Thermal Analysis of an Object with Large Surface Area Under Controlled Conditions Regarding Radiative Sky Cooling and with High Emissivity in the 8-13 μM Wavelength Range

Peesapati Venkata Rangacharyulu[1],Kiran Kumar Chittiboyina[2]

[1]*Assistant Professor, Mechanical Engineering Department & Visakha Institute of Engineering and Technology*
[2]Assistant Professor, Mechanical Engineering Department & Visakha Institute of Engineering and Technology

---***---

Abstract - Radiative Sky cooling is an eco-friendly method of using the deep sky as a heat sink and transferring heat into space with a specific wavelength of 8-13 μm (atmospheric window), which is ideal for penetrating the atmosphere by avoiding scattering and total internal reflection in it. Because space acts as a sink, any object emitting heat in those wavelengths acts as a source. As a result, no external energy is required to cool the material. Though the average temperature of the outer sky is 3K, the effective sky temperature is affected by atmospheric factors such as humidity, air temperature, sky clearness etc. In this case, the emitter has been precoated with a specific radiative paint that allows high emissivity of the object in target wavelengths. The effectiveness of surface geometry on this radiative heat transfer is studied in various temperatures and humidity conditions under clear sky also conductive and convective modes of heat transfer and dust in the air are neglected. The view factor is considered along with the surface roughness for comparison. The results of simulation of a corrugated sheet with high relatable high surface area is compared with published results of an experimental model. The surface emissivity is maintained same as that of the experimental model. The behaviour of the both models at different conditions are noted and correlated.

Keywords: Radiative Sky Cooling, Atmospheric Window, Specific Emissivity, Ziblod condensers, Dew harvesting, Nocturnal cooling, space cooling, Spectral emission, Total Heat Flux

1.INTRODUCTION

The increasing demand for thermal comfort is causing more and more greenhouse emissions. To overcome that scientists are discovering new possibilities for space cooling. Jiri Simaa et al. (2013) established that one of these techniques is cooling based on radiation into outer space, which is basically heat loss by long wave infrared radiation emission towards the sky [1]. Bartoli et al. (1977) found that the radiative sky cooling cells are the objects which emit infrared radiation within the bandwidth of 8-13μm which cannot be reflected by air and escapes the earth's atmosphere [2]. When this object is isolated from all other heat sources around it, it will continuously cool down below ambient temperatures and can be used effectively in the space cooling applications as a passive cooling system.

As this technology doesn't have any coolants which cause ozone depletion or have compressors which consume large amount of electricity, it can be used as a greener alternative for space cooling units. In general, this effect is highly pronounced in dry environments like deserts. Because the humidity and dust in the air, cloudiness plays a significant role in the sky cooling. Under isolation, a flat disc is replaced with a corrugated disc of higher surface area to verify if there is any improvement in the performance with respect to surface area. The consideration of the temperature of the surface of the specimen is treated as constant for the following analysis.

2. Methodology

The primary objective is to verify the relevance of the surface area and projected area of the radiative cooling cells in different environmental conditions. This is a surrogate model related to the established "Czech Model" which is used to test the radiative cooling cell performance in Czech Republic by Ondrej Sikula et al. (2015) [3]. The system has also used the novel approach by Bikram Bhatia et al. (2018) as they have isolated the cooling cells made form polished aluminum sheet from convective wind currents and also used a reflective shield to eliminate the radiation input from the Sun. The radiative cooling system is insulated from all sides by polystyrene except the top and it is covered with a polyethylene sheet in order to prevent incoming diffuse radiation from sky and allow the emitted radiation form the object into the sky [4].

Raman AP et al. (2014) experimentally found that the performance of spectral emission can be achieved by coating a 1D stack of hafnia and silica, consisting of seven bilayers, was shown to be sufficient to achieve cooling below ambient temperatures in experiment [5].

