Article **Journal of Technological Development**
June, 2023 Vol.7 No.19 10-16

Integration of a malt kilning model and a solar air heater model for its use as a viability estimation tool

Integración de un modelo de secado de malta y de un calentador solar de aire para su uso como herramienta para estimar viabilidad

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DOI: 10.35429/JTD.2023.19.7.10.16 Received March 26, 2023; Accepted June 28, 2023

Abstract

The current work deals with a model of malt kilning, coupled to the design equation of a solar air heater, to use it as a tool for the estimation of the energy saved through its operation. The kilning model was previously validated by previous works, while the design equation for the solar air heater was obtained by a published characterization of a solar air collector manufactured in Mexico, to use it as a platform to evaluate its behavior in the solar conditions with a known equation. The kilning model was obtained previously by other works, where the malt was characterized, and its drying parameters were obtained, this model was modified to improve its convergence. This coupled model will be used to do experiments on the thermal behavior of the process, being able to predict the behavior of the process and being capable of modifying the heating schemes and reflux fractions, and verifying if the solar heating of the process is viable.

Malt Kilning, Solar energy, Mathematical model

Resumen

El presente trabajo es un modelo del secado de malta, acoplado a las ecuaciones de diseño de un calentador solar de aire, para su posterior uso para la estimación de la energía ahorrada a través de su operación. El modelo de secado esta previamente validado por trabajos previos, mientras que las ecuaciones de diseño se obtuvieron de una caracterización de un colector solar fabricado en México, para utilizarlo como plataforma para poder conocer el comportamiento del modelo con una ecuación de diseño conocida. El modelo de secado se obtuvo de trabajos previos, en donde se caracterizó la malta y se obtuvieron sus parámetros de secado, el modelo se modificó para aumentar su convergencia. A partir de este modelo entonces se puede experimentar en el futuro con distintas configuraciones, en especial al variar la cantidad de colectores o los esquemas de reflujo o temperatura, para poder obtener un mejor uso de la energía en el proceso y, además, saber si el proceso en conjunto es viable.

Malta, Secado, Energía Solar, Modelo Matemático

Citation: LANDA-RIVERA, Ismael, HERNÁNDEZ-RUÍZ, María de los Ángeles, PILATOWSKY-FIGUEROA, Isaac and GARCÍA-GONZALEZ, Juan Manuel. Integration of a malt kilning model and a solar air heater model for its use as a viability estimation tool. Journal of Technological Development. 2023. 7-19: 10-16

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Introduction

The beer brewing industry in Mexico produces 2,615 kt of malt each year as feedstock [I], in order to achieve this production, fossil fuels are used to obtain energy, most of this energy is used during the kilning of green malt, where germinated barley is dried to achieve the optimal characteristics for its use and storage. To achieve a reduction in the use of fossil fuels, and hence, the reduction of emission of CO_2, it is possible to integrate solar thermal energy to the process.

Therefore, green malt kilning is central process in the brewery, and this process consumes between 1,058 KWh and 1,543 KWh per ton of malt, consuming about 900 to 1,200 KWh as thermal energy for heating air. As this process consumes a great amount of energy, it is possible to conduct strategies to reduce the burning of fuel. The process of malt kilning was modeled to know the behavior of a previously stablished temperature scheme, therefore enabling it to be coupled to the design equation of a solar collector and, through that coupling, being able to estimate the outlet temperature of the device and the energy difference between the outlet air temperature of the collector and the target temperature of the process, in this way solar energy contribution could be calculated via this difference.

Visual Basic for Applications was used to model the process, using Microsoft Office Excel 365 as a platform and data output. The model is based on the balances and proprieties previously derived and estimated from validated models, whilst the behavior of the solar collectors is based on the design curves obtained experimentally for flat plate solar air heaters, previously reported in studies of their performance.

Malt kilning model

Since 1974, the deep bed drying of grains has been studied [II]. The simulation of such process is based in the assumption that the water is evaporated from the surface of the grain, and the limiting factor is the formation and drying of a thin film of water on its surface [II]. This model was subsequently adjusted to malt and barley in 1984 [III] and has transcended until the most recent studies, where it has been improved by providing better experimental parameters [IV].

The last of this study adapts the kinetics and equilibrium to the matter and energy balances provided by Nellist and adapted by Bala and Woods [V].

