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Simplified Method for Night Sky Radiation Analysis in a Cool-Pool System

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Abstract The conventional mechanical building cooling systems are energy demanding equipment. Needing for low-energy consumption systems is a motivation for utilizing ambient energy resources such as ground, ambient air, sky and water as alternative resources. Night sky can be a good candidate as a heat sink to be used in cooling systems. The present study proposes and presents a simplified method for computing net outgoing energy exchanged between night sky and a cool-pool in a building cooling system. Considering a real night condition with a 3 m × 4 m pool and overall energy conversion efficiency of 75%, we obtained that the aforementioned system can replace a 4000 watts swamp cooler works for 6 hours a day.

Keywords: *building passive cooling, night sky radiation cooling, cool-pool*

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1. Introduction

The global energy consumption is growing, and simultaneously, the conventional energy sources are depleting. On the other hand, climate change and global warming have recently raised concerns all over the world. The building sector comprises 40% of the total energy consumption [1], while the remarkable part of this includes heating, cooling and artificial ventilation systems [2]. Finding and integrating alternative low-energy consumption and environmental-friendly systems in the buildings would be the only response to the above problems. Zero energy building (ZEB) is a concept based on minimized energy demand and maximized harvest of local renewable energy resources. Here, we consider the thermal aspect of a ZEB while the electrical aspect is studied in reference [3].

Lots of research and review works have been carried out in these areas which usually focus on describing and modeling alternative systems. Leo Samuel [4] reviewed some passive alternatives of mechanical air conditioning systems for buildings. Bagiorgas and Mihalakakou [5] used an aluminum nocturnal radiator to find the dynamic thermal operating performance of such system in the summertime. Considering passive cooling systems, rejection of unwanted heat can be generally achieved by the following methods [6]: shading from sun, reflection of solar heat, insulation, ground cooling, wind cooling (natural breeze or induced convection), water cooling, evaporative cooling, dehumidification, night radiant cooling, night cooling of thermal mass in buildings, exotic passive cooling methods and seasonal cold storage.

Due to the diversity of such systems, night radiant cooling is considered in this paper. The most sky-exposed part of a building, its roof, provides the opportunity of using sky as a heat sink at night. Heat is dissipated through all three mechanisms of heat transfer to ambient: conduction, convection and radiation [7]. The primary mechanism is radiation and such systems are referred to cool-pool. A schematic of the system is shown in Figure 1. Karen Crowther and Melzer introduced this system for the first time in 1979, in USA [7]. A cool-pool uses the storage of water on the top of the building to mediate the room temperatures. During night time, the insulating panels are removed and water is exposed to sky, so that considerable amounts of heat is mainly removed by radiation to the night sky. As the ambient temperature rises in the morning, the insulation is put in place to protect water from direct solar radiation and heat interaction with the surroundings. Most experts agree that the areas with night time temperatures ranging from 45°F to 55°F are the best potential places. It would work best in an area with cold-clear nights at a dry-desert type climate.

2. Night Radiant Cooling

2.1. Radiation from Sky

To calculate the incoming downward radiation from sky, we can utilize the so-called Stefan-Boltzmann law, but this method will not reach to result if we don't know the night-sky temperature. Instead, the ambient temperature can be measured and then the radiation will be calculated using some experimental models like the modified Swinbank model as [8]:

$$\dot{q}_{sky} = \vartheta(1+kc^2)T_a^{5.852}\varphi^{0.07195} \tag{1}$$

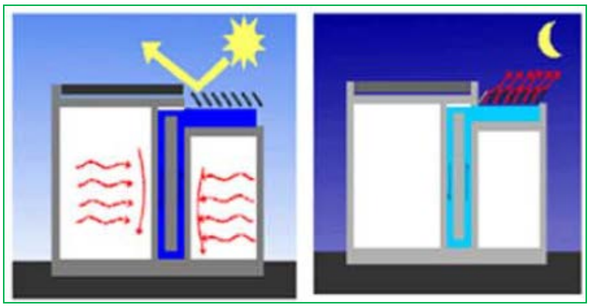

Figure 1. Cool-pool operation during day (left) and night (right)

where $\dot{q}_{sky}$, T_a and φ denote the incoming downward sky radiation (W/m^2), the ambient absolute temperature (K) and the percentage of relative humidity, respectively. Also, the correction factor of $1+kc^2$ is defined for a cloudy sky. The dimensionless parameters k and c are used to account the effect of cloud on sky radiation (Table 1) and ϑ is a constant equal to 8.78×10^{-13}.

