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Analysis of a Solar Dryer Box with Ray Tracing CFD Technique

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Abstract— A growing preservation technique in western part of Nigeria is the use of solar dryer box. Conventionally, exposure to direct sun light has been the practice to preserving farm produce because majority of the farmers cannot afford advanced techniques that may depend on electricity supply from the national grid. Recent studies have shown that alternatives to direct exposure to the sun are preferable for vitamin preservation. A simulation of a solar box design for such purpose is presented for temperature distribution based on sun direct solar irradiation of 1423W/m^2 of Akure (5.304º Latitude 7.258º Longitude). Results compare well with experiment.

Index Terms— Irradiation, Iru, RTE, Solar box, Solar Ray Tracing.

1 INTRODUCTION

SUN is highly abundant in tropical countries like Nigeria with clear sunny skies for about 12hrs daily. Many of the small scale farmers rely on the traditional preservation techniques. Produce like cocoa and corn are sun dried by spreading the crops on open ground. The *African fermented locust beans*, Iru (*Parkia biglobosa*), is used as a local seasoning in many African dishes. The exposure of these produce to direct sun light may not provide good preservative characteristics and the distinctive aroma and taste expected from its use. The local farmers usually cannot afford the high technology preservation methods, so they still rely on direct exposure to sun light. Although Sun drying is the cheapest preservation method for the farmers, they however face the significant destructive actions of microbes, insects and birds. A larger proportion of the produce may be lost to theft and sometimes the produce may be contaminated with grains of sand and unwanted debris.

Recently, the use of cheaper preservation technologies like the solar box dryer is gaining more attention of the local farmers because it is relatively inexpensive to produce and they also provide good food with preservative qualities. Ojike *et al* [1] analysed fresh and dried samples of pawpaw using direct sun light and solar box techniques. The two drying processes (direct sunlight and solar drying) were separately done under fairly the same weather conditions. It was observed that there were significant drops in the levels of vitamins A, B, C and D in the produce under the direct sun-drying technique whereas such significant drops were not noticed for the produce under solar box drying but there was an increase in the level of vitamin E. They therefore recommended the use of solar box for entrepreneurs.

In Nigeria, Government parastatals like the Nigerian Stored Product Research Institute (NSPRI) are concerned with methods for the improvement of preservation and quality of food for Nigeria's agricultural self-reliance. Local women are highly involved in small scale farming in Nigeria. NSPRI with other organisations involved in millennium development goals (MDGs) seek to educate farmers on the benefits of the use of this cheap renewable energy. This re-orientation is moving at a very slow pace as Onyene and Bakare [2] findings show that less than 3% have formal training on preservation techniques while about 75% copy from others by observing while over 65% do not have access to micro-credit facilities.

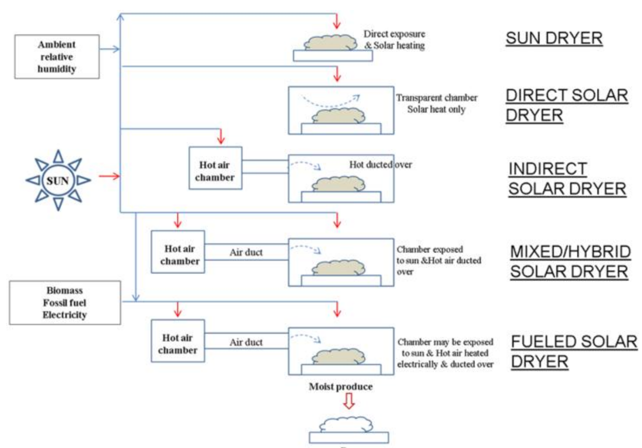

Fig. 1. A schematic diagram of solar drying techniques for agricultural produce

In the recent review by El-Sebaii and Shalaby [3], the solar heaters for agricultural purposes were grouped based on the mechanism for conversion of solar energy to heat energy which is used to remove moisture from the produce. These groups are: Sun/Natural dryers, Direct Solar dryers, Indirect solar dryers and the mixed-type solar dryers. Green and Schwarz [4] included the fueled drying method and identified some advantages of the several methods. Although some merits are there for the more advanced techniques, the overriding effect of cost and simplicity is significant. For a small scale farmer like the Nigerian Iru farmers, the Indirect Solar Dryer option fits well into their economic capability and it is simple

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to construct within the garage and more so the produce output could be of very high market quality. Fig. 1 shows a schematic diagram of the drying techniques used over the years.

