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Enhancement of Building Thermal Performance: A Comparative Analysis of Integrated Solar Chimney and Geothermal Systems

Sanjay Kumar Agarwal[1*], Rafael Cavicchioli Batista[2]

[1] Department of Technical Education, Skylark College of Technical Education & Management, 251001 Muzaffarnagar, India
[2] Department of Mechanical & Manufacturing Engineering Technology, Vermont State University, 05061 Vermont, USA

[*] Correspondence: Sanjay Kumar Agarwal (drsanjaykagarwal@gmail.com)

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Abstract: A comparative investigation is conducted, employing Computational Fluid Dynamics (CFD) simulations to study two distinct room space configurations: one featuring a solar chimney and another integrating both a solar chimney and a geothermal system. The primary objective of this investigation is to scrutinize the thermal behavior, energy efficiency, and mass flow rates of these systems. Results underscore the considerable positive implications of the geothermal system integration. This amalgamation precipitates diminished average room temperatures and elevated mass flow rates, signifying superior thermal comfort and energy performance. The room implementing the geothermal system exhibited an average temperature of 302.2 Kelvin and a mass flow rate of 4.134×10^{-6} kg/s, in contrast to the room without the geothermal system, which demonstrated an average temperature of 309.6 Kelvin and a mass flow rate of 1.878×10^{-6} kg/s. These findings have practical repercussions for architects, engineers, and policymakers, facilitating well-grounded decisions in the domain of sustainable building design. The observed enhancement in thermal performance and mass flow rates underscore the potential merits of integrating geothermal systems, thereby promoting wider acceptance. Further research is recommended to investigate the influence of varied climatic conditions, building orientations, and room layouts on the efficiency of integrated solar chimney and geothermal designs. Examination of alternative renewable energy sources (RES), innovative building materials, and technologies is also suggested to elevate energy efficiency and sustainability in room space designs. This study contributes substantially to the expanding realm of sustainable building design, providing valuable insights for refining room space performance, curbing energy consumption, and heightening thermal comfort. By highlighting the advantages of renewable energy integration, particularly geothermal systems, the study stimulates the development of more energy-efficient and environmentally friendly building spaces.

Keywords: Solar chimney; Geothermal system; Energy efficiency; Thermal behavior; Renewable energy systems; Computational fluid dynamics; Energy modeling; Thermal comfort

1 Introduction

Housing represents one of the fundamental human necessities alongside clothing and food [1]. Interestingly, the procurement of residential and commercial properties is responsible for over a third of the global energy consumption and greenhouse gas (GHG) emissions linked to energy use. Two principal strategies have been identified to mitigate this significant environmental impact: the decarbonization of manufacturing processes and the reduction of energy consumption in construction [2]. Traditional environmental strategies have focused primarily on enhancing energy efficiency and exploiting RES, often neglecting the importance of material efficiency during the construction phase [2]. This oversight potentially leads to missed opportunities for effective emission reductions. Figure 1 provides an illustration of the impact of the greenhouse effect on the environment.

Consideration must be given to the complex trade-offs between emissions generated before and after the utilization of a building. Interestingly, buildings that boast high efficiency may necessitate more resources during construction [3]. The production of building materials, which contributed 11% to global energy- and process-associated

GHG emissions in 2018, remains an area of significant concern. Key building materials such as cement, brick, steel, and other metals and nonmetallic elements have a substantial contribution to environmental pollution.

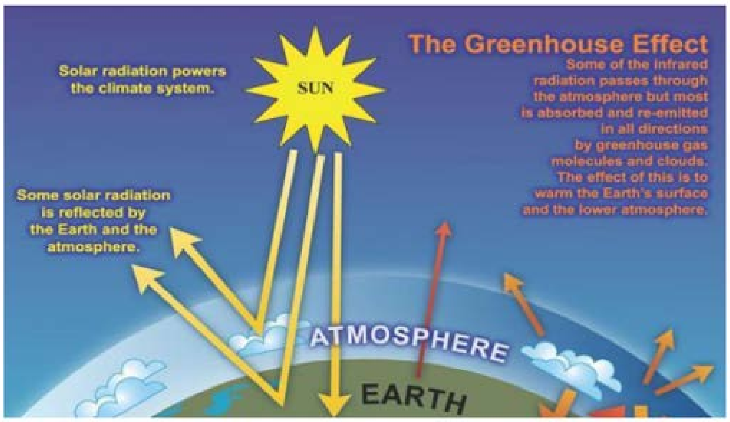

Figure 1. Greenhouse effect on the environment [2]

Predictions indicate a rapid surge in the demand for new structures in the coming decades, driven by expanding populations and increasing income levels, particularly in Asia and Africa [4]. Additionally, the density of populations in urban areas necessitates modifications to housing, leading to an upswing in construction requirements. Despite advancements in building technology that allow for more environmentally-friendly construction methods, less-efficient techniques persist, particularly in regions experiencing the highest demand for new structures. This discrepancy presents a formidable challenge in meeting global climate goals while reducing GHG emissions linked to building materials.

A viable approach to lessen the environmental impact of buildings is through the implementation of green building principles. These principles utilize design strategies, materials, and technologies to minimize adverse effects on the environment and human health. The Green Building Council defines a green building as one that employs planning, construction, and operation methods that significantly curtail its environmental impact and enhance occupant well-being [5]. These buildings are recognized for adhering to specific criteria presented in Figure 2.

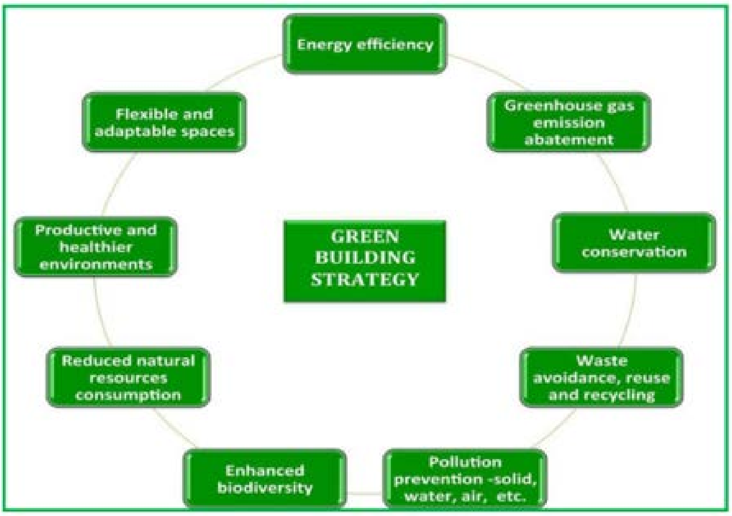

Figure 2. Environment and occupants with strategies [6]

Green buildings distinguish themselves from traditional constructions through their emphasis on several essential aspects: integration and innovative design processes, efficient siting and structure design, material and resource efficiency, energy efficiency, environmental protection, building commissioning, and water and waste management.

In recent years, considerable momentum has been gained in research focused on the environmental impacts of construction materials and mitigation techniques. Previous investigations have concentrated primarily on residential building materials within specific countries [7]. Certain studies have also scrutinized specific material types over time. However, many studies have only contemplated individual factors, making it challenging to provide an accurate estimation of emissions without consistent data on material demand and process emissions intensity. A seminal study [2] delved into the environmental implications of improving building material efficiency in nine major countries. However, it omitted developing regions in Africa and Asia, which are expected to account for a significant portion of the world's housing demand growth in the coming years. Attia et al. [8] proposed an optimization model that dynamically schedules energy consumption from renewable and non-renewable power sources, in tandem with an energy storage system (battery), in smart buildings. The central goal was to curtail CO_2 emissions whilst minimizing customer billing costs. Simulation outcomes demonstrated the efficacy of this approach, whether or not a carbon emissions tax was used to penalize non-green energy usage. Li et al. [9] explored the Internet of Building Energy System, which collects energy use data through sensors in the Intelligent Gateway and provides timely consumption reports. This method enables adjustments to achieve energy-saving objectives, effectively reducing energy consumption and carbon dioxide emissions. Kaushik [10], investigated multi-agent deep learning for cyber-attack detection in IoT systems, specifically in green energy buildings. The proposed framework combines multi-agent systems and deep learning algorithms to enhance IoT network security. The collective intelligence of multiple agents enables real-time detection and mitigation of cyber threats, safeguarding critical infrastructure and sensitive data in green energy buildings.

