INFLUENCE OF MEMBRANE ON AIRFLOW IN HISTORICAL ATTIC SPACES: THE FIRST PRINCIPLES STUDY USING CFD MODELS

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Abstract
This paper conducts an initial analysis of the impact of a vapour permeable membrane on airflow within triangular attic spaces, resembling the shape and dimensions of medieval sanctuaries found in historical rural churches in our region. The first principles study, using Computational Fluid Dynamics (CFD) based on the simulation models, aims to identify potential challenges and research directions regarding how the application of this membrane may affect the microclimatic conditions in the attic spaces and the durability of the historical timber trusses. One significant outcome of the study reveals that on a simulated extremely hot summer day, the application of the vapour permeable membrane reduced airflow by 10 to 15 per cent, thus affecting the overall microclimate in the attic.

Keywords
Vapour permeable membrane, airflow, attic space, CFD, microclimatic conditions

1 INTRODUCTION

An increasingly vital aspect of preserving historical roofs is ensuring optimal conditions of the indoor climate within attic spaces of historical buildings. Despite being typically unused, these spaces are essential for the preservation of historical timber roof trusses, as microclimatic conditions may affect their durability [1].

The microclimate in attic spaces is mainly influenced by the structural design of the roof, its ventilation method and the associated external weather conditions [2], [3]. The absorption of solar radiation by the roof covering, which affects air circulation, also plays an important role [4], [5]. The storage capacity and high thermal inertia of stone masonry wall and ceiling constructions, in turn, contribute to stabilise the temperature in the attic spaces [6], [7]. However, this is not the case for wooden wall and ceiling constructions due to their low thermal inertia making them susceptible to external conditions [8], [9].

Unheated attic spaces, commonly referred to as “cold attics”, are among the most challenging from a hygrothermal point of view [10]. Most roof trusses with impermeable roofing and lacking ventilation holes show the greatest biological damage [11]. Additionally, the orientation of the roof plays a key role. Roofs where one of the main roof planes is oriented to the north often show a higher risk in terms of biological degradation mainly due to lower temperatures, higher relative humidity and limited solar radiation [12].

Currently, several solutions are available to optimise attic ventilation in historical buildings. However, these solutions must be developed and applied, with a focus on preserving the authenticity and historical value of the buildings. One advanced approach is the use of airflow simulations linked to energy simulations, and the results of the energy simulations can serve as input parameters for CFD models [13].

The nature of airflow in triangular spaces is well documented [14]. In a sunny summer day, natural airflow is produced by the difference in surface temperatures between the two roof planes and the stone construction. The question of what the nature of the flow will be in a space with vents and to what extent these vents will affect the nature of the flow on a windless day was attempted to be answered by a study [15] in which the authors simulated the airflow in the attic space of the sanctuary of a Roman Catholic church. The authors created a CFD simulation model to analyse in detail the temperature distribution and airflow. Images from the CFD simulations demonstrated increased airflow around the vents and also on the hot sloping roof planes and cool gable wall surfaces. This suggests that the existence of these zones contributes to air movement even when it is windless. These locations may be key to the analysis of the degradation of the timber parts of the roof truss. However, structural changes, such as the application of a roof vapour permeable membrane, may deprive the attic of the existence of these important zones. This can cause a fundamental change in ventilation and, therefore, a change in the microclimatic conditions in the attic.

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The objective of the present first principles study was to investigate the effect of a vapour permeable membrane on the airflow in a simulated attic space. The first alternative (Alt. 1) analysed the air behaviour in a conventional attic space, while the second alternative (Alt. 2) examines the theoretical assumption that the use of a vapour permeable membrane can significantly alter ventilation, which could increase the risk of biodegradation of the timber elements of a historical roof truss.

2 METHODOLOGY

Prior to creating the simulation models, it was necessary to define climatic data specific to the location [16]. These data were derived from the reference test year, managed by International Weather for Energy Calculations (IWEC), for the city of Ostrava.

Subsequently, the geometry of the attic space was modelled, including the composition of the structures as well as the position and dimensions of the ventilation holes (Fig. 1). The modelled attic space had a rectangular base with plan dimensions of 9.5 × 12.0 m and a gable roof with a usual gothic slope of 60 °. The overall height of this space was 8.2 m, which stemmed from the slope of the roof planes. The roofing consisted of strips of galvanised sheeting. The gable walls and the ceiling were constructed of stone masonry. For the purposes of the study of the first principles, the ceiling was not conceived as vaulted. As a result, the triangular attic space was formed by the ceiling, two gable walls and two roof planes. This space was oriented in the common east-west direction for medieval churches [17]. The ventilation of the attic space was provided in the simulation model by longitudinal vents in the lowest part of the roof, represented by narrow slits at the eaves combined with a longitudinal ridge vent in the highest part of the roof. Such ventilation method has been characterised as one of the basic types for attic spaces in historical buildings [1].

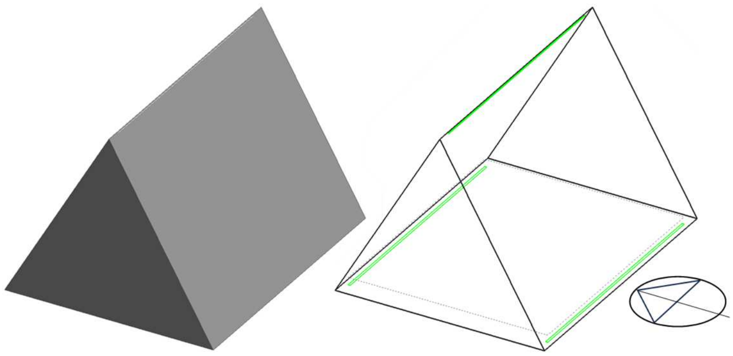

Fig. 1 Geometry and orientation of the modelled triangular attic space with green highlighted vents.

