climatic regions of Ukraine, the parameters of the external environment do not correspond to the parameters of the internal microclimate, providing comfortable conditions for human stay.

Exterior fences of the house are primarily a barrier to create a separate volume with an artificial microclimate. Since such fences are at the boundary of two environments, heat, moisture and air transfer processes are continuously taking place in them. Such processes have an active influence on the parameters of the microclimate in the room.

Under the conditions of increasing cost and limited reserves of traditional fossil fuels, the problem of reducing energy consumption and energy saving in the housing and communal sector of Ukraine is currently extremely important. Due to the rapid growth of the cost of utility payments, the population has a need to implement various measures aimed at energy saving and capital repairs of low- and high-rise buildings.

To date, the main efforts are aimed at a simplified approach to creating energy efficient solutions, that is, almost all problems with energy saving are solved by engineering means, which are aimed at increasing the efficiency factor of the equipment installed in the houses and increasing the thermal resistance of building structure. These are, as a rule, installation of metal-plastic windows, increasing the thickness of thermal insulation of walls, floors and roofs, additionally loading the foundations.

2. Improvement of the regulation and legal framework

Heat loss in buildings occurs mainly in the form of dispersion of heat by the external structure, which occurs and intensifies with the increase in the temperature difference between the inside and outside of the housing, and also as a result of increased infiltration of outdoor air under wind pressure due to the emergence of various aerodynamic effects in the building.

Practice of inspection of external enclosing structures of buildings by thermo-vision cameras testifies that six buildings from ten checked up have enormous losses of heat, mainly because of insufficient insulation of external structures – foundations, walls, windows, covering [2]. One of modern methods of an estimation of heat losses in buildings is thermography with the high permission, allowing to find out possible defects inside an external structure of a building by use of the thermal image of various surfaces of a construction (fig. 1).

Serdyuk V.R. in his work [3] identified the main causes of high heat losses in the housing and communal sector and outlined the main directions of their reduction (fig. 2).

The first step in improving energy-efficient systems is to improve the relevant legal and regulatory documentation. To solve the problem of excessive energy consumption in Ukraine, construction standards that impose higher requirements for the thermal insulation of structures have been introduced.

General principles of ensuring the requirements of the Technical Regulations of building structures, buildings and structures in the design and application with facade thermal insulation in Ukraine are regulated by DBN B.2.6-33:2018 Structures of exterior walls with facade thermal insulation. Design requirements [4]. This normative document contains the basic requirements for the design and operational suitability of structures with facade thermal insulation.

In turn, the technical parameters to ensure energy efficiency of buildings, the reduction of energy consumption in buildings in accordance with the Law of Ukraine "On energy efficiency of buildings" are defined in the DBN B.2.6-31:2021. Thermal insulation of buildings [5]. The first edition of this normative document is dated 2006, the second - 2016, the last and currently valid – 2021. Table 1 presents a comparison of the normative values of thermal resistance of building structures in Ukraine [5, 6, 7].

As can be seen from table 1, in Ukraine there is a tendency to increase the minimum allowable value of heat transfer resistance of building structures, which leads to improved energy efficiency of buildings. In Ukraine it is customary to use the thermal resistance index $R_{q\ min}$ (m^2K/W) that is inversely proportional to the heat transfer coefficient, while in Western European countries the thermal insulation of outer building structures is rated by the $U_{i(max)}$ (W/m^2K) heat transfer coefficient. After conducting mathematical transformations, we obtained the values of the heat transfer coefficient for the external enclosing structures.

For better understanding of the tendency of changes in the normative documentation about the value of heat transfer resistance, we calculated its increase as a percentage of the previous value (table 2). As can be seen from Table 2, there is a positive trend for almost all types of enclosing structures, except for attic ceilings of unheated attics: for I climatic region the minimum allowable thermal resistance to heat transfer has not changed, and for II decreased by 11%.