Whilst for the evaluation of the equilibrium moisture me, the experimental data of different temperatures was fitted to the Guggenheim, Anderson, and Boer Isotherm to obtain temperature dependent coefficients.

For the moisture balance:

$$\Delta w_a = -\rho_m \cdot \frac{\Delta z}{G}\left(\frac{\Delta M}{\Delta t}\right) \quad (1)$$

M: Malt moisture (kg of water/ kg of dry matter).
Δz: Layer thickness (m).
ρ_m: Grain bed density.
Δw_a: air moisture change on the bed layer (kg of water/ kg of dry air).
Δt: Elapsed time (s).
G: mass flow (kg of air/s m^2).

For the moisture equilibrium on the bed layer:

$$M_{(t+\Delta_t)} = M_{(t)} \cdot e^{-k\cdot\Delta t} + M_e\left(1 - e^{-k\cdot\Delta t}\right) \quad (2)$$

$M_{(t+\Delta t)}$: Malt equilibrium moisture in the elapsed time (kg of water/ kg of dry matter).
$M_{(t)}$: Starting malt moisture (kg of water/ kg of dry matter).
M_e: Equilibrium moisture of the layer (kg of water/ kg of dry matter).
k: drying constant.

Where:

$$k = \frac{D_{ef}}{r^2} \qquad r = 5mm \quad (3)$$

$$D_{ef} = 0.41036 \cdot exp\left[-\frac{5108.4454}{(T_a + 273.15)}\right] \quad (4)$$

D_{ef}: Diffusion coefficient of water into air.
r: grain diameter.
T_a: Air temperature.

Whilst for the evaluation of the equilibrium moisture M_e, Lopez et al. (1997) [V] fitted the experimental data of different temperatures to the Guggenheim, Anderson, and Boer Isotherm to obtain temperature dependent coefficients [V]:

$$M_e = \frac{AB \cdot C \cdot a_w}{(1 - C \cdot a_\omega)[1 + (B - 1) \cdot Ca_\omega]} \qquad (5)$$

a_w: Water activity coefficient.

Where:

$$A = 0.01183 \cdot exp\left(\frac{464.017}{T}\right) \qquad (6)$$

$$B = exp\left(\frac{943.854}{T}\right) \qquad (7)$$

$$C = exp\left(-\frac{28.639}{T}\right) \qquad (8)$$

T: Absolute temperature of air(K)

And for the energy balance:

$$\Delta T_a = \frac{\frac{\rho_m \cdot \Delta z}{G \cdot \Delta t} \cdot [\Delta M \cdot (C_v \cdot T_a + L_a - C_w \cdot T_m) - \Delta T_m \cdot (C_a + C_w \cdot (M + \Delta M))]}{C_a + C_v \cdot \left(w_a - \rho_m \cdot \frac{\Delta z}{G} \cdot \frac{\Delta M}{\Delta t}\right)} \qquad (9)$$

C_v: Water steam heat capacity (kJ/kg°C)
C_w: Water heat capacity (kJ/kg °C)
C_a: Dry air heat capacity (kJ/kg°C)
w_a: Water content of air (kg of water/ kg of dry air)
L_a: latent heat of vaporization of water (kJ/kg)
ΔT_a: Air temperature chance in the grain layer (°C)

Whilst for the heat transfer balance:

$$\Delta T_m = \frac{A + \rho_m \cdot \frac{\Delta M}{\Delta t}\left[\frac{2 \cdot Y}{h_{ev}} + \frac{\Delta z}{G \cdot E} \cdot F\right]}{1 + \frac{\rho_m}{\Delta t} \cdot \left[\frac{2 \cdot B}{h_{ev}} + \frac{\Delta z}{G \cdot E} \cdot (B + C_w \cdot \Delta M)\right]} \qquad (10)$$

ΔT_m: Malt layer temperature change (°C)
h_{ev}: Convective heat transfer coefficient of air.