The outgoing radiation from water body can be calculated using the Stefan-Boltzmann law given by Eq. (2).

$$\dot{Q}_{water} = A\varepsilon\sigma T_w^4 \tag{2}$$

where $\dot{Q}_{water}$ is the radiated power from cool-pool water, A is the surface area (m^2) and T_w is the water absolute temperature (K), σ is the Stefan-Boltzmann constant and ε is its emissivity. Assuming a suitable value for sky emissivity, Eq. (2) can also be used to determine the night sky temperature. Generally, calculating the sky emissivity is important because of its application in radiation cooling as well as determining solar collector losses [9]. In some literatures, some methods have been investigated to correspond sky emissivity with other important parameters such as dew point [7,8], but in the present work, we assume ε_{sky} to be *0.74*. The sky emissivity (ε_{sky}) is defined in a way, so that Eq. (1) can be rewritten in the following form [10]:

$$\dot{q}_{sky} = \varepsilon_{sky}\sigma T_a^4 \tag{3}$$

where T_a is the ambient absolute radiative temperature. It means that sky acts as a gray body with the absolute temperature equal to ambient and apparent emissivity of ε_{sky}. According to the following equation, we conclude that ε_{sky} can be found by [10]:

$$\varepsilon_{sky} = \left(\frac{T_s}{T_a}\right)^4 \tag{4}$$

Here, $\dot{q}_{sky}$ is measured using a pyrgeometer then, by dividing the data by σT_a^4, the sky emissivity can be expressed by fitting a curve usually with least square lines [11]. The net rate of energy loss $\dot{Q}_{net}(W)$ from water body with area A can be computed using Eq. (5), where $\dot{Q}_{sky}$ is the downward radiation power on the surface with area A.

$$\dot{Q}_{net} = \dot{Q}_{water} - \dot{Q}_{sky} \tag{5}$$

2.2. Radiation Cooling Time

For a case with just outgoing radiation from an object assuming no work done, the total energy loss or gain can be expressed by:

$$\dot{E} = \dot{Q}_{out} = A\varepsilon\sigma T^4 \tag{6}$$

Where, E is the internal energy. If a pure translational kinetic energy theory can be utilized, according to the equipartition of energy, the object's energy will be described as:

$$E = \frac{3}{2}kNT = \frac{3kmN_A}{2M}T \tag{7}$$

where $k = 1.38\times10^{-23}\,m^2 kg\, s^{-2}\, T^{-1}$ is the Boltzmann constant, N is the number of mole, $N_A = 6.02\times10^{23}$ is the Avogadro's number and m and M are mass and molar mass, respectively. By substituting Eq. (6) in Eq. (7), we obtain the required cooling time Δt in order to reach the final temperature T_f from the initial temperature T_i as:

$$\Delta t = \frac{mN_A k}{2M\varepsilon\sigma A}\left(\frac{1}{T_f^3} - \frac{1}{T_i^3}\right) \tag{8}$$

Luciuk [12] utilized Eqs. (7) and (8) using a scale of $\dfrac{\dot{Q}_{out}}{\dot{Q}_{net}}$ to find the real required cooling time for an object exposed to night sky. But our present work shows that the specific heat wasn't considered in his research. For example, aluminum has a specific heat C of 900 $J/kg.K$ [13] at 300 K, but using the above method shows an apparent specific heat of 460 $J/kg.K$ with the defining of $E = mCT$. The main reason is the allocating of one equal average kinetic energy to all of the body particles.

Assuming internal energy of a liquid or solid to be the product of mass m, specific heat C and temperature T, we obtain the exact governing differential equation for water temperature using Eq. (5) and Eq. (6).

$$mC\frac{dT}{dt} = -A\varepsilon\sigma T^4 + A\dot{q}_{sky} \tag{9}$$

where $\dot{q}_{sky}$ is a function of time. But, for a period of time with constant ambient temperature, $\dot{q}_{sky}$ is constant and the nonlinear differential Eq. (9) can be solved analytically by separating variables method. The final answer is:

$$\Delta t = \frac{a}{4b^3}\left[\ln\left[\frac{|T_i - b|(T_f + b)}{|T_f - b|(T_i + b)}\right] + 2\tan^{-1}\left(\frac{T_f}{b}\right) - 2\tan^{-1}\left(\frac{T_i}{b}\right)\right] \tag{10}$$

where T_i and T_f are the initial and final temperatures of water,

$$a = \frac{mC}{A\varepsilon\sigma} \tag{11a}$$

and

$$b = \left(\frac{\dot{q}_{sky}}{\varepsilon\sigma}\right)^{\frac{1}{4}} \tag{11b}$$

The emissivity of water in Eqs. (11 a, b) is 0.95 [13]. The required cooling time is a strong function of mass and specific heat. The mass of water used in the cooling system can be found, if the cooling load is known.