Using the simulation software DesignBuilder Engineering Pro v6.1.5.1, which consists of several modules [18], two different alternatives regarding the airflow in the triangular attic space were developed (Fig. 2).

Alternative 1 (Alt. 1)	Alternative 2 (Alt. 2)
• galvanised sheet metal roofing, thk. 0.7 mm • spruce wood boards, thk. 25.0 mm or ventilated air gap, thk. 25.0 mm	• galvanised sheet metal roofing, thk. 0.7 mm • spruce wood boards, thk. 25.0 mm or ventilated air gap, thk. 25.0 mm • ventilated air gap, thk. 40.0 mm • **vapour permeable membrane, thk. 0.3 mm**

Fig. 2 Roof sheathing layers in the direction from the outside to the attic space for both alternatives.

Airflow simulations in a dedicated CFD software module used the results of energy simulations from the EnergyPlus engine as boundary conditions. These conditions, such as surface temperatures and airflow through vents, were imported into the CFD module at hourly intervals during the summer day when air temperature peaked.

The airflow simulations were performed based on the finite volume method, where the entire interior space, i.e. 373.3 m^3, was divided into several small, closed volumes, i.e. cells with an edge of 0.2 m (Fig. 3). This division was performed using automatic hybrid discretisation by identifying all edges of the simulation model. As this is a first principles study, 53 cells were used in the X-axis direction, 49 in the Y-axis direction and 40 in the Z-axis

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direction. This grid density adequately captures small differences in flow velocity and air temperature for the purpose of the first principles study.

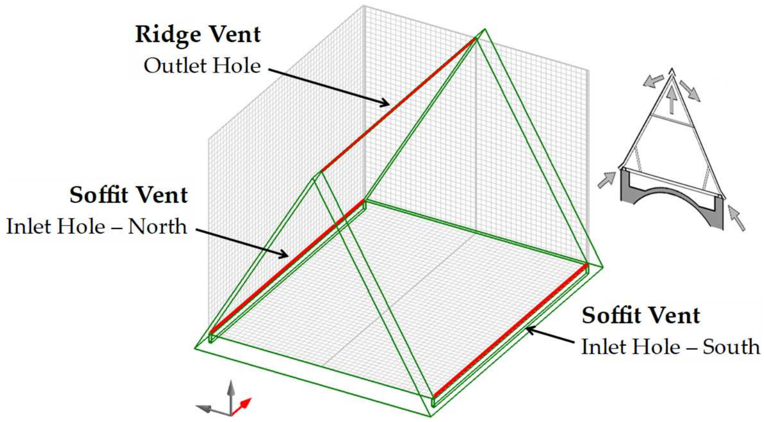

Fig. 3 CFD simulation model with the structured network (with more than 103,000 cells) and vents description.

In each closed cell, the continuity of flow, the law of conservation of momentum, energy and the concentration of the substance had to be observed, which was based on the turbulent flow of an incompressible Newtonian fluid, described by the Navier-Stokes equations [19]. The standard k-ε model was used to model the turbulence in the simulation software. Thus, a system of partial differential equations of conservation of mass and momentum for the three directions of velocity, conservation of energy, and two equations to describe turbulence were solved for the airflow. The simulation models converged after approximately 2500 iterations when the normalised residuals dropped to 10^{-5}.

3 RESULTS

DesignBuilder Engineering Pro v6 enabled detailed analysis and modelling of the attic spaces of historical buildings, incorporating energetic aspects and airflow.

Initially, an energy simulation using EnergyPlus was carried out on a daily and hourly basis for one full year, separately for the two analysed variants. A graphical representation of the results illustrates the difference between air temperature and air relative humidity (Fig. 4) as well as the difference in air change rate (Fig. 5) throughout the year. The data presented reflect the difference between the values from Alt. 1 and Alt. 2. A positive value indicates a higher temperature, relative humidity or air change rate in an attic without a vapour permeable membrane, while a negative value indicates a lower temperature, relative humidity or air change rate. The dotted trend line visualises the long-term trend of increase or decrease in the annual cycle.

