

Thermal Performance Degradation of Vacuum Insulation Panels under Vacuum Loss Conditions

Borys BASOK¹, Andrii DANISHEVSKYI², Hanna Koshlak^{3*}, Svitlana GONCHARUK⁴,
Oleksii SHMATOK⁵, Anna WYPYCH-GAWRONSKA⁶

^{1,2,4,5}*Institute of Engineering Thermophysics, National Academy of Sciences of Ukraine*

^{3,6}*Kielce University of Technology, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland*

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Abstract – This paper presents an experimental study of thermal performance degradation of vacuum insulation panels under vacuum loss conditions. The experiments were carried out under field conditions using heat flux and temperature measurements. Two configurations were investigated: a single intact vacuum insulation panel and a sandwich system consisting of two vacuum insulation panels separated by an air layer after destructive damage. The effective thermal conductivity was determined under quasi-steady-state conditions. The results showed that the effective thermal conductivity of the intact vacuum insulation panel was in the range of 0.0094–0.0105 W/(m·K), which is higher than the nominal value of approximately 0.008 W/(m·K). After vacuum loss, the effective thermal conductivity increased to 0.030–0.035 W/(m·K), approaching the level of conventional thermal insulation materials. This confirms that vacuum loss causes a stepwise degradation of the thermal insulation properties of vacuum insulation panels.

Keywords – Building envelope; degradation; energy efficiency; heat flux; thermal conductivity, thermal resistance; vacuum insulation panel; vacuum loss.

1. INTRODUCTION

Improving the energy efficiency of buildings remains one of the key challenges of modern building physics and thermal engineering. A significant part of heat losses occurs through building envelopes; therefore, the thermal performance of insulation materials directly affects energy consumption, operating costs, and indoor thermal comfort. Traditional, state-of-the-art and advanced insulation materials differ not only in their initial thermal conductivity but also in their long-term stability under real operating conditions [1]–[3].

Vacuum insulation panels are among the most effective thermal insulation materials currently used or considered for building applications. Their thermal performance is significantly higher than that of many conventional insulation materials because heat transfer

* Corresponding author.

E-mail address: hkoshlak@tu.kielce.pl

Borys BASOK  <https://orcid.org/0000-0002-8935-4248>

Andrii DANISHEVSKYI  <https://orcid.org/0000-0002-6166-0999>

Hanna KOSHLAK  <https://orcid.org/0000-0001-8940-5925>

Svitlana GONCHARUK  <https://orcid.org/0000-0002-5609-7337>

Oleksii SHMATOK  <https://orcid.org/0009-0009-2133-2411>

Anna WYPYCH-GAWRONSKA  <https://orcid.org/0000-0003-0956-1624>

by gas conduction is strongly suppressed inside the evacuated porous core [4], [5]. In building envelopes, this feature is particularly attractive because it allows high thermal resistance to be achieved with reduced insulation thickness, which is important for façade renovation, window areas, balconies, historical buildings, and space-limited structures [6].

A typical vacuum insulation panel consists of a porous core material, a gas-tight multilayer barrier envelope, and, in many cases, getter or desiccant components. The core provides mechanical resistance to atmospheric pressure and limits solid conduction, while the barrier envelope maintains low internal pressure. The long-term thermal performance of the panel depends on the stability of the envelope, the gas permeability of its layers, the quality of sealing, and the ageing behaviour of the core material [7], [8].

However, the main weakness of vacuum insulation panels is their sensitivity to vacuum degradation. Even if the panel remains visually intact, internal pressure may increase over time due to gas and water vapour permeation. More severe degradation occurs when the barrier envelope is mechanically damaged. In such a case, air penetrates into the porous core, gas conduction increases rapidly, and the panel loses a significant part of its insulation advantage [9], [10]. Recent studies of barrier films confirm that mechanical stresses and microcracks may accelerate gas leakage and lead to insulation failure [11].

