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Exergetic Analysis of Solar Energy drying Systems

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ABSTRACT

An exergetic analysis of three basic types of solar drying systems is presented. The analysis is used to find the available useful energy and the quality of energy that is obtainable from the dryers. The dryers were installed side by side and tested simultaneously to eliminate influence of solar radiation and environmental changes in comparing their performances. The results obtained show that mixed mode and indirect mode solar dryers are more effective in utilizing the captured energy than direct mode dryer, and mixed mode has a slight edge in superiority over indirect mode system. 78.1% *and* 77% *of energy collected in the mixed mode and indirect mode systems, respectively, were available as useful energy, while direct mode system could only convert* 49.3% *of collected energy to useful energy. The overall exergetic efficiencies of mixed mode, indirect mode and direct mode systems were found to be* 55.2%, 54.5% *and* 33.4%, *respectively.*

***Keywords*:** *Solar, Exergy, Direct, Indirect, Mixed Mode, Dryer*

1. Introduction

Solar drying is one of the important means of utilizing solar energy for low and moderate temperature applications. Solar drying of crops and some fruits and vegetables has been practiced in various parts of the world for centuries the conditions in tropical countries make the use of solar energy for drying foods particularly attractive. The introduction of solar dryers in developing countries can reduce crop losses and improve the quality of dried product significantly compared to traditional drying methods [1-3].

Solar drying may be classified into direct, indirect and mixed modes [4]. In direct solar dryers the air heater contains the grains and solar energy passes through a transparent cover and is absorbed by the grains. Essentially, the heat required for drying is provided by radiation to the upper layers and subsequent conduction into the grain bed. In indirect dryers, solar energy is collected in a separate solar collector (air heater) and the heated air then passes through the grain bed. In the mixed mode type of dryer, the heated air from a separate solar collector is passed through a grain bed, and at the same time, the drying cabinet absorbs solar energy directly through the transparent walls or roof. Grain is dried simultaneously by both direct radiation through the walls or roof of the cabinet and the convection of heat from the solar collector.

Several authors [5-8] have reported both theoretical and experimental studies on the optimization of solar air heaters. Most of them consider the pertinent performance indicator to be the collector's thermal efficiency. Also, many other researchers [9-11] have developed design principles for various classes of solar drying systems. In their studies, thermal efficiency was used to evaluate the performance of the systems.

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 the ambient, the energy will be partially converted to thermal energy in the system and partially lost to the environment. Therefore, for the evaluation of the thermal performance of such a system, descriptive parameter that rates the quantity and quality of energy is required. The objective of this study is to use exergetic analysis that employed heat exergy and anergy as descriptive parameters to rate the availability of energy in three different types of solar dryers (direct, indirect and mixed modes).

2. Material and Methods

2.1. Basic Theory

The energy gained by the collector can be expressed by the following relation [12]:

$$Q_u = \alpha\tau I A_c - U_L A_c \left(T_c - T_a\right) \quad (1)$$

where, A_c = area of transparent cover (m^2); I = incident insolation (W/m^2); U_L = overall heat loss for the collector (W/K); α = solar absorptance; τ = transmittance; T_c = collector temperature (K); T_a = ambient air temperature (K). The energy per unit area of the collector is

$$\frac{Q_u}{A_c} = \alpha\tau I - U_L\left(T_c - T_a\right) \quad (2)$$

If the heated air leaving the collector is at collector temperature, the heat gained by the air Q_g is:

$$Q_g = \dot{m}_a C_{pa}\left(T_c - T_a\right) \quad (3)$$

where, $\dot{m}_a$ = mass of air leaving the dryer per unit time (kg/s^{-1}); C_{pa} = specific heat capacity of air (kJ/kg·K). The collector heat removal factor, F_R, is the quantity that relates the actual useful energy gained of a collector, Equation (1), to the useful gained by the air, Equation (3). Therefore,

$$F_R = \frac{\dot{m}_a C_{pa}\left(T_c - T_a\right)}{A_c\left[\alpha\tau I - U_L\left(T_c - T_a\right)\right]} \quad (4)$$

or $$q_g = A_c F_R\left[\alpha\tau I - U_L A_c\left(T_c - T_a\right)\right] \quad (5)$$

2.2. Exergetic Analysis

In energy systems, not all the energy supplied is available to do work. The part of the supplied energy available to do the required work is known as Heat Exergy, X, while the unavailable energy is known as Heat Anergy, Y [13]. Total energy, $E = X + Y$.

