ENERGY EVALUATION OF HYBRID COLLECTOR FAÇADE USING MITHRA SOFTWARE

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Abstract: The growing demand for building energy efficiency has driven the development of active façade systems that harness solar energy. This study aims to evaluate the performance of a hybrid solar façade collector that utilizes two types of fluids—air and solar fluid—to enhance primary energy efficiency. The method employed is numerical simulation using the specifically developed MITHRA software, based on two-dimensional finite difference modeling and climate data from DWD. Validation was conducted through experiments using four test collector units. A matched-flow control strategy was implemented to optimize system operation based on actual energy efficiency. The results indicate that the use of dual fluids does not always outperform single-fluid systems; however, system efficiency improved significantly—by up to 15%—when the control strategy was applied. The MITHRA software also proved effective as a planning tool for the design of solar energy-based building façades.

Keywords: Solar collector, building façade, renewable energy, solar fluid, MITHRA software

1. Introduction

The global energy crisis and growing environmental sustainability pressures have prompted significant efforts toward transitioning to renewable energy sources. Solar energy stands out as one of the most promising options due to its abundance, zero carbon emissions, and suitability for both local and large-scale applications. In the building sector, solar energy holds great potential to reduce reliance on conventional energy sources, particularly for space and water heating needs. Various technological innovations have been developed to capture and utilize this energy, one of which involves the integration of solar collectors into building façade elements [1].

Building façades play a strategic role in solar energy utilization due to their large surface area and direct exposure to solar radiation. In temperate countries such as Germany, solar radiation on vertical building walls is relatively stable throughout the year, especially during winter when the sun's angle is low. This potential can be harnessed through active façade systems that serve dual functions—as building enclosures and as energy-harvesting media. In Germany alone, the potential façade surface area reaches 500 million square meters, making it one of the most significant contributors to both passive and active solar energy use in the construction sector [2]. Within this context, hybrid collector façade systems have emerged as a promising innovation. These systems combine two types of heat transfer fluids—air and *solar fluid* (thermal liquid)—each offering distinct advantages and limitations. Air, being freely available, is easy to manage and widely accessible, while solar fluids have higher specific heat capacities and can store thermal energy for longer periods [3]. The integration of both fluids into a single system aims to maximize operational flexibility and energy efficiency, especially under variable daily and seasonal climatic conditions.

However, the implementation of dual-fluid systems is not without technical and operational challenges. One of the main issues is the need for additional mechanical components such as pumps and fans, which can increase the system's overall electricity consumption. Without proper control strategies, the use of two fluids may actually reduce **primary energy efficiency**—defined as the ratio of thermal energy output to the electrical energy consumed by the system [4]. Therefore, a systematic approach that integrates physical design, mathematical modeling, and adaptive control strategies is essential to evaluate and optimize the performance of hybrid collector façade systems.

Previous studies have addressed collector systems using a single fluid, either air or solar fluid, and examined their thermal performance under different climatic conditions. One study noted that air-based systems tend to have a faster thermal response, though their energy capacity is limited due to low energy density [5]. In contrast, solar fluid systems provide more stable heat storage but exhibit slower response times and the risk of thermal stratification in storage tanks. A combination of both fluids is expected to offer a balanced solution between energy stability and environmental adaptability.

To address this challenge, a study by Shahbazfar developed an integrated approach through the creation of a thermal simulation tool named **MITHRA**. This software was designed to model the thermal behavior of façade collector systems numerically using a two-dimensional finite difference method, while integrating climate data from *Deutscher Wetterdienst* (DWD) for long-term simulations [6]. MITHRA is also equipped with a control algorithm based on the matched-flow principle, which enables automatic adjustment of air and solar fluid flow rates in real time based on current primary energy efficiency. This strategy allows for the shutdown of mechanical components when their electricity consumption exceeds the thermal energy output, thereby maintaining optimal system efficiency.