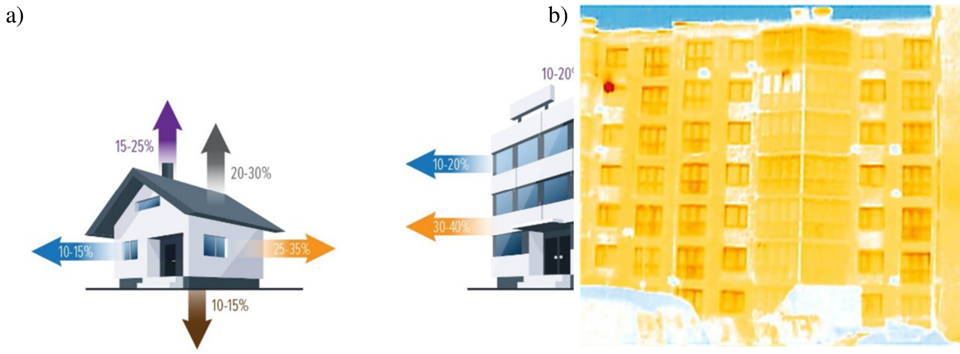

Fig. 1. Heat loss in a private and multi-storey house: a) relative heat losses;
b) determination of heat losses by thermography [2]

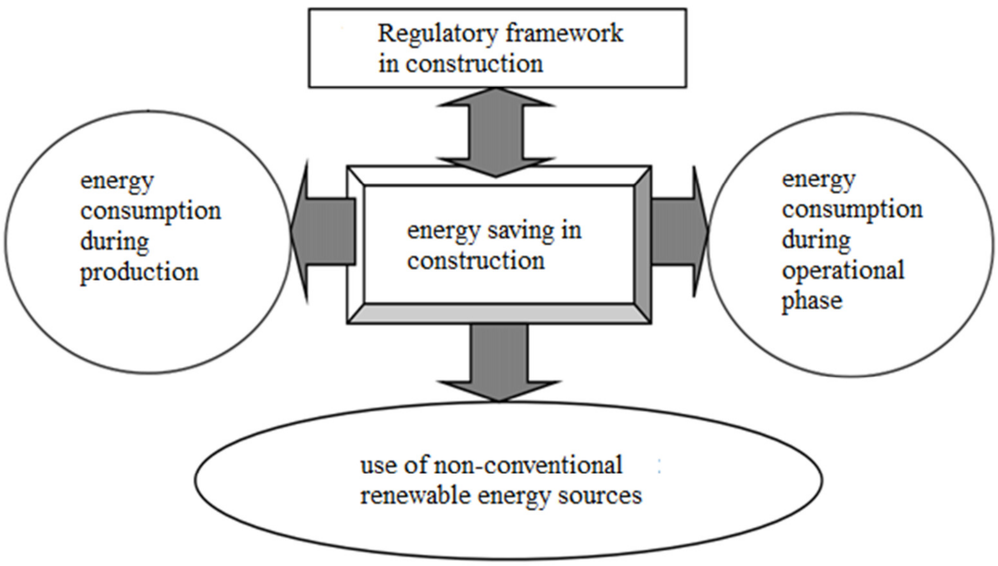

Fig. 2. Determinants of energy saving in the construction industry [3]

Table 3 shows the values of the coefficient of heat transfer and, for comparison, close in climatic conditions of Finland. As a result of comparing the values of heat transfer coefficient for external structures installed in Ukraine with similar values valid in Finland, it is seen that the maximum allowable values of heat transfer coefficient in Ukraine are almost twice lower than the norm of Finland and the level of other European countries.

Table 1. Minimum allowable value of the thermal resistance of the enclosing structure of residential and public buildings R_{qmin}

Type of enclosing structure	**The value of R_{qmin} m^{2}K/W, for temperature zone**					
	2006 [6]		2016 [7]		2022 [5]	
	I	II	I	II	I	II
External walls	2,8	2,5	3,3	2,8	4,0	3,5
Combined covering	-	-	6,0	5,5	7,0	6,0
Covering of heated attics (technical floors) and mansard type coverings	4,95	4,5	4,95	4,5	6,0	5,5
Attic ceilings of unheated attics	4,95	4,5	4,95	4,5	5,0	4,0
Ceiling over driveways and unheated basements	3,75	3,45	3,75	3,3	5,0	4,0
Translucent enclosing structures	0,6	0,56	0,75	0,6	0,9	0,7
External doors	0,6	0,56	0,6	0,5	0,7	0,6

Table 2. Trends in the minimum allowable values of heat transfer resistance of enclosing structures

Type of enclosing structure	**Increase in the minimum allowable value of resistance to heat transfer from 2016 to 2022, %**	
	I	II
External walls	21	25
Combined covering	16	9
Covering of heated attics (technical floors) and mansard type coverings	21	22
Attic ceilings of unheated attics	1	-11
Ceiling over driveways and unheated basements	33	21
Translucent enclosing structures	20	16
External doors	16	20

Although climatic conditions in European countries are more favorable than in Ukraine, the thermal resistance values of building structures are much higher. In addition, the adopted EU Directive 2010/31/EU "On the energy performance of buildings" regulates the gradual increase of heat transfer coefficient values for all external structures. The value of heat transfer coefficient of external walls of buildings in the European Union shall be set at 0.20 W/m^{2}K; (R = 5.00 m^{2}K/W) for buildings constructed after January 1, 2021 [8].

