Passive cooling through the atmospheric window for vehicle temperature control

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Abstract One of the most energy-intensive activities for a vehicle is space air conditioning, for either cooling or heating. Considerable energy savings can be achieved if this can be decoupled from the use of fuel or elec-tricity. This study analyzes the opportunities and effectiveness of deploying the concept of passive cooling through the atmospheric window (i.e. the 8– 14 m wavelength range where the atmosphere is transparent for thermal radiation) for vehicle temperature control. Recent work at our institute has resulted in a skylight (roof window) design for passive cooling of building space. This should be applicable to vehicles as well, using the same materials and design concept. An overall cooling effect is obtained if outgoing (long wavelength greater than 4 m) thermal radiation is stronger than the incom-ing (short wavelength less than 4 m) thermal radiation. Of particular inter-est is to quantify the passive cooling of a vehicle parked under direct/indirect sunlight equipped with a small skylight, designed based on earlier designs for buildings. The work involved simulations using commercial computa-tional fluid dynamics software implementing (where possible) wavelength-dependency of thermal radiation properties of materials involved. The find-ings show that by the use of passive cooling, a temperature difference of up to 7–8 K is obtained with an internal gas flow rate of 0.7 cm/s inside the sky-light. A passive cooling effect of almost 27 W/m^2 is attainable for summer season in Finland. Comparison of results from Ansys Fluent and COMSOL models shows differences up to about 10 W/m^2 in the estimations.

Keywords: Thermal radiation; Passive cooling; Vehicle Skylight; Greenhouse effect; Computational fluid dynamics

Nomenclature

A_{sky} – surface area of sky (upper atmosphere), m^2
A_{sur} – ground level Earth surface area, m^2
A_{uni} – surface area of universe surrounding Earth, m^2
g – gravitational acceleration
Gr – Grashof number
h_c – convective heat transfer coefficient, W/m^2K
Nu – Nusselt number
Pr – Prandtl number
Q – heat transfer, W [Q_R heat transfer by radiation, W]
Q_{00} – heat transfer flux, W/m_2
Ra – Rayleigh number
S – heat transfer surface area, m^2
T_a – air temperature, K
T_g – gas (inside the skylight) temperature, K
T_{sur} – surrounding temperature, K
T_{uni} – temperature of universe, K

Greek symbols

α – absorptivity *ε*
– emissivity
ε_a – air emissivity
κ – absorption coefficient, m^{-1}
λ – wavelength, m
ρ – density, kg/m^3
σ – Stefan–Boltzmann coefficient (= 5.67×10^{-8} W/m^2K^4) *τ* –
transmission

Acronyms

AC – air conditioning
CFD – computational fluid dynamics
GHG – greenhouse gases
ICE – internal combustion engine

1 Introduction

Air conditioning (AC) operation for vehicles has a significant impact on the emissions and fuel economy; e.g., AC usage can increase NO_X emission from 15% to 100% [1]. It has been reported that AC systems are responsible for up to 30% of the fuel used in conventional internal combustion engine (ICE) cars, while the same applies to the use of the electricity of battery-powered cars [2]. For ICE cars the tailpipe emissions of nitrogen oxides (NO_X) and carbon monoxide (CO) may increase by more than 70%. The AC power consumption of mid-size cars is estimated to be more than 12% of the total vehicle power during regular commuting [2]. Furthermore, AC loads are the most significant auxiliary loads present in conventional ICE vehicles today; this energy use may outweigh the energy losses *via* rolling resistance, aerodynamic drag, or driveline losses for a typical vehicle. In the U.S. alone, about 7 billion gallons of fuel is consumed per year for AC systems of light-duty vehicles [3]. Under peak conditions the AC load of a 1200 kg sedan can amount to 6000 W, which can deplete the vehicle's battery pack quickly [4]. Figure 1 depicts the various thermal load categories encountered in a typical vehicle cabin. Some of these pass through certain vehicle body plates/parts, while others are independent of the surface elements of the cabin.

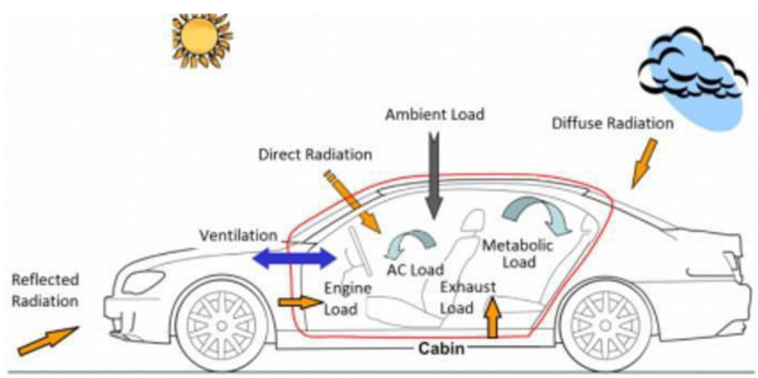

Figure 1: A schematic representative of thermal loads in a typical vehicle cabin [4].