Recent research has explored GHG emissions in European cities over ten periods in the building's life cycle. The study calculated heating and cooling loads using coefficients of heat transfer for external walls, floors, and ceilings, as well as heating and cooling degree day values. Natural gas and electricity were considered as fuel options during the heating season, while emissions from electricity generation were included during the cooling season. The study revealed variations in emissions among different cities, with Tallinn, Estonia, showing the lowest nitrogen oxide emission and Stockholm, Sweden, exhibiting the highest carbon dioxide emission value [11]. Another study proposed an innovative 'Inclined Solar Chimney' (ISC) design, which integrates the collector and chimney along the face of a high-rising mountain to maximize solar insolation throughout the year. This design enhances energy efficiency and harnesses wind energy present at the mountain's summit, providing an economical and reliable option for buildings [12].

In the exploration of renewable heating strategies, a passive solar system termed as the 'Sunspace' alongside a solar chimney (SS) was proposed for rural houses in Iran [13]. Results indicated that this system increased the heat production during the winter while enabling natural ventilation for cooling in hot seasons. The implementation of such a system yielded significant energy savings, marking it as a practical and cost-effective solution. A novel application of deep learning techniques was explored in the context of medical diagnostics, specifically for the diagnosis of brain tumors [14]. The role of precise diagnostics was emphasized, as it can reduce unnecessary medical procedures and energy consumption in healthcare facilities, thereby indirectly contributing to the sustainability and reduced environmental impact within green energy buildings.

An innovative combination of a solar chimney (SC) with a photovoltaic (PV) module and phase-change material (PCM) to enhance PV module efficiency and extend the SC's productive period was suggested. This system, known as the SC-PV-PCM system, presented improved performance with specific PCMs, indicating its potential for natural ventilation and power generation in buildings [14]. For residential buildings, the SC-PV-PCM system emerged as a superior choice, while for office buildings in subtropical environments, the SC-PV system was recommended [15].

The transformative potential of integrating artificial intelligence (AI) with business analytics was underscored, particularly within the green energy buildings sector [16]. The strategic decision-making capabilities enabled by AI's ability to simulate human intelligence and analyze extensive data sets could facilitate optimal energy consumption and enhance overall efficiency in green buildings. AI-powered algorithms were also recognized for their potential in reducing carbon emissions and conserving resources [16].

A unique building structure was proposed on the bank of a river in Jamshedpur, India, utilizing three fundamental passive cooling methods [15]. This method coupled wind-driven natural ventilation with PCM for nocturnal ventilation and incorporated a geothermal cooling technique using a trench dug along the riverbank. The results showed that this approach enhanced cooling efficiency in hot climates. In a separate study, criteria to distinguish between conventional and renewable energy in hybrid power plants were presented [17]. Here, the impact of geothermal fluid temperature on the operation of hybrid power plants was evaluated, providing insights into the potential and limitations of such systems.

Various investigations have focused on potential solutions for reducing carbon dioxide emissions in residential and commercial buildings in the U.S. [18]. These studies highlighted the capacity of energy-efficient technology and processes to significantly reduce future GHG emissions while concurrently lowering energy costs. Elsewhere, green construction concepts were explored for vertical housing, emphasizing the need for indoor comfort and outdoor control based on respondents from diverse age groups and professions [19]. The findings from this study are anticipated to contribute to future green building assessment standards for vertical housing in Indonesia. In addition to these explorations, queueing models' application in the hospital sector was reviewed, offering insights into patient flow, resource allocation, and system efficiency [20]. The use of these models aligns with the broader goal of promoting sustainability in green energy buildings by optimizing operational efficiency and minimizing resource wastage. Moreover, a bilevel new energy planning and simulation operation framework for new distribution networks was proposed, considering green power certificate trading (GPCT) and carbon emissions trading (CET) mechanisms [21]. This model aimed to reduce carbon emissions, operation costs, and overall investment costs in energy planning for distribution networks.

Investigations have also looked at the importance of data scaling methods in machine learning algorithms for accurate predictions in green energy buildings [22]. These studies applied standardization, normalization, and min-max scaling techniques to preprocess and transform data, optimizing energy efficiency and supporting sustainable practices. Emphasis was placed on increasing energy efficiency in the manufacturing sector, particularly in the context of "green manufacturing" [23]. The study discussed key GHG reduction solutions and pathways to transition towards green manufacturing.

A study by Avramidou and Tjortjis [24] developed regression and classification methods to forecast GHG emissions from the construction industry, identifying critical building factors that lead to excessive emissions. This study focused on projecting metric tonnes of CO_2 emissions from buildings and their compliance with environmental legislation, particularly concerning energy, fuel, and water consumption. Natural gas utilization and energy intensity were identified as significant factors influencing the decarbonization of the building sector. Singhal and Sagar [25] conducted an analysis of a recently built hospital building, focusing on energy-efficient and intelligent techniques to optimize energy use and maximize natural resource utilization. The study examined various aspects of hospital green buildings, including electrical equipment based on the Energy Conservation Building Code and Bureau of Energy Efficiency ratings. Key topics covered in the study include the HVAC system, water treatment facility, building management structure, solar water heating system, solid waste generation and management, and sewage treatment facility.

The current study seeks to conduct a comprehensive analysis and comparison of room space designs integrating sustainable technologies. More specifically, the evaluation and comparison of the thermal behavior and mass flow rates of two room space designs, one incorporating a solar chimney and the other combining a solar chimney with a geothermal system, are aimed at. The integration of these technologies has shown promise for enhancing energy efficiency and environmental sustainability in buildings, but there exists a research gap in evaluating their performance in terms of thermal behavior and mass flow rates.

The guiding research questions for this study are:

(1) How does the incorporation of a geothermal system along with a solar chimney affect the thermal behavior of a room space design compared to the use of a solar chimney alone?

(2) What is the impact of adding a geothermal system on the mass flow rates in a room space design with a solar chimney?

Based on the existing knowledge, it is hypothesized that the room space design incorporating both a solar chimney and a geothermal system will show superior thermal behavior and higher mass flow rates compared to the design with only a solar chimney. To verify these hypotheses, CFD simulations will be utilized to evaluate the thermal behavior and mass flow rates of each design. It is expected that the findings of this investigation will provide valuable insights into the performance and feasibility of sustainable room space designs, thus facilitating the development of energy-efficient and environmentally conscious building practices.

2 Methodology

The analytical methodology employed herein consists of several precise steps for a comprehensive evaluation of the room space design. Initially, an individual room space was accurately rendered using Creo, an advanced 3D modeling software [26]. This stage of the modeling procedure incorporated sophisticated techniques such as sketching and extrusion, with dimensions derived from authoritative literature to safeguard accuracy and consistency [27].

Following the completion of the room space design within Creo, a seamless importation of the model into the ANSYS design modeler was conducted, as demonstrated in Figure 3. This step is crucial, permitting an exhaustive examination and validation of the model's integrity, inclusive of potential surface anomalies such as roughness and waviness, thereby confirming optimal performance and reliability [28].

Through stringent adherence to these methodological procedures, the production of precise and dependable results was ensured [29]. The meticulous modeling process in Creo, accompanied by rigorous error-checking in ANSYS, laid a solid foundation for subsequent analyses and findings. This combination of advanced 3D modeling software and meticulous error-checking in the design modeler culminated in a holistic evaluation of the room space design's performance and behavior, ensuring the accuracy and reliability of the results obtained in subsequent analyses.

Subsequently, a second room space design was constructed, incorporating both a solar chimney and a geothermal tube system. The combined design is visually represented in Figure 4. Within this geothermal system, heated fluid (air) is circulated through the ground loop, instigating the transfer of heat to the cooler surrounding soil, rock, or groundwater. The integration of both solar chimney and geothermal components aimed at enhancing the thermal efficiency and sustainability of the room space.

