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Published in:
Proceedings of the 6th International Conference on Contemporary Problems of Thermal Engineering

Published: 01/01/2020

Document Version
Final published version

Document License
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Link to publication

Please cite the original version:
Khan, U., & Zevenhoven, C. A. P. (2020). Passive cooling through the atmospheric window for vehicle temperature control. In W. Stanek, P. Gladysz, S. Werle, & L. Czarnowska (Eds.), *Proceedings of the 6th International Conference on Contemporary Problems of Thermal Engineering* (pp. 291-300). Article 1040 (International Conference on Contemporary Problems of Thermal Engineering; No. 6). The Silesian University of Technology. https://urn.fi/URN:NBN:fi-fe202201147980

Passive cooling through the atmospheric window for vehicle temperature control

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Keywords: Thermal radiation, Passive cooling, Vehicle Skylight, CO2, Computational fluid dynamics

Abstract
One way of countering climate change is the efficient use of energy. One of the most energy-intensive activities for a vehicle is the space air conditioning, either for cooling or for heating. In this sense, considerable energy savings can be achieved if air conditioning and cooling can be decoupled from the use of fuel or electricity. The study aims to analyse the opportunities and effectiveness of applying the concept of passive cooling through the atmospheric window (i.e. the 8-14 µm wavelength bandwidth where the atmosphere is transparent for thermal radiation) for the temperature control of vehicles. A recent dr. Thesis work by M Fält at Åbo Akademi (ÅA) has resulted in a skylight (roof window) design for the passive cooling of building space, and 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, > 4 µm) thermal radiation is stronger than the incoming (short wavelength, < 4 µm) thermal radiation. Of particular interest is the passive cooling of a vehicle parked under direct sunlight. The goal is to give engineering designs for passive cooling units for a passenger car or a truck, equipped with a skylight window as designed at ÅA for buildings. The work is done using CFD software implementing (as far as possible) wavelength-dependency of thermal radiation properties of the materials used. For the size of the vehicle, standard dimensions of 4-person family car are considered. The results of this study help in estimating reduced cooling loads for cars. The findings report that by the use of passive cooling, a temperature difference of up to 7-8 oC is obtained with an internal gas flow rate of 0.07 cm/s depending on the configuration and operating conditions. The passive cooling effect of almost 27 W/m2 (COMSOL) from the vehicular skylight is attainable for the summer season in Finland. Comparison of results from ANSYS and COMSOL model shows differences of ~10 W/m2 in the estimation of passive cooling effect for a vehicle skylight.

1 Introduction

Air conditioning (AC) operation for vehicles is proven to have a significant impact on the emissions and fuel economy; e.g., AC usage can increase NOx emission from 15% to 100% [1]. It has been reported that AC systems consume up to 30 % of the fuel in conventional internal combustion engine (ICE) cars, while they consume up to 30% of the energy in battery-powered cars [2]. Moreover, the tailpipe emissions of NOx and 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; its energy use often even outweighs the energy loss to rolling resistance, aerodynamic drag, or driveline losses for a typical vehicle. The U.S. alone consumes about 7 billion gallons of fuel a year for AC systems of light-duty vehicles [3]. The AC load of a 1200-kg sedan, under peak conditions, can amount to 6 kW, which can deplete the vehicle's battery pack quickly [4].

Figure 1 schematically shows the various thermal load categories encountered in a typical vehicle cabin. Some of the above loads pass across the vehicle body plates/parts, while others are independent of the surface elements of the cabin.

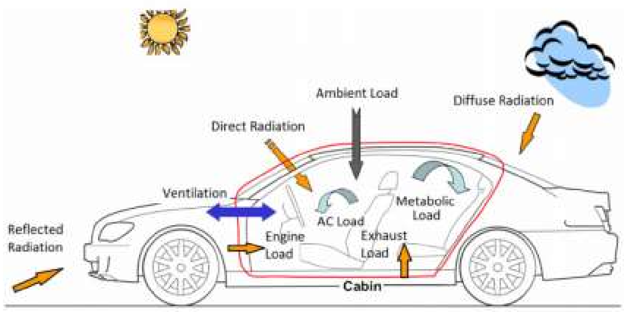

Figure 1: A schematic representative of thermal loads in a typical vehicle cabin [4]

