EXPERIMENTAL-THEORETICAL ANALYSIS OF SOLAR DRYERS WITH INFRARED THERMOGRAPHY AND INTEGRAL TRANSFORMS

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Abstract. *The present work deals with heat transfer in inclined plane solar collectors as employed in small scale agricultural solar dryers, according to a constructive model proposed by the Instituto Agronômico do Paraná (IAPAR). The experimental analysis is performed by employing a combination of thermocouples, heat flux meter and infrared thermography. A classical lumped-differential model for heat conduction along the plate length is combined with available correlations for local Nusselt numbers along the natural convection boundary layer over the inclined plate to simplify the heat transfer analysis of the metallic collector plate. The resulting transient one-dimensional model is solved by Integral Transforms (UNIT code) and critically compared with the experimental results. The proposed model is fairly simple but requires experimental information on the temperatures of the glass cover and on the incident radiation heat flux. Therefore a more complete model is then proposed, including the coupling with the heat conduction equation in the cover glass, again applying concentrated parameters in the transverse direction but now not requiring experimental data input, which is finally validated by the experimental results. The coupled model is found to be more adequate in predicting the heat transfer phenomena along most of the plate length.*

Keywords: *solar collector, conjugated problem, integral transforms, natural convection, infrared thermography*.

1. INTRODUCTION

Solar drying is an old technique employed in many contexts of agriculture and agro-industrial production, with different goals such as reducing humidity to storage, weight reductions for transportation, dehydration for conservation or consumption, and other purposes. In the domains of agriculture and industry enormous amounts of energy are in general required for drying. Developing countries have long used solar energy for drying various harvests such as coffee, tobacco, tea, beans, bananas, mangoes, etc, and to conserve perishable foods such as fish and meat. The traditional method consists of exposing the products to the sun and to the fresh air, but the present rules of hygiene relating to food products exclude the traditional solar drying, intended not only to improve local hygiene standards, but also to create new consumer markets (Palz, 1995). In this context, interest has been growing in the use of solar collectors with natural circulation for drying processes, with the aid of fundamental studies on natural convection along inclined cavities, coupled with heat conduction on the plate collector and the radiation inherent to the process. The present theoretical-experimental study is aimed at understanding the thermal performance of a passive solar dryer built from the model proposed by the Instituto Agronômico do Paraná (IAPAR; ESALQ, 2004; Feiden et al., 2008), which is based on a simple and inexpensive plane solar collector for family-based agriculture, with an adjustable inclination and input/output orifices for circulation of heated air along the surface collector.

The solar dryer was built and transient experiments were carried out in the summer season at the town of Silva Jardim, State of Rio de Janeiro, at different days and times of the day, employing thermocouples, a fluxmeter and infrared thermography in the data acquisition. The heat flux meter was employed to measure the net heat flux that enters the collector plate, positioned at the center of the collector. Infrared thermography was utilized to monitor the transient external temperature of the glass cover, as well as the quasi-steady temperature of the metallic collector plate at the end of each experimental run, immediately after removing the glass cover. Using this technique it is possible to acquire images of the temperature field on the surfaces of the glass cover and of the collector plate, allowing one to clearly observe aspects related to spatial distribution, such as uniformity and symmetry. The camera captures the infrared radiation emanating from the surface which depends on the temperature and emissivity of the surface, but in some cases it is also relevant to account for the reflection of the radiation incident on the surface.

A simple heat conduction model is initially constructed to determine the longitudinal and time evolution of the collector plate temperature, based on empirical correlations for the local Nusselt numbers for natural convection along inclined plates, and on experimental information of the glass cover temperature evolution and of the flux meter readings for determining the incident radiative heat flux. This first model is basically aimed at demonstrating the closure of the energy balance and thus verifying the experimental measurements. A second more predictive model is then proposed that couples the temperature distributions at the collector plate and at the glass cover, yielding a more predictive tool of interest to the design and optimization of such fairly simple solar dryers. Critical comparisons of experimental and theoretical results then allow for the demonstration of the prediction capabilities of the proposed coupled model.

The resulting nonlinear partial differential formulations for the transversally lumped temperatures are solved by the integral transform method (Cotta & Mikhailov, 1997), employing the UNIT code (Sphaier et al., 2011; Cotta et al., 2010). The UNIT code is an open source software built in the *Mathematica* v.7.0 symbolic computation system, so as to facilitate the solution of all the analytical steps that are inherent to the use of the Generalized Integral Transform Technique (GITT). The UNIT code was built in order to provide a robust, automatic and precision controlled simulation for either one-dimensional (UNIT 1D) or multidimensional (UNIT MD) non-linear transient convection-diffusion problems, able to cover a wide range of applications. The user essentially needs to specify the partial differential formulation according to the generalized equations specified within the code and then choose how to display results according to specific needs. However, individual applications may require the use of some variants of the algorithm provided within the code, beyond the default algorithm that is automatically triggered when running UNIT (Cotta et al., 2010).

