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Exergetic Analysis of a Mixed-Mode Solar Dryer

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Abstract: The utilization of energy in a Mixed-Mode Solar Dryer is evaluated in this work. Exergetic analysis of the dryer revealed that drying in a cabinet other than direct sun drying made drying more attractive and as well conserve energy. It has an overall average exergetic efficiency of 56% and thermal efficiency of 66.95%.

Key words: Mixed-mode, energy, exergy, anergy, efficiency

INTRODUCTION

Modern methods of food preservation such as canning and refrigeration are very expensive due to the soaring prices of energy. In developing countries, the traditional direct sun-drying method is slow. The shortcoming of this method has been overcome by the use of solar dryers[1,2].

Solar energy is an ideal alternative source of energy, as it is abundant and inexhaustible. There are promising strategies for harnessing solar energy resources, which are environmentally friendly and have less damaging impact on public health and security[3-5].

It is recognized that the ideal thermodynamic efficiency of a system is the ratio of useful work performed to the amount of energy supplied to the system. Since the solar collector absorbs energy at a higher temperature than ambient, the energy will be partially converted to thermal energy in the system and partly lost to the environment[6]. For the evaluation of the thermal performance of such a system therefore, descriptive parameters that rates the quantity and quality of energy is required.

In this study, exergetic analysis that employed heat exergy and anergy as descriptive parameters was used to rate the availability of energy in the Mixed-Mode Solar Dryer. The objectives are to determine if the dryer made use of the exergy effectively and to identify reasons for any loss.

Basic theory: Useful information on energy related equations on fenestration and energy balance on flat plate collectors had been presented in standard texts[4,7].

The energy from the Mixed-Mode Solar Dryer was calculated from the following energy equations.

$$Q_u = (\alpha_C \tau) I_T A_c - U_L A_c (t_c - t_a) \qquad (2.1)$$

The energy per unit area of the collector is given by:

$$q_u = (\alpha_C \tau) I_T - U_L (t_c - t_a) \qquad (2.2)$$

The thermal; efficiency of the collector is;

$$\eta_c = \frac{q_u}{I_T}$$

$$\eta_c = \eta_o - \frac{U_L}{I_T}(t_c - t_a) \qquad (2.3)$$

where

$$\eta_o = (\alpha_C \tau)$$

Hourly efficiency is given by:

$$\eta_h = \frac{q_u(h)}{I_T(h)} \qquad (2.4)$$

and Daily efficiency, η_D,

$$\eta_D = \frac{\sum q_u}{\sum I_T} \qquad (2.5)$$

The following quantities were computed from measured parameters for the dryer using standard equations[7]

Solar insolation on the plane of the collector plate, 'I_δ'

$$I_\delta = I \sin\beta \cos\delta + I \cos\beta \cos n \ \sin\delta \qquad (2.6)$$

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Sun's declination 'δ' is given by;

$$\delta = 23.47 \sin \frac{360}{365}(284 + N) \quad (2.7)$$

Hour angle, 'H'

$$H = \frac{360T}{24} = 15T \quad (2.8)$$

Solar Altitude 'β'

$$\sin\beta = \cos L \cos H \cos\delta + \sin L \sin\delta \quad (2.9)$$

Direct Normal Solar Intensity, 'I_{DN}' is given by:

$$I_{DN} = \frac{A}{\exp B / \sin\beta} (W/m^2) \quad (2.10)$$

The total energy is the sum of useful or available energy (Exergy) and the unavailable or remaining energy (Anergy). The available energy or 'Exergy' is a measure of the maximum useful work that can be performed by a system interacting with an environment. The key exergy parameters are heat exergy, 'X', Heat anergy, 'Y', Exergetic potential, 'γ_p' and Exergetic Efficiency, 'η_x'. These are evaluated from the following equations[8]

$$\text{Heat exergy, } X = \left(\frac{T - T_a}{T}\right) q \quad (2.11)$$

$$\text{Heat anergy, } Y = T_a/T\, q \quad (2.12)$$

$$\text{Exergetic potential, } \gamma_p = (T - T_a/T) \quad (2.13)$$

Therefore:

$$X = \gamma_p q \quad (2.14)$$

and

$$Y = (1\ \gamma_p)q \quad (2.15)$$

The quality of heat energy is therefore estimable using the exergetic potential, which is a measure of the ability of energy to produce work. It may thus be deduced that for heating purposes, energy should be released from a source having an exergetic potential economically near to that corresponding to the temperature at which the heat is required.

