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AMBIENT COMFORT IN MEMBRANE HALLS AS A FACTOR IN ENHANCING FUNCTIONAL AND ARCHITECTURAL BUILDING VALUES

Abstract:

Membrane halls represent a specific category of light, membrane constructions that are widely used for sports and recreational purposes due to their quick construction and economic efficiency. However, their application is often accompanied by challenges related to inadequate thermal performance, suboptimal daylight conditions and limited architectural expression. This paper shows the possibilities for improving the thermal performance of membrane structures, while simultaneously enhancing their visual and aesthetic qualities, as well as improving acoustic performance. The research analyzes key factors affecting ambient comfort and, consequently, thermal comfort and energy efficiency, including envelope materials, insulation strategies, pressurization and ventilation systems, and daylighting strategies. Enhancements in the performance of membrane structures are fundamentally based on the application of contemporary materials such as Polytetrafluoroethylene (PTFE) Coated Glass Fiber, PVC-coated polyester fabrics, and ETFE foils.

Keywords: membrane halls, ambient comfort, architectural design, contemporary membranes

АМБИЈЕНТАЛНИ КОМФОР МЕМБРАНСКИХ ХАЛА КАО ФАКТОР УНАПРЕЂЕЊА ФУНКЦИОНАЛНИХ И АРХИТЕКТОНСКИХ ВРЕДНОСТИ ОБЈЕКТА

Сажетак:

Мембранске хале представљају специфичну категорију лаких конструкција које се широко користе у спортске и рекреативне сврхе због брзе изградње и економске исплативости. Међутим, њихова примена је често праћена изазовима везаним за неадекватне термичке перформансе, неоптималне услове дневне светлости и ограничен архитектонски израз. Овај рад приказује могућности за побољшање топлотних карактеристика мембранских структура, уз истовремено побољшање њихових визуелних и естетских квалитета, као и унапређење на пољу акустичких перформанси. Истраживање анализира кључне факторе који утичу на амбијентални комфор, и последично, термичку удобност и енергетску ефикасност, укључујући материјале омотача, стратегије изолације, системе за регулацију притиска и вентилацију и оптимизацију дневне светлости. Побољшања перформанси мембранских структура у основи се заснивају на примени савремених материјала као што су стаклена влакна обложена PTFE-ом, полиестерске тканине обложене PVC-ом и ETFE фолије.

Кључне ријечи:мембранске хале, амбијентални комфор, архитектонско пројектовање, савремене мембране

1. INTRODUCTION

Contemporary architectural practice is increasingly oriented toward energy-efficient and functionally optimized buildings that meet criteria related to durability and structural performance. Membrane halls, as a specific category of lightweight prefabricated structures, are widely used in sports facilities, industrial buildings, and other temporary applications.

Membrane structures, unlike conventional structural systems that require extensive concrete work, have significantly shorter construction periods, resulting in reduced labor demand and lower energy consumption. However, their economic efficiency and rapid construction are often in conflict with the quality of the indoor environment.

Thermal and visual comfort, together with indoor air quality, are key parameters that determine the quality of occupancy within membrane structures. Improving the performance of such structures is not only a technical issue but also an architectural and design challenge that directly influences the visual experience, functionality, and overall sustainability [1].

As a rule, membrane structures can be harmoniously integrated into their surroundings. In the design process, special attention should be given to the relationship between the building and the surrounding landscape to ensure that the structure functions as an integral and coherent element of the space [2].

1.1. TYPOLOGY AND MATERIALIZATION OF MEMBRANE STRUCTURES

Membrane structures are characterized by their lightweight construction and the predominance of tensile forces in their structural behavior. Their typology is primarily defined by the structural principle through which stability is achieved [2], [3]. Understanding the relationship between structural type and material properties is essential for achieving durability, energy efficiency, and architectural expression.

1.2. CONSTRUCTIVE SYSTEMS OR TYPOLOGICAL DIVISION

The typological division of membrane halls is most commonly based on construction system, shape, support method, and purpose. From a typological standpoint, architectural membrane structures are grouped into three categories: tension and suspension membrane structures, frame membrane structures and air-inflated membrane structures.