We live in a large greenhouse: our planet, the Earth. This sustainable system is almost closed, except for the radiative energy emitted from the Sun. The greenhouse effect is a process in which part of the incident solar energy is trapped in the lower atmosphere due to action of certain atmospheric gases, called greenhouse gases (GHGs). A part of the Earth's surface infrared radiation, which would otherwise go into space, is transmitted back by the greenhouse gases and the clouds, thus the temperature of the lower atmosphere becomes higher than it would otherwise be. This effect has similarity with the overheating inside an agricultural greenhouse, and likewise a cooling effect can be obtained if thermal radiation out of a system is larger than incoming thermal radiation (other heat in- and outflows being unchanged).

Passive cooling reverts the heat gain by solar radiation (windows), internal heat sources, potential sources (humidity) and heat sinks. Passive cooling can be achieved using a skylight window in the roof car by applying the greenhouse effect inside the skylight. This work follows earlier work at our laboratory by Fält [5] for a building skylight. It uses the fact that the composition of the atmosphere is such that only a very high humidity (and clouds) interferes with the thermal radiation wavelength range 8-14 µm which is referred to as the atmospheric window. Long-wave thermal radiation in this range (or band) can be transferred directly to space, which is at 3-4 K.

2 Numerical Model development

2.1 Thermal Radiation Wavelength Bands

To analyse the greenhouse effect and the resulting heating or cooling inside a (vehicular) skylight window, the infrared spectrum is divided into four sections, one short-wavelength (<4 µm) and three long-wave radiation (4-8 µm, 8-14 µm, and 14-100 µm) bands. The purpose of dividing the long-wavelength spectrum into sections is because the atmosphere is opaque to longwave radiation outside the 8-14 µm atmospheric window [6].

2.2 Geometry, Domain, and Mesh

The proposed, downscaled (compared to Fält's 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 (termed middle window) in between as shown in Figure 2. The upper and lower windows must be (highly) transparent for long-wavelength radiation, especially the 8-14 µm atmospheric window while the middle window is opaque. For the size measurement of the vehicle, standard dimensions of 4 person family car were considered. The skylight has a square size of 0.01 by 0.01 m; the total height is also 0.01 m. The thickness of both the upper and bottom window is 0.4 mm, while the thickness of the middle window is 0.6 mm. The dimensions of the middle window were selected according to [7] using a modified predator-prey algorithm approach to designing a cooling (during summer) or insulating (during winter) skylight. In that work, an optimised skylight window design was primarily based on its cooling properties. The middle window when in cooling mode is set to cover 40% of the height of the window. The inclination angle has been optimized to be 7 degrees. The width of the middle window is set to be 20% shorter than the width of the skylight needed to ''close'' the window.

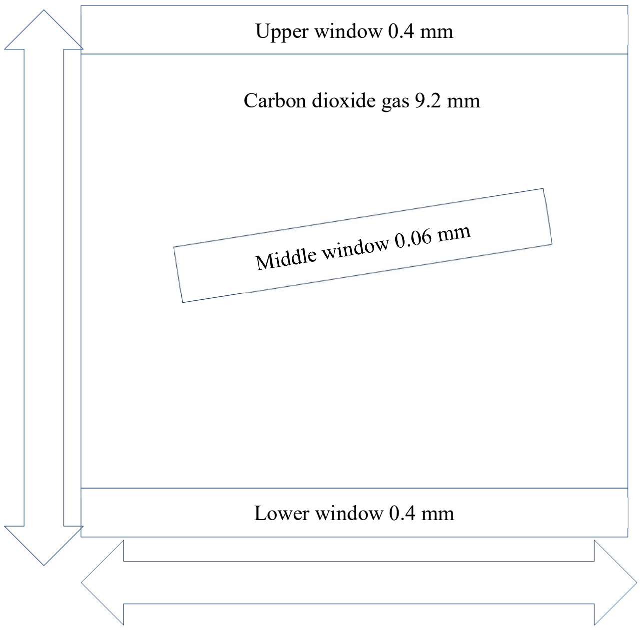

Figure 2: Dimensions of a skylight window for a car

Carbon dioxide is used here as a participating gas in the volume inside the skylight. The gas located below the middle window will absorb thermal radiation from the space located below it if the lower window is sufficiently transparent for long-wavelength radiation. As the temperature of gas increases, the density decreases, and it will flow to the volume above the middle (opaque) window. Here the radiative cooling to the sky, in turn, increases the density of the gas and make it flow back to the lower part again, giving rise to convective flow between the upper and lower window space. (Fält tested also other GHGs for use in the skylight, such as NH_3 and HFC-125 [5].)