We live in what is basically a large greenhouse: our planet, the Earth. As a system this is almost closed, except for the radiative energy emitted from the Sun and eventually re-emitted from Earth. The greenhouse effect is a process in which part of the incident solar energy is trapped in the atmosphere due to action of several gases, called greenhouse gases (GHGs). Most of the Earth's surface infrared radiation, which would otherwise go into space, is transmitted back to Earth by the greenhouse gases and the clouds, and as a result the temperature of the lower atmosphere is higher than it would otherwise be. This effect has similarity with the overheating inside the agricultural greenhouse. Likewise, however, a cooling effect can be obtained if thermal radiation out of a system exceeds the incoming thermal radiation (assuming other heat in- and outflows unchanged).

Passive cooling is based on reversing the heat gain by solar radiation (windows), internal heat sources, and potential other sources (humidity) and heat sinks. Passive cooling can be achieved using a skylight window in the roof (or window) of a car and creating a greenhouse effect inside the skylight. The work reported here follows earlier work at Process and Systems Engineering Laboratory (Abo Akademi University) by Zevenhoven and Fält for a building skylight [5–8]. It makes use of the fact that the composition of atmosphere is such that only a very high humidity (and clouds) will interfere with thermal radiation in the wavelength range 8– 14 m which is referred to as the 'atmospheric window'. Long-wave thermal radiation in this range (or band) can be transferred directly to space, which can be seen as a (very cold) heat reservoir at 3–4 K.

2 Numerical model development

Computational fluid dynamics (CFD) softwares have developed into powerful tools for simulation of existing systems and devices as well as the design and optimisation stages for future ones. Added routines allow CFD to be used for cases with multiple heat transfer mechanisms with or without a fluid flow, while thermal radiation still presents a challenge by bringing strongly non-linear terms into the equations to be solved. Fortunately, especially in the field of combustion engineering much progress was made – see e.g. [9] – that has been implemented in the heat transfer models of CFD tools. Natural convection and buoyancy complicates matters since gradients of scalars (temperature, concentration) become more computationally demanding than flow fields [10, 11]. For cases involving thermal radiation, different commercial software tools often give different outcomes, as shown below. This is mainly as a result of how boundary conditions information can be given and how physical properties of material as function of ther-mal radiation wavelength or frequency can be selected and used or must be added and implemented by the user [6].

2.1 Thermal radiation wavelength bands

To analyse the analogue of the greenhouse effect and the resulting heating or cooling inside a skylight window in a vehicle, the infrared spectrum is divided into four sections, one short-wavelength (< 4 m) and three long-wave radiation (4–8 m, 8–14 m, and > 14 m) bands. Dividing the long-wavelength spectrum into sections is motivated by the atmosphere being opaque to longwave radiation outside the 8–14 m atmospheric window [6]. The shortwave radiation band corresponds to solar irradiation.

2.2 Geometry, domain, and mesh

Proposed herein downscaled (compared to Fält's earlier designs for buildings) skylight window for use in a vehicle is a double glazed window consisting of an upper and lower window with a third movable window (here referred to as a middle window) in between as shown in Fig. 2. The upper and lower windows must be (highly) transparent for long-wavelength radiation, especially the 8–14 m atmospheric window while the middle window is opaque. For the size measurement of the vehicle, standard dimensions of a four-person family car were considered. The skylight has a square size of 0.01 m by 0.01 m; the total height is also 0.01 m (and may also be cylindrical). The thickness of both the upper and bottom window is 0.0004 m; the thickness of the middle window is 0.0006 m.

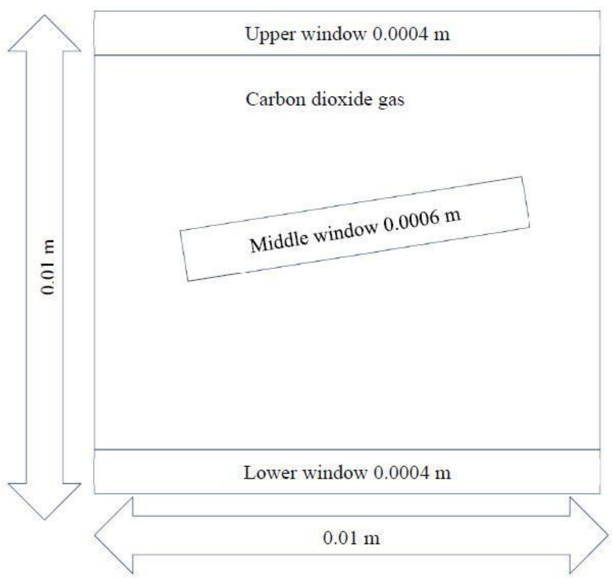

Figure 2: Dimensions of a skylight window for a car.

The dimensions of the middle window were selected according to [7] using a modified predator-prey algorithm approach to designing for the conflict-ing objectives of a cooling (during summer) or insulating (during winter) skylight effect. In that work, an optimised skylight window design was pri-marily based on cooling properties as this is also the main objective here. The middle window comes with an adjustable angle separating the two sections. The middle window when in cooling mode is set to cover 40%

(0.003 m from top and bottom windows) of the window height. The inclination angle has been optimized to be 7 degrees. For the insulating (winter) mode the middle window is closed off, stopping the convection between the two sections. The width of the middle window is set to be 20% shorter than the width of the skylight needed to “close” the window.

