ENHANCING THERMAL COMFORT IN BUILDINGS
Innovations in Sustainable Cooling and Heating Systems Utilizing Geothermal Energy

by

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This research paper explores the potential of passive heating and cooling strategies in buildings utilizing geothermal resources. The focus is on renewable energy solutions, including geothermal energy, solar systems, and Earth-to-air heat exchangers, with the aim of reducing energy consumption for cooling and heating loads. The investigation primarily centers on the performance and optimization of the Trombe wall system, a well-known passive solar system. Numerical studies are conducted to analyze the thermal and fluid-dynamical behavior of the Trombe wall system. The findings provide valuable insights into its operational characteristics and efficiency, aiding in the refinement of design approaches and optimization of system performance. The analysis of temperature distributions within the building and underlying soil reveals the stability of soil temperatures throughout the day, indicating its potential as a reliable heat sink and source for heating and cooling. The dynamic variations in room temperatures, influenced by solar flux fluctuations, convection processes, and the functioning of the air-to-earth heat exchanger, highlight the importance of effective system design and control for achieving optimal thermal performance.

Key words: *buildings, environmentally friendly, sustainable development, geothermal energy, renewable*

Introduction

Passive solar systems have gained considerable attention as a viable approach for integrating renewable energy into HVAC systems. These systems rely on natural processes without the need for mechanical devices, making them attractive for solar energy collection

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and indoor air ventilation. Among various passive solar systems, the Trombe wall has emerged as a prominent solution [1-5], see for example fig. 1. The Trombe wall configuration involves positioning a glazing panel near a substantial thermal mass wall. This configuration facilitates the capacity of the wall to assimilate solar radiation and transfer a fraction of the harnessed energy into the interior of the structure via the process of natural convection occurring within a solar chimney generated by the glazing and the wall. This thermos-circulation process occurs as the heated air in contact with the wall rises through the lower vent and reenters the room via the upper vent, transferring solar heat flux to effectively heat the building [6-10].

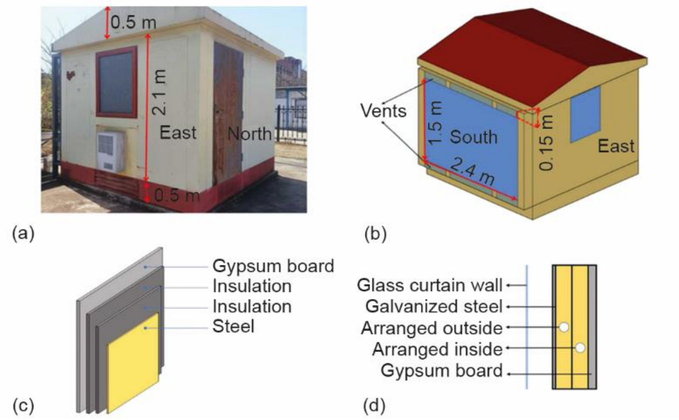

Figure 1. An exemplification of an experimental building situated in Changsha, a region characterized by a hot summer and cold winter climate in China [5]; (a) experimental lightweight building, (b) retrofit building with Trombe wall, (c) conventional building envelope, and (d) Trombe wall building envelope

Although passive solar systems, such as the Trombe wall, have exhibited their inherent potential, current investigations persist in delving into their continuous refinement and optimization. One avenue of exploration involves integrating geothermal energy as a supplementary or alternative heat source within Trombe wall systems. Geothermal energy, harnessed from the Earth stored heat, offers a renewable and sustainable resource that can enhance the overall efficiency and effectiveness of the Trombe wall system [11-15]. The integration of geothermal energy into Trombe wall systems has the potential to provide additional heating capacity and extend the system operational capabilities. By utilizing the consistent and stable heat from geothermal sources, the Trombe wall system can operate more efficiently and provide a reliable heating solution. Additionally, the combination of solar and geothermal energy sources can contribute to enhanced energy savings and reduce reliance on conventional heating systems [16-20].