2. THEORETICAL ANALYSIS

The collector plate thermally responds to direct sunlight and diffuse radiation which cross the cover glass, to the heat exchange by natural convection with the air flowing along its length, and to the radiation exchange between the plate surface and the glass cover (neglecting exchanges with the remaining walls of the cavity). The net heat flux measured by the flux meter is a result of the energy balance on the collector plate surface. Also one should not neglect the losses along the inner surface of the collector plate, through the styrofoam insulation and the wood structure of the dryer. The proposed mathematical formulation of the problem here considered involves constant thermophysical properties and there is no significant variation in the temperature along the horizontal direction. Starting from these hypotheses, the transient heat conduction formulation for the collector plate is given by:

$$k\left(\frac{\partial^2 T(x,y,t)}{\partial x^2}+\frac{\partial^2 T(x,y,t)}{\partial y^2}\right)=\rho c_p\frac{\partial T(x,y,t)}{\partial t},\ 0<y<\varepsilon,\ 0<x<L \tag{1.a}$$

with the following boundary and initial conditions

$$\left.\frac{\partial T(x,y,t)}{\partial x}\right|_{x=0}=0 \qquad \left.\frac{\partial T(x,y,t)}{\partial x}\right|_{x=L}=0 \tag{1.b,c}$$

$$-k\left.\frac{\partial T(x,y,t)}{\partial y}\right|_{y=0}+h_{is}(T(x,0,t)-T_\infty)=0 \tag{1.d}$$

$$k\left.\frac{\partial T(x,y,t)}{\partial y}\right|_{y=\varepsilon}+h_c(x)(T(x,\varepsilon,t)-T_\infty)+\epsilon\sigma\left(T^4-\epsilon_v {T_{v,i}}^4\right)-q_{inc}(t)=0 \tag{1.e}$$

$$T(x,y,0)=T_0 \tag{1.f}$$

In the above formulation one may observe that the effective heat transfer coefficient on the insulation side was considered uniform, while the heat transfer coefficient by natural convection on the hot side was considered to vary with the length along the plate. For simplicity, the view factor between the heater plate and the glass cover is considered equal to 1, with emissivity in the infrared range near unity thus with negligible multiple reflections. The solar radiation, either direct or diffuse, transmitted through the glass cover and effectively absorbed by the collector plate in all ranges of the solar spectrum, $q_{inc}(t)=\alpha_s q_{tran}(t)$, was also considered uniform over the collector surface, but time dependent. The incident heat flux can be determined from measurements of the flux meter, and the corresponding collector temperature at $x = x_{flux}$, from the following expression:

$$q_{inc}(t)=q_{flux}(t)+h_c(x_{flux})\left(T(x_{flux},y,t)-T_\infty\right)+\epsilon\sigma\left(T^4(x_{flux},y,t)-\ \epsilon_v {T_{v,i}}^4\right) \tag{2}$$

Since the transversal Biot number can be rather small due to the small thickness, high thermal conductivity and low heat transfer coefficient at the plate surfaces, one may propose a partial lumped system analysis, by averaging the plate temperature in the thickness, from definition of the average temperature below:

$$\bar{T}(x,t)=\frac{1}{\varepsilon}\int_0^\varepsilon T(x,y,t)\,dy \tag{3}$$

The averaging process is applied to equation (1.a), which after employing the boundary conditions results in:

$$\rho c_p\frac{\partial\bar{T}}{\partial t}=k\frac{\partial^2\bar{T}}{\partial x^2}+\frac{1}{\varepsilon}\left(q_{inc}(t)-h_c(x)(\bar{T}-T_\infty)-\epsilon\sigma\left(\bar{T}^4-\epsilon_v {T_{v,i}}^4\right)-q_p(t)\right) \tag{4.a}$$

where $q_p(t)$ are the heat losses to the external ambient through the insulation, and the boundary and initial conditions are rewritten in terms of the average temperature:

$$\left.\frac{\partial \bar{T}}{\partial x}\right|_{x=0} = 0 \qquad \left.\frac{\partial \bar{T}}{\partial x}\right|_{x=L} = 0 \tag{4.b}$$
$$\bar{T}(x,0) = T_0 \tag{4.c}$$

This simple heat transfer model was first employed so as to verify the overall energy balance, by employing as input the measurements of the glass cover temperature, the flux meter readings and the external insulation temperatures, but is not possible to use it as a tool to predict the thermal behavior of the collector. The solution methodology for the simple problem above is based on the Generalized Integral Transform Technique, GITT (Cotta & Mikhailov, 1997) implemented in the UNIT code (Sphaier et al., 2011) under the *Mathematica* 7.0 platform.