1.2.1. Tension and Suspension Membrane Structures

The supporting system consists of cables, masts, and tensioners. The shape is obtained exclusively through membrane tensioning. These structures are widely used for covering large-span spaces, particularly sports facilities. The membrane structure is typically curved; also, its ability to span large areas without internal columns, makes this system particularly suitable for large enclosures, providing high spatial flexibility. However, the structure's large volume and absence of partitions present challenges in achieving adequate microclimatic conditions, as shown in Figure 1.

Figure 1. Example of tensile membrane structure used to cover large spaces [7], [8].

1.2.2. Frame Membrane Structures

This type of membrane structure consists of a rigid supporting system—most commonly a steel frame—over which a membrane is tensioned to form roofs or façade elements. Structural stability is ensured by the frame, arches, or spatial systems, allowing flexibility in design and adaptability to different scales, as shown in Figure 2. Due to its durability, versatility, and cost efficiency, this solution is widely applied and represents a more permanent alternative to pneumatic membrane structures.

Figure 2. *Frame-supported membrane structure, Akita Sky Dome in Japan [9].*

1.2.3. Air-Supported Membrane Structures

This type of membrane structure relies on continuous internal air pressure to inflate and stiffen membrane envelope, enabling the structure to carry self-weight and external loads, as shown in Figure 3.

Figure 3. A new generation of double membrane systems with several innovative sustainable solutions [10].

Air-supported structures are composed of one or more layers of high-performance membrane fabric that are thermally welded to ensure continuity and airtightness. Structural stability is achieved by maintaining constant internal air pressure generated by continuously operating air blowers, which counteracts external loads such as wind and snow.

In some cases, the membrane envelope may be additionally reinforced by a steel cable harness system, which enhances load distribution and overall structural reliability. Integrated HVAC systems regulate internal temperature, ensuring adequate environmental comfort under varying climatic conditions.

1.3. MEMBRANE ENVELOPE MATERIALS

Membrane structures are based on the use of high-strength, flexible, and lightweight materials that are capable of efficiently resisting tensile stresses. Common materials include PTFE-coated glass fiber, PVC-coated polyester fabrics, and ETFE foils.

Polytetrafluoroethylene (PTFE) Coated Glass Fiber, a high-performance composite material combining woven fiberglass with polytetrafluoroethylene (PTFE/Teflon™) resin, known for exceptional durability, self-cleaning properties, and longevity (over 25 years). It is commonly used for permanent, large-scale structures such as stadiums.

Polyvinyl Chloride (PVC) Coated Polyester is a synthetic polymer from the group of vinyl polymers, which is obtained in the process of polymerization of vinyl chloride. Its great advantage is primarily thermoplastic properties, mechanical strength and resistance to many substances. A cost-effective, flexible, and lightweight material frequently used for temporary structures, event tents, and smaller, semi-permanent projects.

Ethylene Tetrafluoroethylene (ETFE) Foil is a transparent fluoropolymer material ETFE foil demands less structural steel support than traditional glazed systems, resulting in an easier installation, and typically a lower cost alternative.

ETFE foil envelope can be supplied as a single layer membrane supported by a cable net system or as a series of pneumatic cushions made up of between two and five layers of ETFE. A transparent, lightweight, and recyclable polymer used in cushion or single-layer forms for high-light-transmittance envelope, such as in botanical gardens or modern stadiums.

Silicone-Coated Glass Fabric combines woven fiberglass for structural strength with a durable silicone rubber coating on one or both sides. It offers extreme temperature resistance, from -50°C to +300°C, excellent flame retardancy, and chemical resistance. Specialty/Mesh Fabrics: Other materials include HDPE mesh, PVDF-coated PVC for improved dirt resistance, and ETFE with internal mesh (STFE).

Figure 4. The application of Ethylene Tetrafluoroethylene (ETFE) and Silicone Glass Fabric [8], [11].

2. CHALLENGES IN ACHIEVING AMBIENT COMFORT IN MEMBRANE STRUCTURES

Membrane halls offer significant spatial and aesthetic advantages, but maintaining indoor comfort presents considerable engineering challenges. Their thermal behavior differs significantly from conventional buildings and strongly influences environmental design strategies.

