UDC 614.842
DOI: 10.15587/1729-4061.2026.352433

ESTABLISHING PATTERNS IN THE FORMATION OF A FIRE-RESISTANT SIP PANEL WITH HEMP INSULATION

Yuriy Tsapko
Corresponding author
Doctor of Technical Sciences, Professor
Department of Environmental Protection Technologies and Labour Safety**
E-mail: juriyts@ukr.net
ORCID: https://orcid.org/0000-0003-0625-0783

Aleksii Tsapko
PhD, Senior Researcher*
ORCID: https://orcid.org/0000-0003-2298-068X

Oksana Berdnyk
PhD, Associate Professor
Department of Technology of Building Structures and Products**
ORCID: https://orcid.org/0000-0001-5321-3518

Ruslan Likhnyovskyi
PhD, Senior Researcher
Research and Testing Center***
ORCID: https://orcid.org/0000-0002-9187-9780

Kseniia Bielikova
Doctor of Public Administration Sciences, Professor
Research and Testing Center***
ORCID: https://orcid.org/0000-0001-7475-2115

Oksana Slutska
PhD, Senior Researcher
Scientific Research Center of Civil Protection***
ORCID: https://orcid.org/0000-0003-1723-8181

Anna Borysova
PhD, Senior Researcher
Scientific Research Center of Civil Protection***
ORCID: https://orcid.org/0000-0002-8700-0761

Vasyl Lomaha
PhD, Assistant
Department of Technology and Design of Wood Products
National University of Life and Environmental Sciences of Ukraine
Heroiv Oborony str., 15, Kyiv, Ukraine, 03041
ORCID: https://orcid.org/0000-0002-0569-9987

Olha Uzhehova
PhD, Associate Professor
Department of Building and Civil Engineering
Lutsk National Technical University
Lvivska str., 75, Lutsk, Ukraine, 43018
ORCID: https://orcid.org/0000-0002-2352-2907

Vitalii Chaikovskiy
PhD Student*
ORCID: https://orcid.org/0009-0008-5493-5633

*Department of Building Materials**
**Kyiv National University of Construction and Architecture
Povitrianykh Syl ave., 31, Kyiv, Ukraine, 03037
***Institute of Scientific Research on Civil Protection of the National University of Civil Protection of Ukraine
Tsentralna str., 60, Dmytrivka vil., Ukraine, 08112

This study investigates the process that forms fire-resistant properties of SIP-panels with hemp insulation based on reactive coating and lime. The task addressed is to ensure the stability of SIP-panels and components when treated with coatings to changes in operating conditions. This is important since production from renewable sources for construction is a relevant issue.

It has been proven that during thermal action on samples of hemp insulation treated with reactive coating and lime, no ignition and flame spread along the surface occurred. A layer of foam coke formed on the surface of the sample treated with reactive coating, which is 22 mm.

The study has shown that when a burner is applied to a sample of SIP-panels with hemp insulation treated with reactive coating, after 110 s of thermal exposure, the process of forming a heat-insulating layer of coke began, which inhibited heat transfer. Instead, after the burner was exposed to a sample of SIP panels with hemp insulation treated with lime, a charring process occurred at the site of thermal action, but ignition and flame spread did not occur.

Based on the results of determining the strength, it was found that treating the surface of hemp insulation with a coating increases the tensile strength by more than 2.5 times. Thus, increasing the amount of reactive coating on the surface of hemp insulation by half increases the tensile strength by 2.3 times. In the case of treating hemp insulation with lime, the tensile strength decreases by 3.4 times while increasing the amount of lime when treating the surface of hemp insulation to 0.38 kg/m^2 increases the tensile strength by 5.3 times.

Thus, there is reason to argue about the possibility to design effective and operationally stable biocomposites for construction

Keywords: hemp insulation, reactive coating, lime, SIP panels, fire resistance, coke layer

Received 18.12.2025
Received in revised form 02.02.2026
Accepted date 16.02.2026
Published date

How to Cite: *Tsapko, Y., Tsapko, A., Berdnyk, O., Likhnyovskyi, R., Bielikova, K., Slutskaya, O., Borysova, A., Lomaha, V., Uzhehova, O., Chaikovskiy, V. (2026). Establishing patterns in the formation of a fire-resistant sip panel with hemp insulation. Eastern-European Journal of Enterprise Technologies, 1 (10 (139)), 39–48. https://doi.org/10.15587/1729-4061.2026.352433*

1. Introduction

The use of SIP panels in construction continues to grow every year as they are characterized by significant strength and durability, reduce labor costs, construction time, and losses at the construction site. SIP panels are a three-layer structure. Between two layers of OSB (oriented strand board), which can withstand significant loads, a layer of insulation is glued under pressure, which is polystyrene foam, polyurethane foam, or polypropylene. However, this structure is characterized by environmental problems associated with the significant use of polymers and their composites, in particular, the exploitation of non-renewable oil resources, which are characterized by emissions of significant amounts of greenhouse gases into the environment and poor biodegradability.

All this led to a change in the concept towards the use of environmentally friendly and sustainable materials that are biodegradable; the industry began to explore biocomposite materials based on natural renewable resources. The use of natural fibers for reinforcement in composites has become an area of considerable interest in recent years from the point of view of fundamental and applied research, as they offer unprecedented advantages over inorganic fibers. Among them, cellulosic fibers derived from various plants, such as wood, plant fibers, and straw, in particular, wood chips, hemp, and flax fibers, can be distinguished. They are effectively used as reinforcing materials in thermoplastic and thermosetting matrices for insulation of buildings and structures and can replace polymeric materials in SIP panels.

However, the above components of SIP panels are characterized by significant flammability because the results of ignition quickly spread throughout the entire area of the building, causing significant thermal damage. One of the methods for protecting building structures made from SIP panels is their fire-retardant treatment with both inorganic materials (plasters) and special fire-retardant coatings. However, the use of products during fluctuations in temperature and humidity fields must ensure sufficient adhesion strength to the building structure and not reduce fire protection efficiency. That requires fundamental research into the impact of high temperature on the fire resistance of SIP panels to destruction.

Therefore, it is a relevant task to carry out studies aimed at defining fire-resistant SIP panels and identifying the effect of amount and nature of the coating on the occurrence of combustion process.

