# Thermal insulation coating based on water-based polymer dispersion

**Saienko Natalia[1*], Skripinets Anna[2], Gurina Galina[2], Saienko Leonid[3] and Hryhorenko Oleksandr[1]**

[1] Fire and technological safety of facilities and technologies, National University of Civil Defence of Ukraine, Kharkiv, UA
[2] Chemistry and integrated technologies, O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, UA
[3] Automation and computer-integrated technologies, O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, UA

*E-mail: *Nataliia.Saienko@kname.edu.ua

**Abstract.** The paper presents a study on the development of thin-layer thermal (with a thermal conductivity coefficient ranging from 0.0416 to 0.083 W/(m·K)) insulation coatings based on styrene-acrylic aqueous dispersion with improved adhesion properties and regulated technological characteristics. The simplicity and speed of applying liquid thermal insulation provide significant advantages over standard insulating materials. An advantage is the ability to insulate surfaces of complex configuration.

## 1. Introduction

Thermal insulation materials find applications in various sectors, including industrial and civil construction, where they are used as coatings for external insulation of buildings and structures to prevent heat loss to the surrounding environment [1–3]. Additionally, they are employed in insulating the pipelines of heating networks, boilers, and other thermal appliances to reduce heat loss and protect personnel from contact burns caused by hot metal surfaces of pipelines and reactors. These materials are also suitable for protecting refrigeration equipment and serving anti-condensation and protective-decorative functions [4, 5]. Apart from the energy saving and the related reduction in $CO_2$ emissions, insulation also offers additional advantages: in an insulated building or industrial piping system one encounters a more uniform temperature distribution which results in a more agreeable living experience or improved plant operation respectively [6–8].

Modern thin-layer polymer thermal insulation materials can be categorized into roll-type and paint-type [9, 10]. In the Ukrainian and international markets, a variety of modern roll-type thermal insulation materials are used, which are based on foamed polyethylene, polypropylene, polyvinyl chloride, polystyrene, polyurethane foam, and carbamide resins [11]. Thermal insulation based on foamed polyethylene (thermal conductivity coefficient: 0.044-0.051 W/(m·K)) and polypropylene (thermal conductivity coefficient: 0.034 W/(m·K)) exhibits low water absorption and is considered chemically and biologically resistant. It is important to highlight that these materials are flammable, which results in flame propagation along the material's surface. Furthermore, they possess low adhesion, making their installation challenging and diminishing their anti-corrosion properties [12, 13].

Polyvinyl chloride foam has a thermal conductivity coefficient of 0.059 W/(m·K). However, it is associated with the risk of plasticizer migration to the surface, toxicity from combustion products during material smoldering, and significant smoke generation capability [14].

One of the most traditional thermal insulation materials is polystyrene foam (thermal conductivity coefficient: 0.037-0.05 W/(m·K). But the primary concern is not its low fire resistance but its low heat resistance. At a certain temperature, thermo-oxidative degradation processes begin in polystyrene foam, leading to volume changes and the release of harmful substances into the surrounding environment [15, 16].

Polyurethane foam is commonly used for insulating pipelines in district heating, oil, and gas pipelines (thermal conductivity: 0.04 W/(m·K)). It provides effective waterproofing and insulation for structures of any complexity, preventing the formation of “cold bridges”. However, the production of such materials involves the use of flammable and toxic substances, posing toxicological risks during operation, which places limitations on their use [17].

Penoizol is a porous material made from urea resins, designed to eliminate 'cold bridges' through which substantial heat loss occurs. Its thermal conductivity ranges from 0.035 to 0.047 W/(m·K). The very low mechanical strength of Penoizol complicates its direct application. Therefore, it is primarily used as thermal insulation filler and sound-absorbing material in frame structures [18, 19].

One drawback of using rolled materials is the need for adhesive compositions, which necessitates additional technological processes and difficulties when applied to objects with complex geometric shapes.

