Long-term thermal performance of vacuum insulation panels in district heating pipes: Nine years of field measurements

Long-term thermal performance of vacuum insulation panels in district heating pipes: Nine years of field measurements

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Abstract

Swedish district heating networks lose up to 10% of the produced energy through thermal transmission from distribution pipes. Vacuum insulation panels (VIPs) have attracted growing interest in the district heating sector due to their low thermal conductivity. Hybrid-insulated pipes, with VIPs applied around the steel supply pipe, have demonstrated heat loss reductions of up to 40% compared to conventional polyurethane insulation. However, their long-term performance under typical district heating operating temperatures (80-100 °C) remains insufficiently explored. This study presents field measurement results from two district heating networks in Sweden. In Varberg, a twin pipe system with VIP insulation was monitored for over nine years. In Linköping, a single pipe system was used to compare two types of VIPs, metallized and aluminum-coated, over seven years of operation. Measurements included supply and return temperatures as well as surface temperatures at multiple radial positions within the pipe cross-section. The results show that VIP-insulated sections consistently outperformed those insulated with conventional polyurethane, with temperature differences of up to 20%. In Varberg, a degradation rate of approximately 1.6% per year was observed in one measurement position, aligning with previously reported values from the initial four years of operation. In Linköping, metallized VIPs showed lower exterior insulation temperatures than aluminum-coated panels, indicating better overall thermal performance at the center of the panel. Although the temperature gap increased over time, the differences were minor and may reflect operational variability. Long-term performance differences could not be confirmed. Further research should investigate material-specific properties, including gas permeability and mechanical durability.

Keywords: District heating pipes; Vacuum insulation panels; VIP; Hybrid insulation

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Introduction

District heating (DH) networks are a cornerstone of urban energy systems, yet they can still be subjected to substantial thermal losses during distribution of heat. In Sweden, it is estimated that up to 10% of the energy supplied to the DH network is lost through pipe transmission [1-2]. These losses are particularly critical in areas with low heat demand density [3].

Conventional district heating pipes are typically insulated with polyurethane (PUR) foam, with a thermal conductivity of approximately 24–28 mW/(m·K) at 50°C [4-5]. Efforts to improve the thermal efficiency of DH systems have included optimized pipe geometry and improved insulation strategies [6]. Among these, hybrid insulation concepts, where high-performance materials are applied close to the service pipe, have gained increasing attention. Vacuum insulation panels (VIPs) have emerged as a promising solution due to their relatively low thermal conductivity when properly sealed and evacuated. VIPs represent an advanced insulation alternative for district heating pipes, achieving thermal conductivities of 4–5 mW/(m·K) at the center of panel, provided the vacuum is maintained [7]. A standard VIP consists of core material, commonly made of porous fumed silica, enclosed within a gas-tight laminate envelope, alternating polymer layers and aluminum layers. The edge of the VIP, where the envelope is sealed, creates a trade-off: increasing the metal content in the barrier reduces gas permeability and can extend the lifespan, but also introduces thermal bridges. In high-temperature applications such as district heating, potential degradation mechanisms include elevated gas diffusion rates and thermal damage to the polymer components, both of which can compromise insulation performance over time.

In cylindrical geometries, the effectiveness of insulation increases closer to the pipe center due to radial heat transfer performance [7]. This has led to the development of hybrid insulation concepts, where high-performance materials such as VIPs are placed adjacent to the supply pipe, and conventional PUR insulation is used in outer layers, see Figure 1. This configuration aims to combine the superior thermal performance of VIPs with the cost-efficiency and mechanical resilience of PUR.