The main parameters used to evaluate the performance of these cooling cells are the ambient temperature and the sky temperature. Even though the sky is not a solid object, considering the atmospheric plane as a solid plane reduces many computational complexities and we can even neglect the effect of the gases in the atmosphere. The Sky temperature is highly affected by the dust particles in the air, the cloud type, the effective area they cover, the local relative humidity and dew point temperature. It is complex to exactly calculate the sky temperature, so Pramod V Mulik et al. (2019) approximated it as follows,

$$T_{sky} = T_{air} * (\varepsilon_{clear\ sky})^{0.25} \quad \ldots\ldots\ldots\ldots (1)$$

$$\varepsilon_{clear\ sky} = 0.711+0.56(T_{dp}/100)+0.73(T_{dp}/100)^2 \quad \ldots\ldots. (2)$$

Here T_{sky} = the effective temperature of the sky (K)

T_{air} = the ambient temperature (K)

$\varepsilon_{clear\ sky}$ = the emissivity of the clear sky

T_{dp}= Dew point temperature (°C)

And to reduce the complexity, the sky is assumed to be clear [6]. The comparison is made as functional analysis between the aforementioned Czech model and the specimen. The specimen is the corrugated disk with the projected diameter of 0.1m and a surface area 12312.42 mm^2 and projected area of 7854 mm^2 whereas the Czech model has the projected area of 15000 mm^2.

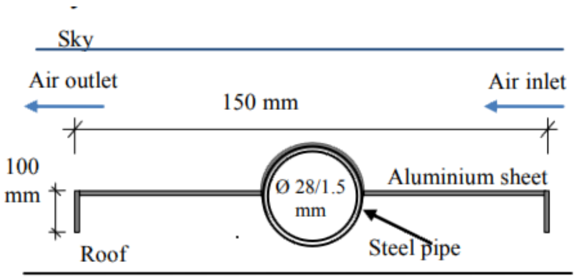

Fig.1. Geometry of the Czech model

The comparison is done between the Czech model under normal exposure to ambient conditions and the corrugated model under isolated conditions so that the effectiveness of the performance can be analyzed. The main parameters considered is Total Heat Flux (THF) at various ambient temperatures at 20%,40%,60% and 80% constant Relative humidity (RH). This is to keep the degree of variation of Dew point temperature constant.

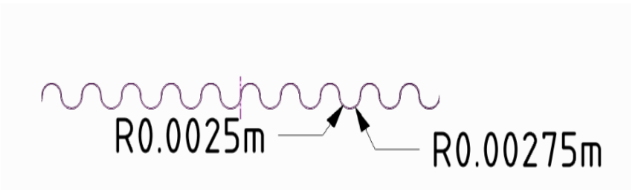

Fig.2. Corrugated Model (Side view)

The reason to consider various humidity points and also ambient temperatures is that the sky temperature is dependent on them and also the performance of the emitter can be analyzed under a wide range of operating conditions. The prominent reason to consider only from 20% to 100% Relative humidity and also considering the temperature range of 12°C to 22°C is because that is the range in which the validation has the tolerance in experimental comparison.

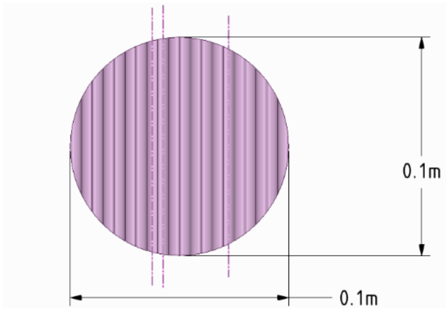

Fig.3. Corrugated Model (Top view)

3.1. Behavior of emitter at different ambient temperatures

The Total heat flux of the emitter is plotted against relative humidity at constant ambient temperature. The behavior of the emitter is not a linear function and has a sudden increase in the THF value with respect to the values of the Czech model and the reason for this is yet to be investigated.

