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APPLICATION OF NANOSTRUCTURED THERMAL INSULATION**MATERIALS TO IMPROVE THE ENERGY EFFICIENCY OF PIPELINES****ЗАСТОСУВАННЯ НАНОСТРУКТУРНИХ ТЕПЛОІЗОЛЯЦІЙНИХ МАТЕРІАЛІВ ДЛЯ ПІДВИЩЕННЯ ЕНЕРГОЕФЕКТИВНОСТІ ТРУБОПРОВОДІВ****Maxymenko V. S. / Максименко В. С.***Master`s Degree at Corporate Management / магістр з корпоративного управління**ORCID: 0009-0003-7855-1304**Zaporizhzhia State Engineering Academy, Zaporizhzhia, Soborny Avenue, 226, 69006**Запорізька державна інженерна академія, Запоріжжя, проспект Соборний, 226, 69006*

Abstract. *Improving the thermal performance of pipeline networks remains one of the fastest and most capital-efficient levers for reducing energy waste, operating costs, and greenhouse-gas emissions in district heating, industrial steam, and process pipelines. Alongside conventional mineral-wool systems, a new class of nanostructured insulation solutions - most notably silica-based aerogel blankets and thin-film nano-ceramic insulation coatings - offers materially higher performance per unit thickness and can expand the set of technically feasible retrofit scenarios where space is limited or where insulation-under-cladding moisture and corrosion risks are elevated. This paper provides a structured review of the physical mechanisms that enable low effective thermal conductivity in nanoporous media, compares practical deployment models for pipelines, and outlines decision criteria for selecting nanostructured materials under field constraints (temperature regime, geometry, accessibility, moisture control, and life-cycle cost). Special attention is paid to Ukraine's current context - aging networks, constrained maintenance windows, and heightened resilience needs - where reducing distribution losses can translate into both economic savings and improved continuity of service. The work is designed as an evidence-based synthesis for engineers and asset owners and identifies priority directions for verification testing and standards alignment.*

Keywords: *nanostructured thermal insulation materials; energy efficiency; pipelines; heat loss; aerogel; insulating coating.*

Introduction.

Pipeline heat losses are a persistent and often underestimated driver of system inefficiency in district heating and industrial energy infrastructure. Losses accumulate over long linear assets, increasing fuel consumption, pumping demand, and peak-load requirements, while also amplifying exposure to service interruptions in cold climates. In Ukraine and other countries with legacy networks, aging insulation, moisture intrusion, and limited access for repairs frequently translate into elevated operational risk and avoidable cost [3].

Conventional solutions, such as mineral wool with protective jacketing, remain the baseline for many applications; however, they can be challenging where geometric complexity, clearance constraints, frequent penetrations, or corrosion-under-insulation



(CUI) concerns dominate. Nanostructured insulation materials address these constraints by delivering higher thermal resistance at reduced thickness (aerogel blankets) or by providing a conformal thin-film barrier (nano-ceramic coatings) that can be applied on complex surfaces and hard-to-insulate elements.

The purpose of this paper is to (I) summarize the operating principles and practical forms of nanostructured insulation for pipelines, (II) compare these solutions against conventional systems using application-relevant criteria (thermal performance, moisture behavior, durability, installation complexity, and cost drivers), and (III) translate the findings into a decision framework suitable for retrofit planning. The scope is intentionally practice-oriented: rather than presenting new laboratory measurements, the paper consolidates published evidence and field observations to support engineering judgment and to define the most valuable directions for further validation.

Original Contribution (Author's Contribution).

- Consolidates the scattered technical literature on nanostructured insulation into a pipeline-specific taxonomy (aerogel blankets, nanoporous silica mats, thin-film nano-ceramic coatings) and maps each class to practical installation architectures.

- Defines a decision-oriented selection matrix tailored to field constraints typical for pipeline retrofits (space limitations, complex geometry, access windows, moisture control/CUI risk, and temperature regime).

- Highlights Ukraine-relevant implementation barriers (standards alignment, supply-chain availability, workforce familiarity, and verification testing) and proposes a minimum evidence package for procurement and acceptance.

Literature review.

