Radiative cooling in northern Europe for the production of freezer temperatures

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Abstract: The sky should not only be seen as a potential source of energy in the form of the sunlight but also as a source of energy in the form of cooling. This cooling is obtained through radiative heat exchange between a radiator, located on the surface of the earth, and cold air masses situated above this radiator. The possibility of using radiative cooling for areas located in northern Europe is investigated in this paper. Since the amount of cooling needed for refrigeration and air conditioning is expected to increase in the near future, so will also the amount of energy needed to produce it; as this is usually done through vapor compression. However, by the use of radiative cooling, energy need not be used in this same manner. Here, the potential of radiative cooling is investigated and compared for two different locations in Finland.

Keywords: Radiative cooling, Northern regions.

1. Introduction

The potential of using radiative cooling in northern Europe is investigated in this paper. A vast amount of cooling, and therefore energy, is needed for refrigeration and air conditioning. This paper will assess the possibility of using the sky instead of a vapor compression refrigeration processes as a passage to low temperatures. Radiative cooling has been studied for air conditioning by the use of flat plate solar collectors [1] and by the use of roof based components [2], even its’ use during the day has been studied [3]. But its’ potential availability has been poorly studied for northern Europe although some studies have been made for southern Europe [4].

In northern Europe, low temperatures are available during winter, which is also a time when the air is dry and the skies are clear, even the days are short, all conditions that are the most favorable for radiative cooling. Therefore, since optimum conditions exist for low temperature skies, what would the performance of radiative cooling be?

In this study, a mathematical model was set up for a refrigeration system where weather data from two Finnish locations were used to assess its performance. These two different locations were selected as to give a representation of the different weather conditions that prevail in a northern country.

The apparatus that would perform the cooling would be a flat plate metal cooler containing a refrigerant. This refrigerant would be transported from the radiative cooler to the refrigerator where the heat exchange would take place through convection and conduction as it is done today. The surface of the metal plate would be coated with a suitable paint to give the surface good emitting properties in the infrared spectrum. The most important wavelength for radiative cooling is the interval 8-14 µm, referred to as the atmospheric window, which is the main interval where earth emits the heat it receives from the sun at shorter wavelengths. During the summer when sky temperatures are too high for deep cooling, the same refrigerant would be utilized to run in combination with a vapor compression refrigeration process cycle, thus giving the same cooling effect as in a conventional system. Alternatively, the flat plate collector could be used during the summer for air conditioning or as flat plate heat collectors for water.

2. System description

The system modeled in this paper consists of a radiator at a constant surface temperature \( T_{surf} \). This radiator is subjected to different heat exchange processes, which are presented in Fig. 1. The different heat exchange processes involve both long and short wave radiative heat and forced convection heat. The results of the different heat exchanges are combined to get the total heat exchange of the system.
2.1. Weather Data

As this paper studies the availability of passive cooling through heat radiation and convection in northern Europe, weather data was needed. The data was acquired from the Finnish Meteorological Institute for weather stations located in Sodankylä, Finland (67°22'N, 26°37'E) and in Helsinki, Finland (60°10'N, 24°56'E) [5]. These locations are presented in Fig. 2.

The data contains hourly average data for the years 2008 and 2009, of the ambient temperature, wind speed, long and short wave heat radiation data. The long-wave heat radiation data was measured by a CG4 pyrgeometer, which measures the incoming heat radiation in the range of 4.5µm – 40µm [7]. With this data, the temperature $T_{sky}$ can be calculated with (1). Here the emissivity $\varepsilon_{sky}$ is chosen to be $=1$ since the emissivity is already included in the $Q_{long\ \text{wave}}$ measured data. Here, $\sigma$ is the Stefan-Boltzmann constant, with a value of $5.67 \times 10^{-8}$ W/m$^2$K$^4$.

$$T_{sky} = \sqrt[4]{\frac{Q_{long\ \text{wave}}}{\varepsilon_{sky}}} \cdot \sigma.$$  

(1)

Wind that blows parallel to the roof window causes heat exchange by forced convection. To calculate this forced convective heat (2) and (3) are used. These equations give the convective heat exchange for turbulent exchanges over smooth surfaces at low wind speeds (<3 m/s). Here, $v_{rad}$ is a reduced wind speed, at the radiator, that originates from the fact that the wind speeds are measured at a higher altitude than where the radiator is situated.

$$h_c = 1.8 + 3.8 \cdot v_{rad}.$$  

(2)