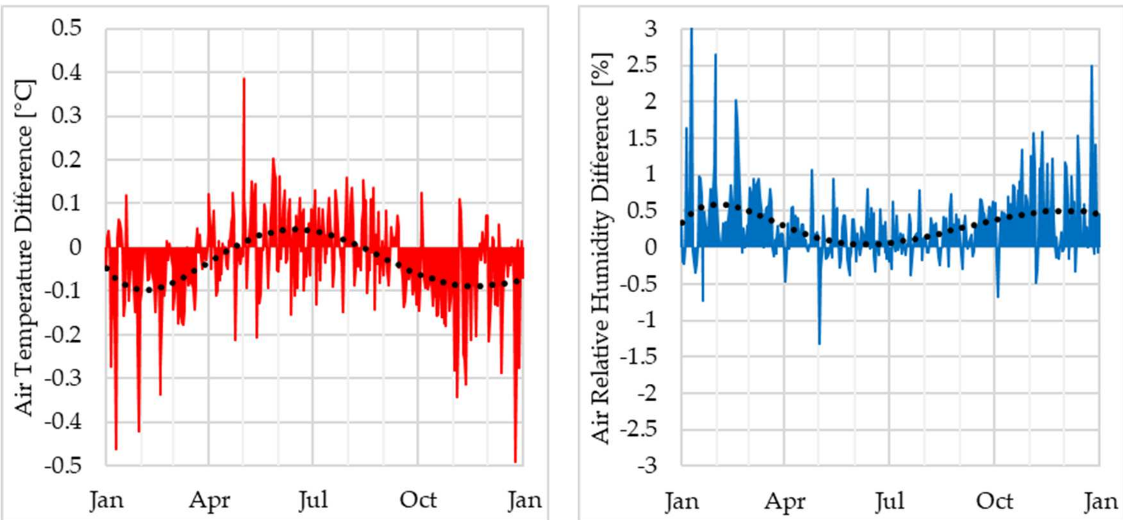

Fig. 4 Difference between Alt. 1 and Alt. 2 in terms of temperature and relative humidity in an annual cycle.

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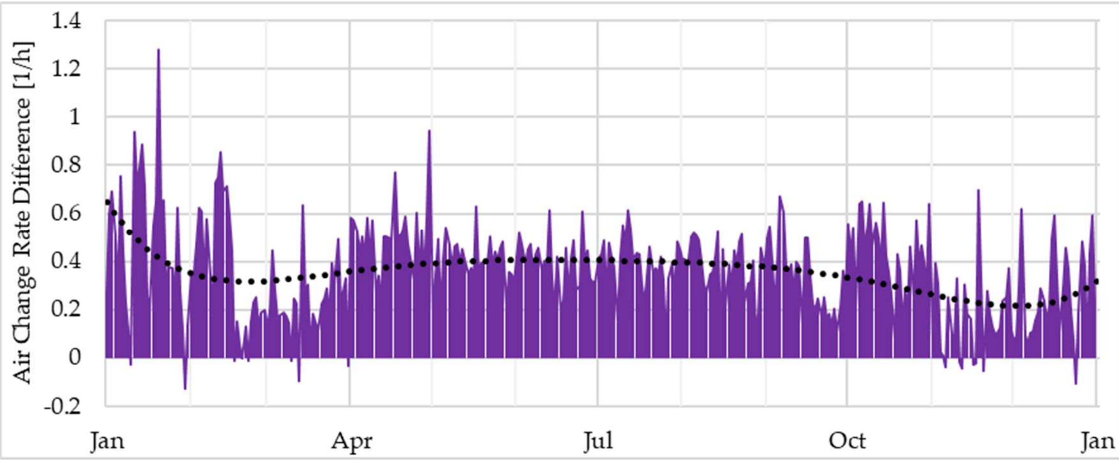

Fig. 5 Difference between Alt. 1 and Alt. 2 in terms of air change rate in an annual cycle.

The energy simulation showed, among other findings, extreme days during the year when the attic air temperature reached summer maxima (5 August) and winter minima (9 January). Further work focused on the extreme summer day, i.e. 5 August. The mentioned day was sunny in the morning, but in the afternoon, especially towards the evening, there was a noticeable decrease in the temperature at the external surface of the roof, which is evident in Alt. 1 (Fig. 6) and Alt. 2 (Fig. 7). This is related to the increased wind speed (Fig. 8). It is possible that this phenomenon could be associated with increased cloud cover in the afternoon.

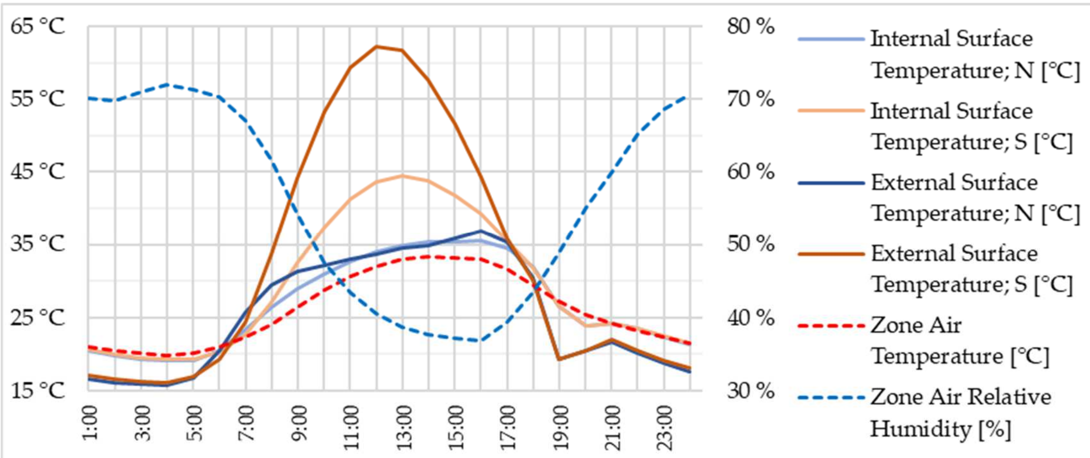

Fig. 6 Temperatures and relative humidity on 5 August for Alt. 1 (N – North Roof Plane; S – South Roof Plane).