Another more complete theoretical model was then proposed, aimed at enabling the actual prediction of the dryer thermal behavior under different configurations of physical and geometrical parameters. It requires the coupling of the energy balances on the collector plate and on the cover glass, and again using the lumping procedure, it is given as,

for the collector:

$$\rho c_p \frac{\partial \bar{T}(x,t)}{\partial t} = \quad k\frac{\partial^2 \bar{T}(x,t)}{\partial x^2} + \frac{1}{\varepsilon}\left(\alpha_s \tau_{s,v} q_{sol}(t) - h_c(x)\left(\bar{T}(x,t) - T_\infty\right) - \epsilon\sigma\left(\overline{T}^4(x,t) - \epsilon_v \overline{T_v}^4(x,t)\right) - q_p(t)\right) \tag{5.a}$$
$$\left.\frac{\partial \bar{T}}{\partial x}\right|_{x=0} = 0 \qquad \left.\frac{\partial \bar{T}}{\partial x}\right|_{x=L} = 0 \qquad \bar{T}(x,0) = T_0 \tag{5.b-d}$$

where $q_p(t)$ can be obtained from:
$$q_p(t) = \frac{1}{\frac{1}{h_{is}} + \frac{\varepsilon_{is}}{k_{is}} + \frac{\varepsilon}{k}} A\left(\bar{T} - T_\infty\right) \tag{5.e}$$

and for the glass cover:

$$\rho_v c_{pv} \frac{\partial \bar{T_v}(x,t)}{\partial t} = k_v \frac{\partial^2 \bar{T_v}(x,t)}{\partial x^2} + \frac{1}{\varepsilon_v}\left(\alpha_{vs} q_{sol}(t) - h_{c,e}(x)\left(\overline{T_v} - T_\infty\right) - h_{c,i}(x)\left(\overline{T_v} - T_\infty\right) - \epsilon_v\sigma\left(\overline{T_v}^4(x,t) - \epsilon\overline{T}^4(x,t)\right)\right) \tag{6.a}$$
$$\left.\frac{\partial \bar{T}_v}{\partial x}\right|_{x=0} = 0 \qquad \left.\frac{\partial \bar{T}_v}{\partial x}\right|_{x=L} = 0 \qquad \bar{T_v}(x,0) = T_0 \tag{6.b-d}$$

This coupled heat transfer model only requires the information of solar incidence in the region where and when the colletor is located and can be solved within the same computational platform *Mathematica* v.7.0. Empirical correlations for the local heat transfer coefficient in natural convection over inclined plates have been recently proposed, as a function of a modified Rayleigh Number (Kimura & Kitamura, 2010), including both the laminar and turbulent flow regions. Thus, the adopted correlations for the local Nusselt number, for the specific inclination of the dryer here analyzed, are given by:

For laminar flow: $\mathrm{Ra}^*_{x\varphi} < 2.5x10^7 \quad \mathrm{Nu_x} = 0.52{\mathrm{Ra}^*_{x\varphi}}^{1/5}$ (7.a)

For turbulent flow: $\mathrm{Ra}^*_{x\varphi} > 2.5x10^7 \quad \mathrm{Nu_x} = 0.19{\mathrm{Ra}^*_{x\varphi}}^{1/4}$ (7.b)

where the modified Rayleigh and Grashof numbers for a prescribed heat flux condition are given by:

$$\mathrm{Ra}^*_{x\varphi} = \mathrm{Gr}^*_{x\varphi}\,\mathrm{Pr} \qquad \mathrm{Gr}^*_{x\varphi} = \frac{\mathrm{g}\,\beta\,\mathrm{q_{flux}x^4}}{\mathrm{k}\,v^2}\cos(\varphi - 90) \tag{8.a,b}$$

where g is the gravitational acceleration, β is the thermal expansion coefficient of the fluid, k is the thermal conductivity of the fluid, v is the kinematic viscosity and φ is the plate inclination angle.

The heat losses from the heated surfaces facing down, namely, the inner surface of the glass cover and the external face of the insulation, are predicted from a correlation of the average Nusselt number for this case (Ozisik, 1990):

$$Nu_m = 0.56\left(Gr_L Pr\cos(\varphi - 90)\right)^{1/4} \tag{9.a}$$

for the glass cover: $Gr_L = \frac{\mathrm{g}\,\beta(\bar{T}_{vidro} - T_\infty)\mathrm{L}^3}{v^2}$ for the insulation: $Gr_L = \frac{\mathrm{g}\,\beta(T_{insulation} - T_\infty)\mathrm{L}^3}{v^2}$ (9.b,c)

For the local heat transfer coefficient at the external face of the glass cover, in the case of a forced convection condition due to blowing winds, the laminar flow correlation for a prescribed heat flux condition is used (Bejan, 1993):

$$Nu_x = 0.453 Re_x^{1/2} Pr^{1/3} \qquad Re_x = \frac{u_\infty x}{v} \tag{9.d,e}$$

where u_∞ is the free stream velocity of the external environment.

3. EXPERIMENTAL SETUP AND PROCEDURE

IAPAR published a manual with instructions for assembling this unexpensive solar dryer with the intention of making it readily available to everyone that works with small scale agricultural production, and following such instructions the collector was built at LTTC, COPPE/UFRJ, in the realm of a cooperation with the Université de Reims, France. The IAPAR dryer was built on ordinary wood, an aluminium plate, regular window glass and styrofoam. The aluminium plate was painted with graphite spray ink of known emissivity (0.97). For improved solar energy absorption, the collector is fixed on an easel with hinges and a support system that enables inclinations (φ) that are recommended by the IAPAR manual and should be adjusted according to the season of the year and the region of the country.

