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Research Paper

DETERMINATION OF CONVECTIVE COEFFICIENT AT THE OUTSIDE COVER OF A MONITOR GREENHOUSE IN INDONESIA

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Abstract: This research determined convective heat transfer coefficient at the outside cover of a monitor greenhouse by means of in situ method. The method was based on the energy balance of the greenhouse cover. The convective heat transfer coefficient at the outside cover (h_o) was a function of the air velocity outside the greenhouse for daytime with continuous roof vent and low wind speed of less than 3 m sec^{-1}. The results of h_o values were in agreement with the fundamental calculation. This study revealed that mixed convection was the prevailing convection heat transfer mechanism at the outside cover. Inside or outside cover heat transfer coefficient could be determined for other specific greenhouse geometry under similar climatic conditions.

Keywords: Convective coefficient, greenhouse, heat transfer, tropical conditions

INTRODUCTION

The convective heat transfer is one of the main exchange processes that directly influencing crop production under greenhouse. However, experimental estimation of a convective heat transfer flux might be extremely complicated to be performed for many surface shapes such as a greenhouse cover. Thus, an empirical approach was used for the estimation of the flux, particularly convective heat transfer coefficient (inside or outside) of the greenhouse cover. Some studies presented empirical formulae for convection coefficient at the outside cover under in situ measurements [1-4]. The convection coefficient at the outside of the greenhouse cover must be determined from in situ measurement on the specific type of the greenhouse [4]. There was no general equation that could be applied for every greenhouse geometry. Of many trials, as reviewed in Roy *et al*. [5], none had been carried out for a greenhouse with continuous roof ventilation like most tropical greenhouses have. Therefore, the determination of this coefficient for tropical greenhouses was imperative. A simple method from Papadakis *at al*. [4] was developed to determine the convection coefficient at the outside cover of a naturally ventilated greenhouse under in situ condition. An empirical formula had been provided as a function of outside wind speed derived from the heat balance equation of the greenhouse cover. This paper presented a method of convection coefficient determination with simply correlating the coefficient with the wind velocity and/or the temperature difference between the outside air and the greenhouse cover. The fundamental calculation of the convection coefficient to determine the mode and the airflow was also presented for the constraints of the formula and to validate the coefficient.

MATERIALS AND METHODS

Identifying the heat balance of the greenhouse cover

The convective coefficient at the greenhouse cover was determined using the same method as Papadakis *at al*. [4] did. It was based on the energy balance of the greenhouse cover. For a single glass covering, usually with a thickness of 0.004 m, it was reasonable to assume that both temperatures at the inside and the outside surface of a greenhouse cover were equal. Thus the heat storage capacity of the cover was small compared to the existing fluxes. It was also assumed that no temperature gradients exist horizontally along the cover surface and no temperature changes exist during one hour interval of measurement. Therefore, a steady state analysis was applied and the energy balance of the greenhouse cover could be described [4] as follows:

$$R_n + Q_o + Q_i = 0 \qquad (1)$$

where R_n is the full spectrum net radiation at the greenhouse cover (Wm^{-2}), Q_o is the convective heat flux at the outside of the cover (Wm^{-2}), and Q_i is the convective heat flux at the inside of the cover (Wm^{-2}).

The heat transfer to and from the cover is schematically represented in Fig. 1. At the inside of the cover, convective heat flux from the inside air appears together with some long wave radiation fluxes. At the outside of the cover, heat is transported by convection and long wave radiation to the sky. The short wave radiation absorbed by the greenhouse cover contributes directly to the energy balance of the cover [1].