Carbon dioxide (CO_2) is used here as a participating gas and is added in the space between the upper and lower window. Gas located below the middle window will absorb thermal radiation from the space located below it if the lower window is sufficiently transparent for a long-wavelength radiation. As the temperature of gas increases, its density decreases, making it flowing to the volume above the middle (opaque) window. Here the radiative cooling to the sky above the skylight increases the density of the gas and makes it flowing back to the lower part, giving rise to convective flow between the upper and lower window space. Besides CO_2, Fält tested also other GHGs for use in the skylight, such as NH_3 and HFC-125 [8].

2.3 Mathematical and physical models

To analyse the suggested design of the proposed vehicular skylight window, thermal and flow field modelling of the window with wavelength-dependent emissivity, absorptivity, reflectance, and transmittance is carried out us-ing two commercial CFD softwares for modeling engineering applications and scientific research: COMSOL Multiphysics 5.3a [12] and Ansys Fluent 19.1 [13], respectively. For this case study, the physics controlled finer mesh was generated and COMSOL set up the meshing sequence automatically. The mesh for the Ansys Fluent case was produced using ICEM 19.1 [13], and the geometry was separated into multiple boundaries and domains (up-per window, middle window, lower window and middle space section). For both models, values for specific parameters are determined beforehand.

The thermal modelling is carried out for a 2D model of the window. Heat transfer from the inside space of a car through the vehicular skylight window toward the sky, upwards and preferably through the atmospheric window (8–14 m) is simulated, cooling directly to the universe (at 3–4 K). In practice, the skylight may be cylindrical which may be easier to construct and install than a square (cubic) shape. The thermal radiation modelling for this study neglects scattering and reflectance. This implies the following relation between emissivity, ε, absorptivity, α, and transmission, τ, for the material as a function of wavelength λ:

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

Weather data that gives information on the emissivity of the atmosphere can be acquired from the on-line data source containing hourly data for a given year [14]. To determine the sky temperature, the approach given in [15], for calculating the temperature difference between Earth surface and the sky can be used. The reference system for that is shown in Fig. 3. With temperatures T_{uni} = 3−4 K $T_{sky} \approx T_{sur}$, and surface areas A_{uni} $A_{sky} \approx A_{sur}$ this gives the following heat balance for the sky temperature, for a steady-state situation:

$$Q_{R,\, sky \leftrightarrow uni} = Q_{R, sur \leftrightarrow sky}\ , \tag{2}$$

$$\frac{A_{sky}\sigma(0.5T_{sky}^4 - T_{uni}^4)}{\frac{1}{\varepsilon_{sky}} + \left(\frac{1}{\varepsilon_{uni}} - 1\right)\frac{A_{sky}}{A_{uni}}} = \frac{A_{sur}\sigma(T_{sur}^4 - 0.5T_{sky}^4)}{\frac{1}{\varepsilon_{sur}} + \left(\frac{1}{\varepsilon_{sky}} - 1\right)\frac{A_{sky}}{A_{sur}}}\ . \tag{3}$$

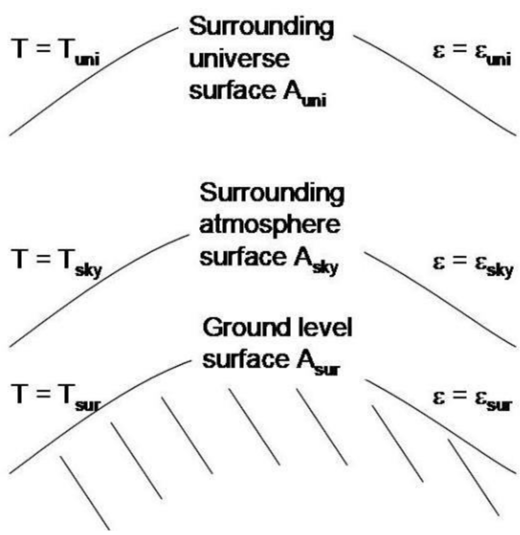

Figure 3: Arrangement for thermal infrared (TIR) radiation involving Earth, sky, and the universe [15].

Here the (view) factor 0.5 accounts for the fact that half the radiation from the sky is directed away from Earth, into space, and the other half is towards the Earth. With a typical ground-level emissivity ε_{sur} = 0.8–0.9 and emissivity values for the sky ranging from ε_{sky} = 0.6–0.9 (for either a clear or a cloudy/humid sky), temperature differences $T_{sur} - T_{sky}$ of the order of 5–10 K are calculated, as also mentioned in [15]. Typically, under annual global mean conditions, incoming solar radiation to Earth reaches 341 W/m^2. Of this radiation, the atmosphere absorbs 78 W/m^2, and the surface absorbs 161 W/m^2. Eventually, these 341 W/m^2 must be re-emitted to space as longwave radiation.