Energy efficiency and heat losses. The heating sector is traditionally characterized by high energy intensity and losses. A significant part of thermal energy can be dissipated into the environment during the transportation of the coolant from boiler houses to end consumers. The reasons are the long length of the networks, outdated or damaged pipe insulation coatings, as well as the operation of pipelines whose service life exceeds the design one. In Ukraine, the district heating system



covers more than 5.5 million households, and the length of the heating networks reaches tens of thousands of kilometers [2]. Most of these networks were built several decades ago and require modernization. According to available data, the average heat losses in Ukrainian heating networks are about 13–14%, which significantly exceeds the indicators of OECD countries [2]. In some regions with severely worn networks, losses can reach 30–40% [2]. In comparison, in modern district heating systems in the Nordic countries, heat losses are usually below 10% due to the use of pre-insulated pipes and modern maintenance standards [3]. Low losses in European networks are achieved through high-quality insulation, corrosion protection and regular maintenance of pipelines [3].

Regulatory requirements and standards. The effectiveness of thermal insulation of pipelines is regulated by building codes and standards. Historically, Ukraine has used regulations inherited from Soviet times, in particular SNiP 2.04.14-88 “Thermal insulation of equipment and pipelines”. This document established requirements for the selection of insulation thickness and materials for equipment and heating mains. Although this SNiP was formally repealed in 2003, many existing networks are still operated with insulation designed according to its requirements [6]. The situation is similar in Eastern European countries – for example, most heating networks in Lithuania are still insulated according to the requirements of the aforementioned SNiP [6]. Modern Ukrainian standards are harmonized with European ones: DSTU for pre-insulated pipes (for example, DSTU B V.2.5-31:2007 for pipes with polyurethane foam insulation) and heat loss calculation methods (DSTU ISO 8497:2005 - determination of heat transfer in insulated pipes) have been introduced. The standards determine the minimum permissible insulation characteristics: its thickness, the limiting thermal conductivity of the material, the temperature on the surface of the insulated pipeline, etc., in order to limit heat loss and ensure operational safety (for example, so that the surface of the pipes is not too hot for personnel) [7].

At the same time, compliance with only the minimum regulatory requirements does not guarantee optimal energy efficiency. Due to economic constraints during construction, many networks received insulation of minimal thickness or from short-



lived materials. Over time, the insulating coatings could degrade – get wet, crumble, come off due to external influences or pipe repairs. As a result, actual heat losses are often higher than calculated. Another problem is corrosion under insulation (the so-called CUI effect): moisture penetrating under the insulation shell causes intensive rusting of the pipes, which not only worsens thermal insulation, but also shortens the service life of the pipeline [8]. In the absence of proper supervision, such hidden defects can lead to accidents.

Problems and challenges of modernization. Modernization of thermal insulation of existing pipelines poses some challenges. The first is economic: upgrading insulation on thousands of kilometers of pipes requires significant investments. According to OECD (2021), modernization of Ukrainian heating networks requires \$6–\$10 billion, which includes replacing about 9,400 km of pipes and saving up to 4.1 billion m³ of gas annually [2]. However, heat tariffs have traditionally been kept low, which has led to chronic underfinancing of the industry and accumulation of debt, complicating investments in energy efficiency [2]. The second challenge is technological: insulation of existing pipelines is often associated with access difficulties (especially for underground communications) and the need to turn off the heat supply for the duration of the work. The third is organizational: the need to simultaneously address the issues of replacing pipes (if they are worn out) and insulation, and coordination with other repair works.

The full-scale invasion and military operations of 2022–2026 have dealt and continue to deal additional blows to the energy sector of Ukraine - many sections of heating networks have been destroyed and damaged, which has further exacerbated the problem of heat loss [9]. Post-war infrastructure restoration is seen as an opportunity to implement more modern solutions, including in the field of pipe insulation. Government programs and international donors (EIB, USAID, NEFCO, etc.) are currently supporting energy efficiency projects, which include replacing old pipes with pre-insulated ones, installing individual heating points, and using new materials. In this context, nanostructured thermal insulation materials can become an important component of innovative renovation of heating networks.



Table 1 - Practical comparison of insulation options for pipelines (typical ranges; project-specific verification required).