The present paper proposes a comprehensive numerical study aimed at investigating the thermal and fluid dynamical behavior of a Trombe wall system. The study aims to enhance our understanding of the system performance characteristics in passive solar heating applications. Concurrently, there has been an increasing imperative to reduce energy consumption associated with cooling and heating loads in recent years. This imperative can be met through the utilization of renewable energy sources, such as wind, solar, and geothermal energy. Geothermal energy emerges as a substantial renewable resource with diverse applications, including space heating and cooling, water temperature control, and electricity generation. For cooling and heating buildings, geothermal systems rely on the ground as a heat sink during summer and a heat source during winter. This dependency leverages the soil temperature at a specific depth below the ground surface, which remains relatively stable throughout the year and is referred to as the undisturbed temperature. The undisturbed temperature is typically lower than the outside air temperature in summer and higher in winter, making it conducive to achieving thermal balance. One effective approach to harnessing this potential is through the implementation of an Earth-to-air heat exchanger (EAHE), commonly referred to as a ground heat exchanger.

System description

The primary objective of this research study is to assess the performance characteristics of a Trombe wall integrated with an air-to-earth heat exchanger (AEHE) system in a specific geographical location. The studied locale has dimensions of seven meters in length and three meters in height, with an additional five-meter-height extension specifically allocated for the Trombe wall. The Trombe wall comprises a glass wall inclined at an angle of 72° relative to the horizontal, while the AEHE system is constructed using two eleven-meter lengths of polyvinyl chloride (PVC) tubing with a diameter of 20 cm. The tubing is buried at depths of 1.3 meters and 2.6 meters, as illustrated in fig. 2.

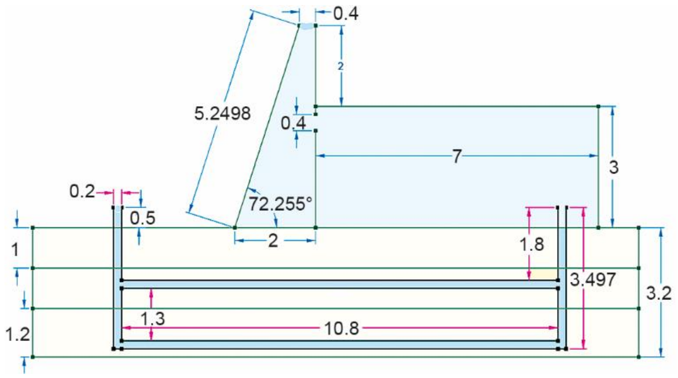

Figure 2. Dimensions of the studied system [m]

Boundary conditions

The boundary conditions utilized in the numerical analysis of the Trombe wall system, fig. 3, are specified as follows.

- *Inlet and outlet 3*: The static pressure at both the inlet and outlet is set to zero ($P_o = 0$).
- *Soil layers*: The three soil layers are maintained at constant temperatures from top to bottom: T_1 = 18 °C, T_2 = 15 °C, and T_3 = 10 °C.
- *Glazing*: At the glazing interface, a variable solar flux is applied.
- *Inflow air temperature*: The temperature of the incoming air introduced into the room is predetermined and prescribed.
- *Other walls and the topmost soil*: The remaining walls and the topmost soil are subjected to a constant temperature of 35 °C.

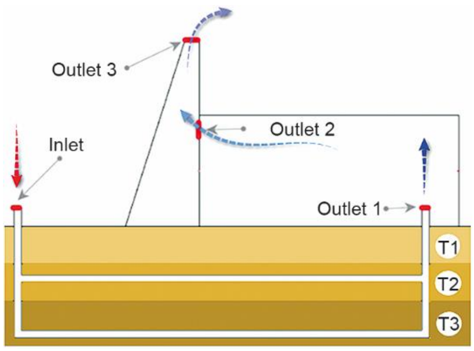

Figure 3. The indoors and outdoors opening of the studied system

– *Boussinesq approximation:* The Boussinesq approximation is employed to model the behavior of air, assuming that density variations due to temperature changes are negligible, except for the buoyancy effect.

By imposing these boundary conditions, the numerical study aims to capture the thermal and fluid dynamics within the Trombe wall system, considering the varying solar flux, inflow air temperature, and the interaction between the wall, soil, and air.

Governing equations

The governing equations for the steady-state natural convection flow are derived through the application of the fundamental principles of mass, momentum, and energy conservation. These equations provide a framework for understanding and analyzing the complex dynamics of fluid motion and heat transfer in natural convection scenarios, driven by the Trombe wall.