Solar energy can be converted to heat or electrical energy in other forms like the photovoltaic cells otherwise called solar panel. The modes of conversion of energy from the sun determine the operational temperatures. Solar boxes are not required to operate in the extremes of which the power plants are required. The temperature achieved by the solar collectors may also have damaging effect like charring of the wooden materials after long exposure. Khouki and Maruyama [5] graphical results shows their solar collector efficiency drops with an increase in temperature and the efficiency can be as low as 10% for air speed of 7m/s and just above 50% for stagnant air when the temperature goes above 110ºC. This shows that the solar boxes can reach far higher temperature than the ambient. The fabrication of the solar boxes therefore requires the understanding of the heat transfer.

The motive of this work is to measure temperature profiles in a local solar box design and simulate using Computational Fluid Dynamics (CFD). The Monte-Carlo ray tracing methodology is used in Li et al [6] for a solar concentrator. Grundy et al [7] developed the S-Scat model which is an extension of the Monte-Carlo model and applies to sub-particle ray tracing like in determining flux distribution and intra-granular illumination or effect of nonrandom orientation. Chen et al [8] employed the Euler-Lagrange model where the rays are tracked as particles and the air is treated as a continuum but this can be computationally expensive.

In this paper, CFD technique is used with the solar ray tracing algorithm to predict the temperature profile in an experimental solar box. The heat source terms are contributed from the radiative components at the semitransparent boundaries. The after effects of the rays are monitored at the participating boundaries in terms of absorptivity and emissivity.

2 THE SOLAR BOX EXPERIMENTAL SETUP

The box is made of wood and transparent glass as shown in Fig. 2. The heat chest is 40cm wide, 79cm tall and 40cm breadth. Usually a set of storage rack are evenly placed within the box. For measurements, Rack-A is 10cm from the base and 10cm below Rack-B. The rack trays were made of wire gauze and thermocouple thermometers were used to measure temperatures. This experiment is similar to the experimental setup of Bolaji and Olalusi [9]. Aladeniyi et al [10] used similar solar box geometry to study the behavior *Iru*. The simplicity of the experiment is in line with the motive that it is meant to be cheap.

The transparent glass is 40 cm wide, 79 cm long and only 3 mm thick, and is tilted at 7^o to the horizontal to ensure maximum solar flux reaching the collector plate. The air vent is 40cm wide and 5cm tall and made of wire gauze to prevent insects from getting into the chamber. The box stands on four 40cm tall legs. The exit air vent is similar to the inlet vent but located at the top rear of the box, 5 cm from the top. The chamber vent also serves to reduce the odour accompanying wet Iru. The exit vent also prevents vapour accumulating on the heater glass as cross ventilation. Rays of light penetrate through the glass and incident on the collector base which was coated with a pigment of good emissivity. The cost of fabrication was NGN 8,000 (USD 60).

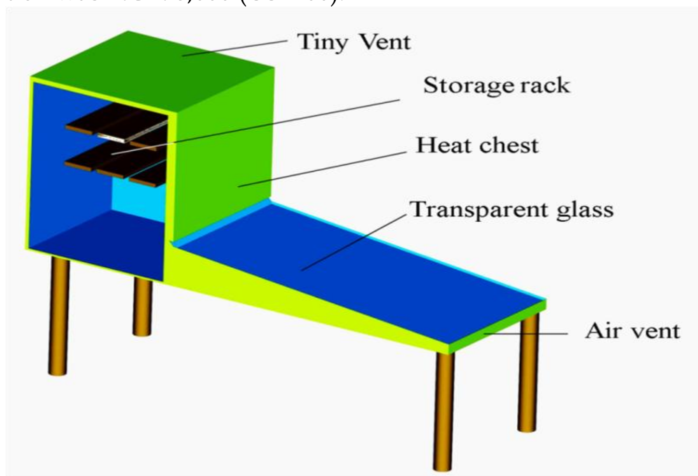

Fig. 2: The Solar box

3 CFD SIMULATION

The 3D simulation was done using ANSYS Fluent version 13. The experimental data validates our numerical model that follows.

