Radiative cooling to cover cooling demands of an Earthbag building in a Training Medical Center in Burkina Faso

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Abstract

Comfort conditions in buildings of developing countries are seldom achieved. Moreover, electricity is usually scarce and unreliable. Therefore, the use of a renewable energy source can be a solution. In this paper the use of radiative cooling to achieve human thermal comfort in an Earthbag building of a Training Medical Center in Ouagadougou in Burkina Faso is studied. The building demands are determined by simulation using EnergyPlus, and are compared to the energy production of a Radiative Cooling (RC) system, which is simulated using Trnsys. Peak cooling powers are expected to be around 3.5-4 kW, with a total annual cooling demand of 2081.58 kWh. The maximum cooling demands appear during April and May (567.18 kWh and 554.07 kWh respectively). Different radiative cooling installed surfaces and inlet water temperatures (T_{in}) are analyzed, achieving annual cooling demand coverages of around 35% for the case of 10 m^2 and T_{in}=25 ºC. Further research is necessary to determine the interaction between the RC and the HVAC distribution system, which is not considered in this paper.

Keywords: Building Energy Simulation, Comfort conditions, Radiative cooling, Earthbag building.

Introduction

In developing countries, comfort conditions in buildings are usually not achieved, resulting in energy poverty, discomfort, illness, etc. In tropical and arid climates, cooling requirements cannot be achieved by conventional technologies such as compression systems, since electrical energy is scarce and unreliable. Moreover, the installation and operation costs are usually too high. Renewable energies can be a feasible solution to improve human thermal comfort in a reliable and non-expensive way (Kaygusuz 2012).

The most common technology used for space conditioning, especially in hot climate countries, is the reversible heat pump, which consumes a large amount of electrical energy. However, there are other renewable sources capable to produce cooling. Solar cooling is one of the most widely studied ones; however, its use for cooling is limited by the implementation of absorption heat pumps, which are complex, present low overall efficiencies, require high operation temperatures, and need large cooling towers (Hassan and Mohamad 2012).

Radiative cooling is another technology that has been studied to provide cooling from a renewable source. It uses the sky as a heat sink taking advantage of its effective temperature lower than ambient (Bell et al. 1960). Radiative cooling is based on emitting long-wave thermal radiation from a terrestrial body toward space through the infrared atmospheric window between 8-13 µm wavelengths. The atmosphere infrared window is the dynamic behavior of earth's atmosphere that allows some infrared radiation pass through the atmosphere without being absorbed and, thus without heating the atmosphere. Therefore, radiative cooling can be useful to provide cooling and improve the comfort conditions in hot climates (Vall and Castell 2017).

Nowadays, a Training Medical Center (TMC) is under construction in Ouagadougou (Burkina Faso). The living quarters for the volunteers are built using an innovative constructive system called Earthbag building. This construction technique consists of introducing an earth mixture of clay, sand, and lime as a binder, inside bags that serve as the formwork and confinement of the filling. Bags are stacked one over the other forming the walls of the house and barwires between rows are used to improve friction and adherence. Rows are disposed in circles to conform a dome shape (Hunter 2004). These structures have been used in the last 25 years in

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emergency situations such as wars or natural disasters, providing quickly, low cost and safe shelters (Khalili, 1999). Although the construction has high thermal inertia and passive strategies, comfort conditions are not achieved due to the extreme weather conditions in Burkina Faso (Peel et al. 2006).

This paper analyzes the potential of radiative cooling to improve the comfort conditions and meet the cooling demand of an Earthbag building located at the Training Medical Center of Ouagadougou in Burkina Faso.