Table 1. Values of parameters *c* and *k* in the modified Swinbank sky radiation model

	no cloud (clear sky)	overcast sky		
		hight<2km	*2km<hight<5km*	*5km<hight*
c	0	0.34	0.18	0.06
k	0	variable from 0 to 1 depending on the cloud coverage		

3. Results

Figure 2 and Figure 3 show the variations of $\dot{q}_{sky}$ with ambient temperature and relative humidity for clear sky.

Considering Figure 2 and Figure 3, we obtain that $\dot{q}_{sky}$ is a linear function of ambient temperature and relative humidity. In Figure 2, $\dot{q}_{sky}$ shows a linear trend with temperature at constant relative humidity; while Figure 3 demonstrates the linear trend of incoming sky radiation with relative humidity at constant ambient temperature (for $\varphi > 20$, the difference between the line and the curve is less than 1 W/m^2). The linear behaviors are extracted as the following equations.

$$\dot{q}^{\varphi}_{clear\ sky} = \alpha_1 T + \beta_1 \tag{12}$$

$$\dot{q}^{T}_{clear\ sky} = \alpha_2 \varphi + \beta_2 \tag{13}$$

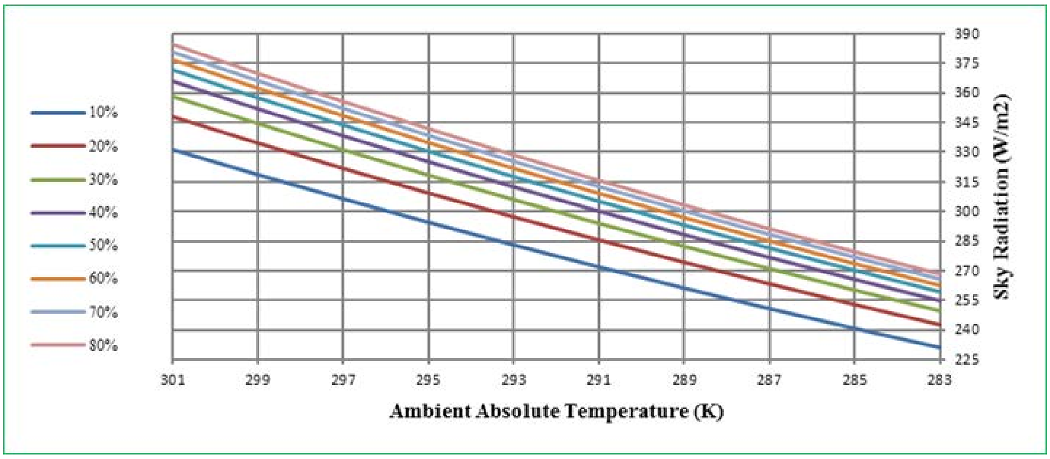

Figure 2. Variation of night sky radiation with ambient temperature and different relative humidity