3.1 Formulation of the CFD Model

The heat source is mainly from the radiant energy of the sun entering the computational domain through the glass. The radiant heat is given in (1).

$$Q_{rad} = A_e \sigma (T_h^4 - T_l^4) \quad (1)$$

In the city of Akure, south-west of Nigeria, like most of the Tropical cities, the weather is generally sunny and with clear skies, therefore the ASHRAE [11] normal direct irradiation for fair weather condition (2), is employed.

$$E_{d_n} = A\left\{\frac{B}{e^{sin\beta}}\right\} \quad (2)$$

Where A is the apparent solar irradiation at zero mass flow rate, B is the atmospheric extinction coefficient. β is the solar altitude above the horizontal.

For boundaries that participate in solar ray tracing, the radiative relationship [12] in (3) applies.

$$\propto_\gamma = 1 - (\rho_\gamma + \tau_\gamma) \quad (3)$$

Where $\propto_\gamma$ is the reflectivity, ρ_γ is the absorptivity and τ_γ is the transmissivity. These are respectively functions of the visible light spectral, direct irradiation components and the diffuse hemispherical components of incident rays or $\rho_\gamma =$

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$f(\rho_V, \rho_{IR}, \rho_{DH})$ and $\rho_\gamma = f(\rho_V, \rho_{IR}, \rho_{DH})$. The subscripts V, IR and DH respectively represent directly-visible, direct irradiation and the diffuse hemispherical components of absorptivity and transmissivity.

Akure city is located on latitude 5.304º and longitude 7.258º, therefore, the global solar position of the sun is computed based on this position. Solar parameters change with time. The parameters are computed from time 08.15hrs and updated through the computation in time steps of 0.1 seconds and very good residuals were obtained. There was no cloud observed during the experiment so the sunshine factor is unity. The illumination of the computational domain is described by a constant direct solar irradiation of 1423W/m^2. The diffuse solar irradiation is assumed to be 200W/m^2.

The collector box below the glass boundary inside the solar box is similar to the one of the pigments used by Levinson et al [13] and from this the spectral fraction is set to 0.51. Spectral fraction, (4), is the ratio of incident solar radiation in the visible part of the solar radiation spectrum. This is a measure of visible and infra-red radiation which represents the direct irradiation flux in the visible band.

$$SF = \frac{I_{visible}}{I_{visible} + I_{IR}} \tag{4}$$

Where $I_{visible}$ is the visible incident rays flux and I_{IR} is the infra-red flux.

The walls are assumed to be adiabatic and not participating in the solar ray tracing except for the collector chamber which has a special material for retaining and onward transmission of the solar contributions. The energy equation solved is of the form in (5) and it accounts for convective and conductive heat transfers in the control volume.

$$\frac{\partial \rho h}{\partial t} + \nabla \cdot (\rho h U) = \nabla \cdot \left(k_{eff} \nabla \mathrm{T}\right) + S_h \tag{5}$$

The source term S_h in the energy equation is computed from the solar ray tracing algorithm. In solar ray tracing, emissions from surfaces and the reflecting components of the primary incident load is distributed uniformly across all the surfaces. The reflected component of sun's direct irradiation otherwise known as internal scattered energy is tracked in the algorithm and area weighted in the solar load computation. Other parts of the internally scattered energy are the diffuse solar load contribution by the penetration of the rays through a semi-transparent wall. These values represent the ambient flux when divided by the areas of the participating surfaces.

The model implemented is the discrete ordinates (DO) radiation model. The finite volume scheme implementation [14] is used, alternative non-CFD approach exists [15]. The drying model can be coupled to this CFD simulation but this is not the interest of the current work. The radiative transfer equation (RTE), for an absorbing, emitting and scattering medium at a position vector $\vec{r}$ and direction vector $\vec{s}$, (6), governs the radiant energy exchange.

$$\frac{dI_{[\vec{r},\vec{s}]}}{ds} + (\alpha + \sigma_s) I_{[\vec{r},\vec{s}]} = \alpha n^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I_{[\vec{r},\vec{s}]} \varphi_{[\vec{s},\vec{s}']} d\Omega' \tag{6}$$

Where σ_s is the scattering coefficient, α absorption coefficient, n is the refractive index, T is the local temperature, φ is the phase functions and Ω' is the solid angle.

Air density, ρ is computed as a function of temperature, T using the ideal gas equation

$$\rho = \frac{P_o}{R_o T} \tag{7}$$

Where R_o is the specific gas constant and P_o is the absolute pressure.