Numerical model

2.1. Building model

The Earthbag building will be the first dwelling of the residential area intended for the sanitary staff that will come as volunteers to Ouagadougou. It consists of four connected domes, two bedrooms of 4 m of diameter (inner size), one bathroom of 3.5 m, and a central living room of 4.5 m (Fig. 1), with a net floor area of 12.50 m^2, 7 m^2 and 15.90 m^2 respectively, and a height of 4.20 m, 3.6, and 4.70 m respectively. The walls of the domes are 32 cm thick and they are reinforced in the lower part with a 64 cm buttress. An extra roof is added as a shadow device over the central dome. All the windows have wooden frame and simple glazing. The energy simulation has been done with EnergyPlus software, using Open Studio as the graphical user interface. As the program does not allow creating such a circular shape, a polygonal dome was used. The default heat balance algorithm based on the conduction transfer function (CTC) transformation and 6 time steps per hour for the simulation are applied. Whole year simulations have been performed using the EnergyPlus weather data file for Ouagadougou. Ouagadougou is the capital of Burkina Faso (Latitude 12.35º North, 1.52º West. Elevation: 316 m). Its climate is hot semi-arid, (BSh – Arid Steppe hot arid climate under the Köppen-Geiger climate classification). This climate has a period of 8 months of hot and dry season and 4 months of wet season. During the hottest months, from March to May, day temperatures surpass 40ºC. From November to February the "hermattan" -a fresh and dry wind from the North- produces day temperatures about 25ºC. The annual average precipitation is 788 mm. The number of hours of solar radiation per day is very similar along the year, about 12 hours. The zenit of the sun is 55º in its lowest point, solstice of December, and 101º in solstice of June, reaching a perpendicular position respect to the horizontal in the months between both equinox and the solstice of June.

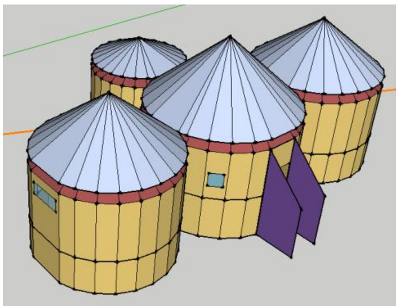

Fig. 1: Construction of the residential area with Earthbag buildings (left), and Earthbag model (right).

2.2. Radiative Cooler model

The architecture of the Radiative Cooler (RC) is similar to the architecture of a flat plate solar collector (Fig. 2). A radiator plate (1) collects or emits the radiation heat. A pipe (2) is welded at the back side of the radiator plate to transfer the heat to/from a fluid. The plate is insulated on the back side with insulation foam (3). On the front, it is insulated from the external air with an air gap (a) and a screen (c).

A detailed numerical model to simulate the behavior of the Radiative Cooler was developed in Trnsys (Vall et al. 2018). The model used one dimension (1D) relations based on electrical analogy. The model equivalent resistance network is shown in Fig. 2. The relations between the nodes are based on heat and mass transfer equations. Each node has a thermal capacity and each relation between nodes is represented by a thermal resistance. A radiation balance between the different surfaces is also performed, taking into account the incoming radiation (sun/sky) and the outgoing radiation (emitted, reflected, and transmitted). The model is used to determine the energy production of the Radiative Cooler model in order to cover the cooling demands of the building in Burkina Faso.

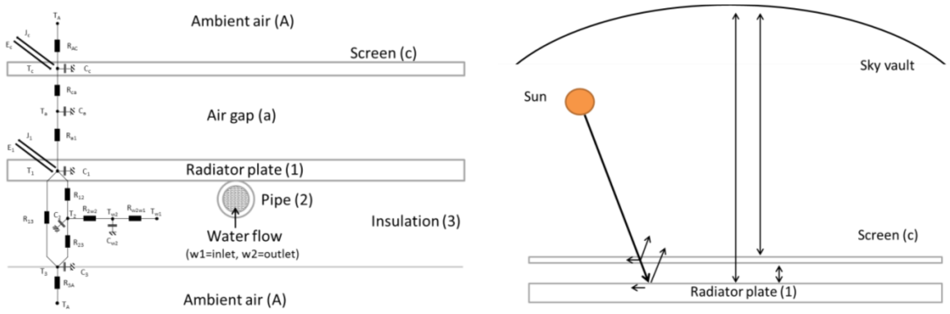

Fig. 2: Sketch of the model and 1D resistor capacitor model (left), and radiation model scheme (right).

