Energy saving potential of a sunspace with passive soil heat storage in Tibet Plateau

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Abstract
The Tibet plateau's frigid and elevated landscape poses a significant challenge in creating comfortable indoor environments while minimizing energy consumption. Attaching sunspaces to buildings presents a promising opportunity to improve the thermal environment and reduce energy consumption. The study aims to assess the annual energy-saving potential of a sunspace that incorporates passive soil heat storage in a plateau region by employing the Computational Fluid Dynamics (CFD) method to conduct a comprehensive system analysis. The study develops a numerical model incorporating the RNG k-ε turbulence model and the discrete ordinate (DO) radiation model. Furthermore, considers the absorption and multiple reflection phenomenon of solar-band and thermal-band radiation of the transparent units is in particular consideration. The study's results demonstrate that soil, as thermal inertia, positively influences temperature maintenance within the sunspace, consequently reducing wall heat flux. The sunspace help protected buildings exhibit an annual average heat load of 87 kWh/m\(^2\), leading to a remarkable 45.78\% energy savings. These findings provide valuable numerical method considering more precise inner radiation distribution with thermal inertia for designing energy-efficient buildings.

Highlights
- A detailed CFD model that considers the radiation passing through transparent insulated material for soil-based sunspaces is created for annual heat load calculation;
- The sunspace has an annual 87 kWh/m\(^2\) heat load, reducing 45.78\% annually;
- Soil inertia positively affects the sunspace's thermal environment and heat load reduction;
- Room roof and soil ground contribute 35.5\% and 50.3\% to the total sunspace energy collection, respectively.

Introduction
In light of the national goal of achieving carbon neutrality, promoting low-carbon and energy-efficient buildings has become a top priority in the building sector(Chen 2020; Li 2022). Passive solar energy and energy-efficient design solutions, such as sunspaces, solar collectors, Trombe walls, and solar chimneys, have garnered increasing attention as practical means of reducing buildings' energy consumption(Ma 2020b). Among these, sunspace, lazed space, has emerged as a promising technology with significant energy efficiency, environmental protection, and sustainability advantages. Sunspace is a passive solar heating system that can gain solar radiation and reduce the heat loss of the building body(Oliveti 2012). Numerous studies have demonstrated the energy-saving potential of a sunspace, particularly in cold regions. For instance, retrofitting traditional Tibetan buildings with sunspace resulted in energy savings of up to 76\%, with a payback period of fewer than five years(Sun and Leng 2015). Zhang et al. analyzed and evaluated seven critical structural factors of sunspace and achieved 44.8\% energy savings while increasing the indoor temperature by 2.38°C(Zhang 2023).

In contrast to the excellent energy performance, multiple studies have raised concerns about the potential overheating risk associated with sunspaces due to their lack of thermal storage capacity(Bakos and Tsagas 2000; Ignjatović 2015; Monge-Barrio and Sánchez-Ostiz 2015). Incorporating thermal storage systems into the sunspace is a practical approach to solving the overheating risk. However, few studies have investigated using sunspaces with enhanced inertial elements. Previous studies have explored the combination of rocks serving as sensible inertia and phase change material (PCM) serving as latent inertia(Ma 2021) with sunspace and achieved significant heating or cooling performance. For example, Asa et al. investigated the energetic performance of an attached solar greenhouse connected to rock-bed thermal storage (Asa’d 2019). Guarino et al. integrated phase change materials within the south wall of the sunspace, reducing heating energy consumption by approximately 10\%(Guarino2017). Owjak et al. analyzed the thermal performance of a daylight space in Iran featuring a heat storage porous floor and a water tank(Owjak 2015); Vukadinović et al. investigated the effect of phase change material type on cooling and heating energy consumption in a sunspace with 20 cm concrete walls in five regions of Serbia(Vukadinović 2020). Meanwhile, Lu et al. integrated an active PCM heat storage floor within the building, resulting in an increased indoor temperature of 7.15°C and savings of 54.27\% in heating energy(Lu 2018). These studies underscore the importance of incorporating thermal storage to enhance sunspaces’ energy efficiency and comfort.

