Experimentation and modeling of an active skylight

Martin Fält[a], Ron Zevenhoven[b]

[a] Åbo Akademi University, Thermal and Flow Engineering Laboratory, Turku, Finland,martin.falt@abo.fi
[b] Åbo Akademi University, Thermal and Flow Engineering Laboratory, Turku, Finland,ron.zevenhoven@abo.fi

Abstract:

Simulations and calculations suggest that cooling as well as insulation can be obtained using a skylight containing the gas pentafluoroethane (HFC-125) between two zinc sulfide (ZnS) windows. The change from cooling to insulation is accomplished by controlling the fluid flow inside the skylight. This article verifies this concept by experimentation and compares using HFC-125 to the use of carbon dioxide (CO_2) and air. For this work, a miniature model (10×10×10 cm^3) of the intended skylight and a suitable "room" were built for testing. The skylight was first designed and analyzed in the Multiphysics tool Comsol. The simulations verified to what dimensions the set-up should be constructed. During experiments, temperatures inside and outside of the test rig were recorded with additional weather data. This information could then be compared and used in simulations. These measurements show that indeed temperatures below that of the ambient surroundings were achieved during night-time. In practice, this may be used for passive cooling of buildings, reducing costs for air conditioning and temperature control.

Keywords:

Radiative cooling, Skylight, HFC-125, ZnS, CO_2, Air.

1. Introduction

1.1. Background and Scope

This paper describes the experimental work that validates previous modeling work on the cooling and insulation possibilities of a skylight (a horizontal roof window) [1-6]. Cooling, even to temperatures below that of the ambient, is made possible by radiating excess heat to cold air masses situated above the skylight i.e. to the sky. This cooling is made possible with materials that decrease heating by the ambient and increase heat transfer between the room and the cold sky. The control between cooling and insulation effects is achieved by altering the heat transfer mechanism inside the skylight. The skylight, as seen in Fig. 1 is filled with a participating ("greenhouse") gas and is divided into two connected compartments. The gas acts like the fluid in a heat exchanger, as it flows by natural convection from one compartment to the other it transports heat from the room to the sky. When cooling is no longer needed, or attainable is this fluid flow cut, and an insulator is created. By utilizing such a skylight savings in the energy use of buildings, primarily for cooling, can be realized.

The theories to assess are: can suitable materials be found, and can temperatures below the ambient be obtained. To validate these theories and previous modeling work three types of experiments were set up. First the radiative properties of the skylight were tested using a thermal imaging camera. Then the gases ability to act as a thermal radiation absorber/emitter was studied and then finally the windows ability to cool a miniature room was assessed.

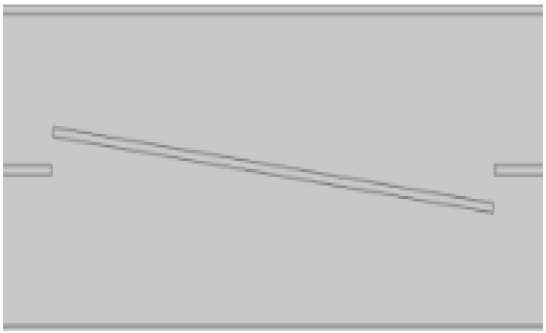


Fig. 1. Schematic layout of the proposed skylight [4].

1.2. Materials selection

Selecting a suitable material for the upper and lower windows is crucial for this skylight system. The window needs to be transparent in the wavelength interval where the so-called “atmospheric window” in the infrared is located (8-14 µm) and (of course) in the range of visible light (0.3-0.7 µm). Studies on radiative cooling have used polyethylene (PE) as a cover material to insulate a radiator from the ambient [3, 7]. The problem with the PE films has been that they need to be thin to be transparent to longwave thermal radiation, and thus become fragile. Therefore, tougher alternatives have been identified such as PE mesh, zinc selenium (ZnSe), calcium fluoride (CaF_2), standard and multispectral ZnS [8, 9]. Of these materials, multispectral ZnS is most suited for our application. Therefore, the skylight proof-of-concept prototype consists of two windows made of a commercial product ZnS Cleartran. This product is transparent to both visible light and longwave heat radiation. The center window in Fig. 1 is only transparent to visible light and thus works as a radiative shield that averts the room from being directly cooled by radiative cooling. This center window thus enables the control between cooling and insulation. The change between cooling and insulation is obtained by rotating the center window in Fig. 1, thus connecting or separating the radiatively cooled upper compartment with the lower compartment heated by the room.