The design of high performance architecture involves the analysis of all the parameters that contribute to the achievement of indoor comfort [4]. The main factors affecting user comfort and contributing to unfavorable indoor conditions are unstable thermal conditions, noise impact, condensation and moisture-related issues, as well as visual and lighting discomfort (Table 1).

Table 1. Overview of building factors and their impact on the internal environment

Factor	**Cause of the problem**	**Consequence for the user**
Thermal conditions	Low thermal mass	Extreme temperature variations
Noise/Acoustic	Geometry shape	Sound focusing and high reverberation
Moisture	Difference in temperature	Condensate formation
Light	Translucency	Glare and visual fatigue

2.1. THERMAL CONDITIONS WITHIN AMBIENT COMFORT

The small thickness of membrane materials results in low thermal mass, limiting the ability to store heat. Consequently, indoor temperatures fluctuate significantly.

In the summer period, the high translucency of the material enables the direct penetration of solar radiation into the interior of the space. Without the application of special protective coatings, the membrane behaves like a solar collector, which leads to excessive overheating and disruption of user comfort. In contrast, during the winter months there is a sudden cooling; as soon as the outside temperature drops, the low insulating power of standard single-layer membranes (high U-value) causes huge heat losses. Figure 5 illustrates the various influences to which the membrane structure may be exposed throughout the year. Different weather conditions and significant temperature variations pose a challenge for membrane structures, particularly in maintaining adequate ambient conditions.

Figure 5. Membrane structures subjected to varying environmental loads (generated using Photoshop, Illustrator and ChatGPT).

In addition to oscillations in air temperature, radiation asymmetry is a special problem. Even when the indoor air is heated, users may feel uncomfortably cold. This phenomenon occurs because the human body, as a warmer object, directly radiates heat towards the cold surface of the membrane ("cold walls" effect), which drastically reduces the subjective feeling of heat despite the operation of the heating systems.

2.2. ACOUSTIC ISSUES WITHIN AMBIENT COMFORT

Acoustics represent one of the most pronounced disadvantages of membrane structures, primarily due to their geometry and small surface mass of the material. Concave shapes, typical of domed and pneumatic halls, lead to sound focusing and the appearance of echoes, thus creating zones of increased noise intensity and reduced speech intelligibility.

The light membrane has limited sound insulation, so external noise (traffic, airplanes, precipitation) easily penetrates into the interior space, while the impact of rain on the membrane often causes a pronounced "drumming effect". An additional problem is the constant noise of ventilation systems, which are necessary to maintain overpressure in pneumatic halls and generate continuous noise, especially in the low frequency domain.

Due to the mentioned factors, providing satisfactory acoustic comfort in membrane sports facilities requires special technical measures and careful design.

2.3. MOISTURE AND CONDENSATION CHALLENGES IN AMBIENT COMFORT

Moisture is one of the key factors affecting the durability of the structure and the quality of internal comfort in membrane and pneumatic halls. Due to the low thermal resistance of the membrane, surface condensation often occurs when warm and moist indoor air comes into contact with the cold membrane. Possible consequences include condensate dripping, localized wetting of the structure, and mold growth, particularly at joints and construction details. At the same time, the high tightness of the building, especially in halls under overpressure, limits the natural exchange of air. Therefore, continuous mechanical ventilation is necessary to control relative humidity and prevent the feeling of stale and "heavy" air, which further increases energy and operating costs.

2.4. VISUAL COMFORT AND GLARE WITHIN AMBIENT COMFORT

While membranes allow diffused daylight, which contributes to energy efficiency and a more pleasant environment, uncontrolled lighting can negatively affect visual comfort. Direct solar radiation that passes through the semi-transparent membrane can cause glare and reduce visibility, especially during sports activities that require precise tracking of the ball or objects in space.

Additionally, most membrane materials are translucent, but not transparent, which limits the visual connection with the outside environment, as shown in *Figure 6*. The absence of a visual connection to the outdoors can lead to feelings of enclosure and isolation, especially for users spending extended periods inside.