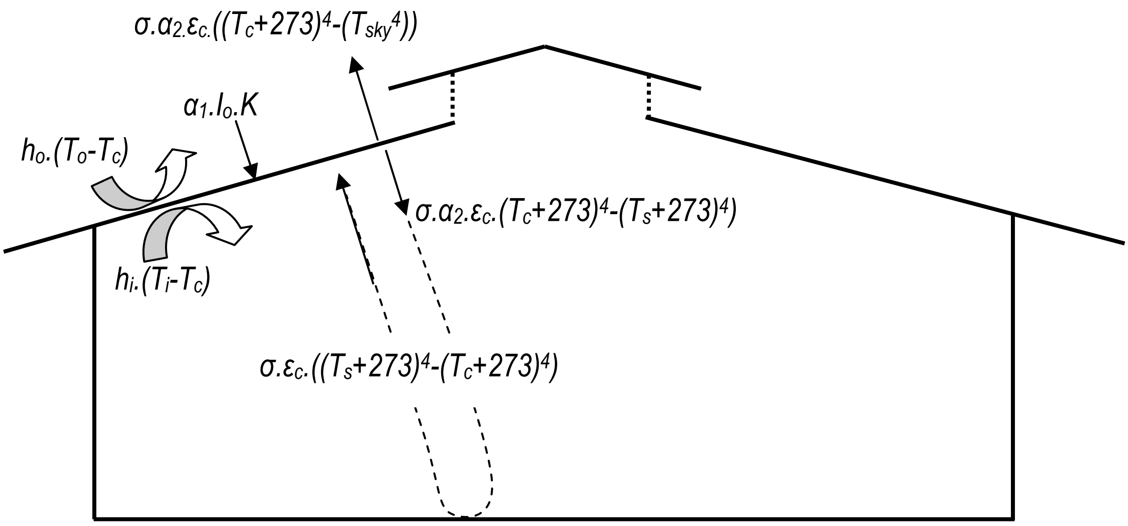

Fig. 1: Energy balance at the greenhouse cover.

R_n is usually measured using net radiometer at the outside and inside greenhouse cover surface. However, for the case in which there was only one set of available equipment or there was only data of external global radiation, representative R_n could be estimated through calculation under some assumptions mentioned earlier instead of being measured. It was given by the difference of net shortwave radiation in-out and longwave radiation in-out. All the energy terms involved in the energy balance of the greenhouse cover which determine its net radiation R_n were shown in Fig. 1. The equation of R_n is as follows:

$$R_n = \alpha_1 I_o K - \sigma\alpha_2\varepsilon_c\left((T_c+273)^4 - T_{sky}{}^4\right) - \sigma\alpha_2\varepsilon_c\left((T_c+273)^4 - (T_s+273)^4\right) + \sigma\varepsilon_s\left((T_s+273)^4 - (T_c+273)^4\right) \quad (2)$$

where α_1 is absorption coefficient in the short wave (solar radiation) region of the cover (0.17), I_o is the measured solar radiation on horizontal plane (Wm^{-2}), K is the cosines of the incident angle of solar radiation, σ is Stefan-Boltzman Constant (5.67x10^{-8} Wm^{-2}K^4), α_2 is the absorption coefficient in the thermal wavelength region of the cover (0.3), ε_c is emission coefficient of the cover (0.3), ε_f is emission coefficient of floor surface (0.88), T_{sky} is temperature of the sky (K), Tc and T_s are temperature of the cover and floor, respectively (ºC).

The fluxes Q_o and Q_i are given by the following equations respectively:

$$Q_o = h_o(T_o - T_c) \quad (3)$$

$$Q_i = h_i(T_i - T_c) \quad (4)$$

where T_o and T_i are outside and inside air temperature respectively (ºC), while h_o and h_i are convective heat transfer coefficient at the outside and at the inside cover, respectively (Wm^{-2} ºC). Following most of the pattern of empirical formulae in previous studies [1-4] and the fact that the convective exchange at the outside cover was dependent on the wind velocity [1, 4] and also from the formulae that there was a considerable amount of buoyancy forces take place (when u=0 and $h_c \neq 0$), thus the convective coefficient at the outside cover h_o could be expressed as follows:

$$h_o = a + bu^c \quad (5)$$

where u is wind speed (m sec^{-1}) and *a, b, c* are coefficients to be determined from experimental data. As for the convective coefficient at the inside cover *hi*, the value is fairly constant between 1.2 and 4.6 Wm^{-2} ºC, depending on the greenhouse size and the amount of ventilation. Thus, *hi* was approximated by the following equation [6]:

$$h_i = d\left(\frac{A_c}{A_s}\right). \quad (6)$$

where *Ac/As* is the ratio of cladding to floor area and *d* is a coefficient to be determined from experimental data.