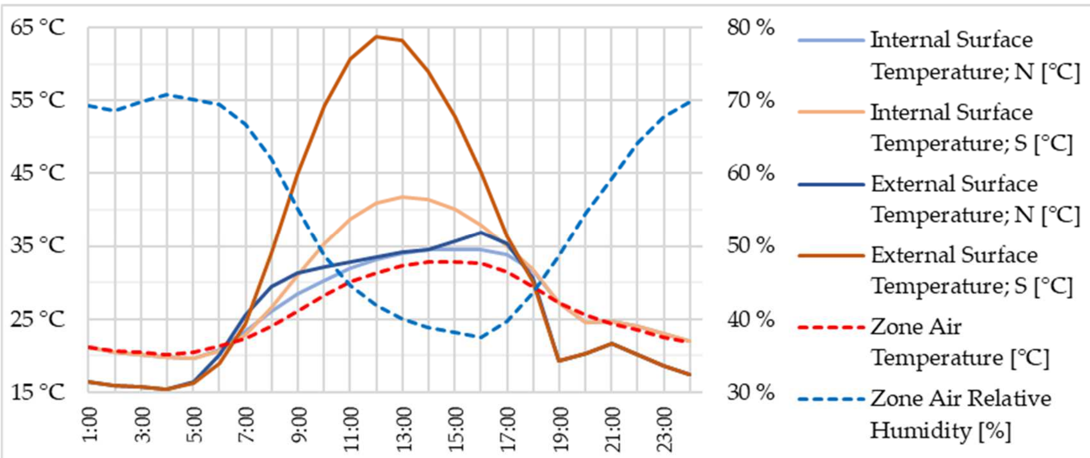

Fig. 7 Temperatures and relative humidity on 5 August for Alt. 2 (N – North Roof Plane; S – South Roof Plane).

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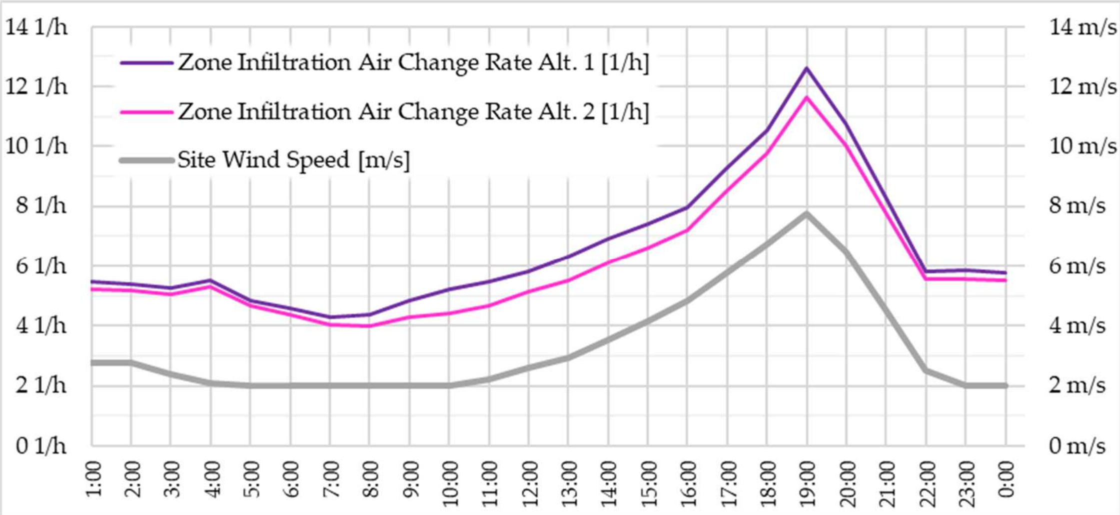

Fig. 8 Comparison of air change rates on 5 August between Alt. 1 and Alt. 2.

Subsequently, airflow simulations were performed at 13.00 h and 19.00 h on 5 August. At 13.00 h, only the south roof plane was illuminated, resulting in a temperature increase on the south side of the roof. At this time, the volume of airflow did not reach extreme values (Tab. 1), but the internal surface temperature on the south side of the roof was showing all-day peaks (Tab. 2). This situation led to different pressures between the two environments, whereby the influence of gravity, i.e. the effect of different air temperatures, led to airflow (Fig. 9). In the evening, at 19.00 h, the air velocity was at all-day peaks, which increased the air change rate in the attic space (Tab. 3). At the same time, the external surface of the roof cooled down due to wind (Tab. 4). Also, the flow that was produced by the different air pressures was caused by the wind when the wind kinetic energy was converted into pressure energy (Fig. 10).

The images from the CFD simulations at 13.00 h (Fig. 9) and 19.00 h (Fig. 10) depict air movement and air temperature. In the analysed space, the air movement is described by vectors, with the orientation of each vector indicating the direction of airflow and the colour representing the velocity of the flow. The colour scale of the texture represents the temperature distribution in this space.

Tab. 1 Airflow characteristics through the vents on 5 August at 13.00 h for both alternatives.

Vent Hole	Area [m^2]	Flow In [l/s]	Flow Out [l/s]	Air Temperature [°C]
		Alt. 1		
soffit vent – north side	1.074	336.567	-	
soffit vent – south side	1.074	336.567	-	30.40
ridge vent	0.644	-	673.134	
		Alt. 2		
soffit vent – north side	1.074	288.226	-	
soffit vent – south side	1.074	288.226	-	30.40
ridge vent	0.644	-	576.452	

Tab. 2 Surface temperatures on 5 August at 13.00 h for both alternatives.