2. Literature review and problem statement

Study [1] states that the vacuum insulation panel (VIP) is an inorganic composite insulation panel with a thermal conductivity of almost 0.004 W/(m·K) and a fire resistance class A (non-combustible), which provides both heat preservation and fire protection. However, the application of VIP in the construction industry still has many problems that need to be studied experimentally. For the research, wall insulation systems with three different insulation materials were used, including glued VIP boards, dry-hung composite VIP boards, and extruded polystyrene (XPS) insulation boards. They were also studied under different conditions, such as winter, summer, dry, and wet, and the insulation efficiency was evaluated under adverse conditions, such as punctures. The conclusions are as follows: the average value of the heat flux on the inner and outer surfaces of the structure should be taken into account when calculating the thermal resistance of the enclosing structure. The error of testing the operating conditions under temperature changes in summer is greater than the operating conditions under constant temperature in winter. The thermal resistance of a dry-laid VIP wall is greater than that of a glued VIP wall, since the static air gap behind the dry-laid VIP wall significantly enhances the insulation effect. The measured thermal resistance with 50 mm glued XPS is 32% lower than that of a wall with 12 mm glued VIP. After a VIP is punctured, its thermal resistance will decrease significantly. However, it is not stated how the degree of decrease in thermal resistance would be affected by a humid environment.

In [2], hemp straw, a by-product of hemp fiber production, was used as a filler to prepare new compostable composites in two different concentrations (22% and 32% w/w, respectively). Hemp straw waste was chosen because of its large quantity and the absence of high-value derivative products. Three different polymers were used, namely poly[(tetramethylene adipate)-co-(tetramethylene terephthalate)] (PBAT) and poly(tetramethylene succinate) (PBS) as composted polymers, and a polyethylene elastomer for comparison. The resulting products were then characterized for their structure and morphology by X-ray diffraction (XRD) and field emission scanning electron microscopy (FESEM), as well as for their wettability, thermal and mechanical properties. The structural and morphological characterization revealed different interactions occurring between hemp and polymer matrices, indicating a major influence of the type of polymer used compared to the percentages of biomass loading. Mechanical tests showed that the properties of the PBAT and PBS blends were comparable to those of the pure polymers. In the case of PBAT, the flexural modulus of the pure polymer was 82.2 MPa, and with hemp, it was about 50 MPa, for the polymers and PBS mixture it was 220 MPa, with no statistical difference between the samples. These biomaterials also have similar thermal properties to the pure polymers, however, no optimal solutions for use have been identified.

In study [3], the ability of natural hemp fibers (HF) to act as fillers in biodegradable biocomposites was evaluated by mixing different concentrations of HF with commercially available biodegradable polyesters. Blends of poly(hydroxybutyrate) (PHBV) and poly(butylene adipate-co-terephthalate) (PBAT) were used as polymer matrix. The HF was washed and ground before use. It consisted of lignin (22%) and carbohydrates (62–67%), but a significant amount of proteins (8.77%) was also found. Polymer-HF composites were prepared by melt-forming under mild conditions and formed into films by compression molding to obtain test specimens used for characterization of the biocomposites. The incorporation of HF improved the mechanical properties compared to polyester blends. To reduce the sensitivity of the composites to water, food-grade beeswax or carnauba wax was incorporated into the HF-filled polymer matrix. The resulting biocomposites showed similar mechanical properties to their wax-free counterparts, but no significant change in hydrophobicity was observed.

The construction sector, as noted in [4], is one of the leading industries in terms of energy consumption, greenhouse gas emissions, waste generation, and pollution. Hemp composites have many advantages as a building material, but they are not load-bearing and must be used in combination with a load-bearing wooden frame. Despite this disadvantage, hemp composites offer several relevant properties, namely low density, good thermal insulation, antiseptic properties, and breathability. The paper investigates the possibility of preparing lightweight composites based on hemp chips (treated and/or untreated) as a filler and an alternative MgO cement as a binder. The properties of hemp composites are characterized by mechanical and physical methods, but their flammability is not defined.

In [5], a very important type of natural fiber, namely hemp fiber, is considered. To expand the use of hemp fibers at the engineering level, research should focus on improving the mechanical, thermal, and high-tech characteristics of these fibers. In particular, the modification or surface treatment of hemp fibers is considered. Modified fibers have proven valuable for the development of certain derived materials, such as polymer composites and nanocomposites, in particular. Consequently, the incorporation of hemp fibers as additives in composite or nanocomposite matrices has been investigated for the production of highly efficient environmentally friendly, recyclable, biodegradable and sustainable materials. The application areas identified for hemp and related composites or nanocomposites include synchrotron and neutron scattering, water purification for the removal of dyes, automobiles, textiles, and construction. However, the literature on these technologically important fibers and the materials derived from them is insufficient. Comprehensive future efforts may better address the issues of reproducibility and long life cycle of high-tech hemp fiber applications.

As reported in [6], pyrolysis biocarbon was produced at 450, 550, and 650°C. Composite samples were prepared with 10 wt. %, 15%, and 20 wt. % biocarbon fillers ranging in size from 50 microns to 100 microns. Under optimized conditions, the water absorption values of hemp biocarbon and millet biocarbon were 70% lower than those of unfilled hemp fiber-reinforced composites. Water absorption improved the tensile strength and hindered the flexural strength. The energy at break increased with increasing particle size; conversely, it decreased with increasing filler content. The maximum tensile strength of 840.75 MPa and 817.02 MPa was achieved for 10 wt. % biocarbon with a particle size of 50 microns obtained at 650°C from millet and hemp stalks, respectively. The pyrolysis temperature, particle size, and filler positively affected the flexural strength of the composite samples. The impact strength of the composite samples decreased by almost 63% when the amount of filler was doubled. The hardness of the composites increases significantly with increasing filler amount. Thermal conductivity increased with increasing filler amount and particle size – biocomposite samples with 20 wt. % filler and 100 μm biocarbon particle size obtained at 650°C showed the maximum flame time and thermal conductivity of the composites filled with biocarbon. Hemp composites with a density of 1300 kg/m^3 and a tensile strength of 800 MPa overlap with the properties of some ceramic materials (Si_3N_4) and some metal alloys (magnesium alloys, aluminum alloys and silicon carbide) on the property diagram. Hemp composites have better tensile strength than polymers and elastomers (PEEK, PC, PA, PMMA, silicone elastomers PET), concrete, wood, as well as rigid and flexible polymer foam and cork. Based on the strength-viscosity material property diagram, the composite samples are in the region of metals and alloys with better stiffness and strength characteristics than ceramics, glass, wood products, polymers, and rubber. These results indicate the potential use of hemp composites for mechanical loads and thermal insulation. However, it is not stated how the composites are operated.