The gas that occupies the skylight needs to have a high emissivity in the region of the infrared atmospheric window. The gas can radiate heat from the room to air masses situated well above the skylight at temperatures below the ambient. Earlier research has shown how gases can interact with longwave heat radiation (>4µm) in windows [10-13]. The problem with the applied gases is that they are either illegal, flammable, toxic or do not give the effect needed here. A candidate for use in the skylight was found to be HFC-125 [4, 6]. This gas is used here and compared to the weaker greenhouse gas CO_2, besides air.

In Fig. 2, the wavelength properties of the sky, HFC-125 gas (1m, 1 bar and 20°C) and the multispectral ZnS window are all presented. This figure shows how the HFC-125 gas can radiate heat almost unhindered through the ZnS window to the cold air masses situated inside the atmospheric window (8-14µm) region.

The results from the experimentation have confirmed that the materials used are suitable for usage in the skylight concept. Temperatures below the ambient are attained in the skylight and then finally cooling with the skylight is possible as presented in the following sections.

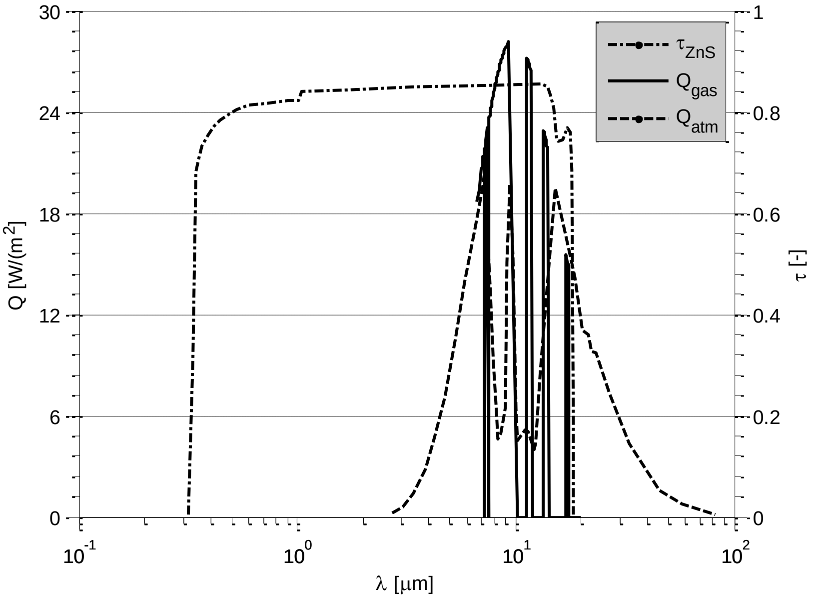


Fig. 2. ZnS Cleartran [14] and Solar and atmospheric radiation absorption by HFC-125 [15].

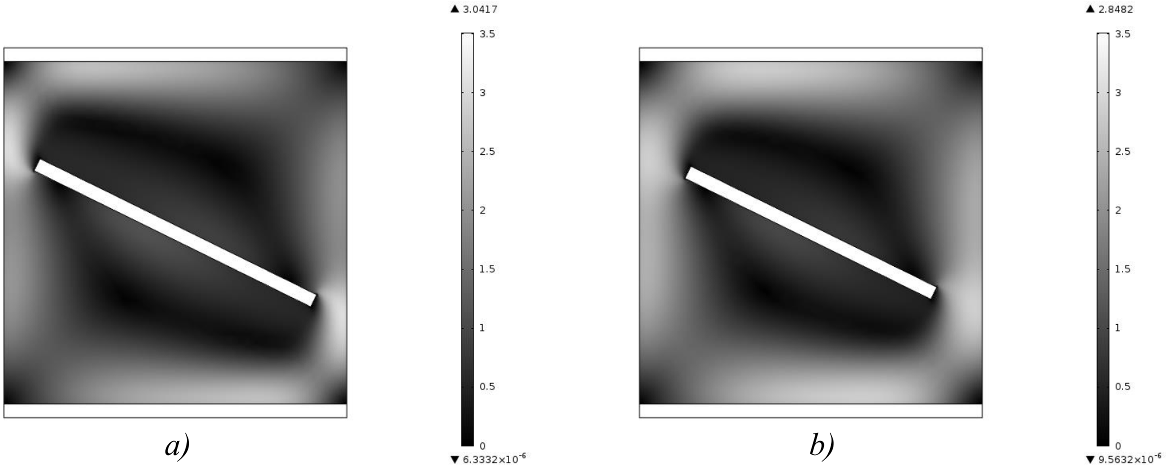
2. Simulations

Since the price of ZnS windows used is relatively high, was there a need to keep the size of the test-rig at a minimum while still obtaining sufficiently relevant results. Simulations were therefore performed prior to the construction of the rig, as to assure that the prototype would function as intended. Simulations were made in 2D as the calculations are computationally heavy. The preliminary idea was that the skylight should consist of a cube with sides of 10 cm. This cube would then be divided into two compartments with a third opaque window that is 10% shorter than the side of the cube, allowing it to move and be adjusted.