Paint-based insulating materials are dispersions based on structured polymers. They consist of fine glass microspheres, in which there is air (vacuum or inert gas). These hollow spheres make up the main volume of thin-layer polymer insulators, while the remaining volume consists of a binder, which acts as a molecular sieve, retaining water molecules but allowing air to pass through. According to the well-known theory of facade protection by Kuenzel [20, 21], a balance between these factors (combining high vapor permeability and low capillary penetration with respect to liquid water) is a necessary condition for the durability of coatings (as discussed in our article) [22]. The principle of operation of thin-layer paint insulators is to create a thermal barrier with the ability to scatter up to 95% of infrared radiation and reflect up to 75 % of incoming light rays. These properties allow such insulators to effectively provide thermal insulation for buildings, protecting them from solar radiation and overheating during the summer [23, 24]. Today, there are a vast number of composite materials positioned as thermal insulation coatings on the market. These coatings are compositions based on polymer binders and hollow microspheres of various natures. Their adhesion and technological properties have a decisive impact on the thermal efficiency and operational reliability of structures and products [25, 26].

In Europe, in 1999, the EU Directive on volatile organic compounds (VOCs) of heavy metals and other hazardous chemical compounds was developed and adopted. As of January 1, 2008, manufacturers of paint materials in EU countries transitioned to very strict regulations on VOC emissions [27].

Considering the above, water-dispersion paint materials (WD) based on styrene-acrylic copolymers are gaining increasing importance due to their environmental friendliness. The production and application of these materials not only reduce labor protection requirements but also decrease the fire and explosion hazards associated with painting work. Additionally, it simplifies the labor-intensive process of cleaning process equipment. Thus, the use of WD contributes to cost savings by reducing the consumption of solvents, which are irreversibly lost during film formation and ventilation, and in safety measures. Furthermore, the WD application process becomes safe and non-hazardous. Such materials solve the tasks of not only decorative finishing of buildings and structures but also protect them from moisture, sunlight, mechanical or chemical damage. However, the challenge of improving and stabilizing the technological and adhesion strength properties of highly filled dispersions remains unresolved.

The aim of this research is to develop thin-layer polymer-based thermal insulation coatings for construction purposes with improved and stable technological and adhesion strength properties. These coatings are formulated using styrene-acrylic dispersion, filled with hollow aluminosilicate microspheres and hydrophobized aerosil.

## 2. Materials and methods

A styrene-acrylic dispersion "Acronal 290D" was chosen as the binding agent for the thermal insulation coating from a range of water-based acrylic polymer dispersions. This dispersion is designed for the production of construction adhesives, paints, coatings for both interior and exterior applications, synthetic resin-based plasters, and putty compounds where high viscosity and a high solid content are required.

High thermal insulating properties of the insulation coating are achieved through the use of hollow aluminosilicate microspheres. Aluminosilicate microspheres are highly dispersed lightweight powders consisting of thin-walled (0.5-2.0 μm) spherical glass particles with diameters ranging from 10 to 150 μm and a thermal conductivity of 0.04-0.2 W/(m·K).

Among the leading companies in the production of microspheres is the American company "Minnesota Mining and Manufacturing Co" (3M). In Ukraine, hollow glass microspheres are produced on a mass scale by the "Microspheres Production Association" located in Kyiv.

In order to regulate the rheological properties, the hydrophobic aerosil AM-1/300 (A) filler was used, which also serves as a stabilizer for water-based polymer dispersions, prevents the pigment sedimentation and attributes thixotropic properties. Hydrophobic aerosil is highly dispersed amorphous silicon dioxide with a hydrophobic surface of the particles obtained by treating the surface of the particles with anchors that replace the silanol groups contained on the surface of the particles with non-polar organic groups such as methyl, with a specific surface of 200 $m^2/g$ and an average density of 0.051-0.059 $g/cm^3$.

The thermal conductivity coefficient was determined using the device THC-1, intended to measure the thermal conductivity and thermal resistance of building and thermal insulation materials by the method of stationary heat flow in accordance with ISO 8301:1991 with a range of thermal conductivity of 0.02-1.5 W/(m·K). This method is capable of determining the heat transfer properties within ±3 % when the mean temperature of the test is near the room temperature.

