Excerpt from the Proceedings of the 2011 COMSOL Conference in Boston

Modeling a Cooling Skylight

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Abstract: Air-conditioning produced by traditional vapor compression cycle is an energy demanding operation. By using passive cooling methods is it possible to avoid, or at least reduce, the need for vapor compression cooling.
A passive radiative cooling method could be a three windowed skylight, filled with a greenhouse gas.
Earlier modeling of such a skylight has shown promising results, and work has now continued with experiments. To produce experimental results a parallel set-up was built that allowed for the testing of different material properties. These results have then in turn been modeled using Comsol 4.2.

Keywords: radiative cooling, heat transfer in participating media, skylight.

1. Introduction

By filling the volumes in a three windowed skylight, Figure 1, with a gas which both absorb and emit heat radiation it is possible to controllably provide a room with cooling or thermal insulation when needed. The participating gas in the skylight works as the heat carrier of the system when the skylight is in its cooling mode, Figure 1A, and as a heat barrier when in the insulating mode, Figure 1B. This means that when in cooling 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 to gas layer 2. Here, the gas is cooled down by radiative cooling which 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, the thicknesses and the temperature differences will be so small that convective swirls will not be formed; consequently, forming an isolating barrier.

Comsol 4.1 was used to assess the cooling and insulating performance of the skylight at different weather circumstances in [1]. The results from the modeling with Comsol 4.1 show that a cooling effect of around 80 W/m^2 can be obtained if the two modes are compared to each other during typical summer conditions in southern Finland. A first attempt to verify calculations/simulations like this has resulted in a simple experimental set-up which in turn has been modeled with Comsol 4.2.

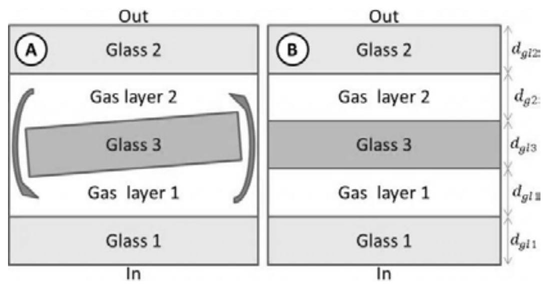

Figure 1 Skylight in cooling mode "A" and in insulating mode "B"

2. Experimental

As results from the modeling were promising work continued, with experiments. A picture of the built test equipment can be seen in Figure 1.

Figure 2 Parallel set-up for passive cooling experiments.

A parallel set-up was built so that different material combinations could be evaluated during equal weather conditions. The materials that have been varied are the gas, cover material, insulation and the emitting properties of the wall.

During experimentation temperatures of the boxes and the ambient were all logged with Testo´s 175T1 that has an accuracy of ±0.5°C (-35°C to 55°C). The temperature of the sky was in turn measured with CGR3 pyrgeometer from Kipp & Zonen that has a sensitivity of 16.57µv/Wm^2.

The data acquired from the experiments showed that temperatures below ambient are achievable with this set-up which is yet far from a finished commercial product.

The mechanism behind radiative cooling 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 also 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. In the experiments, CO_2 and NH_3 gases were used as emitters. These gases were confined in a box which has a thin polyethylene (PE) film facing the sky. These gases possessed partially the emitting properties needed, and the PE film presented the needed transmittance properties. However, the PE film lacks the weather resistance properties needed for a skylight. Experimental results can be seen in Figure 3 and Figure 4.