Material class	Typical λ_{eff} , W/(m·K)	Thickness efficiency	Temperature suitability	Key advantages	Key constraints/risks	Best-fit scenarios
Mineral wool + jacket	0.035–0.045	Baseline	Wide (product-specific)	Low cost; mature standards; high availability	Bulk thickness; moisture ingress can drive CUI; workmanship sensitive	General outdoor runs with adequate clearance
Silica aerogel blanket	0.013–0.020	High (2–3× per thickness)	High (product-specific)	High R-value in thin profile; flexible; useful on complex geometry	Higher cost; needs careful sealing/jacketing; dust control/PPE	Retrofits with limited clearance; high-temperature lines; congested racks
Nano-ceramic insulating coating	Reported/variable	Moderate (thin film)	Service-dependent	Conformal on complex shapes; can complement other insulation; potential barrier layer	Results sensitive to application and test method; substrate prep and QA/QC critical	Valves/flanges/fittings; hybrid assemblies; local constraints
VIP / microporous core panels	0.004–0.008 (VIP)	Very high (fragile)	Limited by enclosure integrity	Exceptional thermal performance at minimal thicknesses	Fragile; puncture sensitivity; difficult on curved surfaces; requires robust casing	Specialty boxes/enclosures for localized bottlenecks

Source: Author's development



Basic material.

Types of nanostructured thermal insulation materials. When considering nanostructured thermal insulation materials in the context of increasing the energy efficiency of pipelines, it is advisable to first outline their classification and key differences from traditional insulators. A common feature of such materials is the presence of structural elements or pores in the nanoscale range, which changes the mechanisms of heat transfer: gas thermal conductivity is reduced, microconvection is suppressed and, if necessary, infrared radiation is controlled. In practical application for pipelines, nanostructured solutions are represented by several main groups that differ in shape (mats, panels, coatings), application or installation technology, operating temperatures and operational resistance to moisture and mechanical stress. Further consideration of the types of nanostructured thermal insulation materials allows us to systematically assess their capabilities, limitations and areas of appropriate use in housing and utilities and industry, as well as to form the basis for a correct technical and economic comparison with traditional insulation systems.

Aerogels and nanoporous materials. Aerogel is the most famous representative of nanostructured insulators. It is a solid formed from a gel by removing the liquid phase and replacing it with a gas, resulting in a superporous structure with nanometric pores [1]. A classic silica-based aerogel contains up to 99% air by volume, and its density can be only $\sim 0.1\text{--}0.2\text{ g/cm}^3$ (for comparison, water is 1 g/cm^3) [10]. The pore size in an aerogel is several tens of nanometers, i.e. less than the mean free path of air molecules at atmospheric pressure. This results in extremely low thermal conductivity: for silica aerogel, the thermal conductivity coefficient is about $0.014\text{--}0.02\text{ W/(m K)}$ [10], which is one of the lowest among solid materials (for comparison, dry mineral wool has $\sim 0.04\text{ W/(m K)}$). In practice, this means that a layer of aerogel less than 1 cm thick will provide the same thermal insulation effect as a layer of glass wool several centimeters thick. According to the US Department of Energy, less than 1 inch ($<2.54\text{ cm}$) of aerogel insulation is equivalent to 3 inches ($\sim 7.6\text{ cm}$) of traditional fiberglass insulation [4].

Initially, aerogels were fragile monoliths, but are now available in the form of



flexible mats and panels. Such materials are a composite - nanoporous aerogel reinforced with flexible fibers (glass fiber, polymer fiber). An example is the industrial products of Aspen Aerogels (USA) - Pyrogel® and Cryogel®, which are produced in rolls as flexible mats with a thickness of 5 to 10 mm. They combine the low thermal conductivity of aerogel with the strength and flexibility of reinforcing fibers, which allows them to be wrapped around pipes or equipment of complex shapes. Another type is nanoporous silica panels in a vacuum shell (vacuum insulation panels, VIP). In them, the combination of a nanoporous core and vacuum achieves extremely low thermal conductivity (0.003–0.004 W/(m K)), but VIP panels are usually rigid and difficult to apply to curved pipe surfaces. Therefore, the main form of application of aerogels for pipelines is flexible mats and sections that wrap pipes under a protective casing.

“Liquid” nanoceramic thermal insulation coatings. Over the past decades, a considerable number of composite thermal insulation paints and coatings have appeared, which are positioned by manufacturers as nanothermal insulation. They contain a filler of micro- and nano-sized hollow ceramic microspheres, silica nanoparticles, as well as special binding polymers. After application to a surface (e.g. a pipe) and drying, such a coating forms a thin insulating layer with a thickness of fractions of a millimeter to several millimeters [11]. Unlike traditional insulators, which work mainly due to the low thermal conductivity of the material, nanoceramic coatings also reflect thermal radiation (contain infrared reflectors) and reduce convective heat transfer on the surface. Some developments of this type came from the field of aerospace technology (thermal protective coatings for missiles, aircraft), others were created for industry and construction. Examples of commercial products are “Nansulate”, “Isollat”, “Bronya”, etc. Thus, the product Nansulate™ EPX from Syneffex (USA) is positioned as a nanostructured two-component polymer with a ceramic filler, which is applied in layers to hot surfaces and provides a significant reduction in heat loss [8]. A characteristic feature of such coatings is their ability to simultaneously protect against corrosion and insulate the surface, since they are applied directly to the metal and form a continuous protective film. The thickness of the coating