Moreover, the radiation balance is done for 4 different wavelength bands (0-4µm, 4-7µm, 7-14µm and >14µm). Thus, the model distinguishes between different wavelength bands, with special care for the infrared atmospheric window (7-14µm).

First order ordinary differential equations in time are used in the model. The backward Euler method (or implicit Euler method) is used to solve the set of equations by using the Gauss-Seidel iterative method.

The model was experimentally validated using empirical data (Vall et al. 2018), comparing the predicted outlet water temperature to the measured one. Experimental and numerical results showed good agreement.

Results and discussion

Fig. 3 shows the energy demand of the simulated building located in Ouagadougou (Burkina Faso). The simulation assumes that the building is unoccupied during the day. The setpoint for the occupied hours is 27 ºC and the unoccupied hours setpoint is fixed at 30 ºC. Cooling demands may increase if occupancy schedules change. Peak cooling powers are expected to be around 3.5-4 kW, with a total annual cooling demand of 2081.58 kWh (Tab. 1). The maximum cooling demands appear during April and May (567.18 kWh and 554.07 kWh respectively). January and December are the months with lower cooling demands (7.72 kWh and 2.94 kWh respectively).

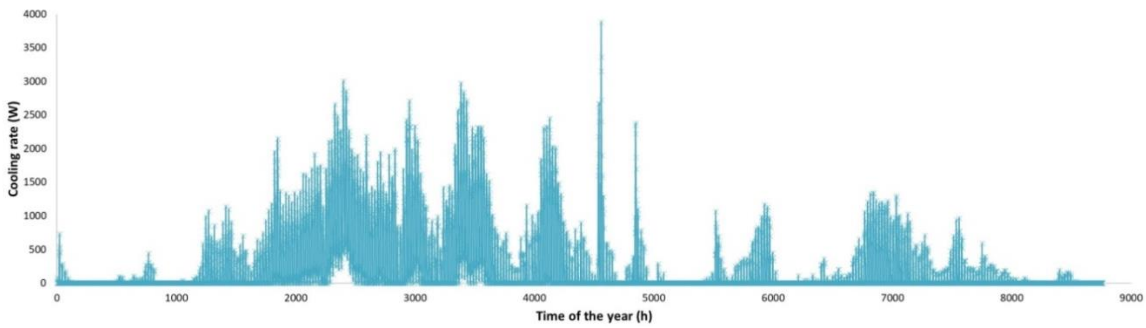

Fig. 3: Cooling rate required to meet comfort conditions in the TMC of Ouagadougou.

Tab. 1 and Tab. 2 present the cooling demands of the building for each month, the Radiative Cooler production for different installed surfaces, and the cooling demand coverage achieved with the RC production. Since the simulations do not consider the HVAC distribution system in the building, Tab. 1 considers an inlet water temperature to the RCE of 20ºC, while Tab. 2 considers a temperature of 25ºC.

The cooling demand coverage increases with the RC installed surface (Fig. 4). Results show the potential of the RC to cover part of the cooling demand of the building, being able to achieve full coverage for the months with lower demands. However, during the months with higher demands, the coverage is small. Annually, a significant coverage of around 35% can be achieved with 10 m^2 of RC installed surface and an inlet water temperature of 25ºC (Tab. 2). For this case, the system achieves full coverage during 6 months, while it is below 25% during 3 months. Even in this partial coverage months, the use of the cold produced by the RC can help significantly reduce the hours and degree-days of thermal discomfort, especially if the adaptive comfort model. ASHRAE Standard 55 Adaptive Comfort model is used to assess comfort conditions (ANSI/ASHRAE Standard 55-2013). This model is especially suited for naturally ventilated buildings with no mechanical cooling systems, such as the one in this study.

Tab. 1: Cooling demand, RC production and demand coverage for different installed surfaces of RC and an inlet water temperature of 20ºC.

