Journal of Engineering and Technology
Vol. 1 No. 1 January – June 2013

Sky Temperature Estimation by Three Metallic Plates Method

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Abstract - **Sky temperature (T_{sky}) is an important parameter used in the design of solar collectors and nocturnal cooling systems. Thus, correct estimation of the T_{sky} is essential. In this study, a novel three-metallic-plate (3MP) method has been proposed for the T_{sky} estimation in which a principle of different heat exchange rates between each metallic plate and the sky dome has been used. The 3MP method uses three aluminium plates coated with various coating materials, which have different absorptivities. By measuring ambient temperature, absorptivities and plate temperatures of each plate and then taking these parameters into account in energy balance equation, the T_{sky} can be estimated. The 3MP experimental results were used to develop a correlation of T_{sky}, which were compared with those obtained using pyrgeometer and correlations proposed in previous studies. The results showed that the correlation developed based on the 3MP method can satisfactorily predict the T_{sky}. Therefore, the 3MP method can be a useful alternative of the T_{sky} estimation, which has advantages of simplicity and less monetary requirement.**

Keywords— **Sky temperature; Three-metallic-plate method; Atmospheric radiation; Modeling; Nocturnal cooling**

I. INTRODUCTION

Development and utilization of various renewable energy technologies (RETs) has increased in the global arena in recent years to reduce the fossil fuel dependency and combat global warming. One of the most popular RETs, especially in sunny and dry countries, is solar energy (thermal and photovoltaic). Solar thermal devices employ solar thermal collectors for heating and cooling purposes. One of the parameters influencing the performance is sky temperature (T_{sky}) [1, 2]. This is used to estimate (and therefore minimize losses) the thermal radiation exchanged between the surface of the collector and the sky.

The T_{sky} is defined as the temperature of blackbody radiation having the same flux as the downward atmospheric radiation [3], and is estimated by considering the long-wave radiation (Infrared radiation). The long-wave radiation rate depends on many parameters, namely, quantity of humidity contained in the atmosphere (dew-point temperature), nebulosity, time and position of the sun.

Generally, the T_{sky} is estimated by two methods; experimental and empirical. The experimental method uses instruments, and can be further categorized into two sub-methods, direct and indirect measurements. In direct measurement, pyrradiometer and pyrgeometer, which detect long-wave radiation directly from the sky, are employed. The long-wave radiation is automatically converted to the value of the T_{sky} using correcting factors and related equations. This direct measurement is convenient; however, these instruments are expensive, complex and need regular periodic calibration. On the contrary, in indirect measurement, long-wave radiation is not measured directly, but energy balance equations and the knowledge of heat transfer are applied in order to estimate the T_{sky}. Simple heat flux meter and metallic plates are examples of instruments used in this method. Though by indirect measurement, highly accurate results are difficult to obtain, but it is much less expensive and easy to be construct vis-à-vis the direct measurement. The second method of the T_{sky} estimation is by using empirical correlations by which T_{sky} can be quickly determined at very low cost. Nevertheless, the major disadvantage of the empirical method is that the agreement of T_{sky} results calculated by different correlations is very poor because each of the correlation was developed based on certain weather conditions or for a specific location [2, 4]

In this research, a novel indirect measurement called three-metallic-plate (3MP) method was developed and used to estimate the T_{sky}. The experimental results of the T_{sky} was determined and then used in developing an empirical correlation, as a function of solar radiation, dew-point temperature and ambient temperature. To validate, the T_{sky} results obtained from the developed correlation were compared with those obtained from meteorological data and correlations proposed in previous studies.