3. STRATEGIES FOR IMPROVING THE PERFORMANCE

Contemporary design practice has developed a series of technical measures that mitigate the problems of thermal, acoustic and visual comfort in membrane and pneumatic sports facilities [4], [5]. These strategies include improving materials, introducing multi-layer systems and combining lightweight membranes with more massive structural elements. The following strategies are organized according to the main categories of comfort: thermal, visual, and acoustic, in order to ensure a clear and systematic overview.

3.1. THERMAL COMFORT PERFORMANCE

One of the most advanced solutions involves the use of multi-layer ETFE cushions. By introducing air gaps between layers, the overall thermal insulation of the envelope is significantly enhanced. The air layer acts as an effective insulator, reducing the heat transfer coefficient (U-value) and minimizing heat losses [4], [5].

In addition, the implementation of two-layer and three-layer membrane systems reduces the risk of surface condensation by stabilizing the internal surface temperature, as shown in *Figure 6*.

"Double-skin" systems, consisting of two membranes with a controlled air cavity, further improve thermal performance. This intermediate space reduces heat gain by allowing overheated air to be extracted before it enters the interior. The innovative double-layer membrane system contributes to the reduction of condensation within the hall (Figure 6).

Hybrid structural systems also contribute to thermal comfort. By combining lightweight membranes with solid base elements (typically 2–3 m high walls), additional thermal mass is introduced in the occupied zone, which helps stabilize indoor temperature fluctuations.

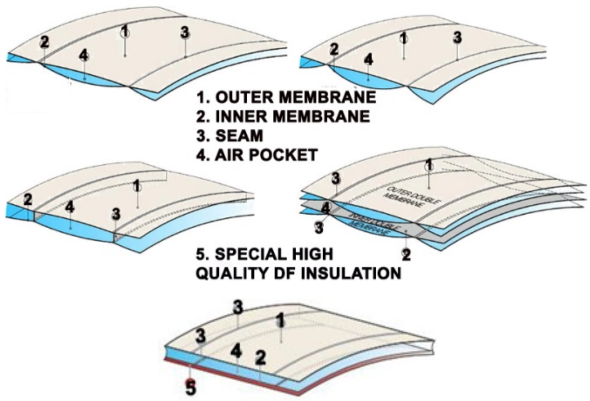

Figure 6. Contemporary Design Strategies for Improving Thermal Performance [13]

3.2. VISUAL (LIGHT) COMFORT PERFORMANCE

Visual comfort is enhanced through advanced control of daylight transmission and solar radiation. A key strategy is the application of ETFE cushions with printed patterns (fritting). These patterns reduce excessive solar radiation and glare while still allowing sufficient natural light into the interior space, as shown in *Figure 7*. Furthermore, by adjusting the pressure within multi-layer ETFE cushions, the distance between layers can be modified. This enables dynamic control of light transmission and solar gains, allowing the indoor environment to adapt to different climatic conditions and functional requirements [6].

Figure 7. Air-supported membrane structures provides a space with a controlled environment [12].

3.3. ACOUSTIC COMFORT PERFORMANCE

Acoustic comfort in membrane sports facilities is improved through the use of multi-layer membranes and hybrid structural solutions.

Multi-layer envelope systems act as barriers that reduce the transmission of external noise, such as traffic and precipitation. At the same time, they help mitigate internal sound reflections and reverberation, which are typically pronounced in dome-shaped structures.

Hybrid systems, which incorporate solid base elements, further enhance acoustic performance (Figure 8). The added mass reduces sound penetration and improves sound absorption, leading to better speech intelligibility and reduced acoustic fatigue for users.

Figure 8. The integration of light membranes with robust, solid bases [13]

3.4. INTEGRATED AND ENERGY-EFFICIENT SYSTEMS

The integration of structural and mechanical systems plays a crucial role in achieving overall environmental performance and energy efficiency.

Modern pneumatic halls increasingly rely on "double-skin" systems combined with active ventilation and humidity control. These systems maintain the required internal overpressure while ensuring adequate air quality and thermal stability.

The controlled air layer between membranes serves multiple functions: it improves insulation, enables the removal of excess heat, and contributes to a more stable indoor microclimate.