Table 3. Comparative indicators of the maximum allowable values of the heat transfer coefficient for the outer building external structures

Type of enclosing structure	**Ukraine Value of heat transfer coefficient $U_{i(max)}$ W/(m^{2}K) for temperature zone**				**Finland Value of heat transfer coefficient $U_{i(max)}$ W/(m^{2}K)**
	2016		2022		
	I	II	I	II	
External walls	0,3	0,357	0,24	0,28	0,17
Combined covering	0,16	0,18	0,13	0,14	0,09
Covering of heated attics (technical floors) and mansard type coverings	0,2	0,22	0,16	0,17	-
Attic ceilings of unheated attics	0,2	0,2	0,16	0,16	0,17/0,16
Ceiling over driveways and unheated basements	0,266	0,3	0,21	0,24	-
Translucent enclosing structures	1,33	1,66	1,05	1,31	1,0
External doors	1,66	2,0	1,31	1,58	1,0

3. The prospect of aerogel use

One of the most significant directions of reducing the energy consumption of the building is to increase the thermal resistance of the external enclosing structures. Requirements for thermal protection of buildings and constructions fully apply to the window elements as well, since they are the main cause of heat loss. Typical wooden windows occupy 20–25% of the total area of the facade of the house (the average figure) and cause losses of about 40% of the heat energy. Along with this, window systems at the same time are the main source of heat input into the building due to solar radiation, so they require a special approach in the energy supply of the building compared to other external structural elements [9].

The most common materials for insulating structures in Ukraine are foam plastic, extruded panopolystyrene, sprayed polyurethane foam, cellulose wool, mineral wool, fiberglass, expanded clay, cork sheet, cellulose wool. When choosing insulation, in addition to the coefficient of thermal conductivity takes into account a number of other characteristics, namely: volume weight, flammability, water absorption, sorption humidity, vapor barrier properties, sound insulation, environmental friendliness, durability, air permeability.

The optimal choice of material for thermal insulation of structures implies the provision of low thermal conductivity coefficient at the lowest possible volume weight in order to reduce the load on the foundation. According to calculations of the State Energy Efficiency Agency, a comprehensive thermo-modernization of residential buildings will save up to 50% of the energy currently consumed. For a 9-storey house with an area of facade insulation ~ 1500 m^2 weight only subsystem for external insulation "ventilated facade" will be ~ 15 thousand kg. Filling mineral wool slabs with a density of 100 kg/m^3 and a thickness of 50 mm, fixing to the wall with glue (consumption – 3.5 kg/m^2) and dowels, will add another ~ 12.7 thousand kg, namely, lightweight cladding, vinyl siding weighs about 3.5 thousand kg. In total, the load on the foundation will increase by more than 31,000 kg. [9].

At the current stage of development of energy-saving technologies, such a class of material as aerogel has found wide use. Aerogel is a broad term used to refer to a group of materials that have a special form of highly porous material with very high porosity, low density, low thermal conductivity and high transparency. Making an aerogel is the replacement of the liquid, wet gel component with air [10]. It consists of individual nanoscale particles combined with each other to form a three-dimensional grid.

The most common are quartz aerogels. Their minimum density is 1 kg/m^3 (vacuum version), which is 1000 times less than the density of water and even 1.2 times less than the density of air. Due to their extremely low thermal conductivity ($\approx$ 0.017 W/m K in air at atmospheric pressure), less than the thermal conductivity of air (0.024 W/m K) they are used in construction as insulating materials. The melting temperature of quartz aerogel is 1200°C.

Currently, silicone aerogel is known as the best material for insulation. The porosity of aerogel is 80 ~ 99.8%, and the pore diameter in aerogel is smaller than the average free path of air molecules, so air molecules in aerogel are almost in a static position, which avoids air convection, leading to heat dissipation. The low density and nanosize structure of the scattering pathway in the aerogel also effectively stops thermal radiation both in the material itself and through the air pathways. In addition, the large number of pore walls in the aerogel can reduce the thermal radiation to a minimum. We can conclude that they practically block all thermal radiation pathways, which makes aerogel the best thermal insulation material compared to other thermal protective coatings.