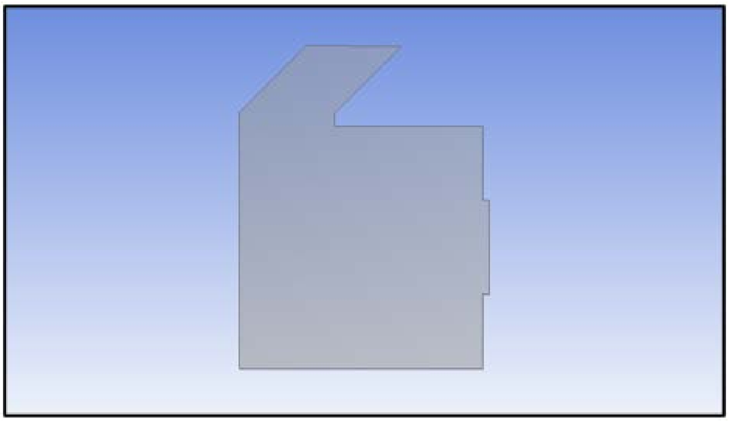

Figure 3. Imported design of the room with solar chimney

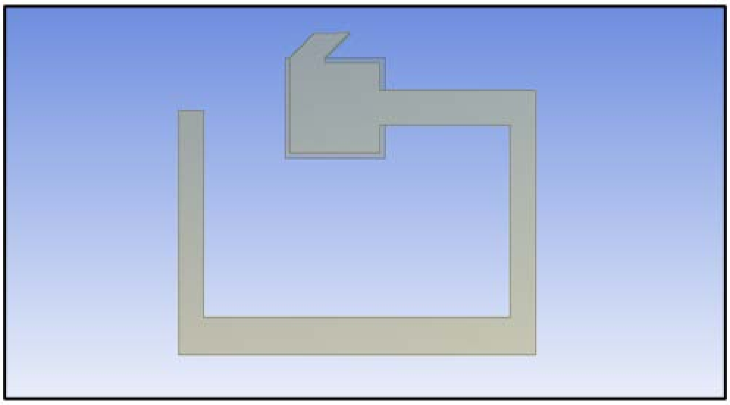

Figure 4. Imported design of the room with solar chimney and geothermal system

Post the CAD modeling of the room space with a solar chimney, meshing of the model was carried out [30]. This process was executed using fine relevance settings for the chimney, both with and without the geothermal mechanism, as depicted in Figure 5.

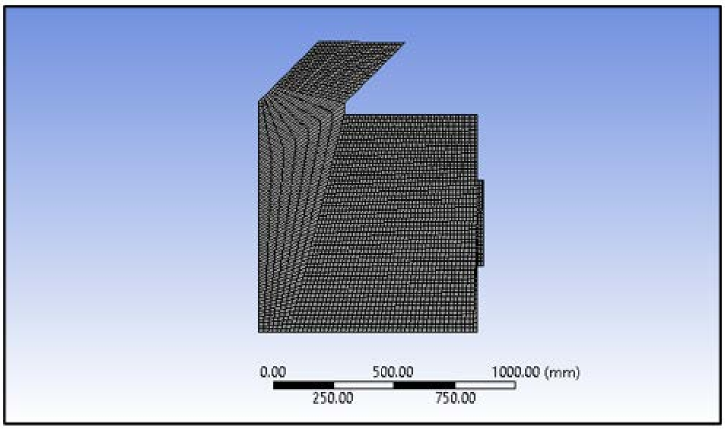

Figure 5. Meshed model of the room with solar chimney

A growth rate of 1.1 was established for meshing, ensuring an accurate and detailed mesh, with the curvature angle set at 120 to effectively capture intricate details. For the design with only the solar chimney, the meshing procedure generated 32,148 elements and 67,269 nodes. These elements and nodes comprise a discretized representation of the model, enabling an analysis of thermal behavior and mass flow rates within the room space.

Similarly, for the room design that integrates the geothermal system, the meshing procedure yields a total of 1,710 elements and 3,890 nodes. This refined mesh aptly encapsulates the geometric intricacies of the room space, enabling precise CFD simulations to scrutinize the thermal behavior and mass flow rates. Despite the reduced number of elements and nodes compared to the solar chimney-only design, the resultant mesh maintains an adequate level of accuracy and resolution necessary to capture the detailed features of the geothermal system. This optimized mesh permits efficient simulations, offering critical insights into the performance and effectiveness of the geothermal system within the room space.

By deploying appropriate meshing techniques and settings, the generation of reliable numerical models that aptly represent the room designs was ensured [30]. These meshes constitute the foundation for subsequent accurate and enlightening simulations, contributing substantially to an all-encompassing analysis and comparison of the two designs as shown in Figure 6. Notably, these techniques facilitate a more efficient evaluation of the geothermal system within the room space, thereby enhancing the understanding of its thermal behavior and effectiveness, and advancing knowledge in this field of study.

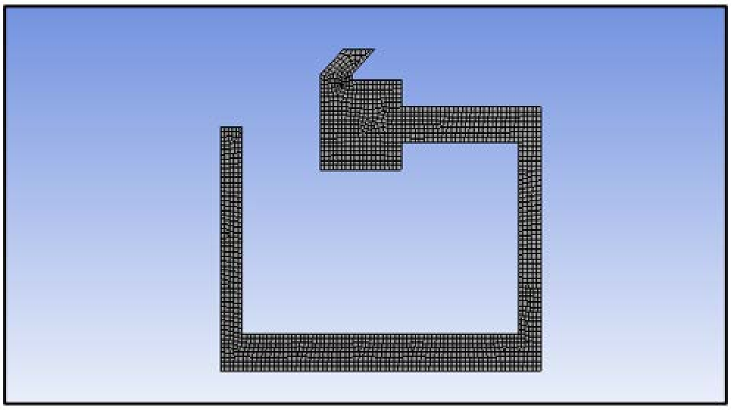

Figure 6. Meshed model of room with solar chimney and geothermal systems

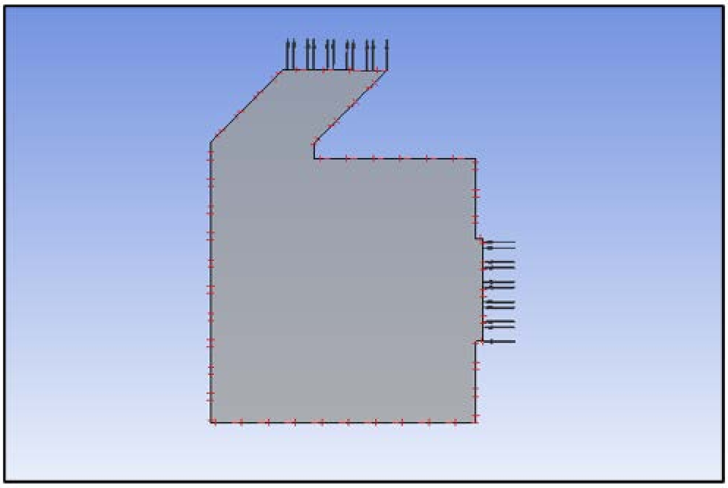

Figure 7. Inlet and outlet boundary conditions of room with solar chimney

Subsequent to the meshing procedure, loads and boundary conditions were meticulously imposed on the computational domain as shown in Figure 7. Recognizing the airflow and heat transfer characteristics within the room space, the domain type was determined as fluid. Given the specifics of this study, air was designated as the fluid material for the domain, and the turbulence model employed was the k-omega model, known for its efficacy in capturing turbulent flow behavior. To provide a realistic representation of heat transfer within the room space, the thermal radiation model employed throughout the domain was the Monte Carlo method, which accounts for complex surface interactions and their radiative exchanges.

The exacting configuration of loads, boundary conditions, and material properties, tailored to align with the unique requirements of this study, helped to ensure a credible representation of the physical phenomena within the computational domain. Such settings permitted precise and comprehensive simulations, thus enabling a detailed analysis of the thermal behavior and energy performance of the room space designs.