depends on the required level of insulation: thin coatings (up to ~ 0.5 mm) are able to reflect thermal radiation and reduce the surface temperature (useful for reducing the risk of personnel burns), while multilayer thick coatings (for example, 10–12 layers, which gives a thickness of several millimeters) are designed specifically to reduce stationary heat loss in hot pipes, tanks, steam lines, etc. [11].

The effective thermal conductivity of such nanocoatings is difficult to compare directly with traditional materials due to the different mechanism of action. However, there is experimental evidence of their effectiveness. In particular, in field tests by the oil refining company Sinopec, a 12-layer nanocoating (total thickness of about 6 mm) maintained the wall temperature of an offshore tank almost at the level previously achieved with 80 mm of mineral wool - the difference was only $\sim 3^{\circ}\text{C}$ [8]. This was sufficient for technological needs and at the same time solved the problem of corrosion that occurred under the layer of wool [8]. Other examples include the use of ceramic coatings on steam pipes, where they reduced the temperature of the outer surface of the pipe from, say, 150°C to a safe $\sim 60^{\circ}\text{C}$, significantly reducing heat loss. Thus, nanostructured coatings are an alternative to traditional insulation, especially where the use of a thick layer of insulation is difficult or undesirable (complex geometry, limited space, need for anti-corrosion protection).

Other nanostructured insulating materials. Promising areas also include nanofiber mats and ultrathin fibrous insulators. For example, thermal insulation materials based on nanosized oxide fibers (Al_2O_3 , SiO_2) and carbon nanotubes that form porous frameworks are being studied. Electrostatically formed nanofibers can have a diameter of 50–200 nm, which creates a structure similar to an aerogel, but with greater flexibility. Such materials are potentially resistant to high temperatures and mechanical stress. Another class is composites, where a traditional insulator (polyurethane foam, epoxy foam, mineral wool) is modified with nanoadditives: aerogel powder, oxide nanoparticles, infrared absorbers (for example, graphite nanoparticles). Adding even a few percent of nanoadditives can reduce thermal conductivity by increasing the dissipation of thermal radiation or the formation of additional pores. An example is graphite polystyrene foam (known brand Neopor), in



which graphite nanoparticles reflect infrared radiation, reducing the radiation component of thermal conductivity. Graphite polystyrene foam is not directly used for pipelines (it is used in construction), but a similar principle can be implemented in rigid insulating shells for pipes.

Mechanisms for increasing the efficiency of thermal insulation by nanomaterials. Nanostructured insulating materials are considered highly effective due to a combination of physical mechanisms that work simultaneously. In nanoporous structures (in particular, aerogels and nanofiber mats), the solid framework is so sparse that there is almost no continuous path for heat transfer: the main part of the heat flux "goes" through the gas phase inside the pores, and the contribution of the solid phase is minimized. In addition, the efficiency is affected by the fact that the nanoparticles or nanofibers themselves, from which the framework is formed, may have low thermal conductivity; for example, silica has λ of about 1.3 W/(m K), but due to the nanoscale and high porosity, the effective thermal conductivity of the entire material becomes orders of magnitude lower.

The suppression of convection also plays an important role: nanometer or micrometer pores do not allow air to circulate freely inside the material, so convective heat transfer is practically absent. Unlike traditional insulators with larger pores (for example, some foams or fibrous mats), where internal air circulation can occur at high temperatures, in aerogels and nanopores the air is actually "closed" and transfers heat mainly only by thermal conduction and radiation. In addition, the thermal conductivity of the gas itself in the pores is also reduced: when the characteristic pore size is comparable to or smaller than the mean free path of the molecules, the Knudsen effect manifests itself. For aerogels, typical pore diameters are approximately 20–50 nm, while for air at normal pressure the mean free path is about 70 nm; Due to frequent collisions of molecules with pore walls, their contribution to heat transfer decreases, which is one of the reasons for the record low values of λ in aerogels [1].