The rheological properties of high-filler compositions, which are crucial for the application technology of these coatings, were determined using a Reotest-2 rotary viscometer (Germany) equipped with a cylinder-cylinder working assembly and a measuring cylinder H. The flow curves of the compositions were recorded with a change in the speed from 0.1667 to 72.9 $s^{-1}$ at temperature 296 K. The sample of the prepared compositions was then temperature-controlled for 15 minutes.

To establish the fact that the compositions under study have thixotropic properties (form a hysteresis loop), the flow curves were also measured for forward and reverse travel, that is, for the rise and fall of the shear stress ($\tau$), respectively. Prior to the test, the composition was subjected to a 10-minute deformation at the maximum shear rate (72.9 $s^{-1}$) and a rest period of 10 minutes during the reverse course of the measurements.

The technological and operational characteristics of the developed coating were determined using the following methods:

1. Thermal conductivity and thermal resistance were determined under steady-state thermal conditions in accordance with the regulatory documents DSTU B V.2.7-105:2000.
2. The magnitude of heat loss was calculated by analyzing heat transfer through a cylindrical wall in steady-state conditions.
3. Adhesion strength to concrete was determined using the peel test method according to ISO 4624:2002.

For all tests performed in this study and for all coatings submitted, specimens were produced according to the regulatory document, five in each series. Each series was duplicated to confirm the results, the corresponding specimens in the series being identical.

## 3. Results and discussion

The main parameter of heat-insulating materials that characterizes the ability to conduct heat is thermal conductivity. The coefficient of thermal conductivity serves as an indicator of the degree of heat conductivity of the material. The thickness of the thermal insulation layer to protect the building structure, as well as the amount of heat loss, depend on this indicator.

To provide thermal insulation properties, aluminosilicate microspheres were added to the base water-dispersion styrene-acrylic composition (WD) as the key factor influencing thermal insulation properties in quantities of 20, 30, and 40 wt. %, and the thermal conductivity coefficient was determined.

In the Table 1 presents the obtained data of thermal conductivity coefficient of the basic water dispersion styrene-acrylic coating (WD) and water dispersion styrene-acrylic coating filled with silicate microspheres (WD/MS).

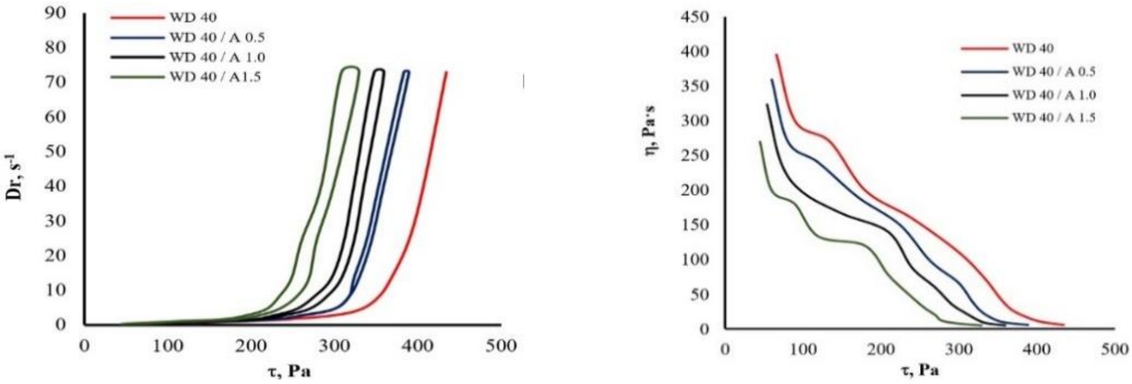
**Table 1.** Thermal conductivity coefficient of the studied thin-layer water dispersion coatings.

| Components, wt. %. | $d_{coating}$, mm | ΔR, ($m^2$ K)/W | $\lambda_{expl}$, W/(m·K) |
|---|---|---|---|
| WD | 4.2 | 0.021 | 0.2000 |
| WD / MS 20 | 4.5 | 0.070 | 0.0639 |
| WD / MS 30 | 4.5 | 0.100 | 0.0444 |

Based on the test results obtained, that the introduction of aluminosilicate microspheres allows to transfer studied styrene-acrylic dispersions ($\lambda_{expl}$=0.2 W/(m·K)) to the class of thermal insulation coatings with low thermal conductivity ($\lambda_{expl}$=0.032 W/(m·K)).