– Continuity:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

– Momentum:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+g\beta(T-T_c) \tag{2}$$

– Energy:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{3}$$

In the context of the presented framework, the variables x and y correspond to the spatial distances measured along the horizontal and vertical axes, respectively. The velocity components in the x- and y-directions are symbolically represented as u and v, respectively. The temperature is represented by the variable T. The kinematic viscosity and thermal diffusivity are denoted by υ and α, respectively. The variables p and ρ correspond to the pressure and density, respectively. The T_c represents the lowest temperature between the glazing and Trombe walls. Furthermore, L represents the side length of the glazing under consideration.

By conducting a thorough analysis and comprehensive understanding of the governing equations governing the Trombe wall system, this research makes a valuable contribution to the broader field of passive solar heating and cooling technologies. This study sets the stage for advancements in sustainable building design and the effective utilization of renewable energy sources, leading to enhanced thermal comfort and improved energy efficiency.

Findings and discussions

The presented figures offer valuable insights into the thermal behavior of passive heating and cooling in buildings utilizing geothermal resources. Figure 4 illustrates the temporal evolution of temperature from 6:00 a. m. to 4:00 p. m., spanning from the lower region to the upper section of the glazing. The graph depicts a notable rise in outside temperatures, starting at 35 °C at 6 a. m. and reaching above 100 °C by 4 p. m. Additionally, it is evident that the lower portion of the glazing maintains lower temperatures due to its proximity to the soil, which serves as a heat sink.

Upon closer examination of the temperature variation throughout a single day at a specific height of 1.5 m from the floor, fig. 5 reveals the presence of an isothermal stratification. Within this stratified zone, the temperature exhibits minimal fluctuations, hovering around 20 °C. This observation indicates a relatively stable thermal environment, likely attributed to the combined effects of geothermal heat transfer and the design of the passive heating and cooling system.

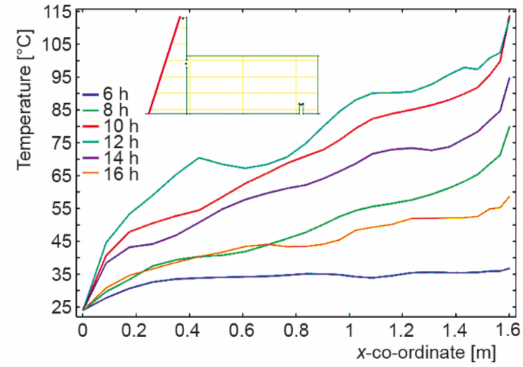

Figure 4. Temperature evolution at the outside glazing

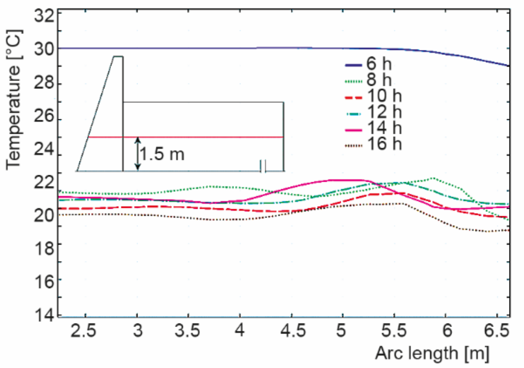

Figure 5. Temperature distribution in a horizontal line 1.5 m above the floor

The clear distinction between the outside temperature fluctuations and the consistent temperature profile within the building is crucial for understanding the effectiveness of the passive heating and cooling strategy. By capitalizing on the geothermal resource and implementing appropriate design measures, such as the strategic placement of glazing and insulation, the indoor temperature remains relatively constant, offering a comfortable living or working environment for occupants.

When measuring the temperature at different inlet outlets boundaries, some difference are observed between inlet-outlet1 and outlet 2-outlet 3, the formers show an increase in temperature till 11 a. m. then a decrease in temperature, because of variation of temperature from HVAC data, in the lathers temperature is disturbed and mixed with the bulk in the room which give a fairly constant temperature as prescribed in fig. 5, see fig. 6.