The standard approach to assess sunspace energy performance in the building industry is to use Energy simulation software (BES), including Dest, Energyplus,
EQuest, and TRNSYS (Zhao 2022b). BES uses a zoning model that divides a single space into a limited number of zones to predict temperature stratification (Lu 2020). However, BES has limitations, including using constant parameters to predict effective solar radiation, which does not consider the incident angles, reflection, and scattering from complex structures (Yang 2022). Researchers have employed innovative techniques such as ray tracing and the Bidirectional Scattering Distribution Function (BSDF) data to represent the complex optical characteristics of sunspaces and TIMs (Sun 2017). However, this workflow relies on BES, using a Conduction Transfer Function (CTF) algorithm. This steady-state heat conduction solver cannot capture diurnal temperature swings in heavy thermal masses (U.S. DOE 2023).

Compared to BES, Computational fluid dynamics (CFD) simulations offer a more precise flow field and temperature distribution, enabling simulations of complex multi-physical field coupling phenomena under more complex working conditions (Afshari 2023); it has been widely used in glazed space such as sunspace. Song et al. evaluated the indoor air temperature and velocity distributions under heating conditions of an atrium space for a design-stage hospital building in Seoul by a commercial CFD code (Song 2007). Jose et al. established a three-dimensional numerical model of the airflow in a solar gallery using CFD to evaluate the thermal energy obtained in the gallery feature (Jose Suarez 2011). Hajdukiewicz et al. presented the application of a calibrated CFD model of a highly-glazed naturally ventilated meeting room, bridging the gap between CFD simulation and field measurement for natural ventilation systems (Hajdukiewicz 2013). Sdringola et al. modeled a bioclimatic greenhouse with COMSOL and assessed the thermal energy gain during the heating season. (Sdringola 2014). Yoon et al. examined the thermal and flow characteristics in the single-span greenhouse and determined the effects of the various design parameters on ventilation performance (Yoon 2020). Afshari et al. investigated the impact of double-glazing, black walls, black carpeted floors, and insulation material on the thermal efficiency of residential balconies by using the ANSYS/Fluent program, obtained temperature distribution inside the balcony and the air velocity due to the natural convection (Afshari 2023).

Apart from the above sunspace’s CFD energy assessment, fewer studies investigated sunspace’s model combining solar radiation, thermal storage, and airflow. Suárez et al. primarily studied the influence of the external window’s optical parameters on the sunspace’s thermal performance containing a sand floor in a CFD way with the Discrete Ordinate radiation (DO) model (Suárez López 2018). The results indicated that most heat exchanges occurred from the upper 10 cm of the sandy floor. Building upon their previous research, Suárez et al. continually explored the potential of a sunspace with a sandy thermal inertia floor combined with an HVAC system for active heat storage (Suárez López 2020).

However, the previous CFD model of the sunspace, which included solar radiation solved by the radiation transfer equation, had limitations due to a simplified radiation boundary condition. This simplified condition only considered the incident radiation intensity and angle without accounting for spectral absorption and multiple reflections caused by the transparent unit. Consequently, the incident radiation intensity in the computed domain could be overestimated, resulting in an inaccurate distribution. This accumulated inaccuracy could lead to significant energy differences across seasons.

There exists a significant challenge to create quality simulation models that predict the performance of the combination of proper inner radiation distribution, soil heat storage, and sunspace internal space environment. This study aims to provide a CFD model with accurate internal radiation distribution, temperature, and airflow, to evaluate the potential for annual energy savings in a sunspace with passive soil heat storage in a plateau area. A numerical CFD model with an RNG k-ε turbulence model and DO radiation model are used. In particular, the transparent units’ two-band non-grey radiation with absorption and scattering of solar-band and thermal-band radiation is considered. The approach enables the calculation of the heat load and energy-saving rate and analyses the soil and sunspace’s spatiotemporal temperature features. The study aims to refine the sunspace CFD models in research on the energy-saving potential of passive soil heat storage in plateau areas. It provides valuable insights into using CFD to design energy-efficient buildings that take advantage of solar radiation and passive soil thermal storage to reduce energy consumption and improve sustainability.