The authors have demonstrated in the article [28] that the introduction of hydrophobized aerosil has minimal effect on the thermal conductivity coefficient but allows for a 10-15 % increase in the thermal insulation efficiency of the investigated coatings. This is evidenced by the reduction in the temperature of the external wall surface and heat flux, attributed to the formation of a more ordered and less stressed structure of the composite polymer-dispersed phase. The thermal conductivity coefficient for thin-layer thermal insulation coatings does not adequately determine their thermal insulation efficiency, as it is significantly influenced by the technological properties of the dispersed system itself, which greatly affect the distribution of fillers within the coating volume, internal stresses between components, and structural defects.

Simultaneously, the introduction of aluminosilicate fillers leads to a significant increase in the composition's viscosity, which is attributed to the high adsorption properties of the fillers. In this context, there is a growing interest in studying their influence on rheological characteristics, which are a determining factor for technological properties [29]. The results of determining the rheological properties of highly filled compositions are presented in the form of flow curves (the relationship between shear stress τ (Pa) and shear rate Dγ ($s^{-1}$), as shown in Fig. (1 a) and viscosity curves (the change in viscosity η (Pa·s) as a function of shear stress τ (Pa), as shown in Fig. (1 b).



a) б)

**Figure 1.** Rheological dependences of WD on the content of MS 40 wt. % and A-300 wt. % in the form of flow curves (a) and viscosity change curves on shear stress (b).

During the film formation process, there are changes in the chemical composition, structure, and properties of the material. Conformational changes in macromolecules occur, surface activation of the substrate is possible, and stresses may appear in the contact layer. All of these factors influence the nature of adhesive interactions, and this influence becomes more significant when there is greater divergence in the conditions of film formation and the application of paint coatings.

Adhesion of film formers refers to the establishment of a bond between the film and the substrate onto which it is applied. Conclusions regarding adhesion are typically made based on adhesive strength, which represents the force required to break the adhesive bond. Adhesion is a critically important property of protective coatings. Many properties of coatings, including durability and protective capabilities in operational conditions, significantly depend on the magnitude and stability of adhesion.

Fig. 2 illustrates the adhesion strength response surfaces ($\sigma_{peel}$, MPa) of WD coatings as a function of the degree of filling with aluminosilicate microspheres 40 wt. % and hydrophobized aerosol 1.5 wt. % (WDTherm).

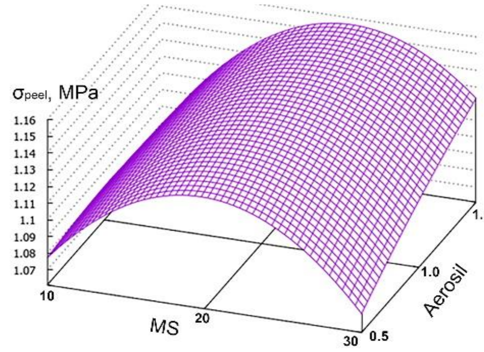


**Figure 2.** Response surfaces of WD adhesive strength from MS content and aerosil.

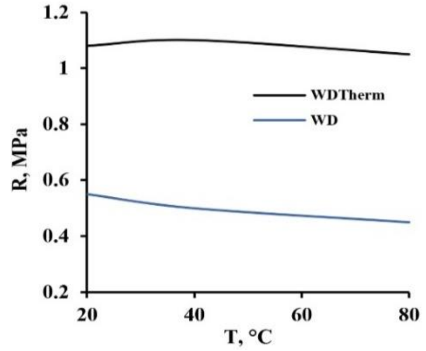


**Figure 3.** The influence of temperature on the adhesive strength of WD and WDTherm.

As shown in Fig. 2, the combined use of the MS filler and aerosil, compared to the unfilled WD, allows for an almost twofold increase in adhesive strength (0.49-0.58 MPa).

It is known that elevated temperatures can affect the adhesive strength of coatings to substrates. To determine the practicality of using the developed formulations for insulating hot water supply pipelines, tests were conducted to assess the impact of temperature on the adhesive strength of the developed thin-film water-dispersion thermal insulation coatings (WDTherm) compared to coatings based on unfilled styrene-acrylic dispersion (WD), as shown in Fig. 3.