Where:

$$A = 2 \cdot (T_a + T_m) \qquad (11)$$

$$B = C_m + C_w \cdot M \qquad (12)$$

$$E = C_a + C_v \cdot \left(w_a - \frac{\rho_m \cdot \Delta z}{G} \cdot \frac{\Delta M}{\Delta t}\right) \qquad (13)$$

$$F = C_v \cdot T_a + L_a - C_w \cdot T_m \qquad (14)$$

$$Y = L_m + C_v \cdot T_a - C_w \cdot T_m \qquad (15)$$

C_m: Heat capacity of air (kJ/kg°C)
L_m: Latent heat of vaporization of water in malt (kJ)
T_m: Malt temperature (°C)

Solar air heating modeling

Solar air heaters are devices that take advantage of materials that absorb a great amount of solar light, to transform radiation to heat and transferring it to air passing through the device. The behavior can be predicted from equations of the type:

$$\eta = a_{01} - a_{11}X - b_{11}G_aX^2 \qquad (16)$$

η: efficiency

Where: $X = \left(\frac{T_m - T_{am}}{G_a}\right)$ y $T_m = \left(\frac{T_e + T_s}{2}\right)$

These equations can be solved by a simple numerical method (Secant method) to obtain the outlet temperature based on the inlet temperature (T_e), the ambient temperature (T_a) and the Irradiance incident on the plane (G_a).

After that, the heat obtained from the heating of air is estimated and the difference between this heat and the objective heat is calculated.

To verify the model, the fitting of the efficiency curve reported by Perez-Espinoza et al (2020) [VI] for three collectors in series:

$$\eta = 0.6173 - 6.3567X - 0.0190GX^2 \qquad (17)$$

A modifier of the incidence angle ($K_{\tau\alpha}$) was reported in the same study; therefore, it was used:

$$K_{\tau\alpha} = 1 - 0.1245\left(\frac{1}{\cos\theta} - 1\right) \qquad (18)$$

θ: Solar radiation incidence angle.

Therefore, efficiency equation becomes:

$$\eta = 0.6173\ K_{\tau\alpha} - 6.3567X - 0.0190GX^2 \qquad (19)$$

Methods

The model was coded as an Excel VBA Macro, starting with the calculation of properties of the inlet air, then the outlet moisture, energy and temperature of the air in the collector was calculated, and also the heat needed to achieve the energy required to raise the air temperature to the desired objective temperature was obtained, after that, the drying process begins, after its completion, the data obtained for each layer of the grain bed and the properties of the air and malt are written in the Excel sheet who serves as data log for the process.

The process takes place in this order (Figure 1), firstly the metrological, solarimetric and malt data are read from the excel data, then, in the point number 1 of the flow chart (Figure 2), the data enters a loop where the processes taking place in the collector are solved.

After doing this, the energy needed for reaching the desired temperature is calculated and the properties of such state are estimated. From this point on, matter and energy balance of each layer of the grain are solved. In this balances, all the equilibrium properties are calculated (malt moisture Me, air- water diffusion constant k), after that the balances are solved, In this point, the process continues with the wetting process, which is signaled on the diagram by the number 2 (Figure 3), this wetting process is put in place to avoid the oversaturation of the air over moisture levels greater than 98%, changing as an objective the difference of moisture of the malt; the process takes place for a n number of layers until the grain bed depth is reached