The preliminary simulations for the design of the skylight were performed using the Multiphysics tool Comsol 4.3b. Here the calculations were done using the built-in physics node for non-isothermal flow. As the simulated problem was found to involve turbulent flow, the simulations were solved using the k-ω turbulent model. Since the flow and the heat transfer are coupled the dispersion of heat transfer due to turbulence was taken into account via the Kays-Crawford heat transport turbulence model. The discrete S4 ordinate method is used to solve the radiative transfer in the participating media. The simulations of the experiments were performed with Comsol 5.0. Due to updates in the software the simulations were set up in a slightly different way than in the preliminary simulations. The final model uses two built-in physic nodes: laminar flow and heat transfer in fluids. The selection of laminar flow was made based on the finding that the flow was laminar. The discrete S4 ordinate method was also used to solve the radiative heat transport model.

The material properties of HFC-125 were obtained from [16-18], the properties of ZnS were found from [6, 14], the radiative properties of CO_2 were taken from [19] and the rest of the material properties of CO_2, air and acrylic plastic were taken from Comsol´s internal library,

The preliminary simulations for the design showed that cooling is attainable and that the intended flow does arise. However, as the velocity changes significantly (40%), when it passes the narrow gap between the wall and the middle window, a change was needed. The gap size was increased by decreasing the width of the middle window so that it is 80% of the width of the skylight instead of the 90% that it was initially. The results from the reduction can be seen in Fig. 3, where the original skylight is presented to the left, and the adjusted on to the right. The speed reduces now only by 24%, and thus the middle window was constructed to be 8 cm wide.



a) *b)*

Fig. 3. Velocity profiles in [cm/s] with: a) 9 cm wide middle window; b) 8 cm wide window.

3. Experimental Section

To test theories described in section 2 was a miniature skylight constructed. It is built from 6 mm thick acrylic plastic side walls and two 4 mm thick ZnS windows for the top and bottom. The joints between the box and the ZnS window are made gastight by using a gasket sealant and compression by bolts and rods. The two ZnS windows contain the gas HFC-125 inside the skylight. In the middle of the window, a third window of acrylic plastic can be placed so that the flow can be controlled.

3.1. Material suitability

In the first set of experiments, a thermal imager (Fluke Ti9) was pointed to look through the skylight at a beaker of water heated to 40°C; as seen in Fig. 4. In this experiment, the middle window was removed as the thermal imager cannot see through acrylic plastic as it can see through the ZnS windows. The effects of the air, CO_2, and HFC-125 were studied. During the experiment, the temperature of the ambient (laboratory), the water, and the gas were all measured.

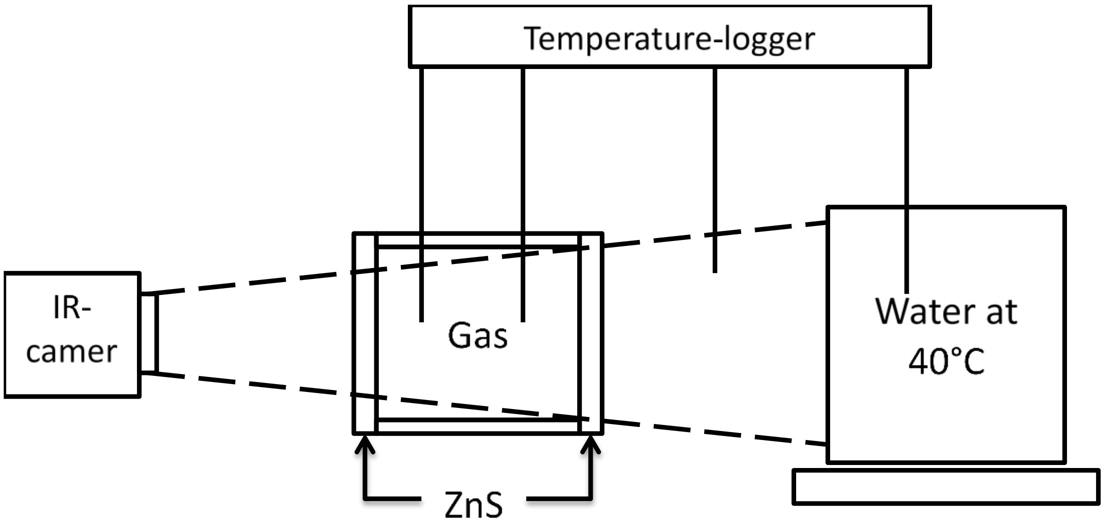


Fig. 4. Experimental setup for material suitability testing.