Study [7] proposes a life cycle analysis (LCA) for the environmental study of the supply chain of a hemp-based biocomposite, including agricultural activities, pre-processing, transportation and bioconversion. In addition, the LCA comparison with petroleum-based composites is carried out using the SimaPro software. The results show that the emission profile associated with the production of biocomposites is closely linked to the agricultural sector. This is primarily due to factors such as diesel fuel consumption in agricultural machinery and nutrient runoff into water bodies as a result of the use of nitrogen fertilizers. In this regard, the study considers eight agricultural practice cases, focusing on the use of organic fertilizers and natural gas fuel in agricultural machinery. The implementation of these approaches leads to a reduction of 80%, 70%, 60%, and 50% in the impact categories for non-carcinogenic, carcinogenic, ecotoxic, and eutrophication properties, respectively. Using analysis of variance (ANOVA), it was found that the choice of energy sources for agricultural machinery and the type of fertilizer used in hemp cultivation significantly affect most environmental impact categories, except for carcinogenic effects, which are not affected by the type of fertilizer. However, its effect on improving the overall environmental profile was not noted.

In [8], new biocomposites made of bioresin based on acrylated epoxidized hemp oil, reinforced with a random mat of hemp fibers, were manufactured by vacuum infusion. Mechanical properties (tensile, flexural, impact, and interlayer shear), dynamic mechanical properties (glass transition temperature, storage modulus, and crosslinking density) and water absorption properties were investigated. At the same time, they were compared with samples manufactured under the same conditions, but using a commercial synthetic vinyl ether resin as a polymer matrix. The results showed that the mechanical properties of the 100% biocomposites were comparable to hybrid composites made using synthetic resin. Moisture absorption tests showed that the samples based on acrylated epoxidized hemp oil exhibited both higher diffusion coefficient and saturation moisture content; however, fiber reinforcement was the dominant transport mechanism. The samples based on vinyl ether were found to have higher storage modulus, glass transition temperature, and crosslink density, but this was not the case for the samples based on acrylated epoxidized hemp oil.

Study [9] described novel hemp-based composite materials intended as components of a multilayer dowel for concrete, steel, or wood structures, providing both thermal insulation and physical and mechanical resistance. The composite panels were manufactured by bonding hemp chips with a novel hybrid organic-inorganic binder. The panels were characterized in terms of physical and microstructural properties, bulk density, water absorption, thickness swelling after immersion in water, microstructural features using a scanning electron microscope, and a stereo optic microscope, ss well as thermal properties (thermal conductivity, reaction to fire) and mechanical properties (compressive strength, flexural strength, tensile strength, resistance to axial screw pullout). The panels demonstrated promising physical, thermal, and mechanical characteristics, generally comparable to those of commercially available products. In addition, the new composites have the advantage of significantly low environmental impact (due to the dispersed and binding phase) and the absence of negative effects on human health, which are responsible for formaldehyde emissions. Considering all this, the new composites seem to be very promising materials for use in the construction industry, but tests to assess the strength of the panels have not been performed.

The authors of [10] noted that polymer composite sandwich panels are of increasing interest and are being used for lightweight structures in the transportation and construction industries. However, there can be conflicts in design requirements regarding flammability performance, which requires creative design to meet the test requirements and produce a useful panel. In the paper, composite materials were fabricated from phenolic and fiberglass face and balsa wood sandwich panels. The specimens were tested for fire resistance using a cone calorimeter (ASTM E1354) at various heat fluxes, and then a full-scale room corner test (ISO 9705) was conducted on these panels. The results showed that those composites could pass the room corner test only if an aluminum skin was used to provide additional fire protection to the base composite. The mechanical attachment of the aluminum skin to the panel, as well as the underlying composite structure, have played an important role in full-scale fire resistance tests, but the importance of material selection and component design for fire performance has not been established.

The results of research reported in [11] propose an intermediate free-standing box test method that could evaluate the fire performance of sandwich panel systems. ISO 13784-1 (free-standing room corner test) and three types of free-standing box tests were conducted. It was found that there is some correlation between IS013784-1 and the free-standing box test in terms of achieving flashover. However, no key role was noted in their resistance under severe fire exposure.

In [12], a self-supporting facade system made of sandwich panels under fire was investigated. First, a thermomechanical FE model, which includes the complete facade system and includes material degradation and geometric nonlinear behavior, except for the insulation material and joints, is loaded with a fire temperature curve. The Eurocode design rules assume that the screw connections of the sandwich panels will fail in shear. Second, an existing program, FDS-2-Abaqus, is extended to allow for two-way coupled analysis, in which the CFD fire simulation is updated for changes in the thermomechanical FE model, for application to the facade system. Again, these simulations show the failure of the screws in shear. Parameter studies show differences in system behavior for improved screw properties; fuel-driven versus ventilation-driven fires; and different panel thicknesses. Interestingly, since thermal flexing of the panel slows down the failure of the screws, and thicker sandwich panels flex less than thinner panels, thicker facade panels will reduce the time to failure. Thus, the predicted failure of two tiny but critical screws within 80 s, compared to the 150-minute service life of the sandwich panels during standard fire tests. This highlights the need to study entire systems in realistic fires, rather than studying individual components in standard fire tests.

Our review of the literature [4, 10–12] has established that the treatment of SIP panels with hemp insulation with coatings can provide their protection from thermal effects during operation. However, the parameters that guarantee the effectiveness of protection against high-temperature action required for their manufacture have not been defined. Therefore, determining the fire resistance characteristics of structures made of SIP panels with hemp insulation and the impact on the pyrolysis process of the components necessitated the need for research in this area.