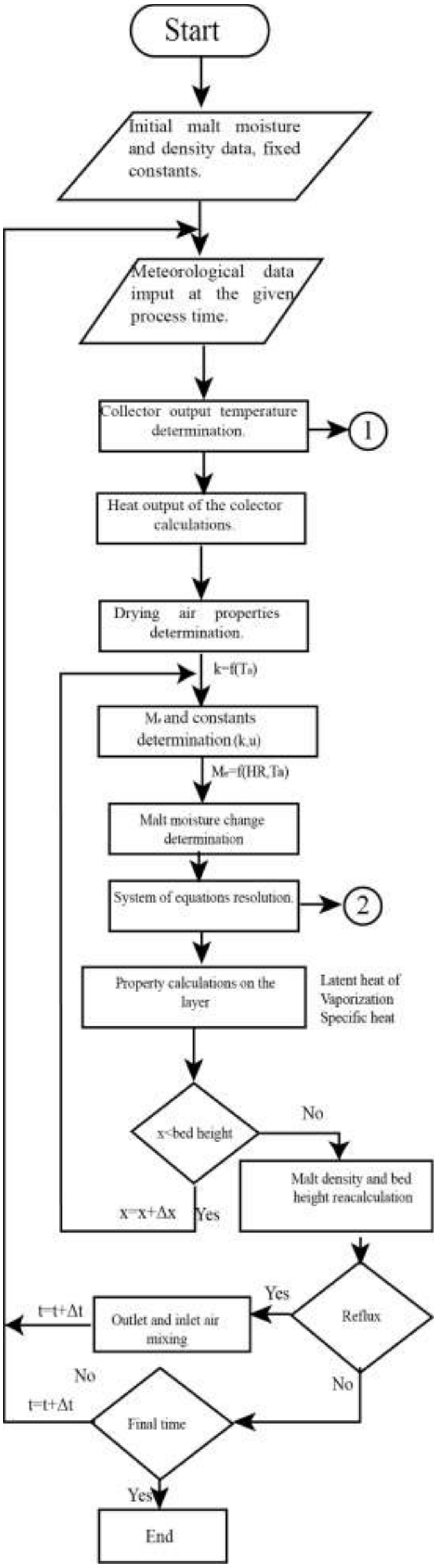


Figure 1 Process Flow chart

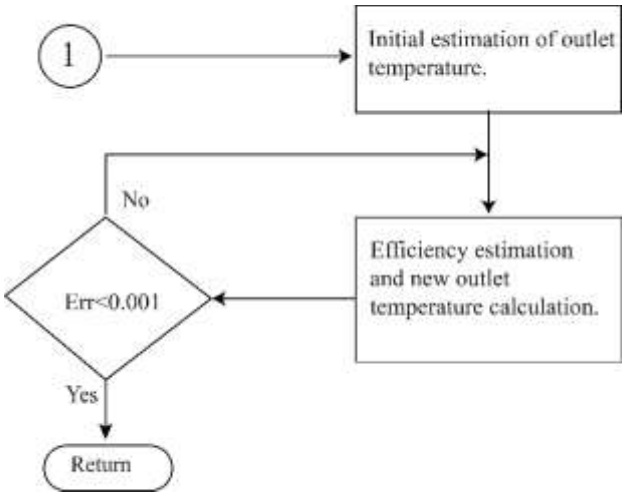


Figure 2 Solar Collector outlet temperature estimation

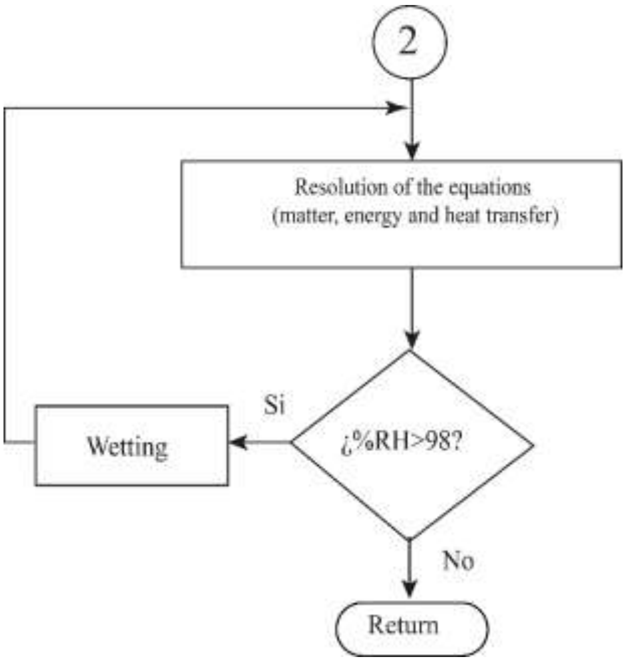


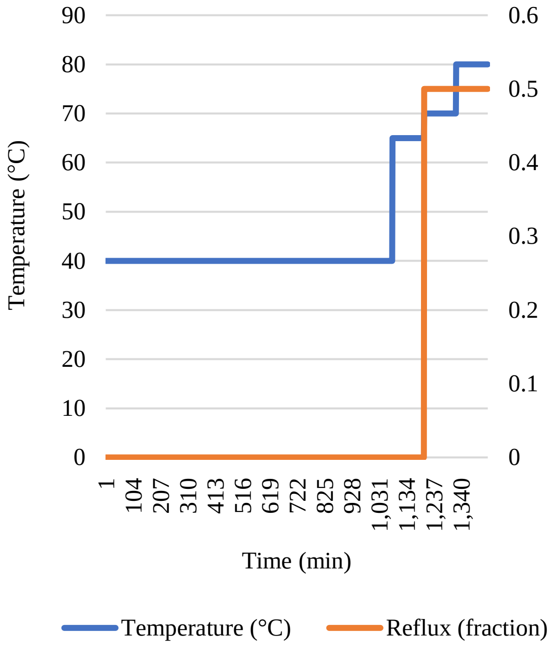
Figura 3 Ciclo de resolución del sistema de ecuaciones, con etapa de mojado

The solar energy cycle was solved using the secant method, mostly because it uses multiple parameters dependent on the outlet temperature.

