The Relation between Indoor and Outdoor Air Temperatures in Membrane-Covered Building

Measurements in Winter Conditions

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***Abstract*—Membrane-covered sports buildings have become increasingly common and widely used over the past decades. The primary reasons for selecting membrane covers are twofold: they are more cost-effective than the alternatives and they provide excellent natural illumination. Additionally, they offer protection from direct sunlight, wind, rain, and snow. However, it is well known that single-layer membranes do not provide sufficient thermal insulation. This research aims to investigate the relationship between indoor and outdoor air temperatures in a membrane-covered buildings. It is well established that in warm conditions, the indoor air temperature tends to be higher than the outdoor temperature. However, it remains unclear whether, in cold conditions, the indoor temperature can drop below the outdoor temperature.**

To explore this question, a field study was conducted on a selected building in Montenegro, which is entirely enclosed by a membrane structure. Indoor and outdoor air temperatures were recorded simultaneously over a 10-hour period during a winter day. The building was unoccupied during the measurement period, and no temperature control systems were in operation. The results showed that indoor temperatures rose significantly during daylight hours but dropped well below outdoor temperatures during the night. This unexpected nighttime temperature drop calls for further investigation to understand the underlying causes and potential implications for the thermal performance of membrane-covered buildings.

***Key words*—Membrane structures; air temperature; measurements; winter conditions.**

I. Introduction

The need for energy efficiency in buildings has become a top priority. Engineers are continuously seeking ways to reduce energy consumption and integrate innovative approaches utilizing renewable energy sources. At the same time, financial constraints are a significant consideration, urging designers to develop cost-efficient buildings. Membrane structures meet the demand for affordability well but are known for their low thermal insulation properties. In these structures, the membrane serves both as a covering material and, in many cases, as a load-bearing element. However, membranes are very thin and offer minimal thermal resistance. Therefore, additional improvements are necessary to reduce the energy required to maintain optimal indoor conditions.

This research focuses on the problem of indoor air temperature in a membrane-covered building during winter conditions. Specifically, it aims to confirm or refute claims from users of such buildings that, under certain circumstances, the indoor temperature drops below the outdoor temperature. This phenomenon seems counterintuitive and required scientific verification. If the claim is proven correct, further research will be necessary to identify the factors contributing to this behavior. Conversely, if the claim is proven false, the study will investigate why occupants perceive the indoor temperature as lower than it actually is.

Membrane structures possess unique properties compared to other building materials and structural systems. Their thermal performance has been the subject of multiple studies. Harvie's doctoral thesis [1] was a pioneering work in this field. Since then, various aspects have been analyzed in detail, though a definitive solution to the low thermal resistance of membranes has yet to be developed. One proposed solution is to install insulation on the membrane. Aerogels have been suggested as a potential insulation material [2], while other studies have explored double or multi-layered membrane structures as an alternative [3]. Recent advancements have enabled the installation of photovoltaic systems on membrane surfaces [4], [5]. Although PV systems do not directly reduce energy loss, they contribute to energy generation, albeit at a high initial cost, limiting widespread adoption.

Several studies have examined the thermal behavior of membrane-covered buildings. He and Hoyano analyzed the thermal environment under a semi-enclosed membrane structure in summer conditions [6], [7]. Another study investigated the thermal characteristics and comfort levels in large membrane-enclosed stadiums [8]. A comparison of single and double-membrane configurations has also been conducted [9], and the thermal behavior of the air layer between membrane layers has been analyzed [10]. Researchers from the University of Tokyo have published multiple studies on membrane structures. One paper explored the impact of retractable membranes on the indoor environment of a residential building [11], while another examined the effects of a retractable membrane ceiling in a large swimming hall on energy performance [12] and its long-term performance [13]. Additionally, a review of indoor thermal environments in membrane structures has been presented [14], along with an analysis of solar radiation heat transfer through membranes [15].

This paper presents research investigating the relationship between indoor and outdoor air temperatures in a membrane-covered building. Measurements were conducted during winter conditions in a single-layer membrane structure. The results will help guide further research and contribute to a better understanding of how membranes affect indoor environments. Understanding this relationship can aid in developing strategies to improve the thermal performance of membrane-covered buildings and reduce their energy consumption.

II. METHODOLOGY

The methodology for this study follows the approach proposed in [16]. This section provides a detailed explanation of the measurement setup used in the research.

A. *Selected building*

A single membrane-covered building was selected for this study. The building is located in Podgorica, Montenegro, in the western part of the city, in an area called Tološi, situated along Partizanski put street. The building is oriented approximately along a north-south axis. An aerial view of the structure is provided in Figure 1.

