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Improving Skylight Geometry for Daytime Passive Radiative Cooling

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Abstract. Åbo Akademi University (ÅAU) is researching a passive radiative cooling (PRC) skylight window prototype utilizing greenhouse gases (GHGs) that interact strongly with thermal radiation. The current prototype achieved 100 W/m^2 passive cooling using two ZnS windows, one at the bottom and one at the top, both transparent to long-wave (LW) infrared, and a central window. The aim of this ongoing work is to improve the skylight design by utilizing computational fluid dynamics (CFD) software (Ansys Fluent). The objective of this design improvement is to eliminate the usage of central window used in the earlier design. In this improved design, sections of ZnS glass is positioned symmetrically, at the top and at the bottom. The remaining window is composed of conventional window glass, while the side walls are made of wood. Another objective entails using various greenhouse gases, such as CO_2 and NH_3, inside the skylight and subsequently calculating the transmittive radiative fluxes within the atmospheric window (8-14 μm) wavelength range, followed by a comparative analysis with using air. Thus far, the radiative heat fluxes achieved with the new skylight design are as follows: 85.5 W/m^2 when CO_2 is used as the participating medium, 83.0 W/m^2 with air, and 88.5 W/m^2 when NH_3 is used. Additionally, temperatures of the ZnS Cleartran glasses give a calculated lowering of approximately 3 to 4°C in comparison to the ambient temperature. The ultimate aim is to develop a transparent PRC skylight with a net cooling capacity >>100 W/m^2 without moving parts also during daytime.

Keywords: Daytime cooling, Longwave heat radiation, Participating gases, Atmospheric window and Transmittive radiative fluxes.

1 Introduction

1.1 Passive Skylights for Daytime Cooling

Heating and cooling energy needs in buildings depend on various factors like solar irradiation, outdoor temperature, humidity, and wind speed. Due to climate change, estimated reductions in heating demand are 21% by 2050 and 43% by 2080, while cooling demand is projected to increase by 111% by 2050 and 269% in 2080 [1]. Passive cooling can address building energy needs effectively, especially at night when radiation cools spaces. However, maintaining indoor comfort in hot daytime conditions presents challenges. Sunlight absorption through roofs, walls, and windows causes daytime heat buildup. Methods to counter this include redirecting sunlight, heat dissipation, and managing internal heat sources. [2]. Glass skylights are a popular choice in building technology as they introduce natural light into interior spaces. Conventional window glass allows short-wave (SW) radiation (0.2–3 μm) from sunlight to enter, leading to indoor heat absorption. Additionally, they contribute to a greenhouse effect, allowing SW radiation in but hindering the exit of long-wave (LW) heat in the 5-20 μm range, resulting in elevated indoor temperatures. In the realm of energy-efficient buildings, thermal radiation heat transfer through passive systems is gaining prominence [3]. Since 2007, ÅAU has studied transparent PRC skylight windows with greenhouse gas (GHG) between glass sheets for interaction with thermal radiation. Unlike conventional models, this design relies on natural convective heat transfer, improving passive cooling. As Fig. 1 shows, the prototype contained a center window for guiding the natural cvection once that is induced. While it demonstrated around 100 W/m^2 of PRC at night [3-5], achieving Daytime Passive Radiative Cooling (DPRC) remains a challenging. This research aims to redesign a skylight into a rectangular shape without using the (movable) center window, enhancing its cooling capacity by strategically placing ZnS Cleartran® windows. Using Ansys Fluent CFD simulation software, it analyzes heat fluxes and temperatures within the skylight, building on previous work on skylights. GHG's like CO_2, NH_3, and a freon-type gas can be engaged to optimize LW radiation absorption and emission within this range.