2.3 Mathematical and Physical Models

To analyse the engineering design of the proposed vehicular skylight window, thermal and flow field modelling of the window with wavelength-dependent emissivity, absorptivity, reflectance and transmittance is done using CFD softwares COMSOL Multiphysics 5.3a and ANSYS FLUENT 19.1, respectively. For both models, values for specific parameters are determined beforehand.

The thermal modelling is carried out for a 2-D model of the window, that is 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 μm cooling directly to the universe (at 3-4 K). In practice, the skylight may be cylindrical.

The thermal radiation used for this work-study involves no scattering or reflectance. This suggests the following relation between emissivity, ε, absorptivity, α and transmission,τ for the material as function of wavelength λ:

$$\alpha(\lambda) = \varepsilon(\lambda) = 1 - \tau(\lambda) \tag{1}$$

Weather data that gives information on the emissivity of the atmosphere can be acquired from an internet source containing hourly data for a given year [8]. To determine the sky temperature, the approach given in [9], for calculating the temperature difference between earth surface and the sky can be used. The reference system is shown in Figure 3. With $T_{uni} = 3 - 4$ K << $T_{sky} \approx T_{sur}$, $A_{uni} >> A_{sky} \approx A_{sur}$ this gives the following heat balance for the sky temperature, for a steady-state situation:

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

$$\frac{\mathrm{A_{sky}}.\,\sigma.\,(½.\,\mathrm{T_{sky}^4} - \mathrm{T_{uni}^4})}{\frac{1}{\varepsilon_{\mathrm{sky}}} + \left(\frac{1}{\varepsilon_{\mathrm{uni}}} - 1\right).\frac{\mathrm{A_{sky}}}{\mathrm{A_{uni}}}} = \frac{\mathrm{A_{sur}}.\,\sigma.\,(1/2\,.\,\mathrm{T_{sur}^4} - \mathrm{T_{sky}^4})}{\frac{1}{\varepsilon_{\mathrm{sur}}} + \left(\frac{1}{\varepsilon_{\mathrm{sky}}} - 1\right).\frac{\mathrm{A_{sky}}}{\mathrm{A_{sur}}}} \tag{3}$$

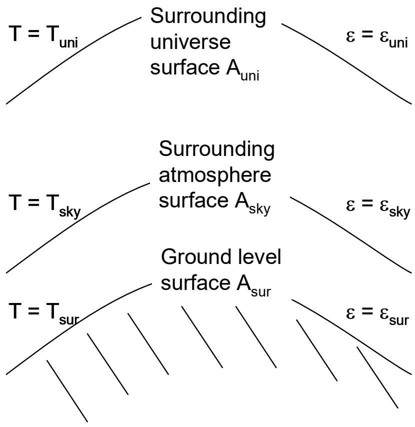

Figure 3: Arrangement for TIR radiation involving earth, sky, and the universe [9].

Here the (view) factor ½ accounts for the fact that half the radiation from the sky is in directions 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 cloudy/humid sky), temperature differences $T_{sur} - T_{sky}$ of the order of 5 - 10 K are predicted, as also mentioned in [10].