It is established (Fig. 3) that raising the temperature to 80 °C has almost no effect on the adhesive strength of both the developed WDTherm composition and the unfilled styrene-acrylic dispersion DW. This is because these compositions are in the glassy state, which is characterized by the stability of their physical and mechanical properties. At the same time, the fracture behavior is cohesive, and no delamination of coatings from the substrate was observed during a 240-hour exposure at a coolant temperature of 80 °C. Thus, the results of determining the adhesive strength of the investigated highly filled styrene-acrylic water dispersions (WDTherm) indicate that coatings based on them have high adhesive properties to the concrete surface. The adhesive strength of WDTherm to dry concrete (with moisture content in the surface layer up to 4 %) exceeds 1.0 MPa, and delamination mainly occurs in the surface layer of concrete.

During the research to assess the potential application of the developed acrylic water dispersions as thermal insulation coatings for pipelines, the alteration of heat transfer through the cylindrical wall of a metal pipe with the application of the developed thermal insulation coating on its surface was investigated.

The parameters of the metal pipe are as follows: the wall thickness with an internal diameter ($d_{int}$) is 36.3 mm, and the external diameter ($d_{ext}$) is 41.5 mm. The ratio of the steel pipe's diameter to its length (L) is relatively small, which allows neglecting heat losses through the end faces of the wall. The pipe carries water heated to a temperature of 90 °C.

The thermal conductivity coefficient is constant and taken as $\lambda_m$=50.6 W/(m·K). To evaluate the effectiveness of WDTherm, paint layers of 1 mm, 2 mm, and 4 mm are applied to provide insulation for the pipe.

The results of measuring the temperatures of the surface (t, °C) and the heat flow density ($q_l$, Wt/m$^2$) and thermal conductivity coefficient (k) depending on the temperature of the heat carrier are shown in Table 2 and Fig. 4.

**Table 2.** Surface temperature of the metal pipe and heat losses.

| t, °C | Metal pipe | | Metal pipe with the coating | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | WD 0.5 m | | WDTherm 1 mm | | WDTherm 2 mm | | WDTherm 4 mm | |
| | $q_l$ | k | $q_l$ | k | $q_l$ | k | $q_l$ | k | $q_l$ | k |
| 20 | 0.2 | 0.89 | 0.5 | 0.37 | 0.5 | 0.22 | 0.5 | 0.21 | 0.6 | 0.20 |
| 30 | 0.7 | | 1.8 | | 1.5 | | 1.7 | | 1.7 | |
| 40 | 1.4 | | 3.2 | | 2.3 | | 2.9 | | 2.9 | |
| 50 | 1.6 | | 3.7 | | 2.7 | | 2.9 | | 3.1 | |
| 60 | 1.8 | | 4.4 | | 3.4 | | 3.5 | | 3.6 | |
| 70 | 2.7 | | 6.2 | | 4.9 | | 5.2 | | 5.2 | |
| 80 | 3.2 | | 7.3 | | 6.7 | | 6.9 | | 6.8 | |
| 90 | 3.9 | | 9.4 | | 7.9 | | 7.8 | | 7.8 | |

The data in Table 2 and Fig. 4 convincingly demonstrate that applying WDTherm thermal insulation to the metal pipe with a thickness ranging from 1 mm to 4 mm at a heat transfer fluid temperature of 80 °C helps reduce the external surface temperature of the metal pipe by 25 % to 31 % and decreases the heat transfer coefficient by 75-78 % compared to a bare metal pipe.