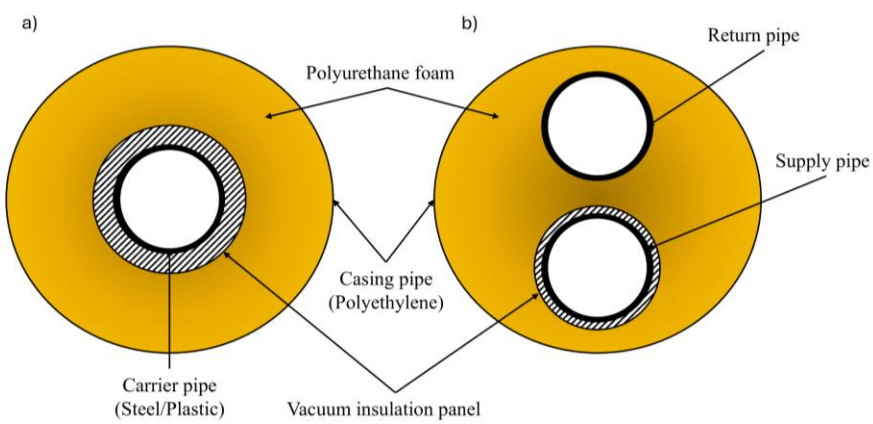

Figure 1. Schematic concept of hybrid insulation in district heating pipes using vacuum insulation panels. a) Single pipe, b) Twin pipe configuration.

Laboratory studies by Berge and Adl-Zarrabi [8–10], using the guarded hot pipe method, have validated the effectiveness of this concept in both single and twin pipe configurations. For single pipe systems, the addition of a 10 mm VIP layer to a DN 100/225 pipe reduced heat losses by nearly 30%. Notably, even damaged VIPs exhibited thermal conductivities comparable to that of intact PUR foam. In twin-pipe

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systems, applying a 10 mm VIP around the supply pipe in a DN 2×80/315 configuration resulted in total heat loss reductions of 12–18%. The supply pipe alone showed a reduction of nearly 40%, highlighting the potential of VIPs to significantly improve thermal efficiency in DH applications.

Despite these promising results, the long-term thermal stability of VIPs under operational DH temperatures (80–100 °C) remains a key uncertainty. Elevated temperatures may accelerate gas diffusion into the panels or degrade the polymer-laminate envelope, thereby diminishing their insulating capacity over time. Early field measurements by Berge and Adl-Zarrabi [2,10] monitored VIP-integrated DH pipes in Sweden over a period of up to four years. Based on in-situ temperature data, the panels appeared to remain intact after four years. While minor gas diffusion may have occurred, no clear degradation could be detected within the measurement accuracy interval during that period.

This study addresses this knowledge gap by extending the field evaluation of VIPs under long-term DH operation. Building on previous work [2,10], it presents results from two Swedish DH networks. The first case study spans over nine years and assesses the long-term performance of VIPs in a twin pipe configuration. The second case investigates the comparative performance of two VIP envelope types, metalized and aluminum-coated, installed in a single pipe DH system.

Field measurements

Varberg station- Twin pipe

The primary field measurements analyzed in this study were conducted at a district heating test site located in Varberg, a coastal city in southwestern Sweden. The station was established in 2012 as part of an early initiative to evaluate the long-term performance of VIPs in hybrid-insulated district heating pipes.

The installed system consisted of a twin pipe configuration with dimensions DN 2×80/250. The supply pipe was insulated using 10 mm metallized VIPs, while the remaining cavity was filled with conventional PUR foam. For reference, a parallel section of the same pipe type was insulated entirely with PUR to allow for comparative analysis. Type T thermocouples were embedded at multiple radial and axial positions before the PUR insulation was applied, allowing continuous temperature monitoring across the pipe cross-section, as shown in Figure 2. Only sensor positions relevant to the presented results are included in the figure, while positions with missing or unreliable data have been omitted to maintain clarity. Data was recorded continuously from January 2012 to August 2021, corresponding to 9 years and 7 months of normal district heating operation.

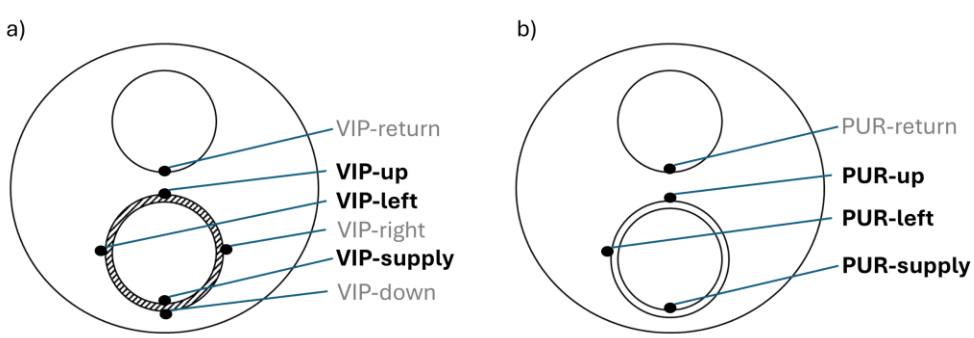

Figure 2. Measurement positions and sensor labels used in the twin pipe field installation in Varberg. a) Pipe section with VIP around the supply pipe. b) reference pipe section fully insulated with PUR.

