The Study of Sky Emissivity in Thailand

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Abstract

Theoretical studies of sky emissivity in Thailand are summarized in this paper. The emissivity of clear sky was calculated based on monthly averaged upper air data (1997) obtained from four main stations of meteorological department, namely, Bangkok, Chiang Mai, Songkhla and Ubon Ratchathani. Sky emissivity as a function of water vapor optical depth was computed. Calculation results show that the sky emissivity was in the range of 0.8-0.875. The emissivity of sky at Chiang Mai was lower than the other locations during December-April. The application of the downward long-wave radiation in nocturnal passive cooling system is also discussed.

1. Introduction

The magnitudes of radiative exchange especially long-wave radiation depend mainly upon the power four of temperature difference of two arbitrary surfaces, surface emittance, view or shape factor and the constant term, named after Stefan-Boltzmann [1]. Long-wave radiation exchange near the ground surface is the result of earth-atmosphere energy balance. Some of the atmosphere constituents, for instance, water vapor, CO_2, O_2, O_3, aerosol and trace gas absorb upward terrestrial long-wave radiation and then re-radiate downward, therefore, keeping the warmth for objects on the earth. The characteristic of spectral atmospheric absorption is shown in Fig. 1.

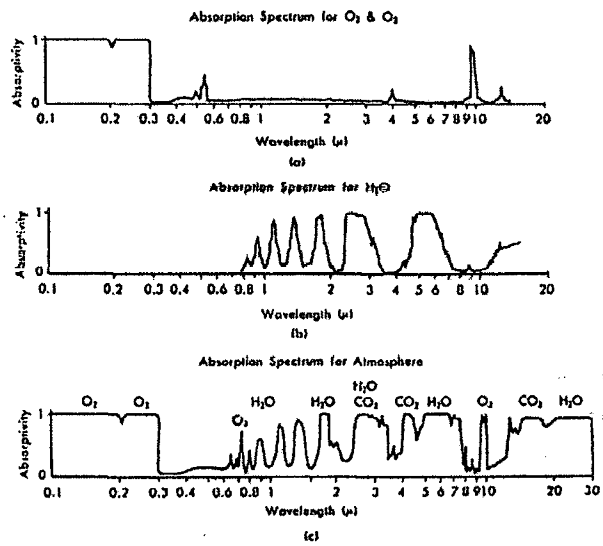

Fig. 1. Spectral atmospheric absorption [2].

Downward atmospheric radiation is difficult to measure as the environment and instrument temperatures are very close. Moreover, the cost of measurement is rather high. Although, there was some effort to correlate the downward atmospheric radiation to some surface meteorological parameters in Thailand, however, the results have not been published yet. Consequently, the study of sky emissivity seems to be a practical solution to attain either downward atmospheric radiation or sky temperature.

The study of sky emissivity in Thailand began in 1978 by R. H. B. Exell [3]. Total emissivity of sky as a function of optical depth at Bangkok was calculated using upper air data, which obtained from meteorological department. The downward atmospheric radiation was estimated. Results showed that downward atmospheric radiation at night was 384 W/m^2 approximately.

Subsequently, P. Boon-Long [4] calculated the long-wave spectral emissivities of sky at Chiang Mai using upper air data by assuming "Clear Skies". Calculations were conducted using monthly averaged upper air data obtained for the year 1970. The spectral emissivity of sky is a function of density-length product (m_g) of water vapor as given in Eq. (1).

$$\varepsilon_{\lambda} = 1 - \exp(-K_{\Delta\lambda} m_g) \qquad (1)$$

Where ε_{λ} is the emissivity in the wavelength range $\Delta\lambda$

$K_{\Delta\lambda}$ is the absorption coefficient of water vapor [5]

m_g is the density-length product of water vapor in the sublayer [6].

Calculation results showed that the spectral atmospheric emissivities were in the range of 0.77-0.87.

Later, B. Givoni [7] reviewed the cooling by long-wave radiation and derived a formula for the emssivity of clear sky as a function of dew point (in °C) as given in Eq. (2).

$$\varepsilon_S = 0.787 + 0.0028 T_{dp} \qquad (2)$$

In 1990, Skarviet et al [8] formulated emissivity of sky under cloudless and cloudy sky by using empirical formula expressing the downwelling irradiance simply in terms of scaled surface air temperature (T_S / T_*) and scaled surface water vapor pressure (e_S / e_*) as given in Eq. (3).

$$\varepsilon = \varepsilon\left(\frac{T_S}{T_*}, \frac{e_S}{e_*}\right) = \frac{\phi}{\sigma T_S^{\,4}} \qquad (3)$$

Where ε is dimensionless atmospheric emittance

ϕ downwelling irradiance at the horizontal surface.

σ Stefan-Boltzmann constant

T_S surface air temperature in Kelvin.

