Pergamon

PII: S0038-092X(96)00145-4

Solar Energy Vol. 60, No. 1, pp. 35–40, 1997

0038-092X/97 $17.00+0.00

RADIATIVE HEAT TRANSFER IN A SOLAR AIR HEATER COVERED WITH A PLASTIC FILM

YVES JANNOT *† and YÉZOUMA COULIBALY **
* ENSP, Energy Laboratory, PO Box 8390, Yaoundé, Cameroon, and ** EIER, Energy Department, PO Box 7023, Ouagadougou, Burkina Faso

(Received 21 December 1995; revised version accepted 18 October 1996
(Communicated by Brian Norton)

Abstract—This article presents a new set of equations for the radiative balances of the absorber plate and the transparent cover of a solar air heater covered with a plastic film. Air flow is supposed to pass between the absorber plate and the bottom of the collector, while the transparent cover and the absorber plate are separated by an immobile air layer. This configuration is shown to be the best suited for a plastic covered solar air heater used in tropical countries, from a practical point of view. © 1997 Elsevier Science Ltd.

1. INTRODUCTION

Most of the covered solar collectors used in developed countries are single- or double-glazed. Glass is quite interesting as a cover for solar thermal devices because it absorbs almost all the infrared (IR) radiation re-emitted by the absorber plate, resulting in an enhancement of the thermal efficiency of the solar collector by creating a greenhouse effect. Nevertheless, the use of glass as a solar collector cover in rural zones of developing countries has two major disadvantages, its high cost, as underlined by Njomo (1995), and its fragility both during transportation and in service. It is the reason why, for several years, transparent plastic covers have been used widely in these zones (particularly polyethylene because of its widespread availability) to construct moderate cost solar air heaters. These solar collectors are used mainly for foodstuff drying as reported by Charters *et al.* (1989) and GRET (1986).

However, it is not possible to predict the performance of a plastic covered solar collector using the classical models which assume that the transparent cover is totally opaque to infrared radiation ($\tau_{ci}=0$) as supposed by Sfeir and Guarracino (1981) and Choudhury *et al.* (1995) among many authors. This hypothesis is quite correct for a glass cover but is unacceptable for some plastic covers such as polyethylene which transmissivity to infrared radiations is $\tau_{ci}=0.82$ according to Claassen and Buttler (1980). A heat transfer model taking into account this partial transparency of a solar collector cover towards IR radiation has been presented previously by Njomo (1991). But in the air solar collector considered by Njomo (Fig. 1(a)), the air passes between the plastic cover and the absorber plate which is in direct contact with bottom thermal insulation. From the operating experience we acquired, and that we have reported from solar air heaters operators in Burkina Faso and in Mali, two major disadvantages of this configuration can be underlined: (1) the collector performance is highly sensitive to air leakage and it is quite difficult to obtain a perfect air tightness with a plastic cover (small accidental perforations can occur); (2) during the dry season in tropical countries, dust content of atmospheric air is quite high, and this causes dust deposits both on the lower face of the plastic cover (by electrostatic forces) and on the upper face of the absorber plate exposed to the solar radiation, the result is a lowering of the plastic cover transmittance, as reported by Das and

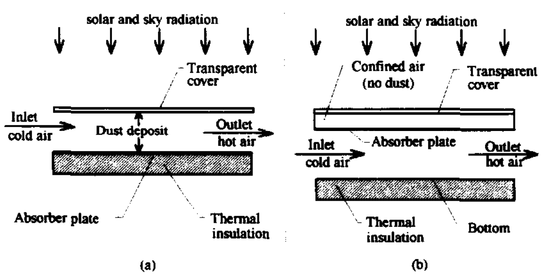

Fig. 1. Schematic view of solar air heaters.

†Author to whom correspondence should be addressed.

Chakraverty (1991), and of the absorber plate absorptivity towards solar radiation.

For these reasons, it seems that the best configuration to get sustainable performances with a plastic covered solar air heater in tropical countries is the one represented in Fig. 1(b), with a confined and immobile air layer between the cover and the absorber plate, and the air flow to be heated passing between the absorber plate and the bottom of the collector.