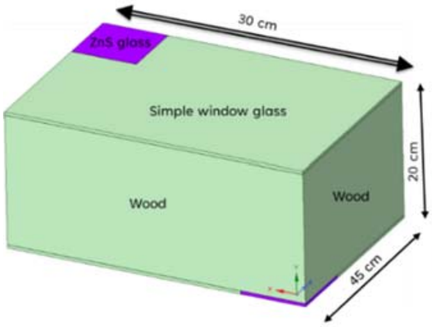
Fig. 1 ÅA skylight prototype with central window [4,5]

2 Model Development

Thermodynamics principles underpin the design of transparent passive cooling skylights, which involve heat transfer through conduction, convection, radiation, and fluid mechanics/natural convection. Windows are crucial for allowing daytime energy flow and effective nighttime cooling via longwave (LW) radiation. This study classifies infrared thermal radiation into four groups: one short-wave (SW) band (< 4 μm) and three LW bands (4-8 μm, 8-14 μm, >14 μm) to examine greenhouse effects and heating/cooling dynamics in passive skylights, considering that the atmosphere blocks LW radiation beyond a certain range. The 8-14 μm range is the so-called atmospheric window, where a dry atmosphere is transparent for thermal radiation.

2.1 Simulation setup: Geometry, Problem domain, and Mesh

Using advanced CFD software, heat transfer prediction focuses on two key aspects: modeling thermal radiation from a 298 K room to the skylight window on a rooftop and simulating natural convection heat transfer inside the geometry. The envisioned 3D rectangular skylight (see Fig. 2a) measures L = 0.3 m in length, W = 0.45 m in width, and H = 0.2 m in height. Materials include ordinary window glass and ZnS Cleartran® glass, each with a thickness of 0.005 m, along with wood (only for side walls) of the same thickness.



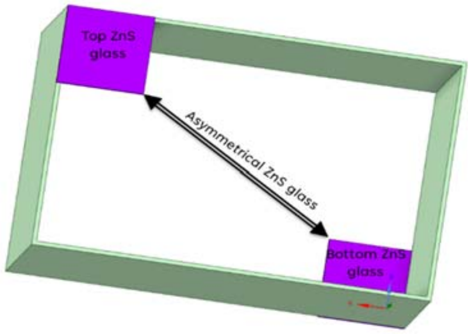


Fig. 2a. Modified skylight geometry Fig. 2b. Asymmetrically positioned ZnS glass section

The lower ZnS window in Fig. 2b directs interior radiation towards the roof, while the upper ZnS window serves as an outlet for radiation to space, ideally via the atmospheric window, providing cooling (around 3-4 K). ZnS Cleartran® windows are highly transparent ($\tau \approx 0.75$), especially in the LW radiation range within the atmospheric window. Inside the skylight, air, CO_2, or NH_3 is used as interacting gases with LW thermal radiation from the building below. The next section discusses using CO_2 and NH_3 in the skylight, calculating radiative fluxes in the 8-14 μm atmospheric window range, and comparing it with air. The model in Ansys Workbench was configured, and a refined mesh was generated. While a finer mesh improves accuracy, it increases computation time. The analysis of natural convective flow inside the skylight uses the viscous-laminar model. These numerical simulations, in a 3-D computational domain, follow steady-state conditions and employ CFD techniques.

2.2 Mathematical and Physical Models

Ansys Fluent R2 2023 was used to analyze heat and flow in a redesigned skylight, considering parameters like emissivity (ε), absorptivity (α), reflectance (ρ), and transmittance (τ), following Kirchhoff's Law for wavelength-dependent properties.

$$\varepsilon\,(\lambda) = \alpha\,(\lambda) = 1 - \tau\,(\lambda) \quad (1)$$

2.3 Choice of Radiative Heat Transfer Model

The discrete ordinates (DO) model is valuable in simulations that require precise treatment of directional radiation effects, often encountered in thermal radiation, natural convection, or situations involving participating gases. Ansys Fluent offers an extended gray-band model option, which discretizes radiation intensity into a number of wavelength bands (here: four). The radiative transfer equation (RTE) for spectral intensity $I_\lambda(\vec{r},\vec{s})\vec{s}$ is utilized [6]:

$$\nabla \cdot (I_\lambda(\vec{r},\vec{s})\vec{s}) + (a_\lambda + \sigma_s) I_\lambda(\vec{r},\vec{s}) = a_\lambda I_{b\lambda} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I_\lambda(\vec{r},\vec{s}\,')\Phi(\vec{s}\cdot\vec{s}\,')d\Omega' \quad (2)$$