	Cooling Demand (kWh)	Cooling Production – Inlet water temperature T_{in}=20ºC									
		2 m^2		4 m^2		6 m^2		8 m^2		10 m^2	
		Prod. (kWh)	Cvg. (%)	Prod. (kWh)	Cvg. (%)	Prod. (kWh)	Cvg. (%)	Prod. (kWh)	Cvg. (%)	Prod. (kWh)	Cvg. (%)
JAN	7.72	37.38	100	74.76	100	112.14	100	149.52	100	186.90	100
FEB	47.50	31.41	66	62.81	100	94.22	100	125.62	100	157.03	100
MAR	253.18	20.98	8	41.95	17	62.93	25	83.91	33	104.89	41
APR	567.18	3.04	1	6.07	1	9.11	2	12.15	2	15.18	3
MAY	554.07	0.90	0	1.80	0	2.70	0	3.59	1	4.49	1
JUN	241.71	1.14	0	2.28	1	3.42	1	4.56	2	5.70	2
JUL	109.28	1.89	2	3.78	3	5.67	5	7.57	7	9.46	9
AUG	27.16	1.97	7	3.94	15	5.91	22	7.88	29	9.85	36
SEP	46.73	3.17	7	6.34	14	9.51	20	12.67	27	15.84	34
OCT	181.16	2.26	1	4.52	2	6.78	4	9.04	5	11.30	6
NOV	42.97	17.25	40	34.50	80	51.75	100	69.01	100	86.26	100
DEC	2.94	32.98	100	65.96	100	98.94	100	131.91	100	164.89	100
ANN	**2081.58**	**154.36**	**4.5**	**308.72**	**7.8**	**463.07**	**10.0**	**617.43**	**11.6**	**771.79**	**13.3**

Tab. 2: Cooling demand, RC production and demand coverage for different installed surfaces of RC and an inlet water temperature of 25ºC.

	Cooling Demand (kWh)	Cooling Production – Inlet water temperature T_{in}=25ºC									
		2 m^2		4 m^2		6 m^2		8 m^2		10 m^2	
		Prod. (kWh)	Cvg. (%)	Prod. (kWh)	Cvg. (%)	Prod. (kWh)	Cvg. (%)	Prod. (kWh)	Cvg. (%)	Prod. (kWh)	Cvg. (%)
JAN	7.72	61.22	100	122.43	100	183.65	100	244.86	100	306.08	100
FEB	47.50	51.55	100	103.09	100	154.64	100	206.19	100	257.74	100
MAR	253.18	41.44	16	82.88	33	124.32	49	165.77	65	207.21	82
APR	567.18	17.93	3	35.85	6	53.78	9	71.70	13	89.63	16
MAY	554.07	10.30	2	20.60	4	30.90	6	41.20	7	51.49	9
JUN	241.71	10.70	4	21.39	9	32.09	13	42.79	18	53.48	22
JUL	109.28	13.55	12	27.10	25	40.65	37	54.21	50	67.76	62
AUG	27.16	15.41	57	30.82	100	46.22	100	61.63	100	77.04	100
SEP	46.73	17.52	38	35.04	75	52.57	100	70.09	100	87.61	100
OCT	181.16	15.62	9	31.23	17	46.85	26	62.46	34	78.08	43
NOV	42.97	38.79	90	77.57	100	116.36	100	155.15	100	193.94	100
DEC	2.94	56.79	100%	113.58	100	170.38	100	227.17	100	283.96	100
ANN	**2081.58**	**350.80**	**11.5%**	**701.60**	**18.4**	**1052.41**	**24.2**	**1403.21**	**29.5**	**1754.01**	**34.7**

