Drying Capacity of Underpressure and Mechanical Ventilation Solutions in Low-Slope Roof Structures

By Katarina Hellén

MOISTURE MANAGEMENT IN low-slope roof structures is a challenge for long-term integrity. When present, moisture within roof structures can reduce the functional properties of the insulation layer, increase the risk of mold proliferation that can cause premature decay of the structures, and shorten the lifespan of the roof itself. Moisture accumulation within the roof structure can result from various factors, including condensation due to temperature differences or shifts and unintended water ingress from leaks. Moisture can also enter the roof assembly through air leakage paths in the vapor barrier or other layers. In such cases, warm, humid indoor air moves by convection into cooler parts of the insulation, where the water vapor condenses. This process can lead to localized wetting deep within the insulation, even in the absence of a bulk water leak.

One established, though less commonly used, strategy to mitigate moisture-related issues is the ventilation of roof structures, aimed at facilitating the drying of accumulated moisture. In some regions and countries, incorporating ventilation into roofing design is more common than in the United States. For instance, Finland—located in Northern Europe—explicitly recommends roof ventilation due to its substantial annual temperature fluctuations and pronounced differences between indoor and outdoor conditions, which notably amplify condensation risks.

Although ventilation comes with benefits, many aspects remain underexplored in both academic literature and industry practice, making the implementation of ventilated roof structures challenging. Specifically, questions regarding the effectiveness of ventilation systems in adequately addressing moisture require further investigation. For instance, how much ventilation is necessary to achieve effective drying?

This article addresses this gap by focusing on the drying capacity of ventilation in low-slope roof structures. Using modeling techniques to simulate a roof leak, two ventilation strategies were examined: underpressure ventilation, in which wind-induced suction at roof vents creates negative pressure to draw moist air from the roof assembly; and mechanical ventilation, which actively extracts air using a fan. Findings indicated that both systems facilitated drying of the insulation layer, but the process was twice as fast with mechanical ventilation compared to underpressure ventilation (1.5 years compared to nearly 3 years). In some cases, the drying achieved through underpressure ventilation was not sufficient to prevent mold growth.

VENTILATION OF ROOF STRUCTURES

Underpressure ventilation functions through the interaction of wind flow and specially designed ventilation vents installed on the roof. As wind moves across and around these vents, a vacuum is created, drawing moist air from within the roof structure and promoting the drying of the insulation layer. This method relies entirely on natural forces, such as wind speed and atmospheric pressure differences, to facilitate air movement. The number and placement of ventilation vents are typically determined by factors such as roof size, climate conditions, and the complexity of the roof's geometry. Air exchange rates for passive underpressure systems generally range from 20 to 40 air changes per hour (ACH).

In contrast, mechanical ventilation integrates an electrically powered fan into the ventilation system to actively extract moist air from the structure, making it independent of weather variability. These systems can achieve air exchange rates of up to 140 ACH. Advanced mechanical systems often feature demand-based steering, in which the fan operation dynamically adjusts based on real-time conditions. When moisture levels within the structure rise and outdoor air is sufficiently dry, the fan increases its speed to maximize drying efficiency. Conversely, when the outdoor air is humid or when temperatures drop to freezing, the fan slows down or shuts off completely to prevent adverse effects. Sensor arrays embedded in the system continuously monitor both temperature and humidity inside the roof assembly and in the outdoor environment to guide these adjustments.

CALCULATION MODEL AND METHOD

To investigate the drying performance of roof ventilation systems, a hygrothermal simulation study was conducted. The objective was to compare the moisture removal capability of underpressure ventilation and demand-controlled mechanical ventilation in a low-slope roof assembly following a moisture event. The simulations were carried out by Ramboll Finland Oy using WUFI Pro 5.3 software, commissioned by VILPE Oy.

Roof Assembly and Boundary Conditions

The modeled structure represents a low-slope roof featuring integrated ventilation grooves within the insulation layer. These grooves—small air channels either premanufactured or formed on-site—are designed to facilitate airflow within the structure and support moisture removal. The assembly consists of a 40 mm (1.6 in.) precast concrete slab (double-tee slab), a bitumen vapor barrier, and a 370 mm (14.6 in.) mineral wool insulation layer topped with an additional 30 mm (1.2 in.) surface insulation layer. Ventilation grooves (20 mm × 30 mm [0.8 in. × 1.2 in.]) were placed between the insulation layers with a spacing of 200 mm (7.9 in.).