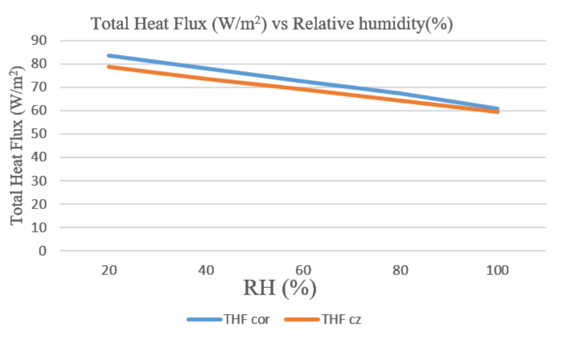

Fig. 4. At 12°C, THF at different RH

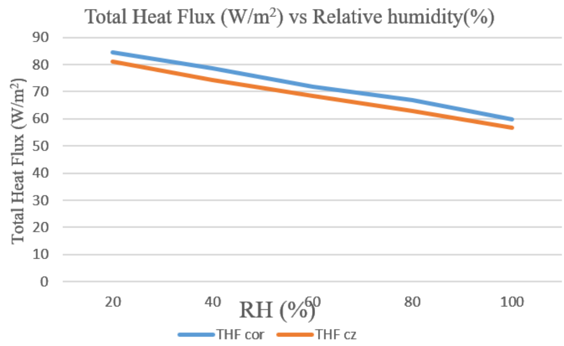

Fig. 5. At 14°C, THF at different RH

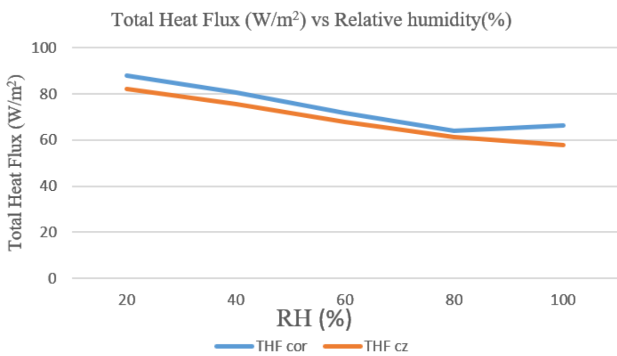

Fig.6. At 16°C, THF at different RH

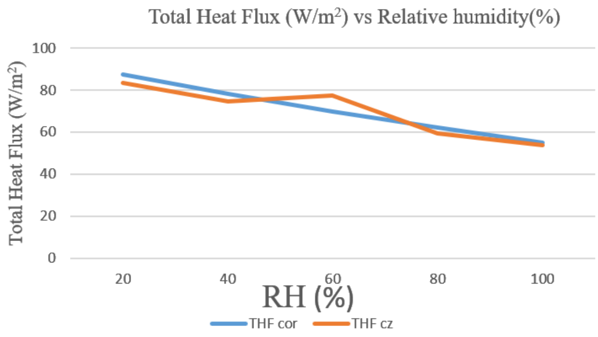

Fig.7. At 18ºC, THF at different RH

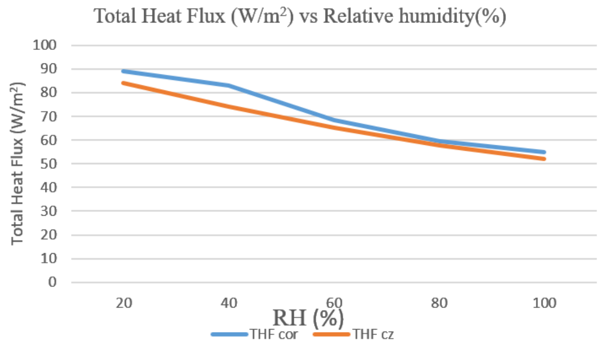

Fig.8. At 20ºC, THF at different RH

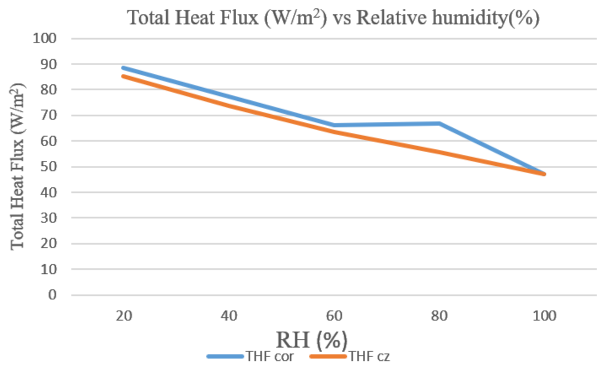

Fig.9. At 22ºC, THF at different RH

3.2. Behavior of emitter at different relative humidity conditions

The Total heat flux of the emitter is plotted against Ambien temperature with constant humidity. The behavior of the emitter here is also a non-linear function and is wavy in nature. If we observe closely, there are slight fluctuations even in the Czech model values. The maximum and minimum fluctuated values of the emitter is amplified when compared to the Czech model. These anomalies appear to be in synchronization with the THF value with respect to the values of the Czech model.

