Passive Cooling Against the (Night) Sky

Ron Zevenhoven*1 and Martin Fält1

1Thermal and Flow Engineering Laboratory, Åbo Akademi University, Turku Finland,

*Corresponding Author - E-mail: ron.zevenhoven@abo.fi

Abstract This paper summarises R&D work that evolved towards the design of a smart skylight (roof window) aiming at keeping its inside compartment at a lower temperature than the surroundings. A skylight that gives maximum cooling (summer) or insulating (winter) performance is being optimised at Åbo Akademi University for conditions in (northern) Europe. As passive cooling through long-wave (LW) thermal radiation must counteract incoming short-wave (SW) thermal radiation, a drawback to that region is the length of daytime during summer. For equatorial locations like Kenya the use of a passive cooling skylight would benefit from the more constant duration of night-time and temperature. Depending on location for application, a two- or more-windowed skylight must be designed. Results presented include the modelling of skylight windows using a four-band thermal radiation model and Comsol Multiphysics software for simulation. Several cases show that very significant increases in (passive) cooling heat output can be achieved.

Keywords Thermal radiation, Radiative cooling, Sky

1. Introduction

The cooling of residential and office space is very energy intensive and represents a significant part of the electricity use worldwide. Thermal radiation heat transfer using passive systems is therefore receiving increased attention from the field of energy-efficient building, with cooling being equally important as heating.

An unbalance between thermal radiation in short-wave (SW, <4µm) and long-wave (LW, >4µm) bands can lead to a net heating or cooling effect. Well known is the enhanced greenhouse effect that results from an influx of short-wave thermal radiation from the sun that nowadays is not balanced by long-wave outgoing radiation. Likewise, passive cooling can be achieved if outgoing radiation in certain wavelength bands cannot be balanced by incoming thermal radiation [1,2].

This paper summarises R&D work that evolved towards the design of a smart skylight (roof window) aiming at keeping its inside compartment at a lower temperature than the surroundings. The physical mechanism is cooling against the sky which has a (5-15°C, or more) lower temperature than the (ground level) surroundings. The so-called “atmospheric window” of the sky (8-14 µm) is made use of as much as possible. After this idea was first presented at the “Keenan symposium” at MIT in October 2007 [3], recent work by others has addressed the control of window glass transmittance [4] and even the option of running water through a double glass window for combined water heating and air conditioning [5], but the use of so-called participating gases that interact with thermal radiation in certain, pre-selected wavelength bands has not received much attention.

![Fig. 1. Skylight in cooling (A) or insulating (B) mode](image.png)

A skylight that gives maximum cooling (summer) or insulating (winter) performance is being optimised at Åbo Akademi University for conditions in (northern) Europe. As passive cooling through LW thermal radiation must counteract incoming SW thermal radiation, a drawback to
that region is the length of daytime during summer. Fig. 1 shows a schematic of the skylight operating in cooling mode (A) or insulating mode (B), respectively [6]. Typical dimensions are a height of 0.1-0.5 m, a width of 0.5-1 m. By filling the volumes in the skylight with a gas that absorbs and emits heat radiation it is possible to controllably provide a room with cooling or thermal insulation when needed. When in cooling mode, the gas located in gas layer 1 will absorb heat from the room located below it. As the gas temperature increases the density decreases, and it will flow to gas layer 2. Here, radiative cooling to the sky in turn increases the density of the gas and thus makes it flow back down to gas layer 1. When the skylight is in its insulating mode convective swirls will not be formed.

For equatorial locations like Kenya the use of a passive cooling skylight would benefit from the more constant duration of night-time and temperature. Then the skylight would operate in cooling mode most of the time, being most efficient after sunset, under clear skies.

