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COMPUTATIONAL FLUID DYNAMICS SIMULATION OF THE BATCH PROCESS IN A RECTANGULAR PASSIVE GREENHOUSE DRYER

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ABSTRACT

Dryers for drying products in post-harvest processing are technologies involving complex system of transient heat, mass and momentum transfer combine with material science. A detailed understanding of the behaviour of the processes to analyze the interactions between various components of the system cannot be gained by testing alone especially not within the time and economics constrains that the market allows. This paper proposes a simulation framework to the transient convection-diffusion model of the batch process in a rectangular passive greenhouse dryer. Computer aided engineering analysis (CAE) approach in a user friendly computer package ANSYS 14.0 involving computational fluid dynamics (CFD) simulation was employed to evaluate the performance of the dryer. Results obtained which compared with validations showed that the numerical procedure is able to predict the greenhouse dryer design parameters as well as the batch process parameters. The results of the simulations of temperature within the rectangular passive greenhouse dryer's cavity were within $25^0C \leq T \leq 49.18^0C$ and those of experimental studies yielded the range $25^0C \leq T \leq 49.42^0C$. These results represent accuracy of 85.77%. Hence, the numerical simulations predict with degree of accuracy the transient temperature distribution as well as the thermophysical properties of the drying medium in the multi-racks passive greenhouse dryer.

KEYWORDS: Passive greenhouse dryer, Computational fluid dynamics, Simulation, Computer aided engineering.

1. INTRODUCTION

Natural convection in cavities has been the topic of much research in recent decades because of its numerous applications in engineering. Understanding the fundamental flow characteristics of these types of engineering applications is imperative for engineers to design low energy conversion system such as dryers. A batch process dryer is that in which the air temperature and humidity inside the dryer change in time as well as solid moisture content and temperature [1].

Traditionally, both experimental and theoretical methods have been used to develop designs for equipment like dryers. Most greenhouse dryers developed have been based on the assumption of the thin layer (single layer where constants are product dependent and the conditions of the drying air are kept constant throughout the material) drying equation and therefore implies that these are low-capacity solar dryer with no stratification in greenhouse air temperature [2], [3], [4] [5]. The thin layer drying models are divided into three main categories [6]. The empirical models applied to drying simulation due to dependency on experimental data. The theoretical approach (mechanistic models) concerns the simultaneous heat and mass transfer equations while the semi-theoretical approach concerns estimated theoretical equations. Out of these three models, empirical and semi-theoretical models considered only the external resistance to moisture transfers between the air and product whereas the theoretical approach considers only the internal resistance to moisture transfer. Generally they are

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based on the assumption that the ratio of air volume to the product volume is substantially large. In view of this assumption, the drying rate depends only on the properties of the material to be dried, that is, product temperature, size of the material and the moisture content. Hence, these models approach dryer design based on the manner in which the material is handled within the dryer and location which are most useful in the selection of a group of dryers for preliminary consideration in a given drying problem and therefore select dryer parameters implicitly. In high-capacity greenhouse dryers that necessarily involve the inclusion of more drying layers (deep bed drying with multi-racks) the solid phase is immobile and remains in the dryer for a particular time as air flows through it permanently. Consequently, air moves from the lower to the upper layer and increases its moisture content and cools due to evaporation. In this way, temperature and relative humidity gradient is formed between the lower and the upper layer, which is a measure of drying rate. The thin layer model and its associated assumptions therefore, become inadequate in addressing explicit dryer parameter selection. A third method, the numerical approach, has become available with the introduction of digital computer [7].

[1]However, pointed out that the first consideration in developing a dryer is to identify a volume of space that will represent a dryer which allows the method of transferring heat energy to the product. From drying process point of view, the batch process for the product concerns the manner in which the material is handled within the dryer and is most useful in the selection of a group of dryers for preliminary consideration in a given drying problem. However, the batch processes for the dryer concern the manner in which the heat is supplied to the material and reveals differences in dryer design and operation. The design consideration for the solar drying system used for bulk product drying consist of the solar air heater used to supply hot air, drying chamber and ducting [8]. Nevertheless, the design consideration for a passive greenhouse dryer concentrates on fixing the mechanical details of the drying chamber which also serves as the solar collector with some measure of performance in focus. Design studies focus on the basic processes that lead to energy accumulation, materials for the greenhouse fabrication, cabinet size, tray volume, number of trays, size of ducting and cladding. The dryer design problem is therefore the specification of all process parameters and dimensioning of the selected dryer type so that the set of design parameters (assumptions) are fulfilled. Greenhouse dryers have been studied experimentally and numerically mostly based on the handling characteristics and physical properties of the wet materials.