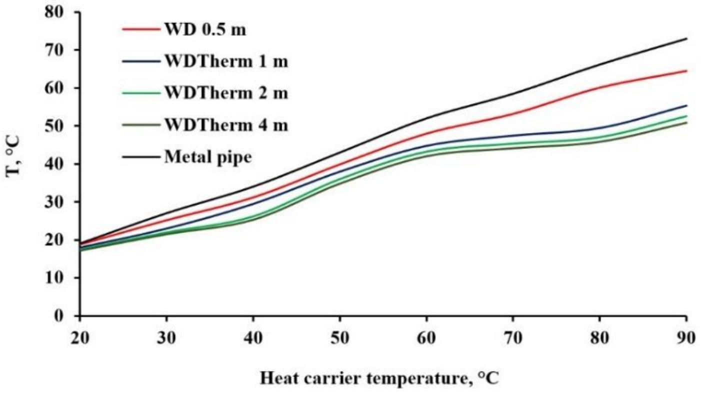


**Figure 4.** The relationship between the change in surface temperature of the cylindrical wall and the temperature of the heat transfer fluid for the metal pipe, the metal pipe with the WD coating, and the WDTherm coating.

Thus, the temperature dependence of the bare metal pipe is linear, unlike the metal pipe with the applied WDTherm coating, where there is a plateau in the temperature range of 60-80 °C, corresponding to the operating temperature range of hot water supply. This demonstrates the effectiveness of using thin-film thermal insulation coatings in the high-temperature range. The technological and operational parameters of the developed coating are provided in Table 3.

**Table 3.** Technological and operational parameters of the developed coating.

| Parameters | Value |
|---|---|
| Mass fraction of non-volatile substances in the composition, %, not less than | 50.0 |
| Drying time to degree 3 at a temperature of (20±2) °C, min | 40.0 |
| Density in the liquid state, g/m$^3$ | 0.6 |
| Hydrogen ion concentration, pH of the composition, not less than | 8-9 |
| Coverage, g/m$^2$ | 105 |
| Resistance to static water exposure, hours, not less than | 72 |
| Water permeability class, kg/(m$^2$ ·h$^{0.5}$) | W3 (low) |
| Water vapor permeability class, g/(m$^2$·day) | V2 (medium) |
| Adhesive strength to concrete, MPa | 1.2 |
| Thermal conductivity coefficient, W/(m·K) | 0.0416 |
| Linear thermal transmittance coefficient for a 2 mm thick coating | 0.21 |
| Kinetic resistance of the compositions, months | 7 |
| Consumption of WDTherm per square meter, thickness of 1 mm, kg/m$^2$ | 0.6 |

The developed thin-film thermal insulation water dispersion coating has a low density, so it does not impose additional loads on the object, does not create a sail effect, is environmentally safe, and generates no waste during application.

Thus, the developed thermal insulation coating demonstrates quite high operational characteristics. The manufacturing process of the coating is relatively simple and involves mixing the components in a single technological cycle, enabling the production of a homogeneous mixture with improved technological and operational parameters.

## 4. Conclusions

As a result of the conducted research, new thin-film thermal insulation compositions (with a thermal conductivity coefficient ranging from 0.0416 to 0.083 W/(m·K)) for building applications with improved technological and operational properties have been developed. It has been established that the application of the developed coatings with a thickness of 4 mm allows for a 31 % reduction in the external surface temperature of the metal pipe and a 78 % reduction in the heat transfer coefficient compared to a metal pipe without coating.

Introduction of aerosil into the high-fill water dispersion system to regulate the rheological properties at the stage of production of coatings or before using them. That allows to combine a number of positive effects simultaneously: decrease in the viscosity of the material during application (without dilution) due to application of high shear rate and viscosity increase (structuring) after application, as well as during storage and transportation.

The results of the adhesion strength tests for the developed thermal insulation coatings indicate that these coatings have high adhesive properties to the concrete surface. The adhesion strength of the coatings to dry concrete (with surface moisture up to 4 %) is more than 1.0 MPa. At the same time, the detachment primarily occurs at the concrete's surface layer.

The simplicity and speed of applying thin-layer thermal insulation paint coatings offer significant advantages over traditional insulation materials. The use of such insulation can significantly reduce the cost and complexity of insulation work. An advantage is the ability to insulate surfaces with complex configurations. When using traditional insulation materials, certain components in thermal systems, such as shut-off valves and relief valves, often remain uninsulated or partially insulated, leading to additional heat losses. These coatings can substantially reduce these additional heat losses on challenging-to-insulate surfaces and also protect them from potential freezing during sub-zero temperatures.