Aerogel has been widely used, which can include:

1. Insulation of building structures. External insulation of the walls of the building, which prevents freezing of the facade and increases the service life of the structure. Internal insulation of walls using aerogel from the inside allows you to save the maximum area of the insulated room due to the small thickness of the insulation.
2. Thermal insulation of internal and external corners of the premises, elimination of freezing of walls. Insulation of internal corners of a building or apartment on aerogel allows you to avoid freezing walls and condensation, which often leads to mold and mildew. Exterior corners are subject to precipitation in the form of rain and snow, and aerogel is effectively used as protection against this effect.

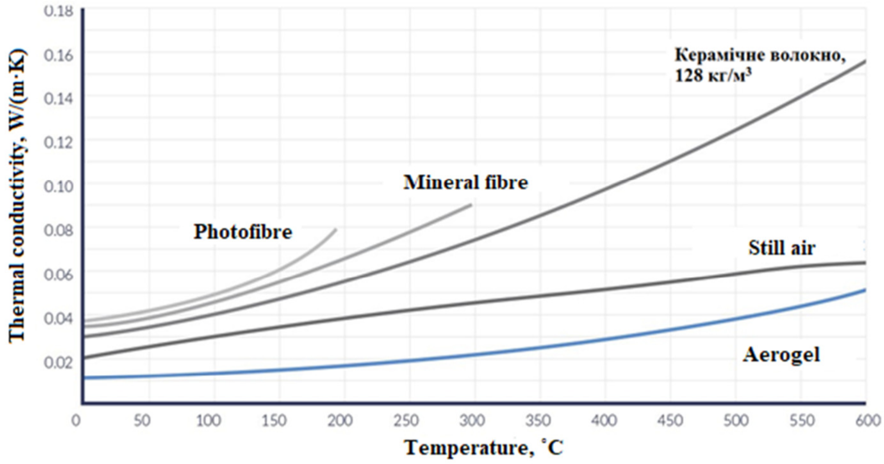

Fig. 3. Comparison of changes in thermal conductivity of materials depending on temperature

3. Thermal insulation of floors under the screed. Aerogel is used as thermal insulation of floors. Due to the small required thickness of the insulation, allows you to significantly reduce the height of the concrete screed. Due to the low thermal conductivity coefficient, aerogel floor insulation achieves the same performance as other materials with a thickness of 2.5 times greater.
4. Insulation of door and window openings. The principle of aerogel insulation of window and door apertures is similar to that of facade insulation, but in addition aerogel can be used instead of EPDM rubber in window profiles.
5. Noise insulation and soundproofing of the walls. As a result of its structure aerogel has unique acoustic properties. The low speed of sound propagation in aerogels (up to 100 m/s) allows it to be used as a soundproofing material.
6. Insulation of chimneys, ventilation ducts, thermal insulation of pipelines, fittings and fittings.

Aerogel has more stable characteristics when the temperature conditions of its application change. Fig. 3 shows a comparison of curves of change in thermal conductivity depending on temperature for glass fiber, ceramic fiber, mineral fiber and aerogel. The thermal conductivity of aerogel increases with increasing temperature conditions of its use (Table 4).

Table 4. Comparative indicators of the maximum allowable values of the heat transfer coefficient for the outer building external structures

Temperature, °C	<25	100	200	300	400	450	500	650
Thermal conductivity, W/(m·K)	0,018	0,021	0,025	0,034	0,045	0,050	0,051	0,062

In [11] the authors compared the main characteristics of common materials used to insulate the facades of buildings in Ukraine (table 5). It was found that polyurethane foam, polystyrene foam, glass wool, basalt wool emit toxic substances, are not completely safe for humans, and during installation require additional equipment and protection of specialists. Foamed glass, ecowool and basalt wool are the most optimal in terms of thermal-technical, operational, physical and mechanical properties.

It should be taken into account that not all insulating materials analyzed in [11] are suitable for insulation of pipelines. Table 6 shows a comparison of the characteristics of thermal insulation materials with aerogel.