The results showed that emissivities of sky under cloudless (ε_O) as a function of surface air temperature and surface dew point temperature are expressed in Eqs. (4) and (5) respectively.

$$\varepsilon_O = \frac{\phi_O}{\sigma T_S^{\,4}} = \left(\frac{T_S}{T_*}\right)^2 \qquad (4)$$

Where ϕ_O is downwelling irradiance originated under clear sky

T_* is equal to 326.8 K for the Swinbank (1963) formula and 317.8 K for the Czeplak and Kasten (1987) formula.

$$\varepsilon_O = a + \left(\frac{t_{ds}}{t_*}\right) \qquad (5)$$

Where a is 0.745

t_{ds} is surface dew point temperature

t_* is 179 °C for the Frank and Püntener (1986) formula.

Furthermore, the effect of clouds on sky emissivity was also formulated and an expression was developed by Martin and Berdahl (1984). The sky emissivity increased

$(\varepsilon - \varepsilon_O)/(1 - \varepsilon_O)$ in terms of the temperature difference $\Delta T_C = T_S - T_C$, the cloud emittance (10-12 μm) and fractional cloud cover (n) as given in Eq. (6).

$$\frac{\varepsilon - \varepsilon_O}{1 - \varepsilon_O} = n\varepsilon_C \exp\left(-\frac{\Delta T_C}{\Delta T_O}\right) = n\varepsilon_C \exp\left(\frac{\gamma h_C}{\Delta T_O}\right) \quad (6)$$

Where $\Delta T_O = 46\,K$

$\Delta T_C = -\gamma h_C$ is given by the cloud base height h_C and the average sub-cloud temperature gradient γ (-5.6 K/km by Martin and Berdahl).

Recently, clear sky emissivity as a function of the zenith direction was established by C. N. Awanou [9] as given in Eq. (7).

$$\varepsilon_{(\lambda,\theta)} = 1 - \exp - \frac{k_{\lambda,g} \cdot m_{\lambda,g}}{\cos\theta} \quad (7)$$

Where $k_{\lambda,g}$ is the spectral absorption coefficient of the gases

$m_{\lambda,g}$ is the absorber amount in g/cm^2

$k_{\lambda,g} \cdot m_{\lambda,g}$ is the equivalent absorber in g/cm^2

Absorber amount in Eq. (7) is related to water vapor only but the integral take into account all other gases. The hemisphere integral of Eq. (7) conducts to spectral emissivity as expressed in Eq. (8).

$$\varepsilon_\lambda = 1 - \exp - \left[1.8 \cdot k_{\lambda,g} \cdot m_{\lambda,g}\right] \quad (8)$$

The expression of the emissivity in the direction for θ different from 90 can be deduced from Eq. (7) and (8). Rearranging Eq. (8) in term of $k_{\lambda,g} \cdot m_{\lambda,g}$ and then substituting it in Eq. (7) yields:

$$\varepsilon_\theta = 1 - (1 - \varepsilon_\lambda)^{1/1.8\cos\theta} \quad (9)$$

$$\varepsilon_\theta = 1 - (1 - \varepsilon_\lambda)^{\cos 56.25/\cos\theta} \quad (10)$$

From the review above, it can be concluded that there are two main studies of sky emissivity: total and spectral sky emissivity under clear or cloudless and cloudy skies. In this study, the total emissivity of sky as a function of optical depth was computed using monthly averaged upper air data (1997), which obtained from four main stations of meteorological department, ministry of science, technology and environment (MOSTE) shown in Fig. 2.

Fig. 2. Meteorological stations reporting upper air data.

2. Calculation Procedure [10]

The precise calculation of sky emissivity, which has contributions from absorber gases, water vapor, CO_2, O_3, aerosols and other trace gas emitters in the atmosphere, is rarely due to an overlapping of the water vapor and CO_2 emission spectra that has to be taken into consideration. However, emissivity of sky can be computed with the acceptance of little errors by treating sky emissivity as a function of the water vapor optical depth u at standard temperature 273.15 K and pressure 1013.25 mbar only.

The total sky emissivity can be obtained by using Eq. (11).

$$\varepsilon_T = \int_{z=0}^{\infty} \left(\frac{T_{(z)}}{T_{(0)}} \right)^4 d\varepsilon(F) \qquad (11)$$

The integral can be evaluated numerically by

$$\sum_{i=0}^{n} \left(\frac{T(z_{i+1}) + T(z_i)}{2T(o)} \right)^4 \left[\varepsilon_F(z_{i+1}) - \varepsilon_F(z_i) \right] \qquad (12)$$