3.2. Cooling to temperatures below ambient

In the second set of experiments, the skylight was subjected to the sky. For this, the skylight, without the center window, is mounted on top of a temperature controlled box, simulating a room. The outer walls and bottom of the box are made of plywood. The roof is made of a 10 cm thick polyurethane layer. The room walls and the floor are insulated with a 10 cm thick insulation layer. The thermal conductivity of this insulation material is λ= 0.023 W/(m•K). Copper tubing is cast on top of the insulation layer with self-leveling mortar. Water from a temperature controlled water bath can be pumped through the copper piping in the floor to control the "room" temperature. The resulting floor area is approximately 0.5 m × 0.6 m = 0.3 m^2. The mass of the room is 84.5 kg, the outer width is 84 cm, and the outer length is 63.6 cm, its height 62 cm, and the thickness of plywood is 17 mm.

The room insulates the skylight from the ambient as it is not heated in this experiment. This insulation increases the significance of the radiative heat transfer between the skylight and the sky. The test consisted of three parts that all lasted for three hours. During each period, one gas was evaluated, starting with CO_2, followed by air and then finally HFC-125.

During experimentation temperature changes in and around the skylight were logged using six J-type thermocouples. These temperatures were those of the upper and lower ZnS windows, two temperatures inside the skylight, the temperatures of the ambient and the miniature room. Moreover, weather data from a weather station (http://at8.abo.fi) located a few meters from the test set-up on the roof of the laboratory, and downward atmospheric longwave radiation data from a pyrgeometer (CGR3, Kipp&Zonen), were also used.

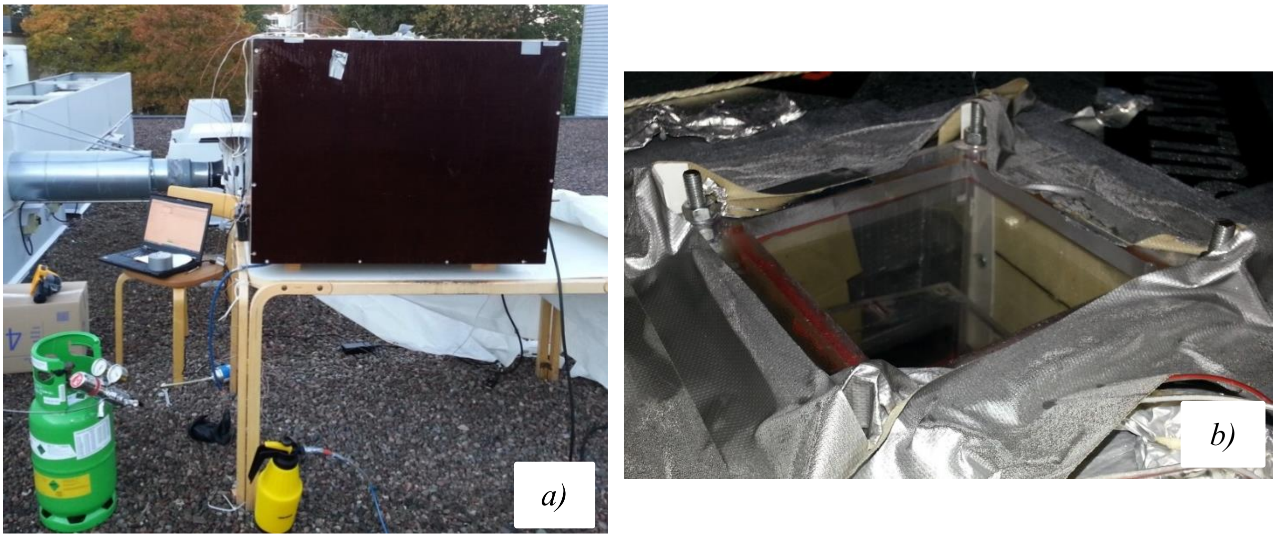


Fig. 5. Experimental set-up for the second and third set of experiments: a) the total set-up, showing the dark side wall of the "room";b) the skylight top window in the "room".

The obtained temperatures can then be compared against simulations with Comsol 5.0 were heat flows had been calculated.