2. Gas-filled double glass window modelling
The first steps of the work involved the assessment of the heat transfer through a double glass window with air or CO$_2$ filling the spacing between the windows. Gray media were assumed, which assumes thermal radiative properties of materials (emissivities $\varepsilon$, absorptivities $\alpha$, transmissivities $\tau$ and reflectances $\rho$) independent of wavelength. The geometry for the window is given in Fig. 2 (left), with the equivalent radiation network for this system (where nodes $J_3$ and $J_4$ represent the left-hand and right-hand side window, and $E_{bg}$ gives the blackbody radiation from/to the enclosed gas) as in Fig. 2 (right).

Calculations with this system showed that a double glass window set-up using different types of “glass” with different transmissivities can result in altered heat fluxes and changed temperatures for the gas that is enclosed between the windows. Further changes could be obtained when using a gas that contains CO$_2$ or another participating gas: if window emissivities $\varepsilon_A \neq \varepsilon_B$ then a changing $\varepsilon_G$ for the gas changes its temperature. Thus, the heat flux for given $\varepsilon_A$, $\varepsilon_B$ and temperatures $T_A$ and $T_B$ can be controlled by varying gas emissivity $\varepsilon_G$ (taken equal to gas absorptivity $\alpha_G$) [7].

![Fig. 2. Double-glass window geometry (left) and equivalent radiation network for the window (right)](image)

These findings were applied in [8] to passive heating / cooling for buildings, where also conduction and convection heat transfer were taken into account, with further detail and progress reported in [6]. Important for the local situation in Finland are significant variations in temperature and length of day during the year, not to mention the differences in temperature between the ambient surroundings and the upper sky. This is illustrated by Table 1 that gives the ambient and sky temperatures as well as wind velocity as averaged values for February and July 2008, respectively, for Helsinki Finland. (Data obtained from the Finnish Meteorological Institute).

<table>
<thead>
<tr>
<th>Unit</th>
<th>February 2008</th>
<th>July 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{amb}$ (°C)</td>
<td>0.73</td>
<td>17.62</td>
</tr>
<tr>
<td>$T_{sky}$ (°C)</td>
<td>-7.51</td>
<td>3.67</td>
</tr>
<tr>
<td>$v_{wind}$ (m/s)</td>
<td>5.18</td>
<td>4.01</td>
</tr>
</tbody>
</table>

3. Skylight Design Optimisation
A special design for a skylight was introduced in [6] as well, with simulation results obtained with multiphysics software Comsol 4.1. The results show an increased heat flow from a room to the sky above as a result of a natural convection flow that is induced which, moreover, is enhanced by the presence of greenhouse gas CO$_2$. Fig. 3 gives simulation results for gas convection and the temperature profile, respectively, for the skylight in cooling mode during July 2008 [6]. The corresponding results for the skylight filled with air are given in Fig. 4. For all cases the width of the skylight is 0.5 m while the height is 0.1
Table 2: Cooling and insulation performance of the skylight

<table>
<thead>
<tr>
<th></th>
<th>Summer cooling (W/m²)</th>
<th>Winter insulating (W/m²)</th>
<th>Summer insulating (W/m²)</th>
<th>Winter cooling (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>117</td>
<td>966</td>
<td>88</td>
<td>883</td>
</tr>
<tr>
<td>Air</td>
<td>15</td>
<td>983</td>
<td>19</td>
<td>655</td>
</tr>
</tbody>
</table>

A much higher cooling effect is obtained with the CO₂-filled skylight with a heat flux of 117 W/m² against 15 W/m² for air. Table 2 summarises the results of the calculations.

Important features made use of here are the temperature difference that exists between the (ground level) surroundings and the sky, and as shown here, the so-called atmospheric window 8-14 μm for which the atmosphere is transparent for thermal radiation.

In a recent paper the dimensioning of the skylight was optimised using an evolutionary algorithm procedure where Comsol 4.3a is repeatedly called from Matlab [9]. An optimal geometry (i.e. height and width) for the skylight gives a maximum heat flow in cooling mode (Fig. 1–A) and a minimum heat flux in insulation mode (Fig. 1–B). A width and height of 0.90-0.92 m and 0.45 m, respectively, were found to be optimal. Special features are:

- the use of ZnS windows that offer transparency for LW thermal radiation (“normal” glass is opaque to that);
- the use of HFC-125 gas which has high emissivity / absorption for the 8-14 μm LW range which is not covered by CO₂.