**Method**

**Numerical model**

In this study, numerical simulations employed a transient implicit pressure-based solver. The governing equations for heat and momentum were solved for the steady incompressible flow. The velocity-pressure coupling was accomplished using the SIMPLEC algorithm, and a second order upwind scheme was selected for the solution scheme. To capture the turbulence, the RNG k-ε turbulence model with full buoyancy effect and standard wall functions were utilized for near-wall treatment. The Solar Ray Irradiation model was employed to determine the direct and diffused intensity and incident angle for the outer transparent PC panel surface.

Previous studies have generally assumed that the thermal interface material (TIM) behaves as a diffuse-gray medium, yet the polycarbonate (PC) panel is a semitransparent medium. To reconcile this discrepancy, the discrete ordinates (DO) radiation model was utilized to solve the radiation problem with non-grey multi-band radiation for the solar-band and thermal-band. The DO radiation method addresses the radiative transfer equation (RTE) in the direction s of a field equation and solves it for a finite number of discrete solid angles, each associated with a vector direction fixed in the Cartesian system. To achieve acceptable results with a fair calculation cost for problems involving semi-transparent
The spectral intensity \( I_\lambda(r, s) \) is expressed as a function of the position vector, the direction \( s \) of the solid angle, and the frequency of the radiation:

\[
\Psi \cdot (I_\lambda(r, s)) + (a_\lambda + \sigma_\lambda)I_\lambda(r, s) = \frac{a\lambda n^2}{\pi} + \frac{\alpha}{\Omega} \int_0^{4\pi} (r, s') \phi(s, s') d\Omega.
\]

Here \( \lambda \) is the wavelength, \( a_\lambda \) is the spectral absorption coefficient with the unit in \( 1/\text{m} \), including solar-band absorption coefficient \( \alpha_s \) and thermal-band coefficient \( \alpha_t \). The solar band corresponds to wavelengths smaller than 2.9 \( \mu \text{m} \), while the thermal band corresponds to wavelengths larger than 2.9 \( \mu \text{m} \) (Suárez López 2018). \( I_{\text{black}} \) is the intensity of black body radiation given by the Planck function. \( \sigma \) is the Stefan Boltzmann constant. Additionally, the scattering coefficient \( \sigma_s \) and refractive index \( n \) are assumed to be independent of wavelength.

Radiation penetrating through a semi-transparent wall exhibits specular and diffuse transmission characteristics, as shown in Fig 2. Furthermore, the interior wall can reflect radiation to the surrounding medium if the refractive index of the zone representing the medium differs from that of the surrounding medium. Reflected radiation can manifest as specular and diffuse reflection. The wall's diffuse fraction determines the proportion of diffuse to specular radiation transmitted and reflected.

For specular semi-transparent walls without considering diffuse transmission, the transmitted radiation energy can be expressed as:

\[
r_e(\xi) = \frac{1}{2} \left( n_a \cos \theta_a - n_b \cos \theta_b \right)^2 + \frac{1}{2} \left( n_a \cos \theta_a + n_b \cos \theta_b \right)^2
\]
environment was added to the periphery of the soil heat storage domain directly under the sunspace. This approach enabled a comprehensive evaluation of the soil's thermal conduction concerning the external environment and the deeper soil layer.