The continuity and momentum equations (8) and (9) are solved. The effect of gravity on heat transport is considered negligible.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{8}$$

$$\frac{\partial \rho U}{\partial t} + U \cdot \nabla \rho U = -\nabla P \tag{9}$$

3.2 Simulation Setup

A 3D hexa-mesh of 50,000 nodes was developed using ANSYS-ICEM 13. Advantage is taken of the geometry symmetry. The glass is defined as wall boundary condition with no slip and the semi-transparent sub model applied at the glass boundary. The glass boundary and the collector base participate in the ray tracing algorithm. The wooden parts are adiabatic walls and have zero heat fluxes. The inlet vent is described by pressure inlet at a zero gauge pressure. The transient flow is run at a time step of 0.1 seconds for 8 hours. The equations are discretized in second order advection. As the time steps are relatively large, the PISO (Pressure Implicit Splitting of Operators) algorithm is used for coupling the equations.

4 RESULTS AND DISCUSSIONS

Experimental measurements of temperatures in the collector and the ambient are shown in Fig. 3 taken over 3 days. The darker lines are the 3 day averages of the temperatures. The average ambient temperature is roughly constant although the weather characteristic is clearly stochastic. The average collector temperature reaches over 340K (67^{o}C); way too high for the produce.

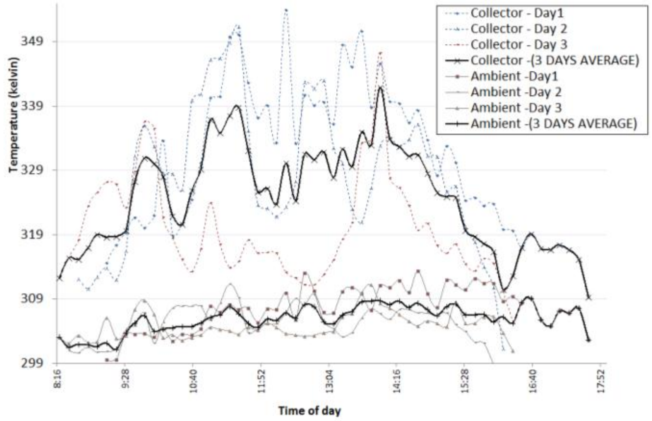

Fig. 3. Collector and Ambient Temperature (Experiment)

The temperatures at the Racks (Rack-A and Rack-B) and the ambient temperature are shown in Fig. 4. The maximum temperature in the heater chamber reaches about 320K (47^{o}C) which is reasonably good for the produce preservation. The maximum average over the 3 days is around 315K (42^{o}C). For over 7hours of exposure to sun, the rack temperatures exceed 313K (40^{o}C) or over 8^{o}C above the ambient.

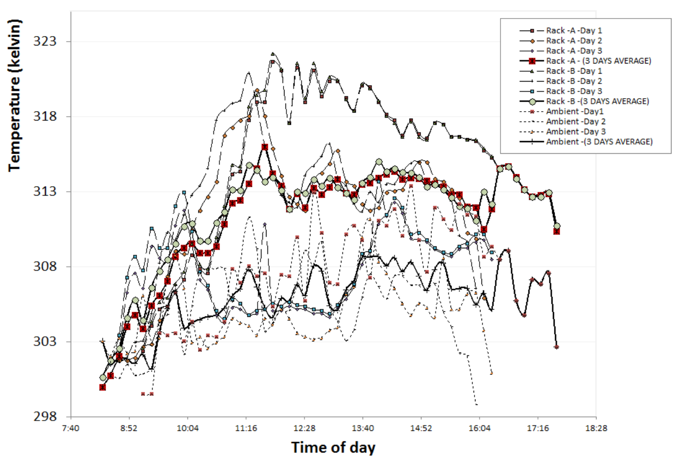

Fig. 4. Temperatures at the Racks (Experiment)

Fig. 5 shows the results from the simulation and the experimental average readings. The experimental data shows that it takes time to warm up the box and the ambient temperature actual increases for the first 3 hours of the experiment and stays almost constant. The assumption used in the simulation that the ambient temperature is not exactly correct, however, it is quite representative and moreover simplifying. The deviation of the simulation result in the early hours is caused by this assumption. The collector temperature in the simulation is about 328K (55^{o}C).

The temperature distribution, showing the racks and the base, of the box at about 1:13pm is shown in Fig. 6 (A). The velocity streamlines at the same time is shown in Fig. 6(B).