Surface	Temperature [°C]	Surface	Temperature [°C]
		Alt. 1	
roof – north side	35.16	attic floor	30.59
roof – south side	44.70	stone masonry walls	30.41–30.44
		Alt. 2	
roof – north side	34.27	attic floor	29.92
roof – south side	41.92	stone masonry walls	29.77–29.79

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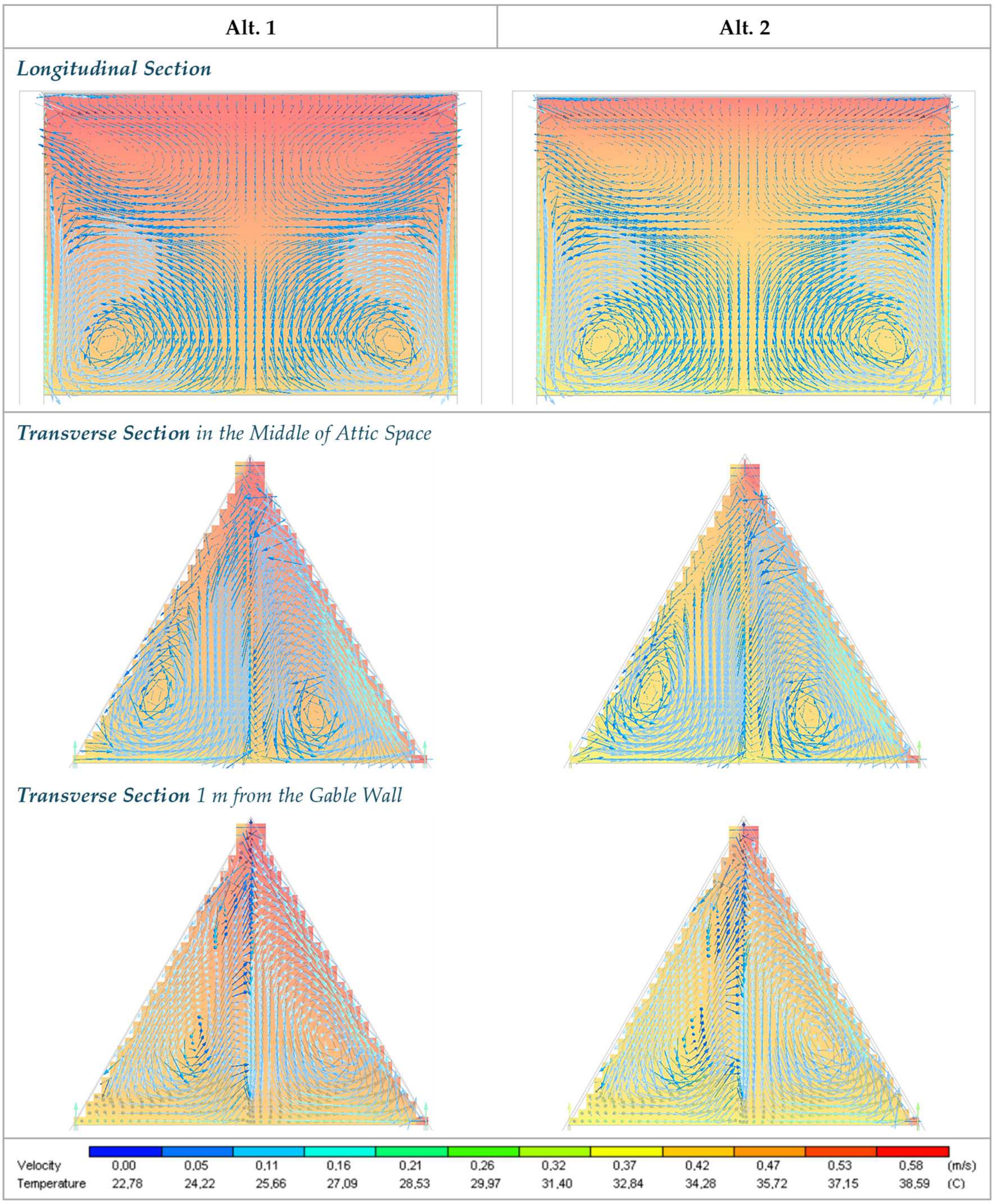

Fig. 9 Simulated airflow trajectories on 5 August at 13.00 h for both alternatives.

Tab. 3 Airflow characteristics through the vents on 5 August at 19.00 h for both alternatives.

Vent Hole	Area [m^2]	Flow In [l/s]	Flow Out [l/s]	Air Temperature [°C]
		Alt. 1		
soffit vent – north side	1.074	668.662	-	
soffit vent – south side	1.074	668.662	-	26.10
ridge vent	0.644	-	1337.324	
		Alt. 2		
soffit vent – north side	1.074	604.796	-	
soffit vent – south side	1.074	604.796	-	26.10
ridge vent	0.644	-	1209.592	

Tab. 4 Surface temperatures on 5 August at 19.00 h for both alternatives.

Surface	Temperature [°C]	Surface	Temperature [°C]
		Alt. 1	
roof – north side	26.74	attic floor	30.59
roof – south side	26.68	stone masonry walls	29.13–29.30
		Alt. 2	
roof – north side	27.47	attic floor	30.44
roof – south side	27.42	stone masonry walls	28.96–29.13