For the model calculations given below, the following temperature con-ditions are calculated and taken from meteorological data of Turku (a city on the southwest coast of Finland) for July 2018 [14]: $T_{ambient}$ = 280.15 K (7°C), T_{sky} = 273.22 K (0.07°C), and T_{room} = 290.55 K (17.4°C). The typ-ical values of emissivity of the atmosphere are as follows: $\varepsilon_{<4\ m}$ = 0.26, $\varepsilon_{4-8\ m}$ = 1, and $\varepsilon_{>14\ m}$ = 1 outside the atmospheric window wavelengths. Moreover, for the 8–14 m wavelength band (the atmospheric band), emis-sivity is calculated as follows [16]:

$$\varepsilon_{8-14\ m} = 1 + \frac{107952\,(1-\varepsilon_a)}{T_a^2 - 680.8T_a + 73594.9}, \text{ where } \varepsilon_a = \frac{T_{sky}^4}{T_a^4}. \quad (4)$$

Carbon dioxide has high transparency for short-wavelength radiation while showing a high absorbance in the atmospheric window (8–14 m) range – this is a major driver behind today's climate change and global warming. The emissivity of the gas is calculated according to the method described above, see also [17]. To calculate the absorption coefficient for use in the CFD simulations given below, the following equation (Beer–Lambert law) is used, for thickness (or path length) d:

$$\kappa = \frac{-\log \tau}{d}. \quad (5)$$

Following Fält, for the upper and lower window of the vehicular skylight window, the material chosen is zinc sulfide, (ZnS Cleartran). This material is transparent to both short- and longwave heat radiation and is mechani-cally strong enough to contain the gas. The transmission of the material is calculated from the transmission spectra [18]. Equation (5) is also used to calculate the absorption coefficient from the transmission. The transmission of the ZnS material came out to be τ = 0.67 for a thickness of 0.0008 m.

For the middle window, the material chosen is acrylic plastic (plexiglas), based on its optical clarity, low weight and high breakage resistance com-pared with glass and the variety of available sizes and thicknesses. Its total light transmission is 92% for wavelengths less than 1 m, and its measured haze averages of only 1%. Colourless plexiglas sheet transmits most of the invisible near-infrared energy in the 0.7–2.8 m hort wavelength region, but it does absorb certain bands [8]. The surface emissivity of the acrylic plastic sheet equals $\varepsilon = 0.94$. For sidewalls of the skylight, an insulating material is chosen, giving zero heat transfer.

2.4 Comparison between using the COMSOL and Ansys Fluent models

The simulation are conducted at steady-state and for a two-dimensional computational domain. The heat transfer module on COMSOL was enabled to model surface-to-surface radiation using the radiosity method combined with radiation in participating media using the discrete ordinate (DO) method [19].

For monitoring the radiation in participating media, the absorption coefficient and scattering coefficient are provided for the gas inside the skylight, i.e. carbon dioxide. For this study, time-dependent calculations were made. As an initial value of the temperature a transient simulation or as an ini-tial guess for a non-linear solver, an expression was derived based on heat transfer through a slab [17]. All the boundaries except for the two (top and bottom) windows were set as opaque, while the side walls were assumed to be perfectly insulated. The surface emissivity values of opaque surfaces were taken from the material properties database.

As for one important detail: for the laminar flow in the skylight inside volume domain, the body force was given a value across the volume in the vertical direction. The following equation was given for the volume force component

$$f(r) = -\rho(r)g(r) = -9.8\ \mathrm{spf}\rho, \tag{6}$$

where spf stands for single phase flow, g for gravity, r for position and ρ for density (‘rho’ in COMSOL). The volume force was added from the physics toolbar when selecting the laminar flow. The equation follows from the Navier–Stokes and continuity equations for laminar flow calculation.

For the Ansys Fluent model, natural convection is considered at the outer boundary of the upper window. To calculate the heat transfer coefficient for the boundary property following approach is taken. The equation used for convective heat transfer is as follows:

$$Q = h_C S(T_S - T_a), \tag{7}$$

hence

$$T_S = T_a + \frac{Q}{h_C S}\ , \tag{8}$$

where h_C is the convective heat transfer coefficient, S is the transfer area, T_S is the window outer surface temperature (equal to 280.15 K), and T_a is the air temperature (equal to 280.15 K).

An iterative method was used for a given input window surface temperature to determine Grashof number. Once the dimensionless parameters: Grashof number, Gr, Prandtl number, Pr, Rayleigh number, Ra, and Nusselet number, Nu, are calculated, a value for heat transfer coefficient was obtained for the heat transfer in the air above the upper window. By introducing that value of h_C, a new value of T_S was obtained from Eq. (8). The obtained T_S was then used to determine the value of Gr iteratively for the particular model by using it in the above equation. The obtained value of h_C was then used again to estimate the Gr parameters, in an iterative way that rapidly converges to an estimation of h_C.

A grid dependence study was undertaken to ensure the adequacy of the mesh density used. Spatial discretisation of the governing equations was achieved via the finite volume method using the pressure-based solver. The equations discretisation was carried out using second-order scheme for pressure and momentum (upwind scheme) and a first-order upwind schemes for energy including radiation. Momentum and pressure-based continuity equations were solved simultaneously with the coupled algorithm.