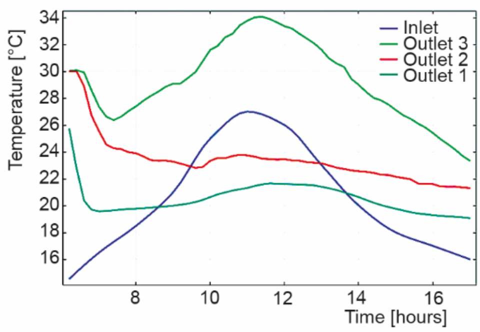

Figure 6. Temperature distribution during one day from different boundaries

An analysis of temperature measurements at different inlet and outlet boundaries provides valuable insights into the thermal dynamics of the system. It is noteworthy that distinct temperature variations are observed between the inlet-outlet 1 and outlet 2-outlet 3 sections. Specifically, the former experiences an initial increase in temperature until approximately

11 a. m., followed by a subsequent decrease. This behavior can be attributed to variations in temperature derived from HVAC data, as illustrated in fig. 7. In contrast, the temperature in the latter section exhibits a more stable and consistent pattern, indicating a more uniform distribution throughout the room, as depicted in fig. 5. These observations are further supported by fig. 6, which visualizes the disturbance and mixing of temperatures within the room, resulting in a relatively constant temperature profile.

The discrepancy in temperature behavior between the two sections can be attributed to the interplay of several factors. The inlet-outlet-1 region experiences fluctuations due to the influence of external environmental conditions and the operation of the HVAC system, causing fluctuations in the incoming air temperature. Consequently, these variations affect the overall thermal dynamics within the building, leading to corresponding fluctuations in temperature at the inlet and outlet boundaries. On the other hand, the outlet 2-outlet 3 section demonstrates a more consistent temperature profile, indicating a more effective distribution and mixing of the air within the room. This homogenization of temperatures can be attributed to the combined effects of the geothermal heating and cooling system, the thermal properties of the materials used, and the strategic arrangement of the inlet and outlet vents.

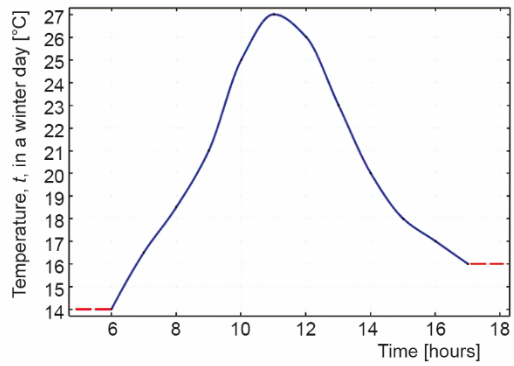

Figure 7. Temperature (winter) *vs.* time

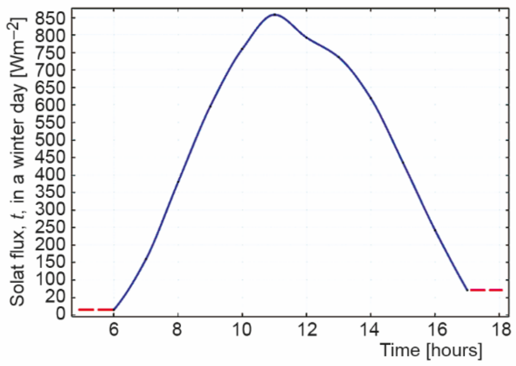

Figure 8. Solar heat flux (winter) *vs.* time

The study of the distribution in the temperature within the room and the underlying soil during peak hours, specifically at 6 a. m., 7 a. m., 12 p. m., and 5 p. m., is presented in fig. 9. Upon examining the data, several key observations can be made. Firstly, it is evident that the temperature of the soil remains relatively constant throughout the day, displaying a distribution pattern with values ranging from approximately 30 °C at the surface to 10 °C at a depth of 3 m. Conversely, the temperature within the room undergoes significant changes during the discussed hours.

Initially, the temperature within the room was relatively high, reaching nearly 30 °C. However, as time progresses, there is a gradual cooling of the room due to the inflow of air from the AEHE. This gradual decrease in temperature continues until it reaches a minimum at around 12 a. m. Subsequently, the temperature begins to rise, driven by variations in solar flux that activate convection processes influenced by variable HVAC data, as illustrated in fig. 8. The solar flux reaches its maximum around 12 p. m., resulting in increased air movement in proximity to the glazing (with an accompanying rise in air velocity). This heightened air movement leads to a strong suction effect from the AEHE, further contributing to the temperature dynamics within the room. The temperature profiles displayed in fig. 9 provide valuable insights into the intricate interactions between the room, the soil, and the external environment. The stability of soil temperatures throughout the day suggests the effectiveness of the geothermal heat transfer mechanism in maintaining a consistent thermal environment. This stability is crucial in supporting the passive heating and cooling strategies employed in the building.

These observations contribute to advancing the knowledge and optimization of passive heating and cooling systems utilizing geothermal resources, fostering the development of sustainable building practices.