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Linköping station- Single pipe with two VIP types

The second field study was conducted in Linköping, located in southeastern Sweden. This measurement started in August 2016. In contrast to the Varberg installation, the Linköping setup consisted of a single pipe configuration with dimensions DN 50/140. Two types of VIPs were applied around the supply pipe: one enclosed in an aluminum-coated polymer film, and the other in a metallized polymer film. Both variants feature a fumed silica core. The remaining pipe cavity was filled with conventional PUR foam. For each VIP type, four sections of the district heating pipe were included in the measurement study. Like the Varberg setup, type T thermocouples were embedded at various radial and axial positions to monitor temperatures at the supply pipe surface, VIP surface, PUR region, see Figure 3. Data was collected continuously from August 2016 to August 2023, corresponding to a full seven-year operational period.

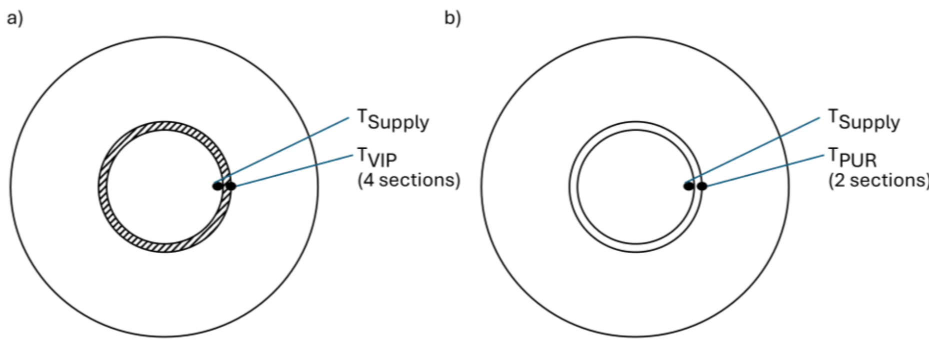

Figure 3. Measurement positions and sensor labels used in the single pipe field installation in Linköping. a) VIP-insulated sections, with four monitored sections for each VIP type (metallized and aluminum-coated), where surface temperatures of the VIP (T_{VIP}) were recorded. b) Reference section insulated with conventional PUR foam, where two sections were monitored for surface temperatures (T_{PUR}). For the supply pipe temperature (T_{Supply}), two positions were monitored across all sections.

Results and discussion

In this section, the results from both field installations are presented and discussed. To ensure accuracy and clarity, any time intervals with missing or physically inconsistent data, due to sensor or system malfunctions, have been excluded from the presented results. This applies to all figures and measurements reported in this section.

Figure 4 shows the monthly average supply temperatures measured at the Varberg field station for the two sections of the twin pipe system: one insulated with VIP and the other with conventional PUR foam. The regular fluctuations in supply temperature primarily reflect typical seasonal adjustments in the DH network to accommodate changing outdoor conditions and heating demand. As expected, the supply temperatures in both sections were nearly identical, since they belong to the same DH pipeline. Between 2012 and 2016, the supply temperature in the network varied seasonally between approximately 65 °C and 80 °C. In 2016, the DH network increased its supply temperature setpoint, resulting in higher operational levels of 80 °C to 95 °C from 2017 onward.