A significant difference between the models is that for the Ansys Fluent model emissivity for four wavelength bands could be defined for the gaseous medium (CO_2), ZnS, and acrylic plastic. The differences encountered while modeling the cases using both CFD softwares are summarised in Tables 1 and 2, respectively:

Table 1: Comparison of case model using COMSOL Multiphysics and Ansys Fluent.

	COMSOL Model	Ansys Fluent Model
Memory allocation	Not optimal (more simulation time)	Less simulation time
Meshing	Physic-controlled automatic	ICEM CFD
The emissivity of CO_2	The average value is given for the whole domain	Different values are given for all the four wavelength bands
Natural convection	Natural convection not assumed at the outer boundary of the upper window	Natural convection is assumed.
Boundary inputs	Less input required	More input required
Comments	More user-friendly	More accurate

3 Results of the simulations

The following section presents and discusses the results obtained from mod-eling the small skylight window on COMSOL and Ansys Fluent. The simu-lation model solves the thermal balance for the windows and carbon dioxide gas flowing in between. Inside the skylight, heat is transported via convec-tion in the participating gas. The transport of heat at the outside of the upper and lower windows is dominated by convection. Convection inside the window affects the heat transfer especially around the middle window. As this case study focuses on passive cooling of a vehicle only a few calcu-lations were done for insulation mode. (The latter would apply for a winter situation; in a vehicle the skylight would be easily covered to prevent passive cooling).

3.1 Participating gas – carbon dioxide

The flow fields in Figs. 4 and 6 show a cross-sectional plot of the velocity contours inside the skylight using the two softwares, including the scale of flow velocity. The map plot in the fluid domain ranges from 0 to 0.07 cm/s.

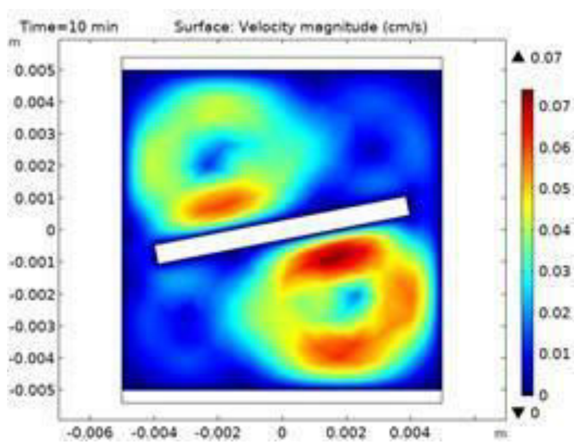

Figure 4: Velocity profile cooling: COMSOL, CO_2, inside skylight.

A separation zone was observed around the middle window, causing a sharp variation in velocity in this region. This is the result of the buoyancy effect that drives the free convection. The cold skylight glazing (upper window) surface cools the carbon dioxide gas adjacent to it giving the passive cooling effect aimed at. This denser gas then falls back to the lower space, starting a convection current. The gas, which flows between the glass layers, can remove heat from the space below it (here: the vehicle interior). The cooling capacity of the window is determined by the temperature gradient across the windows.

Figures 5 and 7 display for the two software tools a cross-sectional plot of the temperature distribution inside the skylight. The average tempera-ture inside the room was 310.4 K when the ambient temperature was set at 318 K. The temperature is as low as 309 K inside the skylight. Similar results for a 0.1 m × 0.1 m × 0.1 m skylight have been experimentally con-

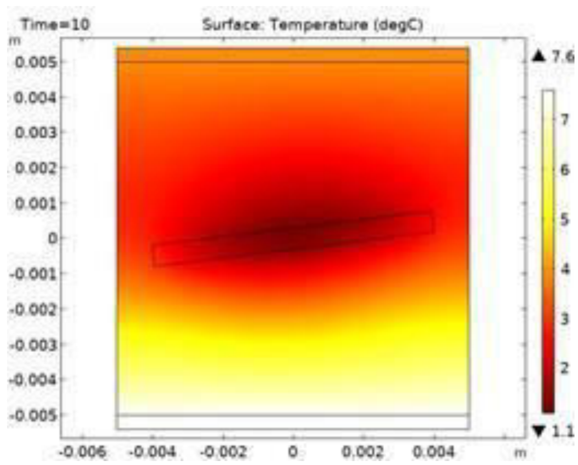

Figure 5: Temperature profile cooling: COMSOL, CO_2 inside skylight.

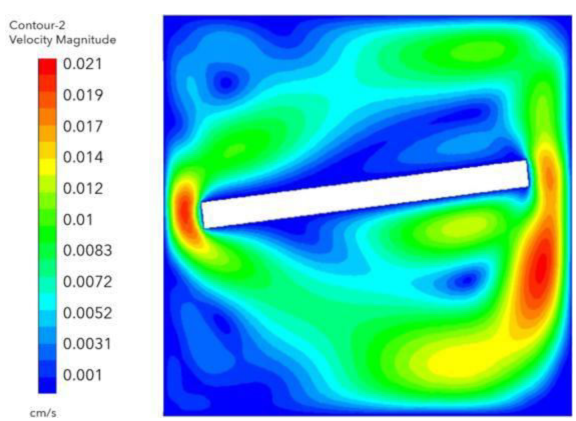

Figure 6: Velocity profile cooling: Fluent, CO_2 inside skylight.

firmed [8]. The figures show a significant temperature decrease around the middle window which may be caused by radiation from the upper surface of it through the upper window of the skylight.