The exergetic efficiency 'η_x'

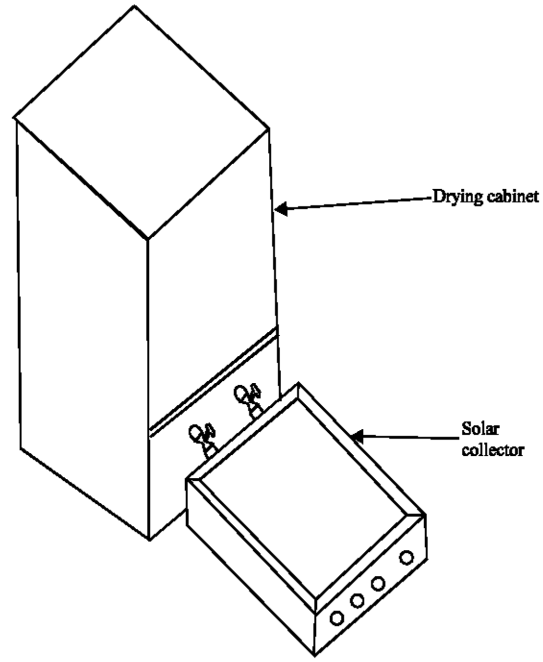

Fig. 1: Isometric view of the mixed-mode dryer

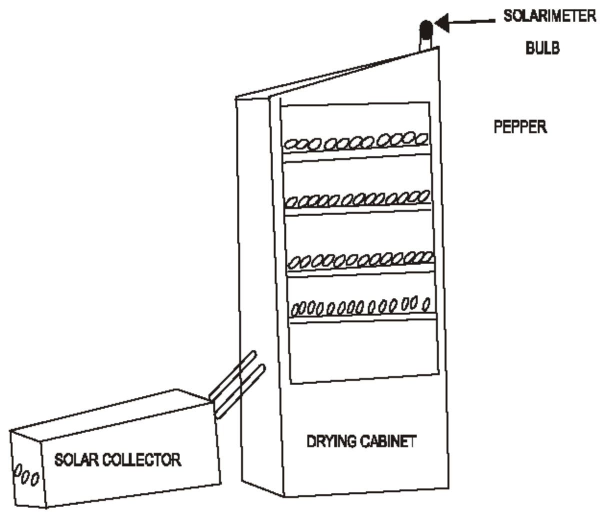

Fig. 2a: Testing with pepper

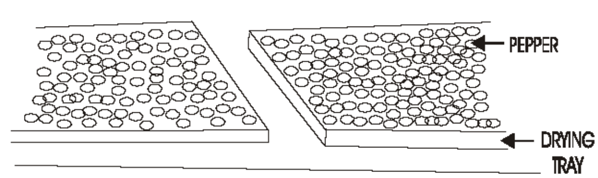

Fig. 2b: Control test for pepper

η_x = Useful output energy/Input energy x 100

$$= \frac{X_{out}}{X_{in}} = \frac{\gamma_{pot}}{\gamma_{pin}} x \frac{q_{out}}{q_{in}} \quad (2.16)$$

If the energy efficiency 'η_e' is defined as;

$$\eta_e = \text{Useful output energy/Input energy} = q_{out}/q_{in} \quad (2.17)$$

Then, the exergetic efficiency η_x becomes;

$$\eta_x = \left(\frac{\gamma_{pout}}{\gamma_{pin}}\right)\eta_e \text{ x } 100 \quad (2.18)$$

These exergetic parameters were used in this study to rate the effectiveness of the solar dryer on No-load condition and when used to dry various products.

Description: The Mixed-Mode Solar Food Dryer consists of the drying cabinet and the solar collector (Fig. 1).

The drying cabinet frame was fabricated from Afara wood (*Terminalia superba*), size 25 mm x50 mm. It has a roof, 1000 mm x960 mm, covered with 5 mm thick transparent glass inclined at 7.25°, which is the latitude of Akure, to the horizontal. The Eastern side was also covered with glass of dimension 1000 mm x960 mm x5 mm, while the other sides (West, South and North) were covered with plywood. The bottom of the cabinet was covered with 25 mm thick Afara (*Terminalia superba*). Galvanized pipe of diameter 25 mm was used as the air duct from the solar collector through the Southern side of the cabinet and the Northern side has a door to reduce shadowing during handling. Six holes of diameter 12 mm were drilled on the upper part of the Northern side to serve as ventilation for spent air. The inner part of the cabinet was painted white to reduce heat losses and the outside painted black to aid heat absorption into the system.