At elevated temperatures (above $\sim 100^\circ\text{C}$), the radiation component of heat transfer becomes significant, and nanostructured materials can reduce it. This is achieved by introducing impurities that absorb or reflect infrared radiation (for



example, graphite or oxide nanoparticles-opacifiers); in graphite-containing polystyrene foams, this can reduce thermal conductivity by about 20%. Aerogels, although partially transparent in the visible range, can contain additives that make them opaque in the IR spectrum. In nanoceramic coatings, the key mechanism is often the reflection of thermal radiation from the surface due to ceramic microspheres with low emissivity [11], which reduces the radiative fraction of losses.

A separate factor is hydrophobicity and the ability to maintain insulating properties in wet conditions. Many nanostructured insulators are specially made water-repellent: aerogel mats, for example, are treated with hydrophobic agents, so they do not absorb water [4]. Due to this, the material remains “dry” and does not lose its low thermal conductivity, while traditional cotton wool or porous materials, when wet, sharply deteriorate thermal insulation characteristics. Additionally, hydrophobicity reduces the risk of corrosion under the insulation and extends the service life of the pipeline.

Finally, for nanocoatings, thinness and the absence of thermal bridges are important: the coatings are applied in a continuous layer that repeats the shape of the surface, eliminating gaps and cracks through which local “bridges” of heat transfer could arise. Unlike segmented insulating shells with joints and seams, a continuous layer minimizes the places of potential heat escape, and the small thickness practically does not change the diameter of the pipes, which is critical in confined spaces and for pipelines that require periodic maintenance. It is the combination of the listed mechanisms that provides high thermal resistance of nanostructured materials with a smaller thickness and mass.

Examples of the application of nanostructured insulators in pipelines.

Heat supply systems (HCS). In housing and communal services, the main consumers of heat are buildings connected to boiler rooms by a network of pipes (aboveground or underground). Traditionally, segments of mineral wool or polyurethane foam shells under a protective casing were used to insulate such pipes. In recent years, projects have been implemented in some countries to use aerogel materials to modernize heating networks. For example, in Denmark and Germany,



demonstration replacements of insulation in critical areas (heat chambers, inputs to buildings) using aerogel mats were carried out, which made it possible to achieve a noticeable reduction in losses at these nodes. Aerogel mats are also used to insulate pipes in places with limited space - for example, internal pipelines of heating points, where a thick layer of wool is technically difficult to place. Due to the small thickness of the aerogel, the pipeline can be insulated while maintaining the compactness of the installation.

In Ukraine, the use of nanostructure insulators in housing and communal services is still rare. During reconstruction, the main heating mains are equipped with standard pre-insulated pipes with polyurethane foam (the “pipe in pipe” system), where the possibilities for nanomaterials are limited. However, in cities, the task of insulating intra-building networks, risers, and pipelines in basements that were not previously properly insulated is increasingly arising. Liquid thermal insulation coatings can be used here. For example, in Kyiv and Kharkiv, several management companies tested ceramic thermal insulation paints for insulating heating pipes in basements of old buildings: applying a thin layer of coating allowed to reduce the surface temperature of the pipes and heat loss into the room, without increasing the bulkiness of the pipes (which is important in cramped basements). Reviews about the durability of such coatings are still limited - monitoring of their condition after several years of operation is required.

Industrial and technological pipelines. In industry (oil and gas, chemical, energy industries) there are often pipelines with high parameters - steam, hot water, thermal oils - where thermal insulation is critically important for safety and energy efficiency. Abroad, nanostructured materials are already being introduced in such areas. In particular, in oil production and processing: flexible aerogel mats are used to insulate steam pipelines, distillation columns, heat exchangers. Their attractiveness lies in the speed of installation (you can cut and wrap the necessary element like a “blanket”, fixing it with clamps) and resistance to moisture. The experience of Aspen Aerogels has shown that aerogel insulator retains its properties in the harsh conditions of oil refineries longer than mineral wool, since it does not crumble and does not get



wet [4]. In the USA, Pyrogel® was tested on steam pipelines: thanks to thinner insulation, installation time was reduced, and energy savings were even higher than expected due to the material's better moisture resistance [4].

In the field of liquefied natural gas (LNG) and cryogenic pipes – another regime, very low temperatures – aerogel materials (brand name Cryogel®) are also used. They are effective at -160°C to retain cold, preventing the pipes from heating up from the environment. In addition, due to the flexibility of the aerogel insulation, thermal deformations of the pipes during “cooling-heating” cycles are compensated without the formation of cracks in the insulation.