Here, λ represents the wavelength, a_λ signifies the spectral absorption coefficient (unit:1/meter), and $I_{b\lambda}$ denotes the black body intensity, calculated according to the Planck function. It is assumed that the scattering coefficient here $\sigma_s=0$ in equation (2). The absorption coefficient a_λ for a gas contained in a given geometry can be determined according to the Beer-Lambert law by knowing the transmittance (τ) of the material.

$$a_\lambda = \frac{2.3026}{t} * \log_{10}(100/\tau\ \%) \quad (3)$$

where, t (m) denotes the thickness of the glass sample for solid materials. However, for gases within the skylight design studies here, where thickness is not readily known, t is estimated as the path length = $\sqrt[3]{(L \cdot W \cdot H)}$ = 0.3 m. The system's overall performance depends on values for α and τ which for the gas can be calculated from the emissivity, ε. For a gas, ε varies with factors such as temperature, pressure, and gas path length.

2.4 Material Properties

The skylight model includes solid materials like window glass, Cleartran ZnS® glass, and wood, as well as gases like air, CO_2, or NH_3. Tables 1 and 2 list emissivity properties for these materials, while Table 3 provides absorption coefficients (a_λ) calculated with t = 0.3 m using equation (3).

Table 1. Emissivities of the solid materials used for the skylight

Skylight material	0 – 4 µm (SW)	4 – 8 µm (LW1)	8 – 14 µm (LW2)	14 – 1000 µm (FIR)
Standard window glass	0.1	0.9999	0.9999	0.9999
ZnS glass	0.25	0.25	0.25	0.9999
Wood	0.85	0.85	0.85	0.85

Table 2. Emissivities of the gases used in the skylight

Skylight material	0 – 4 µm (SW)	4 – 8 µm (LW1)	8 – 14 µm (LW2)	14 – 1000 µm (FIR)
Air	0.0001	0.0020	0.0005	0.1174
Carbon dioxide	0.000012	0.0022	0.0008	0.1317
Ammonia	0.0291	0.0971	0.53	0

Table 3. Absorption coefficient in m^{-1} for the gases used in the skylight

Skylight material	0 – 4 µm (SW)	4 – 8 µm (LW1)	8 – 14 µm (LW2)	14 – 1000 µm (FIR)
Air	$3.46.10^{-5}$	$6.83.10^{-3}$	$1.66.10^{-3}$	$4.16.10^{-1}$
Carbon dioxide	$4.03.10^{-5}$	$7.33.10^{-5}$	$2.65.10^{-5}$	$4.71\ 10^{-1}$
Ammonia	0.0984	0.3404	2.516	0

The total emissivity of skylight participating gases, was determined using previously published data from Mehrotra et al [7] and Tien [8]. The following equation (4) is used to calculate it as a function of gas temperature T (K) and the product of partial pressure p (kPa) and mean gas path t in equation (3) above, as t = 0.3 m.

$$\log(\varepsilon) = \frac{a + \sum_{i=1}^{3}[b_i T^i + d_i(\log pt)^i]}{1 + \sum_{i=4}^{6}[b_i T^{i-3} + d_i(\log pt)^{i-3}]} \quad (4)$$

The constants a, b_1 to b_6, and from d_1 to d_6 in the preceding equation are documented in [7]. The total emissivities of the participating gases, namely air, CO_2, or NH_3, have been determined to be 0.11, 0.134, and 0.656, respectively at 288 K.

3 CFD Calculation Results and Discussion

Transmitted radiative fluxes for various wavelengths (0-4 μm, 4-8 μm, 8-14 μm, and > 14 μm), comparing CO_2 and NH_3 with air as reference inside skylight. CFD simulations assumed room (298 K) below skylight and ambient (278 K) above, excluding solar irradiation.

3.1 Heat Transfer analysis: Skylight filled with CO_2 as a participating medium

CO_2 exhibits transparency in the SW range but absorbs in the 8-14 μm range. Steady-state calculations were conducted, aiming to understand skylight wall temperatures.