The building has a footprint of approximately 24x42 m, with a maximum height of 10.5 m. The supporting structure consists of an arched steel truss framework, with 11 arches spaced 4.2 m apart. The trusses have a height of 0.9 m. The membrane, made of PVC/polyester, serves as the primary covering material. The thickness of the membrane is approximately 1 mm. The north and south facades are also enclosed with the same membrane, without additional structural support.

Fig.1. Aerial view of the analyzed building in Podgorica

Fig.2. Exterior view of the analyzed building in Podgorica

Fig.3. Interrior view of the analyzed building in Podgorica

The building is intended for sports activities and is currently used for indoor football. The flooring consists of artificial turf. The structure is a standalone building with no annexes for changing rooms or restrooms. There are no adjacent high-rise buildings, though a large tree is located near its southern side. The building lacks heating, cooling, or ventilation systems. While the membrane had some minor damage, all detected issues were repaired before the study, ensuring there were no unintended openings. The building has only one entrance/exit, located on the northern section of the western wall. Figures 2 and 3 show the exterior and interior views of the building, respectively.

B. *Measurements*

To investigate whether the indoor temperature could drop below the outdoor temperature, a measurement methodology was established. A simple setup with two air temperature sensors was used. One sensor was placed outside the building, while the other was positioned inside. Both sensors were mounted at a height of 1.5 m. The sensors are very close one to another, as they are placed symmetrically with respect to the eastern wall, in the middle of the building. The outdoor sensor was shielded from direct sunlight and wind, while the indoor sensor was positioned near the eastern wall. The measurements were recorded using a Testo 735 device. The accuracy of the used sensors is ±0.2°C. As no automatic data collection system was available, manual readings were taken. The recording interval was set to 15 minutes, as air temperature fluctuations over shorter intervals were not expected to be significant.

Due to limited resources, measurements could not be conducted over multiple days. Therefore, a single day was selected for data collection, based on the criterion that the expected outdoor temperature range should be significant – ideally fluctuating by at least 10°C throughout the day. In contrast, some expected daily fluctuations were as low as 2°C, which would not provide sufficient data for analysis.

It was hypothesized that during nighttime, the indoor temperature would match the outdoor temperature due to the low insulation properties of the membrane, allowing rapid thermal equilibrium between the two environments. As the sun rises and outdoor temperatures increase, it was expected that the membrane would absorb solar radiation, becoming warmer than the outdoor air. Consequently, it was assumed that the indoor air temperature would rise above the outdoor temperature but remain lower than the membrane surface temperature.

