Reduce building energy loss with liquid thermal insulation containing nanoporous silica aerogels

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Excessive consumption of energy and the production of various pollutants in the last century has caused global warming. Also, due to the increase in fossil fuel prices in recent decades and non-renewable sources, the country's annual energy consumption has become a fundamental challenge for developing countries. In Iran, energy consumption in various sectors is several times higher than global consumption, and the -building sector has the highest energy consumption. In the building sector, despite the emphasis on insulation, traditional insulation is rarely used due to its problems. A new generation of water-based paints containing silica aerogels is thermal insulators that can be used in various parts of the buildings. These insulation paints with their unique properties are a good option for insulating buildings and preventing excessive energy loss. This research investigates the effect of these paints on energy loss at different thicknesses and environmental conditions. © 2022 Journal of Energy Management and Technology

keywords: *Building, energy loss, liquid insulation, silica aerogel, simulation.*

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1. INTRODUCTION

Usually, energy consumption in advanced and developed societies is higher due to high per capita income and the possibility of having more diverse and energy-intensive devices and equipment. But in recent decades, per capita consumption has moderated due to measures that have led to increased productivity in these countries. According to international statistics, in 2016, the total per capita consumption (both energy and non-energy) in Iran was 2.35 tons equivalent to crude oil, which is 1.8 times the global level. Also, Iran's per capita final energy consumption in agriculture, household, commercial and public sectors, transportation, and industry was 3.3, 2.2, 1.5, and 1.5 times the global average, respectively. A comparison of Iran's per capita final energy consumption by energy carriers on a global scale shows that the per capita final consumption of natural gas is 6.6 and crude oil and petroleum products are 1.4 times the global average per capita consumption. This is due to low productivity in exploitation, high energy consumption as well as the use of energy-intensive goods and services [1, 2]. Energy intensity is an indicator for determining energy efficiency at the national economy level of each country, which is calculated by dividing final energy consumption by GDP and shows how much energy is used to produce a certain amount of goods and services. Countries with higher living standards consume much more energy, and as a result, their energy intensity is affected. Optimization of buildings and equipment, combinations of fuels used in the transportation sector and even the distance between geographical locations, methods of transportation and technology used in cars and vehicles, public transportation capacity, and measures are taken to optimize energy consumption, natural disasters, and energy prices or subsidies are some of the factors influencing energy intensity. Iran is not in a favorable position in terms of energy consumption for the production of goods and services and is one of the countries with very high energy intensity. Accordingly, the intensity of final energy consumption in the country is not only much higher compared to oil-rich countries, but also higher than in some regions such as the Middle East. In 2016, the world's primary energy supply intensity index based on GDP in terms of exchange rate and purchasing power parity was 0.18- and 0.13-tons equivalent to crude oil per thousand dollars, respectively [1, 2]. However, this figure in Iran is more than 2.9 and 1.3 times the global average. Also, the global final energy consumption intensity index based on GDP in terms of exchange rate and purchasing power parity was 0.11- and 0.08-tons equivalent to crude oil per thousand dollars, respectively. However, is while this figure in Iran is more than 3.0 and 1.4 times the global average. The Energy Productivity Index, like labor and capital productivity, measures the output of goods and services compared to inputs.