The wetting cycle was solved using a LaGrange polynomial to interpolate towards a relative humidity of 98%, replacing the use of the Aitken-Neville search algorithm used by López et al. (1997) & Nellist (1974) [II & V].

Results

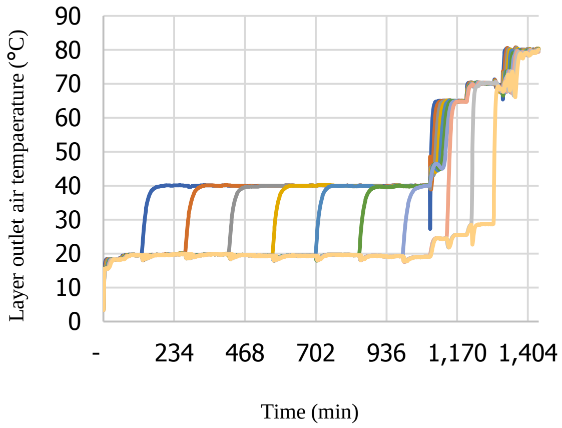
To test the system, a previously known and characterized scheme was used (Graph 1), this scheme includes a reflux of 0.5 at objective temperatures higher than 70° C [V].



Graph 1 Drying scheme used to carry out the simulation.

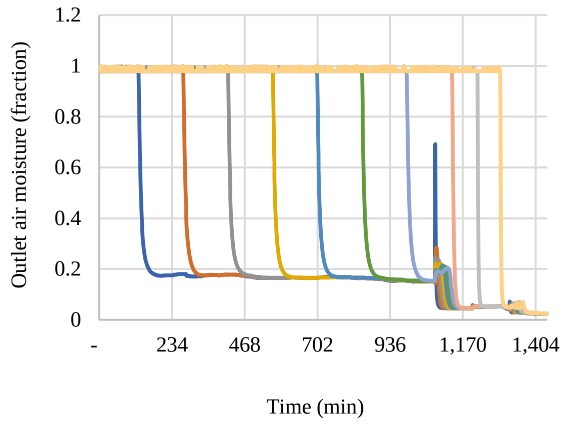
Drying model

The drying model was done in Excel® through a VBA macro, meteorological data was ordered from the first minute of the day, and missing data points where extrapolated, the temperature on each layer of the bed behaved as reported by López et al (1997) [V] and is shown in graph 2:



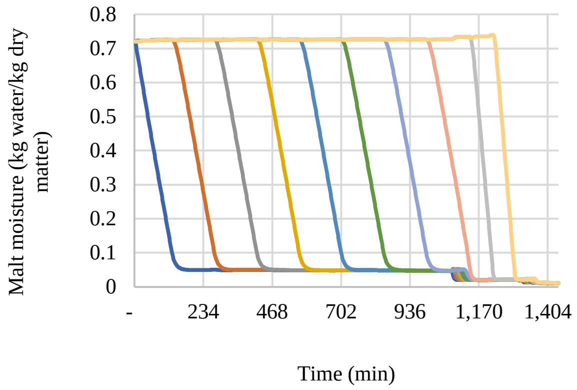
Graph 2 Behavior of the outlet temperature for each layer on the bed, from n=1 to n=10

The consistently, the behavior of the outlet temperature it's consistent with the behavior of the moisture leaving each layer and its evolution through time (Graph 3).