Fig. 3. Velocity profile (cm/s) (left) and temperature profile (right) for a CO₂-filled skylight, cooling mode

Fig. 4. Velocity profile (cm/s) (left) and temperature profile (right) for an air-filled skylight, cooling mode
A small test set-up was built and is being tested that should allow for verifying the findings, using these special materials.

Depending on location for application, a two- or more-windowed skylight must be designed. Important design parameters are 1) opacity in one wavelength region while being (sufficiently) transparent in another, 2) the use of a participating gas that has absorption / emission bands in the long-wave thermal radiation region and, of course, 3) optimised dimensioning with regard to the height and width of the skylight.

During experimentation temperatures in the boxes and of the ambient were all logged while the temperature of the sky measured with a Kipp & Zonen CGR3 pyrgeometer (for LW, 4-42 µm thermal radiation). The data acquired showed that temperatures below ambient are indeed achievable with this set-up [10].

The mechanism behind the radiative cooling that is aimed at is that an emitter sends heat radiation to the sky that absorbs the emitted heat at lower temperatures. This heat transfer depends on both the emitter and absorber properties and the transmitting properties of the medium through which heat is radiated. As the absorbing body is the sky, and the transmitting material is air, the only property that can be improved is the properties of the emitter.

The gases used to some extent possessed the emitting properties needed, and the LDPE film presented the needed transmittance properties. However, the LDPE film lacks the weather resistance properties needed for a skylight.

5. Four-Band Thermal Radiation Modelling

With the goal to bring wavelength-dependence into the modelling and simulations, the thermal radiation bandwidth was divided into four sections: < 4 µm, 4 µm - 8 µm, 8 µm - 14 µm and > 14 µm. These represent short-wave (SW) and three bands of long-wave (LW) radiation separated by the atmospheric window, respectively.

A model for a horizontal double-glass window as in Fig. 2 was combined with a model for the atmosphere, sky and sun as given in Fig. 6, and this was solved as set of twenty-five expressions [11].

For this, four equivalent radiation networks as in Fig. 2 (right) are integrated with the network as shown in Fig. 6,
giving the network as in Figure 7: nodes J, J, J, and J in Fig. 6 are each replaced with a network as in Fig. 2. (For SW radiation, for example, node J and resistance R in Fig. 6 overlap with node J and resistance R in Fig. 2, respectively). Simulations were made for air-filled, CO2-filled (absorbing in the > 14 µm band) and HFC-125 (absorbing in the 4-8 µm and 8-14 µm bands) windows during day-time and night-time, for February and July in southern Finland. (Gas pressure is 1 bar, the optical path is 0.05 m.) The modelling expressions are given below as an Appendix.

The tables below give a comparison to wavelength-dependent thermal radiation (Q) during July, southern Finland, for these three gases, for day-time and night-time for two different windows. Window transmittance is either τ = 0.9 for SW radiation and τ = 0 for LW radiation (Table 3) or τ = 0.9 for both SW and LW radiation (Table 4).

Table 3: Four-band thermal radiation through gas filled double glass windows, Helsinki, Finland, July 90 % transparent for