By using this index, general goals and policies of energy demand and productivity, as well as the relationship between energy demand and economic growth can be analyzed. Improving the energy efficiency index can be done by reducing the energy inputs required to produce a certain amount of energy services or by increasing the quantity or quality of economic output activities. The energy efficiency index is obtained by dividing the value of products by the amount of energy consumed. To calculate energy efficiency at the national level, GDP can be divided by the final energy consumption. In the last decade, the energy efficiency index in the country has not undergone significant changes. This index is 2017 compared to the previous year with an increase of 2.9 percent, from 5644.5 to 5806.4 thousand IRR per barrel equivalent of crude oil has reached [1, 2]. The above set of statistics shows that a suitable solution to reduce energy consumption, especially in the buildings and industry sectors, has not been considered. One of the most important issues, which unfortunately is not seen in the country's energy balance, is the lack of special attention to the issue of insulation and the quality and standards of insulation used in the country. In the buildings and industry sectors, it is clear that contractors and builders are looking to use no insulation or to use the cheapest type of insulation, regardless of the efficiency and costs of energy consumption and production of pollutants. On the other hand, the low specifications and quality of some insulations, such as fiberglass and Mineral wool, have caused that despite the requirements in article 19 of the national building code of Iran, manufacturers do not use these insulators in practice. Due to the increase in energy prices in recent years, environmental issues, water shortage, water drought, increasing the level of general culture, education and public information, international requirements, etc., if there is a suitable and easy to install insulation, you can expect the usage of thermal insulation in various buildings. Table 1 shows the amount of electricity consumption by different sectors in terms of gigawatt-hours in years. On average, more than 50% of electricity consumption occurs in the building sector. Also, in Table 2, the total energy consumption in terms of million barrels of crude oil equivalent in different years shows that about 40% of energy consumption is in the buildings sector [1, 2]. In our country, buildings account for about 40% of total energy consumption. Unfortunately, however, the measures taken in recent years have not had the expected effectiveness in reducing the energy consumption of the building sector, and consumption growth is also experiencing a worrying upward trend. The continuation of this situation will lead to irreparable economic and environmental consequences for the country. In 1991, the first edition of Article 19 of the National Building Regulations was prepared under the title of energy-saving, most of which was the design criteria for thermal insulation of the outer shell of the building. Unfortunately, due to the lack of susceptibility in the civil engineering community, the terms and conditions in most construction projects were ignored [3]. Hopefully, by removing the ambiguities in the previous edition and providing the necessary additional information, the groundwork for launching this topic in construction, especially in government projects, will be provided more than before. The criteria considered in this edition are also far from the regulations in industrialized countries. Most of the energy consumed in buildings is expenditure on heating and cooling in the seasons. In addition, the need for high energy in certain seasons of the year causes a sudden increase in consumption and problems in supply. Based on all the cases studied, using proper thermal insulation in Iranian buildings is essential, and suitable insulation should be examined and used correctly. The cost of new liquid thermal and cryogenic insulation with silica aerogel additive will reimburse with a significant reduction in energy loss and its costs in a short period, and with their long life, they cause comfort, welfare, reduce production of pollutants and increase the safety of the building. In this research, thermal and cryogenic insulators based on water-based paints containing nanoporous silica aerogel powder, which can apply by spray, pen, and roller, are introduced and their properties will investigate. Also, the efficiency of these liquid thermal insulators is studied and analyzed by simulating their performance in the building under different conditions [4–9].