Combining Eq. 1 and 3-6, the following equation was obtained:

$$R_n + a(T_o - T_c) + b(T_o - T_c)u^c + d\left(\frac{A_c}{A_s}\right)(T_i - T_c) = 0 \tag{7}$$

By means of a minimization method for a non-linear function of many variables, such as Eq. 7, the coefficients *a, b, c,* and *d* could be determined. For the convenience, Microsoft Excel Solver tool could also be used to determine the coefficients, using the Generalized Reduced Gradient (GRG2) nonlinear optimization. The constraints were based on the convective mode and type of flow of the experiment.

Identifying the convective mode and flow type

In order to determine the convective heat transfer coefficient, a criterion must be defined for identifying the convective mode (forced or free or mixed) and the type of flow (laminar or turbulent). This could be judged by comparing various combinations of Reynolds number *Re* and Grashof number *Gr*.

In the present study, the Richardson number R_i (Eq. 8) was used, suggesting a criterion to distinguish free from forced convection. When Re^2 is much larger than *Gr*, buoyancy forces are negligible and forced convection is dominant while the inverse condition results in free convection. The critical values of R_i for horizontal plates similar to the greenhouse cover were reviewed in Roy *et al.*, [5] and some were provided in Table 1. The criteria for the determination of convection modes and flow types were according to Montheith [7] and Campbell [8].

$$Ri = \frac{Gr}{\mathrm{Re}^2} \tag{8}$$

Gr and Re numbers are calculated by Eq. 2 and 3 respectively.

$$Gr = \frac{\beta L^3 g \Delta T}{v_m^2} \tag{9}$$

$$\mathrm{Re} = \frac{uL}{v_f} \tag{10}$$

where β is the thermal expansion coefficient of air (3.31×10^{-3} K^{-1} for T=29.15ºC), *L* is a characteristic length of the surface considered (for greenhouse cover, the roof slope length was used i.e., 4.675 m), *g* is gravitational acceleration (9.8 m sec^{-2}), ΔT is the temperature difference between the cover surface and the air (ºC), v_m is the kinematic viscosity of the air evaluated at the mean temperature of the surface and air (1.60×10^{-5} m^2sec^{-1} for T=29.15ºC), and v_f is the kinematic viscosity of the air evaluated at fluid temperature (1.58×10^{-5} m^2sec^{-1} for T=27.16ºC).

Table 1: Criteria for the determination of convection modes, flow types and coefficients used in calculating the Nusselt number for the present study [5].

Criterion of convection mode		Convective mode	Equation used	Laminar flow	Turbulent flow
General criterion	$Ri = \frac{Gr}{\mathrm{Re}^2} > 16$	Free convection	Eq. 12	$Gr<10^8$ K=0.25; C_n=0.54	$Gr>10^8$ K=0.33; C_n=0.14
General criterion	$Ri = \frac{Gr}{\mathrm{Re}^2} < 0.1$	Forced convection	Eq. 13	$Re<5\text{x}10^5$ Cf=0.67; n=0.5; m=0.33	$Re>5\text{x}10^5$ Cf=0.036; n=0.8; m=0.33

After the convective mode and the type of air flow had been determined, the heat transfer coefficient h_o could be calculated as follows [9]:

$$h = \frac{k_a Nu}{L} \tag{11}$$

where Nu is the Nusselt number and k_a is thermal conductivity of the air ($Wm^{-1}\,{}^oC$). In the case of free convection, Nu was calculated by Eq. 5 as follows [9]:

$$Nu = C_n (Gr\,\mathrm{Pr})^k \tag{12}$$

where Pr is Prandtl number while C_n, and κ are coefficients that can be found theoretically or experimentally. The power κ is dependent upon the nature of fluid flow over the surface, while C_n is not only dependent on the nature of fluid flow but also on whether the surface is at constant temperature or is subjected to constant heat flux [9]. The Nusselt number in the case of forced convection is a function of Re and Pr numbers [9] as follows:

$$Nu = C_f\, \mathrm{Re}^n\, \mathrm{Pr}^m \tag{13}$$

where C_f, n, and m are coefficients that are depended on the geometry and flow type. The coefficients are available in many textbooks on heat transfer. The coefficients listed in Table 1 are from Monteith [7] and Campbell [8].