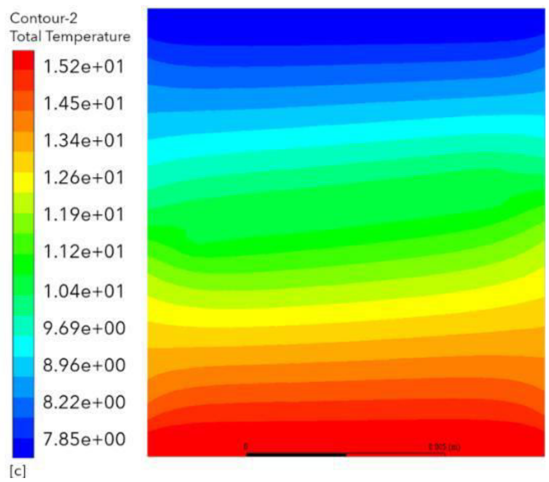

Figure 7: Temperature profile cooling: Fluent, CO_2 inside skylight.

Figures 8 through 11 give the simulation results for the skylight in insulation mode (middle window closed over the whole width of the skylight)

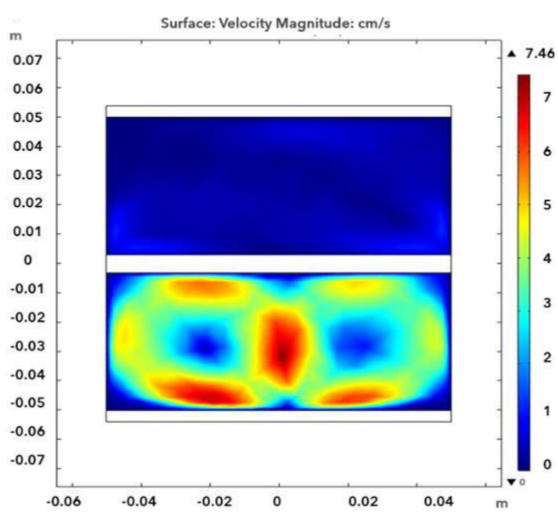

Figure 8: Velocity profile insulating: COMSOL, CO_2 inside skylight.

with carbon dioxide as participating gas. The figures show that there is some convection current within both sections of the skylight (upper section of the middle window and lower section of the middle window).

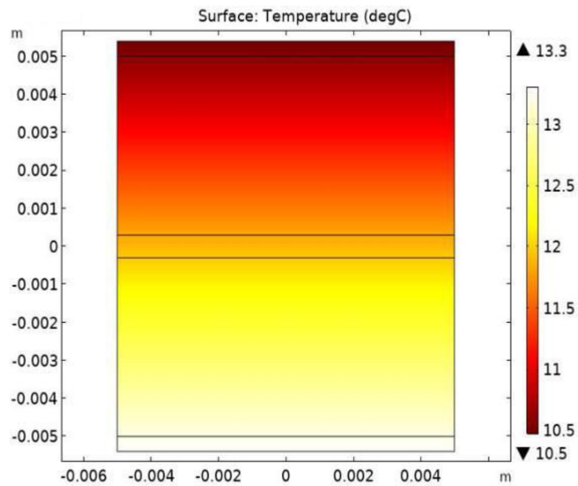

Figure 9: Temperature profile insulating: COMSOL, CO_2 inside skylight.

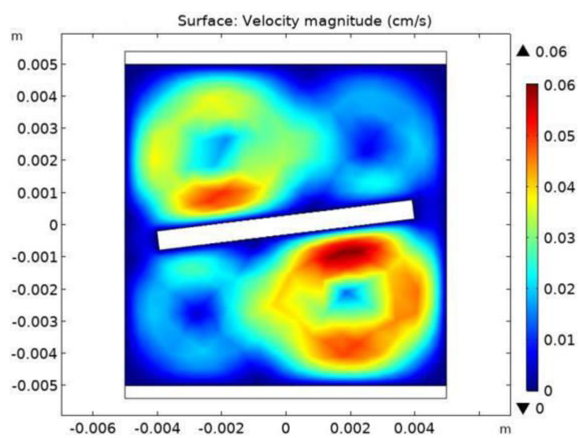

Figure 10: Velocity profile cooling: COMSOL, CO_2 inside skylight.