2. THERMAL AND CRYOGENIC INSULATION BASED ON WATER-BASED PAINT CONTAINING NANOPOROUS SILICA AEROGEL

Nanoporous silica aerogels are the lightest commercialized solid material with more than 96% porosity in dimensions of 2 to 50 nanometers with an average specific surface area of 500-800 m^2/g and are open pores and have the lowest thermal conductivity (0.012 W / m.K) among the insulations in the world [10-14]. The low density and silica material make the conductivity much lower than conventional insulation. Nanometer pores cause heat transfer change to the Knudsen diffusion mechanism, which is about several times weaker than the heat transfer in larger pores [15]. In nanometer pores, heated air molecules are forced to crawl on the walls to transfer heat, which slows the heat transfer. Various additives, such as titanium dioxide particles, can also drastically reduce radiant heat transfer. Due to the high porosity of silica aerogels, these materials can be easily crushed and pulverized in different sizes and are added to water-based paints as additives in different amounts. One of the main characteristics of nanoporous silica aerogels is their hydrophobicity with a contact angle of more than 140 degrees [16]. Hydrophobic powder of aerogel inside water-based paints does not allow the polar materials of water-based paints to penetrate the nanometer pores, and by adding the powder to the liquid insulation coating, lots of air which trapped inside the nanometer pores enters the paint. The presence of air inside the nanometer pores of the aerogels inside the paint and the uniform distribution of the powder inside it cause the extraordinary property of hot and cold insulation in thicknesses of 0.5 to 4 mm. Thermal insulation paints are now noteworthy in the world and many companies have introduced new thermal insulation products to the market by supplying silica aerogel from manufacturers and adding it to their paints. Jios Rova, Aeropaint, Aerohot, Aerolon, Quartzene, Aeropan, Aeromirum, Hip, Barozzi, Vernici, Aerulate, etc. are among the manufacturers of thermal insulation paints containing aerogels [10, 12, 17, 18]. In Iran, thermal paints with the name of IRopaint have been produced and supplied by Danesh Bonyan Pakan Atieh Nanodanesh Company. Table 3 presents the different benefits of aerogel paint hot and cold insulation. Figure 1 also shows the various applications of this insulation. Unlike traditional insulation, aerogel insulation paints have several advantages that make it easy for builders and engineers to heat-insulate parts with high efficiency and low cost.

3. MECHANISM OF PERFORMANCE AND EFFICIENCY OF LIQUID THERMAL INSULATION BASED ON NANOPOROUS SILICA AEROGELS

Liquid paint thermal insulations with aerogel additive, in a wet state, contain about 50% of aerogel, which reaches about 70% by volume as the paint is dried. Nanoporous silica aerogels have a very low density of about 0.1 g/cm^3, which means there is no mass for conductive heat transfer. Silica is also not a good

Table 1. Power consumption by different sectors (GWh) [2].

Year	buildings	public	Commercial	Industrial	Transportation	Agriculture	Other uses	total	% Of total household, public and commercial
2005	44108	16350	8541	43014	108	16469	4305	132897	51.91
2008	52896	20428	10741	51863	245	21178	4090	161445	52.07
2011	56773	16751	12663	63590	353	30020	3752	183905	46.86
2014	71162	19767	15404	73932	363	35188	3837	219653	48.4
2017	83403	24328	18681	84177	477	38952	5009	255026	49.56

Table 2. Energy consumption by different sectors (million barrels equivalent to crude oil) [2].

Year	buildings, public, and commercial	Industrial	Transportation	Agriculture	Non-energy consumption	Total	% Of total household, public and commercial
2005	372	181	253	34	63	903	41.196
2008	417	253	282	42	120	1114	37.4327
2011	430	288	288	46	136	1188	36.1999
2014	444	323	316	50	144	1277	34.7666
2017	464	339	331	59	168	1361	34.0831

Table 3. Advantages of paint containing nanoporous silica aerogel in comparison with traditional insulations such as Rockwool.

1	Do not occupy the space of the building	16	Flexible colors with elastic properties
2	No growth of algae or fungi on the paint and surface	17	Low heat transfer coefficient and very low heat penetration coefficient (∼0.03 - 0.05 w / m.K)
3	Reduce the great amount of energy loss of buildings depending on the thickness used	18	Very fast and convenient execution with air spray guns, pistols, pens, and rollers
4	Ability to run on all internal and external surfaces of buildings and facilities (exterior and built-in)	19	High adhesion to metal surfaces, plaster, cement, wood, polymers, etc.
5	Lack of any of the prevalent insulation problems such as shedding, water absorption, and sagging	20	Operational temperature of negative 30 to positive 150 degrees Celsius
6	Excellent simultaneous sound insulation	21	Applicable in thicknesses of 0.5 to 4 mm
7	Prevent burns from contact with hot surfaces in very thin thicknesses	22	Waterproof and prevent corrosion below the insulation surface on metal faces
8	Ability to prepare in any desired color	23	Very long-lifetime
9	Very reasonable price and return on investment in a short time	24	Water-based and biocompatible, no allergies and no particulate matter production
10	No need for a professional installer and high drying speed	25	Ability to run on any geometry and shape through easy spraying and repair
11	Independent of any holding or sealing equipment, etc.	26	Significant reduction of radiant, conduction, and convection heat transfer
12	The ability to breathe and not have the problem of moisture accumulation below the surface	27	Ability to run in old and new buildings without restrictions
13	No need for primer of top coat in many applications	28	Prevent moisture from condensing in humid environments on cold surfaces
14	Resistance to fire and spread of fire	29	Odorless and anti-UV.