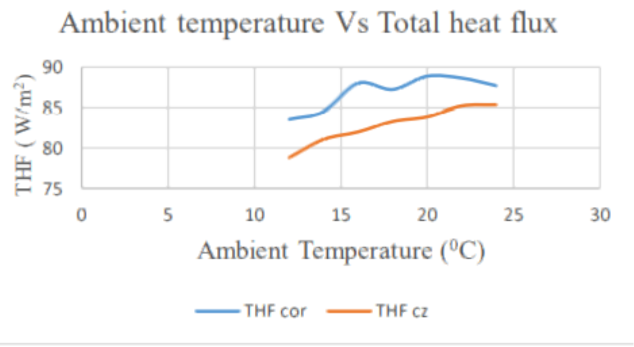

Fig.10. At 20% RH, THF at different Ambient temperatures

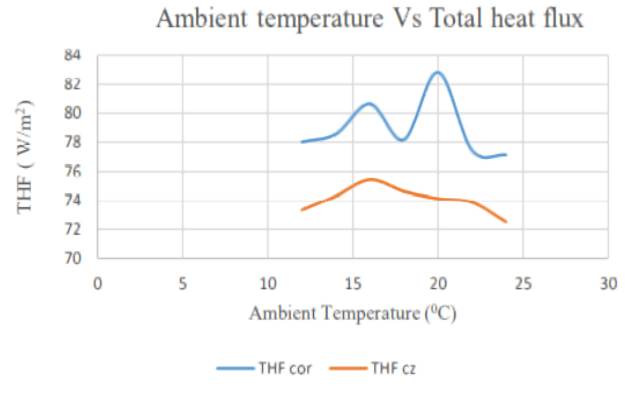

Fig.11. At 40% RH, THF at different Ambient temperatures

The corrugated model has 50% more surface area and 60% less projected area than the Czech model. This is to make sure that the change in the heat flux is only due to the effect of surface area and not due to radial heat transfer. If both the models have the equal amount of the projected area, then the effect of the surface area can be easily masked by the view factor of the surface. So that is why the ratio of projected area and the surface area is consistently maintained in all the simulations. The other effect which should be mentioned is that the Czech model is influenced by the convection but the Corrugated model is completely shielded from convection and solar interference. The emitter is appeared to be highly functional in insulated chamber than the conventional setup such as a Czech model. The maximum cooling effect possible is at 20ºC and at a relative humidity at 20% is 177.29 W/m^2 for corrugated model and at 26ºC is 532.91W/m^2 at 20 % Relative Humidity.