For this case the wind data that was acquired was measured at a height of 10m and the assumed location of the radiator is set at a height of 5m. From this, a correction of the wind speed is made using (3). Here, $\gamma$ and $\alpha$ are terrain parameters that describe the location of the radiator and the location for the wind measurement. The heights of the locations are the given by $H_w$ and $H_r$, where the lower casings stand for the weather station and the site of the radiator. [8]

$$v_{rad} = \frac{\alpha_w \left( H_w / 10 \right)^{\gamma, w}}{\alpha \left( H_r / 10 \right)^{\alpha}} \cdot v.$$  

(3)

2.2. Heat exchanges

When $T_{sky}$ is known the heat exchange from the radiator to the sky can be calculated for fixed radiator temperatures according to (4).

$$Q_{rad\leftrightarrow \text{sky}} = \left( \varepsilon_{rad} T_{rad}^4 - \varepsilon_{sky} T_{sky}^4 \right) \sigma - \varepsilon_{rad} Q_{\text{short\ wave}}.$$  

(4)

Here $Q_{\text{short\ wave}}$ is the total heat radiation in the shortwave spectrum that originates from the sun. This shortwave heat radiation can cancel out the radiative cooling effect and therefore has to be taken into account. The emissivity of the radiator has been assumed to be $\varepsilon_{rad}=1$; this assumption is made since the potential of passive cooling is investigated and thus the maximal cooling effect is given when $\varepsilon_{rad}=1$. However, this article assumption of $\varepsilon_{rad}=1$ has also a disadvantage as it is assumed to be the same over the whole
wavelength spectrum. By the use of selective coatings that have high reflecting properties in the shortwave spectrum and high emitting properties in the long wave spectrum, it could be possible to avoid or diminish the heating effect caused by the sun.

The convective heat exchange was implemented into our model also according to (5) so that its’ effect could also be evaluated.

\[ \dot{Q}_{\text{rad-sky}} = h_c \cdot (T_{\text{rad}} - T_{\text{amb}}). \]  

(5)

The different heat exchange processes calculated by (4) and (5) are then combined together according to (6).

\[ \dot{Q}_{\text{tot}} = \dot{Q}_{\text{rad-sky}} + \dot{Q}_{\text{rad-amb}}. \]  

(6)

This way of combining convective and radiative heat exchange is called the additive method. Since this method has no physical basis an error is introduced, but as the temperature differences are small and air is not greatly affected by heat radiation the error should be negligible. [9]

3. Results and discussion

In this section various measurements and calculations based on these measurements are presented. First the temperature of the sky and ambient is calculated for the two locations. After this, the average radiative heat exchange per day is presented for a radiator temperature of 10°C; this is then further expanded to 3D-graphs which illustrate the same heat exchange for different radiator temperatures. The reason for choosing the average heat exchange per day originates from the fact that the cooling effect can be canceled out during the day by the sun. Finally, the radiator's cumulative frequency distribution of heat exchange at varying radiator temperatures is presented; where the heat for the radiative, convective and total heat transfer are all presented separately.

3.1. Temperature data

The temperature of the sky and the ambient for Sodankylä and for Helsinki are presented in Fig. 3 and Fig. 4.

This data was smoothed out with the Savitzky-Golay filtering method because the noise in the measurement was disturbing. A third order polynomial filter with a frame size of eighty-nine days was applied on the data to obtain a satisfactory result. When comparing these figures it is observable that the temperatures for both the ambient and the sky are lower in Sodankylä than in Helsinki. However, the temperature difference between the ambient and the sky is larger in Helsinki than in Sodankylä. It is also observable that the temperature difference is largest during autumn for both locations and for both year 2008 and 2009.

Due to the lack of measurement data for the end of the year 2009 in the long wave heat radiation data, \( T_{\text{sky}} \) could not be calculated for the whole time period of 2008 to 2010 for Sodankylä. Smaller gaps in the order of some hours were also found elsewhere in the data, but these gaps could be filled with interpolated data.

3.2. Radiative heat exchange

The radiative heat radiation for a radiator at 10 °C is presented in Fig. 5 for Sodankylä and for
Helsinki. Since sky temperatures were lower in Sodankylä than in Helsinki the heat exchange between the radiator and the sky was therefore larger in Sodankylä. The largest difference occurred during the winter when the difference between the two locations was 35 W/m². However, since Sodankylä is situated more to the north than Helsinki the amount of sunlight that strikes the radiator during the summer is larger than that in Helsinki; this reduces the amount of cooling attainable in Sodankylä to become smaller than that in Helsinki. This conclusion is further supported by comparing Fig. 3 and Fig. 4 where $T_{sky}$ is higher in Helsinki than in Sodankylä during the summer. The difference is, however, not larger than 5 W/m².