Experimental campaigns were performed which allowed to determine temperature measurements through thermocouples at selected surface locations along the length of the collector and at the air inlet and outlet orifices, besides the net heat flux at the center of the collector plate via the flux meter. This set of results was intended to verify the energy balance on the plate and check the experimental procedure in comparison to the proposed heat transfer model. The experimental apparatus is shown in Fig. 1, where one can observe the following components: (a) Solar dryer, (b) Data acquisition system (Agilent 34970-A), (c) Notebook for acquisition and data processing. The dryer section is shown schematically in Fig. 2.

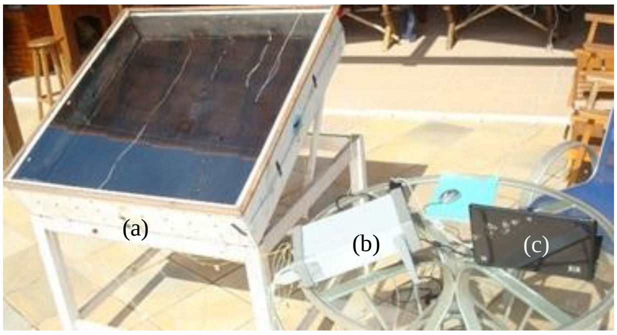


Figure 1. Overview of the experimental setup.

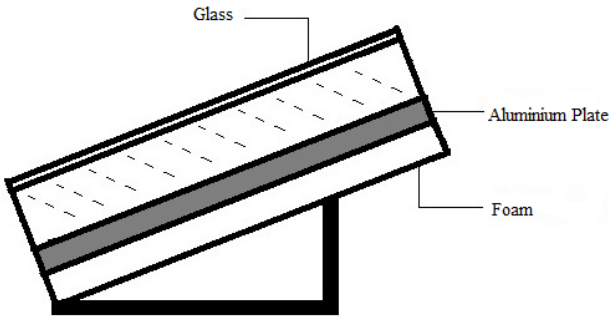


Figure 2. The dryer transversal section.

The dryer is thus an inclined square cavity (0.96m in lateral dimensions and 25.5º inclination) with a window glass cover that transmits solar radiation to the collector plate due to the high transmissivity in the ultraviolet range, and absorbs a considerable amount of the emitted radiation from the plate, due to the large absorptivity in the infrared range. The cavity has 18 holes in each extremity through which the air circulates. The transient temperature measurements were performed with thermocouples type K fixed on the plate surface and input/output air orifices. The flux meter was fixed at the middle of the plate, and thermocouples were also installed on the inside and outside faces of the glass cover as shown schematically in Fig. 3. Figure 4 summarizes the positions of the installed thermocouples and the flux meter. Finally, a thermocouple was fixed under the dryer structure so was to estimate the heat losses through the insulation.

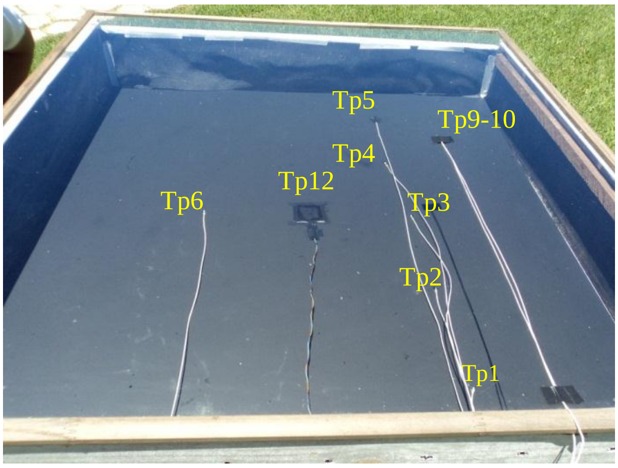


Figure 3. The flux meter (Tp12), thermocouples on the plate (Tp1-Tp6) and on the glass cover (Tp9-Tp10).

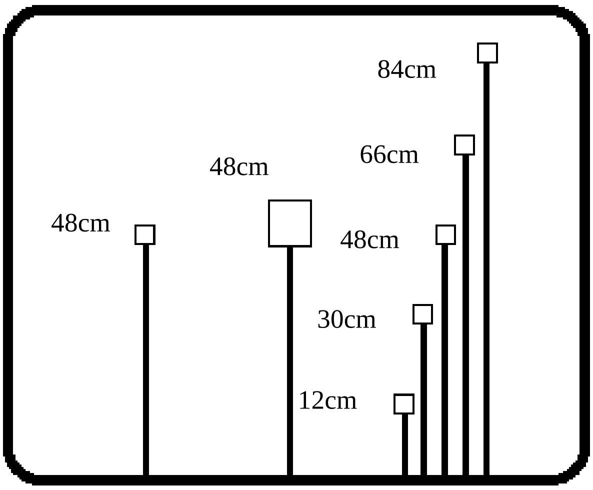
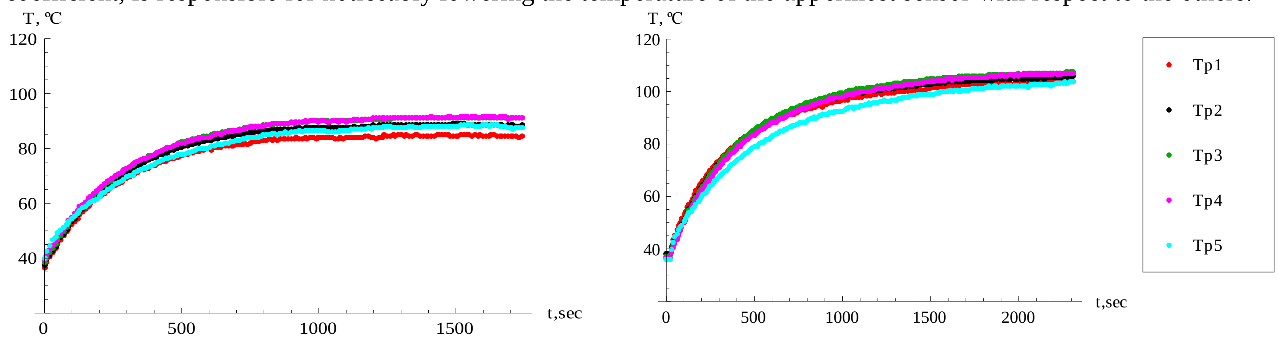