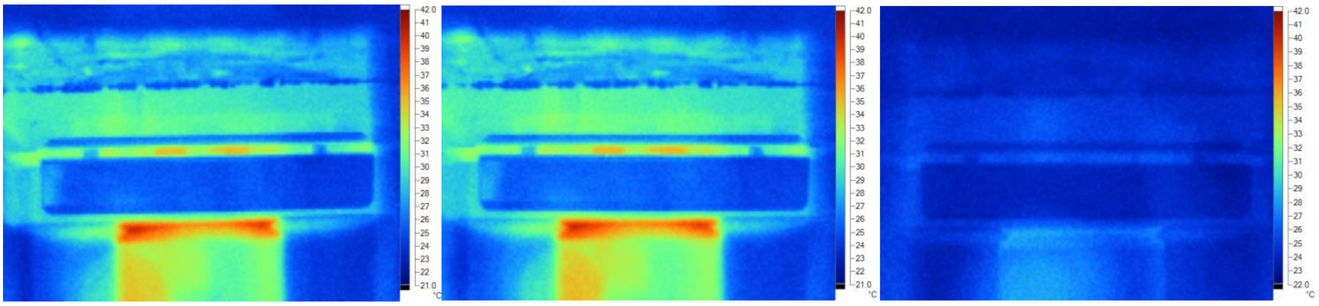
3.3. Cooling of the room

In the final experiment, the skylights cooling ability of a heated room was evaluated. For this set of experiments, the center window was installed inside the skylight at an angle of 10 °. The skylight is mounted on top of a room. Water from a temperature controlled water bath is pumped through the copper tubing inside the room's floor to control its temperature. The temperature of the water bath was set to 5°C above the ambient at the beginning of the experiment. The gas in the skylight was again changed every three hours, between air and HFC-125. During the experimentation, the temperatures of the room, ambient, water bath, lower and upper ZnS windows, lower and upper compartments of the skylight were all logged. Moreover, data from a pyrgeometer and weather station was also used.

4. Results and Discussion

4.1. Material suitability

The results from this set of experiments confirmed that longwave heat radiation from the beaker could be clearly seen with a thermal imager through the skylight when it is filled with air; CO_2 decrease the transmissivity slightly and HFC-125 substantially. Results from this first set of experiments can be observed in Fig. 6 where the thermal imager pictures are presented.



a) *b)* *c)*

Fig. 6. Thermal images of the skylight filled with: a) air; b) CO_2; c) HFC-125.

The difference between air and CO_2 is small. However, the effect of HFC-125 is significant. The differences between the gases are presented in an alternative form in Fig. 7. This graph displays the number of pixels observed at a particular temperature in each picture. The change in HFC-125 significantly compresses the observed temperatures to a more narrow temperature range. This implies that the HFC-125 gas acts as radiative shield while the effects of CO_2 and air are small. During the experimentation, the temperatures of the water glass, box and the ambient were logged using J-type thermocouples. Temperature measurements with thermocouples show that the temperature of the water was 42°C; the temperature of the different gases inside the window was 26°C, the ambient temperature 24°C. The peak on the left in Fig. 7 corresponds well to the combination of the ambient and the temperature inside the window. The temperature peak, on the right in Fig. 7 mainly originates from the area around the heat plate and the glass of the water beaker.

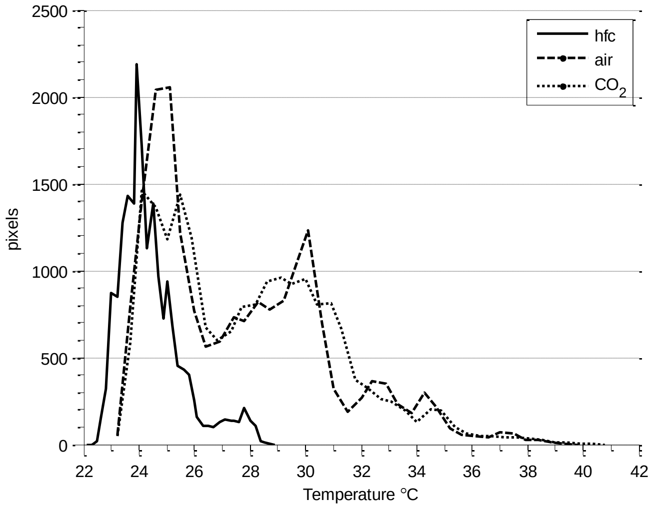
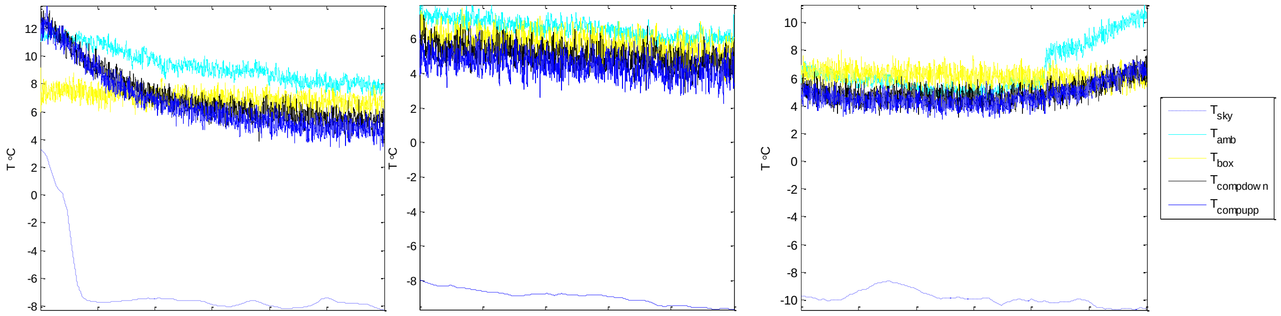


Fig. 7. The number of pixels in the pictures in Fig. 6 taken with the thermal imager at a particular temperature.