The declared thermal conductivity of vacuum insulation panels is usually obtained under controlled laboratory conditions. In real building applications, however, the effective thermal conductivity may differ from the nominal value due to edge effects, thermal bridges, installation quality, panel geometry, moisture conditions, and ageing. Therefore, the use of declared values without correction may lead to an underestimation of heat losses [12], [13].

The degradation of vacuum insulation panels differs fundamentally from the degradation of conventional thermal insulation materials. Traditional materials such as expanded polystyrene, extruded polystyrene, mineral wool, foam glass, and polyurethane foam usually demonstrate gradual changes in thermal properties due to moisture accumulation, structural ageing, mechanical deformation, and gas diffusion [14], [15]. In previous studies, this type of gradual degradation was analysed experimentally, and the degradation coefficient D_t was used to describe the ratio between nominal and actual thermal conductivity during operation [16], [17]. This approach is suitable for materials with continuous ageing behaviour.

For vacuum insulation panels, however, degradation may occur as a transition between two substantially different states: the intact evacuated state and the depressurized state. Therefore, their thermal degradation should be considered not only as a time-dependent process but also as a failure-driven process. This distinction is important for thermal design, energy auditing, and long-term assessment of building envelopes.

The aim of this study is to experimentally investigate the thermal performance degradation of vacuum insulation panels under vacuum loss conditions and to analyse the implications of such degradation for heat transfer assessment in building envelopes.

2. MATERIALS AND METHODS

The experimental study was carried out using two configurations that represent different operating states of vacuum insulation panels. The first configuration consisted of a single intact vacuum insulation panel. This configuration was used to characterize the thermal behaviour of the panel under preserved vacuum conditions. The second configuration was a sandwich system consisting of two vacuum insulation panels separated by an air layer. In this case, the panels were intentionally depressurized by a destructive action in order to simulate a failure scenario associated with vacuum loss. The single panel had dimensions of approximately $600 \times 400 \times 30$ mm. The total thickness of the sandwich configuration was

approximately 80 mm. The sandwich system included the thickness of the two panels and the intermediate air layer. The experimental configurations were installed under field conditions, which made it possible to investigate heat transfer under conditions closer to real building operation than laboratory measurements.

Experimental data on heat flux densities and temperatures were obtained for November 2025. As a result of analysing the temperature gradient ($T_{\text{in}} - T_{\text{out}} > 15 \text{ K}$), data for the nighttime period (from 02:00 AM to 06:00 AM) on November 13, 2025, with a measurement interval of 10 minutes.

Fig. 1 depicts two panel's photographs showing vacuum insulation panels (VIPs) tested before data interpretation.



Fig. 1. Vacuum insulation panels: (a) used in experimental study with installed heat flux density and temperature sensors; (b) mounted in a window frame for field testing.

Heat flux density and temperature were measured simultaneously. Heat flux sensors were installed on the surface of the investigated configuration, while temperature sensors were placed in positions that allowed the temperature difference across the structure to be determined. Measurements were performed with a time step of 10 minutes. Night-time periods were selected for data processing in order to minimize the influence of solar radiation and external disturbances.

The experimental method was based on the heat flux approach, which is commonly used for evaluating the thermal performance of building envelope elements and insulation systems under in-situ or quasi-steady-state conditions [18]–[20]. Before calculation, the measured data were filtered to reduce random fluctuations and to identify intervals in which heat flux density and temperature difference remained sufficiently stable.

The effective thermal conductivity was calculated as Eq. (1):

$$\lambda_{\text{eff}} = \frac{q \cdot \delta}{\Delta T}, \quad (1)$$

where λ_{eff} is the effective thermal conductivity, $\text{W}/(\text{m} \cdot \text{K})$; q is the heat flux density, W/m^2 ; δ is the thickness of the investigated configuration, m; and ΔT is the temperature difference across the configuration, K.

The thermal resistance R was calculated as Eq. (2):

$$R = \frac{\Delta T}{q}. \quad (2)$$

This approach allows the measured heat flux and temperature difference to be directly connected with the effective thermal properties of the investigated system. Since the study was performed under field conditions, the obtained values should be interpreted as effective values that include not only the intrinsic properties of the core material but also real heat transfer effects, such as edge influence, installation conditions, and possible non-uniformity of the temperature field.