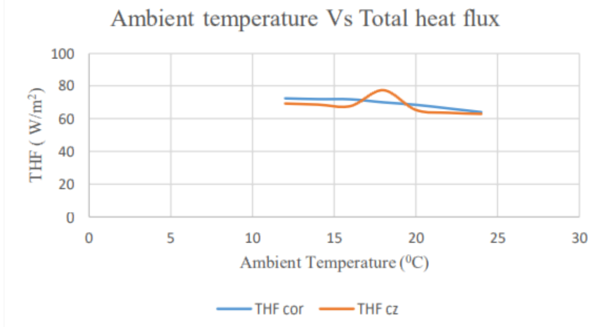

Fig.12. At 60% RH, THF at different Ambient temperatures

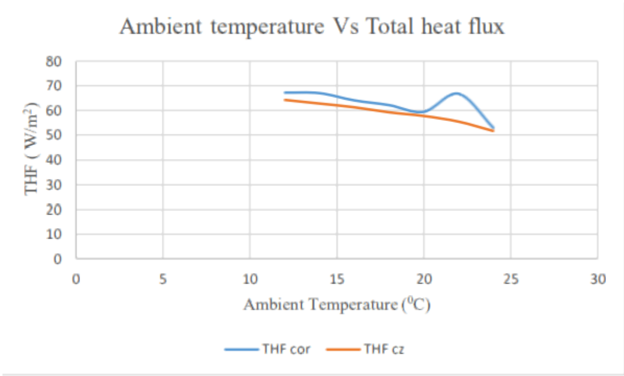

Fig.13. At 80% RH, THF at different Ambient temperatures

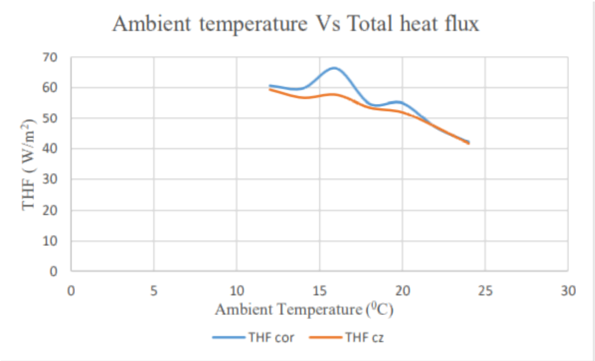

Fig.14. At 100% RH, THF at different Ambient temperatures

4.Conclusions

From the study, it is clear that the effect of surface area is very high in comparison with the projected area. Performance of the Corrugated model with respect to the ambient temperature, the THF is almost similar to the Czech model. The small fluctuation in the graph can be considered as the domination of convection over radiation in case of the Czech model. The decreasing temperature differential between Sky and ambient temperature causes the peaks in the graph of the corrugated model at higher ambient temperatures. But the wave pattern in the graph of the corrugated model graph at constant humidity cannot be considered as the previous reason because, when the humidity is constant, the factors effecting the heat flux are nothing but the ambient temperature, but as we see here the ambient temperature is increased linearly. It is not only for the corrugated model, but also for Czech model. So, this is not a simulation error. If observed closely, the graph of Czech model also consists of the tiny fluctuations and in the corrugated model, the effect is amplified. So, the cause(s) for the fluctuations in the graphs is yet to be studied in the future.

Appendix

A. Cooling effect

Xing Shu Sun et al.(2017) formulated spectral emissivity for radiative cooling effect [6].

$P_{Cool}(T) = P_{rad}(T) - P_{atm}(T_{amb})$ …………… (3)

Here $P_{Cool}(T)$ =Net unit Cooling power of the emitter at temperature T (^{o}C) [W/m^2]

$P_{rad}(T)$ = Heat flux emitted by the emitter at the temperature T (^{o}C) [W/m$^{2]}$

$P_{atm}(T_{amb})$ = Heat flux received by the emitter from the surroundings at ambient temperature T_{amb} (^{o}C) [W/m^2]

B. Sky emissivity

There are many approximations for the emissivity of the sky based on multitude of parameters. Some of them being the latitude and clouds. Bal´azs Bokor et al. (2021) have formulated different formulae for the sky emissivity at various configurations [7]. These equations are from reference sources. It is also said that the Sky temperature models devoid of humidity considerations are not precise and useless.

Starting from equations,

$\varepsilon_{sky\text{-}clear} = 0.711+0.56*(T_D/100) + 0.73*(T_D/100)^2$ [Nominal] ……………………………….. (4)

$\varepsilon_{sky\text{-}cloudy} = (1 - 0.84 * CC) * \left[0.527 + 0.161 * \varepsilon^{\left(8.45*\left(1-\frac{273}{T}\right)\right)} + 0.84CC\right]$ …………………… (5)

Here the CC means Cloud-Clearness factor where, its value is 0 for clear sky and 1 for fully clouded sky with thick cumulonimbus clouds.

$\varepsilon_{sky} = 0.77 + 0.0062*(T_D - 273.15)$ ……………. (6)

$\varepsilon_{sky} = 0.8004+0.00396*T_D$ ……………………………… (7)

$\varepsilon_{sky} = 0.787+0.0028*T_D$ …………………… (8)

$\varepsilon_{sky} = 0.754+0.0044*T_D$ …………………….. (9)

$\varepsilon_{sky\text{-}night} = 0.741+0.0062*T_D$ …………………… (10)

$\varepsilon_{sky\text{-}night} = 0.77+0.0038*T_D$ …………………… (11)