Typically, under annual global mean conditions, incoming solar radiation to earth reaching 341 W/m^2. Out 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 cases given below, the following temperature conditions are calculated/taken from meteorological data of Turku for July 2018 [8]: $T_{ambient}$ = 280.15K = 7°C,T_{sky} = 273.22K =0.07°C and T_{room} = 290.55K =17.4 °C

The typical values of emissivity of the atmosphere are as follows: $\varepsilon_{<4\mu m}$ = 0.26, $\varepsilon_{4\text{-}8\mu m}$ = 1 and $\varepsilon_{>14\mu m}$ = 1 outside the atmospheric window wavelengths. Moreover, for the 8-14μm wavelength band (the atmospheric band), emissivity is calculated as following [11]:

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

Carbon dioxide is a greenhouse gas, transmitting visible light but absorbs strongly in the infrared and near-infrared. To determine the absorption coefficient of carbon dioxide gas, the transmission and absorption spectra of the gas is studied as given in [10]. Carbon dioxide has high transparency for short-wavelength while high absorbance in 8-14 µm range. The emissivity of the gas is calculated according to the method described in [11]. To calculate the absorption coefficient (κ, m^{-1}) for use in the CFD simulations given below, the following equation (Beer-Lambert law) is used, for thickness (or path length) d (m).

$$\kappa\ (\text{gas m}^{-1}) = \frac{-\log(\tau)}{\text{d}} \tag{5}$$

Following Fält, the upper and lower window of the vehicular skylight window, the material chosen is zinc sulfide, (ZnS Cleartran). The reason this material is taken is that it is transparent to both short and longwave heat radiation and is mechanically strong enough to contain the gas. The transmission of the material is calculated from the transmission spectra [10]. 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 0.8 mm.

For the middle window, the material chosen is acrylic plastic (plexiglas). The versatility of the plexiglas sheet is its optical clarity; it is lightweight and has a high breakage resistance compared with glass and the variety of sizes and thicknesses. Its total light transmission is 92% for wavelengths less than 1000 nm (1 µm), and its measured haze averages of only 1%. Colourless plexiglas sheet transmits most of the invisible near-infrared energy in the 700 to 2800 nanometer SW wavelength region, but it does absorb certain bands [10]. The surface emissivity of the acrylic plastic sheet equals 0.94. For sidewalls of the skylight, an insulating material is chosen, giving zero heat transfer.

2.4 Comparison between using the COMSOL and Fluent models

The simulation are conducted at steady state and with a two-dimensional computational domain. The '*Heat Transfer Module'* on COMSOL was enabled to model surface-to-surface radiation using the radiosity method as well as radiation in participating media using the discrete ordinate method (DO method).

As for one important detail: for the laminar flow in the domain, the body force was given value across the volume in the vertical direction. The following equation was given for the volume force component (f in Equation (7)).

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

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 the initial value of the temperature a transient simulation or as an initial guess for a non-linear solver, an expression was derived based on heat transfer through a slab [10].

All the boundaries except the two (top and bottom) windows were set as opaque except the side walls which are assumed to be insulated. The surface emissivity values of opaque surfaces were taken from the material properties database.

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 for FLUENT model following approach is taken. The equation used for convective heat transfer is as follows:

$$Q = h_c * S * (T_w - T_a) \tag{7}$$

where Q = heat transferred (W), h_c = convective heat transfer coeffecient (W/($m^2 \cdot$ K), S = transfer area (m^2), T_w = window outer surface temperature = 280.15 K and T_a = air temperature = 280.15 K.

An iterative method was used for a given input window surface temperature to determine Grashof number Gr. Once the dimensionless parameters Gr, Pr, Ra, and Nu are calculated, the value of heat transfer coefficient was obtained for the heat transfer in the air above the upper window. By introducing the value of h_c, a new value of T_s can be obtained as

$$T_s = T_a + \frac{Q}{h_c * S} \tag{8}$$

Moreover, the obtained T_s was 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 correct 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 employing the finite volume method using the pressure-based solver. The equations discretisation was carried out using second-order schemes for pressure and momentum (upwind scheme) and 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 Fluent model emissivity for four wavelength bands could be defined for the media, i.e. carbon dioxide, ZnS and acrylic plastic.The differences encountered while modeling the cases and simulation result from using both CFD softwares are summarised in Table 1 and Table 2, respectively [12]:

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

3.1 Participating gas CO_2 versus Air

These flow fields in Figure 4 and Figure 5 show a cross-sectional plot of the velocity contours inside the skylight. The plots include the scale of airflow velocity (m/s). The contour plot in the fluid domain is colour coded and related to the CFD colour map, ranging from 0 to 0.07 cm/s.