conductor of heat. Nanometer pores also allow heat to penetrate through the displacement of air molecules inside the pores using the Knudsen diffusion mechanism or the creep of the molecules on the nanometer walls, which is about 100 times weaker than usual penetration into the larger pores of traditional insulation. The white liquid insulation Coating causes about 95% of the radiant heat transfer to be reflected on the insulating surface and not absorbed by it. The low speed of heat penetration in the aerogels, causes heat to be transferred at a lower speed under the same conditions [19, 20]. (Figure 2).

The sum of these factors makes the thermal insulation of the liquid containing the aerogel additive very effective at low thicknesses with thermal conductivity of about 0.03 to 0.05 W/m.K [21]. The mentioned factors also cause the thermal insulation coating to be soundproof and resistant to ignition and flame spread. Figure 3 shows the rate of temperature drop of 100°C at

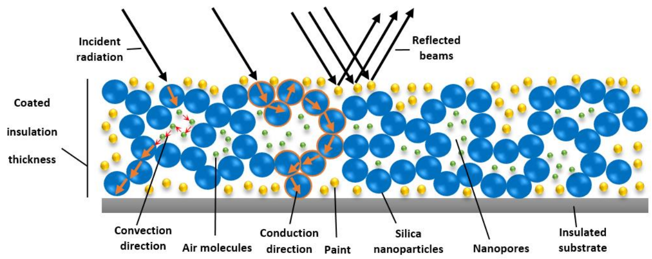

Fig. 1. Schematic of heat transfer of paint containing aerogels.

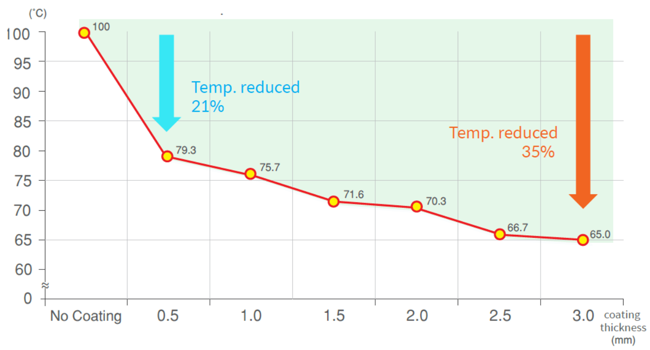

Fig. 2. Surface temperature decreases in different thicknesses of paint containing aerogel (hot side temperature 100°C) [25].

the coating surface at different thicknesses. It should be noted that heat transfer is related to the environment temperature and energy savings will be greater than the percentage of temperature reduction. In different sources, the amount of temperature difference due to the use of heat-insulating paint containing aerogel in different conditions has been reported in the articles and datasheets of the offered products. The results of the experimental data are highly consistent with the products offered in this field. Of course, it should be noted that research in this area is ongoing and little data can be found in scientific sources [17, 22–24]. A typical reduction in the temperature of heat-insulating paints containing aerogels is shown in figure 3 [25].