II. THEORY

A. Empirical Correlations of Sky Temperature Estimation Proposed in Previous Studies

In general, the T_{sky} is expressed in terms of the sky emissivity (ε_{sky}) and the ambient temperature (T_a) as

$$T_{sky} = \varepsilon_{sky}^{0.25} . T_a \qquad (1)$$

Nevertheless, in previous research, the sky emissivity have been proposed as a function of various parameters, e.g., zenith angle (θ), tenth cloud cover (F), dew-point temperature of ambient air (T_d), etc., depending on the experimental methods and conditions in which they were developed. In this research, previous correlations ex-

pressed in terms of T_d and T_a were used in the validation of 3MP-based correlation. These correlations are
Bliss's correlation [5]

$$T_{sky} = T_a(0.8004 + 0.039t_d)^{0.25} \qquad (2)$$

Clark and Allen's correlation [6]

$$T_{sky} = T_a(0.787 + 0.0028t_d)^{0.25} \qquad (3)$$

Berdahl and Fromberg's correlations [7]

For day time: $$T_{sky} = T_a(0.727 + 0.0060t_d)^{0.25} \qquad (4)$$

For night time: $$T_{sky} = T_a(0.741 + 0.0062t_d)^{0.25} \qquad (5)$$

where, t_d is the dew-point temperature of the air in degrees Celsius. Bliss (1961) is the first who developed a correlation for the T_{sky}. Most correlations that were developed later, e.g., Clark and Allen's, have been developed for the estimation during night time on which the T_{sky} has a linear function with the t_d. Berdahl and Fromberg's correlations (Eq. (4) and (5)) are the only correlations developed thus far for the T_{sky} estimation applicable during both day time and night time.

B. Principles of Three-Metallic-Plate Method

The 3MP method of T_{sky} estimation was developed on a basis of the two-metallic-plate (2MP) method proposed by Brau in 1997 [8]. The major improvement in 3MP method was that one more coated metallic plate was added into the instrument. By this modification, the T_{sky} could be estimated during daytime, which was not feasible by the 2MP method.

The three metallic plates were designed to be coated with different paintings, which have radiation absorptivities significantly different from each other, so that the effect of each parameter on the T_{sky} could be observed. The upper surface of the metallic plates was exposed to the sky, whereas the bottom surface was attached to an insulator in order to minimize heat transfer via the bottom of the plates. Therefore, as shown in Fig. 1, the thermal equilibrium of each plate is based on the net radiative heat transfer between the plate and the sky (Q_{emiss}), convective heat transfer between the plate and surroundings (Q_{conv}), heat absorbed on the plate from solar radiation (Q_{absorb}), and conductive heat transfer from the plate to the insulator (Q_{cond}).

$$Q_{emiss} + Q_{conv} + Q_{absorb} + Q_{cond} = 0 \qquad (\mathrm{W/m^2}) \quad (6)$$

Since the radiation absorptivity of a substance can be two values for two different ranges of radiation; short-wavelength (< 3 μm) and long-wavelength (> 3 μm), the Q_{absorb} and the Q_{emiss} was derived as a function of the absorptivity for short-wavelength (α') and for long-wavelength (α), respectively. From Fig. 1, assuming a) the sky emissivity as unity, b) the sky completely surrounds the 3MP instrument, and c) the three plates acts as black bodies ($\alpha = \varepsilon$), the energy balance equation for each metallic plate can be written as

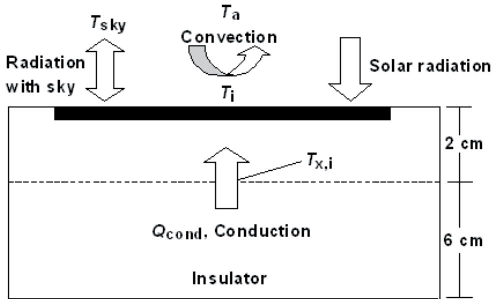

Fig. 1 Schematic of thermal equilibrium of each plate used in 3MP method

$$\text{Plate 1}: \alpha_1\sigma(T_{sky}^4 - T_1^4) + h_e(T_a - T_1) + \alpha_1^{'}E + \frac{k(T_{x,1} - T_1)}{x} = 0$$

$$\text{Plate 2}: \alpha_2\sigma(T_{sky}^4 - T_2^4) + h_e(T_a - T_2) + \alpha_2^{'}E + \frac{k(T_{x,2} - T_2)}{x} = 0 \quad (7)$$

$$\text{Plate 3}: \alpha_3\sigma(T_{sky}^4 - T_3^4) + h_e(T_a - T_3) + \alpha_3^{'}E + \frac{k(T_{x,3} - T_3)}{x} = 0$$