The solar collector was fabricated from 100 mm x96 mm x2 mm corrugated iron sheet and was painted black. The collector was housed by a wooden box; 100 mm x101 mm x30 mm. The lower side of the plate was insulated with polystyrene foam and wood shavings to a thickness of 13 mm.

Experimental procedure: The Mixed-Mode Solar Dryer was first tested on no-load and was later used to dry pepper, sliced yam, water-leaf and okra as specimens[1].

The following parameters were measured between 0900 and 1800 hrs (local time) each day.

- The incident solar radiation intensity using a solarimeter,
- The relative humidity and ambient temperature using a humidity-temperature meter

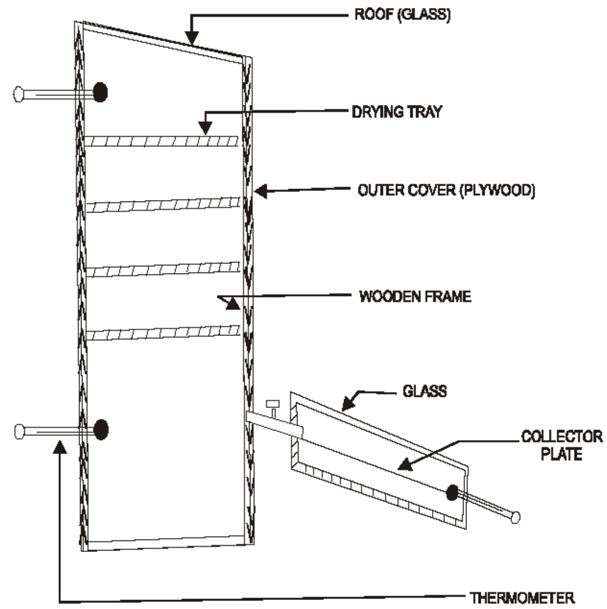

Fig. 3: A sectioned view of the dryer

- The collector plate and dryer temperatures using mercury-in-glass thermometers.

Control experiment was set up in the open for direct sun drying for each of the products. Figure 2(a) shows a typical experimental sep-up with pepper, while Fig. 2(b) shows the corresponding control[9].

Testing on no-load: The dryer was first tested on no-load for five days. It was assumed that the available energy was equal to the useful energy because, no product was dried and no control experiment was set up.

Testing on load: The dryer was tested on load for a total of fifteen days; five days with 3 kg of pepper, six days with 6 kg of 10 mm thick sliced yam, two days with 1 kg water-leaf and two days with 1 kg of okra. An equivalent weight of each product was set-up in the open as control experiment.

The temperatures of the drying cabinet were taken at the lower and upper chambers and the average values were recorded. (Fig. 3).

RESULTS AND DISCUSSION

The total energy for the dryer was calculated using Eq. (2.1). The exergy (available energy) was computed using Eq. (2.14), from which the anergy was estimated (Eq. 2.15). The exergetic efficiency values were obtained using Eq. (2.16).

Figure 4 show the relationship between Exergetic Efficiency, Thermal Efficiency and Time for No-Load condition. The figure indicated that the dryer was very effective at the energy values obtained. The exergetic