Aerogel in most cases is produced in rolls of different thicknesses, that is, the insulation at the initial stage has a high flexibility (unlike Styrofoam) and can be used to insulate structures of complex shape and configuration. Insulation of facades with aerogel is made on the typical technological card (TTK) of external insulation of buildings with a thin plaster on insulation [12]. The TTK

Table 5. Comparative properties of thermal insulation materials [11]

Insulation	**Maximum allowable heating temperature, °C**	**Density, kg/m^3**	**Thermal conductivity, W/m·K**	**Advantages**	**Disadvantages**
Glass wool	+500	9-13	0,044	Elasticity, heat-, sound insulation, no fire hazard	Low service life, the presence of formaldehyde
Ecowool	+1000	30-60	0,036	Long service life, not prone to rot, non-toxicity	Risk of shrinkage, additional equipment required
Basalt mineral wool	+600	35	0,039	High strength, resistance to fungus, mold, non-flammable	Dust formation, non-environmental, high cost
Styrofoam	+60	25	0,037	Resistance to fungus, mold, low thermal conductivity	Flammability, risk of rodents, low sound insulation, fragility
Foam glass	+485	100-400	0,048-0,08	Durability, resistance to deformations, steam and water, nonflammable, biostability	High cost, weight, fragility
Polyurethane foam	+500	40-80	0,029-0,041	Heat and noise insulation, long service life, non-flammability, low hydroscopicity	Color change under ultraviolet light, caustic smoke in case of fire

defines the scope, technology and organization of work, quality requirements and acceptance of work, safety of work, the need for resources and technical and economic indicators.

In addition to high technological characteristics, the process of insulating structures from aerogel is quite simple and consists of the following steps.

Stage 1 is preparation and storage. Aerogel-based insulating materials should be stored in a dry and clean room, protected from the external environment.

Stage 2 is to prepare the web cutting zone. This area will be used to cut solid rolls of aerogel-based material into pieces of the length required for application or into plates of a given shape. This area should be arranged in a sheltered room under the roof.

Step 3 - preparation of the installation area. Once the material has been cut and delivered to the installation area, make sure it is covered and protected from the weather. Ideally, the material should be placed as close to the installation area as possible.

Table 6. Comparative characteristics of thermal insulation materials

Material	**Thermal conductivity coefficient, W/(m·K)**	**Density, g/m^3**	**Water absorption, %**	**Vapor permeability coefficient, mg/(mhPa)**	**Sorption humidity, %**	**Combustibility**	**Soundproofing**	**Durability, years**
Styrofoam	0,036-0,04	15-35	1	0,05	1	Burning for no more than 3 seconds, emits deadly poisons	medium	5-15
Extruded polystyrene foam	0,03-0,035	32-52	0,4	0,005	0,1-0,3	Only under the influence of the flame	medium	15-35
Sprayable polyurethane foam	0,02-0,032	20-200	1-2	0,05	0,2-0,5	Only under the influence of flame releases deadly poisons	medium	15-50
Foamglass	0,048-0,059	15-32	0,3	0,001-0,006	0,001-0,006	non-combustible	good	>30
Mineral wool	0,04-0,048	50-300	16-20	0,3-0,6	-	non-combustible	high	15-30
Aerogel	0,018-0,062	1-150	-	-	0,05	non-combustible or classes A2, B2, C2	high	>30

Installation begins by attaching the leading edge of the aerogel-based insulation material with welded insulation needles. The insulation material is stapled over the area of the tank, tank or facade surface. The welded needles are pressed down at the end and secured with staples. A band is installed along the contour for additional attachment.

Aerogel can be used not only for insulation of facades, but also for insulation of pipelines, communications, fittings, ventilation channels, etc. When using aerogel for insulation of pipelines pipes can be insulated in one, two or more layers (Fig. 5).

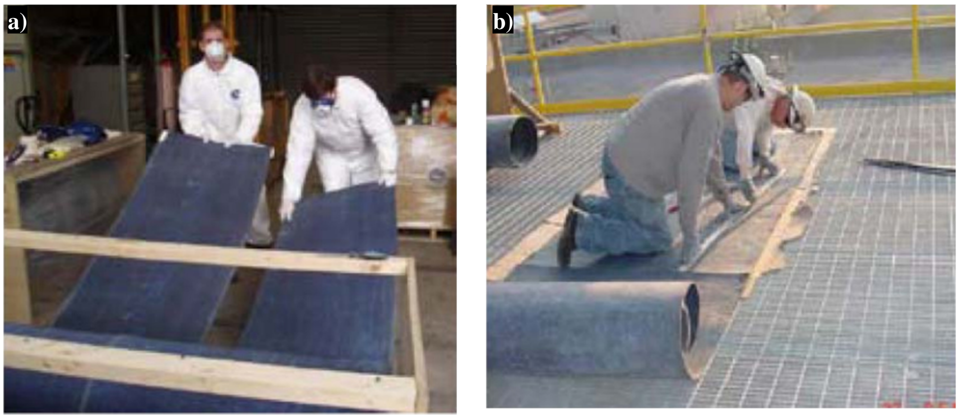

Fig. 4. Typical technology of insulation with aerogel: a) storage in rolls; b) installation and fixing with staples