where, σ is the Stefan-Boltzman's constant (5.67×10^{-8} $\mathrm{W/m^2.K^4}$); h_e is the convective heat transfer coefficient ($\mathrm{W/m^2.K}$); E is solar radiation ($\mathrm{W/m^2}$); k is the thermal conductivity of the insulator ($\mathrm{W/m^2.K}$); and $T_{x,i}$ is the temperature at 2 cm beneath the plate i (inside the insulator). The parameters T_1 to T_3, $T_{x,1}$ to $T_{x,3}$, and T_a were measured by thermocouples. Using Eq. (7), T_{sky}, h_e and E can be determined.

III. EXPERIMENTAL

A. Description of 3MP Instrument

As mentioned in Section 2-B, the painting of each plate should have absorptivity significantly different from the others so that the effect of each parameter on the T_{sky} could be observed. Therefore, a black painting (Nextel-Veluet-Coating 2010), which has very high absorptivities in both short- and long-wavelengths, was coated on the first plate. On the other hand, a very poor absorber in all wavelengths, a silver painting was used for the second plate. The last plate was coated with a white painting, which is a very poor absorber in short-wavelengths but acts as a very good absorber in long-wavelengths. This makes the temperature of the white plate more responsive to the long-wave radiation, and so the T_{sky}.

TABLE 1 shows absorptivities of the three selected paintings of which the absorptivities for short-wavelengths and long-wavelengths were measured by Lambola 900 spectrometer and Infrared Fourier Transform Spectrometer of Bio-Rad, respectively. Each coating was painted on an aluminum plate, which had dimensions of 20 cm × 20 cm × 0.1 cm. The bottom of all plates were attached to a Glascofoam IV insulator having dimensions as described in Fig. 2. Six K-type thermocouples were set at various positions of the instrument; three in the middle of each plate at the interface between the plate and insulator to collect T_i and other three at 2 cm beneath the middle of each plate (inside the insulator) to $T_{x,i}$. The fabricated 3MP instrument is shown in Fig. 3. The relative humidity was measured using a Rotronic

Hygromer-C94 and the data of solar radiation were obtained from meteorological station at INSA, Lyon.

TABLE 1 : CHARACTERISTICS of the THREE SELECTED PAINTINGS

Plate	Painting	Absorptivity for λ<3μm (α')	Absorptivity for λ>3μm (α)
1	Black	0.94	0.95
2	Silver	0.28	0.32
3	White	0.33	0.90

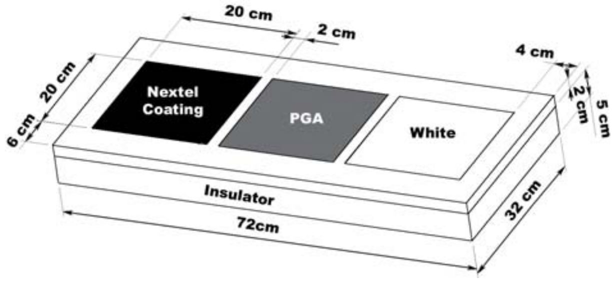

Fig. 2 Schematic diagram of the 3MP instrument

Fig. 3 Complete 3MP instrument

B. Data Collection

To verify that the developed model could be used at any location, experiments were carried out at different locations, i.e., a temperate and a tropical country represented by France and Thailand, respectively. Data collected from 3MP instrument in France was used to develop a correlation of T_{sky} estimation, whereas the data for Thailand was measured using direct measurement and used to validate the developed correlation.

The experiments were conducted at INSA-Lyon, France during June 25th to July 3rd, 2003. The data was collected in ten minute intervals and a total of seven hundred sets of data were collected. At AIT, Thailand, a pyrgeometer, CG1 of SCI-TEC INSTRUMENTS CO., LTD, was installed to directly measure long-wave radiation, and thus estimate the T_{sky}. Data collection was also done every ten minutes from June 5th to 16th, 2003 (1728 sets of data).