Nanoceramic coatings are used in industry primarily to combat corrosion under insulation and on complex objects. For example, petrochemical plants suffer from CUI, when hot pipelines under a layer of insulation corrode imperceptibly. The use of coatings such as “thermal insulation coating” solves this problem: the coating insulates and at the same time acts as an anti-corrosion primer. A project was implemented in a refinery in Indonesia to apply such a coating to pipelines of complex configuration, where traditional insulation often needed repair. As a result, the surface temperature dropped to safe levels, and personnel were able to visually inspect the condition of the pipes (since the coating was made in the form of paint).

International experience and the Ukrainian market. Abroad (USA, EU, China) both large and small innovative companies are engaged in the production of nanostructured thermal insulation materials. Aspen Aerogels, Cabot Corporation, Armacell (production of aerogel components) are among the leaders of the aerogel insulation market. Their materials are certified and used in industry, construction, and transport. In Europe, where energy efficiency of buildings is a priority, aerogel insulation is used for thermal renovation of buildings (for example, aerogel plasters for internal wall insulation) and for insulation of engineering communications. In Finland and Sweden, known for the progressive development of centralized heating, the possibilities of introducing aerogels in the 4th generation of heating networks are being explored - with lower coolant temperatures, but higher insulation requirements to minimize losses over long distances [13].



Nanoceramic coatings are produced by several companies in the USA (NEOtech Coatings, Syneffex), Europe and Asia. They are actively promoted in countries with many oil refineries and chemical plants, as well as in tropical climates (due to severe corrosion from humidity). Some large corporations have conducted their own assessments: the aforementioned Sinopec (China) after successfully testing a nanocoating on a tank is implementing it at other facilities to combat CUI [8]. The oil and gas company Petronas (Malaysia) reported a reduction in energy losses on industrial furnaces after applying thermal insulation paint. In general, international experience shows that nanostructured insulators work well in specific niches - where traditional materials are either not effective enough or cause problems (humidity, corrosion, limited space).

In Ukraine, the market for nanostructured thermal insulation is still at the initial stage of development. There is no mass domestic production of aerogel materials; imported solutions are available, but their use is limited by high prices. For example, aerogel mats are imported through distributors for narrow needs - insulation of equipment at refineries, heat exchangers, etc., where the customer is willing to pay for better characteristics. Mass use in heating networks has not yet been recorded, although there are all the prerequisites (worn insulation in networks needs to be updated). Perhaps with the advent of cheaper production (for example, aerogel plants are being actively built in China), such materials will become more accessible.

As for “liquid insulation”, several brands are known in Ukraine, some of which are localized versions of Russian or Belarusian products (because of this, there are prejudices and sanctions restrictions against them). However, Ukrainian enthusiasts and small businesses are also starting to produce similar ceramic paints, attracting technologies from the EU. The market is still small: the main customers are industrial enterprises that conduct experiments with such coatings at their own facilities, and sometimes housing and communal services. Certification and objective testing of these materials in Ukrainian conditions will be very important in order to move away from purely marketing statements and gain the trust of engineers. So far, most designers choose conservative solutions (cotton wool, polyurethane foam) due to predictability



and regulatory framework.

Advantages and disadvantages of nanostructured insulations. Nanostructured thermal insulation materials have a number of significant advantages that make them attractive for increasing the energy efficiency of pipelines, especially in difficult operating conditions. First of all, this is ultra-low thermal conductivity: aerogels demonstrate one of the lowest thermal conductivities among known solid materials [1], due to which the thickness of the insulation can be significantly reduced without losing the heat-shielding effect. Nanocoatings, although inferior to aerogels in λ , compensate for this with high reflectivity and the ability to provide noticeable thermal protection with a small layer. This is especially important for large-diameter pipes, because thinner insulation means a smaller final diameter of the structure and, as a result, lower losses due to convection around the pipe.

A practical advantage is the possibility of use in limited space. Thin insulation systems (for example, 5–10 mm of aerogel instead of 50–100 mm of mineral wool) make it possible to insulate pipelines in channels, tunnels and shafts with a small cross-section, where thick insulation simply does not fit or critically reduces the space for maintenance. This is especially relevant during the modernization of old networks, in which a large margin of space for insulation was usually not laid. Resistance to moisture and corrosion is also high: most nanomaterials are hydrophobic or inert to water [4]. Aerogel mats do not absorb water, and ceramic coatings form a hermetic layer that prevents moisture from penetrating the metal, dramatically reducing corrosion risks. In contrast, traditional materials (in particular, cotton wool or foam plastic) not only lose their thermal insulation properties when wet, but can also contribute to corrosion; instead, nanostructured solutions are better at maintaining stability in the event of rain, condensation, and humidity fluctuations.