Upon analyzing fig. 10, which aligns with the observations presented in fig. 9, a noticeable variation in air velocity throughout the day is evident. The data reveals a gradual increase in air velocity from 6 a. m. to 12 p. m., followed by a subsequent decrease leading up to 5 p. m.

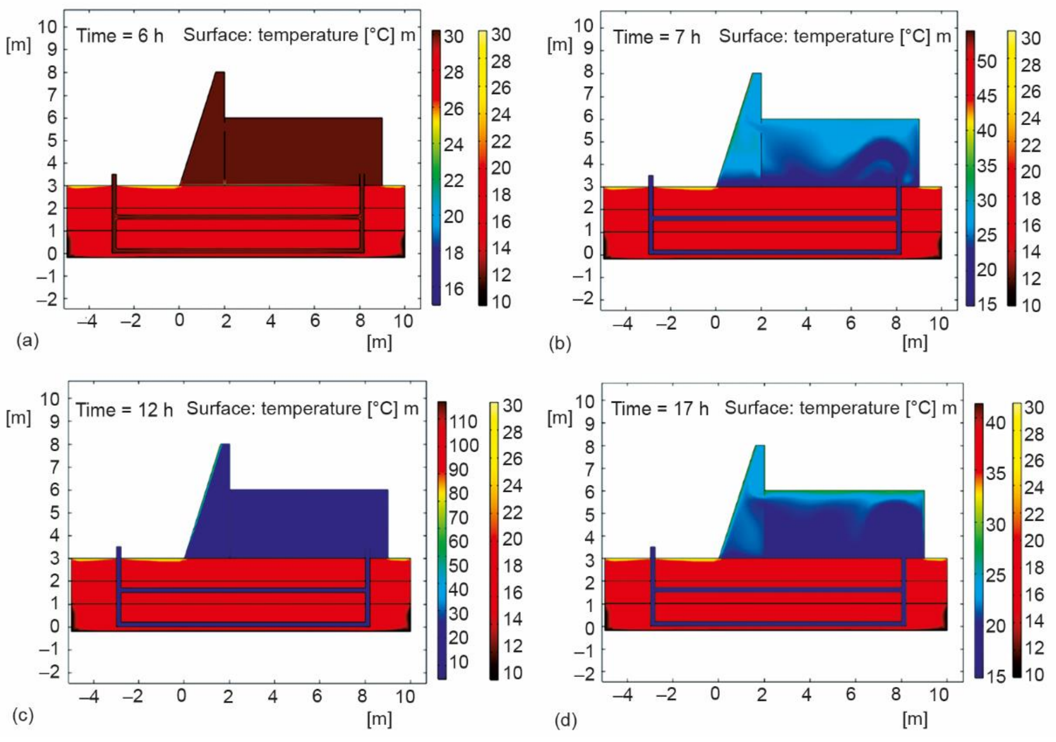

Figure 9. Temperature distribution within the room and the underlying soil during peak hours, specifically at; (a) 6 a. m., (b) 7 a. m., (c) 12 p. m., and (d) 5 p. m.

The rising air velocity observed during the morning hours can be attributed to the combined effects of solar flux variations and the resulting convective processes within the room. As the solar flux intensifies, it stimulates increased air movement near the glazing, promoting a higher velocity. This augmented air movement is closely linked to the aspiration generated by the AEHE, contributing to the overall convective dynamics within the room. Subsequently, as the day progresses, the air velocity begins to decrease.

This diminishing trend can be associated with the attenuation of solar flux, which consequently reduces the convective forces driving the air movement. Moreover, factors such