3. EXPERIMENTAL RESULTS

The experimental results confirmed a clear difference between the intact and depressurized states of vacuum insulation panels. The intact panel demonstrated relatively low heat flux density and stable temperature difference during the selected quasi-steady-state intervals. This made it possible to determine the effective thermal conductivity with sufficient reliability. The figures below show graphs of fluctuations in heat flux densities from the environment and in the middle of the building (Fig. 2) and the corresponding graphs of temperature fluctuations (Fig. 3) for intact VIP.

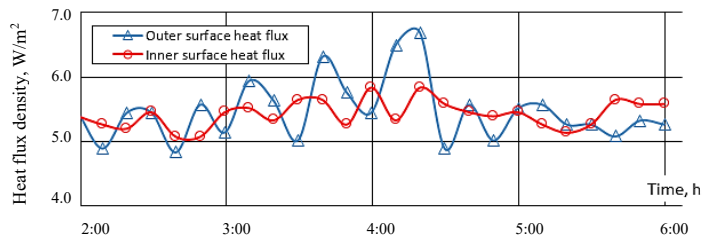


Fig. 2. Time variation of heat flux density for the intact vacuum insulation panel under quasi-steady-state conditions.

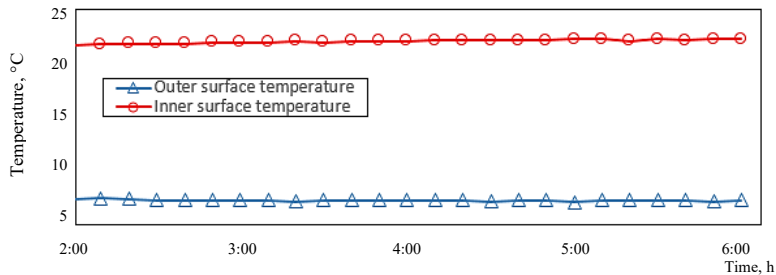


Fig. 3. Time variation of temperature for the intact vacuum insulation panel under quasi-steady-state conditions.

The temperature profiles shown in Fig. 3 confirm quasi-steady-state conditions required for thermal conductivity evaluation.

For the intact vacuum insulation panel, the effective thermal conductivity was determined in the range $\lambda_{\text{intact}} = 0.0094\text{--}0.0105 \text{ W}/(\text{m}\cdot\text{K})$. This value is higher than the nominal value of approximately $\lambda_n \leq 0.008 \text{ W}/(\text{m}\cdot\text{K})$.

For the lower experimental value of $0.0094 \text{ W}/(\text{m}\cdot\text{K})$, the deviation from the nominal value is approximately 17.5 %. This difference may be explained by real operating conditions, edge heat transfer, non-ideal vacuum state, and measurement uncertainty. It also confirms that the

declared thermal conductivity of vacuum insulation panels should not always be used directly for practical thermal calculations without considering actual operating conditions.

For the depressurized sandwich configuration, the measured heat flux density increased significantly. This indicates that the loss of vacuum caused a substantial change in heat transfer mechanisms inside the panel structure.

Figures 4 and 5 show graphs of fluctuations in heat flux densities from the environment and in the middle of the building (Fig. 4) and the corresponding graphs of temperature fluctuations (Fig. 5) for degraded VIP.

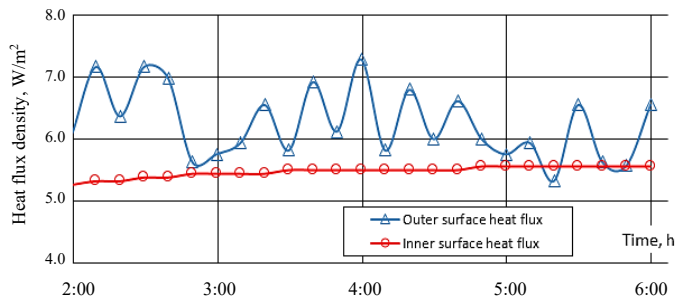


Fig. 4. Time variation of heat flux density for VIP without a vacuum (broken barrier).