Due to enhanced thermal performance, these systems allow more precise environmental control with reduced energy consumption. As a result, they ensure a stable and comfortable indoor environment that is largely independent of external climate variations.

4. ARCHITECTURAL IMPLICATIONS OF AMBIENT COMFORT STRATEGIES

The improvement of thermal, acoustic and visual comfort in membrane structures - halls does not only affect the technical performance of the building, but directly changes its architectural expression and spatial quality. When ambient comfort is understood as an integral component of the design concept [6], membrane halls evolve beyond purely engineering structures and acquire a distinct architectural dimension.

4.1. SPATIAL ARTICULATION AND CLARITY OF DESIGN

Improved indoor comfort conditions enable clearer spatial zoning and more coherent functional organization. The introduction of hybrid systems, combining lightweight membranes with massive base elements, facilitates the formation of transition zones, service belts, and entrance areas, thereby enhancing spatial hierarchy and usability.

This approach mitigates the perception of a single, undefined volume typical of conventional pneumatic halls and supports the creation of differentiated spatial sequences—from public and communication zones to the central sports field. At the same time, controlled natural lighting, achieved through multi-layer systems such as ETFE cushions, enables the modulation of space through light. This contributes to a more dynamic and visually comfortable interior environment, as shown in Figure 9.

Figure 9. Enhancing Visual Comfort through Dynamic Interior Design [14]

4.2. VISUAL IDENTITY AND CONTEMPORARY EXPRESSION

Contemporary membrane systems offer a wide range of formal and aesthetic possibilities, from simple dome geometries to complex organic and parametric forms. The intrinsic properties of membrane materials—transparency, translucency, and reflectivity—become key instruments of architectural expression.

Figure 10. The lighting of the pavilion changes frequently, creating a specific atmosphere during the evening hours [15].

During nighttime, illuminated membranes can function as urban light installations, giving the structure a strong and recognizable visual identity, as shown in *Figure 10*. In contrast, during daytime conditions, diffused natural light creates a light, airy atmosphere, distinguishing these buildings from conventional, massive sports facilities.

4.3. INTEGRATION INTO THE URBAN AND NATURAL ENVIRONMENT

Enhanced thermal insulation and environmental control systems allow greater flexibility in positioning membrane structures across diverse contexts, from dense urban settings to open natural landscapes.

The lightweight nature of these systems reduces the need for extensive foundations, minimizing site impact. At the same time, transparent or semi-transparent envelopes contribute to visual permeability, reducing the perceived mass and dominance of the structure within its surroundings.

In urban environments, pneumatic halls can act as recognizable public landmarks, while in natural settings, their soft, fluid forms enable a more harmonious integration with the landscape.

Traditionally perceived as temporary and purely functional solutions, pneumatic halls today—through the application of advanced materials and indoor comfort strategies—demonstrate the potential to become permanent and architecturally significant structures. By integrating engineering performance with architectural design, membrane buildings evolve into spaces of identity, social interaction, and contemporary expression, rather than merely serving as technical enclosures for sports activities. In this context, indoor comfort is not only a technical requirement, but a key generator of architectural form, spatial quality, and overall design value.

5. CONCLUSION

Improving ambient comfort in membrane halls represents a complex but essential process that goes beyond technical enhancement of the building envelope. It involves transforming a typologically simple and technically conditioned structure into a high-quality, energy-efficient, and architecturally expressive space.

Advanced materials and systems allow membrane envelopes to function not only as protective layers but also as active design elements shaping spatial and environmental quality. Materials such as ETFE films, PVC-polyester membranes, and PTFE-coated glass fibers enable control over solar radiation, effective daylight diffusion, and reduced risk of overheating. In particular, ETFE cushion systems with variable transparency balance natural lighting with protection from excessive solar gain.

The optimization of building orientation, the use of translucent materials, and the integration of energy-efficient lighting and ventilation systems further enhance ambient comfort, providing stable indoor conditions, uniform illumination, and improved air quality.

Overall, the enhancement of ambient comfort serves as a key driver in the architectural evolution of membrane halls. By integrating advanced materials, technological solutions, and design strategies, membrane structures can evolve from temporary, purely functional constructions into energy-optimized, visually distinctive, and functionally adaptable architectural forms.

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