To emulate the influence of direct sunlight, a heat flux of 1,000W magnitude was applied to the face of the room space design exposed to sunlight, depicted in Figure 8. Representing the energy transfer from the incident solar radiation on the specific face, this heat flux enabled an accurate reflection of the thermal behavior under direct sunlight exposure. Additionally, an air inlet velocity of 0.01m/s was introduced to the side face of the computational domain, stimulating initial air movement and encouraging air circulation within the room. These settings took into account natural or forced convection effects and thus, contributed to a realistic simulation of thermal behavior and mass flow rates.

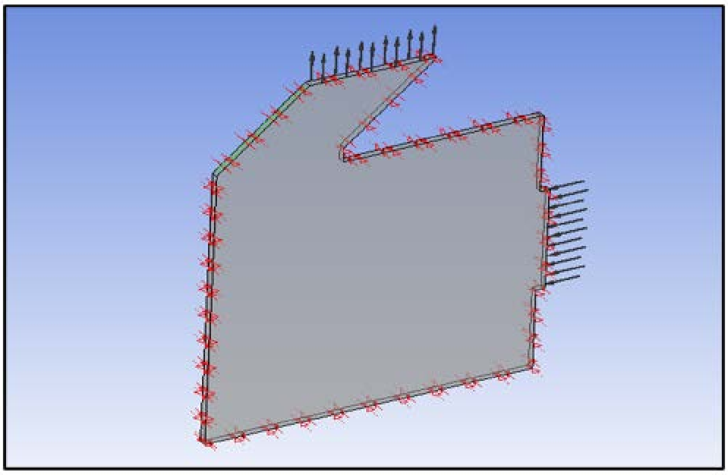

Figure 8. Heat flux boundary condition of room with solar chimney

Accounting for symmetry in the computational domain, a symmetric boundary condition was assigned to both side faces, as indicated in Figure 9. This condition ensured the mirroring of flow and thermal behavior on these faces, effectively reducing computational complexity and improving simulation efficiency.

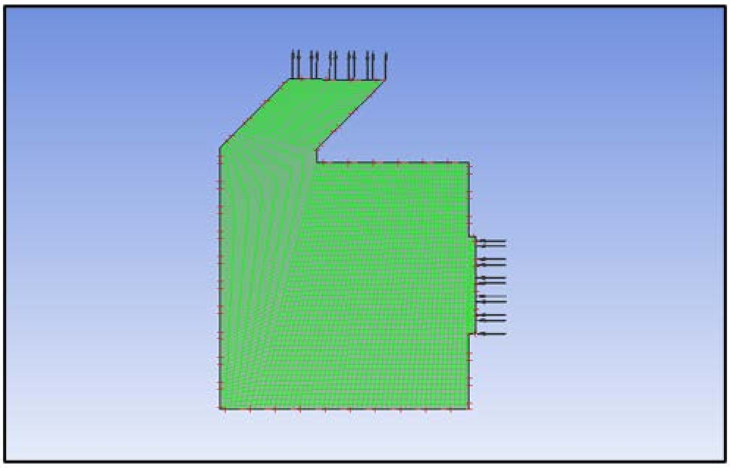

Figure 9. Symmetric boundary condition of room with solar chimney

Post defining the symmetric boundary condition, solver settings were carefully specified to guarantee reliable results. An inclusion of a high-resolution upwind scheme within the solver settings aimed at enhancing the accuracy of the numerical solution by effectively capturing flow and thermal gradients. Moreover, a residual target of 0.0001 was set, establishing the desired level of convergence for the iterative solver and ensuring the stability and precision of the simulation results.

The simulations were then executed, with the CFD solver performing calculations based on the specified settings and boundary conditions. The solver effectively simulated the thermal behavior and mass flow rates within the room space designs. As portrayed in Figure 10, the progress of the simulation was monitored by tracking the root mean square (RMS) residual target values. This process contributed to the overall robustness and accuracy of the CFD analysis and offered valuable insights into the thermal behavior and mass flow rates of the room space designs.

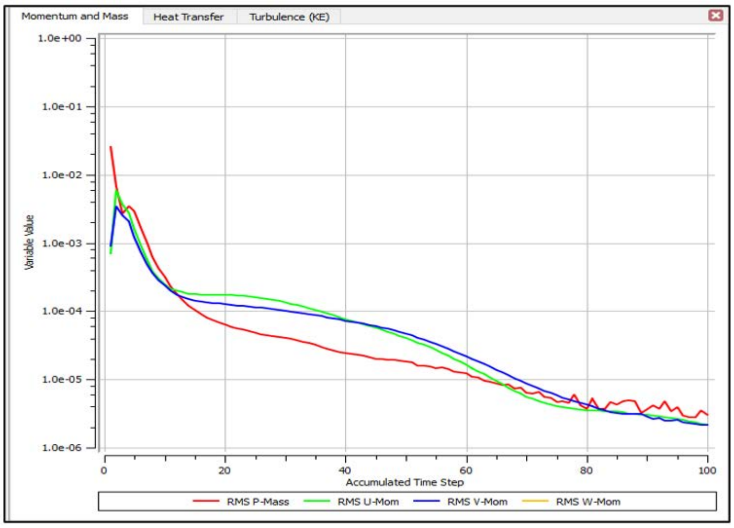

Figure 10. RMS residual values

Throughout the simulation process, the solver functioned in an iterative manner to refine the solution until a desirable level of convergence was attained. The RMS residual target values were accomplished within approximately 40 iterations, as observed. This result suggested the achievement of a stable and precise state of simulation, corroborating the reliability of the resulting data for subsequent analysis. On successful completion of the simulation and upon reaching convergence, the necessary data was procured to evaluate and contrast the thermal behavior and mass flow rates of the room space designs. As such, the simulation results constituted the foundation for inferencing and informing decisions regarding the performance and efficiency of the designs. Figure 11 illustrates the boundary condition of the room integrating both the solar chimney and geothermal system.

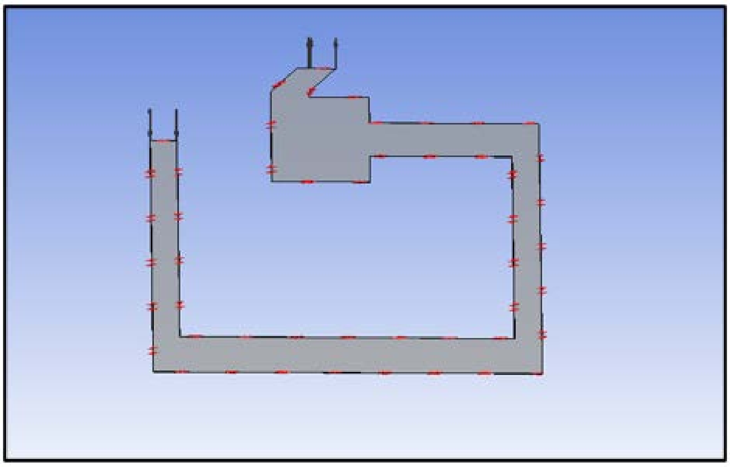

Figure 11. Boundary condition of room with solar chimney and geothermal system

In the computational domain of the geothermal system, specific boundary conditions were established to accurately model heat transfer processes and environmental interactions. These conditions considered the functionality of the geothermal system, designed to discharge heat into the comparatively colder soil, rock, or ground.

The boundary conditions for the computational domain with the geothermal system encompassed:

(1) Air Inlet Velocity: To instigate airflow within the domain, an air inlet velocity was designated, representing the rate of air ingress into the system, optimizing heat transfer via effective air circulation.

(2) Air Outlet Velocity: An air outlet velocity was defined, signifying the flow rate at which air exits the system, ensuring hot air removal and facilitating effective heat dissipation.

(3) Heat Flux: A heat flux boundary condition was applied to depict the transfer of thermal energy from the system to the relatively colder surrounding medium. This heat flux simulated the heat dissipation mechanism intrinsic to the geothermal system.