In this article, the radiative balances of the absorber plate and of the transparent cover of this type of solar air heater are presented. In contrast to Njomo (1991), who neglects the IR absorptance α_{ci} of the plastic cover, no approximation has been done so that the established radiative balances can be used for any type of transparent cover (plastic, glass or other). Compared to the equations presented by Duffie and Beckman (1980) to estimate the radiative heat transfer between the sky and the absorber plate and between the sky and the transparent cover, a more refined analysis has been done by taking into account the multiple reflections of the sky radiation inside the collector. The proposed equations are dedicated for use in a global thermal balance to predict the performance of solar air heaters similar to the one represented in Fig. 1(b).

2. SOLAR COLLECTOR RADIATIVE BALANCE

The various radiative fluxes that must be taken into account in a covered solar air heater are represented in Fig. 2. The evolution of the radiative fluxes inside the collector will be studied theoretically by a ray tracing method applied to each flux, considering the different and successive reflections and absorptions occurring on the absorber plate and on the transparent cover. The thermal analysis will result in the radiative balances of these two components. For simplifying notations, the collector area is assumed to be equal to 1 m^2.

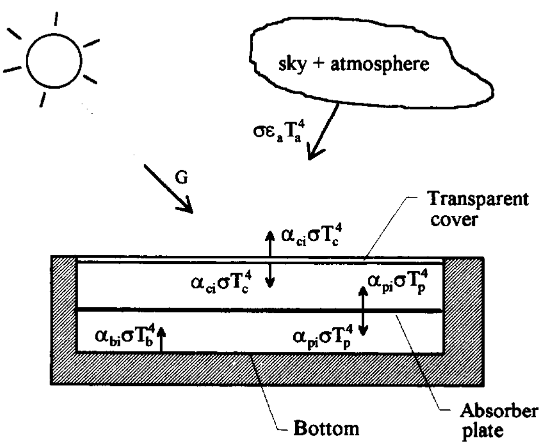

Fig. 2. Schematic view of radiative fluxes in a solar air heater.

2.1. *Incident solar flux*

Figure 3 represents the evolution of incident solar radiation inside the solar collector. The part $\Phi_{s\to c}$ of the incident solar flux G absorbed by the transparent cover can be expressed as

$$\Phi_{s\to c} = G\alpha_{cs} + G\alpha_{cs}\tau_{cs}(1-\alpha_{ps}) + G\alpha_{cs}\tau_{cs}\rho_{cs}(1-\alpha_{ps})^2 + G\alpha_{cs}\tau_{cs}\rho_{cs}^2(1-\alpha_{ps})^3$$

$$+\Phi_{s\to p} = G\alpha_{cs} + G\frac{\alpha_{cs}\tau_{cs}(1-\alpha_{ps})}{1-\rho_{cs}(1-\alpha_{ps})}. \quad (1)$$

The part $\Phi_{s\to p}$ of the incident solar flux absorbed by the absorber plate can be expressed as

$$\Phi_{s\to p} = G\alpha_{ps}\tau_{cs} + G\alpha_{ps}\tau_{cs}\rho_{cs}(1-\alpha_{ps}) + G\alpha_{ps}\tau_{cs}\rho_{cs}^2(1-\alpha_{ps})^2$$

$$+\Phi_{s\to p} = G\frac{\alpha_{ps}\tau_{cs}}{1-\rho_{cs}(1-\alpha_{ps})}. \quad (2)$$

The expression

$$\frac{\alpha_{ps}\tau_{cs}}{1-\rho_{cs}(1-\alpha_{ps})}$$

is usually called the optical efficiency of the solar collector and is often approximated by $\alpha_{ps}\tau_{cs}$.

2.2. *Incident sky radiation*

In the case of a solar collector covered with a glass, it is considered that the incident sky

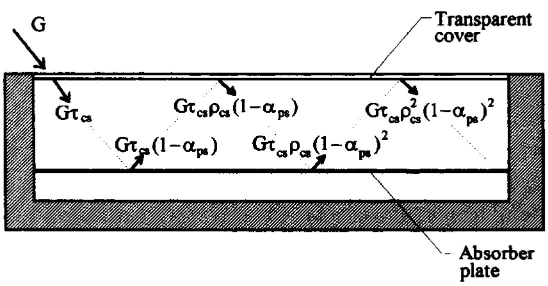

Fig. 3. Evolution of incident solar radiation inside the collector.

radiation does not reach the absorber plate, but this hypothesis is no longer correct if the transparent cover is not totally opaque towards infrared radiation.