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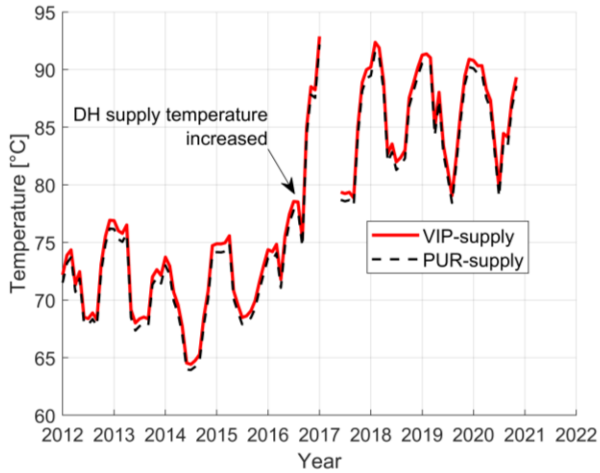

Figure 4. Monthly average supply temperatures measured in the Varberg twin pipe field installation. Sensor positions are labeled in accordance with Figure 2.

The monthly average return temperatures for the PUR-insulated section of the twin pipe system in Varberg are shown in Figure 5a. Values generally ranged between 40 °C and 70 °C. Due to sensor malfunctions, only one return-side thermocouple, located on the PUR-insulated pipe, provided reliable data. Return measurements from the VIP-insulated section were therefore excluded. Figure 5b displays the measured temperatures at the outer surface of the VIP in four positions: up, left, right, and down (see labels in Figure 2). These measurements reveal substantial variation within the same VIP element, highlighting the complexity of performance assessment in twin pipe configurations. The sensors labeled VIP-up, located between the hot supply and return pipes, and VIP-left consistently recorded higher temperatures compared to VIP-right and VIP-down. The VIP-up sensor is affected by heat from both the supply and return pipes, while VIP-down is influenced by the supply pipe on one side and colder surrounding soil on the other. This spatial variation in surface temperature is expected due to the asymmetric thermal environment around the pipe. In particular, the lower temperatures recorded at the VIP-right position may be attributed to the presence of a nearby water stream on that side of the field, which likely increases local soil cooling and enhances lateral heat loss.

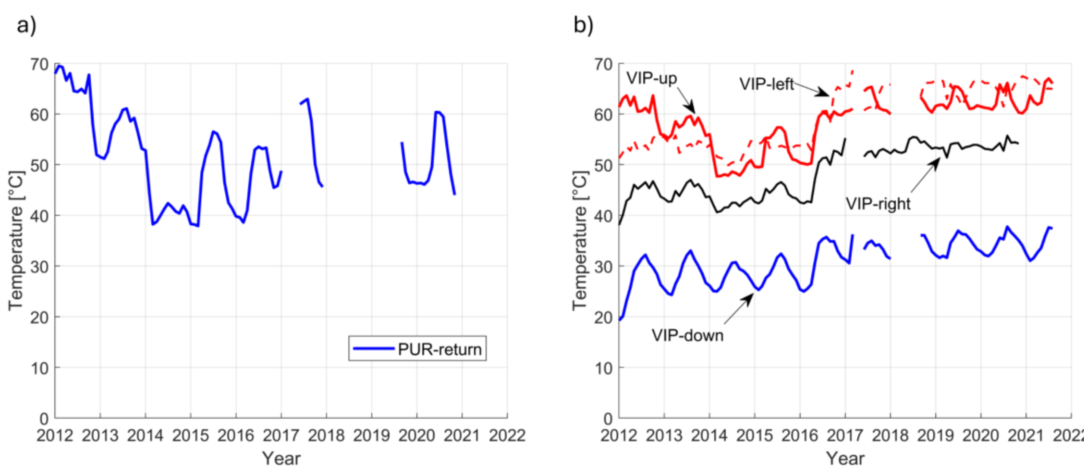

Figure 5. a) Monthly average return temperatures measured in the Varberg field installation. (b) Surface temperatures at four positions on the VIP in the hybrid-insulated section.

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Figure 6 illustrates the fractional temperature difference between the surface of a 10 mm PUR-insulated section and that of a 10 mm VIP-insulated section, for two positions: a) VIP-up and b) VIP-left, as defined in Figure 2. Assuming the thermal performance of PUR remains stable over time, any decline in the fractional difference may indicate performance degradation of the VIPs. For the VIP-up position, which is exposed to high temperatures from both the supply and return pipes, the fractional difference fluctuates seasonally between around 5% and 20% throughout the measurement period. No clear downward trend is observed, suggesting stable thermal performance over the full nine-year span. This also shows that the pipe insulated with VIP shows up to around 20% better thermal performance than the one insulated with PUR. In contrast, the VIP-right position exhibits a gradual decline in fractional difference, with peak values decreasing from approximately 40% at the beginning of the measurement period to around 25% at the end. This trend indicates a potential degradation of the VIP's thermal performance. When comparing seasonal peaks with similar supply temperature conditions, this corresponds to an average annual degradation rate of approximately 1.6%. This estimate is consistent with earlier findings reported in [2,10] based on the first four years of data.