(4) Symmetry: The exploitation of symmetry boundary conditions reduced computational complexity and optimized computational resources. These boundaries ensured mirrored flow and thermal behavior on symmetric faces.

These boundary conditions enabled a precise representation of the geothermal system's functionality within the computational domain, simulating heat transfer processes, airflow, and environmental interactions. Figure 12 represents the symmetric boundary condition of the room with the integrated solar chimney and geothermal system.

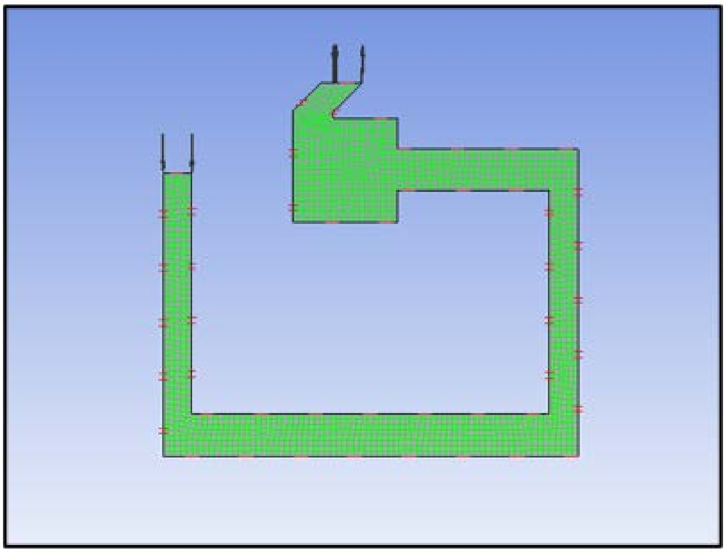

Figure 12. Symmetric boundary condition of room with solar chimney and geothermal system

The boundary conditions played a pivotal role in the accurate modeling of airflow and heat transfer within the room space designs. An inlet velocity of 0.01m/s was defined for the air inlet, instigating dynamic airflow for efficient ventilation and circulation. The outlet boundary condition was set to a relative pressure difference of 0 Pa, ensuring a balanced and continuous flow pattern. To accurately simulate the thermal behavior of the geothermal system, a wall temperature of 295K was established.

Following the detailed definition of boundary conditions, solver settings were specified, encompassing critical parameters such as the time step, convergence criteria, and relevant solver algorithms. These aspects were selected to ensure simulation stability and accuracy and to enhance the efficiency of the governing equation solving process.

The simulation was then executed using a robust CFD solver. The solver iteratively resolved the governing equations, incorporating the defined conditions and settings until a stable and converged solution was obtained. This robust methodology offered a comprehensive understanding of the thermal behavior, airflow patterns, and heat transfer mechanisms within the room space designs. The simulation results, derived from the meticulous application of the defined boundary conditions and solver settings, constituted a reliable foundation for drawing accurate conclusions and making informed decisions in sustainable building design and energy-efficient solutions.

3 Result and Discussion

Simulations of fluid flow were performed successfully for the two distinct room designs. Generated illustrations effectively portrayed the distribution of temperature, velocity, turbulence kinetic energy (TKE), and eddy dissipation for each design. To validate the simulations' accuracy, an examination using a heat flux of 750W was conducted, and this helped to compute the average room temperature.

Significantly, an average room temperature of 306.3K, as inferred from the CFD analysis, corresponded closely with the results documented in the literature [27]. The congruity of these results underscores the dependability of the applied methodology and bolsters the credibility of the findings. By analyzing the temperature distribution, velocity profiles, TKE, and eddy dissipation, a broad understanding of the fluid flow dynamics and thermal behaviors within the room designs was achieved.

These results established a robust foundation for discussions and insightful deductions regarding the designs' performance, efficiency, and optimization potential. The tight agreement between the simulated and literature-reported average room temperatures lends credence to the CFD analysis's accuracy, reinforcing the research outcomes' validity. This agreement also endorses the chosen modeling approach and software tools as apt for evaluating the room designs' thermal behavior. Detailed insights into fluid flow dynamics can guide architects and engineers to enhance room design optimization, energy efficiency, and thermal comfort. Moreover, these results contribute to the broader field of sustainable building design, emphasizing the significance of incorporating advanced fluid flow simulations in architectural decision-making.

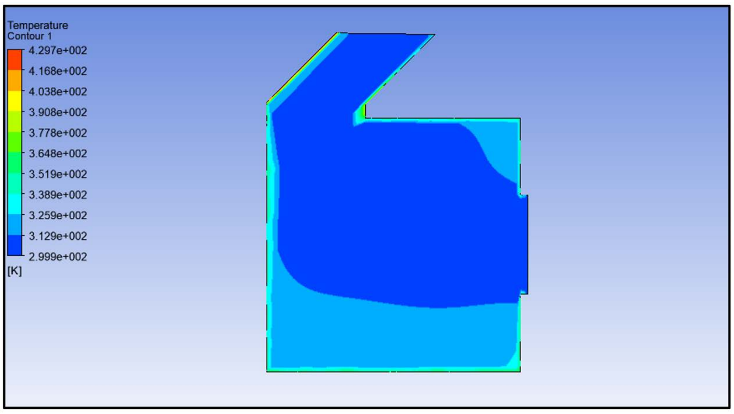

Figure 13. Temperature distribution plot of room with solar chimney

The temperature distribution plot for the room equipped with a solar chimney presented intriguing insights as shown in Figure 13. The surface directly exposed to solar radiation displayed a maximum temperature ranging between 416K to 429K, suggesting substantial absorption of solar energy. Conversely, areas with higher airflow portrayed comparatively lower temperatures, indicated by dark blue regions on the plot, pointing to effective cooling and heat dissipation. Furthermore, the corner regions of the computational space, with less exposure to direct solar radiation, registered temperatures around 325K, demonstrating the influence of surrounding airflow and heat transfer processes.

A comprehensive mesh independence study was conducted to ensure the accuracy and reliability of the simulations. This study involved varying the number of elements in the computational domain systematically and assessing their impact on the average room temperature, as shown in Table 1.

Table 1. Key parameters of our model

Number of Elements	Average Room Temperature (K)
32148	309.18
33875	309.29
34986	309.58
35486	309.62

Initiating the simulation with a coarser mesh, a smaller number of elements were first represented. An incremental refinement in mesh density ensued, and the simulation was re-executed at each interval. The average room temperature, which remained relatively consistent across varying mesh densities, was subsequently recorded. A minor fluctuation was observed between 309.18K to 309.62K, despite the alterations in mesh density. This observation suggested that the results were grid-independent, with the selected mesh density adequately representing the essential fluid flow and thermal characteristics within the room space.

The close agreement between simulated results and those documented in the literature [27] strengthened the conviction in the CFD analysis's accuracy and reliability. The mesh independence study underscored the simulation results' robustness, irrespective of the grid resolution, offering dependable insights for practical application in sustainable building design and optimization.

Regions exhibiting significant heat absorption and effective cooling were identified via the temperature distribution plot. These findings offer essential insights to architects and designers, informing areas that require optimization and design enhancements. Such insights aid in the development of energy-efficient and comfortable room spaces, aligning with sustainable building practices. The solar chimney's role in temperature regulation and enhanced thermal comfort exemplifies its potential as a viable renewable energy component in sustainable building designs.

The fusion of advanced 3D modeling software and meticulous error-checking in the design modeler facilitated a comprehensive evaluation of the room space design's performance and behavior. The accuracy and reliability of the results obtained in the subsequent analyses were ensured, contributing to the study's overall rigor and validity.

The fluid flow simulation results, together with the mesh independence study, elucidate the thermal behavior and heat distribution within the room space designs. These findings augment the understanding of the solar chimney's effectiveness in managing temperature variations and improving the space's overall thermal comfort. Furthermore, the results, in conjunction with the identified optimal mesh density, buttress the credibility of the simulation outcomes, thus fostering meaningful discussions and insightful interpretations pertaining to the room space designs' performance, efficiency, and potential for optimization.