When using CFD for the thermal simulation of a sunspace, it is vital to consider the Fresnel refraction phenomenon of the transparent envelope, which is highly dependent on the incident angle and light wavelength (Arulanantham 1998; Hazem 2015). Neglecting this phenomenon can lead to inaccurate calculations of incident radiation; Therefore, sunspace's transparent insulated material (TIM) was represented as a simplified three-layer polycarbonate panel (PC panel) with cavity structures (shown in Fig 5) due to the TIM's thin vertical structure, which is much smaller than the building model's macroscopic scale. This simplification, used in previous studies, was necessary to reduce computational costs and ensure mesh quality. (Brandl 2015; Zhou 2019). However, this approach introduces inaccuracies. Previous research has shown that a sample with a cavity width of 10mm reduces solar transmittance by up to 7% at a 60º incident angle compared to a panel without a vertical structure (Sun 2016). The uniform PC panel's cavity is always with a width larger than 20mm, so the simplified model with only slats could have a relatively minor impact on light transmission. Therefore, in this study, the PC material's refractive index was slightly increased to minimize the effect of this inaccuracy.

The calculated domain is divided into the following four zones in the mesh division: 1) sunspace and soil zone; 2) PC panel zone; 3) PU wall zone; 4) external soil zone, as described above. The hexahedral mesh is used in the computation model. Non-conformal interfaces are used between different zones. Thus, the PC panel zone mesh can be encrypted without influencing another zone's mesh, as shown in Fig 6. The grid of the soil's shallow layer is encrypted so that its heat transfer can be more accurately described. Though each mesh of the air domain is quite large without describing the boundary layer, enlarging the mesh of the air domain with low spatial resolution can ensure the grid independence of the flow characteristics while solving the Reynolds-averaged Navier-Stokes equations (Wang 2014). The overall mesh number is 219000, with an acceptable mesh quality of orthogonal over 0.618.

**Materials and boundary condition**

To accurately model the airflow and temperature distribution within the sunspace, an incompressible-ideal-gas method was employed to account for the variation in air density. As the sunspace has a large volume, it is necessary to consider the temperature difference between the covered roof and bottom soil to drive natural convection. Thus, the effects of buoyancy are of utmost importance in determining the airflow characteristics within the sunspace. However, the tiny convection in the air cavity of the PC panel was neglected due to the small Grashof number. Table 1 provides a detailed overview of the materials used in the simulation.

| Table 1: Material Property (Zhang 2020) |
|-------------------|-----|-----|-----|-----|
|                   | Air | PC  | Soil| PU |
| Solar-band absorption coefficient (1/m) | -   | 5   | -   | -  |
| Thermal-band absorption coefficient (1/m) | -   | 450 | -   | -  |
| Thermal conductivity (W/m K) | 0.024 | 0.2 | 1.3 | 0.025 |
| Refractive index | 1   | 1.6 | -   | -  |
| Thermal capacity (J/kg K) | 1.003 | 1170 | 1300 | 1200 |
| Density(kg/m³) | 0.82 | 1200 | 1500 | 40  |

Both convective and radiation heat losses have been considered for the surfaces in contact with the external environment. The external radiation temperature has been set to 20°C below the ambient temperature for calculating surface radiation loss (Garg and Bannerot 1983). The ambient temperature, direct solar radiation, and diffuse radiation have been generated using Meteonorm 8 software, as illustrated in Fig 3.

Additionally, to explore the maximum energy collection potential of the sunspace, it has been assumed to be a closed system without any doors or windows that can be switched on or off. The air leakage rate of the sunspace has been considered to be one ach (Hilliaho 2015), and the heat loss due to air leakage has been added to the energy equation of the sunspace air domain as a source term. Moreover, since the overheating effect of the sunspace is almost negligible when combined with controlled natural ventilation (Chiesa 2017), the cooling demand of the sunspace needs to be addressed. The convection heat transfer coefficient between the PC panel and the ambient environment is expressed in terms of wind speed as $h = 5.7 + 3.8v$. Considering an average
windspeed of 2.5 m/s, the coefficient is set to 15.2 \( \frac{W}{m^2\cdot K} \). The detailed boundary conditions for surfaces are shown in Table 2.