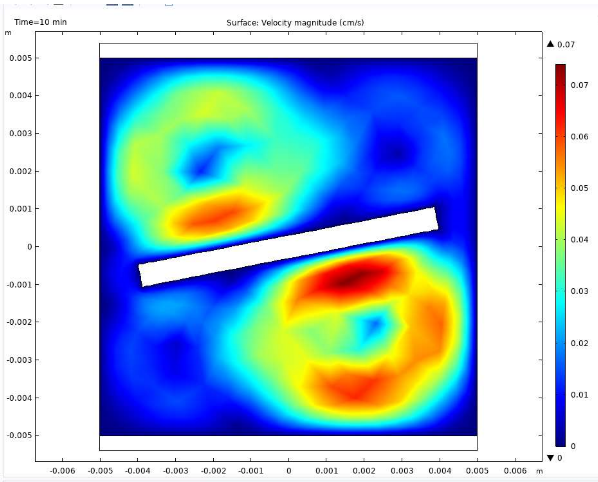

Figure 4: *Velocity profile cooling: COMSOL*

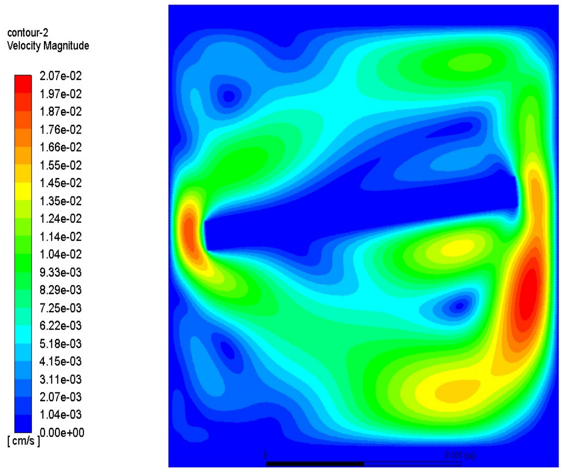

Figure 5: *Velocity profile cooling: FLUENT*

A separation zone was observed around the middle window, which caused a sharp variation in velocity in this region. This is the result of of the buoyancy effect of free convection. Convection inside the window affects the heat transfer in many places in the skylight window: the upper surface, the lower surface, especially around the centre window. A cold interior 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 (the vehicular interior). The cooling capacity of the window is determined by the temperature gradient across the window.

Figures 6 and 7 display a cross-sectional plot of the temperature distribution inside the skylight. The average temperature 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. The figure illustrates that temperature in the upper gas volume decreases close to the centre window before increasing. It shows that the centre window loses energy by convection in the lower gas volume.