Heat exergy, $$X = \left(\frac{T_r - T_a}{T_r}\right)q \quad (6)$$

where, q = rate of heat release (W); T_r = temperature at which heat is released (K).

Heat anergy, $$Y = \left(\frac{T_a}{T_r}\right)q \quad (7)$$

Exergetic potential, $$\gamma = \frac{T_r - T_a}{T_r} \quad (8)$$

Therefore, Equations (6) and (7) can be expressed as Equations (9) and (10) respectively:

$$X = \gamma q \quad (9)$$

$$Y = \left(1 - \gamma\right)q \quad (10)$$

Exergetic efficiency, η_x is defined as:

$$\eta_x = \frac{output\ exergy}{input\ exergy} = \frac{X_{out}}{X_{in}}$$

therefore, $$\eta_x = \left(\frac{\gamma_{out}}{\gamma_{in}}\right)\left(\frac{q_{out}}{q_{in}}\right) \quad (11)$$

Thermal efficiency, η_{th} is:

$$\eta_{th} = \frac{useful\ output\ energy}{input\ energy} = \frac{q_{out}}{q_{in}} \quad (12)$$

Therefore, Equation (11) becomes

$$\eta_x = \left(\frac{\gamma_{out}}{\gamma_{in}}\right)\eta_{th} \quad (13)$$

These exergetic parameters were used in this study to rate the effectiveness of three different types of solar dryers.

2.3. The Experimental Set-up

The three types of solar dryers considered for comparative investigations in this paper are direct, indirect and mixed mode, and they are shown in **Figure 1**, **2** and **3** respectively.

2.3.1. Direct Mode Solar Dryer

This is essentially a rectangular cabinet with an inclined transparent top cover of one sheet of 4 mm thick clear

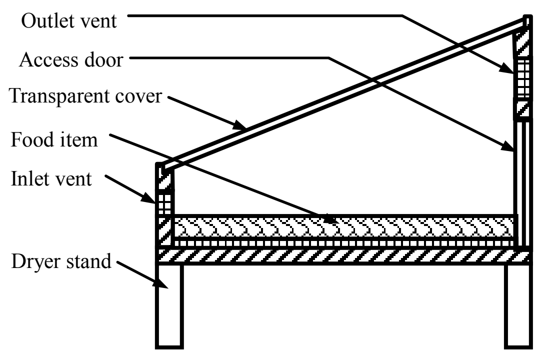

Figure 1. Direct mode solar dryer.

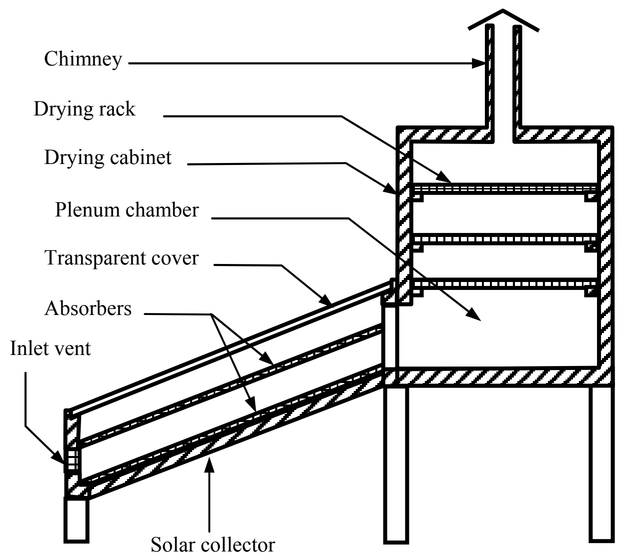

Figure 2. Indirect mode solar dryer.

glass with a total surface area of 1220 mm by 900 mm. The dryer cabinet is made of 25 mm plywood. The front is higher than the rear giving the top cover an inclination of about 17.5˚. This is approximately 10˚ more than thelocal geographical latitude (Ado-Ekiti Nigeria, 7.5˚N), which according to Adegoke and Bolaji [14], is the best recommended orientation for stationary absorber. Air inlet vent in the lower end of the front of the cabinet provide an entry for air which is then heated within the collector metal base and rises to exhaust through outlet vent in the upper parts of the back of the cabinet. The potential of the cabinet to absorb insolation is enhanced by blackening all interior surfaces. The dryer is mounted on legs to facilitate air entry through the inlet vent and to reduce the risk of entry of pests into the cabinet.