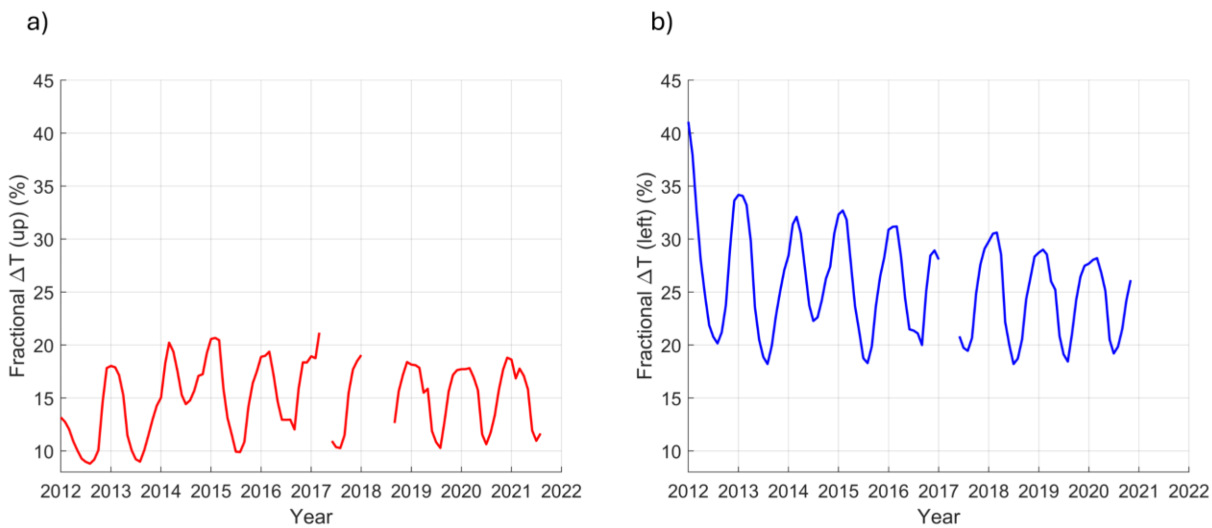

Figure 6. Fractional temperature difference (($\Delta T = \left((T_{PUR}/T_{VIP}) - 1\right) \cdot 100$)) between 10 mm PUR and 10 mm VIP sections in the Varberg field installation. a) Position VIP-up (between supply and return pipes). (b) Position VIP-left.

In the Linköping field station, two VIP types were monitored in a single pipe configuration. As shown in Figure 7a, the monthly average supply temperatures ranged between 70-95 °C over the full seven-year period. Figure 7b illustrates the monthly average temperature difference between the pipe sections insulated with conventional PUR and those insulated with VIPs, measured 10 mm from the pipe surface. The results indicate that the VIP-insulated sections consistently exhibited exterior temperatures approximately 20–30 °C lower than those of the corresponding PUR-insulated sections. A brief anomaly is visible between 2018 and 2019, likely due to a temporary system shutdown or maintenance activity. As this deviation is short and not representative of normal operation, it has not been further analyzed.