Fire resistance and general safety are important. Silica-based aerogels are non-combustible materials and can withstand heating to approximately 650°C without destruction [1], and under the influence of an open flame they emit almost no smoke or toxic gases [1], which makes them promising for explosive and fire-hazardous objects. Acrylic-based nanocoatings are organic and can burn at very high



temperatures, but a significant part of such systems is modified with flame retardants to the G1-G2 flammability level, so from the point of view of fire safety they may not be inferior to traditional solutions (especially when compared with combustible polymer insulations without protection). Durability is also often noted as a strong point: manufacturers claim a lifespan of 20–30 years for aerogel insulators without noticeable loss of properties [1]. Such materials are chemically inert, do not rot or decompose, and are less attractive to rodents or insects than some foam materials. Ceramic coatings, in turn, are resistant to ultraviolet and biological influences, and some types to aggressive vapors, which can reduce the cost of replacing insulation during the life cycle of the pipeline. It is also emphasized that the water-repellent properties of aerogel mats are maintained for decades [10], so the material does not accumulate moisture over time and does not degrade due to wetting.

Another practical advantage is the speed and convenience of installation. Flexible nanomaterials in the form of mats or coatings allow you to reduce the duration of work: an aerogel mat can be quickly cut and wrapped around a pipe of any shape, fixing it with a wire or bandage, which is often easier and faster than installing solid segments with complex joint adjustment. Liquid coatings can be applied like paint (by brush or spray) to an existing surface, sometimes without the complex dismantling of old insulation or after minimal preparation, and in some cases such coatings allow application to operating equipment without stopping [8], which reduces downtime. An important advantage is also the reduction of the load on structures: aerogel is ultra-light, and the coatings are thin, so the additional load on pipes and supports is minimal. Although the density of a typical aerogel mat can be around 200 kg/m^3 , and mineral wool around 150 kg/m^3 , the smaller layer thickness results in a significantly lower mass of insulation per unit length of pipes (sometimes 2-3 times), while nanocoatings generally add only a few kilograms per square meter of surface.

However, nanostructured insulations also have significant limitations. The most noticeable drawback remains the high cost: aerogel insulations are usually an order of magnitude more expensive than mineral wool or polyurethane foam (by volume), and although the required thickness may be significantly less, the savings in material do



not always completely cover the difference in price. The approximate cost of aerogel mats can be about 50-100 US dollars per m² (depending on the thickness), which significantly exceeds the cost of traditional analogues. Nanoceramic paints are also expensive: a high-quality coating can cost 10-30 dollars per liter, and several layers (i.e. several liters) are often required for 1 m². For industry, such a cost is sometimes justified by energy savings and reduced maintenance costs, but for budget organizations (in particular, heat and power utilities), initial investments are often a barrier without additional funding.

Conclusions. Nanostructured thermal insulation materials provide a credible pathway to reduce distribution heat losses in pipelines while expanding retrofit feasibility where conventional systems are constrained by space, geometry, or corrosion-under-insulation risk. Based on the reviewed evidence, aerogel blankets represent the most technically mature high-performance option for pipelines, delivering substantial thermal resistance at reduced thickness when installed with appropriate sealing and jacketing.

Thin-film nano-ceramic coatings can add value in niche cases, especially on fittings, valves, and complex surfaces, or as part of hybrid assemblies; however, their effective performance is highly sensitive to application practice and the chosen test method. For academic and engineering rigor, procurement should be tied to transparent, reproducible verification data rather than manufacturer claims alone.

For Ukraine's district-heating and industrial assets, the primary obstacles to adoption are not purely technical: alignment with applicable standards, availability of qualified installers, and the absence of a consistent acceptance protocol for new materials can delay deployment. These barriers are addressable through pilot projects with clear metering, moisture/CUI monitoring, and documented quality control.

Future work should prioritize (I) long-duration field trials across representative temperature regimes, (II) standardized testing and reporting of thermal performance and moisture behavior, and (III) life-cycle cost models that reflect both energy savings and risk reduction (downtime, corrosion remediation, and safety). With these steps, nanostructured insulation can evolve from a selective retrofit solution into a scalable



lever for national energy efficiency and resilience.