2.3.2. Indirect Mode Solar Dryer

The dryer differs distinctly from direct mode dryer in that the solar collector and the drying chamber are principally separated as shown in **Figure 2**. Air is heated during its flow through the collector and passes into the drying chamber before exhausting through the chimney. The function of the extended chimney is that the black sides absorb insolation and so heat the air within, thereby enhancing the natural convective flow of air through the dryer. The drying chamber houses drying racks which contained food item to be dried.

2.3.3. Mixed Mode Solar Dryer:

In this dryer, the drying cabinet and solar collector are separated like in the case of indirect dryer as shown in **Figure 3**. But the dryer differs from the indirect mode in that additional drying is achieved from direct solar radiation incoming through the transparent walls and roof. An outlet vent is made at the upper end of back of the cabinet to facilitate and control the convection flow of air through the dryer.

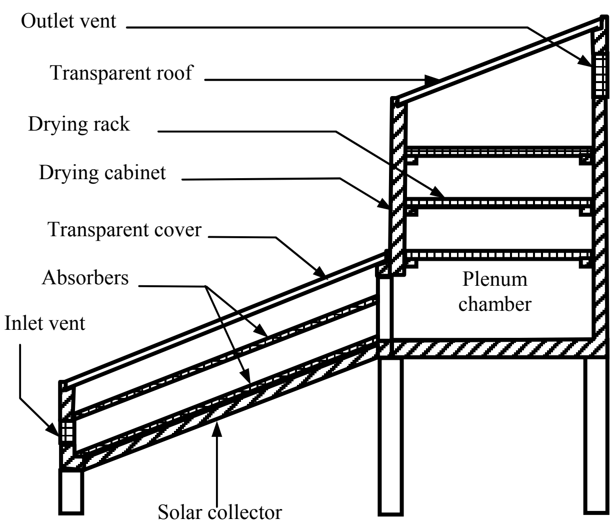

Figure 3. Mixed mode solar dryer.

The solar collectors of both the indirect and mixed modes are the same in their construction. The collectors consist of an absorber back plate insulated with foam material of about 30 mm thick at the bottom and covered by transparent glass of 4 mm thick at the top. The solar collectors are 420 mm × 980 mm × 150 mm in dimensions; they are south-facing and titled 17.5˚ to the horizontal so that they can take advantage of the maximum insolation. Air enters through the inlet vent at the lower end of the collectors. An absorber mesh screen midway between the glass cover and the absorber back plate provides effective air heating because solar radiation that passes through the transparent cover is then absorbed by both the mesh and back-plate. The upper end of the collectors is connected to the vertical drying cabinets, which hold drying trays in layers.

2.4. Experimental Procedure

The solar dryers were tested and the parameters needed for the evaluation of the systems were measured at interval of one hour between the hours of 8.00 and 18.00. Thermometers were placed through the walls in the collectors and in the drying cabinets to measure their temperatures. The relative humidity and ambient temperature was measured using humidity-temperature meter. The incident solar radiation intensity was measured using a portable Kipps Solarimeter.

The dryers were installed side by side and tested simultaneously to eliminate influence of solar radiation and environmental changes in comparing their thermal performances. The dryers were used to dry shelled corn (as a sample of food item). For each of the dryers, weight of the food item was measured at the start and at one-hour intervals thereafter. Knowing the initial weight and the final weight at the point when no further weight loss was attained, the weight loss was used to calculate the moisture removed in kg water per kg dry matter at intervals as the food item dried.

3. Results and Discussion

An exergetic analysis of the drying systems was carried out to find out the effect of available energy (heat exergy) on the performance of the systems. The total energy for each of the dryers was calculated using Equation (5). The exergetic potential, exergy and anergy were computed using Equations (8), (9) and (10). The values of exergetic efficiencies were obtained using Equation (13).