<table>
<thead>
<tr>
<th></th>
<th>Q,0-4 µm (W/m²)</th>
<th>Q,4-8 µm (W/m²)</th>
<th>Q,8-14 µm (W/m²)</th>
<th>Q,&gt;14 µm (W/m²)</th>
<th>Q, total (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air, night</td>
<td>1.40</td>
<td>1.77</td>
<td>33.65</td>
<td>1.77</td>
<td>38.59</td>
</tr>
<tr>
<td>Air, day</td>
<td>-140.32</td>
<td>1.77</td>
<td>33.65</td>
<td>1.77</td>
<td>-103.13</td>
</tr>
<tr>
<td>CO2, night</td>
<td>1.39</td>
<td>1.77</td>
<td>33.65</td>
<td>1.74</td>
<td>35.53</td>
</tr>
<tr>
<td>CO2, day</td>
<td>-140.32</td>
<td>1.77</td>
<td>33.65</td>
<td>1.74</td>
<td>-103.10</td>
</tr>
<tr>
<td>HFC-125, night</td>
<td>1.39</td>
<td>1.38</td>
<td>32.37</td>
<td>1.39</td>
<td>36.53</td>
</tr>
<tr>
<td>HFC-125, day</td>
<td>-140.32</td>
<td>1.38</td>
<td>32.37</td>
<td>1.39</td>
<td>-105.18</td>
</tr>
</tbody>
</table>

Table 4: Four-band thermal radiation through gas-filled double glass windows, Helsinki, Finland, July 90 % transparent for SW and LW

<table>
<thead>
<tr>
<th></th>
<th>Q,0-4 µm (W/m²)</th>
<th>Q,4-8 µm (W/m²)</th>
<th>Q,8-14 µm (W/m²)</th>
<th>Q,&gt;14 µm (W/m²)</th>
<th>Q, total (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air, night</td>
<td>1.40</td>
<td>3.79</td>
<td>39.71</td>
<td>3.79</td>
<td>48.69</td>
</tr>
<tr>
<td>Air, day</td>
<td>-140.32</td>
<td>3.79</td>
<td>39.71</td>
<td>3.79</td>
<td>-93.03</td>
</tr>
<tr>
<td>CO2, night</td>
<td>1.39</td>
<td>3.79</td>
<td>39.71</td>
<td>3.66</td>
<td>48.55</td>
</tr>
<tr>
<td>CO2, day</td>
<td>-140.32</td>
<td>3.79</td>
<td>39.71</td>
<td>3.66</td>
<td>-93.16</td>
</tr>
<tr>
<td>HFC-125, night</td>
<td>1.39</td>
<td>2.36</td>
<td>35.53</td>
<td>2.40</td>
<td>41.68</td>
</tr>
<tr>
<td>HFC-125, day</td>
<td>-140.32</td>
<td>2.36</td>
<td>35.53</td>
<td>2.40</td>
<td>-100.03</td>
</tr>
</tbody>
</table>

It also shows that increased emissivity / absorption for the gas gives an insulating effect while expanding the wavelength range of window transmittance has the opposite effect. (Calculation results for February and for several windows transmittance wavelength bands are given in [11].)

The numbers in Tables 3 and 4 suggest that changes of a few % to up to 10% in thermal radiation heat flows can be achieved through passive, window design means. This becomes more attractive when cooling is needed during darkness, which is common at locations near the equator, such as Kenya but is less common in Finland, with very short summer nights.

6. Conclusions
A brief summary is given to R&D work at Åbo Akademi University towards a better description of thermal radiation heat transfer through gas-filled double glass and skylight windows. In-house models are combined with Comsol simulations and experimental work. Several cases show that very significant increases in (passive) cooling heat output can be achieved. Because the described passive cooling is most effective during night-time it may offer more potential for equatorial regions than for long-summer-night northern Europe, although of course clear skies are needed for taking benefit of the “atmospheric window”.