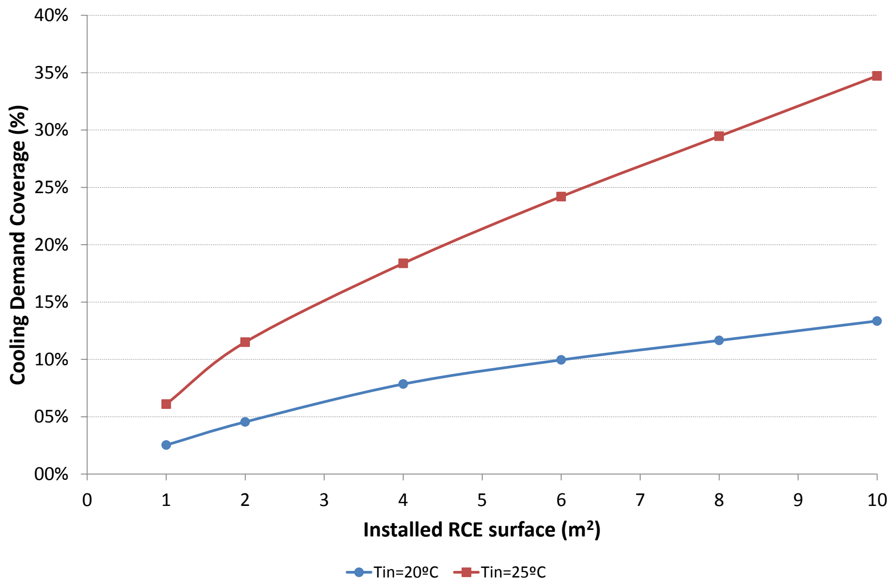

Fig. 4: Cooling demand coverage for different RC installed surfaces and inlet water temperatures.

On the other hand, the HVAC distribution system is not considered in the simulations, which will affect the inlet water temperature. Thus, the interaction of the RC system with the HVAC distribution system of the building must be evaluated in detail. A distribution system which can operate with high water temperatures is advisable in order to take more advantage of the RC system. Otherwise, the combination of the RC with a conventional, non-renewable cooling production system (such as compression heat pumps) would be necessary.

Conclusions

The potential implementation of a Radiative Cooler (RC) device in a Training Medical Center (TMC) under construction in Ouagadougou (Burkina Faso) is studied in this paper. The TMC is build using an innovative constructive system called the Earthbag building. The residential area of sanitary staff is simulated with EnergyPlus to determine the cooling demands in such extreme weather conditions. A numerical model of the RC developed in Trnsys is used to determine the cooling production. Different RC installed surfaces and inlet water temperatures are analyzed to determine the cooling demand coverage achievable with such technology. The RC shows potential in covering a significant demand of the cooling loads of the building, with coverage of around 35% for 10 m^2 of installed RC and an inlet water temperature of 25ºC. Although these results demonstrate the potential of such technology to cover part of the demand, it is not sufficient to cover the full demand during the most demanding months. Further research is required to take into account the interaction between the RC and the HVAC distribution systems.

References

ANSI/ASHRAE Standard 55-2013, 2013, Thermal Environmental Conditions for Human Occupancy.

Bell E., Eisner L., Young J., Oetjen R. 1960., Spectral-Radiance of Sky and Terrain at Wavelengths between 1 and 20 Microns. II. Sky Measurements. J Opt Soc Am 50, 1313–1320. doi:10.1364/JOSA.50.001313.

Hassan H.Z., Mohamad A.A., 2012. A review on solar cold production through absorption technology. Renew Sustain Energy Rev 16, 5331–5348.

Hunter K., Kiffmeye D., 2004. Earthbag building: the tools, tricks and techniques. 1st ed., New Society Publishers. Gabriola Island, BC, Canada.

Kaygusuz K., 2012. Energy for sustainable development: A case of developing countries. Renew Sustain Energy Rev 16, 1116-1126.

Khalili E.N., Earthquake resistant building structure employing sandbags, US5934027A (1999). https://patents.google.com/patent/US5934027A/en (accessed April 6, 2018).

Peel M.C., Finlayson B.L., McMahon T.A., 2006. Updated world map of the Köppen-Geiger climate classification. Meteorol Zeitschrift 15, 259–263. doi:10.1127/0941-2948/2006/0130.

Vall S., Castell A., 2017. Radiative cooling as low-grade energy source : A literature review. Renew Sustain Energy Rev 77, 1–18. doi:10.1016/j.rser.2017.04.010.

Vall S., Johannes K., David D., Castell A., 2018. A new flat-plate radiative cooling and solar collector numerical model: evaluation and metamodeling. App Energy, submitted.

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