Recently, computational fluid dynamics (CFD) has been used progressively to improve process design capabilities in many industrial applications; including industrial drying processes [9], [10], [11], [12].

Mathematical models that allow for the evaluation of the spatial behaviour of a greenhouse solar dryer are represented by partial differential equations and use numerical solutions based on computational fluid dynamics (CFD), which have only been applied in an incipient manner. Therefore, there is great potential for computational fluid dynamics to become a very important research tool that can contribute to the development of a solar dryer optimum design with a more appropriate interior distribution of climatic variables. In the approach computational fluid dynamic simulation is used for the selective abstraction of the natural convection (batch process) in the rectangular passive greenhouse cavity into a computer program to study the temperature distribution of the drying medium (air) in the greenhouse cavity and predict system performance.

1.1. System dynamics approach

Batch process dryer has been identified as one of the generic dryer types based on the flow of material to and from the dryer, and characterized by the presence of the accumulation term in the general balance equation of a given entity for a specific volume of space (e.g., the dryer or a single phase contained in it) defined by the basic classes of model [1], [13]:

$$Material\ Inflow - Material\ Outflow = Accumulation \qquad \text{(i)}$$

It has also been observed that the true mechanism for the energy build up within a greenhouse is due to the enveloping of air and the decrease in air exchange between the inside and the outside of the greenhouse. Hence, air is used as the working medium and serves as medium of energy and moisture transfer within the dryer cavity [14], [15].

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Rectangular passive dryers are therefore classified according to their heating modes and the manner in which the heat energy is utilized as a dynamic drying system in which the principle of natural convection in rectangular enclosed cavity applies to the batch process. System dynamics approach is therefore utilized in the modelling and performance analyses to understand the dynamic nature of the batch process in the dryer in order to predict system behaviour and performance.

1.2. Boussinesq-approximation

The expansion of air in an isobaric process is related to the temperature through the volumetric expansion coefficient (β)[16]. The density of the air in the cavity of the rectangular passive dryer is a function of temperature and pressure as shown in Eqn. (5) [17]:

$$\rho = \rho(T, P) \qquad \text{(ii)}$$

Density (ρ) of air within the dryer is related to temperature (T) and pressure (P) through the truncated Taylor series expansion expressed as [17]:

$$\rho - \rho_\infty \cong (T - T_\infty)\frac{\partial \rho}{\partial T}\bigg|_P + (P - P_\infty)\frac{\partial \rho}{\partial P}\bigg|_T + \cdots \qquad \text{(iii)}$$

Where T_∞ =Temperature of the ambient air, ρ_∞ =Density of the ambient air
Buoyancy forces are therefore expressed in terms of air temperature differences through the volume expansion coefficient expressed given as [18], [19], [20], [21], [22]:

$$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)\bigg|_P = \frac{-1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)\bigg|_P$$

$$\Rightarrow \qquad \rho_\infty - \rho = \rho\beta(T - T_\infty) \qquad \text{(iv)}$$

Provided that $\beta(T - T_\infty) \ll 1$[17].
Eqn. (4) is the Boussinesq-approximation which states that the fluctuation in density which appears in the advent of motion of fluid in buoyancy driven flow result principally from thermal (as opposed to pressure) effect [23]. The buoyancy force per unit volume (F) on the air in the rectangular cavity of the passive dryer is therefore:

$$F = (\rho_\infty - \rho)g \qquad \text{(v)}$$

g = acceleration due to gravity
[22], [24] however, observed that it does not mean that the density is regarded as constant along the direction of motion, but simply that the magnitude of $\frac{1}{\rho}\frac{\partial \rho}{\partial t}$is small incomparison to the magnitudes of the velocity gradients in $\nabla . u$ in the continuity equation.

1.3. Mathematical approach to kinematics of materials in passive dryer

The dryer is a volume of space and the drying medium is moist air classified as Newtonian fluid. Therefore, the material flow that results in the accumulation of energy required for drying in the dryer involves the laws of continuum mechanics and kinematics in fluid dynamics [25], [26], [27], [28], [29].