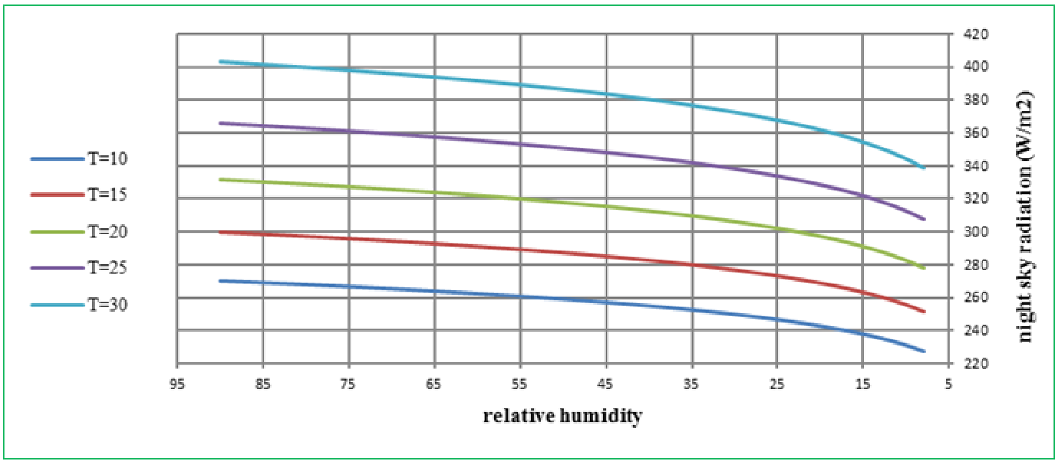

Figure 3. Variation of night sky radiation with relative humidity and different ambient temperatures

where the superscript denotes constant variables. Then the total energy received from sky per unit area, $q_{clear\ sky}$, during period Δt can be theatrically calculated as below when the ambient temperature and relative humidity change from T_1 to T_2 and φ_1 to φ_2, respectively.

$$q_{clear\ sky} \approx \int_{t_1}^{t_2} \dot{q}^{\varphi}_{clear\ sky} dt \approx \int_{t_1}^{t_2} \dot{q}^{T}_{clear\ sky} dt \tag{14}$$

or

$$q_{clear\ sky} \approx \int_{t_1}^{t_2} (\overline{\alpha_1} T + \overline{\beta_1}) dt \approx \int_{t_1}^{t_2} (\overline{\alpha_2} \varphi + \overline{\beta_2}) dt \tag{15}$$

where $\overline{\alpha}_i$ and $\overline{\beta}_i$ are the averages of slope and vertical-axis intersect of the lines, respectively, at the end points or midpoints according to their variation with time. Now we should decide choosing between the first or the latter integrals. The calculation is continued using the first one, because the function behavior is really more similar to straight line than the latter. Another reason appears when we use differential of temperature, instead of time. So, the following correlation may be achieved.

$$q_{clear\ sky} \approx \int_{T_1}^{T_2} \frac{(\overline{\alpha_1 T + \beta_1})}{\dfrac{dT}{dt}} dT \tag{16a}$$

Assuming linear change of *T* with *t*, we have:

$$q_{clear\ sky} \approx (\overline{\alpha_1}\overline{T} + \overline{\beta_1})\Delta t \tag{16b}$$

Where, $\overline{T}$ is the mean temperature during night time. As the following real example shows, the variation of temperature during night can be considered linear but it is not true about relative humidity. So, the integral can be calculated with good approximation. For the surface area of *A*, we use the following relation.

$$Q_{clear\ sky} = (\overline{\alpha_1}\overline{T} + \overline{\beta_1}) A\Delta t \tag{17}$$

The values of α_1, β_1, α_2 and β_2 can be found in Table 2 and Table 3. The numbers are generated using the least mean squares line method.

Table 2. Values of α_1 and β_1 in Eq. (15) and Eq. (16)

φ	10	12	14	16	18	20	22	24
α_1	5.5682	5.6417	5.7047	5.7597	5.8087	5.8529	5.8932	5.9302
$-\beta_1$	1347.1	1364.9	1380.2	1393.5	1405.3	1416.0	1425.8	1434.7
φ	26	28	30	32	34	36	38	40
α_1	5.9645	5.9964	6.0269	6.0542	6.0807	6.1058	6.1296	6.1522
$-\beta_1$	1724.0	1450.7	1458.0	1464.7	1471.1	1477.2	1496.0	1488.4
φ	42	44	46	48	50	52	54	56
α_1	6.1739	6.1946	6.2144	6.2335	6.2518	6.2695	6.2865	6.3030
$-\beta_1$	1493.7	1498.7	1503.5	1508.1	1512.5	1516.8	1520.9	1524.9
φ	58	60	62	64	66	68	70	72
α_1	6.3189	6.3344	6.3493	6.3639	6.3780	6.3917	6.4050	6.4180
$-\beta_1$	1528.8	1532.5	1536.1	1539.6	1543.1	1546.4	1549.6	1552.7
φ	74	76	78	80	82	84	86	88
α_1	6.4307	6.4430	6.4551	6.4668	6.4783	6.4896	6.5006	6.5113
$-\beta_1$	1555.8	1558.8	1561.7	1546.6	1567.3	1570.1	1572.7	1575.3