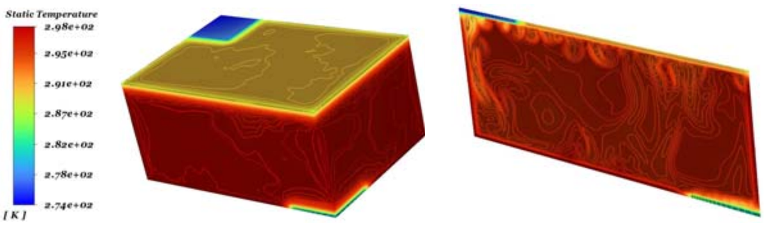


Fig. 3a. The temperature of the skylight walls. Fig. 3b. Temperatures of cross section diagonal.

The focus was on investigating the temperatures (ΔT) between upper window glasses and the outside ambient, especially with ZnS Cleartran® glass versus ordinary windows using CO_2. A ΔT of 4°C was calculated for the top ZnS cleartran glass compared to ambient conditions (see Fig. 3a, Fig. 3b). Not surprisingly, the top ordinary window glass temperature is lower than the bottom, while the same applies to the ZnS Cleartran ® glasses. Velocity profiles were computed in X, Y, Z directions – see Figs. 4a – Fig. 4d). Here, X = horizontal long side, Y = horizontal short side, Z = vertical upwards. Gravity exerts its force vertically downward in the Z direction.

Gas motion in the skylight is driven by several factors. Heat from the room (298 K) transfers to the gas through the lower Cleartran® ZnS window glass via LW radiation, conduction, and convection. Heating the gas results in a decrease in its density, calculated from the temperature profile, which in turn generates a buoyancy force, causing it to ascend towards the upper window glass.

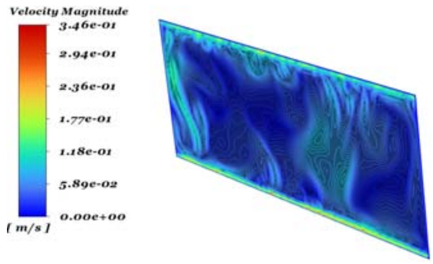


Fig. 4a. CO_2 velocity magnitude in m/s

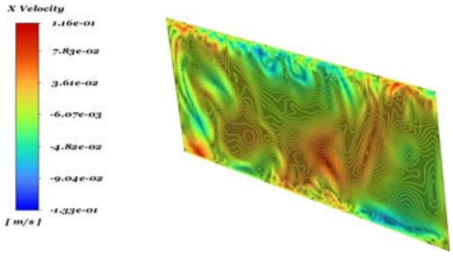


Fig. 4b. CO_2 velocity in X-direction.

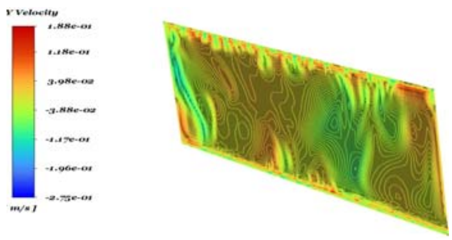


Fig. 4c. CO_2 velocity in Y-direction

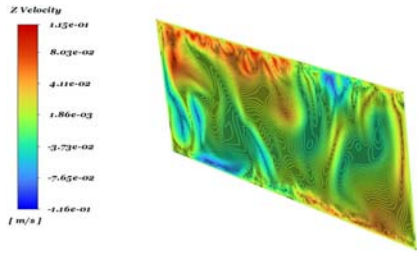
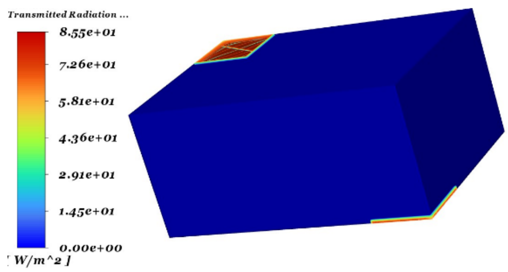


Fig. 4d. CO_2 velocity in Z-direction



Radiative heat transfer through ZnS Cleartran® and natural convection facilitate heat transfer through the upper ZnS window glass and the atmospheric window to cooler air masses. Cooling near the upper ZnS Cleartran® glass induces downward gas movement, driven by LW radiation, creating natural convection.