Fig. 5. Pipeline insulation using aerogel

The process of insulation also begins with a piece of material, and the length can be determined either by measuring the diameter of the pipe, or by wrapping a piece of material around the pipe. The material is wrapped around the pipe, secured with special needles and fixed with tapes, wires or bandage. Fig. 6 shows a comparison of the thicknesses of different insulation materials when insulating pipes to ensure the same coefficient of thermal conductivity.

In Ukraine, finished aerogel products can be divided into two types. Technical roll thermal insulation in thicknesses of 3, 5, 6 and 10 mm. This is thermal insulation for cryogenic heat-insulation objects with application temperature from -260ºC, as well as for hot production and fire protection of industrial facilities with application temperature up to +1000ºC. Such insulation is supplied in rolls of 1400-1500 mm width. The cost of such insulation is given in the table 7.

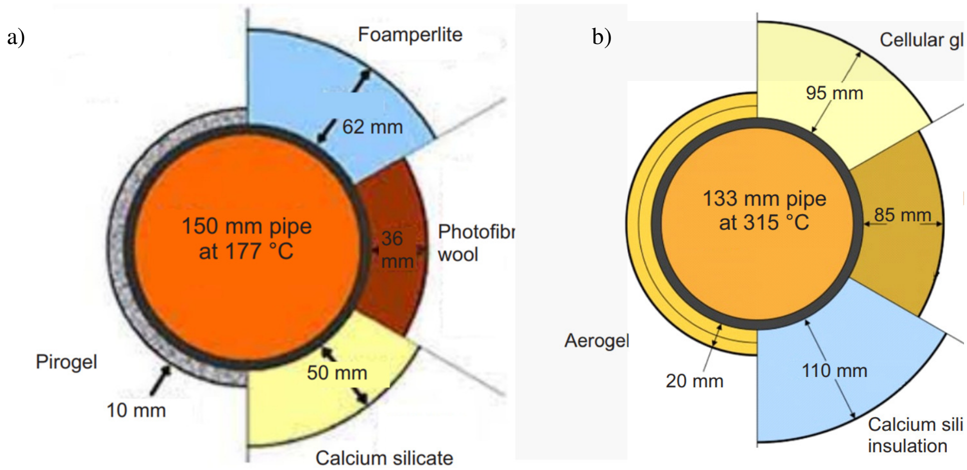

Fig. 6. Comparison of thermal insulation thicknesses of different materials:
a) 150 mm pipe at 177. ; b) 133 mm pipe at 315 °C

Table 7. Cost of aerogel [13]

Brand	Pyrogel XT		Cryogel®Z	
Thickness, mm	5	10	5	10
Cost, hrn. for 1 m^2 (conversion into Euro)	1783,45 (48.35 €)	2591,98 (70.26 €)	2144,02 (58.12 €)	2774,46 (75.21 €)

Technical thermal insulation in the form of liquid paste applied where complex geometric surfaces preclude the use of roll thermal insulation with a temperature of application up to +1400°C or as a supplement to roll thermal insulation. Such thermal insulation is supplied in sealed containers of 16–20 kg [13].

As can be seen from a comparison of the characteristics of insulation materials, aerogel is characterized by maintaining a relatively constant coefficient of heat transfer with changes in ambient temperature, as well as a relatively low price, which, combined with the ease of installation makes aerogel thermal insulation materials promising areas to improve energy efficiency of facilities.

4. Conclusions

Given the development of technologies of insulation of structures and pipelines using different insulation materials, there have been changes in state regulation of the minimum energy efficiency indicators of construction projects. Therefore, the actual task at this stage is to improve the regulatory framework in the areas of construction and energy efficiency of facilities at the stage, design, construction, operation and reconstruction.

After analytical studies of various insulating materials, it was found that aerogel in roll in addition to low coefficient of heat transfer is characterized by better operating properties, namely, non-combustibility of the material, environmental safety, light weight, which reduces the burden on the structure, ease of installation, the possibility of using the structures with high rate of sound insulation.

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