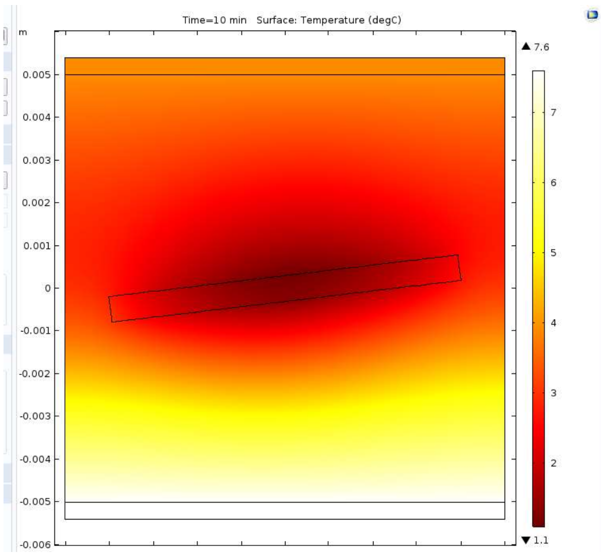

Figure 6: *Temperature profile cooling: COMSOL*

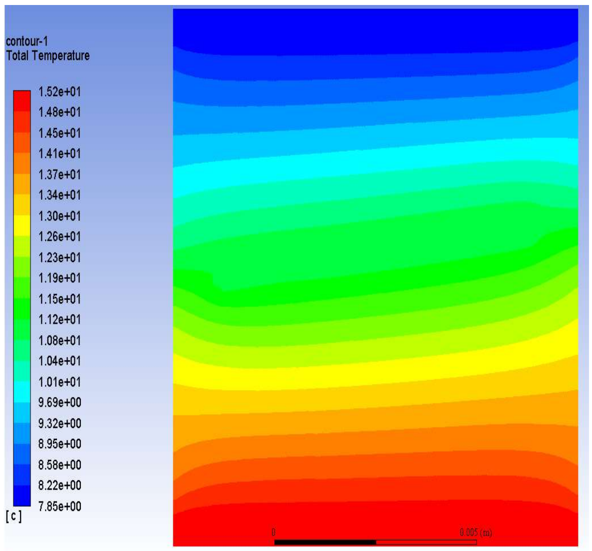

Figure 7: *Temperature profile cooling: FLUENT*

Figures 8 through 11 give the simulation results when the skylight is in insulation mode (middle window closed over the whole width of the skylight) with carbon dioxide as participating gas. The figure shows 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).