Graph 3 Evolution of the relative humility at the outlet of each layer of the bed

Also, the moisture content of the malt, behaves in a similar manner consistent with the change on the equilibrium (Graph)

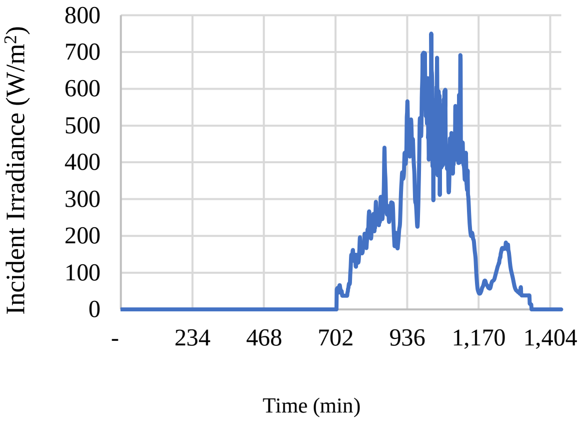


Graph 4 Evolution of malt moisture in each layer

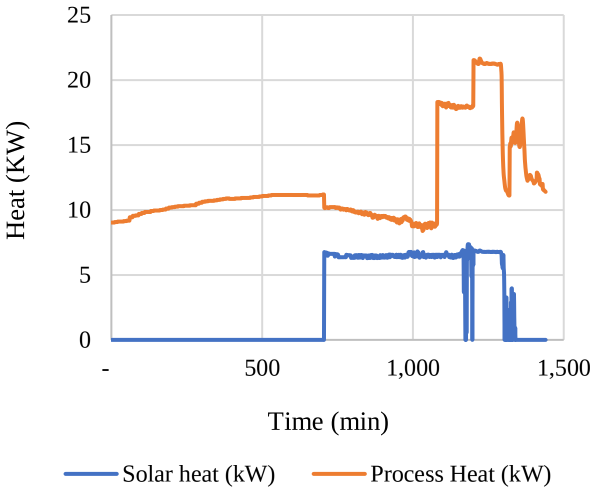
Solar heating model

Plane incident radiation was calculated by the model of Hottel y Woerts [VII y VIII] for clear sky radiation (with an inclination of 46° over the horizontal plane) this incident of radiation is shown on Graph 5.

The solar heating model was able to predict that for a day wait particularly low radiation (not greater than 800 W/m^2) The estimated energy saving amount to 22%. This behavior it's shown on Graph 6 together with the required heat.

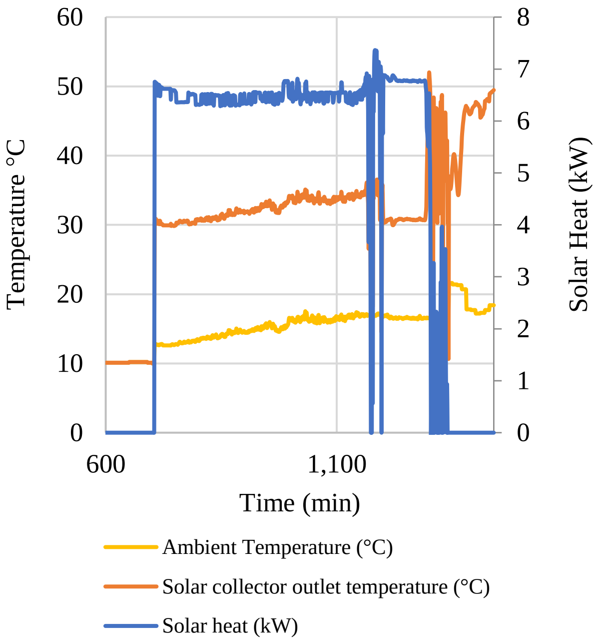


Graph 5 Irradiance incident on the collector.



Graph 6 Process heat

Also, the outlet temperature of the collector it's consistent with the thermal energy output from the collector and the fluctuations of ambient temperature (Graph 7).



Graph 7 Inlet temperature, output heat and ambient temperature

Financing

This work was funded by the CONAHCYT scholarship Number 1144534.

Conclusion

The behavior of the drying model is consistent with previously reported models, having variation in the drying rate, which can be attributed to the diminishing atmospheric pressure in the place were data was gathered, Zacatecas, Zacatecas, Mexico.

The model described in this work for the solar collectors tends to fail when the reflux temperatures start to increase but, this can be attributed to the limitations of the design equations of the solar collector, since it only can predict the behavior at days with a continuous incident radiation because the model omits response time of the collector.

As subsequent work, the application of the model is postponed until the data of a month is processed so viability can be properly estimated.

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