Experiments

The experimental greenhouse (Fig 2.) was a 150 m^2 single-span greenhouse (by 20m length, 7.5m width, 4m height at gutter and 7.346m height at the ridge) located in Bogor Agricultural University farm, Cikabayan, Bogor, Indonesia that represents a humid tropical region. The greenhouse has a monitor roof (roof slope of 30º) covered with glass (0.004 m thickness) with continuous roof vent openings.

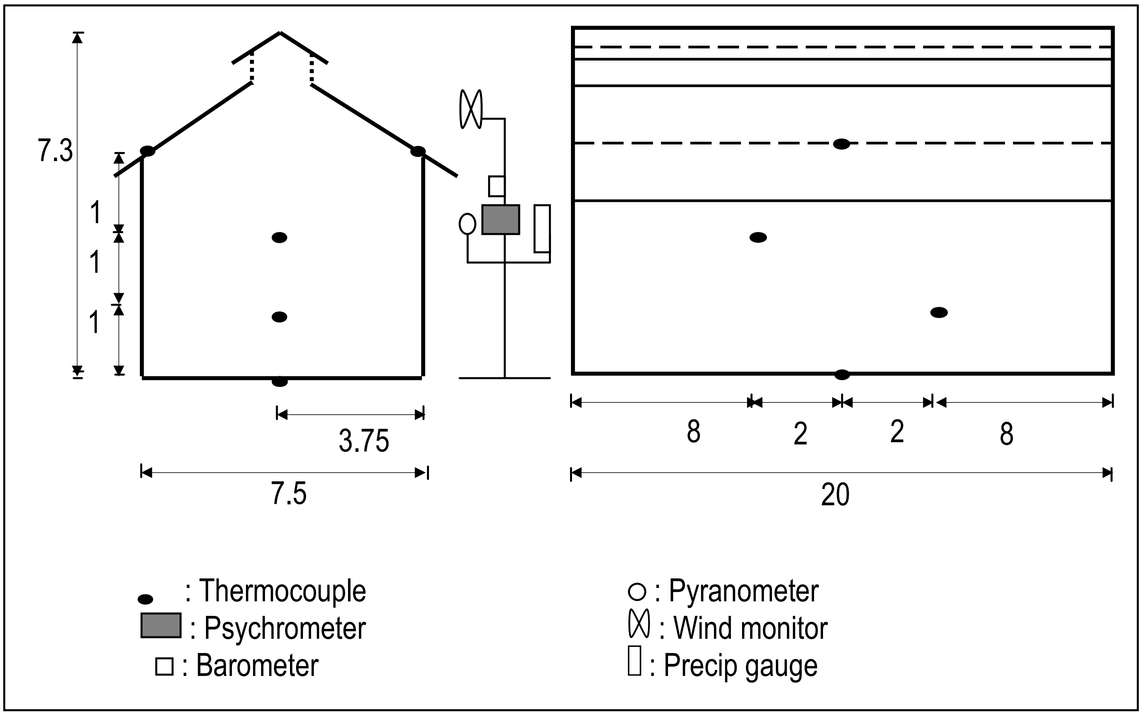

Fig. 2: Schematic representation of the position of several sensors and instruments in the experiment (dimensions in m).

Experimental data was taken in June 2006 at daytime (6.00-18.00 local time). Solar radiation (Wm^{-2}), wind speed (m sec^{-1}), and outside air temperature (ºC) were measured using pyranometer (model 70090), wind monitor (20118 series), and pshychrometer, respectively. Temperatures of the cover, inside air, and the greenhouse floor (ºC) were measured with thermocouples and connected to a hybrid recorder (Type HR 2300). The schematic representation of the position of sensors and instruments used in the experiment was given in Fig. 2. All parameters were measured in an hourly basis.