The temporal variations in heat flux density for the depressurised VIP are presented in Fig. 4; the data clearly illustrate two distinct thermal regimes at the system boundaries. The external boundary heat flux (blue line) exhibits pronounced, high-frequency oscillations, which are a direct response to the transient environmental forcing of the external climatic conditions. In stark contrast, the internal boundary heat flux (red line) remains relatively constant and heavily damped. It must be noted that, given the thermal gradient depicted in Fig. 5 ($T_{\text{inner}} \approx 14.5^\circ\text{C}$ vs $T_{\text{outer}} \approx 7.5^\circ\text{C}$), the heat flux is directed outwards, representing thermal loss through the building envelope. The external surface heat flux exhibits significant sinusoidal fluctuations, which are characteristic of the transient boundary conditions of the external climatic environment. Conversely, the internal surface heat flux demonstrates a markedly stable profile. This damping of the thermal signal is a direct consequence of the panel's internal thermal inertia. The porous core material acts to filter high-frequency environmental perturbations, allowing the internal boundary to remain in a quasi-steady state. Despite the loss of vacuum, the structural matrix of the panel continues to provide thermal resistance, preventing immediate thermal equalization. However, the elevated magnitude of the heat flux confirms a severe degradation in overall performance compared to the intact state.

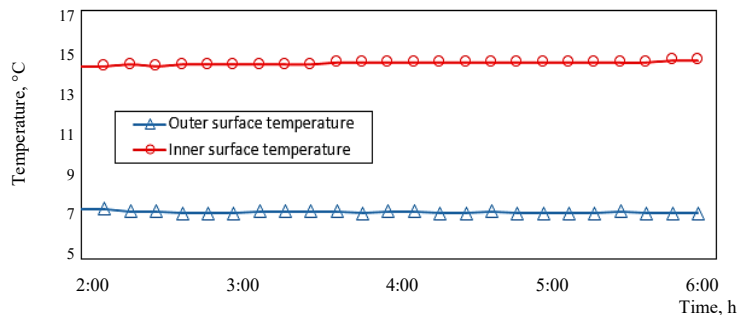


Fig. 5. Time variation of temperature for the degraded VIP under quasi-steady-state conditions.

The temperature profiles shown in Fig. 5 confirm quasi-steady-state conditions required for thermal conductivity evaluation.

The effective thermal conductivity of the depressurized configuration was determined in the range $\lambda_{\text{degraded}} = 0.030\text{--}0.035\text{ W/(m}\cdot\text{K)}$. This range is close to the thermal conductivity values of conventional insulation materials. Thus, after loss of vacuum, the vacuum insulation panel loses its main thermal advantage and approaches the performance level of traditional insulation.

The comparison between the intact and degraded states shows that vacuum loss leads to more than a threefold increase in effective thermal conductivity. This transition cannot be interpreted as a small deviation from the nominal value; it represents a qualitative change in the thermal state of the panel.

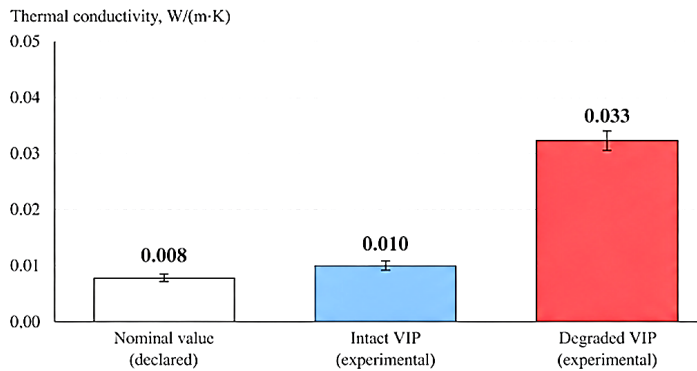


Fig. 6. Comparison of thermal conductivity for nominal, intact, and depressurized states of vacuum insulation panels.