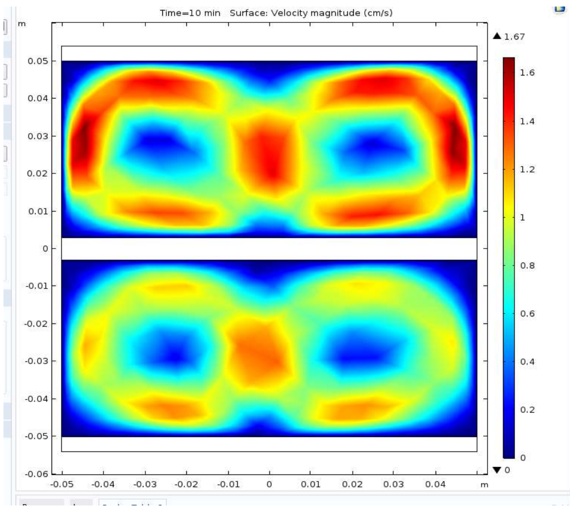

Figure 8: *Velocity profile insulating: COMSOL*

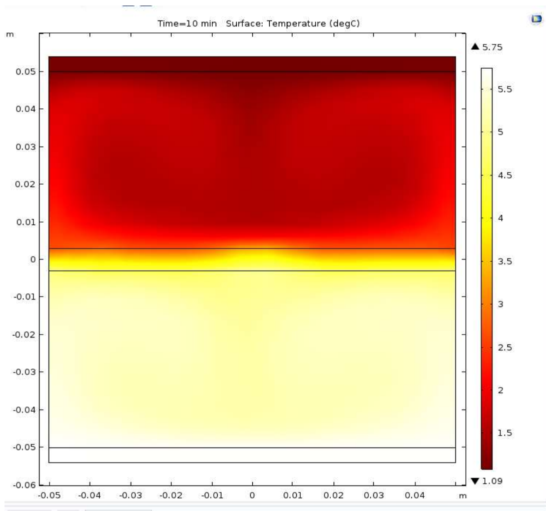

Figure 9: *Velocity profile insulating: FLUENT*

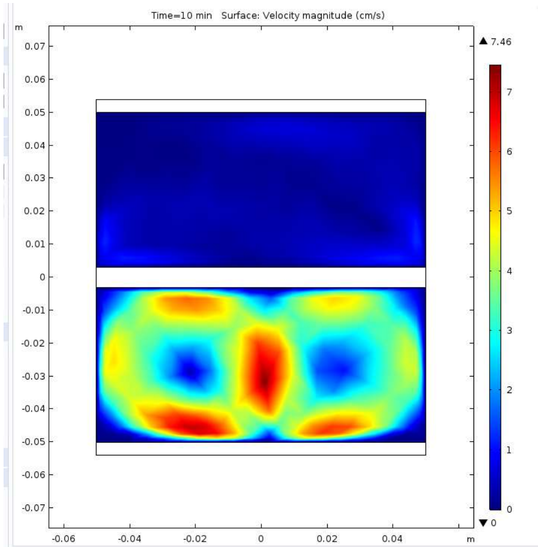

Figure 10: *Temperature profile insulating: COMSOL*

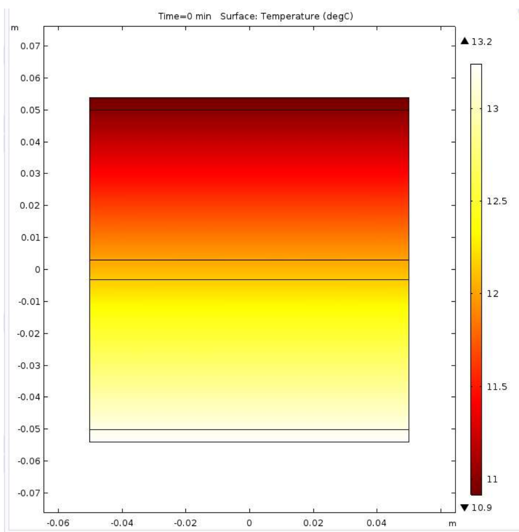

Figure 11: *Temperature profile insulating: FLUENT*

If the results for passive cooling mode are compared with using air as the participating gas, it is observed that the velocity of convective current formed are relatively slow in case of air. Besides, the temperature profile for the air case demonstrates that temperature decreases of only 1-3 ºC lower is achieved within the skylight, meaning that less of a cooling effect is obtained than when CO_2 is used.

3.2 Heat fluxes through the skylight

The results of the COMSOL and ANSYS Fluent model calculations were processed to give heat transfer in W/m^2. The following expression is given at the upper window (outside boundary) for the calculation of the passive cooling effect:

$$\dot{Q}_{net} = \left(-Net\ radiative\ heat\ flux - \varepsilon_{sky}\sigma T_{sky}^{4}\right) + Net\ Convective\ heat\ flux \qquad (9)$$

The above expression gives the net effect of the radiative and convective heat transfer from the skylight to the sky and to the ambient surroundings. The software itself calculates the net radiative heat flux and net convective heat flux at the outer boundary of the upper window at the end of the simulation. The results are summarised in Table 2 for the the skylight used in the cooling mode.

For the sake of comparison, the skylight was analysed using air as participating gas. The detailed results of the analysis are given in a separate report [12]. Also, when the middle window inside the skylight is titled at various angles (7°, 10°, 11°), an obvious upstream of gas is obtained in all the cases. Only a slight change in the velocity of the gas is observed.

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

CFD software	Width (m)	Inclination angle (middle window)	Participating gas	Gas emissivity	T_g at top surface of window (°C)	T_g at bottom surface of window (°C)	Passive Cooling (W/m^2)
COMSOL	0.01	7	CO_2	0.055	2.3	7.6	27
ANSYS FLUENT	0.01	7	CO_2	0.055	9.6	15	18
COMSOL	0.01	0	CO_2	0.055	2	5.75	14
ANSYS FLUENT	0.01	0	CO_2	0.055	13.2	10.9	7
COMSOL	0.01	7	Air	0.7	8	14	10
ANSYS FLUENT	0.01	7	Air	0.7	7	15	8

4 Conclusions

A commercial general-purpose CFD software COMSOL Multiphysics and ANSYS FLUENT is used in this study to analyse the engineering design of the proposed vehicular skylight window, in the car. The simulation is conducted at steady-state and with a two-dimensional computational domain. The study revealed many significant findings, including that passive cooling effect of almost 27 W/m^2 (COMSOL) from the vehicular skylight is attainable for the summer season in Finland. However, its efficiency depends on the car type, indoor conditions, and weather conditions (e.g., air temperature, relative humidity, velocity and direction of winds). Thus, the annual energy consumption of a car may reduce when a car uses skylight for passive cooling. There are more parameters that will influence the effectiveness of the skylight window but are not taken into account in this study. For instance, simulation for the height effect. In addition, the cavity width will influence the gas temperature and internal flow profile, therefore altering the energy flow.

Acknowledgements

The authors would like to acknowledge the work of Martin Fält at Åbo Akademi (ÅA) that has resulted in a skylight (roof window) design for the passive cooling of building space. Henry Ford Association funded the work presented in the paper.

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