Table 3. Values of α_2 and β_2 in Eqs. (15) and (16)

T (°C)	9	10	11	12	13	14	15	16
α_2	0.43414	0.44322	0.42247	0.46187	0.47144	0.48116	0.49106	0.50112
$-\beta_2$	0.43414	234.69	239.59	244.57	249.63	254.78	260.02	265.35
T (°C)	17	18	19	20	21	22	23	24
α_2	0.51135	0.52176	0.53234	0.54310	0.55403	0.56516	0.57646	0.58795
$-\beta_2$	270.76	276.28	281.88	287.58	293.37	299.26	305.24	311.33

Table 4. Specification of the considered cooling pool

Water density	Water Emissivity	Water Depth	Cool-pool Length	Cool-pool Width
990 kg/m^2	0.98	30 *mm*	4 *m*	3 *m*

Table 5. Required data and radiated energy for the 1st day of August 2013 in Isfahan, Iran

Time	Temperature	Dew Point	Relative Humidity	30-min Radiation (kJ/m^2)
12 AM	31.0°C	4.0°C	18%	658.96
12:30 AM	31.0°C	4.0°C	18%	658.96
1:00 AM	31.0°C	4.0°C	18%	658.96
1:30 AM	31.0°C	6.0°C	21%	666.31
2:00 AM	30.0°C	5.0°C	20%	651.29
2:30 AM	29.0°C	6.0°C	23%	645.27
3:00 AM	29.0°C	6.0°C	23%	645.27
3:30 AM	28.0°C	9.0°C	30%	645.08
4:00 AM	28.0°C	10.0°C	32%	648.08
4:30 AM	28.0°C	10°C	23%	632.86
5:00 AM	28.0°C	10.0°C	32%	648.08
5:30 AM	28.0°C	9.0°C	30%	645.08
6:00 AM	26.0°C	9.0°C	34%	626.01
6:30 AM	25.0°C	9.0°C	36%	616.39
7:00 AM	26.0°C	8.0°C	32%	623.29
7:30 AM	25.0°C	7.0°C	32%	611.18

The coefficients listed in Table 2 and Table 3 are used to measure the clear sky radiation. The correction factor of $1 + kc^2$ should then be introduced to the final result. To calculate the night sky radiation cooling potential, the following steps shall be taken:

- Preparing a datasheet of hourly ambient temperature, relative humidity and cloudiness degree.
- Finding the mean temperature as well as the coefficients of Eq. (15) using Table 2 and Table 3 based on the most occurred relative humidity.
- Calculating the total radiation energy on the surface, using Eq. (16).
- Correcting the total radiation energy by introducing the cloudiness degree, using Table 1.
- Using Eqs. (10) and (11) to find the required time or temperature.

In Table 4, the first three columns show the required meteorological data and radiated energy for the first of August, 2013 (a sample day in summer) in Isfahan, Iran [14]. We use the above simplified model and compare the results. For $\varphi = 18$ and $\varphi = 32$ (two typical relative humilities), we have $\alpha_1 = 5.8529$, $\alpha_2 = 6.0542$, $\beta_1 = -1405.3$ and $\beta_2 = -1464.7$, hence $\bar{\alpha}_1 = 5.9536$, $\bar{\beta}_1 = -1435.0$ and $\bar{T} = 28°\mathrm{C}$ is taken as the linear average of T_1 and T_2. Using Eq. (16), the result is $q_{clear\ sky} = 10282\,kJ/m^2$ or equally, $\dot{q}_{sky} = 380\,W/m^2$ which is very close to the total radiated energy in Table 4. A cool-pool with the specifications in Table 5 is considered in this study. Using Eqs. (10) and (11), it is understood that the required time to reach the water temperature from $T_i = 25°\mathrm{C}$ to $T_f = 8°\mathrm{C}$ is nearly 7 hours, which is less than the available time (7 hours and 30 minutes).

A conventional 4000 *W* room cooler which works for 6 hours a day, consumes 86400 *kJ* of electricity. Our calculated cool-pool system with dimensions of 3 *m* × 4 *m* has an ideal cooling capacity *L* of about

$$L = Aq_{clear\ sky} = 12 \times 10282 = 120000kJ \tag{18}$$

which seems that compensate all the day cooling demands. Figure 4, based on Eq. (10), shows the temperature variation with time using the aforementioned model. Because we used the mean radiation value, the required time will be more but still less than the available night time.