The radiative heat exchange for various radiator temperatures is presented in Fig. 6 for Sodankylä and in Fig. 7 for Helsinki. When radiator temperatures decrease so does the rate of heat exchange, which is according to (4). The decreased heat exchange is shown in Fig. 6 and Fig. 7. The form of the cooling distribution is also seen in these figures as it was already in Fig. 5. This shows that the main cooling potential is attainable during the winter months, but that cooling to temperatures below room temperature, is also possible during the summer.

3.3. Probabilities, frequency distributions

The distribution of the cooling potential is further assessed in Fig. 8 to Fig. 14 where the cumulative frequency distribution of the heat exchange for various radiator temperatures is assessed. [10] Here the heat exchange is presented as isolines in W/m². These cumulative frequency distribution isolines describe for what length of time, a certain heat exchange could have been achieved, for a defined radiator temperature during the two-year measurement period. So for example Fig. 9 describes that a heat exchange of 50 W/m² could have been attained at a radiator temperature of -20°C for 10% of the time during the two-year period.

First the cumulative frequency distribution of heat radiation is assessed separately in Fig. 8 for Sodankylä and in Fig. 9 for Helsinki. When comparing, these two figures it is observable that...
lower radiator temperatures are reachable for the same heat exchange in Sodankylä than in Helsinki. The radiator temperature difference between the two locations for equal heat exchanges is around 5°C.

The influence of convective heat transfer must also be assessed. This is done in Fig. 10 and in Fig. 11 which present the cumulative frequency distribution of the convective heat exchange at various radiator temperatures for both Sodankylä and Helsinki. The amount of convective cooling is larger in Helsinki for higher radiator temperatures, but for lower radiator temperatures the amount of cooling is larger in Sodankylä.

The larger cooling potential in Helsinki at higher ambient temperatures originates from higher wind speeds in Helsinki than in Sodankylä; these wind speeds are presented in Fig. 12. The larger cooling at lower temperatures originates from lower ambient temperatures in Sodankylä than in Helsinki; the ambient temperatures were presented in Fig. 3. and in Fig. 4.
When comparing the radiative transfer with the convective heat transfer it is obvious that convection has to be taken into account. The biggest difference that convection makes is that the order of magnitude of the heat transfer changes quite significantly. However, convective heat transfer can occasionally diminish the effect of radiative cooling and even sometimes cancel the cooling effect. The risk of cancelling effects is especially large during the summer when the ambient temperature is higher than that of the radiator.

The cumulative frequency distribution of the total heat transfer of a radiator is presented in Fig. 13 for Sodankylä and in Fig. 14 for Helsinki. When comparing the total heat transfer of these two locations it is obvious that for higher radiator temperatures a larger amount of heat can be dissipated from the radiator to the ambient and to the sky in Helsinki. However, when radiator temperatures drop, the amount of dissipated heat will be larger in Sodankylä than that in Helsinki as was the case also for the pure convective heat transfer.

4. Conclusions

The needed electricity for air conditioning is expected to increase by a tenfold during the next 40 years in Finland. [11] Therefore new cooling methods are needed also for the northern European conditions.

This article has presented the potential of utilization of radiative cooling in northern Europe. Radiative cooling has yet to be utilized for cooling in northern Europe but this paper showed that it can be used for air conditioning and even for cooling to lower temperatures. By the use of meteorological data obtained from the Finnish Meteorological Institute the heat exchange from a flat plate radiator has been modeled. This paper shows that a significant amount of cooling can be
obtained from a source that does not include the power intensive compression work as the traditional cooling does. By the utilization of radiative coolers, savings could be achieved for air-conditioning but also for the refrigeration of food products. The radiative coolers could also be used as solar collectors during times when sufficient cooling is not needed or attainable.

**Nomenclature**

- $c$: specific heat, J/(kg K)
- $h$: heat exchange coefficient, W/(m$^2$ K)
- $H$: height m
- $t$: temperature, °C
- $\dot{Q}$: Heat flux density, W/m$^2$
- $v$: wind speed at measured site, m/s

**Greek symbols**

- $\alpha$: Alpha terrain parameter
- $\gamma$: Gamma terrain parameter
- $\varepsilon$: Emissivity of a material
- $\sigma$: Stefan Boltzmann constant, W/(K$^4$ m$^2$)
- $\tau$: Transmissivity of a material

**Subscripts and superscripts**

- $\text{amb}$: ambient
- $c$: convection
- $\text{long wave}$: long wave radiation (>4.5µm)
- $\text{rad}$: radiator
- $s$: site
- $\text{short wave}$: short wave radiation (<~3µm)
- $\text{sky}$: sky
- $w$: wind tower

**References**


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