If Φ_{sk} is the flux radiated by the sky and the atmosphere, it is often expressed as follows:

$$\Phi_{sk} = \sigma \epsilon_a T_a^4,$$

where ϵ_a is the atmospheric emittance that can be calculated by the Clark and Allen formula selected by Abulgana (1986):

$$\epsilon_a = 0.787 + 0.764 \ln\left(\frac{T_{da}}{273}\right) \quad (3)$$

where T_{da} is the dew point of the atmospheric air.

This sky radiative flux can reach important values in the tropical area. As an example, the average monthly values of the sky radiative flux Φ_{sk} and of the solar flux G on a horizontal plane in Ouagadougou at 9 a.m., 12 a.m., and 3 p.m. have been reported in Table 1. These values have been calculated using eqn (3) and Ouagadougou's meteorological data reported by Jannot (1994). One can see in Table 1 that the sky radiative flux is greater than half of the global solar flux that is far from negligible.

Figure 4 represents the evolution of the incident sky IR radiation inside the solar collector. The part $\Phi_{sk \to c}$ of the incident flux Φ_{sk} radiated by the sky and absorbed by the transparent cover can be expressed as

$$\begin{aligned} \Phi_{sk \to c} &= \Phi_{sk}\alpha_{ci} + \Phi_{sk}\alpha_{ci}(1-\alpha_{pi})\tau_{ci} \\ &\quad + \Phi_{sk}\tau_{ci}\rho_{ci}(1-\alpha_{ps})^2\alpha_{ci} \\ + \Phi_{sk \to c} &= \Phi_{sk}\alpha_{ci} + \Phi_{sk}\frac{\alpha_{ci}\tau_{ci}(1-\alpha_{pi})}{1-\rho_{ci}(1-\alpha_{pi})}. \end{aligned} \quad (4)$$

The part $\Phi_{sk \to p}$ of the incident flux Φ_{sk} radiated by the sky and absorbed by the absorbed plate can be expressed as

$$\begin{aligned} \Phi_{sk \to p} &= \Phi_{sk}\tau_{ci}\alpha_{pi} + \Phi_{sk}\rho_{ci}(1-\alpha_{pi})\tau_{ci}\alpha_{pi} \\ &\quad + \Phi_{sk}\rho_{ci}^2(1-\alpha_{pi})^2\tau_{ci}\alpha_{pi} \\ + \Phi_{sk \to p} &= \Phi_{sk}\frac{\tau_{ci}\alpha_{pi}}{1-\rho_{ci}(1-\alpha_{pi})}. \end{aligned} \quad (5)$$

2.3. Absorber plate radiation

Figure 5 represents the evolution of the IR radiation emitted by the upper face of the absorber plate inside the solar collector. The part $\Phi_{p \to c}$ of the flux Φ_p radiated by the absorber plate and absorbed by the transparent cover can be expressed as

$$\begin{aligned} \Phi_{p \to c} &= \alpha_{pi}\alpha_{ci}\sigma T_p^4 + \alpha_{ci}\rho_{ci}(1-\alpha_{pi})\alpha_{pi}\sigma T_p^4 \\ &\quad + \alpha_{ci}\rho_{ci}^2(1-\alpha_{pi})^2\alpha_{pi}\sigma T_p^4 \\ + \Phi_{p \to c} &= \alpha_{pi}\sigma T_p^4 \frac{\alpha_{ci}}{1-\rho_{ci}(1-\alpha_{pi})}. \end{aligned} \quad (6)$$

Table 1. Sky radiative flux Φ_{sk} (Wm^{-2}) and global solar flux G (Wm^{-2}) on a horizontal plane in Ouagadougou

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
$\Phi_{sk\ 9\ a.m.}$	348	358	384	407	404	397	386	385	387	395	379	352
$\Phi_{sk\ 12\ a.m.}$	373	394	412	435	428	414	403	401	405	420	409	381
$\Phi_{sk\ 3\ p.m.}$	387	406	423	441	439	420	411	405	414	424	415	389
$G_{9\ a.m.}$	323	349	364	399	405	382	350	332	389	412	408	339
$G_{12\ a.m.}$	768	861	850	869	842	831	792	747	824	819	811	724
$G_{3\ p.m.}$	657	757	732	710	691	683	667	627	658	622	611	577

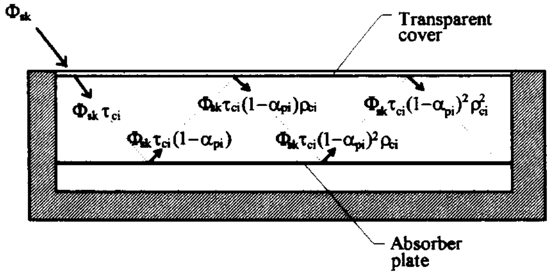

Fig. 4. Evolution of incident sky radiation inside the collector.