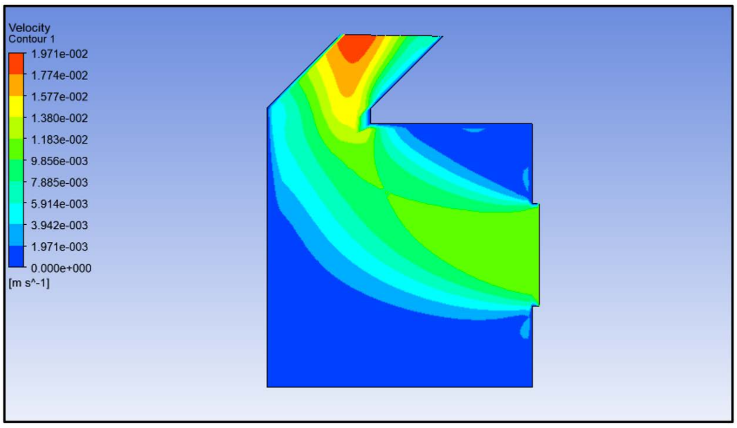

Figure 14. Velocity distribution plot of room with solar chimney

As shown in Figure 14, the velocity distribution plot for the room equipped with a solar chimney prominently portrays the non-uniform airflow within the space. The green and red marked regions, denoting maximum airflow approximately at 0.0098 m/s, play a crucial role in enhancing ventilation and air circulation, thereby fostering a more comfortable indoor environment.

In the chimney region, a notable increase in air velocities, ranging roughly from 0.015 m/s to 0.017 m/s, is observed. This amplified velocity signifies the escalated air movement within the chimney, fostering efficient heat transfer and improved ventilation throughout the room space. The upward airflow, promoted by the solar chimney, contributes significantly to the overall circulation and ventilation within the room, ensuring the effective expulsion of excess heat and maintaining thermal comfort.

Valuable insights into the airflow patterns and distribution within the room space equipped with a solar chimney are offered by the velocity distribution plot, identifying regions of maximum airflow and velocity variations. This understanding of the solar chimney's efficacy in promoting air circulation and ensuring thermal comfort is enhanced, underscoring its potential as an eco-friendly, energy-efficient solution for sustainable building designs.

The velocity distribution plot, illustrating the non-uniform airflow distribution, informs architects and designers about the specific regions of the room space contributing significantly to air circulation. This knowledge forms the basis for further design optimizations, aiming to optimize the room's airflow for enhanced comfort and energy efficiency. Incorporating a solar chimney into the room design augments its natural ventilation capabilities, mitigating the requirement for mechanical cooling and thus contributing to the building's overall energy efficiency and environmental sustainability. Figures 15 and 16 depict the velocity vector plot for the room equipped with a solar chimney.

The velocity vector plot, as illustrated in Figures 13 and 14, presents the magnitude and direction of airflow within the room space. Significantly, vortex regions at both the upper right corner and lower right corner of the room are discerned, suggesting swirling air patterns that indicate the existence of vortices or eddies in these areas. The formation of such vortices can have significant implications on airflow, heat transfer, and ventilation within a space. Consequently, it is critical to understand their presence and behavior to optimize ventilation system designs and ensure efficient air movement.

Gaining insights into the airflow patterns and circulation within a room equipped with a solar chimney is facilitated by visualizing the velocity vector plot and identifying vortex regions. These insights offer a comprehensive understanding of thermal behavior and ventilation effectiveness, allowing informed design decisions for enhanced thermal comfort and energy efficiency.

Localised air movement and heat transfer are suggested by the presence of vortices in specific areas of the room. This knowledge could guide architects and designers in strategically placing ventilation outlets and optimizing airflow pathways to ensure effective ventilation and thermal comfort. With the aid of natural airflow patterns facilitated by the solar chimney, a comfortable indoor environment can be designed to minimize energy consumption.

Essentially, the velocity vector plot offers valuable visualizations and insights into the airflow patterns and the role of vortices within a room equipped with a solar chimney. This knowledge proves instrumental in refining the room's design and ventilation systems, aiming for energy-efficient and sustainable building spaces that prioritize occupants' thermal comfort and well-being.

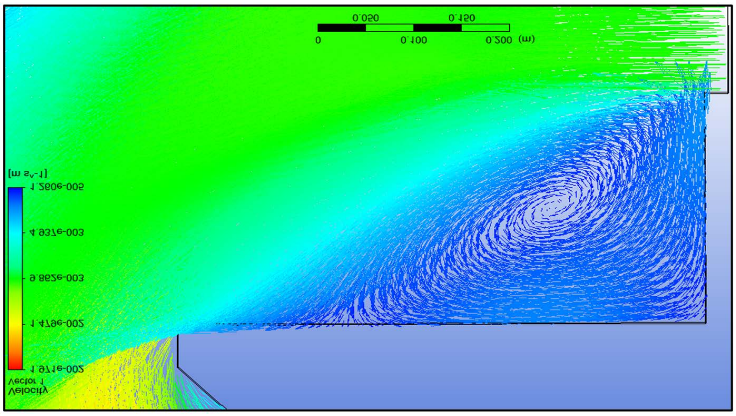

Figure 15. Velocity vector plot of room with solar chimney (upper right corner)

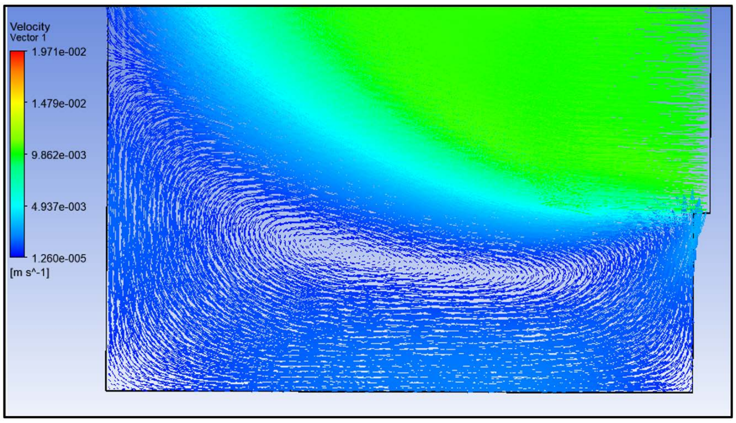

Figure 16. Velocity vector plot of room with solar chimney (lower right corner)

Distinct airflow patterns across various regions are disclosed in the velocity analysis of a room fitted with a solar chimney. Identified within the central region of the room are two zones: one highlighted in green indicating a stronger air movement with an airflow velocity of approximately 0.009 m/s, and a contrasting light blue region denoting a gentler airflow velocity of around 0.0049 m/s. These divergent areas suggest efficiency of ventilation and airflow within the room.

Understanding the velocity distribution across these distinct regions is paramount for evaluating ventilation effectiveness and ensuring occupants' thermal comfort. These identified zones, with their unique airflow velocities, allow an insightful look into the airflow patterns and distribution within the room, thus providing valuable data for the optimization of ventilation strategies. As a result, the overall indoor air quality and thermal comfort can be enhanced. For instance, the regions with higher airflow velocities may be tactically employed for efficient air circulation and cooling, while the zones with softer airflow might benefit from additional ventilation measures to ascertain uniform air distribution and thermal comfort.

Consequently, these velocity analysis insights can assist architects and designers in making informed decisions to create a well-ventilated and comfortable indoor environment within the room featuring a solar chimney. This contributes to the overall energy efficiency and sustainability of the building as effective ventilation reduces dependency on mechanical cooling systems and fosters natural airflow. The result is a decrease in energy consumption and improvement in indoor air quality.

An integral parameter characterizing the energy associated with turbulent motion within a flow is the TKE, quantifying the velocity fluctuations in turbulent flows and representing the energy transferred from larger to smaller scales within the turbulent motion. Within the context of this study, a TKE plot was produced for the room with a solar chimney design to visually represent the TKE distribution within the space, as depicted in Figure 17.