**Table 2: Boundary condition**

<table>
<thead>
<tr>
<th>Associated zone</th>
<th>Surface Type</th>
<th>Solar emissivity</th>
<th>Thermal emissivity</th>
<th>Scattering coefficient</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-transparent wall</td>
<td>Sunspace opaque wall</td>
<td>0.64</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sunspace opaque wall</td>
<td>Soil ground</td>
<td>0.64</td>
<td>0.95</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PC panel cavity wall</td>
<td>Room-side surface</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Outer wall</td>
<td>-</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>Ambient</td>
</tr>
</tbody>
</table>

The initial temperature distribution of soil will significantly influence the thermal storage and release process. The initial temperature distribution of soil (Wang and Zhao 1999) in January is shown in Fig 7.

![Figure 7: Ground temperatures in January](image)

**Mesh and Time independence**

The mesh independence study was conducted to ensure the accuracy and reliability of the simulation results. To this end, different meshes and timesteps were employed, and their effects on the surface heat transfer coefficient driven by natural convection on the sunspace inner north wall were analyzed. As illustrated in Fig 8, five meshes with varying levels of detail were utilized to determine the mesh dependence, and five samples with different timesteps were used to investigate the timestep dependence. It was found that increasing the number of meshes beyond 219,000, as selected in this case, had a relatively minor impact on the final results. Similarly, simulations with a timestep of 300 seconds yielded acceptable results. Therefore, 219,000 meshes and a timestep of 300 seconds were chosen as the reference mesh and timestep, respectively.

![Figure 8: Mesh and Time independence](image)

**Results and Discussion**

**Air Temperature**

Figure 7 depicts the temporal evolution of temperature within the sunspace. The maximum temperature is observed between 15:00 and 18:00, while the lowest temperature occurs at approximately 09:00, coinciding with the sunrise and dusk times of the day. The sunspace is characterized by superior insulation performance and thermal inertia of the soil thermal storage layer, resulting in a minimum temperature above -10°C during winter, significantly higher than the outdoor temperatures. However, this insulation performance poses a risk of overheating during summer. Temperature ranges below 0°C and above 30°C are respectively defined as the overcooling and overheating periods. The overcooling period occurs for 1947 hours annually, while the overheating period persists for 2640 hours yearly. Without any control measures, the sunspace's temperature in summer can reach above 50°C, whereas the average outdoor temperature during summer is only around 10°C. During summer nights, the temperature remains high due to the combined effect of soil thermal release and the PC panel's insulation characteristics, culminating in a maximum temperature range of approximately 30-40°C.

![Figure 9: Sunspace air temperature heatmap](image)

Furthermore, Fig 10 illustrates the monthly distribution of the indoor-outdoor temperature difference. It reveals that the indoor-outdoor temperature difference is minor in winter and more significant in summer. The upper and lower ranges of indoor-outdoor temperature differences are more substantial in summer, indicating a more significant seasonal temperature fluctuation. For instance, in June, the maximum indoor-outdoor temperature difference is 68.64°C, while the minimum temperature difference is 10.84°C, with lower 25% and upper 75% quartiles of 25.05°C and 39.47°C, respectively. In comparison, in January, the maximum indoor-outdoor...
temperature difference is 39.86°C, while the minimum temperature difference is 0°C, with lower 25% and upper 75% quartiles of 7.71°C and 17.34°C, respectively. In addition, when comparing the early heat storage period in January with the released period in December, we observe that the median temperature difference increases from 11.47°C in January to 15.57°C in December. Despite no significant difference in the solar radiation intensity and ambient temperature between the two months, the difference between the 25% and upper 75% quantile decreases from 9.63°C to 6.08°C. The results indicated that the soil thermal storage layer could increase the sunspace's overall temperature and reduce temperature fluctuations after one year of thermal storage.