IV. RESULTS and DISCUSSION

A. Effect of Parameters on the Sky Temperature

By writing the energy balance equations, as stated in Section 2-B, the results of T_{sky} using 3MP method were determined. The results of T_{sky} were then analyzed based on different parameters, i.e., T_a, T_d, and E so as to investigate the effect of these parameters on the T_{sky}. The reason these parameters were selected for this analysis is because from the literature, T_a and T_d were the most responsive parameters on the T_{sky} and with the advantage of the 3MP method, the E is, for the first time, proposed as a parameter for the T_{sky} estimation (Note that all temperatures in the following sections are in °C).

All 751 sets of data were distinguished into two groups for day time (516 sets) and night time (235 sets), and were then converted into hourly basis. As a result, 93 and 39 sets of data were available for day time and night time, respectively.

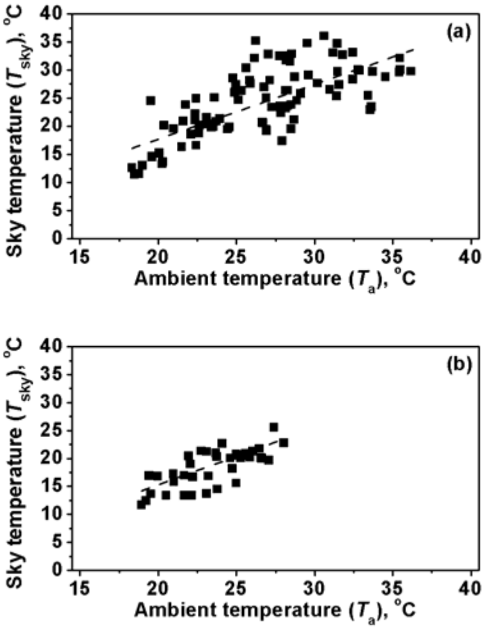

Fig. 4 Dependence of the sky temperature on the ambient temperature during (a) day time and (b) night time

Fig. 4 (a) and (b) shows the effect of the T_a on the T_{sky} during day time and night time, respectively. As expected, the T_{sky} was observed to have a linear relationship with the T_a, which is in concurrence with the observation in previous studies [5-7]. Using SPSS software, Pearson's correlation coefficient of these two parameters was found to be 0.704 and 0.737 for day time and night time, respectively. This implied that the influence of T_a on T_{sky} was stronger during night time than day time.

Previous studies [5-7] suggested that T_d is an important parameter affecting the T_{sky} both during day time and night time. However, using the 3MP method, the T_{sky} was noticed to be independent of the T_d during day time, as shown in Fig. 5 (a) in which the values of T_{sky} are scattered in the T_d range of 7–18°C. On the contrary, during night time, a linearly positive relationship between these parameters could be observed in the T_d range of 10–20°C with a Pearson's correlation coefficient of 0.595 (Fig.5 (b)). Based on the Pearson's correlation coefficient, the T_{sky} estimated by 3MP method was found to be influenced by T_a more than the T_d.

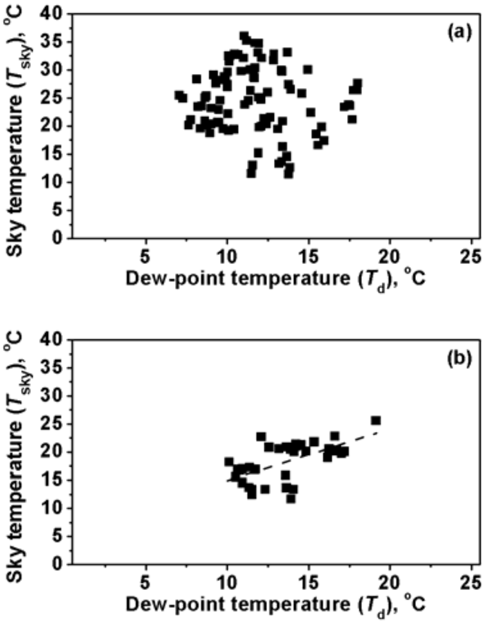

Fig. 5 Dependence of the sky temperature on the dew-point temperature during (a) day time and (b) night time