T_D = Dew point Temperature in K

ε_{sky} = Emissivity of the sky

C. Sky temperature

The sky temperature is dependent on various parameters from the same author Bal´azs Bokor et al. (2021) as follows [8]

$$T_{sky} = 0.0552*T^{1.5} \quad (12)$$

$$T_{sky}= T*\varepsilon_{sky}^{1/4} \quad (13)$$

$$T_{sky}=T*[0.711+0.0056*T_d+0.000073*T_D^2+0.013*\cos(15t)]^{1/4} \quad (14)$$

Here T = ambient temperature (^{0}C)

T_{sky}= Temperature of sky (^{0}C)

T_D = Dew point temperature (^{0}C)

ε_{sky} = emissivity of sky

t = hours in integers from midnight

D. Materials used for coating

The radiative cooling effect can be effectively studied and used for various purposes such as dew harvesting in low moisture conditions like deserts [9]. These types of condensers are called Zibold condensers [10]. Their main purpose is to extract the moisture from the air for drinking and also for soil cooling for agricultural purposes [11]. Lawsonite $CaAl_2Si_2O_7(OH_2).H_2O$ tabular crystal is a famous mineral used for the detecting the moisture content in the air which can be used as a coating on the radiative cooling cell [12]. Then it can be used for both water collection and also as a cooling equipment [13]. Silica paste is used for the Commercial White Coating (CWC) [14]. With some mixed solar vacuum cooling and collector can also use the Lawsonite [15].

REFERENCES

1. Jiri Simaa, Ondrej Sikulaa, Katarina Kosutovaa , Josef Plaseka. Theoretical evaluation of night sky cooling in the Czech Republic. SHC 2013, International Conference on Solar Heating and Cooling for Buildings and Industry September 23-25, 2013.
2. Bartoli, B. et al. Nocturnal and diurnal performances of selective radiators. Appl. Energy 3, 267–286 (1977).
3. Ondrej Šikula, Petra Vojkuvková, Jiri Šíma, Josef Plášek, Günter Gebauer. Hybrid roof panels for night cooling and solar energy utilization in buildings. International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES15, 2015.
4. Bikram Bhatia et al. Passive directional sub-ambient daytime radiative cooling. Nature- Communications. DOI: 10.1038/s41467-018-07293-9
5. Raman AP, Anoma MA, Zhu L, Rephaeli E, Fan S. Passive radiative cooling below ambient air temperature under direct sunlight. Nature 2014;515:540–4.
6. Xing Shu Sun et al. Radiative sky cooling: fundamental physics, materials, structures, and applications. Nano photonics 2017; 6(5): 997–1015
7. Bal´azs Bokor, Hacer Akhan, Dogan Eryener, Mikl´os Horv´ath. Nocturnal passive cooling by transpired solar collectors. Applied Thermal Engineering 188 (2021) 116650. https://doi.org/10.1016/j.applthermaleng.2021.116650
8. Zibold FI et al. Significance of underground dew for water-supply in Feodosia-city Collect. Foresty Trans 1905;3(1905):387–441.
9. M. A. Knapen et al. Dispositif intérieur du puits aérien Knapen Extrait des mémoires de la société des ingénieurs civils de France (Bulletin de Janvier-Fevrier) (Paris: Imprimerie Chaixs) 1929.
10. Libowitzky E, Rossman GR. Am Mineral 1996;81:1080–91.
11. Baur WH. Crystal structure refinement of lawsonite. Am Mineral 1978;63:311–5.
12. Wickman FE. The crystal structure of lawsonite, .Arkiv för Kemie Mineralogi och Geologi 1947;25A:1–7.
13. Labotka TC, Rossman GR. The infrared pleochroism of lawsonite: the orientation of the water and hydroxide groups. Am Mineral 1974;59:799–806
14. Jie Huang et al. Core-shell particles for devising high-performance full-day radiative cooling paint. Applied materials today. Volume 25. https://doi.org/10.1016/j.apmt.2021.101209.
15. Albert Castel et al. Adaptive covers for combined radiative cooling and solar heating. A review of existing technology and materials. Solar Energy and materials and solar cells. Volume 230. https://doi.org/10.1016/j.solmat.2021.111275

Authors:

P.V.Rangacharyulu. Mtech
Assistant Professor
VIET, Visakhapatnam.

Ch.Kiran Kumar. Mtech (P.HD)
Assistant Professor
VIET, Visakhapatnam