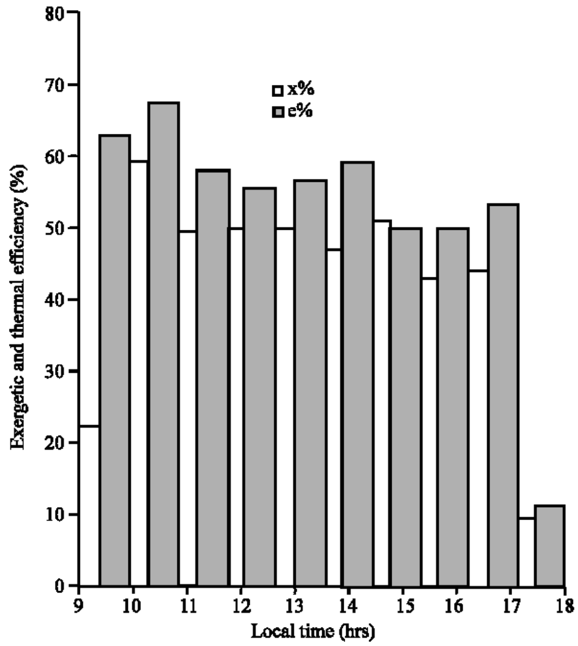

Fig. 4: Exergetic efficiency, thermal efficiency and time on No-load

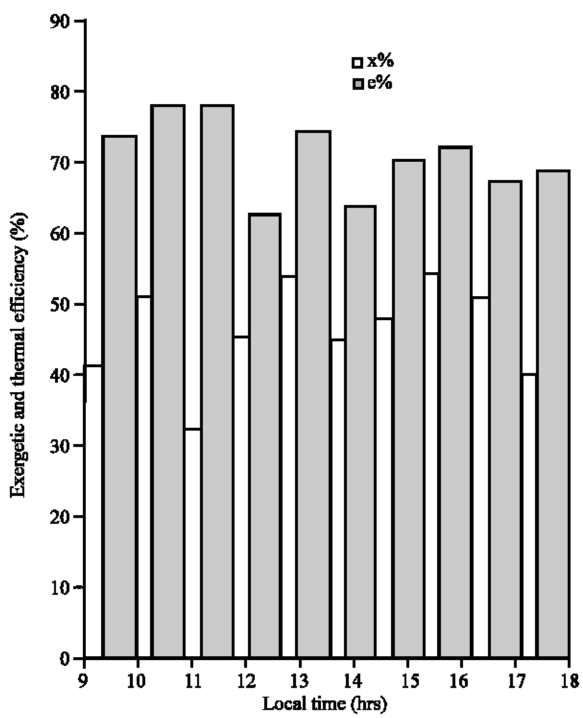

Fig. 5: Exergetic efficiency, thermal efficiency and time for pepper

efficiency values were almost equal to the thermal efficiency values, justifying the statement that the total energy equals the useful energy on No-Load condition as

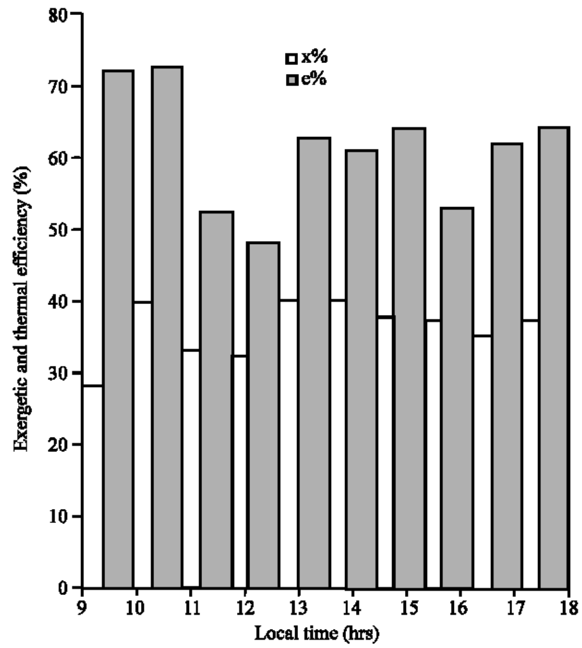

Fig. 6: Exergetic efficiency, thermal efficiency and time for Yam

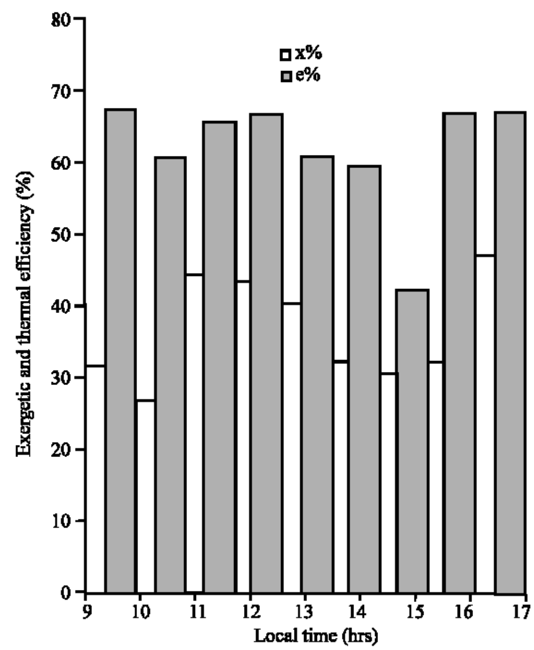

Fig. 7: Exergetic efficiency, thermal efficiency and time for water leaf

no product was dried. The differences in these efficiency values could be attributed to heat losses.