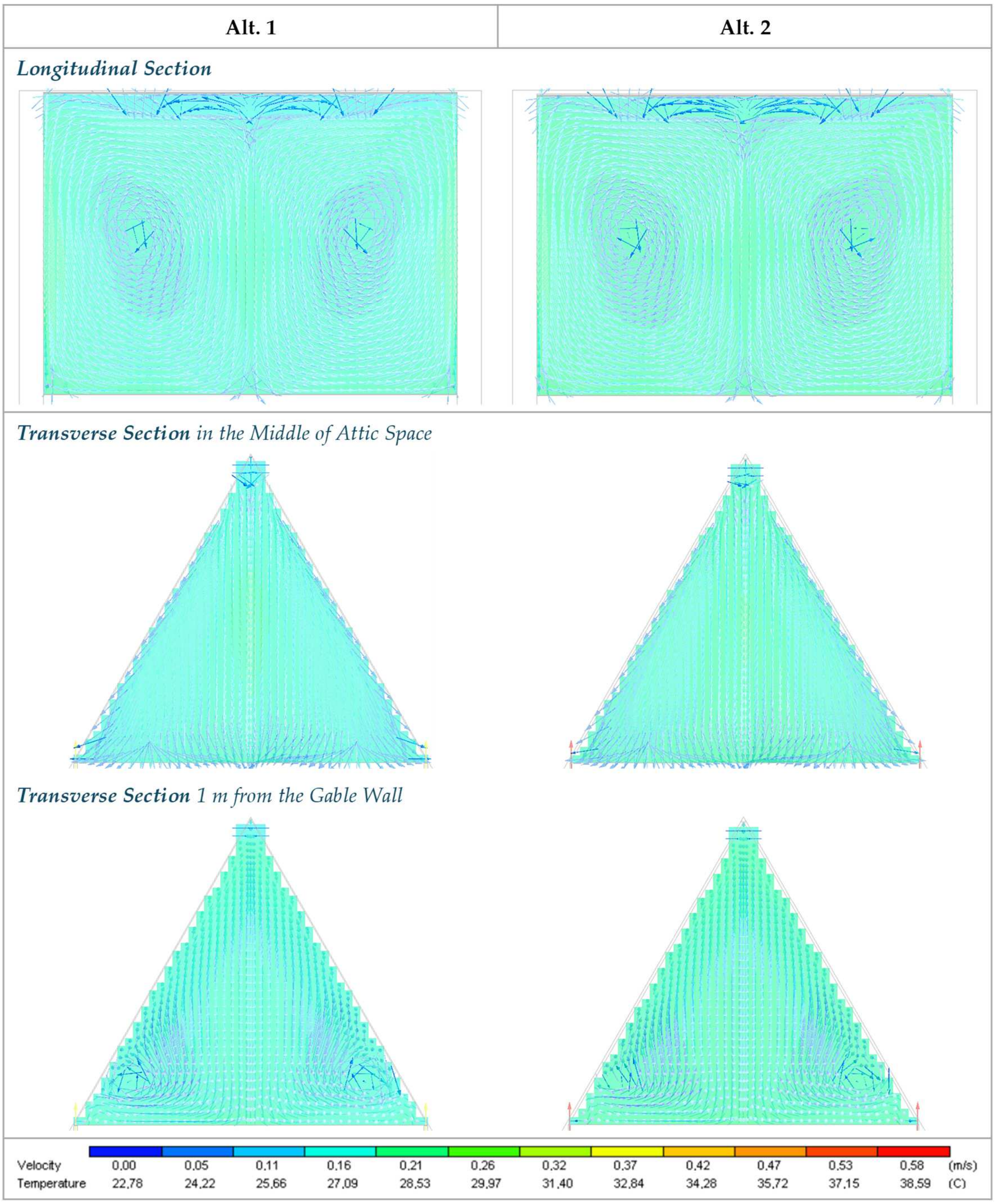

Fig. 10 Simulated airflow trajectories on 5 August at 19.00 h for both alternatives.

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4 DISCUSSION

The results of the annual simulation in a daily cycle indicate that the simulated attic space experiences a decrease in air temperature between May and mid-August when using a vapour permeable membrane. Daily fluctuations during this period are minimal, ranging from 0.1 to 0.2 °C. At the beginning of May, the air temperature in the attic space without a membrane is 0.4 °C higher than with a membrane. For the rest of the year, i.e. from January to May and then from mid-August to December, the situation changes. The roof sheathing without a membrane has lower temperatures in the attic space than the roof sheathing with a membrane. However, the air temperature is rarely higher in the attic without a vapour permeable membrane. The maximum difference in air temperature between the two alternatives during this period is 0.5 °C. On average, however, the difference is 0.05 °C. Regarding relative humidity, it can be observed throughout the year that the use of a vapour permeable membrane leads to a slight decrease in relative humidity in the attic space. The maximum decrease occurs in winter when it reaches up to 3%. At the beginning of May, when the effect of the vapour permeable membrane on the air temperature changes, it is possible to observe a 1.5% higher relative humidity in the attic with a membrane than in the attic without a membrane. However, a slight decrease in relative humidity, on average 0.25%, can be observed on the annual cycle. In general, the above shows that temperatures beyond the summer period are higher and relative humidity lower when using a membrane (Fig. 4).

The effect of the vapour permeable membrane on the indoor climate is more severe in terms of the air change rate. The simulation shows that the air change rate is higher in the alternative without a membrane than in the alternative with a membrane. This difference is most striking in winter when it can reach up to 1.3 1/h. Higher fluctuations are also observed in winter. In May, when the influence of the membrane on the air temperature changes, a second extreme is observed, which is close to 1.0 1/h. This occurrence in early May confirms the correlation between temperature, relative humidity and airflow [20]. Overall, the use of the membrane leads to a reduction in air change rate of approximately 0.3 1/h throughout the simulation (Fig. 5).