### Soil Temperature

Fig 11 presents the soil temperature distribution throughout the year, demonstrating a consistent trend with the air temperature variation. The upper surface of the soil layer maintains a higher temperature than the deeper soil layer throughout the year under solar radiation, with the highest surface temperature reaching 40°C during summer. Moreover, the temperature of the deeper soil layers gradually increases over time as the ambient temperature is transferred downward, with the temperature of the 1m soil layer reaching about 25°C in August. The soil temperature then begins to decrease, stabilizing in December, with an average temperature at a depth of 1m of approximately 7°C.

![Figure 11: Spatiotemporal Distribution of soil temperature](image)

The soil temperature rises relatively slowly during the first few months, known as the early heat storage period. From May to September, the temperature increases rapidly, known as the heat storage period, due to solar radiation. As the ambient temperature decreases, the soil temperature also drops, releasing the stored heat during the heat release period. The heat release period has a higher soil temperature of about 6°C compared to the early heat storage period, indicating that the amount of energy stored is greater than the amount released over the annual year time scale.

Figure 12 illustrates the spatiotemporal fluctuations in soil ground net heat flux, depicting the temperature distribution dynamics correlated with the soil thermal storage systems stored and released potential. Meanwhile, Figure 10 displays the system's stored and released contributions, with positive values indicating released activity and negative values indicating thermal storage. Heat storage mainly occurs between 14:00 and 19:00 hours daily, with a broader temporal range in summer than in winter. The peak stored power is observed from March to September, with a maximum value of 313 W/m². Conversely, released energy typically occurs at night, ranging from 0-63 W/m². It is worth noting that, during the heating season, the average heat release power from October to December is considerably higher than that from January to March, indicating an increase in average heat storage power from approximately 35 W/m² to 54 W/m². As a result, the temperature of the sunspace rises, reducing the heat load on the SIP.

### Energy saving

Fig.13 presents the incident solar radiation density on various absorbed wall surfaces. The room roof has the highest instantaneous solar radiation intensity annually, followed by the soil ground. The maximum instantaneous radiation intensity on the room roof occurs in July, reaching 515.41 W/m², with an average radiation intensity ranging from 205 W/m² to 379 W/m². In January, the maximum instantaneous radiation intensity on the room roof was 267 W/m², with an average radiation intensity range of 205 W/m² to 379 W/m². The soil ground has a maximum instantaneous radiation intensity of approximately 483.28 W/m². In January, the maximum instantaneous radiation intensity is 267 W/m², and the average radiation intensity ranges from 53 W/m² to 165 W/m². In July, the maximum instantaneous radiation intensity of the soil ground reaches 483.28 W/m², and the average radiation intensity varies from 198 W/m² to 363 W/m². In January, the average radiation intensity ranges from 45 W/m² to 151 W/m². Both of these surfaces are horizontal. The other surfaces are vertical walls, including the north, south, and east walls, and west, south exits. The south wall has the lowest instantaneous radiation intensity among all vertical wall surfaces, while the north has the highest. The east and west walls have similar radiation intensity distributions.

Fig 14 illustrates the temporal energy absorption of soil ground, room roof, and vertical wall over time and area. The data is obtained by integrating each surface's daily instantaneous radiation intensity data. The soil ground and room roof are the primary sources of energy absorption in sunspace, whereas the vertical wall absorbs a comparatively smaller fraction of the energy. The daily energy absorption of soil ground and room roof varies significantly, with the former reaching a peak of 2134 kWh/d and the latter at 1632 kWh/d. Interestingly, despite the lower solar radiation intensity absorbed by soil ground compared to the room roof, the former's daily heat absorption
collection is higher due to its larger area. Soil ground and room roofs dominate the overall sunspace energy collection, contributing 50.3% and 35.5%, respectively. In contrast, the vertical wall only contributes 14.1% to the energy collection.