4. FABRICATION OF LIQUID PAINT INSULATION COATING WITH SILICA AEROGELS AS AN ADDITIVE

Nanoporous aerogels can be added to a variety of water-based paints. The liquid insulation coating holds the aerogel and sticks it on different surfaces [26]. Water-based acrylic paints, latex, silicone, stain, glossy, semi-gloss, matte, etc. can be used for this purpose. Obviously, the better the quality of the base liquid insulation coating, the higher the quality of the final product. Silica aerogel granules can be powdered with a variety of mechanical agitators or mills into various sizes. Aerogel additive in paints is usually used in three sizes: fine (particle size about 20 micrometers), medium (particle size of aerogel about a few tenths of a millimeter), and large (particle size of aerogel close to millimeters). The finer the particle size, the better the final liquid insulation coating appearance in terms of smoothness.
Coarse particles are commonly used in industry, but medium and smaller particle sizes are used in buildings due to their apparent importance. Due to the brittleness of silica aerogels, it is possible to crush them quickly by controlling the speed of the blade or mill in any size. Superhydrophobic silica aerogels are used in water-based paint substrates so that the materials in the paint cannot enter the aerogel pores and destroy their thermal efficiency. The main point in preparing this type of insulation is that it should be possible to put hydrophobic aerogel powder into the water-based substrate. Normally, by adding aerogel in water-based paints, it is observed that the aerogel is located on the surface of the paint and does not show any tendency to mix and disperse inside the liquid insulation Coating. There are several methods for this purpose, one of which is the use of various surfactants. Surfactants with a polar head and a non-polar head act as a bridge between non-polar aerogel and water-based polar molecules and allow the addition of aerogel to the paint. Surfactants can be added in different amounts depending on the type and quality of the paint. Different percentages of aerogels can be added to the liquid insulation coating, depending on the type of paint, there is an optimal amount for it. Low addition will not cause proper thermal efficiency and high addition will prevent adhesion and sufficient strength of the paint. On average, in water-based paints, about 50% of the fresh paint volume and about 70% of the dried paint could be aerogel [22, 27].

5. BUILDING ENERGY LOSS SIMULATION

In research and case studies about the building, the amount of reduction of energy or electricity consumption has been measured experimentally using paints containing aerogels in different proportions and with different thicknesses from about 10% to 30% [23, 28–30]. Of course, it should be noted that there were different environmental conditions in these -studies. All studies have concluded that paints containing silica aerogel are very effective in reducing energy loss and are also economically viable [30]. Economic research in Iran based on different conditions requires separate and complete research. Studies show that thermal insulation paints containing aerogels have been marketed economically by several companies in Iran such as Pakan atiye nanodanesh co., Nanotechfam co., Pavan protective coating group, etc.
A model with real dimensions has been used to simulate the function of insulation paint. For this purpose, a unit with $10m \times 10m$ dimensions with a height of 3.5 m has been designed and assembled. According to the construction regulations, the thickness of each wall is about 0.3 meters. The components of the building are made of ordinary concrete, which has a rough surface, by its nature, has a low radiation reflection coefficient. Vaghefi et. al. [26] show that Iran is experiencing unprecedented climate-related problems such as drying of lakes and rivers, dust storms, record-breaking temperatures, droughts, and floods. Results (Figure 4) show that compared to the period of 1980–2004 (B), from 2025 through 2049 (C), Iran is likely to experience more extended periods of extreme maximum temperatures with an average of $40°C$ in the southern part of the country, more extended periods of dry (for ≥ 120 days) conditions, and higher frequency of floods (Figure 4).
Insulation paint has been tested in the worst-case scenario to show the capability of the aerogel-based paint in reducing energy consumption. The ambient temperature is set to 40°C [26], and the sun is placed perpendicular to the roof of the house, also to bring the simulation model closer to reality besides sunlight to the ceiling of the house, the radiant heat transfer of the warm environment to the house also considered. Solar radiation data have been determined following the climate of the Iranian plateau. In the simulated model, four split air conditioners are used. The primary purpose of the simulation is to calculate the

Fig. 3. Applications of thermal insulation paints containing nanoporous aerogels.