3. The aim and objectives of the study

The purpose of our work is to determine the conditions for the formation of a fire-retardant coating on a SIP panel with hemp insulation. This makes it possible to expand the scope of application of these products in the construction of buildings and structures.

To achieve the goal, it was necessary to solve the following tasks:

– to establish the features of the suppression of combusиtion of a fire-resistant SIP panel under thermal action;

– to establish the strength characteristics of hemp insulałtion when treated with a coating.

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the process of designing fire-resistant SIP panels with hemp insulation based on a reactive coating and lime. The principal hypothesis assumes the possibility of designing a fire-resistant SIP panel with hemp insulation when treated with a coating based on lime and a reactive coating.

In the process of the study, it was assumed that the process of designing a fire-resistant SIP panel is constant under the influence of external conditions. It was simplified that the temperature, humidity, as well as pressure of the wood processing process, do not change.

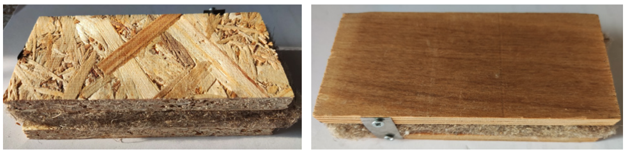
4. 2. Materials under investigation used in the experiment

To study the possibility of fire protection of hemp insulation, KONSULATE® building insulation made of hemp firewood produced by TM KONSULATE by Sumykamvol was used, with a size of 220 × 180 mm, a thickness of 20 mm and a density of 63…65 g/m^3 (Fig. 1). A reactive coating “SKELA-W” (Ukraine) was applied to the surface of the hemp insulation with a consumption of 260 g/m^2 and lime plaster with a consumption of 300 g/m^2. After drying the insulation, a study was conducted on its resistance to thermal action.

Fig. 1. Hemp insulation

To study the possibility of using hemp insulation as a component of the thermal insulation material for a SIP panels, a sample of insulation was placed between OSB-3 boards manufactured by Kronospan (Ukraine), size 150×60 mm, thickness 10 mm, density 630÷640 kg/m^3. Also, for the SIP panel sample, the insulation was placed between plywood boards manufactured by Fanplit (Ukraine), size 150×60 mm, thickness 10 mm, density 650÷670 kg/m^3 (Fig. 2). To increase fire resistance, the surface of the samples was coated with a reactive coating “SKELA-W” (Ukraine) at a consumption of 260 g/m^2 and lime plaster at a consumption of 360 g/m^2.

After drying and aging for 14 days, the SIP panel samples were subjected to thermal treatment.



a b

Fig. 2. General view of SIP panel samples:
1 — based on OSB board and hemp insulation;
2 — based on plywood and hemp insulation

4. 2. Methodology for determining the resistance of SIP panels to destruction after coating

The study of the fire resistance of hemp insulation was carried out using a methodology that involved evaluating the combustion characteristics of the material under the influence of a burner flame under controlled laboratory conditions [13]. The test was carried out under the influence of a burner for 300 seconds; for this purpose, the material sample is fixed on the spikes of the sample holder, the burner is installed in a horizontal position 40 mm above the lower edge of the sample and moved to the sample at a distance of 17 mm. During the tests, the duration of residual flame combustion, material burnout, surface flash propagation, and the average length of the charred area were recorded.

The essence of the test method for experimental determination of the flammability of SIP panels is to expose the sample located in the installation to the flame of a burner or a radiation panel with specified parameters [14]. During experimental studies to determine the flammability of the product, the absence of ignition and flame spread over the surface, the value of the mass loss indicator of the tent sample, which should be no more than 10%, as well as the final combustion after removing the burner, are recorded.

Determining a change in the structure of hemp insulation when interacting with the coating was carried out by studying Fourier transform infrared spectroscopy (FTIR), which was carried out taking into account [15]. Research method: 0.5 mg of the sample was crushed from 70 mg of potassium bromide (split from a single crystal). From the resulting mixture, a tablet was compressed under a pressure of 10 MPa, achieving maximum optical transparency (to reduce scattering). The spectrum was recorded in the range of 4000–400 cm^{-1}, with an optical slit width of 4 cm^{-1}, the spectrum was averaged over 12 scans. The analysis was performed on a Spectrum One spectrometer (Perkin Elmer) (USA).

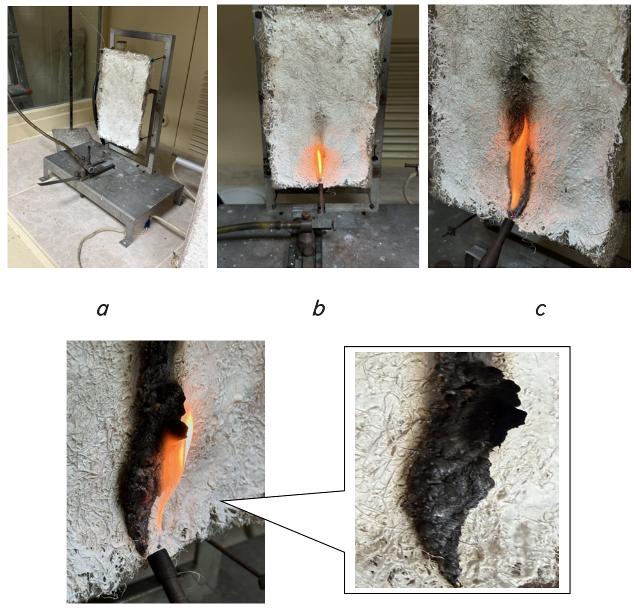
To establish the performance properties of hemp insulation treated with a coating, tensile strength was determined according to ASTM D5035-11 [16].

5. Results of determining the resistance to destruction by SIP panels with hemp insulation

5. 1. Experimental studies on the thermal resistance of SIP panels treated with a coating

To establish the resistance to thermal effects of hemp insulation treated with a coating, studies were conducted to determine the flammability under the influence of a gas burner flame. The results of our studies are shown in Fig. 3, 4, and Table 1.

After testing, it is clear that the sample of hemp insulation treated with a reactive coating and lime does not support combustion and the spread of flame along the surface.