Figures 5 to 8 show the relationship between Exergetic Efficiency, Thermal Efficiency and Time for the products tested (Pepper, Yam, Water leaf and Okra). From the figures, it is observed that the dryer was effective at

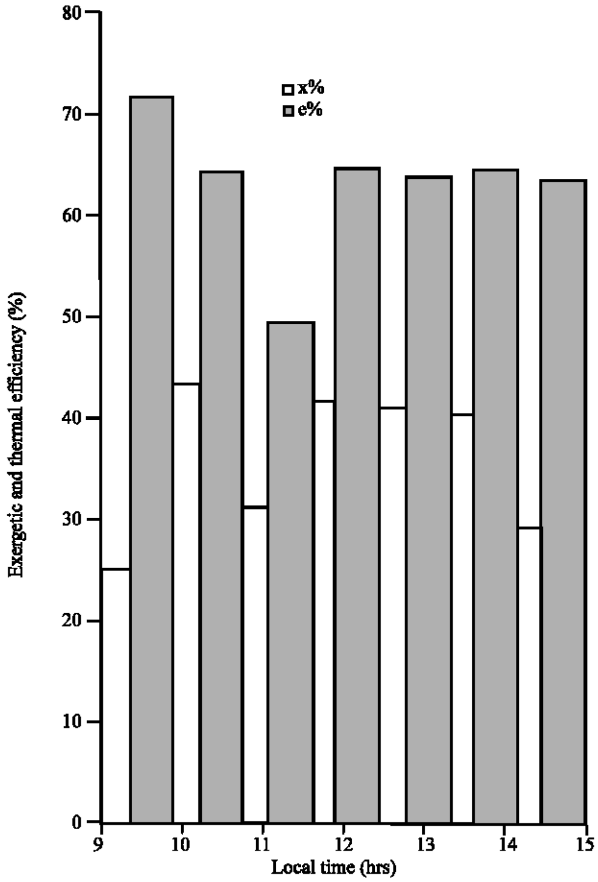

Fig. 8: Exergetic efficiency, thermal efficiency and time for Okra

the obtained thermal efficiency values. However, the exergetic efficiency was always low in the early hours of the day. Some heat loss does occur through imperfect absorptivity of the blackened drying cabinet in addition to the quantity of heat that is presumably stored in the mass of the dryer itself during these periods. This latter amount however, can be utilized during the later hours of the day when there can be a negative heat balance.

CONCLUSION

This study shows that the dryer is effective in utilizing the available energy and is more effective than direct sun drying. Although, 44% of the available energy was wasted, overall analysis gave an average exergetic efficiency of 56%. Also from experimental results and analysis, the dryer converted the absorbed incident energy to available energy, most of which was in turn converted to useful energy or exergy.

NOMENCLATURE

- A^c Collector's area (m^2)
- B Atmospheric Extinction Coefficient
- H Hour angle
- I_{DN} Direct Normal Solar Intensity (Wm^{-2})
- I_δ Solar Insolation
- I_T Rate of total radiation incident on the collector's surface (Wm^{-2})
- L Latitude
- q Rate of heat release (W)
- qu Energy per unit absorber area (Wm^{-2})
- Q_u Useful energy collected by solar collector (W)
- t_a Outside Temperature (°C)
- t_c Collector Temperature (°C)
- T Temperature at which heat is released (K)
- T_a Prevailing environmental Temperature (K)
- UL Overall heat transfer coefficient of absorber ($Wm^{-2}.K$)
- X Heat Exergy
- Y Heat Anergy
- α_c Absorptance of collector
- β Solar Altitude
- δ Sun's declination
- τ Transmissivity of glass
- τ_p Exergetic potential
- η_c Thermal efficiency
- η_o Net transmissivity absorptivity product (conversion factor)
- η_D Daily efficiency
- η_h Hourly efficiency
- η_x Exergetic Efficiency
- η_e Energy efficiency

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