This plot provides valuable insights into regions of higher turbulence and energy dissipation. Notably, the chimney region displays the highest TKE, with a magnitude of approximately 0.000231 m^2s^2, indicating that this area experiences significant levels of turbulence and vigorous fluid motion, thereby leading to enhanced mixing and heat transfer. Understanding the distribution and magnitude of TKE within the room is crucial for assessing the solar chimney design's efficiency and its impact on promoting air circulation and ventilation.

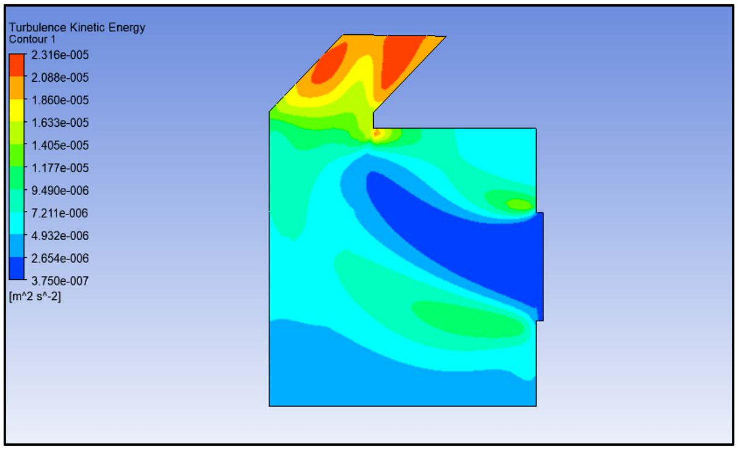

Figure 17. TKE distribution plot of room with solar chimney

By identifying the regions with higher TKE, this analysis aids in optimizing the design and placement of the chimney system to enhance thermal comfort and energy performance. This insight contributes to a comprehensive understanding of the fluid dynamics within a room featuring a solar chimney. It is valuable information for architects and designers to fine-tune design parameters, ensuring effective ventilation, and improved thermal comfort for occupants. Harnessing turbulent energy effectively can implement sustainable building practices, thereby reducing energy consumption and enhancing the room space's overall environmental performance.

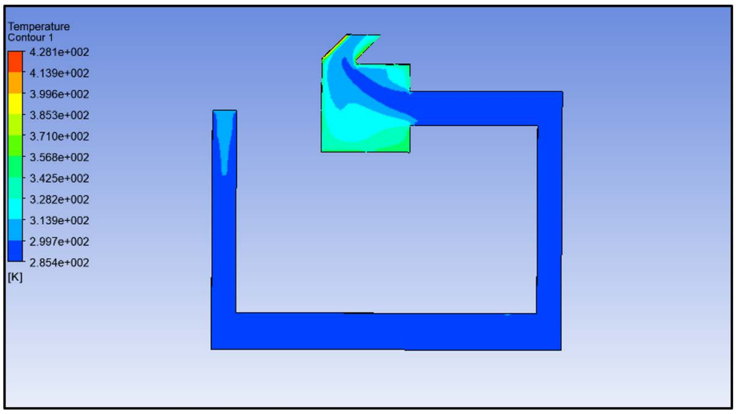

Figure 18. Temperature distribution plot of room with solar chimney and geothermal system

A temperature distribution plot, as depicted in Figure 18, is generated to detail the thermal behavior within the room space, which integrates both solar chimney and geothermal systems. As a pictorial representation of temperature variations, this plot offers pivotal insights into the thermal dynamics of the environment.

The maximum temperature detected within the room space is found to reach 428K, highlighting areas of concentrated heat absorption from the solar and geothermal systems. These higher-temperature regions contribute to the efficiency of heat transfer and thermal performance. However, notable temperature distinctions within certain regions of the room space are observed. The lower left region records a relatively cooler temperature of 312K, in contrast to the room's corner region, which exhibits a slightly higher temperature of 340K.

This detailed examination of the temperature distribution plot provides valuable knowledge regarding the effectiveness of the integrated solar chimney and geothermal systems in room temperature regulation and the enhancement of thermal comfort. Such findings enhance the comprehensive understanding of the thermal behavior within the space, aiding in the optimization of sustainable technology design and operations for improved energy efficiency and overall environmental performance. Architects, engineers, and policymakers can employ this knowledge to make informed decisions on sustainable building design, ensuring enhanced thermal comfort and energy performance in room spaces.

Following this, a pressure distribution plot is generated, as seen in Figure 19, for the room space that incorporates both solar chimney and geothermal systems. This plot, a visual representation of pressure variations within the space, offers essential insights into the airflow patterns and pressure distribution.

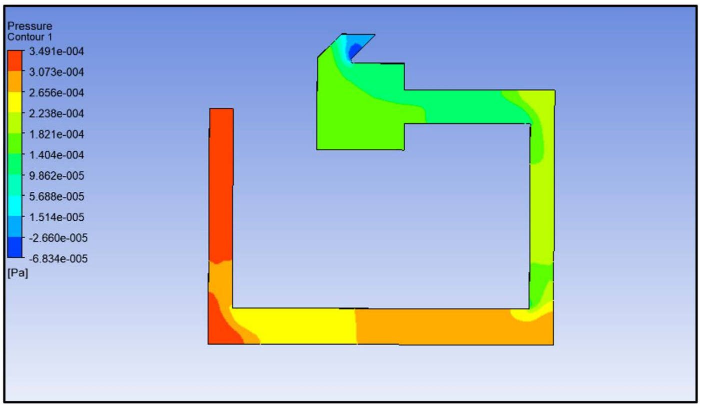

Figure 19. Pressure distribution plot of room with solar chimney and geothermal system

The analysis illustrates a higher pressure at the geothermal tube inlet, which gradually decreases along the tube's length. This pressure drops along the geothermal tube, a result of flow resistance and heat exchange within the system, signals efficient heat transfer and energy utilization. Meanwhile, a relatively uniform pressure is observed within the room space, suggested by the green-colored region on the plot, indicative of a balanced and well-ventilated environment ensuring optimal air circulation and thermal comfort.

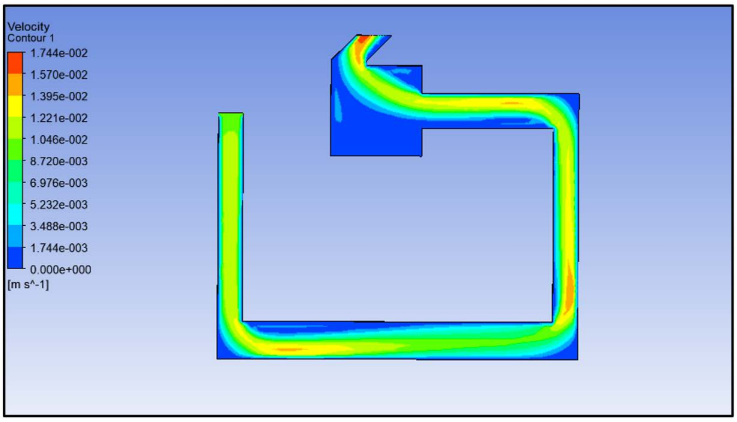

Figure 20. Velocity distribution plot of room with solar chimney and geothermal system

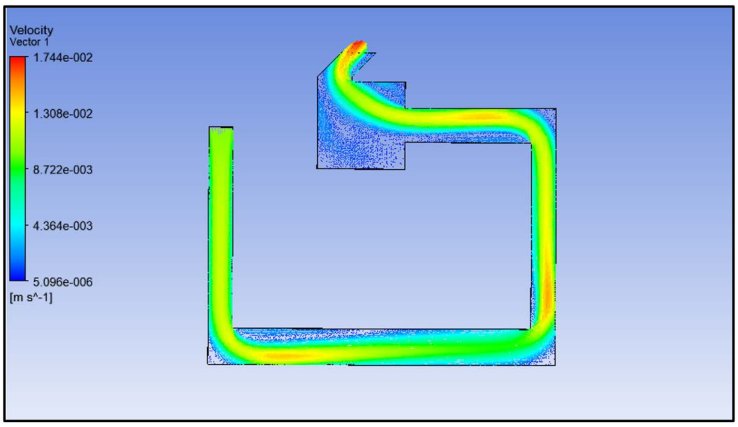

Figure 21. Velocity vector plot of room with solar chimney and geothermal system

This pressure distribution plot provides crucial insights into the airflow patterns and pressure variations within the room space integrating solar chimney and geothermal systems. By identifying areas of high and low pressure, this analysis aids in understanding the effectiveness of these systems in promoting air circulation, heat transfer, and maintaining a balanced pressure distribution throughout the space. These findings contribute to a comprehensive understanding of the performance and efficacy of integrated sustainable technologies in room space design. Architects and engineers can use this information to optimize the design and operation of the solar chimney and geothermal system, ensuring enhanced energy efficiency and overall environmental sustainability. Additionally, these insights can aid policymakers in encouraging the widespread adoption of green building practices and technologies, leading to a more sustainable and energy-efficient built environment.