energy expended to keep the indoor environment at a constant temperature (Figure 5). The temperature inside the building is set to be 22°C at a pressure of 1 atm.
Most of the heat received is due to the radiant heat received from the roof of the house. Convective heat transfer term is also active inside the house and the vertical walls of the house and therefore causes a temperature difference on all five sides of the house. Insulation paint in three thicknesses of 0.5, 1, and 2 mm are simulated and bare walls are used as a reference.
Also, in three wind conditions with speeds of 0, 5, and 15 meters per second as a crosswind to simulate the effect of forced conduction heat transfer has been simulated and studied. To further investigate the impact of liquid insulation Coating on the reflection of the sun's radiation, two simulations of completely black paint have been performed, in which the dark liquid insulation Coating absorbs most of the radiation and only by reducing the heat transfer between the air and the house wall. It will reduce energy.

6. RESULTS AND DISCUSSION

Different paint thicknesses and forced wind flow conditions have been used to evaluate the aerogel paint effect on the energy consumption of the building. Increasing the thickness of the paint increases the cost of insulation, but at the same time reduces the amount of energy loss. The results for the white paint and windless states are shown in Figure 6. It is visible in a thickness of 0.5 mm, compared to the reference state, about 21.3% less energy is needed to keep the temperature inside the house. By increasing the thickness of the paint to 1 and 2 mm, the reduction in energy consumption is 26 and 30.3 %, respectively, compared to the uninsulated state. By applying airflow at a speed of 5 m/s, the amount of energy loss reduction was 35.8, 41.8, and 44.54 % for a thickness of 0.5, 1, and 2 mm compared to the reference state. It is visible that with increasing wind speed, the effect of insulation in reducing energy loss becomes more noticeable. The results show that by creating wind from 0 to 5 m/s the energy loss grows from 5.8 MJ to about 10 MJ in 12 h in the uninsulated state of the building. In other words, with the wind, the heat transfer mode changes from free to forced displacement, which has a higher heat transfer coefficient (Figure 7). On the other hand, with increasing wind speed to 15 m/s, the convective heat transfer coefficient has increased and, the amount of heat transfer has grown throughout the wall (Figure 8). Due to the insulation resistance to convective heat transfer, there is a more reduction in energy loss compared to the wind speed of 5 m/s. To further investigate the properties of the paint, a completely black color paint with a low radiation reflection

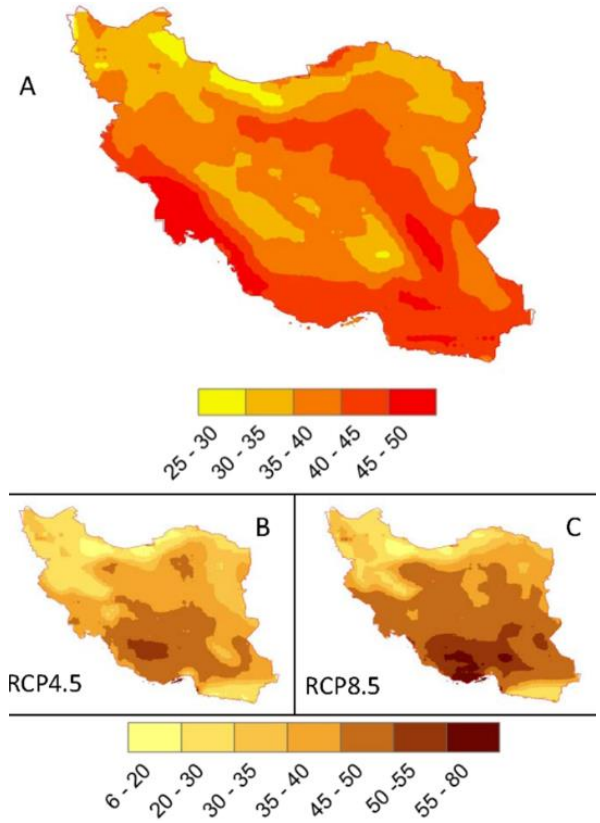

Fig. 4. A shows the extremely hot days for the historical and future periods. B shows the number of days per year (1980–2004). C shows the number of days per year in the future (2025–2049). Most regions in Iran may experience longer extreme hot days of up to 2 months per year [26].