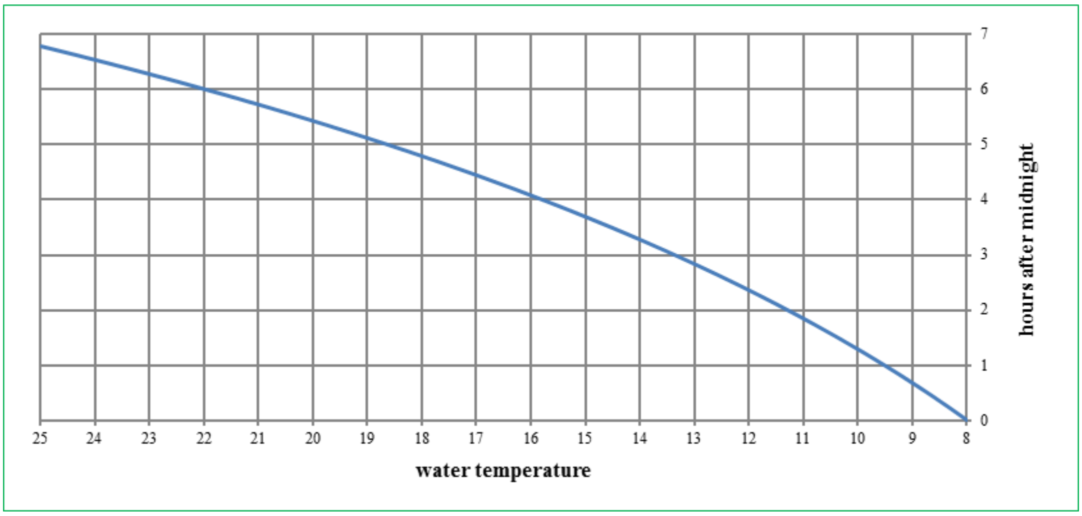

Figure 4. Variation of cool-pool water temperature with time

4. Conclusions

A simplified model was developed with good accuracy to calculate the night sky radiation. Also, a step-by-step procedure was proposed to use the model. An example was solved to show that the system can be a real alternative for a small building. The system is best suited with the desert-type climate. The real example has shown that such system can be an alternative to the conventional air cooling systems for houses and apartments. A 12 m^2 cool-pool in Isfahan (a city in Iran) with 75% efficiency can replace a 4 *kW* swamp cooler which is widely used during summer in hot and dry provinces in Iran.

The passive cooling system described in this paper does not actually have a separate storage medium. A storage medium is an essential part of a renewable system owing to its intermittent nature. It is recommended to use a phase change material (PCM) medium in the building envelop so that it is cooled by the chilled water in the pool. In this way, the reliability of the system will increase, whereas its efficiency will decrease due to the use of a new heat exchanger. It is recommended that the thermodynamic behavior of the aforementioned system would be simulated and compared with Crowther and Melzer design.

Nomenclature

α : Slope of a line
β : *y*-axis intersect of a line
a, b : Constants in Δt formula
T : Absolute temperature
T_a : Ambient absolute temperature
T_w : Water absolute Temperature
T_s : Sky absolute Temperature
T_i : Initial absolute temperature of water
T_f : Final absolute temperature of water
q_{sky} : Downward sky energy in Δt per unit area
$\dot{q}_{sky}$: Incoming sky radiation per unit area
Q_{sky} : Incoming sky radiation energy during Δt
$\dot{Q}_{sky}$: Incoming sky radiation
$\dot{Q}_{water}$: Radiated power from cool-pool water
$\dot{Q}_{out}$: Outgoing radiation
$\dot{Q}_{net}$: Net rate of the energy loss
φ : Percentage of relative humidity
k, c : Dimensionless parameter in Swinbank model
A : Surface Area
ε : Emissivity
ε_s : Sky emissivity
σ : Stephan-Boltzmann constant
N : Number of mole
N_A : Avogadro's number

k : Boltzmann constant
E : Internal energy
m : Meter
m : Mass
M : Molar mass
Δt : Cooling time
C : Specific heat
L : Cooling capacity
$\overline{x}$: Average of variable x
$\dot{x}$: Change rate of variable x
W : Watt
J : Joule
K : Kelvin scale
s : Second

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