Passive cooling against the (night) sky
Ron Zevenhoven and Martin Fält

**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

I. 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.

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.

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 [1]. Typical dimensions are a height of 0.1-0.5 m, a width of 0.5-1 m.

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

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 increases, and it will flow back down 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.

II. 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 CO₂ filling the spacing between the windows. Gray media were assumed, which assumes thermal radiative properties of materials (emissivities ε, absorptivities α, transmissivities τ and reflectances p) independent of wavelength. The geometry for the window is given in Fig. 2, with the the equivalent radiation network for this system (where nodes J₃ and J₄ represent the left-hand and right-hand side window, and E₉G gives the blackbody radiation from/to the enclosed gas) as in Fig. 3.

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 CO₂ 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 $\alpha_G$).

These findings were applied in [3] to passive heating / cooling for buildings, where also conduction and convection heat transfer were taken into account, with further detail and progress reported in [1]. 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 I 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 I

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

### Table II

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

**III. Skylight Design Optimisation**

A special design for a skylight was introduced in [1] 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 CO₂. Figs. 4 and 5 give simulation results for gas convection and the temperature profile, respectively, for the skylight in cooling mode during July 2008 [1]. The corresponding results for the skylight filled with air are given in Figs. 6 and 7. For all cases the width of the skylight is 0.5 m while the height is 0.1 m.
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 [4]. 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.

Currently, a small test set-up is being built 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.

IV. LW THERMAL RADIATION MEASUREMENTS

During spring/summer 2011, a parallel set-up was built and used for measuring thermal radiation heat exchange of a contained gas with the atmosphere and sky. Using a thin plastic (LDPE) foil cover, heat exchange with air in one box was compared with heat exchange with CO₂ or NH₃ gas in the other. The set-up is shown in Fig. 8.

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 trough 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.

V. 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. 9, and this was solved as set of twenty-five expressions [6]. (For this, four equivalent radiation networks...
as in Fig. 3 are integrated with the network as shown in Fig. 9: nodes J1, J2, J3 and J4 in Fig. 9 are each replaced with a network as in Fig. 2: for SW radiation, for example, node J1 and resistance R1 in Fig. 9 overlap with node J2 and resistance R2 in Fig. 3, 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 tables below give a comparison to wavelength-dependent thermal radiation (Q_R) during July, southern European countries are expected to achieve more potential for equatorial regions than for long-summer-night northern Europe.

VI. CONCLUSION

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.

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. Luis P. Gomes, visiting from Coimbra, Portugal in 2012 is acknowledged for highly valuable support and contributions. R.Z. acknowledges Åbo Akademi University for partial travel funding.

REFERENCES