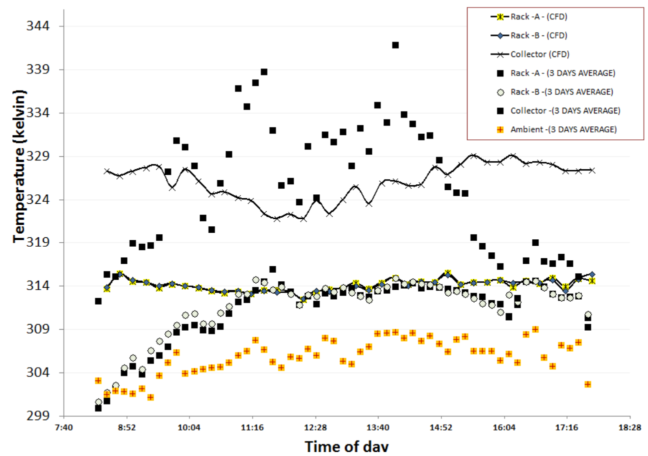

Fig. 5. Experiment and Simulation results

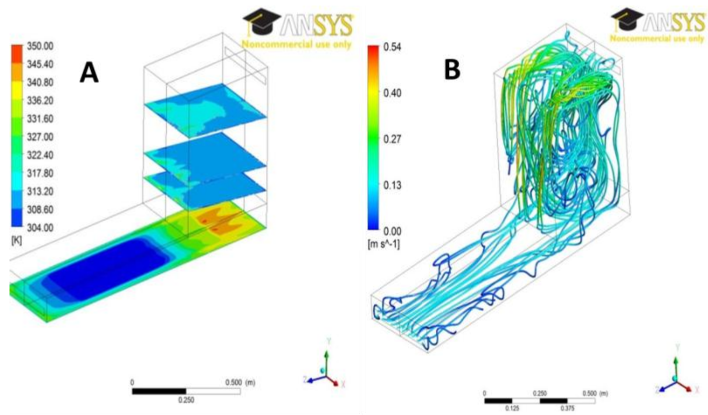

Fig. 6. Temperature distribution (A) and velocity streamlines (B) at 1:13pm

Fig. 7(**A**) is the profile at 4pm and (**B**) is at 6:15pm respectively. The streamlines shows that not much of the gas escapes through the exit vent but serve to heat up the volume. The likelihood of vapour from the produce accumulating on the glass is low as the streamlines show recirculation of air occurs mainly in the heat chest.

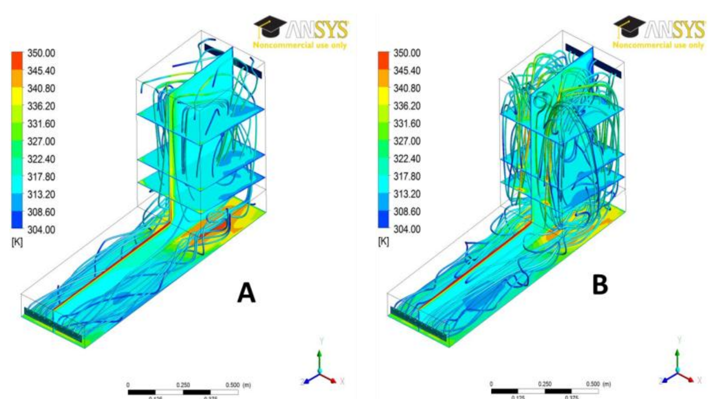

Fig. 7. Temperature and Streamlines at 4pm (A) and 6:15pm (B)

4 CONCLUSION

Sun is highly abundant in Nigeria, shining from about 7.00am till 6.30pm on very sunny days. Local farmers seek to use this natural source of energy in various forms to protect their farm produce. Power supply from the national electric grid is usually too expensive for most of the peasant farmers. Farm produce like the *African fermented locust beans*, Iru, can be dried in direct sun light as conventionally done but farmers would prefer to not expose to too much or direct sun light to preserve the taste and increase shelve life. The simulation is based on Sun Direct solar irradiation of 1423W/m^2 and the Akure Western Nigeria 5.304^{o} Latitude 7.258^{o} Longitude show that temperatures as high as 315K (42^{o}C) average are achievable. The simulation compares well with experiment. The simulation also shows that not very long exposure to sun rays is required to achieve temperatures high enough for preservation. This implies that solar box dryers may be applicable in regions of the world with fewer hours of sun shine.

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