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Experimental investigation of the drying characteristics of a mixed mode natural convection solar crop dryer with back up heater

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A B S T R A C T

A mixed mode natural convection solar crop dryer with a backup heater was designed and constructed from locally available materials and used to dry freshly prepared pineapples under four drying Scenarios for drying to correspond to specified drying periods for four typical seasons in Ghana. The experiments were devised for the material moisture content to be monitored continuously till the desired moisture content of between +106% and 184% (d.b) was achieved. In solar heating mode of operation, results show that the thermal mass was capable of storing part of the absorbed solar energy but the quantities involved are insufficient to sustain night drying. It was possible to dry a batch of pineapples in each mode of operation. The dryer reduced the moisture content of pineapple slices from about; 924% to 106% in 19 h; 1049% to 184% in 10 h; 912% to 155% in 7 h; and 1049% to 144% (d.b) in 23 h, for drying in Scenarios 1, 2, 3 and 4, respectively. The average moisture pickup efficiency values obtained were 27%, 24%, 11%, and 32% for drying in Scenarios 1, 2, 3, and 4, respectively.

1. Introduction

Open sun drying is a traditional method practiced widely in tropical climates for drying agricultural products. Considerable savings can be made with this type of drying since the source of energy is free and sustainable. However, this method of drying is extremely weather dependent and has the problems of contamination, infestation, microbial attacks, etc., thus affecting the product quality. Additionally, the drying time required for a given commodity can be quite long and result in post-harvest losses. Solar drying of agricultural products in enclosed structures by natural convection is an attractive way of reducing post-harvest losses and low quality of dried products associated with traditional sun-drying methods [5,7,8,13,19].

The advantages of solar drying over sun drying have been well-documented [14,20]. However, compared to some other applications of solar energy, solar dryers continue to struggle to gain popularity among large scale producers of dried products, especially in the developing countries. The reasons for this are complex and varied, and depend on many factors [4,5]. For instance, in Ghana, commercial producers of products like dried salted fish (known locally as 'Kobi'), dried paper, and dried cassava chips, depend largely on open sun drying.

One significant limitation of solar dryer is that it can only be used during the daytime when there is adequate solar radiation. This hampers the ability of commercial crop dryers to process the products continuously with reliability. Therefore, it is necessary to provide solar dryer with a suitable form of back-up heating.

When using the sun's radiation as the energy source for drying, two principal difficulties must be overcome in order to exploit the full potential of solar dryers: the periodic character and the time dependence of the solar radiation. The influence of weather changes must be considered. The periodic character of the solar radiation can partly be balanced by employing an intermittent drying operation. However, because the number of hours of available sunshine is very much dependent on the prevailing weather conditions, the use of a heat storage unit may be needed. The dependence of the dryer performance on the weather, especially in large systems, should be minimised by providing an auxiliary energy source.

Literature sources reveal sufficient documentation of a number attempts that have been made at devising auxiliary heating systems aimed at overcoming this limitation in simple natural convection solar dryers. One exception is a cabinet solar dryer reported

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Nomenclature

A_{db}	effective drying bed area, m^2
G	acceleration of gravity, m/s^2
H	height, m
h_{fi}	Specific enthalpy of air at dryer inlet, kJ/kg
$h_{db,i}$	Specific enthalpy of air at drying bed inlet, kJ/kg
H_d	Daily solar radiation received per collector surface area, MJ/m^2
h_L	depth of drying bed, m
H_i	absolute humidity of the ambient air, (kg dry water/kg dry air)
H_s^*	adiabatic saturation humidity of air entering drying chamber, (kg dry water/kg dry air)
L_D	Loading density, kg/m^2
$\dot{m}_a$	Air mass flow rate, kg/s
m_p	mass of the crop to be dried, kg
m_w	Mass of water evaporated from sample and absorbed by drying air, kg
M_1	Initial moisture content of wet product, %wb
M_2	Desired final moisture content of wet product, %wb
P	pressure, N/m^2
ΔP	Pressure difference, Nm^{-2}
$\dot{Q}$	Heat transfer rate, W
R	specific gas constant, kJ/(kg K)
T_{fi}	air inlet/ambient temperature, °C
T_f	plenum fluid temperature, °C
$T_{pst,1}$	product surface temperature at tray 1, °C
$T_{pst,2}$	product surface temperature at tray 2, °C
$T_{pst,3}$	product surface temperature at tray 3, °C
ΔT	temperature difference, °C
T_{fo}	drying air outlet temperature, °C
V_a	Volume of drying air required, m^3
W_1	Humidity ratio of air entering drying chamber, kg moisture/kg dry air
W_2	Humidity ratio of air exiting drying chamber, kg moisture/kg dry air
W_o	initial mass of the commodity, kg
W_t	mass of the commodity at the time *t*, kg
ρ	density, kg/m^3
ρ_i	Ambient air density, kg/m^3
ρ_h	Density of heated air, kg/m^3
ρ_{gr}	bulk density of the crop on wet basis, kg/m^3
ξ	crop porosity
ε_v	loading bed void fraction
η_p	moisture pick up efficiency, %
Φ	Relative humidity, %
η_t	Opto-thermal efficiency of single glazing collector system, %