Fig. 5. Radiative flux in the 8–14 μm range with CO_2 as a participating medium.

Utilizing CO_2 as the participating gas, calculated the long-wave (LW) heat radiation emitted within the atmospheric window region, yields a value of 85.5 W/m^2 (see Fig. 5) at the top ZnS Cleartran® surface.

3.2 Skylight filled with weakly participating gas: Air

Air-filled skylights have lower gas emissivity compared to CO_2, especially in the LW spectrum, spectrum, making them less efficient at radiating heat. This results in only a ΔT of 1°C between the top ZnS Cleartran® glass (277 K) and ambient temperature (278

K) – see Figs. 6a – 6b. Ordinary window glasses heat up more than ZnS Cleartran® glass. Similar to Fig. 4a – Fig. 4d, natural convection velocities were computed in all three spatial directions (X, Y, and Z) - See Figs. 7a – 7d..

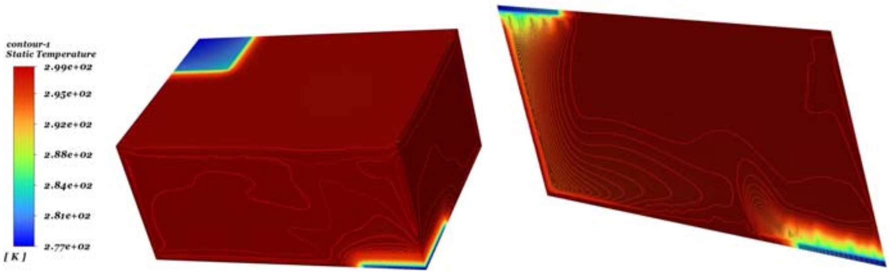


Fig. 6a. The temperature of the skylight walls. Fig. 6b. Temperatures of cross section diagonal.

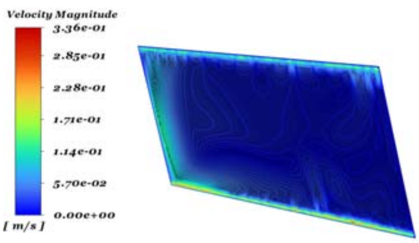


Fig. 7a. Air velocity magnitude in m/s.

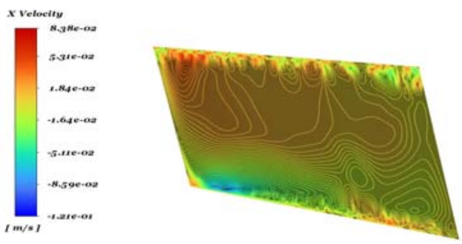


Fig. 7b. Air velocity in X direction.

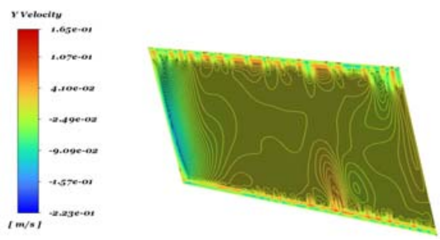


Fig. 7c. Air velocity in Y direction.

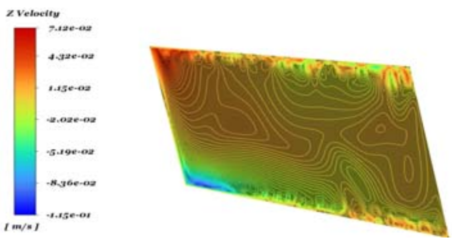
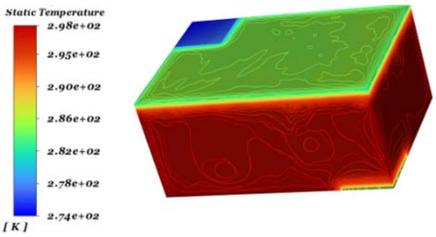


Fig. 7d. Air velocity in Z direction.