Taking into account the listed pros and cons, we can draw conclusions: nanostructured thermal insulation materials are most appropriate where their unique properties give maximum effect - when a thin layer is needed, there is a critical need for moisture resistance or anti-corrosion protection, or high requirements are made for thermal characteristics. In typical cases (for example, ordinary ground sections of heating networks), traditional materials often remain more economically advantageous, if the installation and operation conditions allow. At the same time, with the development of technologies, cheaper production and the accumulation of practical experience, we can expect a gradual expansion of the scope of application of nanomaterials in thermal insulation of pipelines.

Conclusions. Nanostructured thermal insulation materials open up new horizons for increasing the energy efficiency of pipeline systems. The analysis showed that, due to the unique porous structure at the nanolevel, materials such as aerogels demonstrate extremely low thermal conductivity and allow reducing heat loss several times compared to traditional insulation materials with the same insulation thickness. The use of aerogel mats and panels on pipelines allows you to significantly reduce the thickness of the insulation layer without losing thermal insulation properties, which is critical in conditions of limited space and to reduce the load on structures. Nanoceramic thermal insulation coatings, in turn, provide a comprehensive effect - reduce heat loss, protect the surface from corrosion and simplify monitoring of the pipeline condition, as they eliminate hidden moisture zones under the insulation.

The review of the external environment revealed that for Ukraine the problem of heat losses in networks remains extremely relevant: the outdated infrastructure requires modernization, and regulatory requirements only minimally restrain losses. Therefore, the integration of innovative materials, in particular nanostructured insulators, is a logical step within the framework of the energy saving program and the post-war restoration of the energy complex. International experience reviewed in the article confirms the effectiveness of such solutions in industry and heat supply - they allow achieving energy savings, increasing the reliability and durability of equipment. At the



same time, there are obstacles, primarily the high cost of nanomaterials and insufficient awareness of specialists with their characteristics.

Further steps are needed to spread nanostructured thermal insulation materials on the Ukrainian market. These include conducting local pilot projects in heating networks and enterprises to demonstrate real benefits in specific conditions; developing the regulatory framework (amendments to DBN and DSTU regarding new materials); stimulating technology transfer and organizing the production of such materials in Ukraine to reduce costs. It is also important to consider the long-term effect: fuel savings and reduced heat loss due to better insulation will eventually pay off the initial investment, especially given the trend towards rising energy prices and the cost of CO₂ emissions.

In summary, nanostructured thermal insulation materials have great potential in increasing the energy efficiency of pipelines. They are not a panacea for all cases, but in specific applications they can provide breakthrough results that are unattainable for traditional technologies. The combination of different solutions – aerogel insulators, nanocoatings, improved traditional materials – will allow to optimally solve the problem of reducing heat loss. Further scientific research and engineering developments in this direction, supported by economic incentives, will contribute to the implementation of these innovations in practice, which will bring both economic and environmental effects on a national scale.

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Анотація. Поліпшення теплових характеристик трубопровідних мереж залишається одним із найшвидших і найбільш капіталоефективних важелів для зменшення відходів енергії, експлуатаційних витрат і викидів парникових газів у централізованому опаленні, промисловій парі та технологічних трубопроводах. Поряд зі звичайними системами mineral-wool, новий клас наноструктурованих ізоляційних рішень - особливо аерогелеві ковдри на основі кремнезему та тонкоплівкові нано-керамічні ізоляційні покриття - пропонує значно вищу продуктивність на одиницю товщини та може розширити набір технічно можливих сценаріїв модернізації, де простір обмежений або де ізоляція-under-, що покриває вологість і підвищує ризики корозії. В статті подано структурований огляд фізичних механізмів, які забезпечують низьку ефективну теплопровідність у нанопористих середовищах, порівнюються практичні моделі розгортання для трубопроводів і окреслюються критерії прийняття рішень для вибору наноструктурованих матеріалів за польових досліджень (температурний режим, геометрія, доступність, контроль вологи та вартість життєвого циклу). Особлива увага приділяється поточному контексту України - застарілим мережам, обмеженим можливостям технічного обслуговування та підвищеним потреб у стійкості - де зменшення витрат розподілу може призвести як до економії, так і до покращення безперервності обслуговування. Стаття ґрунтується як синтез на основі доказів для інженерів і власників активів і визначає пріоритетні напрямки для верифікаційного тестування та узгодження стандартів.

Ключові слова: наноструктуровані теплоізоляційні матеріали; енергоефективність; трубопроводи; тепловтрати; аергель; ізоляційне покриття.