Figure 4. The positions of the thermocouples fixed at the surface of the collector plate.

The experimental procedure begins with the exposition of the dryer to the sunlight, and the first temperature measurements are taken with the glass covered with an opaque thick tissue, so was to provide the initial condition for the plate surface. Next, the surface of the dryer is exposed to the solar incidence, and then temperature measurements are continuously registered in the data acquisition system. After around 30 minutes the dryer is taken off the solar exposition, and once the plate returns to ambient temperature with the aid of a fan, a new experimental run can be initiated. All the measurements are monitored on real time with the notebook, and acquired by the Agilent 34970-A system. Along the experiment the glass cover thermography is recorded with the infrared camera (FLIR SC660), and at the end of the transient period, the glass cover is removed to allow for a few recordings of the collector plate thermography, before the influence of the glass cover removal on the collector thermal behavior is felt. Numerical data of these measurements can be imported to the *Mathematica* software, and subsequent treatment comes down to employing built in functions on this platform for interpolation, analysis and graphical representation of data.

4. RESULTS AND DISCUSSION

A few representative experimental results are here reported for runs performed on February 2012, in the town of Silva Jardim, RJ, for a clear sky condition. Figure 5.a illustrates the evolution of the thermocouple measurements of Experiment no.1 along the length of the collector plate, for increasing positions Tp1 to Tp5 (12, 30, 48, 66, and 84 cm). At the end of 1640sec of experiment, the temperatures reached the values, respectively, of 84.3ºC, 88.5ºC, 91.0ºC, 90.9ºC and 87.6ºC. Figure 5.b illustrates the evolution of the thermocouple measurements of Experiment no.2 along the length of the collector plate, for increasing positions Tp1 to Tp5. At the end of 2250sec of experiment, the temperatures reached the values, respectively, of 103.9ºC, 105.7ºC, 107.3ºC, 107.2ºC and 103.9ºC. It can be noticed from the experimental results that the transition to turbulent flow, with the consequent increase in the local heat transfer coefficient, is responsible for noticeably lowering the temperature of the uppermost sensor with respect to the others.



(a) Experiment no.1 (b) Experiment no. 2

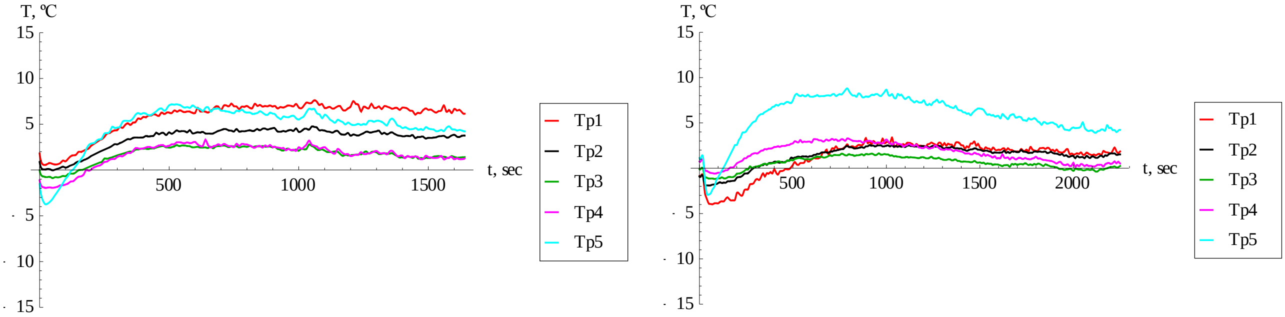
Figure 5. Experimental results from thermocouples installed along the length of the collector plate:
(a) Experiment no. 1 (14:00h Feb.4th), (b) Experiment no. 2 (12:30h Feb.5th).

The convergence behavior of the eigenfunction expansion is briefly illustrated in Table 1 for experiment no.2, where the results obtained by the UNIT code are shown at the same thermocouples position on the plate and for three different times along the transient process, considering increasing truncation orders N = 8, 32 and 50. The converged results are also compared to the *Mathematica* system (NDSolve function) numerical solution, with excellent agreement.