When air is used as the participating gas inside the skylight, the LW heat radiation calculation yields a maximum value of 83.0 W/m². (Figure illustrating this is not given here as it closely resembles Fig. 5.).

3.3 Skylight filled with strong participating gas: NH_3

Calculations involving NH_3 within the skylight were conducted as well: NH_3, like CO_2, creates a 4°C ΔT between the upper ZnS Cleartran® glass and ambient (Figs. 8a - 8b). Velocity profiles (Figs. 9a - 9d) and radiative heat flux transmittance are calculated, reaching a maximum of 88.5 W/m² for LW heat radiation in the atmospheric window range at the top ZnS Cleartran® surface (Figure not included, similar to Fig. 5).



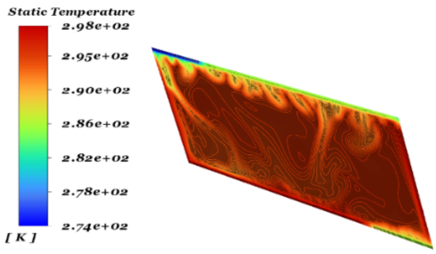
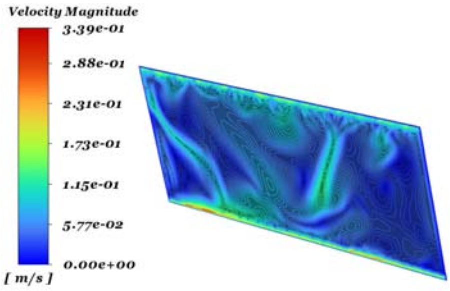


Fig. 8a. The temperature of the skylight walls. Fig. 8b. Temperatures of cross section diagonal.



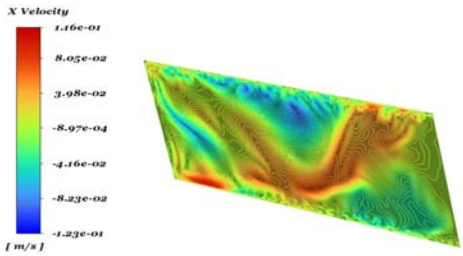
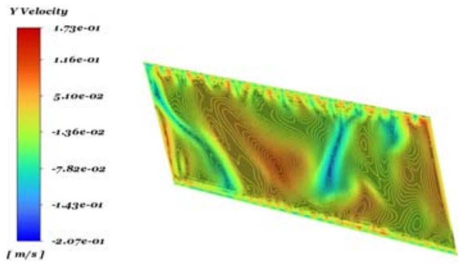


Fig. 9a. NH_3 velocity magnitude in m/s. Fig. 9b. NH_3 velocity in X direction.



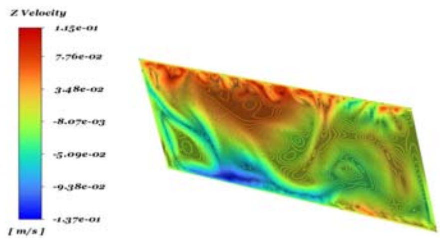


Fig. 9c. NH_3 velocity in Y direction. Fig. 9d. NH_3 velocity in Z direction.

3.4 Skylight filled with CO_2 gas with top and bottom ZnS glasses

In a prior design [4], a 117 W/m^2 cooling effect was achieved using CO_2 in a ÅA skylight (0.1m x 0.1m x 0.1m) with central and ZnS Cleartran® windows. The new skylight prototype (0.3 m x 0.45 m x 0.2 m), both top and bottom glass windows were replaced with ZnS Cleartran® across the entire surface for comparative analysis. In this CO_2 case study, a ΔT of 3°C is calculated between the top ZnS glass (275 K) and ambient (278 K) (Fig. 10a and Fig. 10b). The new skylight design reduces the maximum heat flux to 93.9 W/m^2, a 19.6% reduction from the initial prototype.

This difference is due to the previous prototype's central window and the somewhat different temperatures outside the skylight used. Nonetheless, a good starting point for further optimizing the skylight by adjusting its dimensions.