4.2. Cooling to temperatures below ambient

In the second set of experiments, the gases were subjected to the sky using the skylight prototype. The first gas tested was CO_2 followed by air and then finally HFC-125. The temperature inside the skylight was measured at two locations. Since the temperatures logged with the J-couples were noisy, was the data filtered using a third order polynomial Savitzky-Golay filter with a frame size of 59 seconds. The temperature of the sky is calculated from the data obtained from the pyrgeometer.

Fig. 8a presents the results of the experiment with CO_2. Two major events are happening at the beginning of the experiment that make the temperatures vary; these are sunset and the cooling of the skylight and pyrgeometer as they were brought out from the lab onto the roof of our laboratory.



a) *b)* *c)*

Fig. 8 Temperature profiles from the experiment with: a) CO_2; b) Air, c)HFC-125.

During the night, the gas was changed from CO_2 to air. This was accomplished by purging the skylight with compressed air. The temperatures measurements from the experiment are presented in Fig. 8b. The temperature inside the skylight is now on an average 2°C lower than the ambient.

In the final part of this set of experiments, the gas was changed from air to HFC-125. Fig. 8c presents the results of the temperature measurements. As this is the final test of the night, with the sun rising at 7:40 o'clock, some notable temperature changes are observed around this time.

From these three experiments, four different moments from the night were selected to be simulated using Comsol 5.0. The measured values function as input values and as a reference for comparison. The logged temperatures and those simulated are presented in Table 1. It can be noted that the temperatures inside the skylight compare relatively well with those simulated. The difference between the gases can best be noticed in the heat flow, Q_{tot}, through the skylight ($Q_{tot} < 0$ implies heat from the simulated room to the sky). As CO_2 and air hardly absorb heat radiation will the skylight radiate heat unhindered to the sky and thus the total heat flow is smaller for HFC-125.

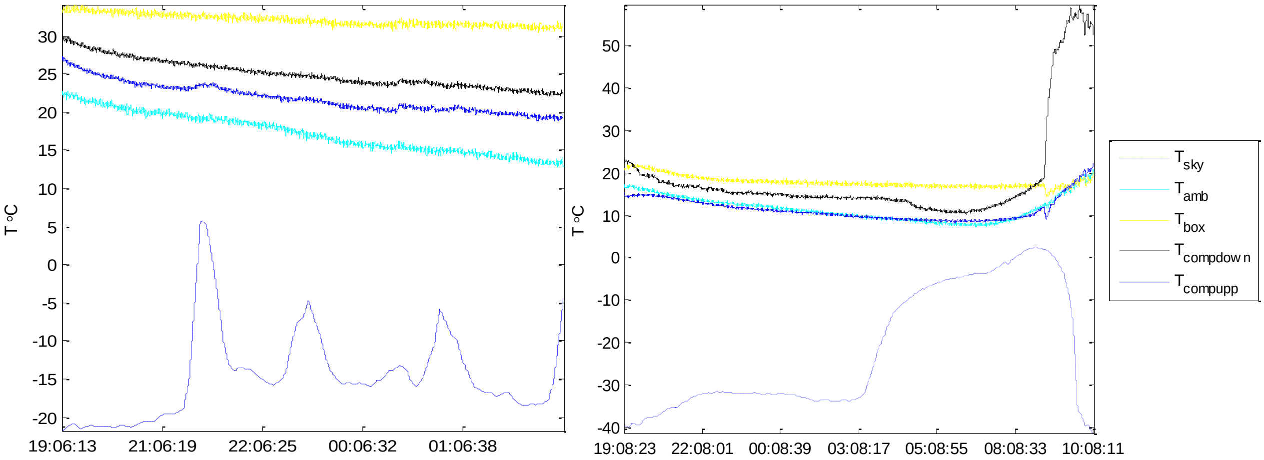
Table 1. Temperature measurements and simulation results for the selected time.