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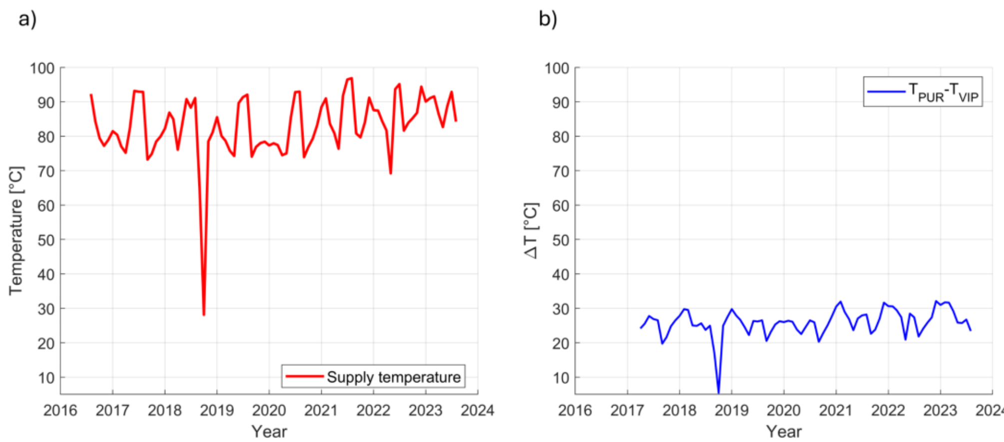

Figure 7.Linköping field installation results. a) Monthly average supply temperature. (b) Temperature difference measured 10 mm from the pipe surface for all VIP and PUR pipe sections.

Figure 8 presents the monthly average temperatures measured at the exterior surface of the 10 mm VIPs in the Linköping single pipe installation, comparing the two envelope types: metallized and aluminum-coated polymer films. Throughout the measurement period, the metallized VIPs consistently exhibited surface temperatures up to 5 °C lower than those of the aluminum-coated VIPs, indicating a better overall thermal performance. This is in line with expectations, as metallized envelopes typically have lower aluminum content and fewer continuous aluminum layers, resulting in reduced thermal bridging effects compared to the aluminum foil variant. While the difference between the two types was relatively small during the first 2–3 years, a gradual increase in the temperature gap is observed over time. This may be partially related to variation in DH supply temperatures but could also reflect material differences. However, due to the small magnitude of the difference and the variations in operating conditions, no definitive conclusion can be drawn regarding long-term performance stability. Notably, the aluminum-coated VIPs are expected to have significantly lower gas permeability than the metallized variant, according to manufacturer specifications, which could result in more stable performance over extended periods.

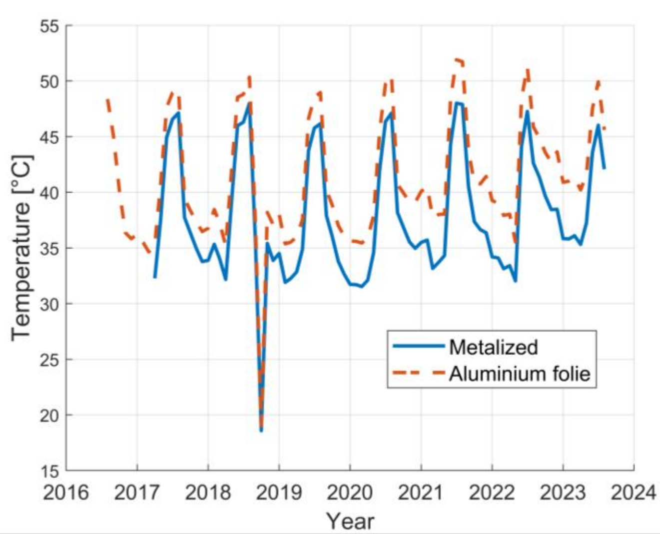

Figure 8.Monthly average temperatures measured at the exterior of 10 mm VIPs in the Linköping installation, comparing metallized and aluminum-coated envelope types.

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Conclusions

This study presents long-term field measurements from two district heating installations in Sweden, assessing the thermal performance and durability of vacuum insulation panels (VIPs) under operational conditions. In Varberg, VIPs installed in a twin pipe configuration were monitored for over nine years. The results indicate that VIP-insulated sections maintained a clear thermal advantage over conventional polyurethane insulation, up to 20 %. In one measurement position, a degradation rate of approximately 1.6% per year was observed, consistent with earlier findings from the same installation. In Linköping, a single pipe configuration was used to compare two VIP envelope types over seven years. Metallized VIPs exhibited better thermal performance than aluminum-coated VIPs. Long-term performance differences could not be firmly established, due to the relatively small temperature variations, and fluctuations in supply temperature. The results confirm the long-term viability of VIPs in district heating applications and underline the relevance of envelope material design. Future research should further investigate material-specific differences, including gas diffusion characteristics and mechanical durability under extended high-temperature exposure.

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