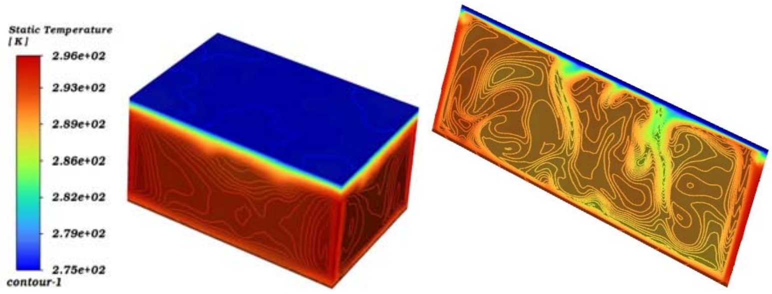
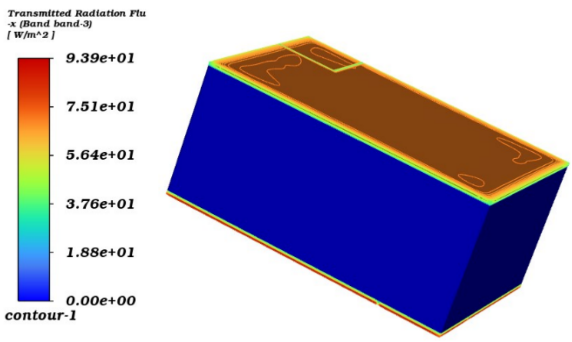


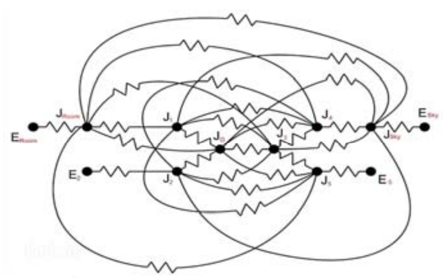
Fig. 10a. The temperature of the skylight walls. Fig. 10b. Temperatures of cross section diagonal.



Replacing ZnS Cleartran® glasses with standard window glasses affects skylight temperatures and radiative heat transfer. Standard windows have low LW heat transparency (see Table 1), resulting in no LW heat flux within the atmospheric window range and causing them to heat up beyond ambient temperatures.

Fig.11. New skylight design (top and bottom ZnS Cleartran glass) for radiative flux in the 8–14 μm range with CO_2 as a participating gas.

4 Further Investigations



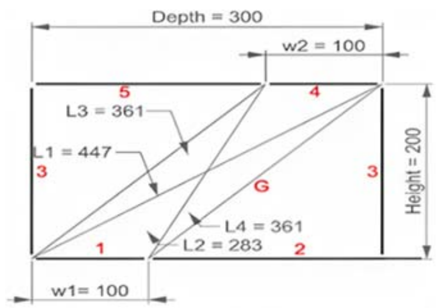


Fig.12. Radiative network model.

Fig.13. 2D Rectangular skylight geometry.

The objective is to establish a heat resistance network for initial skylight heat transfer assessments in CFD simulations. In Fig. 12, E_{room}, E_{sky}, E_2, and E_5 represent blackbody radiation ($E_b = \sigma \cdot T^4$), with nodes J_{room}, J_{sky}, and J_1 to J_5 for heat flow. Calculating radiation resistances forms a matrix equation $\mathbf{A} \cdot J = B$ to determine J values in W/m², giving temperatures calculated from $\sigma \cdot T^4$.

5 Conclusion

The new PRC skylight design makes obsolete the central window and uses asymmetrically positioned ZnS Cleartran® windows for better cooling flows and lower costs. It contains greenhouse gases like CO_2 and NH_3, resulting in radiative heat fluxes of 85.5 W/m^2 for CO_2, 83.0 W/m^2 for air, and 88.5 W/m^2 for NH_3 within the 8-14 µm atmospheric window range. Future research will explore R-32 or similar gases. The top ZnS glass cools to 3-4°C below ambient. Ongoing work aims to enhance cooling by further optimizing ZnS window dimensions and controlling incoming solar irradiation (SW).

6 Acknowledgements

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