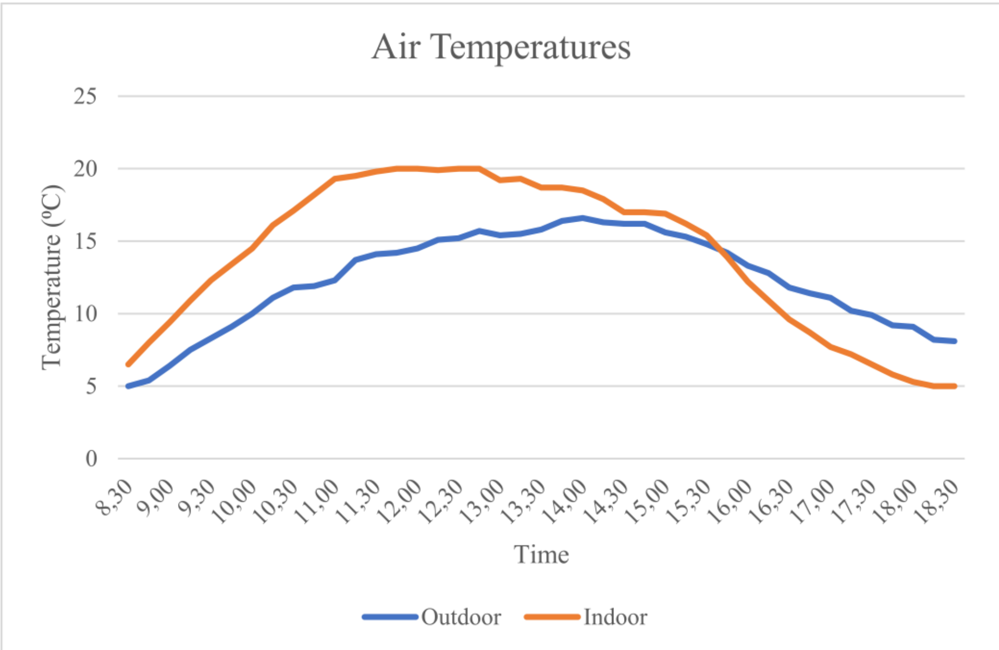

Fig.4. Measured air temperatures at the analyzed building in Podgorica

III. Results

The measurement was conducted in December 2024 at the selected location in Podgorica. The measurement process was intended to begin at sunrise, as it was expected that the indoor and outdoor air temperatures would be equal before this point. While the official sunrise time was estimated at 7:08, the actual sunrise at the site occurred at 7:40 due to the valley's topography.

For safety reasons, the measuring equipment could not be installed the previous day and was set up upon arrival at the site on the morning of the measurement. However, an oversight occurred when the research team failed to account for the initial temperature of the measuring equipment. Since the devices had been stored indoors at a warm temperature, they were significantly warmer than the air at the measurement site. The time required for the equipment to adapt to the ambient temperature was underestimated, resulting in the first reliable measurement occurring at 8:30. From that point onward, measurements were manually recorded every 15 minutes over a period of 10 hours. The recorded results are presented in Figure 4, showing the temperatures of both indoor and outdoor air.

During the measurement period, the building was not in use, eliminating interference from additional heat sources. The only people present were two research team members who recorded the temperature values. Their presence inside the structure was brief and occurred only at 15-minute intervals, making their influence negligible considering the building's size.

A deciduous tree is located on the south side of the building, casting a shadow on the southern façade. This shading effect could influence temperature readings during daylight hours; however, since the measurements were taken in winter when the tree had shed its leaves, its impact was minimal. The building has no heating, ventilation, or air conditioning systems, meaning that the indoor air temperature was passively controlled by environmental factors alone.

IV. Discussion

The obtained results are presented in the graph in Figure 4, allowing for better comparison and analysis. The first reliable measurement at 8:30 showed that the indoor temperature was already slightly higher than the outdoor air temperature. This was expected, as the sun had already been shining for approximately 50 minutes, warming the membrane and consequently increasing the indoor air temperature.

The outdoor air temperature gradually increased until 14:00, reaching a maximum of 16.6°C. After this point, the temperature began to decline. Minor fluctuations can be observed in the graph, likely caused by wind or cloud cover, but these are not significant to the study's primary focus. The largest increase between two consecutive measurements of outdoor air temperature was 1.4°C. Between 8:30 and 14:00, the temperature decreased only once, by 0.3°C at 13:00. After 14:00, no further increases in outdoor temperature were recorded. The lowest recorded outdoor temperature was 5°C at 8:30.

The indoor air temperature followed a somewhat different pattern. From 8:30 to 11:00, the temperature increased almost linearly. Between 11:00 and 12:45, it remained relatively constant before beginning to decrease. Initially, the decline was slow until 15:30, after which the temperature dropped more rapidly, reaching its lowest point at 18:15. The highest indoor air temperature recorded was 20°C, occurring multiple times between 11:45 and 12:45. Minor fluctuations were recorded, but only one instance of an increase was observed after 14:00, rising by just 0.1°C, which is not significant. The difference between the highest and lowest recorded indoor air temperatures was 15°C.

The temperature of the indoor air shows somewhat different behavior. From 8.30 to 11.00 the temperature increases almost in a linear fashion. Then, until 12.45 it stays relatively constant. Afterwards, it starts decreasing, at first slowly until 15.30, and then more rapidly until it reaches minimum at 18.15. The highest temperature of the indoor air is 20ºC, and it is achieved several times between 11.45 and 12.45. Here also some minor fluctuations are recorded. Once the temperature starts to decrease, it increases only once and only by 0.1ºC, therefore it is not significant. Difference between the highest and the lowest indoor recorded temperature is 15ºC.

The comparison between indoor and outdoor air temperatures is the central focus of this study, and the findings were unexpected. Initially, the temperature trends followed the anticipated pattern, with both temperatures rising due to solar radiation, though the indoor air temperature increased at a faster rate. The earlier peak of indoor air temperature can be attributed to the sun's incident angle, which resulted in the membrane reaching its highest temperature around noon, thereby transferring the most heat to the indoor air. Following this peak, the indoor air temperature began to decline. While the outdoor air was still warming, it slowed the rate of indoor cooling. However, as the outdoor temperature started to decrease, the indoor air temperature also dropped more rapidly.