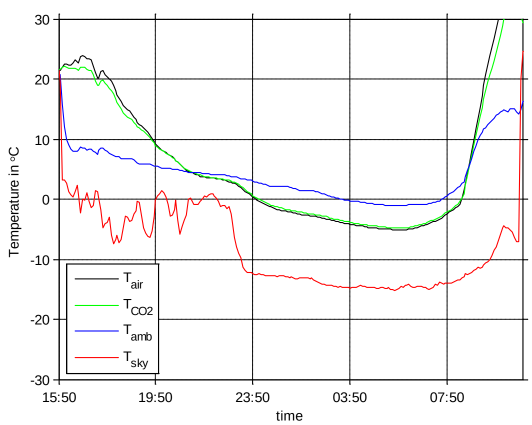

Figure 3 Carbon dioxide experiment 21.4.2011

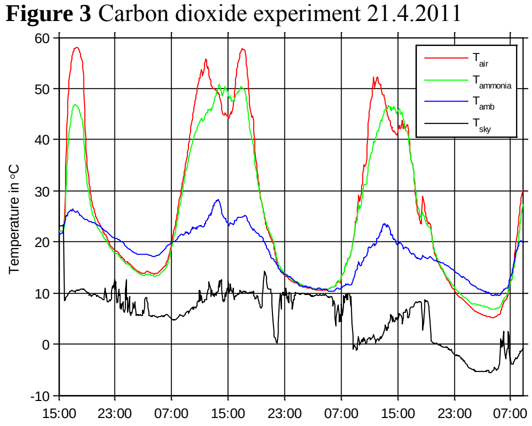

Figure 4 Ammonia experiment 3.6.2011

3. Use of COMSOL Multiphysics

As the material performances during experimentation were unsatisfying, the question that arises from this is why? The result that was expected from the experimental work was that a gas with higher emitting properties would reach a lower temperature than air, as it does not emit heat radiation at these conditions. To answer this question it was decided to use Comsol 4.2 to model one single event in one of the experiments. The data that was chosen was the carbon dioxide experiment presented in Figure 3. The time chosen for experimentation is when the sky temperature reaches its lowest value that is at 5.35 am. The logged temperatures from that time can be seen in Table 1.

Table 1 Temperatures logged at 5.35 am on 4.21.2011

[°C]	T_{amb}	T_{sky}	T_{CO2}	T_{air}
5.35am	-1.1	-15.15	-4.80	-5.1

The temperatures of the ambient and of the sky are used as input values for the Comsol 4.2 models, and the temperatures of CO_2 and air are those to be modeled.

As all the different heat transfer methods are both present and equally important is it impossible to simplify this problem and leave out, for instance, heat radiation. This makes this problem computationally heavy, and therefore, it is done only in 2 dimensions. The case has been evaluated as a time-dependent study so that unstable equilibrium points are avoided. The different physic models that are used are the heat transfer module in participating media and the laminar flow module.

Figure 5 shows the model and the different materials that it is constructed of. It is to be noted that T_{gauge} is the physical location of the temperature gauge in the experimental work. Thus, the average temperature of the modeled T_{gauge} is comparable to the measured temperature in the experiment.

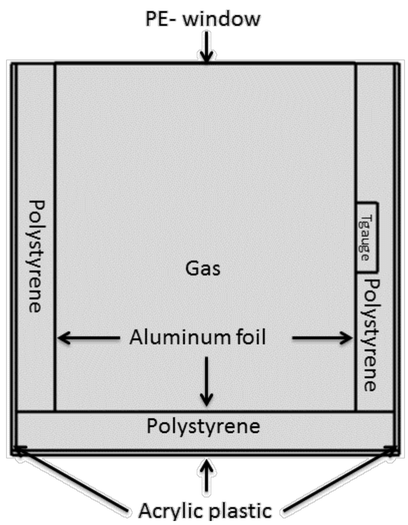

Figure 5 Experimental application

The box is subjected to two different heat flows. The first is the radiative cooling that is a "surface to ambient radiation", this boundary condition is applied to the upper surface of the PE-window. Here, the "ambient" temperature for radiation is set to be the measured sky-temperature. The second heat flow is the forced convective heat flow that is the wind, a wind speed of 4 m/s is assumed.

Other properties that are interesting are the radiative properties of the material. The PE-film is assumed to have a $\tau=1\ m^{-1}$, [2]. The aluminum foil is assumed to have and absorptance of $\alpha=0.04$ [3] and CO_2 was calculated to have a total absorptance of $\alpha=0.16$ [4]. However, as the temperature of the CO_2-filled box was about the same as the air-filled box the question of wave-length dependency needs to be assessed. For an object to be cooled by radiative cooling needs it to emit heat radiation in the ~8-13µm interval; this internal depends on such weather condition as cloudiness and air moisture. As CO_2 emits only some heat in this interval is a case also simulated where CO_2 has no absorptance, $\alpha=0$.

4. Results

The temperatures predicted by the models are somewhat higher than those measured in the experiments. A reason for this could be that the emittance of the aluminum foil is higher than assumed. The different temperatures can be seen in Table 2 where the measured experimental temperatures can be compared to T_{gauge}. The difference between the actual temperature of the gas and that of the gauge seems to be of significance.