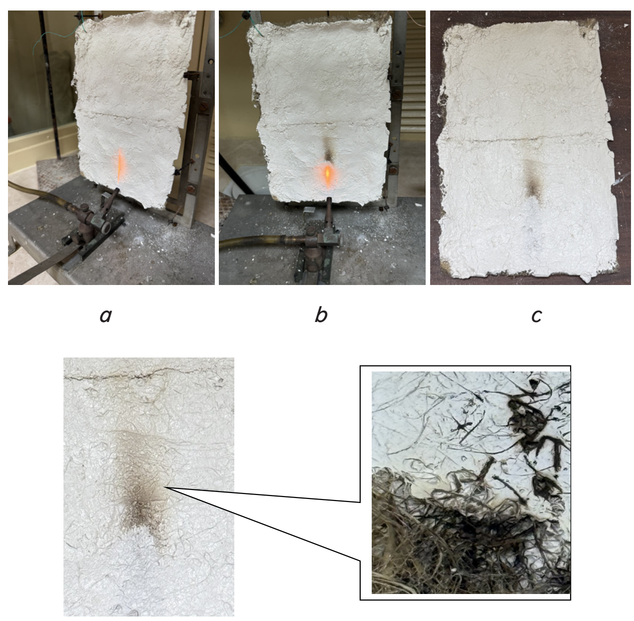


a b c

d

Fig. 3. Results of studies on the ignition process and flame spread of a sample of hemp insulation treated with a reactive coating: *a* — general view of the installation; *b* — effect of flame on the sample; *c* — swelling of the coating; *d* — protective layer of foam coke

On the surface of the sample of hemp insulation treated with a reactive coating, a layer of foam coke with a thickness of more than 50 mm and a width of 20÷30 was formed, and the height of the swelling is 22 mm. For the sample of insulation treated with lime, on the reverse surface, the fibers darkened from the action of high temperature.



a b c

d

Fig. 4. Results of studies on the ignition process and flame spread of a sample of hemp insulation treated with lime: *a* — general view of the installation; *b* — effect of flame on the sample; *c* — darkening of the coating; *d* — burn-through from the reverse side

Table 1

Results of studies conducted to determine the flammability of hemp insulation

Fire hazard indicator	Treated sample of insulation with lime	Treated sample of insulation with a reactive coating
Duration of residual flame combustion, s	absent	absent
Material burn-through	burns out	does not burn through
Propagation of surface flash more than 100 mm from the ignition point	does not spread	does not spread
Average length of charred area, mm	12,78	55,32
Average mass of samples before testing, g	95,01	59,40
Average mass of samples after testing, g	91,02	57,30

Table 1 demonstrates that after the action of the burner on samples of hemp insulation treated with coatings, the absence of residual flame combustion and the spread of surface flash was established, the average length of the charred area was less than 13 mm, and the mass loss after testing is less than 1.0%. Thus, the sample of hemp insulation treated with a coating belongs to flame-retardant materials.

To establish the resistance to thermal effects of SIP panels with hemp insulation, studies on the ignition process of samples treated with coatings were conducted. The results of studies of ignition and flame spread are shown in Fig. 5, 6.

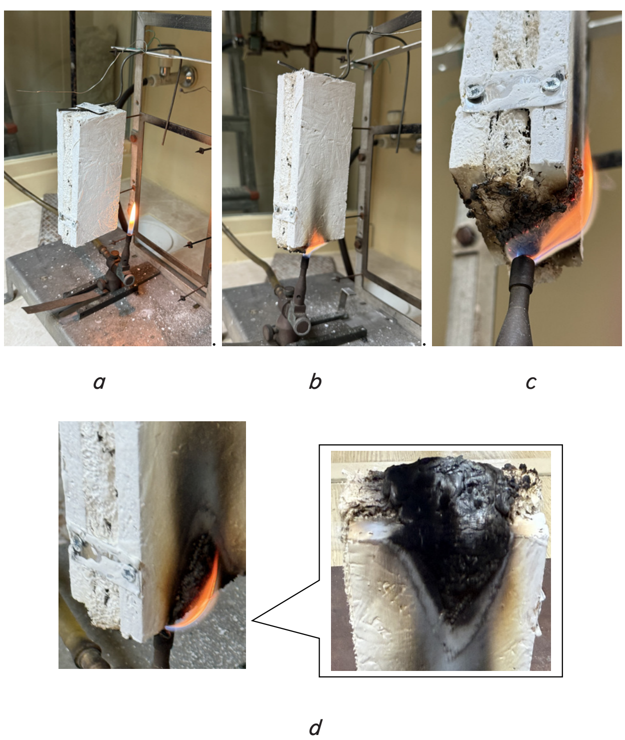


Fig. 5. Results of studies on the ignition process and flame spread of a sample of a SIP panel with hemp insulation treated with a reactive coating: *a* – general view of the installation, *b* – effect of flame on the sample, *c* – swelling of the coating, *d* – protective layer of foam coke

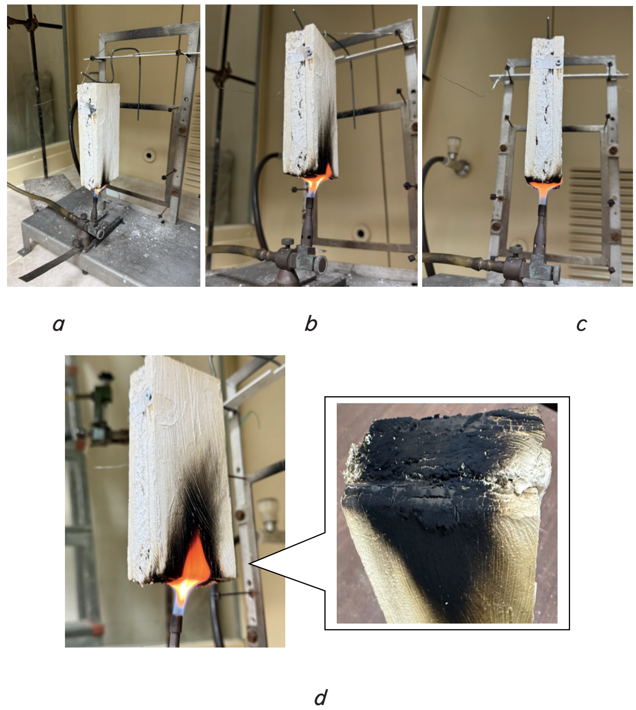


Fig. 6. Results of studies on the ignition process and flame spread of a sample of SIP panel with hemp insulation, treated with lime: *a* – general view of the installation, *b* – effect of flame on the sample, *c* – darkening of the coating, *d* – result of thermal exposure

Studies have shown that when a burner is used on a sample of a SIP panel with hemp insulation treated with a reactive coating, after 110 seconds of thermal exposure, the process of forming a thermally insulating layer of coke began, which inhibited heat transfer. No ignition and flame spread occurred. In contrast, after the burner is used on a sample of a SIP panel with hemp insulation treated with lime, a charring process occurred at the site of thermal exposure, but no ignition and flame spread occurred.