## References

[1] Aditya L, Mahlia T M I, Rismanchi B, Hasan M H, Metselaar H S, Aditiya H B 2017 A review on insulation materials for energy conservation in buildings *Renewable and sustainable energy reviews* **73** 1352–1365 https://doi.org/10.1016/j.rser.2017.02.034

[2] Abu-Jdayil, B, Mourad A H, Hittini W, Hassan M, Hameedi S 2019 Traditional, state-of-the-art and renewable thermal building insulation materials: An overview *Construction and Building Materials* **214** 709–735 https://doi.org/10.1016/j.conbuildmat.2019.04.102

[3] Wi S, Park J H, Kim Y U, Yang S, Kim S 2021 Thermal, hygric, and environmental performance evaluation of thermal insulation materials for their sustainable utilization in buildings *Environmental Pollution* **272** 116033 https://doi.org/10.1016/j.envpol.2020.116033

[4] Yihan X U E 2016 Review of Thermal Insulation Materials for Pipelines *Scholars Journal of Engineering and Technology (SJET)* **4** (5) 258–260 https://saspublishers.com/media/articles/SJET45258-260.pdf

[5] Okokpujie I P, Essien V, Ikumapayi O M, Nnochiri E S, Okokpujie K, Akinlabi E 2022 An Overview of Thermal Insulation Material for Sustainable Engineering Building Application *International Journal of Design and Nature and Ecodynamics* **17** (6) 831–841 https://doi.org/10.18280/ijdne.170603

[6] Xu S, Chen L, Gong M, Hu X, Zhang X, Zhou Z 2017 Characterization and engineering application of a novel ceramic composite insulation material *Composites Part B: Engineering* **111** 143-147 https://doi.org/10.1016/j.compositesb.2016.12.010

[7] Tettey U YA, Dodoo A, Gustavsson L 2014 Effects of different insulation materials on primary energy and $CO_2$ emission of a multi-storey residential building *Energy and Buildings* **82** 369–377 https://doi.org/10.1016/j.enbuild.2014.07.009

[8] Vambol S, Vambol V, Bogdanov I, Suchikova Y, Rashkevich N 2017 Research of the influence of decomposition of wastes of polymers with nano inclusions on the atmosphere *Eastern-European Journal of Enterprise Technologies* **6** (10 (90) 57–64 https://doi.org/10.15587/1729-4061.2017.118213

[9] Martinez R G 2017 Highly insulated systems for energy retrofitting of façades on its interior *Procedia environmental sciences* **38** 3–10 https://doi.org/10.1016/j.proenv.2017.03.065

[10] Panchenko I, Akulova M, Panchenko D 2018 Thermal insulation coating based on water-based polymer dispersion *In MATEC Web of Conferences* **143** 02007 EDP Sciences https://doi.org/10.1051/matecconf/201814302007

[11] Pargana N, Pinheiro M D, Silvestre J D, De Brito J 2014 Comparative environmental life cycle assessment of thermal insulation materials of buildings *Energy and Buildings* **82** 466–481 https://doi.org/10.1016/j.enbuild.2014.05.057

[12] Krasnova N P, Gorshenin A S, Rakhimova J I 2019 Gas-filled thermal insulation use in heat supply *In IOP Conference Series: Earth and Environmental Science* **288** (1) 012099 IOP Publishing https://doi.org/10.1088/1755-1315/288/1/012099

[13] Yang C, Zhang Q, Zhang W, Xia M, Yan K, Lu J, Wu G 2021 High thermal insulation and compressive strength polypropylene microcellular foams with honeycomb structure *Polymer Degradation and Stability* **183** 109406 https://doi.org/10.1016/j.polymdegradstab.2020.109406

[14] You J, Xue J, Jiang Z, Tang T 2022 Simultaneously improving thermal insulation, flame retardancy, and smoke suppression for rigid cross-linked polyvinyl chloride foam through combined copper/molybdenum trioxide *Advanced Engineering Materials* **24** (3) 2100858 https://doi.org/10.1002/adem.202100858

[15] Gomes M G, Flores-Colen I, Melo H, Soares A 2019 Physical performance of industrial and EPS and cork experimental thermal insulation renders *Construction and Building Materials* **198** 786–795 https://doi.org/10.1016/j.conbuildmat.2018.11.151