Figure	8a	8b	8c	8c
time	22:30	2:15	3:50	6:15
T_{room}	6,79	5,36	6,17	5,85
T_{sky}	-7,42	-9,43	-10,00	-9,87
T_{amb}	7,99	6,12	6,21	5,45
v_{wind}	2,65	2,16	1,69	1,58
gas	CO_2	Air	HFC-125	HFC-125
$T_{gas\ measure\ upp}$	4,75	3,91	4,48	3,77
$T_{gas\ measure\ down}$	5,75	4,65	4,08	4,61
$T_{gas\ simulation\ upp}$	2,33	1,30	4,07	3,58
$T_{gas\ simulation\ down}$	3,32	2,26	4,04	3,58
Q_{tot}	-157,95	-151,28	-148,17	-137,66

4.3. Cooling of the room

To be able to change between cooling and insulating the third window is installed. This is done in the final set of experiments were its cooling ability is evaluated. Four experiments with HFC-125 and one with air were performed with the middle window installed. No experiments were made with CO_2 as no difference was observed in the first two set of experiments between CO_2 and air.

In the first experiment, the skylight was filled with HFC-125 and the water-bath is set to 35°C, which was 5°C warmer than the box simulating the room initially was. The test is configured to run for the whole night. However, logging stopped already at 3 am. The logged temperatures are presented in Fig. 9a. The radiative cooling effect can be observed from the temperature of the upper compartment temperature as a sudden increase is observed when the sky temperature increases significantly just after 9 pm. Temperatures below that of the ambient were not obtained inside the skylight as the room temperature was apparently too high.

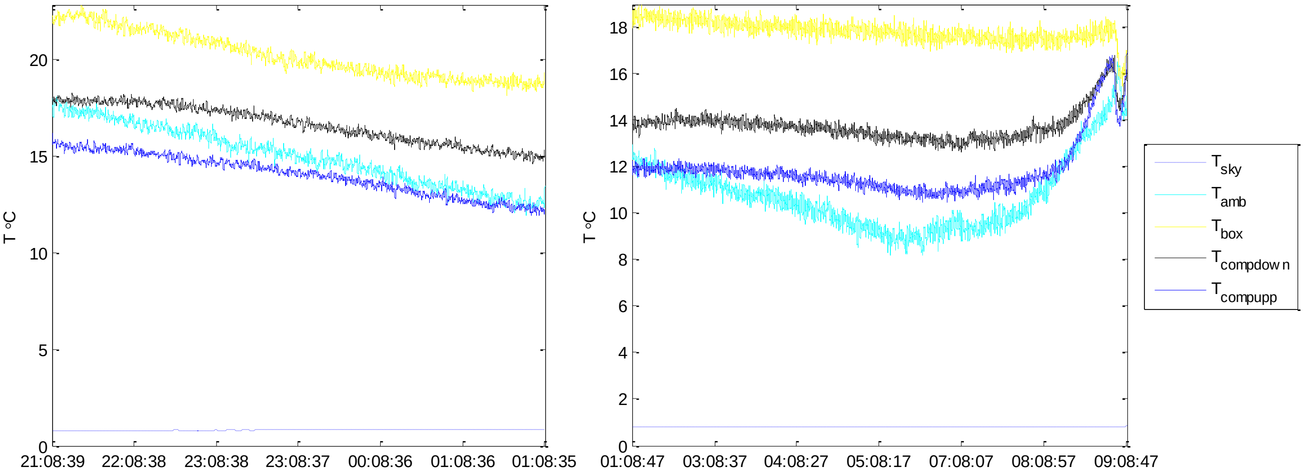


a) *b)*

Fig. 9. HFC-125 experiment with the room heated to: a) 35°C; b) 20°C.

In the next experiment, the temperature of the room was again set 5°C above the temperature of the box at the beginning of the experiment. In this case, the temperature was set to 20°C. The effect of clouds can be seen clearly in Fig. 9b affecting the sky temperature from 3 to 10 am..

The temperature of the box was again set to 5°C above the ambient temperature. However, instead of using HFC-125 as utilized in the experiments described in Fig. 9a and Fig. 9b air was used in Fig. 10a. The temperature in the upper part of the skylight even drops to temperatures below the ambient.



a) *b)*

Fig. 10. Experiment with a heated room with the skylight filled with: a) air; b) HFC-125.

During the night, the gas was changed from air back again to HFC-125 so that comparable results could be obtained. As can be seen in Fig. 10a, the temperature difference between the ambient and the temperature inside the skylight, becomes smaller, until the moment the gas is changed from air to HFC-125 for which the results are given in Fig. 10b.

In the final experiment presented in Fig. 11, the floor heating was switched off. This resulted in that the temperature of the box dropped slowly during the experiment. The temperature of the skylight´s upper compartment follows the temperature of the ambient.

Then as in the section 4.2 a number of moments in time were selected from the experiments for further evaluation using Comsol 5.0. The simulated temperatures follow quite well the measured ones with the exception of the experiments described by Fig. 9b and 10a. The heat flow through the skylight varies with weather (including cloud coverage of the sky). This can be seen clearly in the heat flow difference between the two moments simulated from Fig. 11 with significantly different sky temperatures. It can also be noted that the presence of the middle window seems not to affect the cooling capacity of the skylight. This middle window is in a central role for the skylight as it makes the change from cooling to insulating possible.