Appendix

Resistances in the radiation network for the window (note: ε, = ε, = 1 - τ) (Fig. 2)

\[
R_A = \frac{1}{\varepsilon_A} \frac{1}{A_A} \quad R_B = \frac{1}{\varepsilon_B} \frac{1}{A_B}
\]

\[
R_1 = \frac{1}{A_1} \frac{F_{12} \tau_{G1} \tau_G \tau_{G2}}{1} \quad R_2 = \frac{1}{A_1} \frac{F_{12} \tau_{G1} \tau_G (1 - \tau_{G2})}{1}
\]

\[
R_3 = \frac{1}{A_1} \frac{F_{21} \tau_{G2} \tau_G (1 - \tau_{G1})}{1} \quad R_4 = \frac{1}{A_1} \frac{F_{21} (1 - \tau_{G1})}{1}
\]

\[
R_5 = \frac{1}{A_1} \frac{F_{21} (1 - \tau_{G2})}{1} \quad R_6 = \frac{1}{A_1} \frac{F_{21} \tau_{G1} e_G}{1}
\]

\[
R_7 = \frac{1}{A_1} \frac{F_{21} \tau_{G2} e_G}{1} \quad R_8 = \frac{1}{A_1} \frac{F_{21} (1 - \tau_{G1}) e_G}{1}
\]

\[
R_9 = \frac{1}{A_1} \frac{F_{21} (1 - \tau_{G2}) e_G}{1} \quad R_{10} = \frac{1}{A_1} \frac{F_{21} (1 - \tau_{G1}) (1 - e_G) (1 - \tau_{G2})}{1}
\]

Resistances in the radiation network for the atmosphere / sky (Fig. 6):

The results given in the tables show that the model successfully produces results for four wavelength bands.
List of symbols and abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area</td>
<td>m²</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
<td></td>
</tr>
<tr>
<td>E₀</td>
<td>Blackbody radiation node</td>
<td>W/m²</td>
</tr>
<tr>
<td>F</td>
<td>View factor</td>
<td></td>
</tr>
<tr>
<td>HFC</td>
<td>Hydrofluorocarbon</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>Node identifier number</td>
<td>W/m²</td>
</tr>
<tr>
<td>J₁</td>
<td>Node “i” in equivalent resistance network</td>
<td></td>
</tr>
<tr>
<td>LDPE</td>
<td>Low density polyethylene</td>
<td></td>
</tr>
<tr>
<td>LW</td>
<td>Long wavelength</td>
<td></td>
</tr>
<tr>
<td>NH₃</td>
<td>Ammonia</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>Heat flux</td>
<td>W/m²</td>
</tr>
<tr>
<td>Rᵢ</td>
<td>Resistance “i” in equivalent resistance network</td>
<td>1/m²</td>
</tr>
<tr>
<td>SW</td>
<td>Short wavelength</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>v</td>
<td>Velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>ZnS</td>
<td>Zinc sulphide</td>
<td></td>
</tr>
<tr>
<td>α</td>
<td>Absorptivity</td>
<td>-</td>
</tr>
<tr>
<td>ε</td>
<td>Emissivity</td>
<td>-</td>
</tr>
<tr>
<td>λ</td>
<td>Wavelength</td>
<td>m</td>
</tr>
<tr>
<td>ρ</td>
<td>Reflectivity</td>
<td>-</td>
</tr>
<tr>
<td>τ</td>
<td>Transmittance</td>
<td>-</td>
</tr>
</tbody>
</table>

Subscript

| A      | Left side, Room |       |
| Air    | Air |       |
| Amb    | Ambient |       |
| B      | Right side, Sky |       |
| G      | Gas |       |
| G₁, G₂ | Glass, window 1, 2 |       |
| R      | Thermal radiation |       |
| Sky    | Sky |       |
| Wind   | Wind |       |

Acknowledgement

This work is funded by Maj and Tor Nessling Foundation projects 2009301, 2010362 and 2011285 and 2012310 “Solar heat engineering and carbon dioxide: energy recovery using a greenhouse gas”, the Foundation for Åbo Akademi University and Erkki Paasikivi Foundation. Luís P. Gomes, visiting from Coimbra, Portugal in 2012 is acknowledged for highly valuable support and contributions. R.Z. acknowledges Åbo Akademi University for partial funding for travel to Kenya in April 2013. Finally, the anonymous reviewer is acknowledged for a sharp assessment.

References