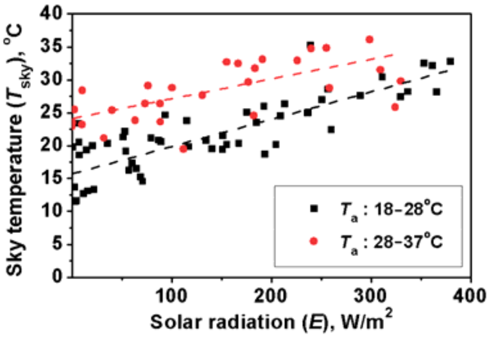

Fig. 6 Dependence of the sky temperature on the solar radiation segregated based on the different ranges of ambient temperature. Data in T_a ranges of 18–28°C and 28–37°C are represented by ■ and ● symbols, respectively

Dependence of the T_{sky} on the solar radiation (E) was observed during day time, as shown in Fig. 6. To identify the best correlation of T_{sky} as a function of E, the data were segregated on the basis of two different ranges of T_a, namely 18–28 °C and 28–37 °C. The solid line and dashed line in Fig. 6 represent the fitting lines of data used in correlation development in the T_a ranges of 18–28 °C and 28–37 °C, respectively. The Pearson's correlation coefficients were estimated to be 0.826 and 0.648 for both T_a ranges, respectively. Hence, the results of Pearson's correlation coefficient concurred that the T_{sky} was strongly dependent on the E.

B. Correlation Development

Based on the results of the effect of various parameters, i.e., T_a, T_d, and E, on the T_{sky}, a configuration of correlations for T_{sky} estimation was designed and developed. The correlations were designed to be used separately during day time and night time. The night-time correlation was developed as a function of the T_d and the T_a. The day-time correlations were further categorized into two sub-correlations (Eqs. (9–10)) for which the T_{sky} can be estimated for T_a ranges of 18–28°C and 28–37°C. In addition, the day-time correlations were developed as a function of E and T_a, since T_d had no effect on T_{sky} during day time. Note that some data at E above 400 W/m^2 were omitted and were not used in the correlation development since the data in that area were significantly scattered. Consequently, the developed correlations were obtained as follows:

For night time: $T_{sky} = -5.221 + 0.445T_d + 0.743T_a$ (8)

For day time:

T_a: 18–28°C; $T_{sky} = 0.181 + 3.175x10^{-2}E + 0.721T_a$ (9)

T_a: 28–37°C; $T_{sky} = 15.979 + 2.751x10^{-2}E + 0.268T_a$ (10)

C. Validation

The validation of the 3MP correlations were carried out by comparing results of T_{sky} obtained from the 3MP correlations with those measured by a pyrgeometer in Thailand and those estimated from previously proposed correlations. These previous correlations were those expressed as a function of T_a and T_d, i.e., those of Bliss [5], Clark and Allen [6], and Berdahl and Fromberg [7]. To verify the versatility of the 3MP correlations, the data used in validation were measured in Thailand (tropical condition), even though the 3MP correlations were developed based on the data measured in France (the temperate condition).

The comparisons were done separately for day-time and night-time data. For during night time (Fig. 7), the values of T_{sky} measured by the pyrgeometer coincided with those estimated from previous correlations. This concurrence is understandable since those previous correlations were developed from a direct measurement method using a pyrgeometer or pyrradiometer. However, it was obvious that 3MP correlations overestimated the T_{sky} for 5–7°C, approximately. This discrepancy may be caused due to the use of different ranges of T_d used for the correlation development and the validation. This refers to the fact that the 3MP correlations were developed based on the data collected in France at which the T_d were within 10–20°C at low RH conditions, whereas the validation was done using the data collected in Thailand where the T_d was within 20–25°C and high RH conditions. To overcome this discrepancy, it is recommended that (in future studies), data used for correlation development should be collected for longer periods under various weather conditions. Another possible reason that could explain the discrepancy is the effect of wind velocity on the convective heat transfer coefficient. Unlike the pyrgeometer that has a glass dome protecting it from being affected by the wind, the 3MP instrument was exposed directly to the sky. Therefore, the convective heat transfer in 3MP method would differ from that in other methods, and thus the difference in the values of T_{sky}.