by Bena & Fuller [5] which used a fuel wood burner to provide heat during poor weather and at night. The burner was constructed from a 0.2-m^3 steel drum by integrating it with the drying cabinet. An overall efficiency of the burner was reported to be 22%. Another significant study reported by Bassey et al. [3] made use of a sawdust burner, constructed as a separate component, to provide a back-up heat. The burner was designed to provide 400 W/m^2 of energy to the drying cabinet, and used steam as the heat transfer medium. Madhlopa et al. [16] designed, constructed and evaluated an indirect type natural convection solar dryer with integrated collector-storage solar and biomass-backup heater. The dryer consisted of biomass burner (with a rectangular duct and flue gas chimney), collector-storage thermal mass and a drying chamber with a conventional solar chimney. Results showed that the thermal mass stored part of the heat from both solar and biomass air heaters, thereby moderating temperature fluctuations in the drying chamber and reducing wastage of energy.

This paper describes a laboratory type mixed mode natural convection solar crop dryer integrated with a simple, well-regulated auxiliary heat source and an integrated concrete slab/rock pebble bed solar collector/thermal mass system for storing heat to be used for drying in periods of low insolation. The results of these tests are reported and discussed. Some recommendations to further improve the dryer's performance are also proposed at the end of this paper.

2. Design and description of the dryer

(a) This design is based on a commercial scale dryer of loading capacity 30 kg. The details of the psychrometric analysis and subsequent sizing of critical system components is presented as follows:

If atmospheric air at temperature $T_{f,i} = 303\ K$ and relative humidity $\phi_i = 80\%$ (specific volume $v_a = 0.888\frac{m^3}{kg}$, $h_i = 86\frac{kJ}{kg}$, $W_i = 0.0215\frac{kg\ H_2O}{kg\ dry\ air}$, see point A on Fig. 1) is heated to TB = 315 K, then ϕ would be reduced to 41% (see point B on Fig. 1). If the resulting heated air is used to remove moisture from pineapple of initial moisture content, $M_1 = 85\%$ (on wet basis) until an equilibrium ϕ of 90% is reached (see point C on Fig. 1), the temperature of the drying air will be reduced to Tc = 304.2 K ($h_{f,o} = 98.8$kJ/kg) and the humidity ratio, W, would change from $W_A = 0.0215\text{kg}\ H_2O/\text{kg dry air}$ to $W_C = 0.0264\text{kg}\ H_2O/\text{kg dry air}$, giving a humidity ratio difference, ΔW = 0.0049 kg moisture/kg dry air. The heating process which occurs passively in the plenum is represented by the path AB whereas the drying process which is characterised by the simultaneous removal of moisture and heat is represented by path BC. To dehydrate a fresh food with an initial mass, m_1, the required mass of dry air (m_a) to vaporise water of mass (m_w) from the fresh food can be calculated by Ref. [2].

$$m_w = m_1(M_1 - M_2)/(100 - M_2) \tag{1}$$

$$m_a = m_w(W_2 - W_1) \tag{2}$$

where m_w is the mass of water evaporated from the sample and absorbed by drying air of mass m_a; M_1 and M_2 are the initial and desired final moisture contents respectively. Therefore, to dehydrate 30 kg of pineapple at $M_1 = 85\%$ to $M_2 = 20\%$, means removing m_w = 25 kg of moisture requiring m_a = 4,975 kg of dry air. The corresponding volume of drying air required for dehydration, $V_a = \frac{m_a R T_{f,o}}{P} = \frac{(4975\text{kg})\times\left(0.2871\frac{\text{kJ}}{\text{kg K}}\right)\times(304.2\text{K})}{(101.3\text{kPa})} = 4,289\text{m}^3$.

The required heat transfer rate for heating air in the air heater passages is given by ASHRAE [1]

$$\dot{Q} = \dot{m}_a\left(h_{db,i} - h_{f,i}\right) \tag{3}$$

Eq. (3) can be transformed to include the total concrete absorber