Table 1. Convergence of temperature eigenfunction expansion for Experiment no.2 at the thermocouple positions.

	N	8	32	50	NDSolve
x (cm)	t (s)				
12	750	92.928	92.931	92.931	92.804
12	1500	102.145	102.149	102.149	101.957
12	2250	104.285	104.289	104.289	104.118
30	750	94.428	94.429	94.429	94.971
30	1500	103.920	103.921	103.921	104.551
30	2250	106.112	106.113	106.113	106.793
48	750	94.976	94.973	94.973	95.152
48	1500	104.587	104.584	104.584	104.790
48	2250	106.783	106.779	106.779	107.015
66	750	94.798	94.798	94.798	94.718
66	1500	104.402	104.402	104.402	104.294
66	2250	106.598	106.597	106.597	106.514
84	750	94.631	94.633	94.633	94.613
84	1500	104.221	104.223	104.223	104.168
84	2250	106.415	106.418	106.418	106.386

Figures 6a,b show for Experiments no.1 and no.2 the absolute deviations between the simplified heat transfer model and the thermocouple measurements along the length of the collector plate, for the same increasing positions shown above. Apparently the uppermost position, which follows the transition to turbulence, is the least accurate in the attempt to predict with the simple model that employs one single correlation for the whole plate length.



Figures 6. Deviations between the simplified heat transfer model predictions and the thermocouple measurements: (a) Experiment no.1, (b) Experiment no.2.

Figure 7a illustrates the heat flux evolution as measured by the flux meter for Experiment no.1, while Figure 7b shows the estimate of the incident heat flux for Experiment no.2, calculated from the flux meter data, the heat transfer coefficient correlation and with the temperatures measured at the inner surface of the cover glass. In the first moments of the experiments, the exposure to sunlight promotes a drastic increase in heat flux, followed by a more gradual increase, towards a quasi-steady behavior that should be in accordance with the expected irradiation levels for the region and the time of the year and day. The experiments were performed in February in a region for which the average solar incidence for a clear sky, indicated by the ASHRAE handbook, should be about 912 W/m². Figure 7b for Experiment no.2 closely reproduces this value after the initial transient has passed.

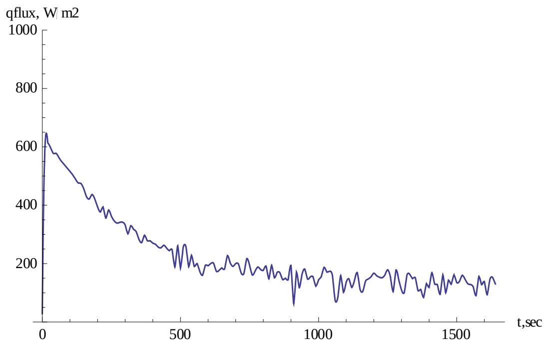


Figure 7a. Heat flux evolution as measured by flux meter placed at the middle of the collector plate (Exp. no.1).

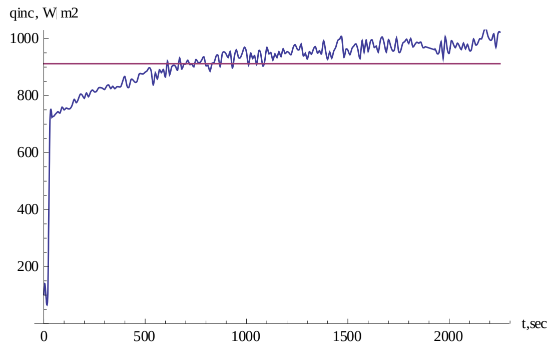
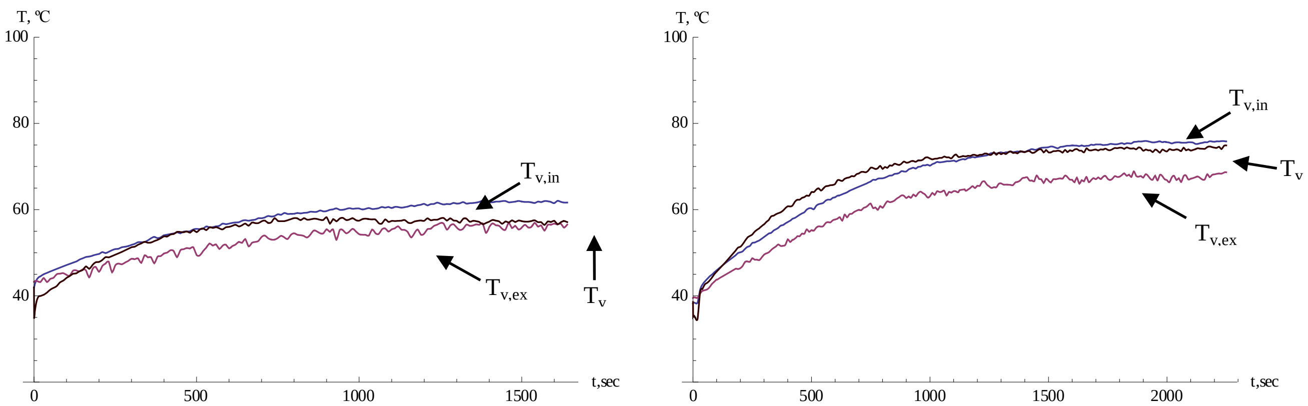