The coefficients *a, b, c,* and *d* were determined with the application of Solver Add-Ins in Microsoft Excel by minimizing the RMSE (Root Mean Square Error) of the expected h_o from Eq. 5 and h_o derived from fundamental calculation (Eq. 11), using Eq. 2 and 7, experimental data for the physical quantities (Irr, T_c, T_o, T_i, T_F, u) and greenhouse dimension.

RESULTS AND DISCUSSION

The convective mode and air flow type

From Eq. 8-10 the Richardson number R_i (Gr/Re^2) of the experiment was found to be 6.51 on average of 39 data. This value did not meet the criteria for a forced convection nor a free convection according to criterion given in Table 1. Therefore, the value of Re^2 was assessed.

The value of Re^2 ($13.51x10^{10}$) was found to be more than twice of *Gr* ($5.15x10^{10}$) which explains that forced convection existed. However, in some cases buoyancy forces were quite significant during the experiment. It was due to low wind velocity (the average was 0.7 m sec^{-1} with a maximum speed of 4.9 m sec^{-1}) or large temperature difference (up to 11.59 ºC). Therefore, the authors assumed that the nature of exchange was in the transition region between free and forced convection. This finding was inline with Bot [1] and Papadakis *et al.* [4]. They found that most of the time mixed convection was the prevailing convection heat transfer mechanism at the outside cover; it depends not only on the wind velocity but also on the temperature difference between the cover and the outside air.

Since forced convection was dominant, Reynolds number was used to determine the flow type (Table 1). *Re* was found to be 2.15×10^5. Thus, the exchange was a laminar flow due to $Re < 5 \times 10^5$. For these reasons, the Nusselt number is then calculated using Eq. 13 with Cf=0.67; n=0.5; m=0.33 and the constraints for Solver application are $a, b, c \geq 0$ and $d \leq 4.41$.

The empirical formula

From the application of the above mentioned software, the coefficients *a, b, c, d*, for Eq. 5 and 6 were obtained i.e., 1.78; 1.84; 0.33; and 3.56, respectively. Thus the equation for convective coefficient at the outside and the inside cover were respectively as follows:

$$h_o = 1.78 + 1.84u^{0.33} \tag{14}$$

$$h_i = 3.56 \frac{A_c}{A_s} \tag{15}$$

In order to show the difference of heat transfer coefficient formulae in some studies (Table 2) [1-4] with the result of this study, the value of the convective coefficients was plotted as a function of external wind speed by fixing the temperature difference of 2 ºC (Fig. 3). The significant difference was of course due to the different geometries of the greenhouse used in the experiments. This variation showed that convective coefficients depended on greenhouse geometry. Although the coefficient in this study was the lowest of all, the values were close to Bot [1] and Kittas [3] when the external wind speed was less than 3 m sec^{-1}.

Table 2: List of empirical formulae for convective heat transfer coefficients between the outer cover surface and the air according to different authors from in situ measurement [4].

Heat transfer coefficient (W m^{-2} K)	Greenhouse conditions	Source
$7.2+3.84u$	Tunnel-type greenhouse covered with polyethylene film	Garzoli and Blackwell (1981)
$2.8+1.2u$	Venlo-type glasshouse ($u \leq 4$ m/s)	Bot (1983)
$1.32(T_c-T_o)^{0.25}+3.12u^{0.8}$	Tunnel-type greenhouse covered with pvc film	Kittas (1986)
$0.95+6.76u^{0.49}$	Twin-span greenhouse with polyethylene film ($u \leq 6.3$ m/s)	Papadakis *et al.* (1992)

T_c and T_o, are temperature of the cover and the outside air respectively (ºC); *u* is wind velocity (m sec^{-1}).