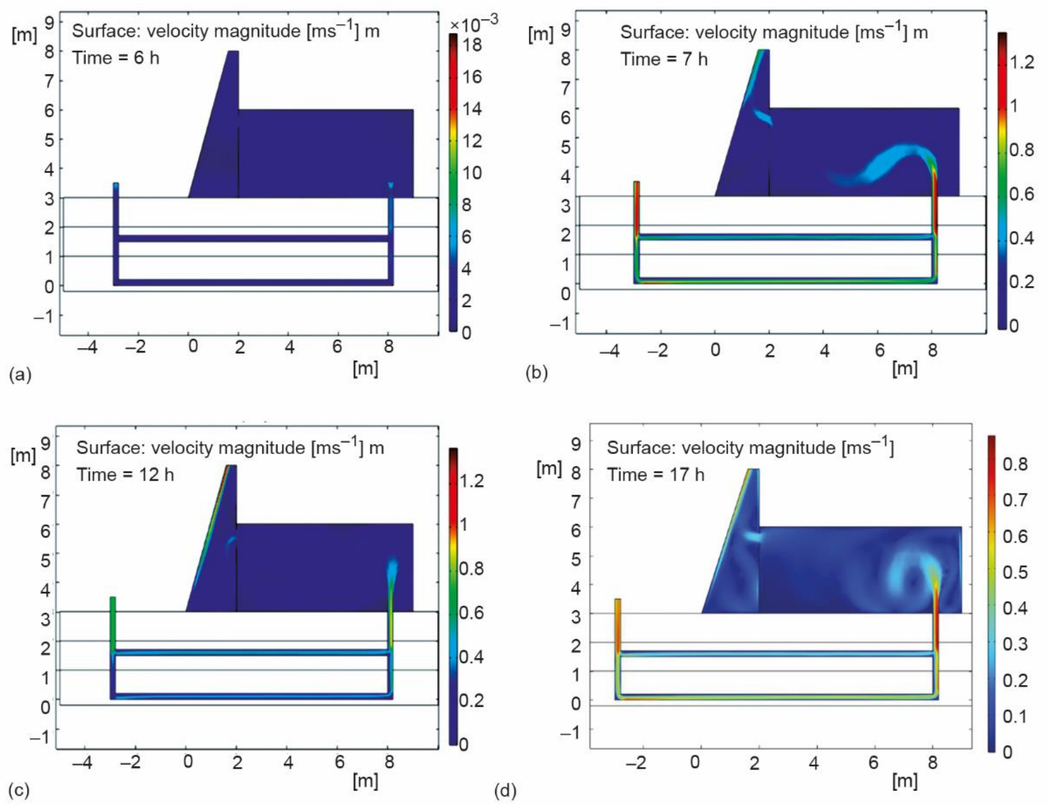

Figure 10. Air velocity distribution within the room and the underlying soil during peak hours, specifically at; (a) 6 a. m., (b) 7 a. m., (c) 12 p. m., and (d) 5 p. m.

as temperature differentials, ventilation patterns, and thermal properties of the room and its surroundings also play a role in influencing the observed changes in air velocity. The findings highlighted in fig. 10 further emphasize the importance of considering air movement and its variations throughout the day in the design and operation of passive heating and cooling systems. By gaining a comprehensive understanding of the temporal changes in air velocity, designers and engineers can implement strategies to enhance air circulation, improve indoor air quality, and maximize energy efficiency.

Conclusions

In summary, the outcomes obtained from this simulation have provided insights into several facets of passive heating and cooling strategies employed in buildings that harness geothermal resources. The imperative to curtail energy consumption associated with heating and cooling demands has spurred a heightened interest in renewable energy alternatives, encompassing geothermal energy, solar systems, and EAHE.

The utilization of passive solar systems, such as the Trombe wall, has emerged as a prominent approach in achieving energy efficiency without the need for mechanical devices in solar energy capture and indoor air ventilation. The functional principle of the Trombe wall, where glazing is installed at a distance from a massive wall, allows for the absorption and transmission of solar radiation into the building through natural convection. This process relies on the thermocirculator phenomenon, whereby the massive wall absorbs solar flux and conducts it inside the building, inducing natural air circulation.

Numerical studies have been proposed to investigate the thermal and fluid-dynamical behavior of the Trombe wall system, providing valuable insights into its performance and optimization. Additionally, the analysis of boundary conditions, including inlet and outlet pressures, soil temperatures, solar flux, and inflow air temperatures, has further enriched our understanding of the system behavior. Moreover, the examination of temperature distributions within the room and the underlying soil has revealed interesting patterns. The stability of soil temperatures throughout the day, with relatively constant values ranging from the surface to a certain depth, demonstrates the potential of geothermal resources as a reliable heat sink and source for building heating and cooling. The dynamic changes in room temperatures, influenced by solar flux variations, convection processes, and the operation of the air-to-earth heat exchanger, highlight the significance of system design and control in achieving optimal thermal performance.

Furthermore, the analysis of air velocity fluctuations throughout the day has emphasized the dynamic nature of airflow within the building. The interplay between solar flux, convective heat transfer, and system design influences the variation in air velocity, thereby impacting ventilation efficiency and energy utilization.

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