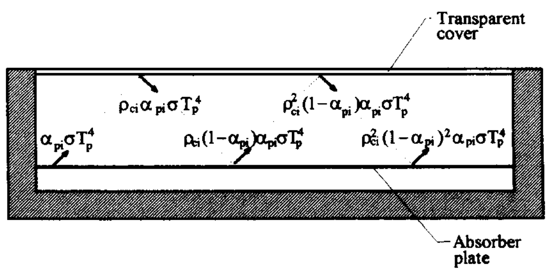

Fig. 5. Evolution of absorber plate radiation inside the collector.

The part $\Phi_{p\to p}$ of the flux Φ_p radiated by the absorber and re-absorbed by itself after multiple reflections can be expressed as

$$\begin{aligned}\Phi_{p\to p} &= \rho_{ci}\alpha_{pi}^2\sigma T_p^4 + \rho_{ci}^2\alpha_{pi}^2(1-\alpha_{pi})\sigma T_p^4 \\ &\quad + \rho_{ci}^3\alpha_{pi}^2(1-\alpha_{pi})\sigma T_p^4 \\ &\quad + \Phi_{p\to p} = \alpha_{pi}\sigma T_p^4 \frac{\rho_{ci}\alpha_{pi}}{1-\rho_{ci}(1-\alpha_{pi})}.\end{aligned} \tag{7}$$

The radiative heat flux exchanged between the lower face of the absorber plate and the bottom of the collector (considered as infinite gray parallel plates and thus assuming $\alpha_{pi}=\epsilon_{pi}$ and $\alpha_{bi}=\epsilon_{bi}$) can be written as follows:

$$\Phi_{b\to p} = -\Phi_{p\to b} = \sigma \frac{T_b^4 - T_p^4}{\dfrac{1}{\alpha_{pi}} + \dfrac{1}{\alpha_{bi}} - 1}. \tag{8}$$

2.4. *Transparent cover radiation*

Figure 6 represents the evolution of IR radiation emitted by the transparent cover inside the solar collector. The part $\Phi_{c\to c}$ of the flux Φ_c radiated by the transparent cover and re-absorbed by itself after multiple reflections can be expressed as

$$\begin{aligned}\Phi_{c\to c} &= \alpha_{ci}^2(1-\alpha_{pi})\sigma T_c^4 + \alpha_{ci}^2\rho_{ci}(1-\alpha_{pi})^2\sigma T_c^4 \\ &\quad + \alpha_{ci}^2\rho_{ci}^2(1-\alpha_{pi})^3\sigma T_c^4 \\ &\quad + \Phi_{c\to c} = \alpha_{ci}\sigma T_c^4 \frac{\alpha_{ci}(1-\alpha_{pi})}{1-\rho_{ci}(1-\alpha_{pi})}.\end{aligned} \tag{9}$$

The part $\Phi_{c\to p}$ of the flux Φ_c radiated by the transparent cover and absorbed by the absorber plate can be expressed as

$$\begin{aligned}\Phi_{c\to p} &= \alpha_{ci}\alpha_{pi}\sigma T_c^4 + \alpha_{ci}\rho_{ci}(1-\alpha_{pi})\alpha_{pi}\sigma T_c^4 \\ &\quad + \alpha_{ci}\rho_{ci}^2(1-\alpha_{pi})^2\alpha_{pi}\sigma T_c^4 \\ &\quad + \Phi_{c\to p} = \alpha_{ci}\sigma T_c^4 \frac{\alpha_{pi}}{1-\rho_{ci}(1-\alpha_{pi})}.\end{aligned} \tag{10}$$

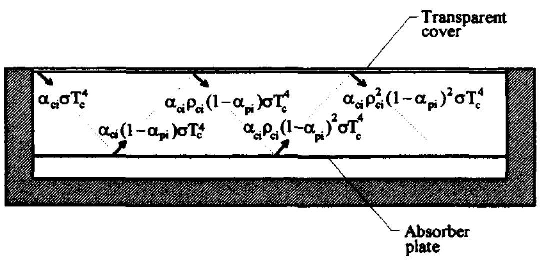

Fig. 6. Evolution of transparent cover radiation inside the collector.