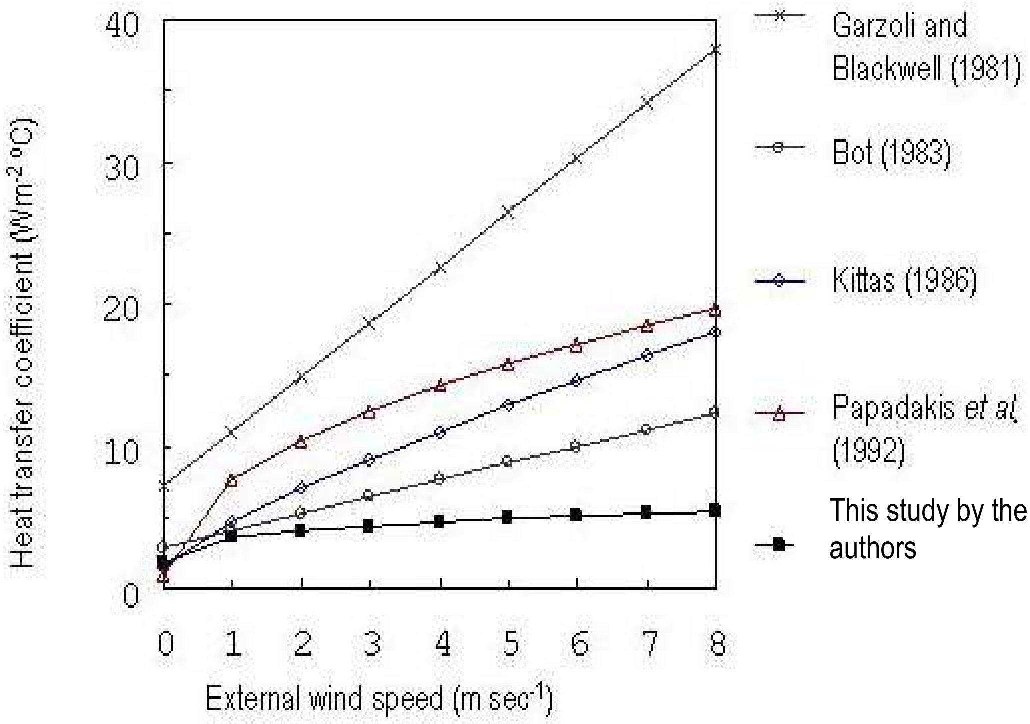

Fig. 3: Variation of the convective heat transfer coefficient h_o for the outside cover surface as a function of the external wind speed according to different authors with different greenhouse geometries.

In fact, h_o is never zero when external wind speed u of 0 m sec^{-1} as shown in Fig. 1 and the power in Eq. 14 is not close to that of 0.8 which characterizes pure forced convection. These revealed that the convection heat transfer at the outside cover in most of the cases was not forced. In other words, the heat transfer coefficient was not significantly dependent on the wind speed alone. The extrapolated value of h_o at wind speed u of 0 and the linear increase with wind speed suggested that free convection due to temperature difference took a substantial part of the exchange, which was in agreement with the identification of the convective mode of the experiment i.e., mixed convection. As for the convective coefficient at the inside cover h_i, the constant d= 3.56 was not much different to that of Jolliet [6] i.e. 3.5. Thus, the coefficients obtained in the study were in fine results with previous studies.

Coefficient verifications

Verifications of the coefficient were carried out to test the method. In Fig. 4 (a), the calculated values of h_o in the present study derived from the heat transfer equation (Eq. 5 and 7) and from fundamental calculation (Eq. 11) were plotted. The coefficient of linear regression between the two h_o values were found to be r^2=0.9777 while the slope of the straight line appearing in Fig. 3 was 0.8909 and the Y intercept value +1.8585. This explained that the developed method to obtain the empirical formulae for the calculation of convective coefficient had yield fine results.