The insulation properties used in this study represent generic mineral wool characteristics. Installation details, such as mechanically fastened versus adhered roof assemblies, were not explicitly modeled, as they do not influence the one-dimensional hygrothermal drying behavior evaluated in this study. Ventilation grooves within the insulation layer can be implemented either by using insulation boards manufactured with integrated channels or by forming ventilation grooves on-site during construction. The specific implementation and detailing of such assemblies depend on local products, codes, and roofing system requirements and must be addressed during project-specific design.

> While both underpressure and mechanical systems were capable of drying the roof structure over time, the mechanical ventilation system consistently outperformed the passive approach in terms of both drying speed and moisture safety.

The initial moisture content of the insulation was set at 30 kg/m^3 (1.9 lb/ft^3), representing conditions commonly observed following a roof leak. Outdoor climate data were based on a representative cold-climate location with significant seasonal temperature and humidity variation. Indoor conditions were modeled to represent a moderate-humidity storage or utility space, with an indoor temperature of 21°C (69.8°F) and seasonal absolute humidity values of approximately 3 g/m^3 (0.19 lb/1000 ft^3) in winter and 1 g/m^3 (0.06 lb/1000 ft^3) in summer.

To isolate the effect of ventilation, no wind-driven rain was modeled, and it was assumed that no airflow occurred through the structure. The roof was modeled as flat and oriented due south.

Ventilation Scenarios

Two ventilation approaches were analyzed:

- *Underpressure ventilation* utilizing wind-driven airflow through an underpressure vent with a diameter of 110 mm (4.3 in.). This type of ventilation creates airflow as wind passes over the vent, generating suction. Air exchange rates between 20 and 40 ACH were used, depending on wind speed, based on empirical measurements provided by the underpressure vent manufacturer.
- *Mechanical ventilation* was simulated using a commercially available demand-controlled mechanical ventilation system, which includes sensors and a fan that adjusts airflow in real time based on measured temperature and humidity inside the structure and outdoors. The system allows for significantly higher air exchange rates—up to 140 ACH—when conditions are favorable for drying. In this study, the system was modeled on the specifications of the manufacturer.

The simulations assumed one ventilation unit per 150 m^2 (1,600 ft^2) for underpressure ventilation and one mechanical ventilation unit per 200 m^2 (2,200 ft^2). The mechanical system's airflow was dynamically adjusted according to a control algorithm, which increased ventilation when outdoor air was dry and indoor moisture levels were high and reduced or stopped airflow during unfavorable conditions (for example, cold or humid outdoor air).

Simulation Parameters

The simulations ran for a 3-year period (January 2023 to January 2026), with moisture content tracked at three key points within the structure: the surface of the top insulation layer, the interface between insulation layers, and the bottom of the main insulation layer.

To assess mold risk, the Finnish Mold Index Model[1,2] was used. Mineral wool was assigned to sensitivity class 3 for both growth and degradation, with a retreat rate of 0.1. The airflow rates (L/s) were converted into ACH using standardized formulas, and the ventilated groove geometry was represented as a continuous 5 mm (0.2 in.) air layer, corrected by a factor of 1.666 to account for the actual groove configuration.

RESULTS

The simulation revealed distinct differences in moisture-drying performance between the two ventilation strategies. While both underpressure and mechanical systems were capable of drying the roof structure over time, the mechanical ventilation system consistently outperformed the passive approach in terms of both drying speed and moisture safety.

With demand-controlled mechanical ventilation, the mineral wool insulation reached equilibrium moisture levels in less than 1.5 years. In comparison, underpressure ventilation required nearly 3 years to reach similar conditions. At the interface between insulation layers, drying occurred in approximately 1 year with mechanical ventilation, whereas underpressure ventilation approached equilibrium only after nearly 3 years. This drying delay highlights a principal limitation of passive systems: while they may eventually remove moisture, they may not do so quickly enough to prevent secondary damage. Faster drying is especially critical in situations involving elevated initial moisture, such as after a leak.

With underpressure ventilation, mold index values exceeded the critical threshold of 3.0 in the upper insulation layer, indicating a potential for visible mold growth. The top layer reached a mold index of 3.3, and the insulation interface reached 3.2. In contrast, the demand-controlled mechanical system maintained all values well below the risk threshold: 0.7 in the top layer and 0.5 at the interface. These results demonstrate that prolonged exposure to high humidity—more likely in passive systems—significantly increases the potential for microbial growth.