In addition, a study was also carried out for varied angle of inclination (7°, 10°, and 11° of the middle window for the cooling mode. Convection of gas is obtained for all the cases but only slight differences in the velocity of the gas were observed. Figures 10 and 11 show the result when the

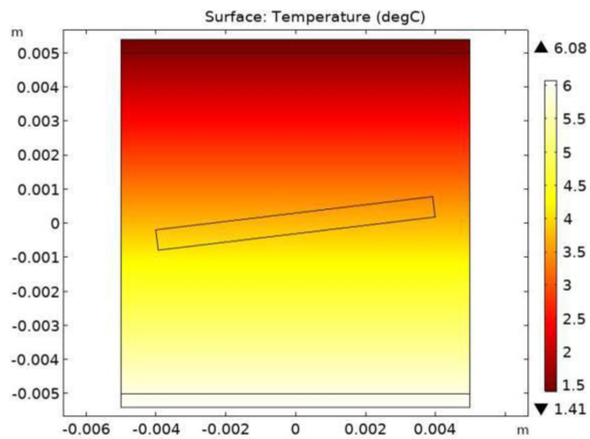

Figure 11: Temperature profile cooling: COMSOL, CO_2 inside skylight.

inclination angle was simulated by COMSOL for 10° instead of 7°. The results revealed that the angle of inclination (in the range studied!) does slightly influences the skylight's passive cooling effect.

3.2 Participating gas – air

The results for using air as participating gas inside skylight window are shown in Figs. 12 through 15. Compared with the use carbon dioxide as

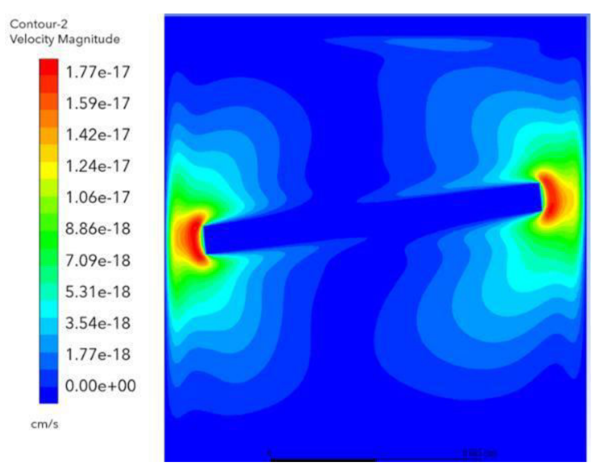

Figure 12: Velocity profile cooling: Fluent, air inside skylight.

the participating gas, it is seen convective current velocities are relatively slow in case of air. Also the temperature profile for the air case shows that temperature decreases of only 1–3 K lower compared to the outside spaces are achieved within the skylight, meaning that less of a cooling effect is obtained than when carbon dioxide is used.

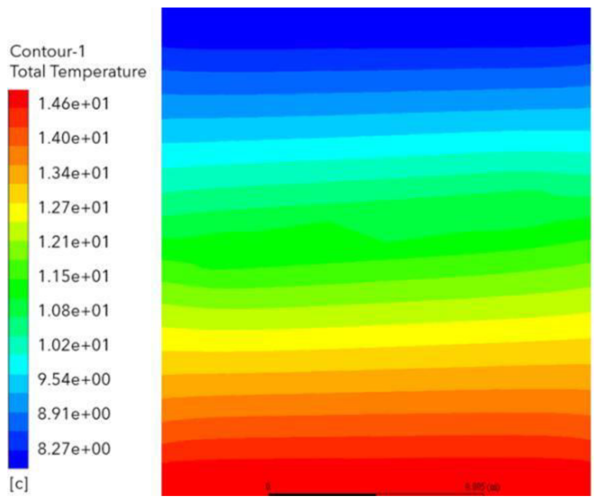

Figure 13: Temperature profile cooling: Fluent, air inside skylight.

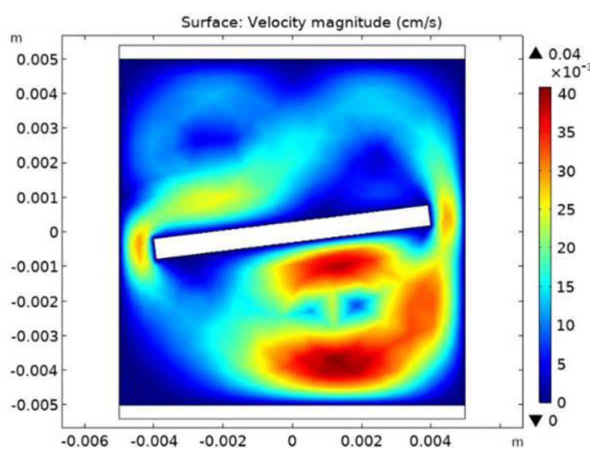

Figure 14: Velocity profile cooling: COMSOL, air inside skylight.

Figure 16 and 17 shows the temperature and velocity profile when air is use as participating gas for insulation mode, using COMSOL.

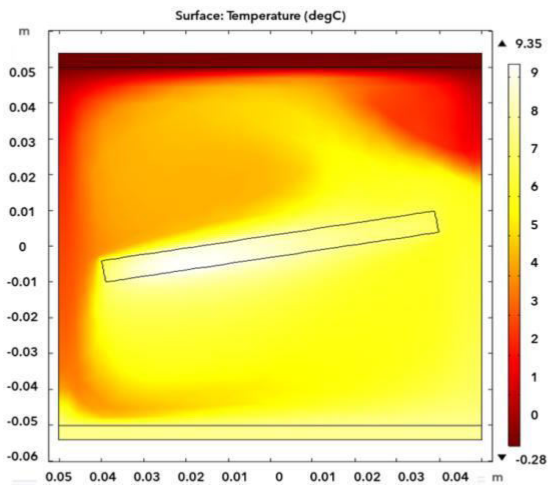

Figure 15: Temperature profile cooling: COMSOL, air inside skylight.