5. 2. Results of determining the strength characteristics of hemp insulation treated with a coating

The study of changes in the structure of hemp insulation when interacting with the coating is illustrated by IR spectra shown in Fig. 7.

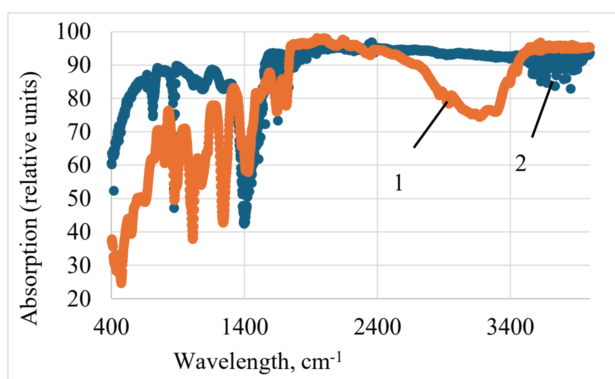


Fig. 7. Absorption spectra of samples of hemp insulation treated with: 1 – reactive coating "SKELA-W"; 2 – lime-based

Since hemp fibers are composed of cellulose, lignin, and hemicellulose, the description of the IR spectra of the samples will be given taking into account their absorption bands. Thus, the main transmission region will lie within 2500–3700 cm^{-1}. In particular, for lignin, the IR spectrum region within 3700–3100 cm^{-1} will characterize the valence vibrations of hydroxyl groups as they are involved in hydrogen bonds.

The presence of a chemical interaction of the reactive coating and lime with cellulose is indicated by an increase in the optical density of the absorption bands: a peak at 1100 cm^{-1}, which corresponds to the valence vibrations of the glycosidic bond in the cellulose macromolecule. As well as absorption bands at 1370 cm^{1}, which characterize the valence vibrations of the ether bond and deformation vibrations of the O-H groups. And the peak at 2900 cm^{-1}, responsible for the valence vibrations of the C-H bonds present in the cellulose molecules.

Thus, when a reactive coating is applied to the surface of the hemp insulation fiber, the intensity of the oscillation peaks in the frequency of the oscillation of aromatic C-H bonds exceeds the intensity of the same peaks in the fiber treated with lime. This proves the attachment of phosphorus-ammonium molecules to cellulose. At the same time, lime is characterized by the interaction that occurs with the hydroxyl groups of cellulose located near the glucopyranose ring and with the carboxyl groups of lignin.

In order to determine the operational properties during the fabrication of SIP panels and the construction of buildings, the tensile strength was determined, shown in Fig. 8, 9.

Fig. 8. Determining the tensile strength of hemp insulation treated with a reactive coating: *a* — sample fixation; *b* — sample tension; *c* — tensile results

The results of determining the tensile strength of coated hemp insulation are given in Table 2.

From Table 2 it is established that treating the surface of hemp insulation with a coating increases the tensile strength by more than 2.5 times. Thus, increasing the amount of reactive coating on the surface of hemp insulation by half increases the tensile strength by 2.3 times. In the case of treating hemp insulation with lime, the tensile strength decreases by 3.4 times; however, increasing the amount of lime during the treatment of the surface of hemp insulation to 0.38 kg/m^2 increases the tensile strength by 5.3 times.

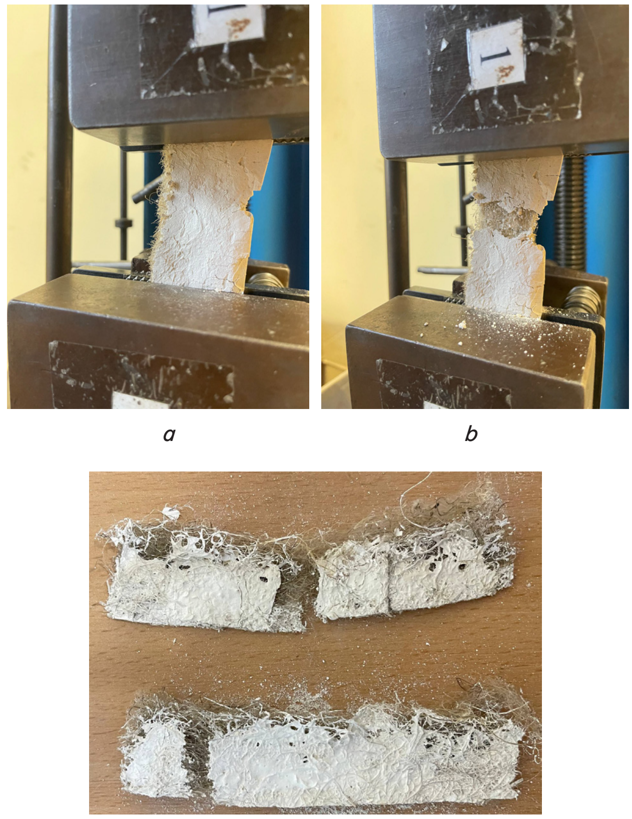


Fig. 9. Determining the tensile strength of hemp insulation treated with lime: *a* – specimen fixation; *b* – specimen tensile; *c* – tensile results

Table 2

Tensile strength of coated hemp insulation

Hemp insulation treated with a coating	Coating consumption, kg/m^2	Tensile strength, MPa
Untreated	–	0.04
Reactive coating based	0.13	0.34
	0.2	0.57
	0.26	0.79
Lime based	0.12	0.10
	0.2	0.22
	0.38	0.53

6. Discussion of results based on investigating the regularities in the formation of fire-resistant SIP panels with hemp insulation

A comparison of studies on determining the fire resistance of hemp insulation treated with a coating (Fig. 3, 4, Table 1) shows that a sample of hemp insulation treated with a reactive coating and lime does not support combustion and the spread of flame along the surface. A layer of foam coke was formed on the surface of the sample of hemp insulation treated with a reactive coating, which is 22 mm. And for the sample of insulation treated with lime, on the reverse surface, the fibers darkened from the action of high temperature, which indicates the inhibition of combustion processes. Thus, during the treatment of the surface of hemp insulation with lime, a structure is formed that prevents the ignition of plant raw materials.