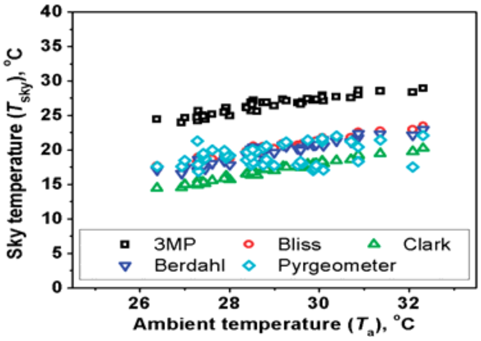

Fig. 7 Comparison of the T_{sky} during night time

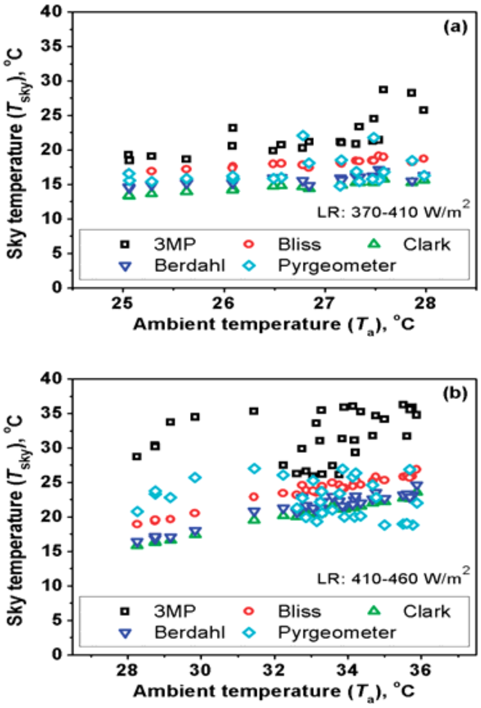

Fig. 8 Comparison of the T_{sky} during day time for T_a ranges of (a) 18–28°C and (b) 28–37°C

Fig. 8 (a) and (b) shows the comparison of T_{sky} predicted for during day time by different methods versus T_a in a range of 18–28°C and 28–37°C, respectively. The long-wave radiation were approximately 370–410 W/m^2 and 410–460 W/m^2 for the T_a range of 18–28°C and 28–37°C, respectively. Considering the results of Fig. 8 (a), the 3MP correlations can satisfactorily predict the T_{sky} in the T_a range of 18–28°C vis-à-vis other methods. However, at T_a about 28°C for which the E was above 400 W/m^2, the results obtained by 3MP correlations were quite different from those obtained by other methods. This was because, as stated in Section 4.2, the 3MP correlations were developed from the data at E less than 400 W/m^2. This was also observed for the T_a range of 28–37°C (E ~ 410–460 W/m^2) in Fig. 8 (b) in which the discrepancy between the 3MP results and the others significantly increased. In addition, the assumption on the convective heat transfer coefficient (h_e) employed in the 3MP method could also be a reason for this overestimation. In this study, the h_e was assumed to be identical for every plate, and thus, it was not taken into account in the correlation development. However, in actuality, h_e will be different for each plate since the plate temperatures differs (significantly) from each other, especially during day time, i.e., the temperatures of the black plate were much higher than those of the silver plate. These reasons could have led to the inaccurate estimation of day-time T_{sky} using 3MP method, especially at high ambient temperatures.

V. CONCLUSIONS

The 3MP method of T_{sky} estimation has been successfully developed in the viewpoint of simplicity and monetary requirement as compared with the direct measurement method. However, the 3MP empirical correlations developed in this study still requires improvments so as to provide accurate and versatile correlations. For example, the data used for developing the correlation need to be collected under various weather conditions, modification of the assumption on h_e and the effect of wind velocity need to be taken into account in future studes. Nevertheless, a key finding discovered and proved by 3MP method is that the solar radiation (E) is an important parameter to be taken into consideration in T_{sky} estimation (daytime). Thus, with some modifications mentioned above, 3MP method can be a useful approach for the T_{sky} estimation.

ACKNOWLEDGEMENTS

The author would like to express his thanks to the Government of France and the CETHIL, INSA de Lyon, France, who provided support for the conduction of this research in France.

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