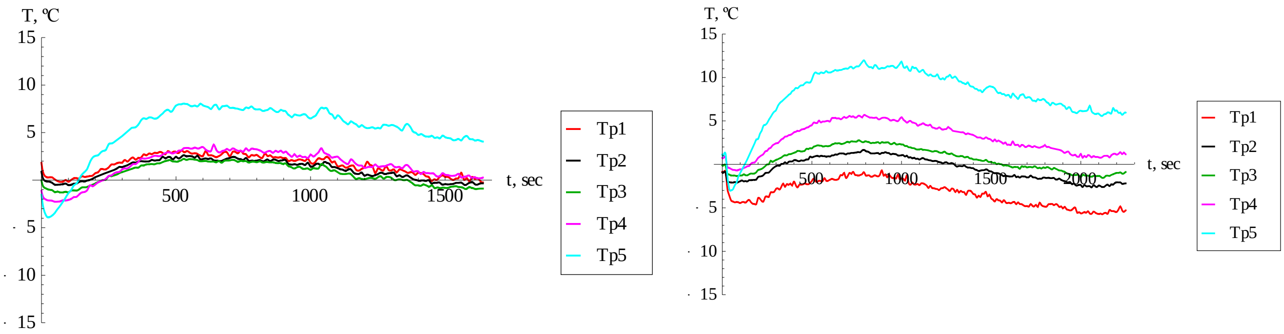
Figure 7b. Evolution of radiative heat flux directly incident over plate estimated from flux meter data (Exp. no.2).

Figures 8a,b show a comparison of the coupled theoretical model prediction of the average glass cover temperature evolution, as compared to the measured internal and external glass cover temperatures at the center of its length (48 cm). The theoretical value from this lumped model is indeed closer to the internal glass temperatures, indicating that an improved lumped approach could be recommended (Cotta & Mikhailov, 1997).



Figures 8. Comparison of coupled model results for glass cover average temperature against experimental results for inside and outside faces temperatures: (a) Experiment no.1, (b) Experiment no.2.

Figures 9a,b show the deviations between the coupled model predictions and the experimental temperature evolutions for Experiments no.1 and 2, respectively. Again, except for the uppermost position, a fairly good agreement between the theoretical and experimental results can be observed. In the present more predictive tool, experimental results are not fed into the model, and we may then conclude that a closer agreement is only feasible by employing a more descriptive correlation that includes a transition region identification or by employing a more complex conjugated analysis with the natural convection flow problem and the possible interaction of the boundary layers.



Figures 9. Deviations between the simplified heat transfer model predictions and the thermocouple measurements: (a) Experiment no.1, (b) Experiment no.2.

Figure 10 provides a printed screen of the ThermaCAM Researcher Professional software (version 2.9) employed with the FLIR SC-660 camera, showing the thermogram of the collector plate at the end of the experimental run, together with the horizontal plot of the temperatures at the heights of the thermocouples Tp1 to Tp5. It can be noticed that the temperature distribution is fairly uniform along the horizontal direction, while the noticeable perturbations are just due to the presence of the thermocouples wires, which alter just locally both the surface emissivity and temperature.