Where T and ε are calculated at a succession of different height z_i. The sky emissivity as a function of water vapor optical depth can be computed starting from the calculation of the amount of precipitable water vapor m in a column of air with vapor pressure e (millibars), absolute temperature T (kelvins) and height h (meter):

$$m = 0.021668 \frac{eh}{T} \text{ centimeter} \qquad (13)$$

The quantity of precipitable water vapor at standard temperature and standard pressure could be used for the optical depth u to find emissivity (Table 1). Actually the emissivity depends on temperature and pressure as well as on m. However, the effect of temperature is small [11] and may be neglected. The pressure effect may be taken into account by using a pressure corrected optical depth $u = m(P/P_O)^{0.8}$ for a layer at pressure P containing precipitable water m. Thus, the practical formula to calculate the pressure corrected optical depth of a layer containing vapor pressure e (millibar), height Δz (meter), temperature T (Kelvin) and pressure P (millibar) is given in Eq. (14).

$$\Delta u = 0.0214 e \left(\frac{\Delta z}{T} \right) \left(\frac{P}{1000} \right)^{0.8} \qquad (14)$$

The vapor pressure e is conveniently found from the relative humidity Rh expression given in Eq. (15).

$$Rh = \frac{e}{E(T)} (\times 100\%) \qquad (15)$$

Where $E(T)$ is the saturation vapor pressure which can be calculated using the following formula

$$E(T) = 6.1 \times exp \frac{[17.3(T - 273.2)]}{T - 35.9} \qquad (16)$$

The unit of saturation vapor pressure is millibar. The pressure corrected optical depth Δu of the different layers were calculated using data from Table 1. in Eq. (14). The total optical depths u were obtained by summing the values of Δu. The flux emissivities $\varepsilon_F(z)$ were obtained from the total optical depth with the help of the data in Table 1. The total emissivities were then computed using Eqs. (11) and (12). Their sum is an approximation to the integral in Eq. (11) for the total sky emissivity ε_T.

Table 1. Atmospheric flux emissivity ε_F versus pressure corrected water vapor optical depth u (cm of precipitable) [11].

$Log_{10}u$	u	ε_F	$Log_{10}u$	u	ε_F
-2.0	0.0100	0.410	-0.5	0.3160	0.692
-1.9	0.0126	0.427	-0.4	0.3980	0.710
-1.8	0.0158	0.445	-0.3	0.5010	0.728
-1.7	0.0200	0.464	-0.2	0.6310	0.745
-1.6	0.2510	0.483	-0.1	0.7940	0.763
-1.5	0.0316	0.503	0.0	1.0000	0.780
-1.4	0.0398	0.523	0.1	1.2600	0.797
-1.3	0.0501	0.542	0.2	1.5800	0.814
-1.2	0.0631	0.562	0.3	2.0000	0.831
-1.1	0.0794	0.581	0.4	2.5100	0.847
-1.0	0.1000	0.600	0.5	3.1600	0.863
-0.9	0.1260	0.619	0.6	3.9800	0.879
-0.8	0.1580	0.637	0.7	5.0100	0.894
-0.7	0.2000	0.656	0.8	6.3100	0.910
-0.6	0.2510	0.674	0.9	7.9400	0.925
			1.0	10.000	0.940

3. Results and Discussion

Based on monthly averaged upper air data (1997), the calculation results of total sky emissivity at four main stations where the upper air data are available are shown in Fig. 3. It was found that, total sky emissivity was in the range of 0.8-0.875. Results showed good agreement when compared to the results calculated previously. Sky emissivity at Chiang Mai was lower than the other stations during December-April.

From the results, it can be interpreted that the variations of sky emissivity as a function of water vapor optical depth u in Northern and Northeastern region of Thailand (Chiang Mai and Ubon Ratchathani) depended on the amount of water vapor, which was affected by the north-east monsoon during November-April (water vapor in the sky is rather low).

As a result, the application of cooling using long-wave radiation technique, such as cooling of building and natural agricultural cold storage in Thailand seems to be practicable in Northern Thailand. Finally, due to the change of atmosphere, increasing CO_2 and trace gas concentration and O_3 depletion, further study of sky emissivity due to the contribution of CO_2, O_3 and other trace gas emitter should be undertaken.

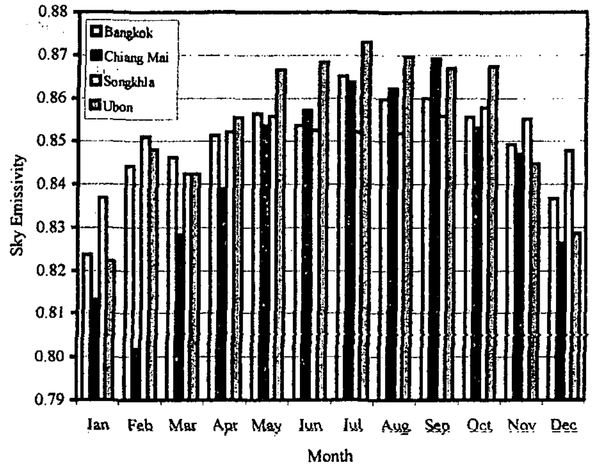

Fig. 3. Total sky emissivity from upper data.

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