[16] Wi S, Yang S, Kim Y U, Kang Y, Kim S 2022 Toxicity characteristics and fire retardant performance of commercially manufactured organic insulation materials for building applications *Construction and Building Materials* **341** 127898 https://doi.org/10.1016/j.conbuildmat.2022.127898

[17] Liu L, Wang Z, Zhu M 2019 Flame retardant, mechanical and thermal insulating properties of rigid polyurethane foam modified by nano zirconium amino-tris-(methylenephosphonate) and expandable graphite *Polymer Degradation and Stability* **170** 108997 https://doi.org/10.1016/j.polymdegradstab.2019.108997

[18] Stec A A, Hull T R 2011 Assessment of the fire toxicity of building insulation materials *Energy and Buildings* **43** (2-3) 498–506 https://doi.org/10.1016/j.enbuild.2010.10.015

[19] Wi S, Park J H, Kim Y U, Kim S 2021 Evaluation of environmental impact on the formaldehyde emission and flame-retardant performance of thermal insulation materials *Journal of Hazardous Materials* **402** 123463 https://doi.org/10.1016/j.jhazmat.2020.123463

[20] Kunzel H M 1995 Simultaneous heat and moisture transport in building components. One- and two-dimensional calculation using simple parameters (Stuttgart, IRB Verlag)

[21] Künzel H M, Fitz C, Krus M 2011 Feuchteschutz verschiedener Fassadensysteme. Beanspruchungen, Systemanforderungen, Langzeitbeständigkeit *Deutsches Institut für Normung e.V. Fassadensanierung. Praxisbeispiele*, Produkteigenschaften, Schutzfunktionen 29–51.

[22] Saienko N V, Bikov R, Skripinets A, Demidov D V 2021 Research of the influence of silicate fillers on water absorption and microstructure of styrene-acrylic dispersion coatings *In Materials Science Forum* **1038** 61–67 Trans Tech Publications Ltd https://doi.org/10.4028/www.scientific.net/MSF.1038.61

[23] Xing Z, Ke H, Wang X, Zheng T, Qiao Y, Chen K, Li Z 2022 Investigation of the thermal conductivity of resin-based lightweight composites filled with hollow glass microspheres *Polymers* **12** (3) 518 https://doi.org/10.3390/polym12030518

[24] Ruckdeschel P, Philipp A, Retsch M 2017 Understanding thermal insulation in porous, *Particulate Materials*. Advanced Functional Materials **27** 1–11 https://doi.org/10.1002/adfm.201702256

[25] Ryzhenkov A V, Loginova N A, Belyaeva E V, Lapin Y Y, Prischepov A F 2015 Review of binding agents in syntactic foams for heat-insulating structures in power industry Facilities *Modern Applied Science* **9** (4) 96 https://doi.org/10.5539/mas.v9n4p96

[26] Saienko N V, Bikov R A, Popov Y V, Demidov D V, Younis B 2022 The effect of silicate fillers on adhesion and adhesion strength properties of water-based coatings *Key Engineering Materials* **864** 73–79 https://doi.org/10.4028/www.scientific.net/KEM.864.73

[27] Directive 2004/42/CE of the European parliament and of the council of 21 April 2004 on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain paints and varnishes and vehicle refinishing products and amending Directive 1999/13/EC http://extwprlegs1.fao.org/docs/pdf/eur43014.pdf.

[28] Saienko N, Bikov R, Skripinets A, Demidov D, Dukarov S 2023 Effectiveness Evaluation of Silicate Fillers for the Creation of Thin-layer Thermal Insulation Coatings *In AIP Conference Proceedings* **2490** 1 050021 AIP Publishing https://pubs.aip.org/aip/acp/article/2490/1/050021/2928273

[29] Saienko N, Demidov D, Popov Y, Bikov R, Butskyi V 2018 Rheological properties of aqueous dispersion of styrene acrylate copolymer incorporating hollow microspheres and AEROSIL® *In MATEC Web of Conferences* **230** 03017 EDP Sciences https://doi.org/10.1051/matecconf/201823003017