Relative humidity (RH) trends further supported these findings. Under underpressure ventilation, RH in the upper insulation remained near saturation (close to 100%) for long periods. Mechanical ventilation, however, reduced RH in this zone to 20% to 60% within the first 1.5 years. While seasonal variation was still present in the lower insulation, overall RH remained consistently lower with mechanically controlled airflow.

DISCUSSION

The findings of this study highlight significant differences in drying performance between underpressure and demand-controlled mechanical ventilation systems in low-slope roof structures. While both approaches were capable of reducing moisture over time, only the mechanical system consistently achieved drying within a time frame likely to prevent damage. This finding has implications for moisture management strategies in modern roof design.

Although the simulated roof structure dried under both ventilation regimes, the pace of drying varied substantially. Mechanical ventilation reduced the moisture content of the insulation to safe levels in under 1.5 years, while underpressure ventilation required nearly 3 years to achieve comparable results. These findings suggest that drying time itself should be viewed as a critical parameter in assessing the performance of ventilated roof systems.

While traditional ventilation design tends to focus on achieving air movement, these results support a more performance-oriented approach—one that considers how rapidly moisture can be removed in the aftermath of a leak, moisture intrusion, or condensation. In particular, buildings in humid or cold climates, where drying potential is already limited, may benefit from adopting drying time as a design criterion alongside thermal resistance, fire ratings, or other performance metrics.

While the results presented here are specific to mineral wool insulation—which has relatively high moisture tolerance and drying potential—other insulation types, such as expanded polystyrene, extruded polystyrene, or polyisocyanurate, differ in vapor permeability and moisture retention. Drying performance can therefore vary, and designers should evaluate ventilation strategies in the context of material properties rather than assume direct transferability of these results.

In many regions in North America, low-slope roof assemblies are not ventilated at all. Even when ventilation is included, its design often lacks detailed performance specifications. The results of this study challenge the assumption that natural drying is sufficient under all conditions and raise questions about the role of ventilation in long-term roof durability. While this study focuses on drying performance, the decision to implement ventilated roof assemblies is ultimately a risk-management question that balances added system complexity against the potential consequences of prolonged elevated moisture. Ventilated solutions may be most appropriate in environments with higher condensation risk, such as climates with cold winters and warm summers or large seasonal humidity swings, where drying potential can vary substantially over the year. In these contexts, improved drying capacity can be viewed as a durability measure intended to reduce time-of-wetness and associated mold risk, rather than as a universal requirement for all low-slope roofs.

Given the increased use of thick insulation layers to meet energy codes and the growing risk of moisture events from extreme weather, revisiting the role of ventilation in roof design may be timely. In particular, demand-controlled mechanical ventilation offers a means to actively manage moisture, accelerating drying when conditions allow and minimizing energy use otherwise. These systems may be especially beneficial in climates with seasonal humidity, limited solar drying potential, or where the consequences of moisture damage are severe (for example, healthcare or high-value facilities).

Real-World Verification and Model Limitations

It is important to acknowledge the limitations of this simulation study. The model assumes no wind-driven rain and no air leakage through the roof assembly. In real-world applications, factors such as installation quality, geometry (for example, parapets and overhangs), vent placement, and local wind exposure can influence ventilation performance. For underpressure systems in particular, localized wind patterns and obstructions may reduce effectiveness, especially on complex or shaded roof sections.

Furthermore, while airflow rates were derived from empirical data, real buildings may exhibit dynamic and site-specific behaviors not captured in the model. This underlines the need for field measurements to validate simulation outcomes and to better understand drying dynamics in occupied buildings.

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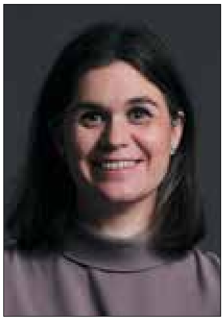
ABOUT THE AUTHOR



KATARINA HELLÉN

Katarina Hellén *is a member of the leadership team at VILPE Oy, where she oversees research and communication with a focus on technical writing and product communication for the building industry. She has a background in developing training programs, conducting market research, and creating technical content for construction professionals. At VILPE, she works closely with product development and engineering teams to translate complex building science topics into practical, application-focused materials for industry stakeholders.*

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