DLP-Based Immersive Three-Dimensional Animation Modeling for Visualizing Indoor Thermal Circulation

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Abstract: Indoor thermal circulation is a spatially continuous and temporally evolving physical phenomenon that is inherently difficult to perceive and interpret through conventional visualization approaches. Traditional representations such as static temperature contours or sectional diagrams often fragment spatial relationships and fail to communicate dynamic behavior effectively. This study proposes a DLP-based immersive three-dimensional animation modeling method for visualizing indoor thermal circulation. By integrating thermal simulation data with digital light processing principles and immersive animation techniques, the proposed method reconstructs thermal behavior as a coherent spatial process that can be visually explored.

A structured modeling framework is developed, encompassing spatial reconstruction, thermal data mapping, and immersive visual rendering. Thermal parameters are translated into controlled visual attributes, enabling dynamic representation of heat movement within enclosed environments. The study emphasizes the balance between physical fidelity and perceptual clarity, positioning visualization as an analytical medium rather than a supplementary display. The results demonstrate that immersive visualization enhances spatial cognition and supports intuitive understanding of complex thermal circulation patterns. This research contributes an original methodological perspective to thermal visualization and provides a practical reference for integrating simulation data with immersive three-dimensional animation systems.

Keywords: DLP visualization; Indoor thermal circulation; Immersive animation; Three-dimensional modeling; Thermal representation

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1. Introduction

Indoor thermal circulation governs how heat is distributed, transported, and transformed within enclosed spaces. It plays a critical role in environmental analysis, spatial performance assessment, and the interpretation of indoor physical behavior. Although numerical simulation techniques have achieved high levels of computational accuracy, the interpretation of simulation results remains a persistent challenge. Thermal circulation is invisible by nature, spatially distributed, and highly dynamic, which makes it difficult to comprehend through numerical outputs alone.

Conventional visualization methods typically rely on two-dimensional temperature maps, vector plots, or static three-dimensional renderings. While these techniques effectively convey localized data values, they often fail to represent spatial continuity and temporal evolution. Fragmented representations can obscure the relationships between heat sources, boundary conditions, and circulation paths, limiting their analytical usefulness and interpretive depth.

Recent advances in immersive visualization and three-dimensional animation offer new opportunities for representing complex physical phenomena. Digital light processing (DLP) technology, characterized by precise control of light modulation and visual output, provides a technical foundation for translating abstract thermal

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data into spatially coherent visual forms. When combined with immersive animation environments, DLP-based visualization enables thermal circulation to be experienced as a spatial process rather than observed as isolated numerical information.

This study investigates a DLP-based immersive three-dimensional animation modeling method for visualizing indoor thermal circulation. The research aims to construct a modeling framework that preserves the integrity of thermal simulation data while enhancing perceptual accessibility and spatial understanding. By repositioning visualization as an integral analytical component, this work seeks to bridge the gap between computational precision and intuitive interpretation.

2. Overview of DLP-Based Visualization Technology

Digital light processing (DLP) technology exhibits significant advantages for scientific visualization due to its high spatial resolution, stable temporal performance, and precise control over visual parameters. Unlike conventional display technologies that primarily emphasize image reproduction, DLP enables dynamic modulation of light intensity and chromatic output at fine spatial scales. This capability makes it particularly well suited for representing continuous scalar fields, such as temperature distributions, where smooth gradients and subtle variations play a critical role in interpretation.

Within the context of thermal visualization, DLP functions as an intermediary that translates numerical simulation data into visually interpretable forms. Thermal parameters are not presented directly as numerical values but are encoded into visual attributes aligned with human perceptual mechanisms. Temperature magnitude can be expressed through continuous chromatic gradients, allowing spatial differentiation of thermal levels, while changes in thermal intensity are conveyed through variations in brightness and saturation. This encoding strategy supports intuitive spatial perception and reduces the cognitive effort required to interpret complex thermal data.

When integrated into a three-dimensional animation environment, DLP-based visualization further extends its representational capacity. A spatial model of the indoor environment provides geometric context, within which thermal behavior is visualized as a dynamic and evolving process. Circulation patterns can be observed from multiple viewpoints, including internal perspectives that are difficult to achieve using conventional visualization approaches. This multi-perspective capability enhances spatial awareness and enables a more comprehensive understanding of heat movement within enclosed spaces.

The principal strength of DLP-based visualization lies in its ability to balance physical accuracy with perceptual clarity. By maintaining consistent and transparent mapping rules between thermal parameters and visual elements, the method ensures that enhanced visual expressiveness does not compromise the integrity of underlying physical data. This balance establishes a robust technological foundation for immersive thermal circulation modeling and supports the integration of visualization into analytical workflows rather than treating it as a purely illustrative tool.

3. Limitations of Conventional Indoor Thermal Visualization

Despite notable advances in computational simulation accuracy, conventional approaches to indoor thermal visualization continue to exhibit structural and perceptual limitations. A primary issue lies in spatial discontinuity. Common visualization techniques, such as sectional temperature contours or planar projections, fragment the thermal field into isolated slices. While these representations may reveal localized thermal conditions, they disrupt spatial continuity and hinder the reconstruction of complete circulation patterns within the indoor environment. Consequently, global thermal behavior must often be inferred through comparison across multiple views rather than perceived directly as an integrated whole.