4. DISCUSSION

The obtained results can be explained by changes in the dominant heat transfer mechanisms inside the vacuum insulation panel. In the intact state, gas conduction is suppressed due to low internal pressure. Heat transfer is mainly governed by solid conduction through the porous core, radiation within the pore structure, and additional edge effects caused by the barrier envelope. The measured effective thermal conductivity of $0.0094\text{--}0.0105\text{ W/(m}\cdot\text{K)}$ is therefore physically reasonable for real conditions.

After depressurization, air enters the porous core. As a result, gas conduction becomes much more significant. This mechanism leads to a rapid increase in effective thermal conductivity. In addition, in the sandwich configuration, the air layer between two panels may contribute to additional heat transfer. Depending on its thickness and temperature difference, the air layer may increase the overall heat transfer through conduction and, in some cases, natural convection.

The key result of this study is that vacuum loss causes stepwise thermal degradation. This is different from the behaviour of conventional insulation materials. For traditional materials, thermal conductivity usually changes gradually over time and can be described as a continuous function as represented in Eq. (3):

$$\lambda = \lambda(t). \quad (3)$$

In this case, a degradation coefficient D_t may be introduced as Eq. (4):

$$D_t = \frac{\lambda_n}{\lambda_t}, \quad (4)$$

where λ_n is the nominal thermal conductivity and λ_t is the experimentally determined thermal conductivity after a certain period of operation. Such an approach has been applied to analyse long-term changes in the thermophysical characteristics of façade insulation materials [14], [15], [21].

For vacuum insulation panels, this coefficient cannot fully describe the observed behaviour because the main degradation event is associated with vacuum failure. Therefore, the panel should be considered as a system with at least two possible thermal states: intact and depressurized.

A simplified failure-based model can be written as Eq. (5):

$$\lambda(t) = \begin{cases} \lambda_{\text{intact}}, & t < t_{\text{fail}} \\ \lambda_{\text{destruction}}, & t \geq t_{\text{fail}} \end{cases}, \quad (5)$$

where t_{fail} is the moment of vacuum failure.

This model reflects the physical nature of vacuum insulation panel degradation more accurately than a purely continuous ageing model.

The engineering implication is that energy auditors and designers should distinguish between nominal performance, intact in-service performance, and degraded performance. If only nominal values are used, heat losses may be underestimated. This is particularly important for building envelopes where panels can be damaged during installation or operation. Similar conclusions on the importance of real thermal conductivity assessment and long-term performance evaluation have been highlighted in recent studies on vacuum insulation panel products and building applications [22]–[25].

5. CONCLUSION

The experimental study confirmed that the thermal performance of vacuum insulation panels strongly depends on vacuum integrity.

The effective thermal conductivity of the intact vacuum insulation panel was found to be 0.0094–0.0105 W/(m·K), which exceeds the nominal value of approximately 0.008 W/(m·K). This deviation can be attributed to real operating conditions, edge effects, non-ideal vacuum state, and measurement uncertainty.

After vacuum loss, the effective thermal conductivity increased to 0.030–0.035 W/(m·K). This range corresponds to conventional thermal insulation materials and indicates a significant loss of the main advantage of vacuum insulation panels.

The obtained results show that degradation of vacuum insulation panels has a stepwise character. Unlike traditional insulation materials, whose ageing can be described by continuous models and degradation coefficients, vacuum insulation panels require a failure-based approach.

A two-state model was proposed to describe the transition between intact and depressurized states. This model can be used in thermal calculations of building envelopes, energy auditing, and long-term performance assessment.

The results demonstrate the need to consider possible vacuum loss scenarios when using vacuum insulation panels in building envelopes, especially in cases where mechanical damage or long-term reliability of the barrier envelope may affect energy performance.

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