Table 1 demonstrates that after the action of the burner on samples of hemp insulation treated with coatings, the absence of residual flame combustion and the spread of surface flash was established, the average length of the charred area was less than 13 mm, and the mass loss after testing is less than 1.0%. Here there is an expediency of the regularity of the results of the inhibition of the ignition process of hemp insulation protected by a reactive coating. It is characterized by the formation of charring of the surface of the sample, which prevents its ignition. Under the influence of thermal action, chemical reactions of the decomposition of the hydrocarbon catalyst begin, which lead to the thermal destruction of pentaerythritol and melamine with the release of non-flammable gases that dilute the flame. All this proves the process of swelling of the coating under thermal action [16].

According to the results of the SIP panel study (Fig. 5, 6), it was shown that when a burner was applied to a sample treated with a reactive coating, after 110 s of thermal exposure, the process of forming a heat-insulating layer of coke began, which inhibited heat transfer. No ignition and spread of flame occurred. In contrast, after the burner was applied to a sample of a SIP panel with hemp insulation treated with lime, a charring process occurred at the site of thermal action, but no ignition and spread of flame occurred. This confirms the mechanism of the protective coating, which enables identification by high-temperature exposure [17].

Analysis of the results of experiments to determine the strength characteristics of hemp insulation treated with a coating (Fig. 8, 9, Table 2) revealed that treating the surface of hemp insulation with a coating increases the tensile strength by more than 2.5 times. Thus, increasing the amount of reactive coating on the surface of hemp insulation by half increases the tensile strength by 2.3 times. In the case of treating hemp insulation with lime, the tensile strength decreases by 3.4 times but increasing the amount of lime when treating the surface of hemp insulation to 0.38 kg/m^2 increases the tensile strength by 5.3 times.

Therefore, taking into account studies [2, 3, 5–7], in which concept was aimed at the formation of hemp-based biocomposites, our work shows the process of designing a fire-resistant insulation using a reactive coating. The effectiveness of treating the surface of hemp insulation with lime is also demonstrated

However, in contrast to the results reported in [18] regarding the fire resistance regulator of the material, the following can be said:

– the main mechanism of inhibition of thermal action is the formation of a significant amount of lime on the surface of the insulation, which prevents the passage of high temperature since individual coatings release water and turn into ceramic phases;

– a significant impact on the protection process when usu ing a reactive coating, which is capable of forming an elastic film resistant to destruction on the surface of the hemp insulation during operation and, under the influence of flame, forming a layer of foam coke.

Interpretation of our results on determining the strength, which is confirmed by tensile experiments, makes it possible to use them. The obtained properties also make it possible to define the conditions for using hemp insulation as a component of SIP panels in the construction of modular buildings, which represents a specific advantage of this study.

Our results on determining the tensile strength of hemp insulation have certain limitations as the use of lime coating is fragile and requires a larger amount.

In addition, the resistance of lime coating to thermal action does not provide the necessary data due to its small amount and limits its use. Among the limitations is the fact that the experimental results are presented in graphical form. However, thanks to experimental studies, it is possible to assess the role of reactive coating and lime treatment of insulation during operation. A further direction of research in the development of fire-resistant materials involves a systematic study aimed at formulating an optimized composition of the reactive coating.

7. Conclusions

1. During thermal action on samples of hemp insulation treated with a reactive coating and lime, ignition and spread of flame along the surface did not occur. A layer of foam coke formed on the surface of the sample of hemp insulation treated with a reactive coating, which is 22 mm. And for the sample of insulation treated with lime, on the reverse surface, the fibers darkened due to the action of high temperature. It was experimentally determined that after the action of the burner on samples of hemp insulation treated with coatings, the absence of residual flame combustion and spread of surface flash was established, the average length of the charred area was less than 13 mm, and the mass loss after testing was less than 1.0%. Thus, the sample of hemp insulation treated with a coating belongs to highly flame-resistant materials.

Our studies have shown that when a burner is used on a sample of a SIP panel with hemp insulation treated with a reactive coating, after 110 seconds of thermal exposure, the process of forming a thermally insulating layer of coke began, which inhibited heat transfer. No ignition and flame spread occurred. In contrast, after the burner is used on a sample of a SIP panel with hemp insulation treated with lime, a charring process occurred at the site of thermal action, but no ignition and flame spread occurred.

2. For hemp insulation treated with a reactive coating, stable hydrolytic esters are formed on the surface of the fibers, which contain phosphorus and nitrogen atoms. Therefore, the intensity of the peaks in the vibration frequency region of aromatic C–H bonds for hemp fibers treated with the reactive coating exceeds that for hemp fibers treated with lime, which confirms the attachment of phosphorus–ammonium molecules to cellulose. At the same time, lime is characterized by an interaction that occurs with the hydroxyl groups of cellulose located near the glucopyranose ring and with the carboxyl groups of lignin.

According to the results of determining the strength of the insulation, it was found that treating the surface of hemp insulation with a coating increases the tensile strength by more than 2.5 times. Thus, increasing the amount of reactive coating on the surface of hemp insulation by half increases the tensile strength by 2.3 times. In the case of treating hemp insulation with lime, the tensile strength decreases by 3.4 times; however, increasing the amount of lime when treating the surface of hemp insulation to 0.38 kg/m^2 increases the tensile strength by 5.3 times.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

The authors express their gratitude for the development of scientific topics within the scientific cooperation program COST Action FP 1407 "Understanding wood modification through an integrated scientific and ecological approach" within the framework of the European Union's HORIZON2020 program.