What came as a surprise was that the indoor air temperature eventually fell below the outdoor air temperature, which occurred at 15:45. All subsequent measurements confirmed this trend, with the indoor temperature consistently remaining lower than the outdoor temperature.

The difference between the two temperatures reached its maximum at 11:00, with the indoor temperature being 7°C higher than the outdoor air temperature. From that point on, the gap decreased, except for two minor increases. The maximum temperature difference where the outdoor temperature was higher than the indoor temperature occurred at 18:00, with a difference of 3.8°C. This significant difference cannot be attributed to minor fluctuations. The graph provides strong evidence that the indoor temperature dropped below the outdoor temperature, confirming the claims made by users of such buildings.

The scope of this study was not extensive enough to determine the precise reasons for this behavior. It is evident that other factors influence indoor air temperature beyond the initial hypothesis. The assumption was that indoor air temperature would follow outdoor air temperature with a slight lag due to the membrane providing minimal thermal resistance. During the day, this relationship was disrupted by solar radiation, which heated the membrane and, in turn, the indoor air. However, this hypothesis was disproven during nighttime observations. In this research, thermal properties of membrane were not considered, as the goal was to just to compare the air temperatures inside and outside of the building.

V. Conclusion

This study investigated the temperature relationship between indoor and outdoor air in a membrane-covered building. The primary objective was to test the claim made by building users that indoor air temperature falls below outdoor temperature at night. It was initially hypothesized that after sunset, indoor and outdoor temperatures would equalize and remain the same until sunrise when the indoor air temperature would rise more rapidly due to membrane heating. The expectation was that the subsequent research will be aimed at identifying the reasons why users perceived indoor air as colder than outdoor air, with a follow-up study planned to analyze influencing factors.

Measurements were conducted in a selected building in Podgorica, chosen for its lack of HVAC systems, absence of occupants during the study, agreement from the owners, intact membrane (preventing unintended ventilation), and status as a typical representative of this type of structure. Data collection was performed using two sensors measuring indoor and outdoor air temperatures, recorded every 15 minutes over a 10-hour period on a winter day.

Unexpectedly, the results confirmed that indoor air temperature did indeed drop below outdoor air temperature at night, with a maximum recorded difference of 3.8°C. During the day, results followed expectations, with indoor temperatures significantly higher, reaching a maximum difference of 7°C. However, the study did not determine why the indoor air temperature dropped below outdoor temperature at night.

Further research is required to identify the factors responsible for this phenomenon. This study's value, despite limited resources, lies in its unexpected findings, which have prompted a follow-up study to explain this behavior and potentially develop solutions to improve comfort for users of such buildings.

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SAŽETAK

Sportske hale prekrivene membranom veoma su česte i intenzivno korišćene u poslednjim decenijama. Razlozi zbog kojih se membrana bira kao material za pokrivanje su dvostruki: jeftinija je od alternativnih rešenja i obezbeđuje odlično prirodno osvetljenje. Pored toga, pruža dobru zaštitu od direktne sunčeve svetlosti, vetra, kiše i snega. Međutim, poznato je da membrane sa jednim slojem ne omogućavaju dovoljnu toplotnu zaštitu. Ovo istraživanje ima za cilj da utvrdi odnos između unutrašnje i spoljašnje temperature vazduha u objektima prekrivenim membranom. Poznato je da se u toplim spoljašnjim uslovima vazduh unutar objekta zagreva više nego spoljašnji. Ipak, nije jasno da li temperatura vazduha unutar objekta može biti niža od spoljašnje temperature u hladnim spoljašnjim uslovima.

Kako bi se odgovorilo na ovo pitanje, sprovedeno je istraživanje na odabranom objektu u Crnoj Gori, koji je u potpunosti zatvoren membranskom strukturom. Unutrašnja i spoljašnja temperatura vazduha beležene su istovremeno tokom perioda od 10 sati u jednom zimskom danu. Tokom merenja objekat nije bio u upotrebi, a sistemi za regulaciju temperature ne postoje. Rezultati su pokazali da se unutrašnja temperatura značajno povećava tokom dana, ali tokom noći opada znatno ispod spoljašnje temperature. Ovaj neočekivani noćni pad temperature ukazuje na potrebu za dodatnim istraživanjima kako bi se razumeli uzroci i moguće posledice po toplotne karakteristike objekata prekrivenih membranama.

ODNOS IZMEĐU UNUTRAŠNJE I SPOLJAŠNJE TEMPERATURE VAZDUHA HALE POKRIVENE MEMBRANOM

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