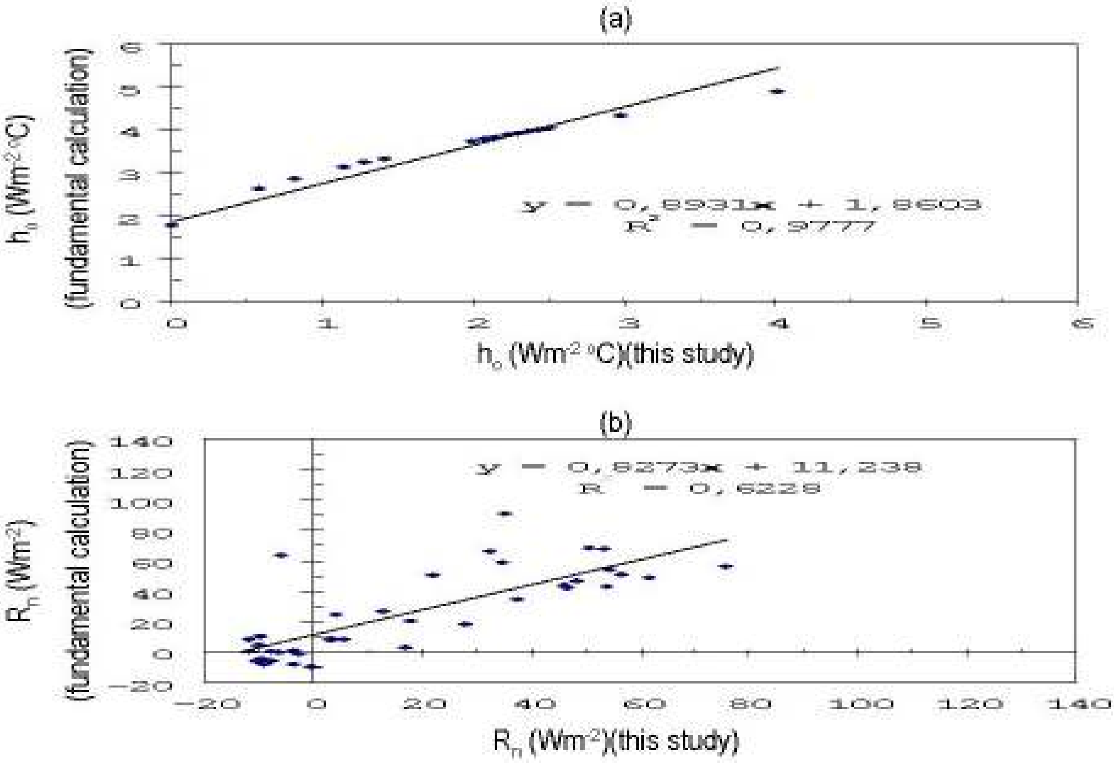

Fig. 4: Verifications of the coefficients: (a) h_o values obtained from fundamental calculation (Eq. 11) and estimated in this study (Eqs. 5 and 7); (b) *Rn* values calculated with heat transfer equation (Eq. 2) and obtained from this study (Eq. 7) respectively.

In addition to check the validity of the developed method i.e., without using measured R_n, the calculated values of R_n in this study derived from the heat transfer equation (Eq. 7) and from fundamental calculation (Eq. 2) were plotted in Fig. 4 (b). The negative values point out that some long wave radiation fluxes were released from the cover. This finding was inline with Papadakis *et al.*[4]. They also found that some R_n values were negative. The linear regression analysis of the fundamental calculation as a function of the values of the present study had an r^2=0.6228 with a slope of 0.8273 and an intercept of 11.238 Wm^{-2}. The standard deviation of full spectrum net radiation at the greenhouse cover between fundamental calculation and the developed method was 27.35 Wm^{-2}. The R_n values from the developed method showed fair agreement with fundamental calculation. Therefore, it was fine to use calculated R_n for the empirical determination of convective coefficient at the greenhouse cover. These facts showed that the formula could be used in practical situation for thermal analysis of the same type of greenhouses located in the regions with similar climatic conditions. Better results will be achieved if measurements are recorded less than an hourly basis.

CONCLUSIONS

A method has been developed to determine experimentally in situ convective heat transfer coefficient at the outside cover of a monitor greenhouse in the humid tropical region. The empirical formula derived was h_o =1.78+1.84$u^{0.33}$. The equation that gives h_o values from the developed method as a function of the fundamental calculation was 1.8585 + 0.8909*hc* where *hc* was nothing less than h_o fundamental calculation. The correlation coefficient of r^2 = 0.9777 was gained. With an empirical method under in situ condition as presented in this paper, one may obtain heat transfer coefficients (inside or outside) for other specific greenhouse geometry under similar climatic conditions.

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