coefficient was simulated to investigate the properties of reducing the free convection heat transfer and forced convection at a wind flow rate of 5 m/s. As can be seen from the simulation results, in the liquid insulation Coating with a thickness of 0.5, 1, and 2 mm, the amount of energy loss was reduced to 2.54, 4.61, and 7.58% (Figure 9). In wind conditions without reflection of sunlight (black color), this property of reducing the convective heat transfer of the liquid insulation Coating is much more visible than before. It is visible in the diagram that by changing the liquid insulation Coating thickness from 0.5, 1, and 2, the amount of energy consumption decreases by 4.11, 8.18, and 13.42%, respectively (Figure 10). The black color, with an emissivity of 1, simulation results without reflecting the sun's energy show that there is still a noticeable reduction in energy dissipation due to the prevention of conductive and convective heat transfer within the paint by the aerogel powder. In the other words, the results show that in paints containing aerogels, the mechanism of reducing energy loss is not only the reflection of sunlight (as in paints containing glass microbubbles only).

7. CONCLUSION

Excessive energy consumption in the country's buildings and the lack of suitable traditional insulation have made it necessary to introduce proper insulation. Increasing energy costs and problems caused by excessive energy consumption such as air pollution, global warming, and water scarcity make it necessary of using hot and cold insulation. Water-based thermal insulation paints containing nanoporous silica aerogel additives are among the best options developed based on nanotechnology and have received much attention in the world. These insulators are liquid and can be easily used with a pen or spray on all interior or exterior surfaces of new or old buildings. A thickness of 0.5 mm of this insulation can reduce energy consumption in the building by 21 to 45 % under different conditions. Insulation liquid paint with aerogel additive shows better performance at ambient high-speed winds. Also using bright color paints, the paint performance was increased by reflecting the radiant heat from the sun. Liquid insulation shows a good effect at just 0.5 mm thickness which is economically applicable in Iran buildings.

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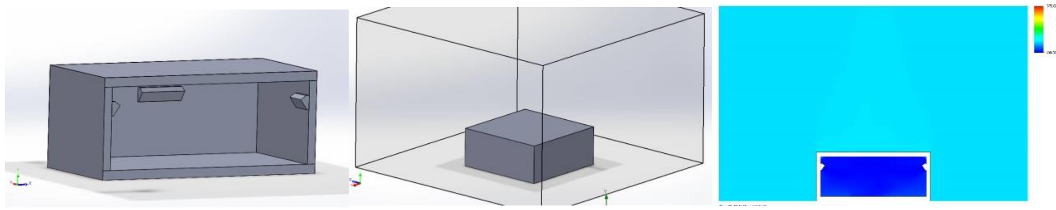

Fig. 5. Simulation of Liquid Thermal Insulation performance on the sample of the studied building in the environment.

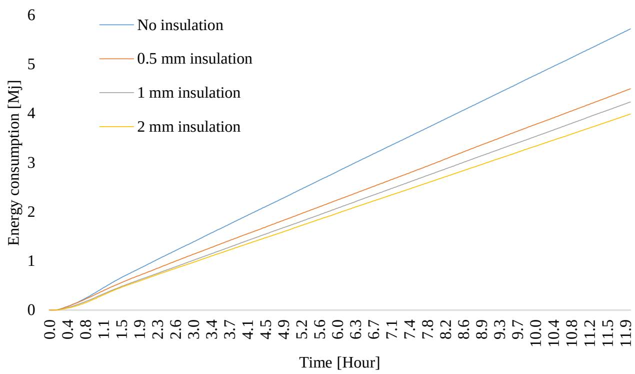

Fig. 6. Cumulative energy consumption in different thicknesses of liquid insulation without ambient wind.