Figure 4 shows a typical day hourly variation of anergy (unavailable energy) for the solar dryers. It was observed that the anergy in direct mode dryer increased drastically reaching peak value of 63 kJ between 12.00 hr and 13.00 hr. On the other hand, the anergy was relatively smaller in both indirect and mixed mode dryers. This is an indication that direct mode system wasted more energy than the other two systems. Also between 10.00 hr and 14.00 hr the anergy in indirect mode system was found greater than that of mixed mode system, but reverse was the case in the last 3 hours of effective sunshine.

Figure 5 shows the hourly variation of heat exergy for the three systems. The figure indicates that more exergy was available in both indirect and mixed mode systems than direct mode system. The better results observed in the mixed mode system justified the additional heat received from direct solar radiation incoming through the transparent walls and roof of the system. Also the ability of the indirect mode system to retain energy and its better performance especially during the hours of low solar radiation intensity justified the insulation of its drying chamber. Further analysis shows that 78.1% and 77% of energy collected in the mixed mode and indirect mode systems, respectively, were available as useful energy, while direct mode system could only convert 49.3% of collected energy to useful energy.

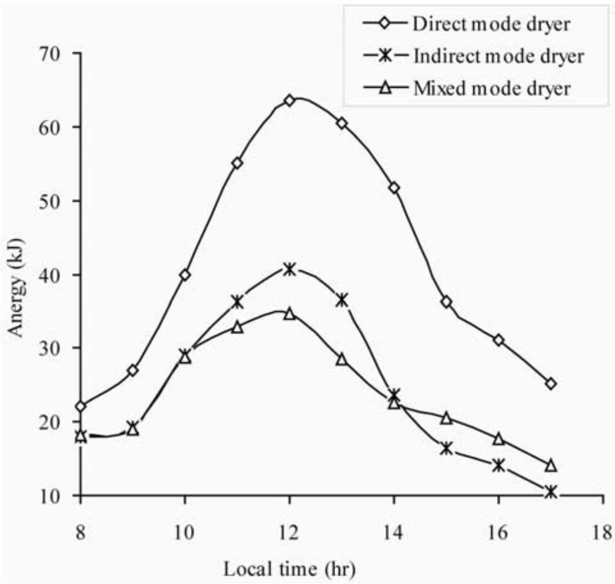

Figure 4. Variation of anergy with time in the solar dryers.

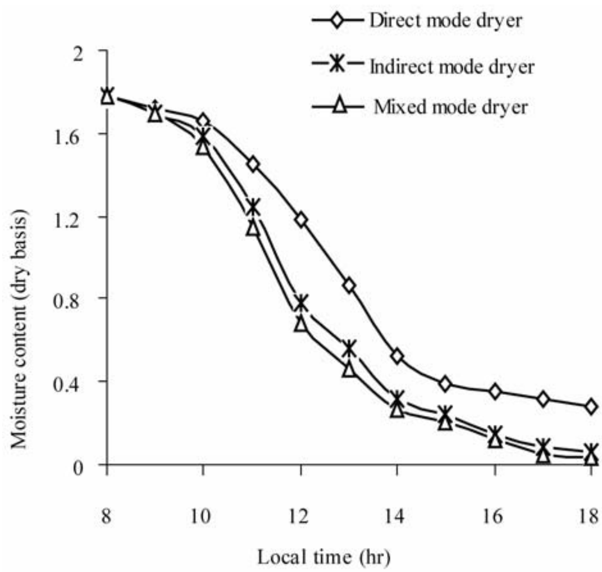

Figure 6. Drying curves of shelled corn in the solar dryers.