Finally, velocity distribution and velocity vector plots have been meticulously generated for the room space design, incorporating both solar chimney and geothermal system, as displayed in Figure 20 and Figure 21, respectively.

Incorporating both a solar chimney and geothermal system, the velocity distribution and velocity vector plots offer a graphic portrayal of airflow patterns and velocity variances within the room space. This crucial data provides foundational understanding for enhancing the design and operation of these integrated sustainable technologies.

In the velocity distribution plot, notable areas of the geothermal tube are observed to manifest higher velocities, as marked by the red and green colored regions. The velocity within these areas is recorded to reach approximately 0.0087m/s, indicative of accelerated airflow and proficient heat transfer within the geothermal system. Such a phenomenon confirms the geothermal system's efficient operation, fostering improved energy utilization and thermal comfort within the space. Moreover, vortices are discerned within the room's corner regions, mirroring the findings of the first design that lacked the geothermal system. These vortices suggest the occurrence of swirling airflow and turbulence, potentially influencing the room's heat distribution and ventilation. Identifying such vortices assists in comprehending the airflow dynamics and locating potential areas for further optimization, thereby promoting enhanced indoor air quality and thermal performance.

The analysis of these plots results in significant insights into the airflow patterns, velocity fluctuations, and the geothermal system's impact on the room space. Understanding these dynamics is critical for optimizing the geothermal system's design and placement, enhancing thermal comfort, and boosting energy efficiency.

These findings can guide architects, engineers, and policymakers in making informed decisions regarding sustainable building technology design and implementation. Through the integration of efficient and environmentally sustainable systems like the solar chimney and geothermal system, green energy buildings can significantly contribute to reducing carbon emissions and conserving natural resources, nurturing a more sustainable built environment. Detailed temperature and heat transfer data are presented in Table 2.

Table 2. Temperature and heat transfer details

Geometry Details	Average Room Temperature (K)
Room without geothermal system	309.6
Room with geothermal system	302.2

A meticulous comparison of average temperatures has been conducted between two designs: one lacking a geothermal system and the other incorporating it. The analysis reveals a notable discrepancy in average room temperature between the two designs. The design incorporating the geothermal system shows a significantly lower average room temperature than the one lacking it. This remarkable reduction in average room temperature is attributed to the efficient heat exchange and cooling provided by the geothermal system.

The geothermal system capably harnesses the stable and cooler underground temperature to extract heat from the room, leading to a more balanced and comfortable indoor environment. With the inclusion of this sustainable technology, the design integrating the geothermal system encourages energy efficiency and enhanced thermal comfort within the room space. These findings underline the importance of integrating green and sustainable technologies, like the geothermal system, into building designs. Such technologies are pivotal in reducing energy consumption, minimizing carbon emissions, and improving the overall well-being of occupants.

Table 3. Average mass flow rate comparison

Geometry Details	Average Mass Flow Rate $(\mathbf{Kg/s})$ $(^{*}\mathbf{10^{-6}})$
Room without geothermal system	1.878
Room with geothermal system	4.134

By optimizing the integration and operation of sustainable systems like the geothermal system, architects and engineers can foster energy-efficient and environmentally conscious buildings that positively contribute to climate change mitigation and a more sustainable future. These insights are crucial for inspiring innovation and encouraging environmentally responsible building practices for a greener and healthier built environment. As shown in Table 3, the average mass flow rate comparison provides a distinct visual representation of the substantial difference between the two room designs.

A notable enhancement in the mass flow rate is observed within the room incorporating the geothermal system as opposed to its counterpart, which lacks such an arrangement. This observation underscores the efficacy of geothermal system integration in augmenting airflow and ventilation in the room space. The elevation in mass flow rate within the design that incorporates the geothermal system is indicative of superior air exchange, an element fundamental to ensuring thermal comfort, better indoor air quality, and increased energy efficiency. The efficient heat exchange facilitated by the geothermal system contributes to a more harmonious and well-ventilated environment, fostering a healthier and more appealing indoor atmosphere.

Such results elucidate essential aspects of sustainable building design and accentuate the importance of renewable energy systems such as geothermal systems. The inclusion of such eco-friendly technologies enables architects and engineers to enhance room space performance, curtail energy consumption, and mitigate overall environmental impact.

The information gleaned from the average mass flow rate comparison chart offers valuable insights, fostering the growth of sustainable building practices and the advancement of green energy solutions within the construction industry. Through the careful integration of renewable energy systems, building designs can be brought into alignment with sustainability principles and contribute meaningfully to a more environmentally conscious future. Consequently, the overall performance and efficiency of building spaces can be elevated, leading to increased comfort and well-being for occupants while diminishing environmental footprint.

To deepen the understanding of these findings, future research may investigate the implementation of these sustainable systems in different climatic conditions and building configurations. Evaluating their performance under various conditions can provide broader insights into the versatility and adaptability of these systems. Moreover, long-term monitoring of these systems may be beneficial to assess the durability and maintenance requirements, further contributing to the optimization of their design and operation. By extending the scope of investigation, architects, engineers, and policymakers can be better equipped to make informed decisions and drive the widespread adoption of these sustainable building practices.

4 Conclusion

This research endeavored to elucidate the thermal performance and airflow dynamics within a room outfitted with a geothermal system, and a comparative analysis was performed with a room bereft of such an arrangement. The intention was to quantify the enhancements facilitated by the geothermal system, elucidate on practical implications for professionals in architecture and engineering, propose prospective future work, and acknowledge the study's limitations.

The conducted simulations unveiled that the room supplemented with the geothermal system registered an average temperature of 302.2 Kelvin, a figure roughly 7.4 Kelvin lower than the room without the geothermal system, which recorded an average temperature of 309.6 Kelvin. Furthermore, the room equipped with the geothermal system witnessed a mass flow rate of 4.134×10^{-6} kg/s, higher than the room without the system, which demonstrated a mass flow rate of 1.878×10^{-6} kg/s. These findings highlight the substantial potential of geothermal systems in ameliorating thermal comfort and bolstering energy efficiency within room spaces.

The escalated mass flow rate observed in the room integrating the geothermal system suggests enhanced air exchange, thereby contributing to the augmentation of ventilation and indoor air quality. Such outcomes carry profound implications for architects and engineers, underscoring the importance of considering the integration of geothermal systems into building designs. The optimisation of the design parameters for the solar chimney and geothermal systems, such as their dimensions, configuration, and orientation, can catalyse their performance, paving the way for more significant improvements in thermal comfort and energy efficiency.

Future research directions could revolve around optimising the design parameters of the solar chimney and geothermal system to maximise energy efficiency and thermal performance. Moreover, the implementation of intelligent control algorithms and feedback mechanisms can optimise the harnessing of RES and uphold optimal indoor conditions.

It is paramount to recognise the limitations of this study, which encompass factors such as boundary conditions, model assumptions, and numerical approximations. Future investigations could address these limitations by deploying advanced modelling techniques and broadening the scope of the analysis.

The study distinctly substantiates the significant benefits of integrating geothermal systems in room spaces, delivering improved thermal comfort, enhanced airflow, and augmented energy efficiency. By optimising design parameters, executing empirical validations, and addressing study limitations, the practical application and impact of these findings can be further amplified. These efforts will contribute to the evolution of more sustainable and comfortable building spaces, fostering a greener future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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