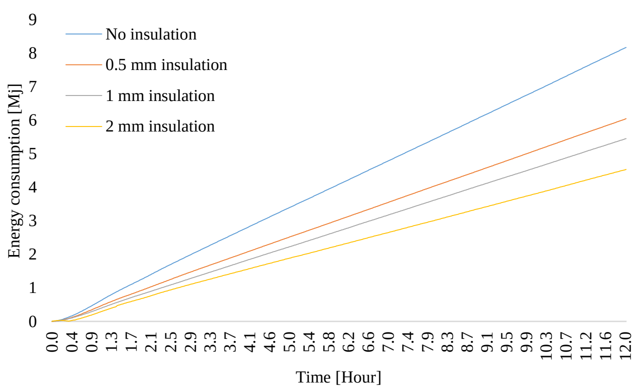

Fig. 7. Cumulative energy consumption in different thicknesses of liquid insulation, wind speed of 5 m/s.

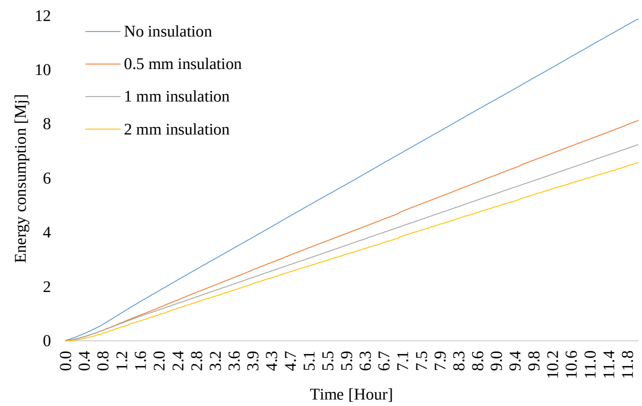

Fig. 8. Cumulative energy consumption in different thicknesses of liquid insulation with a wind speed of 15 m/s.

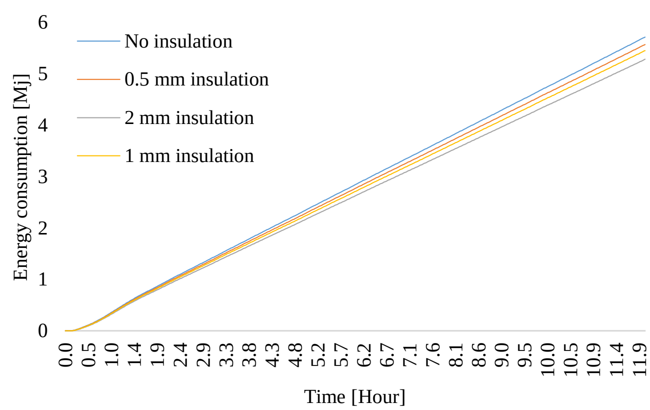

Fig. 9. Cumulative energy consumption in different thicknesses of liquid black color insulation in windless conditions.

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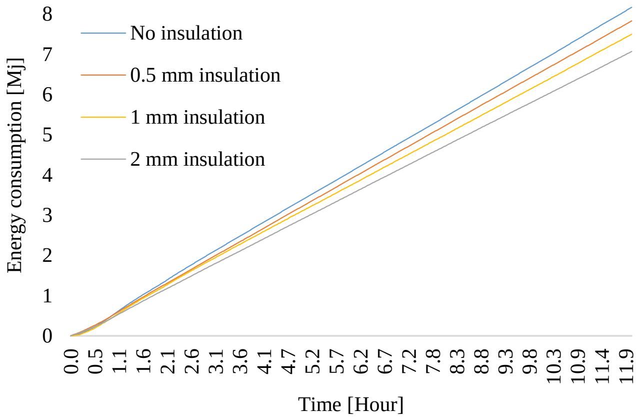

Fig. 10. Cumulative energy consumption in different thicknesses of liquid black color insulation with 5 m /s wind.

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