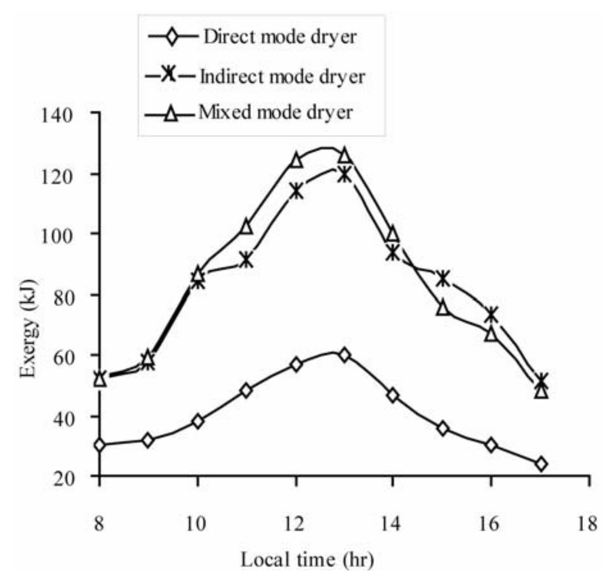

Figure 5. Variation of exergy with time in the solar dryers.

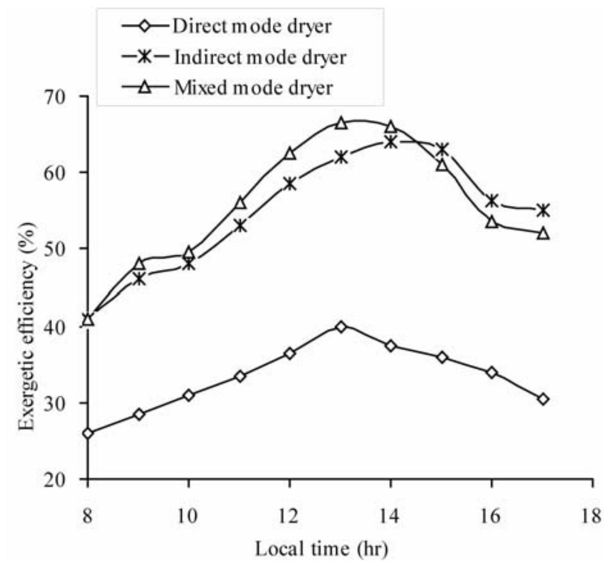

Figure 7. Variation of exergetic efficiency with time in the solar dryers.

The moisture content versus time plot (solar drying curves) for shelled corn is shown in **Figure 6**. For the three dryers, it was observed that the food item in the mixed mode and indirect mode dryers dried faster than in the direct mode dryer. **Figure 7** shows the exergetic efficiency curves of the three drying systems. The overall analysis gave average exergetic efficiencies of 55.2% and 54.5% for mixed mode and indirect mode systems, respectively, while for direct mode, an average exergetic efficiency of 33.4% was obtained.

4. Conclusions

Exergetic analysis was carried out on three types of solar drying systems (direct, indirect, and mixed modes) to find the useful and the quality of energy that are obtainable from the systems. The results obtained show that mixed mode and indirect mode solar dryers are more effective in utilizing the captured energy than direct mode dryer. For mixed mode and indirect mode systems, about 78.1% and 77% of the collected energy respectively is available or useful energy (exergy), while 21.9% and 23% of the collected energy respectively is unavailable or wasted energy (anergy). But the direct mode system could only convert 49.3% of the collected energy to useful energy, while the rest 50.7% is wasted. In the overall analysis of the systems, mixed mode and indirect mode solar dryers were found more efficient than direct mode dryer with mixed mode dryer having a slight edge in superiority over indirect mode dryer. Average exergetic efficiencies of 55.2%, 54.5% and 33.4% were obtained from mixed mode, indirect mode and direct mode systems respectively.

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NOMENCLATURE

A_c – total collector area (m^2)
C_p – specific heat at constant pressure ($kJ \cdot kg^{-1} \cdot K^{-1}$)
E – total energy (kJ)
F_R – collector heat removal factor
I – incident solar radiation ($W \cdot m^{-2}$)
$\dot{m}$ – mass flow rate ($kg \cdot s^{-1}$)
q – rate of heat released (W)
Q – rate of heat collection (W)
T – temperature (K)
T_r – temperature at which heat is released (K)
U_L – heat loss coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
X – exergy (kJ)
Y – anergy (kJ)

Greek:

α – solar absorptance
η – efficiency (%)
τ – transmittance
γ – exergetic potential

Subscripts:

a – ambient air
g – energy gained by air
in – input
out – output
th – thermal
u – energy gained by collector
x – exergetic