2.5. *Global radiative balances*

The net radiative flux $\Phi_{\to p}$ received by the absorber plate can be expressed as

$$\begin{aligned}\Phi_{\to p} &= \Phi_{s\to p} + \Phi_{c\to p} + \Phi_{sk\to p} \\ &\quad + \Phi_{p\to p} + \Phi_{b\to p} - \alpha_{pi}\sigma T_p^4\end{aligned}$$

$$\begin{aligned}\Phi_{\to p} &= G\frac{\alpha_{ps}\tau_{cs}}{1-\rho_{cs}(1-\alpha_{ps})} + \alpha_{ci}\sigma T_c^4 \frac{\alpha_{pi}}{1-\rho_{ci}(1-\alpha_{pi})} \\ &\quad + \Phi_{sk}\frac{\tau_{ci}\alpha_{pi}}{1-\rho_{ci}(1-\alpha_{pi})} + \alpha_{pi}\sigma T_p^4 \frac{\rho_{ci}\alpha_{ci}}{1-\rho_{ci}(1-\alpha_{pi})} \\ &\quad - \sigma\frac{T_p^4 - T_b^4}{\dfrac{1}{\alpha_{pi}} + \dfrac{1}{\alpha_{bi}} - 1} - \alpha_{pi}\sigma T_p^4.\end{aligned} \tag{11}$$

The net radiative flux $\Phi_{\to c}$ received by the transparent cover can be expressed as

$$\Phi_{\to c} = \Phi_{s\to c} + \Phi_{c\to c} + \Phi_{sk\to c} + \Phi_{p\to c} - 2\alpha_{ci}\sigma T_c^4$$

$$\begin{aligned}\Phi_{\to c} &= G\alpha_{cs} + G\frac{\alpha_{cs}\tau_{cs}(1-\alpha_{ps})}{1-\rho_{cs}(1-\alpha_{ps})} \\ &\quad + \alpha_{ci}\sigma T_c^4 \frac{\alpha_{ci}(1-\alpha_{pi})}{1-\rho_{ci}(1-\alpha_{pi})} \\ &\quad + \Phi_{sk}\alpha_{ci} + \Phi_{sk}\frac{\alpha_{ci}\tau_{ci}(1-\alpha_{pi})}{1-\rho_{ci}(1-\alpha_{pi})} \\ &\quad + \alpha_{pi}\sigma T_p^4 \frac{\alpha_{ci}}{1-\rho_{ci}(1-\alpha_{pi})} - 2\alpha_{ci}\sigma T_c^4.\end{aligned} \tag{12}$$

2.6. *Case of a transparent cover opaque to IR radiation*

Glass is an example of such a cover characterized by $\tau_{ci}=0$ and $\rho_{ci}=1-\alpha_{ci}$. Taking these two relations into account, eqn (11) and eqn (12) become

$$\begin{aligned}\Phi_{\to p} &= G\frac{\alpha_{ps}\tau_{cs}}{1-\rho_{ps}(1-\alpha_{ps})} - \sigma\frac{T_p^4 - T_c^4}{\dfrac{1}{\alpha_{pi}} + \dfrac{1}{\alpha_{ci}} - 1} \\ &\quad - \sigma\frac{T_p^4 - T_b^4}{\dfrac{1}{\alpha_{pi}} + \dfrac{1}{\alpha_{bi}} - 1}.\end{aligned} \tag{13}$$

Table 2. Sky radiative flux $\Phi_{sk\to p}$ (Wm^{-2}) and solar flux $\Phi_{s\to p}$ (Wm^{-2}) absorbed by a horizontal solar collector covered with polyethylene in Ouagadougou