Analysing surface temperatures, air temperature and air relative humidity waveforms on 5 August, several observations are made. On this day, which falls between May and mid-August, significantly higher surface temperatures can be observed on the south roof plane compared to those on the north roof plane. This difference is mainly influenced by the outside air temperature and solar radiation [21]. In terms of external surface temperatures, the maximum difference between the climatically different roof planes was approximately 25 °C. In the case of internal surface temperatures, this difference was around 10 °C and decreased by 7 °C when a vapour permeable membrane was used. The surface temperatures followed the pattern of air change rate, which was strongly influenced by the external weather conditions, in both Alt. 1 (Fig. 6) and Alt. 2 (Fig. 7).

The air change rate correlates with the wind speed and a roof without a vapour permeable membrane results in a higher air change rate. The difference between the attic with and without a membrane can be quantified at 0.5 1/h. Attics with an air change rate of 4.0 1/h are considered to be sufficiently ventilated where the risk of biodegradation is minimised [10]. On the day analysed, the average air change rate was 6.0 1/h, so it can be concluded that the simulation model is sufficiently ventilated, and the risk of biological degradation is minimised (Fig. 8).

Although the volume of airflow did not reach extreme values (Tab. 1), significant airflow occurs at 13.00 h near the massive gable walls and the south roof plane, which is exposed to solar radiation and thus significantly heated (Tab. 2). The air temperature increases in the attic space with height. The hot air in the ridge reaches almost 40 °C. Near the roof ridge, it creates overpressure, trying to escape through the ridge vent. However, not all the air can escape through this vent. Instead, it changes direction, bypassing the cooler roof plane and gable walls. This creates a large air vortex, which cools the air in the attic and eventually causes the air temperature in the simulated space to homogenise in the late afternoon (Fig. 9). The above findings confirm that locations influencing airflow may be more susceptible to changes in wood moisture content, as presented in another study [15]. At 19.00 h, the airflow is more pronounced than at 13.00 h, which is mainly due to higher wind speed. Thus, at this time, the air change rate increases (Tab. 3) and at the same time the roof surface cools (Tab. 4). In terms of airflow velocity, the highest velocities are achieved at the locations of the inlet vents. The situation is similar in the case of vapour permeable membrane application, with the difference that the temperature extremes in the attic space with the membrane are not as pronounced (Fig. 10).

Inaccuracies in the simulation model may be due to the fact that the ventilated air gap behind the vapour permeable membrane acts more as an insulating layer, which does not account for the actual airflow in the cavity as CFD simulations would require. Without taking into account the actual flow, this layer acts as an insulation that has a marginal effect on the hygrothermal performance of the attic space. Therefore, it is essential to find a way to properly model the airflow in the ventilated cavity created when using a vapour permeable membrane in the roof construction and how to apply it to these simulations.

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5 CONCLUSION

The presented first principles study focused on the analysis of the effect of a vapour permeable membrane on the airflow in the attic space, which was designed to replicate the dimensions, shape and construction of historical roof trusses in medieval sanctuaries of rural churches. Using energy simulation, the annual cycle was analysed, while the CFD-based analysis was aimed at an extremely hot summer day when airflow was affected by differences in thermal buoyancy and wind pressure.

The results of this initial study identified several key findings that provide valuable insights for future research and possible research directions:

- **Air Temperature** – The use of a vapour permeable membrane resulted in a slight reduction in attic air temperature during the simulated period, approximately May to mid-August. In the remaining parts of the simulated year, the situation was reversed, with minimal differences.
- **Air Relative Humidity** – The vapour permeable membrane caused a reduction in relative humidity in the simulated attic space, most pronounced in the winter period.
- **Air Change Rate** – The roof in which the vapour permeable membrane was absent had a higher air change rate, especially in winter. The use of the membrane reduced the air change rate by approximately 0.3 1/h in the simulated period.
- **Airflow Thermodynamics** – The vapour permeable membrane affected the airflow in the simulated attic space by reducing the airflow by 10 to 15% compared to the alternative without membrane. CFD simulations showed that the vapour permeable membrane affected the temperature and velocity patterns in the simulated space, especially around the roof planes and gable walls.

Overall, the presented study confirms that vapour permeable membranes have a significant influence on the microclimatic conditions in attic spaces. Future research should include more accurate modelling of airflow concerning realistic boundary conditions, geometry and materials. Investigating the influence of timber truss elements that create resistance to airflow may also provide new insights into this field. Nevertheless, all future research steps are limited by a proper understanding of the simulation software and its capabilities.

This study highlights the importance of computer simulations, ideally calibrated based on experimental measurements, in solving problems related to the analysis and preventive conservation of old ventilation techniques in historical buildings. Over and above that, by using these simulations, it would be possible to test various intelligent systems in the virtual world minimising risks before their implementation in real-world operations.

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References

[1] KORENKOVÁ, Renáta. Analýza podstrešných priestorov historických krovov. *36. mezinárodní vědecká konference kateder a ústavů pozemního stavitelství*. 2012. Pp. 49–52. (In Slovak)

[2] WALKER, I. S. and FOREST, T. W. Field Measurements of Ventilation Rates in Attics. *Building and Environment*. 1995. Vol. 30, no. 3, pp. 333–347. DOI 10.1016/0360-1323(94)00053-U

[3] SIBILLA, Luboš, VLČEK, Milan, STRUHALA, Karel and KŘÍŽ, Pavel. Analysis of Damage to the Historic Roof Truss in Terms of Internal Environment. *Advanced Materials Researc*h. 2014. Vol. 1041, pp. 341–345. DOI 10.4028/www.scientific.net/AMR.1041.341