Table 2 Temperatures modeled after 1500 seconds

[°C]	T_{amb}	T_{sky}	T_{air}	T_{CO2} (α=0)	T_{CO2} (α=0,16)
Exp.	-1.1	-15.15	-5.1	-4.80	-4.80
T_{gauge}	Input	Input	-4,50	-4,50	-4.42
T_{gas}	Input	Input	-5,32	-5,43	-5.27

The modeling predicts that the CO_2-gas that absorbs heat radiation has a higher temperature than the gas that does not. This effect can also be seen in Figure 6 that presents the results from a parametric sweep. Here, the gauge temperature increases as the absorptance of the gas increases until it reaches a level of 268.5 Kelvin.

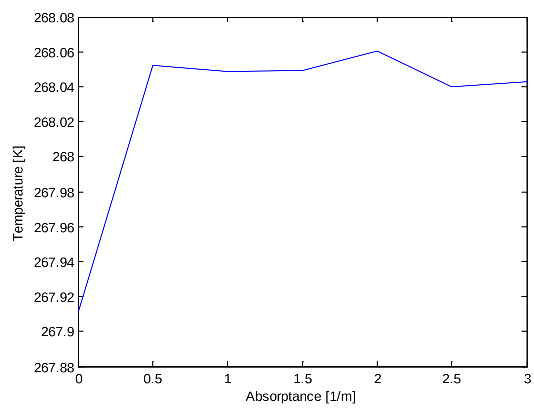

Figure 5 Gauge temperatures at different gas absorptance values.

From these results, one can determine that improvements on the experimental setup are needed so that more conclusive data can be obtained. Improvements could be done to decrease the absorptance of the walls. This could decrease temperature variances in the vertical direction, as we can see in Figure 6. However, of more importance would be to increase the amount of insulation to decrease the temperature difference between that of the actual gas temperature and what is measured. This can also be seen in Figure 6 where temperature gradients are formed in the insulating material.

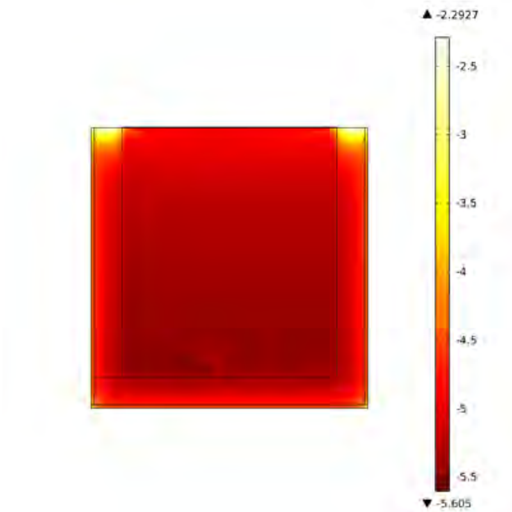

Figure 6 Temperature profile of CO_2 box when α=0.16 in °C.

5. Conclusions

Radiative cooling is an untapped source of energy with great potential. A preliminary study of this potential for northern Europe was made in [5]. This knowledge was in turn put to use in [6] and [1] that presented an option for using radiative cooling in an adaptive skylight.

Modeling heat radiation in participating media is somewhat complicated, and resource demanding. It has only been possible in Comsol 4.X. Considering this, Comsol gives good suggestions how to continue with one's research.

6. References

1. M. Fält, R. Zevenhoven, Combining the radiative, conductive and convective heat flows in and around a skylight, *Journal of Energy and Power Engineering*, Submitted after invitation to submit WREC-2011conference paper, (2011)

2. A.H. Youssef, M.R. Ismail and M.A.M. Ali, Studies on sugarcane bagasse fiber-thermoplastics composites, *Journal of Elastomers and Plastics*, **41**, 245-262, (2009).

3. J.R. Howel, R. Siegel, M.P. Mengűç, *Thermal Radiation Heat Transfer 5th edition*, 874, CRC Press, London (2011)

4. J.R. Howel, R. Siegel, M.P. Mengűç, *Thermal Radiation Heat Transfer 5th edition*, 460-466. CRC Press, London (2011)

5. M. Fält, R. Zevenhoven, Radiative cooling in northern Europe for the production of freezer temperatures, *conference proceedings of ECOS-2010*, paper 208, (2010)

6. M. Fält, R. Zevenhoven, Radiative cooling in northern Europe using a skylight, *Journal of Energy and Power Engineering,* **5**, 692-702 (2011)

7. Acknowledgements

This work is funded by Maj and Tor Nessling Foundation projects 2009301, 2010362 and 2011285 "Solar heat engineering and carbon dioxide: energy recovery using a greenhouse gas", and the Foundation for Åbo Akademi University.