In addition to numerical simulation, experimental validation was conducted using four custom-designed small-scale collector units. These collectors were equipped with sensors to monitor temperature, humidity, and solar radiation intensity, allowing for real-time tracking of the system's response to environmental variations. The validation results demonstrated that the developed simulation model could accurately represent the system's physical behavior, making it a reliable foundation for planning larger-scale collector designs [7].

Furthermore, MITHRA was developed into a **design** planning too**l** usable by architects and building planners. The software enables users to estimate the annual energy potential of façade systems by inputting simple parameters such as location, orientation, and fluid type. This functionality bridges the gap between energy engineering and architectural design practice, supporting the integration of solar energy systems into buildings from the early conceptual stage [8].

Overall, this study aims to comprehensively evaluate the performance of hybrid solar façade collector systems through both simulation and experimental approaches, while also investigating the effectiveness of control strategies in improving primary energy efficiency. By combining technical, algorithmic, and design planning aspects, the system is expected to contribute to the development of energy-efficient buildings that are responsive to today's and future environmental challenges.

2. Research Method

This study employs a combination of numerical simulation and experimental validation to evaluate the primary energy efficiency of a hybrid solar façade collector system. A physical and mathematical model was developed to represent the processes of conduction, convection, and radiation heat transfer within the collector, which utilizes air and solar fluid as heat transfer media. Simulations were conducted using the MITHRA software, specifically developed for this purpose, based on a two-dimensional finite difference method and annual climate data provided by Deutscher Wetterdienst (DWD).

Experimental validation was carried out using four small-scale test collector units, with measurements including fluid temperatures, flow rates, and solar radiation intensity. A matched-flow control strategy was implemented to optimize the use of pumps and fans based on real-time energy efficiency performance. In addition to simulation and validation, MITHRA was further developed as a design planning tool for solar façades, enabling architects to estimate energy potential using key parameters such as location, orientation, and system configuration.

3. Discussion

This discussion addresses the results of simulations and experiments on a hybrid façade collector system that combines air and solar fluid as heat transfer media. Based on simulation outcomes using the MITHRA software, it was found that the system's energy efficiency is significantly influenced by design parameters such as minimum operating temperature, protective glass transparency, and the control strategy applied. Solar fluid showed advantages in long-term heat storage, whereas air offered faster thermal response but lower thermal stability [9, 10].

Experiments using four test collector units demonstrated that the dual-fluid system can enhance operational flexibility but requires intelligent control mechanisms to ensure that the energy consumption of fans and pumps does not outweigh the thermal energy gained. In this regard, the matched-flow control strategy proved effective in improving system efficiency by up to 15%, by shutting down components when primary energy performance was suboptimal [11, 12].

Modern energy-efficient building design demands the integration of solar systems from the early planning stages, as emphasized in sustainable building design guidelines [13], and necessitates simulation tools that comply with international standards such as **VDI 6020** [14]. Experimental data also revealed that **high-**transparency protective glazing significantly enhances solar radiation input, consistent with material thermal property standards such as ISO 10456 [15].

Thermal stratification effects within the liquid-based system were observed and aligned with established fluid dynamics theory [16] and classical thermodynamics regarding heat capacity and transfer efficiency [17, 18]. Sensitivity analysis showed that parameters such as threshold temperature and façade insulation quality must be carefully considered to achieve optimal efficiency [19, 20]. Additionally, building characteristics and microclimatic variables such as humidity and indoor temperature influence simulation results, consistent with the principles of building physics [21].

The use of environmental sensors to measure temperature, humidity, and air velocity aligns with recommendations from ISO 7726 [22] and is essential for validating the accuracy of spatial simulation models [23]. Moist air calculations in the air-based collector system were conducted using the Mollier Diagram, which serves as the basis for determining **air** enthalpy values [24].

Ultimately, the MITHRA software not only facilitates technical simulations but also provides design planning features that enable architects to estimate energy outputs based on building orientation and location. This approach aligns with best practices in solar thermal system design, as discussed by Wesselak [25].