Authors' contributions

Yuriy Tsapko: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision. **Oleksiy Tsapko:** Conceptualization, Investigation, Data analysis, Writing – original draft. **Oksana Berdnyk:** Investigation, Data analysis, Formal analysis, Writing – original draft. **Ruslan Likhniovsky:** Methodology, Data curation, Validation. **Kseniia Bielikova:** Resources, Validation, Funding acquisition. **Oksana Slutskaya:** Resources, Supervision, Validation. **Anna Borysova:** Validation, Funding acquisition, Visualization. **Vasyl Lomaha:** Funding acquisition, Validation, Visualization. **Olha Uzhehova:** Investigation, Resources, Funding acquisition. **Vitalii Chaikovskiy:** Resources, Supervision, Validation.

References

1. Li, X., Peng, C., Liu, L. (2020). Experimental study of the thermal performance of a building wall with vacuum insulation panels and extruded polystyrene foams. Applied Thermal Engineering, 180, 115801. https://doi.org/10.1016/j.applthermaleng.2020.115801
2. Gallina, L., Chaji, S., Manzoli, M., Cravero, F., Gnoffo, C., Gesti, S. et al. (2024). Preparation of hemp-based biocomposites and their potential industrial application. Polymer Composites, 46 (4), 3791–3802. https://doi.org/10.1002/pc.29206
3. Pereira, J. F., Núñez, E., Reyes, A., Mali, S., Lopez-Rubio, A., Fabra, M. J. (2024). On the use of lignocellulosic hemp fibers to produce biodegradable cost-efficient biocomposites. Future Foods, 10, 100507. https://doi.org/10.1016/j.fufo.2024.100507
4. Cigasova, J., Stevulova, N., Schwarzova, I., Sicakova, A., Junak, J. (2015). Application of Hemp Hurds in the Preparation of Biocomposites. IOP Conference Series: Materials Science and Engineering, 96, 012023. https://doi.org/10.1088/1757-899x/96/1/012023
5. Kausar, A., Ahmad, I. (2023). Hemp Fibres: Essentials, Composites or Nanocomposites and Technical Applications. Nano-Horizons: Journal of Nanosciences and Nanotechnologies, 2. https://doi.org/10.25159/3005-2602/13835
6. Dahal, R. K., Acharya, B., Dutta, A. (2023). The Interaction Effect of the Design Parameters on the Water Absorption of the Hemp-Reinforced Biocarbon-Filled Bio-Epoxy Composites. International Journal of Molecular Sciences, 24 (7), 6093. https://doi.org/10.3390/ijms24076093
7. Akbarian-Saravi, N., Sowlati, T., Ahmad, H., Hewage, K., Sadiq, R., Milani, A. S. (2025). Life cycle assessment of hemp-based biocomposites production for agricultural emission mitigation strategies: a case study. Biocomposites and the Circular Economy, 261–285. https://doi.org/10.1016/b978-0-443-23718-8.00012-0
8. Francucci, G., Manthey, N., Cardona, F., Aravinthan, T. (2013). Processing and characterization of 100% hemp-based biocomposites obtained by vacuum infusion. Journal of Composite Materials, 48 (11), 1323–1335. https://doi.org/10.1177/0021998313485266
9. Sassoni, E., Manzi, S., Motori, A., Montecchi, M., Canti, M. (2014). Novel sustainable hemp-based composites for application in the building industry: Physical, thermal and mechanical characterization. Energy and Buildings, 77, 219–226. https://doi.org/10.1016/j.enbuild.2014.03.033
10. Morgan, A. B., Toubia, E. (2013). Cone calorimeter and room corner fire testing of balsa wood core/phenolic composite skin sandwich panels. Journal of Fire Sciences, 32 (4), 328–345. https://doi.org/10.1177/0734904113514944
11. Yoshioka, H., Tanaka, Y., Tamura, M., Nishio, Y., Tanaike, Y., Ando, T. et al. (2017). Study on intermediate-scale test method for fire safety performance evaluation of sandwich panels. AIJ Journal of Technology and Design, 23 (53), 159–164. https://doi.org/10.3130/aijt.23.159
12. de Boer, J. G. G. M., Hofmeyer, H., Maljaars, J., van Herpen, R. A. P. (2019). Two-way coupled CFD fire and thermomechanical FE analyses of a self-supporting sandwich panel façade system. Fire Safety Journal, 105, 154–168. https://doi.org/10.1016/j.firesaf.2019.02.011
13. Tsapko, Y., Tsapko, A., Bondarenko, O., Chudovska, V. (2021). Thermophysical characteristics of the formed layer of foam coke when protecting fabric from fire by a formulation based on modified phosphorus-ammonium compounds. Eastern-European Journal of Enterprise Technologies, 3 (10 (111)), 34–41. https://doi.org/10.15587/1729-4061.2021.233479
14. Tsapko, Y., Tsapko, A. (2017). Establishment of the mechanism and fireproof efficiency of wood treated with an impregnating solution and coatings. Eastern-European Journal of Enterprise Technologies, 3 (10 (87)), 50–55. https://doi.org/10.15587/1729-4061.2017.102393

15. ASTM D5035-11. Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method). Available at: https://www.mecmesin.com/standard/astm-d5035-11
16. Tsapko, Y., Tsapko, A., Likhnyovskyi, R., Bielikova, K., Berdnyk, O., Gavryliuk, A. et al. (2025). Establishing regularities of fire protection of wood by a composite coating with a biopolymer. Eastern-European Journal of Enterprise Technologies, 3 (10 (135)), 16–25. https://doi.org/10.15587/1729-4061.2025.332443
17. Tsapko, Y., Tsapko, A., Lomaha, V., Illiuchenko, P., Berdnyk, O., Likhnyovskyi, R. et al. (2025). Establishing patterns in the formation of biocomposites for thermal insulation of building structures. Eastern-European Journal of Enterprise Technologies, 4 (10 (136)), 56–64. https://doi.org/10.15587/1729-4061.2025.337401
18. Tsapko, Y., Sukhanevych, M., Bondarenko, O., Tsapko, O., Sarapin, Y. (2023). Investigation of changes in the process of thermal-oxidative destruction of fire-retardant fabric. IX International Conference on Actual Problems of Engineering Mechanics (APEM2022), 2840, 020009. https://doi.org/10.1063/5.0168781