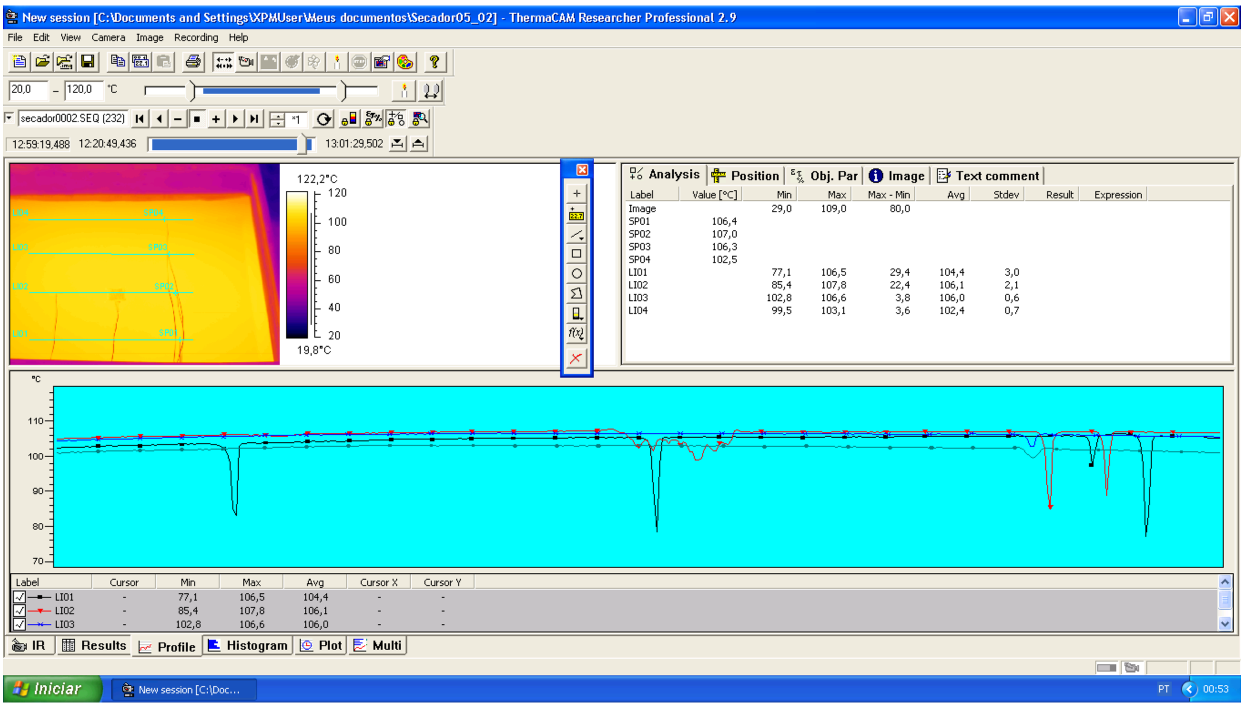
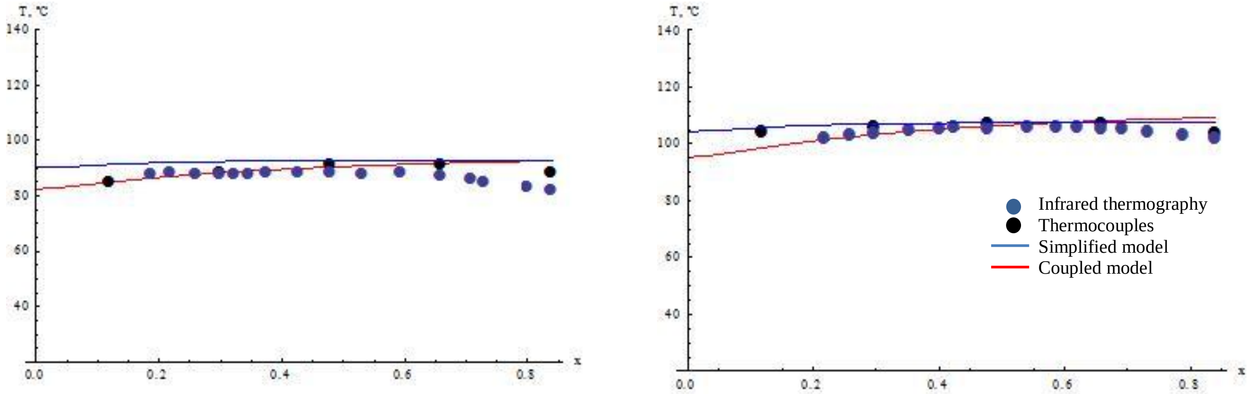


Figure 10. Thermogram of the collector plate at the end of a typical experiment, showing horizontal temperature distributions along the thermocouple positions.

From the infrared camera thermographies such as the one shown above, temperature values can be obtained for critical comparisons with both the thermocouple measurements and the theoretical models predictions, as shown in Figures 11a,b below, at the end of the experiments no.1 and 2, respectively. One can clearly notice that the coupled model corrects to some extent the predictions of the simplified model for the temperatures at the lower portion of the collector plate, by including the more adequate coupling with the glass cover temperature distributions. However, neither of the models are able to more closely reproduce the reduction on the temperature values at the upper portion of the plate, after the transition to turbulent flow, as previously discussed, while the experimental finding by the two techniques, intrusive and non-intrusive, are in quite good agreement.



(a) Experiment 1 (b) Experiment 2

Figures 11. Comparison of thermography and thermocouple results for collector plate temperatures along its length against the simplified and coupled models predictions: (a) Experiment no.1, (b) Experiment no.2.

5. CONCLUSION

A basic heat transfer analysis was undertaken of a simple solar dryer for small agricultural production conceptually proposed by IAPAR (Instituto Agronômico do Paraná), aimed at developing adequate models for its optimization and up-scaling. For this purpose, experimental results were obtained for temperature evolutions at the collector plate and glass cover, at the chosen geographical and corresponding climatic conditions. Data acquisition was based on a combination of thermocouples, flux meter and infrared camera thermography. A simplified model was first proposed which however depends on the availability of temperature measurements at the glass cover, followed by a more complete model that couples the energy equations at the collector plate and the glass cover, and depends solely on the knowledge of the average solar incidence in the region and, eventually, of wind speed and direction if relevant.

It was here demonstrated that the more complete coupled model can provide a fairly good prediction of the temperature distributions in both the collector plate and glass cover, but further improvement is foreseen by adopting an improved lumped approach at the glass cover model, that accounts for the temperature gradients within its thickness. Also, the thermal behavior of the uppermost portion of the collector plate can be more closely reproduced once a more detailed analysis of the transition region extent and corresponding heat transfer coefficients can be made available. Nevertheless, the present model already allows for the selection of basic parameters such as collector dimensions and inclination angle in the desired application.

6. REFERENCES

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