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Figure 13: Monthly variation of wall radiation intensity

Figure 14: Daily energy collection of walls

Energy collection on different walls influences the surface heat flux across the wall. Fig 15 shows the average heat flow reduction rate of SIP houses with sunspace compared to those without sunspace for the room side walls. The heat flow data is one of the monitored quantities for this simulation. The results demonstrate that 61.1% of the year achieves 100% heat flow reduction, mainly in summer. During the winter period, from October to March, 100% heat flow reduction is achieved about 33.9% of the time. Additionally, the wall's average heat flow reduction rate is lower during the winter period from sunrise to noon (10:00-15:00), indicating the existence of some heat load in the SIP during this time. Moreover, the analysis reveals that the percentage of time with 100% heat flow reduction from January to March was 31.3%, while the rate of time with 100% heat flow reduction from October to December increased to 37.36%. These findings suggest that the heat storage in the soil increased the sunspace's temperature and thus positively reduced heat flow in the wall.

Fig 16 summarizes the annual energy consumption of SIP houses with sunspace and soil, revealing a total annual energy consumption of 32,451 kWh, with an average energy consumption of 87 kWh/m² per unit area and an average energy saving rate of 45.78%. Notably, in January, the SIP building with soil-based sunspace displays high energy consumption during winter, with a heat load of 3038.9 kWh. As ambient temperatures rise, the heat load gradually decreases, reaching a minimum of 565.284 kWh in August. Monthly energy savings range from 30% to 62%, with minimum savings observed in January and maximum savings in September. Following a year of heat storage and soil release, the heat load in December was reduced to 2119 kWh, 30.2% lower than the heat load observed in January. As a result, the energy saving rate increases from 30% to 40%. This trend indicates the beneficial impact of soil acting as thermal inertia in the sunspace, ultimately enhancing the building's energy-saving potential.

Figure 15: Hot map of wall flux reduced rate

Figure 16: Annual heat load for sunspace with soil thermal storage

Conclusion

In conclusion, this study has demonstrated the potential of using a soil-based sunspace to reduce energy consumption and improve thermal comfort in cold plateau areas by using CFD method. In contrast to previous studies, when solving for the radiation field using RTE, this study focuses on transparent units' absorption, reflection, and scattering effects on the radiation distribution within the sunspace thermal environment. The CFD simulations showed that the sunspace with soil has superior insulation, providing a minimum temperature above -10°C during winter and a maximum temperature above 50°C during summer without control measures. The thermal storage inertia of the soil can reduce temperature fluctuations and increase the overall temperature of the sunspace. Additionally, the study found that the soil temperature distribution correlates well with the air temperature variation, with higher surface temperatures in summer and gradual increases in the deeper soil layers. The maximum stored power is observed from March to September, while the released energy generally occurs at
night, leading to a corresponding rise in the sunspace's temperature and reducing the heat load on the SIP houses. The room roof and soil ground surfaces were the primary sources of energy absorption, contributing 35.5% and 50.3% to the total sunspace energy collection, respectively. Moreover, the heat flow reduction rate was higher during heat release (October to December) than the early heat storage (January to March), indicating the beneficial impact of soil acting as thermal inertia in the sunspace. The annual heat load of the SIP house was 32,451 kWh, with an average value of 87 kWh/m² and an average energy-saving rate of 45.78%.

The results of this study demonstrate the significant energy-saving potential of a soil-based sunspace design in a plateau region in a CFD method. These findings have implications for designing energy-efficient buildings, not only in the Tibet plateau but also in other areas facing similar challenges. The complete CFD approach utilized in this study, which incorporates solar radiation and soil's thermal properties, has broader applicability and potential for reducing energy consumption and improving sustainability in various scenarios.

Future research could further optimize the sunspace design parameters to enhance its energy-saving potential and evaluate the economic benefits of this design compared to conventional HVAC systems. By demonstrating the generality of the proposed method, this study contributes to the broader efforts toward achieving sustainable development and reducing energy consumption in buildings.

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Reference

ANSYS, Inc (2013) Ansys Fluent 12.0 Theory Guide