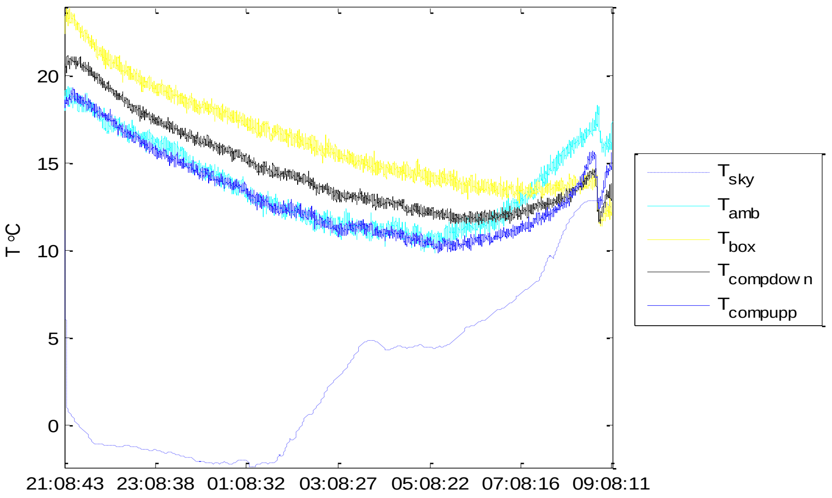


Fig. 11. Final HFC-125 experiment.

Table 2. Temperature measurements and simulation results for the selected time.

Figure	9a	9b	10a	10b	11	11
time	01:00	03:10	01:40	05:45	1:20	5:00
T_{room}	32,09	17,69	18,65	17,57	17,40	14,54
T_{sky}	2,03	-7,94	0,81	0,81	-2,01	4,39
T_{amb}	14,95	9,87	12,36	9,00	13,37	-0,57
v_{wind}	2,21	0,51	0	0	0,84	0
gas	HFC-125	HFC-125	Air	HFC-125	HFC-125	HFC-125
$T_{gas\ measure\ upp}$	20,39	9,60	12,36	11,00	13,50	10,40
$T_{gas\ measure\ down}$	23,99	13,95	15,03	13,16	15,19	12,13
$T_{gas\ simulation\ upp}$	24,25	7,16	11,32	11,63	13,56	10,38
$T_{gas\ simulation\ down}$	25,38	9,811	13,75	12,46	14,23	11,45
Q_{tot}	-131,68	278,24	-90,16	-66,85	-146,8	-8,39

4.4. Discussion

To validate previous modeling work on the performance of the skylight [1-6], three different types of experiments were set up, completed, and analyzed. In the first set of experiments, the radiative properties of the skylight were tested using a thermal imaging camera. These experiments revealed the transparency of the skylight´s ZnS windows to longwave heat radiation and the influence different gases had on this transparency. Of the studied gases, HFC-125 showed to decrease significantly the transparency of the skylight. Thus, HFC-125 possesses appropriate properties for the intended skylight. Namely, the gas absorbs and emits longwave thermal radiation at the designed skylight dimensions.

The next two sets of experiments were designed to confirm simulation results, and to assess the skylight performance in an experimental setup were the skylight was connected to a miniature room. The results of these experiments showed that temperatures even below the ambient could be measured inside the skylight. The experimental results coincided in general well with those simulated. However, some work is still needed on improving the simulations. The simulation results suggested that the addition of the opaque middle window does not significantly diminish the cooling performance of the skylight when set in cooling mode. Thus, allowing a switching between a cooling and an insulation mode is supposedly possible. As no simulations or experiments were performed on evaluating the insulating performance of the skylight should future work focus on this, and to evaluate alternative materials.

5. Conclusions

A skylight built of novel materials can passively achieve a cooling of the room located below it. In this article, the cooling potential of skylights comprised of materials such as ZnS windows, air, CO_2 and HFC-125 were evaluated. The evaluation was done by three different types of experiments and simulations. The experimental work presented in this article confirmed the suitability of the selected materials for the cooling skylight concept. Moreover, the measured experimental results were in agreement with the results simulated with Comsol. This article concludes that on a clear night a passive cooling effect of 100 W/m^2 is certainly achievable.

Acknowledgments

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Nomenclature

T_{amb}	Temperature of the ambient
T_{box}	Temperature of the box simulating the room
$T_{compdown}$	Temperature of the lower section in the skylight
$T_{compupp}$	Temperature of the upper section in the skylight
T_{sky}	Temperature of the sky

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