The following figures illustrate simulation outputs from MITHRA, including temperature distribution, system efficiency, and the impact of parameter variations on annual energy performance:

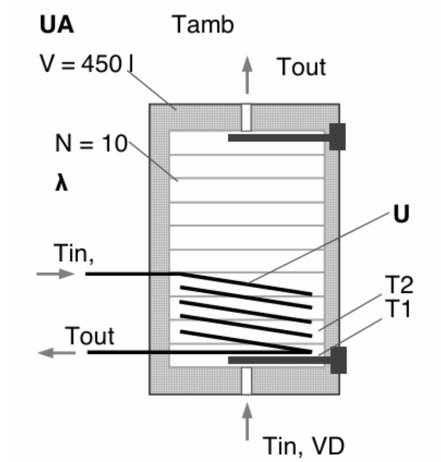

Figure 1: Schematic structure of the storage modeled in MITHRA

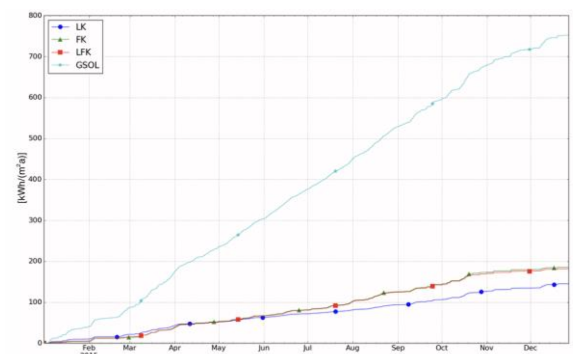

Figure 2: Simulation Output from MITHRA

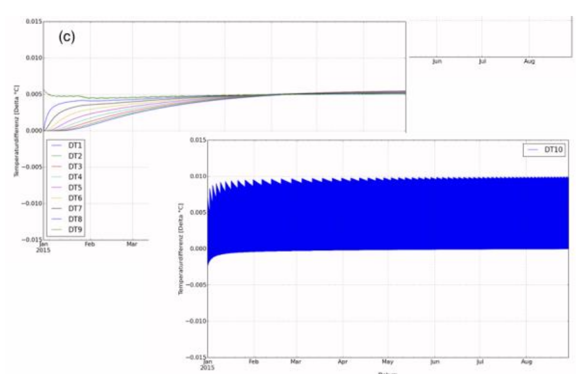

Figure 3: Deviations of the MITHRA, DTi = TiMITHRA

(a) Lambda = 0.315 W/(mK)

(b) 0.630 W/(mK) and

(c) 0.945 W/(mK). The fluctuations in the temperature differences DT10 are based on the set on/off hysteresis of the electric heating element in combination with the explicit numerical solution approach.

Overall, the findings of this study highlight the importance of a multidisciplinary approach in designing hybrid solar façade collector systems. The success of such systems depends not only on the choice of technology, but also on precise operational control, thoughtful architectural integration, and accurate energy simulation modeling. By utilizing tools like MITHRA, the planning process can be conducted more efficiently and accurately. This opens broader opportunities for implementing active façades as a sustainable building design solution that is responsive to contemporary energy and climate challenges.

4. Conclusion

This study concludes that hybrid solar façade collector systems, which combine air and solar fluid as heat transfer media, can enhance operational flexibility but do not necessarily deliver higher primary energy efficiency compared to single-fluid systems. Through numerical simulations using the MITHRA software and experimental validation, it was found that factors such as operating temperature, façade transparency, and the control strategy have a more substantial impact on overall system performance.

The matched-flow control strategy was proven to improve efficiency by up to 15% by optimizing the operation of pumps and fans. Moreover, vertically oriented façades were found to provide more stable annual energy output with reduced risk of overheating. The MITHRA software also successfully functioned as a responsive and efficient design tool for architects and building planners.

By adopting a holistic approach that integrates simulation, experimentation, and tool development, this study offers tangible contributions to the application of solar energy in sustainable building design. The façade collector system can serve not only as a technical component but also as an integral element of energy-efficient architectural design for the future.

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