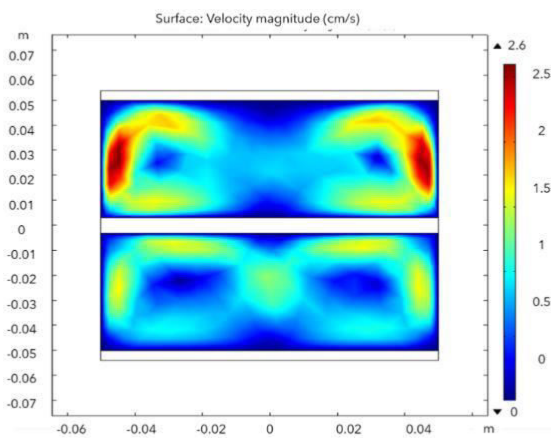

Figure 16: Velocity profile insulating: COMSOL, air inside skylight.

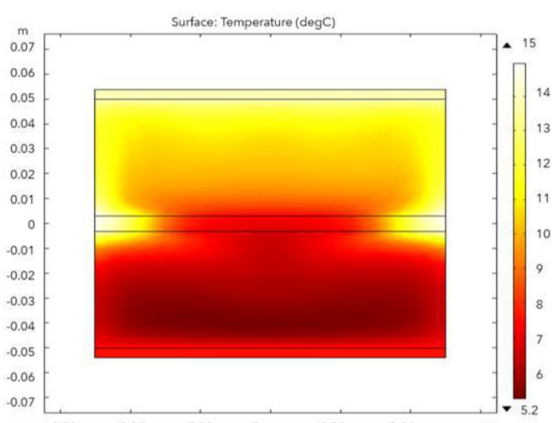

Figure 17: Temperature profile insulating: COMSOL, air inside skylight.

3.3 Heat fluxes through the skylight

The results of the COMSOL and Ansys Fluent model calculations were processed to give heat transfer flux, Q^{00}. The following expression is given at the upper window (outside boundary) for the calculation of the passive cooling effect:

$$Q^{00}{}_{net} = -\text{Net radiative heat flux} - \varepsilon_{sky}\sigma T_{sky}{}^{4} + \text{Net convective heat flux.} \qquad (9)$$

This expression gives the net effect of the radiative and convective heat transfer from the skylight to the sky and to the ambient surroundings. The CFD software calculates and presents as output the net radiative heat flux and net convective heat flux at the outer boundary of the upper window at the end of the simulation (when a steady-state is reached). The results are summarised in Table 2 for the skylight used in the cooling mode. Gas emissivity, given as a gray value (independent of wavelength) integrated over the wavelength is calculated according to [20] using radiation path of 0.01 m, and pressure of 0.1 MPa for CO_2 or air (containing 0.04%vol CO_2).

Table 2: Summary of simulation results from COMSOL Multiphysics and Ansys Fluent: cooling mode.

CFD software	Inclination angle (middle window)	Participating gas	Gas emissivity (300 K)	T_g at top surface of window (K)	T_g at bottom surface of window (K)	Passive cooling effect (W/m^2)
COMSOL	7	CO_2	0.055	275.45	280.75	27
Ansys Fluent	7	CO_2	0.055	282.75	288.15	18
COMSOL	10	CO_2	0.055	275.15	278.90	14
Ansys Fluent	10	CO_2	0.055	286.35	284.05	7
COMSOL	7	Air	0.063	281.15	287.15	10
Ansys Fluent	7	Air	0.063	280.15	288.15	8

4 Conclusions

The commercial general-purpose CFD softwares COMSOL Multiphysics and Ansys Fluent were used in this study to analyse the engineering design of the proposed vehicular skylight window, for a four-person car. The simulation is conducted for steady-state and with a two-dimensional computa-tional domain. The study revealed many significant findings, most impor-tantly that the passive cooling effect of almost 27 W/m^2 (COMSOL) via the assumed vehicle skylight is attainable for the summer season in Finland. However, in practice this will depend on the car type, indoor conditions, and weather conditions (e.g., air temperature, relative humidity, velocity, and direction of winds). Thus, the annual energy use (fuel or electricity consumption) of a car will be significantly less when a car uses skylight for passive cooling. There will be several parameters that will influence the effectiveness of the skylight window but are not taken into account in this study (also because the current CFD software do not allow for that). For example, the effect of skylight height, while also the enclosed gas volume width will influence the gas temperature and internal flow profile, thereby altering the energy flow. One of the biggest challenges with the skylight window also when used in a vehicle is condensation as metal parts con-duct heat very quickly. Excessive condensation can contribute to excess moisture inside the vehicle. Thus, for future work, condensation should be modeled using a user-defined function for the CFD software. Also the imple-mentation of wavelength dependent radiation parameters and calculating wavelength-dependent performance using the CFD softwares needs further improvement.

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