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
$\Phi_{sk\to p\ 9\ a.m.}$	253	267	286	303	301	296	288	287	288	294	282	262
$\Phi_{sk\to p\ 12\ a.m.}$	278	293	307	324	319	308	300	299	302	313	305	284
$\Phi_{sk\to p\ 3\ p.m.}$	288	302	315	328	327	313	306	302	308	316	309	290
$\Phi_{s\to p\ 9\ a.m.}$	263	284	296	325	330	311	285	270	317	335	332	276
$\Phi_{s\to p\ 12\ a.m.}$	625	701	692	707	685	676	645	608	671	667	660	589
$\Phi_{s\to p\ 3\ p.m.}$	535	616	596	578	562	556	543	510	535	506	497	470

$$\Phi_{\to c} = G\alpha_{cs} + G\frac{\alpha_{cs}\tau_{cs}(1-\alpha_{ps})}{1-\rho_{cs}(1-\alpha_{ps})} + \sigma\alpha_{cs}(\epsilon_a T_a^4 - T_c^4) + \sigma\frac{T_p^4 - T_c^4}{\dfrac{1}{\alpha_{pi}} + \dfrac{1}{\alpha_{ci}} - 1}. \quad (14)$$

Equations (13) and (14) are the classical formulations of the radiative balances of the absorber plate and of the transparent cover used in the case of a glass cover, as used by Bala and Woods (1994) for example.

3. CONCLUSIONS

In the case of a solar collector covered with a plastic cover not totally opaque to infrared radiation, eqns (11) and (12) should be used for the radiative balances of the absorber plate and of the transparent cover. The modifications induced by taking into account the partial transparency of the cover towards IR radiation may be important. As an example, let us consider a horizontal solar collector with an absorber plate having $\rho_{ps}=\rho_{pi}=0.9$, covered with polyethylene ($\tau_{ci}=0.9$, $\tau_{cs}=0.82$ and assuming $\alpha_{ci}=\tau_{ci}=0.09$, and $\alpha_{cs}=\tau_{cs}=0.05$) and located in Ouagadougou. Based on the values in Table 1, the part $\Phi_{sk\to p}$ of the sky radiation absorbed by the absorber plate has been calculated by eqn (5) and the part $\Phi_{s\to p}$ of the solar flux absorbed by the absorber plate has been calculated by eqn (2). One can see from the calculated values reported in Table 2 that the absorbed flux $\Phi_{sk\to p}$ is not negligible compared with the absorbed flux $\Phi_{s\to p}$ and thus must be taken into account in this example where polyethylene is used as a cover.

However, in the case of a glass cover, the use of the classical eqns (13) and (14) is quite correct and justified.

NOMENCLATURE

G incident solar flux density (Wm^{-2})
T temperature (K)
T_d dew point (K)

Greek letters

α absorptance
ϵ emittance
ρ reflectance
τ transmittance
Φ flux density (Wm^{-2})

Subscripts

a atmosphere
b bottom of the collector
c transparent cover
i infrared radiations
s solar radiations
sk sky
p absorber plate

REFERENCES

Abulgana E. Baha (1986) Théorie de la réfrigération nocturne par radiation. Brace Research Institute.

Bala B. K. and Woods J. L. (1994) Simulation of the indirect natural convection solar drying of rough rice. *Sol. Energy*. **53,** 259–266.

Charters W. W. S., MacDonald R. W. G., Kaye D. R. and Xiaoren Sun (1989) Passive greenhouse type solar dryers and their development. *RERIC Int. Energy J.*, **11,** 51–60.

Choudhury C., Chauhan P. M. and Garg H. P. (1995) Design curves for conventional solar air heaters. *Renewable Energy*, **6,** 739–749.

Claassen R. S. and Buttler B. L. (1980) Introduction to solar materials science. In *Solar Material Science*, Chapter 1. Academic Press, New York, pp. 3–51.

Das S. K. and Chakraverty A. (1991) Performance of a solar collector with different glazing materials and their degradation under the conditions prevailing in a solar collector. *Energy Convers. Mgmt.*, **31,** 233–242.

Duffie J. A. and Beckman W. A. (1980) *Solar Engineering of Thermal Processes*. Wiley, New York.

GRET (1986) Le point sur le séchage solaire des produits alimentaires. GRET, Paris.

Jannot Y. (1994) Un procédé économique pour l'amélioration du confort thermique en zone tropicale sèche: la ventilation forcée par de l'air extérieur éventuellement humidifé. *Int. J. Refrig.*, **17,** 174–179.

Njomo D. (1991) Modelling the heat exchanges in a solar air heater with a cover partially transparent to infrared radiation. *Energy Convers. Mgmt.*, **31,** 495–503.

Njomo D. (1995) Techno-economic analysis of a plastic cover solar air heater. *Energy Convers. Mgmt.*, **36,** 1023–1029.

Sfeir A. A. and Guarracino G. (1981) Ingéniérie des systèmes solaires. *Technique et Documentation.*