[4] IFFA, Emishaw and TARIKU, Fitsum. Attic Baffle Size and Vent Configuration Impacts on Attic Ventilation. *Building and Environment*. 2015. Vol. 89, pp. 28–37. DOI 10.1016/j.buildenv.2015.01.028

[5] TARIKU, Fitsum and IFFA, Emishaw D. Temperature and Air Flow Patterns in Attic Roofs. *Journal of Architectural Engineering*. 2017. Vol. 23, no. 3, p. 04017014. DOI 10.1061/(asce)ae.1943-5568.0000261

[6] CAMUFFO, Dario, STURARO, Giovanni and VALENTINO, Antonio. Thermodynamic Exchanges between the External Boundary Layer and the Indoor Microclimate at the Basilica of Santa Maria Maggiore, Rome, Italy: The Problem of Conservation of Ancient Works of Art. *Boundary-Layer Meteorology*. 1999. Vol. 92, no. 2, pp. 243–262. DOI 10.1023/A:1002026711404

[7] TSILINGIRIS, P. T. Thermal Flywheel Effects on the Time Varying Conduction Heat Transfer through Structural Walls. *Energy and Buildings*. 2003. Vol. 35, no. 10, pp. 1037–1047. DOI 10.1016/S0378-7788(03)00053-7

[8] JURAS, Peter. Lightweight Timber-Framed Wall and Impact of Ventilated Cladding on the Possibility of Reducing Summer Overheating in Central Europe. *E3S Web of Conferences*. 2020. Vol. 172, p. 03009. DOI 10.1051/e3sconf/202017203009

[9] MARCU, Florin, HODOR, Nicolaie, INDRIE, Liliana, DEJEU, Paula, ILIEȘ, Marin, et al. Microbiological, Health and Comfort Aspects of Indoor Air Quality in a Romanian Historical Wooden Church. *International Journal of Environmental Research and Public Health*. 2021. Vol. 18, no. 18, p. 9908. DOI 10.3390/ijerph18189908

[10] RICHTER, Jan, STANĚK, Kamil, TYWONIAK, Jan and KOPECKÝ, Pavel. Moisture-Safe Cold Attics in Humid Climates of Europe and North America. *Energies*. 2020. Vol. 13, no. 15, p. 3856. DOI 10.3390/en13153856

[11] FRANKL, Jiri. Wood-Damaging Fungi in Truss Structures of Baroque Churches. *Journal of Performance of Constructed Facilities*. 2015. Vol. 29, no. 5, p. 04014138. DOI 10.1061/(asce)cf.1943-5509.0000632

[12] JENSEN, Nickolaj Feldt, BJARLØV, Søren Peter, JOHNSTON, Christopher Just, POLD, Casper Fabian Hillestrøm, HANSEN, et al. Hygrothermal Assessment of North-Facing, Cold Attic Spaces under the Eaves with Varying Structural Roof Scenarios. *Journal of Building Physics*. 2020. Vol. 44, no. 1, pp. 3–36. DOI 10.1177/1744259119891753

[13] ZHAI, Zhiqiang, CHEN, Qingyan, HAVES, Philip and KLEMS, Joseph H. On Approaches to Couple Energy Simulation and Computational Fluid Dynamics Programs. *Building and Environment*. 2002. Vol. 37, no. 8–9, pp. 857–864. DOI 10.1016/S0360-1323(02)00054-9

[14] SAHA, Suvash C. and KHAN, M. M.K. A Review of Natural Convection and Heat Transfer in Attic-Shaped Space. *Energy and Buildings*. 2011. Vol. 43, no. 10, pp. 2564–2571. DOI 10.1016/j.enbuild.2011.06.020

[15] PONECHAL, Radoslav, KRUŠINSKÝ, Peter, KYSELA, Peter and PISCA, Peter. Simulations of Airflow in the Roof Space of a Gothic Sanctuary Using CFD Models. *Energies*. 2021. Vol. 14, no. 12, p. 3694. DOI 10.3390/en14123694.

[16] JURAS, Peter and JURASOVA, Daniela. Outdoor Climate Change Analysis in University Campus: Case Study with Heat-Air-Moisture Simulation. *Civil and Environmental Engineering*. 2020. Vol. 16, no. 2, pp. 370–378. DOI 10.2478/cee-2020-0037

[17] MCCLUSKEY, Stephen C. Orientation of Christian Churches. *Handbook of Archaeoastronomy and Ethnoastronomy*. New York: Springer New York, 2015. pp. 1703–1710. DOI 10.1007/978-1-4614-6141-8_173

[18] DesignBuilder [online]. DesignBuilder Software Ltd, 2024 (accessed 30 October 2023) Available at: https://designbuilder.co.uk/

[19] DEVILLE, Michel O. Incompressible Newtonian Fluid Mechanics. *An Introduction to the Mechanics of Incompressible Fluids*. Cham: Springer, 2022. pp. 1–32. DOI 10.1007/978-3-031-04683-4_1

[20] TEISCHINGER, Alfred, AVRAMIDIS, Stavros, HANSMANN, Christian and MAYRHOFER, Ambros. Sawn Timber Steaming and Drying. *Springer Handbook of Wood Science and Technology*. Cham: Springer, 2023. pp. 1167–1210. DOI 10.1007/978-3-030-81315-4_23

[21] MICHÁLKOVÁ, Daniela and ĎURICA, Pavol. Measured Impact of Material Settlement in a Timber-Frame Wall with Loose Fill Insulation. *Buildings*. 2023. Vol. 13, no. 7, p. 1622. DOI 10.3390/buildings13071622