Temporal representation constitutes another significant limitation. Many visualization outputs emphasize steady-state conditions or time-averaged results, which overlook the inherently transient nature of indoor thermal circulation. Heat transfer involves continuous interaction among thermal sources, airflow paths, and enclosure boundaries. Static or quasi-static representations are unable to convey the evolution of these interactions over time, thereby obscuring transitional phenomena such as the formation, migration, and dissipation of thermal structures. This absence of temporal continuity reduces the explanatory depth of traditional visualization methods.

In addition, conventional visualization techniques frequently prioritize numerical precision over perceptual accessibility. Dense vector plots, numerical overlays, and complex legends may accurately represent data values, yet they often impose a substantial cognitive load on viewers. The lack of intuitive visual cues makes it difficult to identify dominant circulation paths or spatial relationships, particularly in geometrically complex indoor spaces. As a result, interpretation relies heavily on technical expertise rather than intuitive spatial understanding.

Taken together, these limitations indicate that traditional visualization approaches are insufficient for communicating the full complexity of indoor thermal circulation. Overcoming these constraints requires a modeling framework that integrates spatial continuity, temporal dynamics, and perceptual clarity within a unified visual representation, enabling thermal behavior to be understood as a coherent and evolving spatial process.

4. DLP-Based Immersive Animation Modeling Strategy

The proposed DLP-based immersive animation modeling strategy establishes a structured workflow that integrates thermal simulation data with three-dimensional animation techniques to achieve an intuitive and spatially coherent representation of indoor thermal circulation. The workflow is designed to translate abstract numerical outputs into perceptually meaningful visual processes while maintaining consistency with underlying physical behavior.

The modeling process begins with the construction of an accurate spatial model of the indoor environment. This geometric model defines enclosure boundaries, internal volumes, and key architectural features that influence heat transfer and airflow behavior. Spatial accuracy at this stage is critical, as geometric relationships directly affect the interpretation of thermal circulation patterns. The spatial model serves as a stable structural framework upon which thermal data can be visualized and animated.

Thermal simulation outputs are subsequently mapped onto the spatial model through a data-to-visual translation process. Rather than presenting raw numerical values or static temperature fields, thermal parameters are converted into visual attributes aligned with human perceptual mechanisms. Temperature magnitude is represented using continuous color gradients that allow viewers to distinguish subtle variations across space. Circulation direction and relative intensity are expressed through animated flow elements, which visually encode both movement and strength. This approach enables thermal behavior to be perceived as a continuous spatial process rather than a collection of discrete data points.

Digital light processing technology plays a central role in controlling visual output during this stage. DLP enables precise modulation of brightness, color, and transition smoothness, ensuring that changes in thermal conditions are represented consistently across the spatial domain. The use of animation introduces temporal continuity, allowing thermal circulation to be observed as an evolving process. Dynamic visualization reveals patterns such as heat accumulation zones, circulation loops, and transitional flow states that are difficult to identify through static representations.

Immersive rendering further enhances the modeling strategy by enabling spatial navigation and internal observation. Viewers are not limited to fixed viewpoints but can explore the environment from within the modeled space. This internal perspective supports embodied perception, strengthening spatial cognition and facilitating

intuitive understanding of complex thermal interactions. Immersion transforms visualization from passive observation into an experiential analytical process.

Throughout the workflow, careful calibration is applied to maintain fidelity between simulation data and visual representation. Visual abstraction is employed selectively to enhance clarity without distorting fundamental physical relationships. Mapping parameters are adjusted to balance expressiveness and accuracy, ensuring that visual emphasis does not misrepresent thermal behavior. This balance allows the immersive model to function as both an effective analytical tool and a reliable visual representation.

By integrating simulation accuracy, perceptual design, and immersive interaction, the proposed modeling strategy provides a coherent framework for visualizing indoor thermal circulation. It emphasizes process-oriented representation and spatial continuity, offering a method that supports both technical analysis and intuitive interpretation.

5. Development Trends in Immersive Thermal Visualization

The evolution of thermal visualization increasingly aligns with immersive and interactive technologies. One emerging trend is the integration of simulation and visualization platforms, enabling real-time data exchange and dynamic updates. Such integration supports iterative analysis and exploratory observation of thermal behavior within complex spaces.

Another notable trend involves a growing emphasis on perceptual effectiveness. Visualization design is shifting toward user-centered approaches that prioritize spatial understanding and cognitive engagement. Immersive environments that allow users to explore data spatially are becoming central to this development.

Advancements in rendering algorithms and visualization hardware are expected to further enhance the fidelity and responsiveness of immersive thermal models. As these technologies mature, immersive visualization is likely to become a standard analytical tool rather than a supplementary display. This transition reflects a broader recognition of visualization as a cognitive interface between complex data and human understanding.

6. Conclusion

This study presents a DLP-based immersive three-dimensional animation modeling method for visualizing indoor thermal circulation. By integrating thermal simulation data with advanced visualization and animation techniques, the proposed approach reconstructs thermal behavior as a dynamic and spatially coherent phenomenon.

The research demonstrates that immersive visualization enhances understanding by emphasizing spatial continuity, temporal evolution, and experiential perception. Visualization is repositioned as an analytical medium that supports deeper insight into thermal circulation rather than serving solely as a presentation layer.

The proposed framework offers a methodological reference for future research and contributes to the advancement of thermal visualization practices. By bridging computational accuracy and perceptual clarity, DLP-based immersive modeling provides a constructive pathway for improving the interpretation and communication of complex thermal phenomena.

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