From the fundamental law of continuum mechanics, bodies behave in such a way that the universal balance of mass, momentum, energy and entropy are satisfied. The conservation laws involving material flow and related transport phenomena were formulated mathematically adopting the Eulerian approach. Therefore, the energy balance for the drying medium (air) in the batch process in rectangular passive dryer consists of three components given by the transient convection-diffusion equation as:

$$\underbrace{\rho\frac{\partial T}{\partial t}}_{\substack{Transient\\ term}} + \underbrace{\frac{\partial(\rho u T)}{\partial x} + \frac{\partial(\rho v T)}{\partial y} + \frac{\partial(\rho w T)}{\partial z}}_{\substack{Convection\\ term}} = \underbrace{\left(\frac{k}{c_p}\right)\frac{\partial^2 T}{\partial x^2} + \left(\frac{k}{c_p}\right)\frac{\partial^2 T}{\partial y^2} + \left(\frac{k}{c_p}\right)\frac{\partial^2 T}{\partial z^2}}_{\substack{Diffusion\\ term}} \qquad \text{(vi)}$$

u, v, w =velocity (ms^{-1}) in the reference axes x, y, z; t = time; x, y, z = rectangular spatial coordinates in the reference axes; k =thermal conductivity coefficient (W/m.K) of air within the dryer; and c_p =specific heat capacity [J/(kg.K)] of air at constant pressure.

The conservation of energy in the rectangular passive dryer is subject to the conservation of mass and momentum. The conservation of mass in the open system for constant $\rho \neq 0$ is expressed as:

$$\Rightarrow \quad \frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad \text{(vii)}$$

Consequently, the conservation of momentum in the rectangular passive greenhouse consists of the three equations after incorporating the Boussinesq-approximation (Eqns. viii-x):

$$\underbrace{\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}}_{Inertial}=\underbrace{\mathrm{v}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)}_{Friction} \quad \text{(viii)}$$

$$\underbrace{\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}}_{Inertial}=\underbrace{\mathrm{v}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)}_{Friction}+\underbrace{\frac{1}{\rho}g\beta(T-T_\infty)}_{Buoyancy} \quad \text{(ix)}$$

$$\underbrace{\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}}_{Inertial}=\underbrace{\mathrm{v}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)}_{Friction} \quad \text{(x)}$$

v = the kinematic viscosity

The transient convection-diffusion model (Eqn. vi) of the batch process in rectangular passive dryer subject to hydrodynamic boundary conditions of Eqns. (vii and viii-x) is a non-homogeneous, non-linear partial differential equation (PDE requiring numerical solutions: [30]). This is a system of partial differential equations.

2. COMPUTER AIDED ENGINEERING APPROACH

The computation of the greenhouse batch process system dynamics was implemented using computer-aided engineering analysis approach in element-based finite volume software ANSYS 14.0 workbench. The numerical simulation was by computational fluid dynamics (CFD) methodology in ANSYS 14.0 CFX, which includes: creating the computational 3-D model of the passive greenhouse dyer in ANSYS 14.0 Designmodeler [31], meshing of the generated 3-D geometry in ANSYS 14.0 ICEM CFD [32] and implementing the batch process and it technological/practical constraints in ANSYS 14.0 CFX-Pre [33]. Other procedures include solving the equations of the mathematical models (i.e. Eqns. vi-x) iteratively on the computational mesh in ANSYS 14.0 CFX-Solver Manager [34] and the results and the analysis of the simulations in ANSYS 14.0 CFD-Post [35].

The process parameter specifications as well as constants used for the simulations are shown in Table 1 and Table 2 which present the dryer domain physics and the boundary physics respectively.

Table 1. Domain physics for ANSYS CFX

Domain – Default Domain		**Unit**
Type	Fluid	
Location	B31	
Materials		
	Air as Ideal Gas	
Fluid Definition	Material Library	
Morphology	Continuous Fluid	
Settings		
Buoyancy Model	Buoyant	
Buoyancy Reference Temperature	40.7	°C
Gravity Y Component	9.81	m/s^2
Buoyancy Reference Location	Automatic	
Domain Motion	Stationary	
Reference Pressure	1.00	atm
Heat Transfer Model	Thermal Energy	
Thermal Radiation Model	Monte Carlo	
Number of Histories	10000	

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Radiation Transfer Mode	Participating Media	
Spectral Model	Gray	

Table 2. Boundary Physics for ANSYS CFX

Domain	Boundaries		Unit
Fluid Domain	**Boundary - DS_INLET**		
	Type	INLET	
	Location	DS_INLET	
	Settings		
	Flow Regime	Subsonic	
	Heat Transfer	Static Temperature	
	Static Temperature	25	°C
	Mass And Momentum	Normal Speed	
	Normal Speed	1.00	m/s
	Thermal Radiation	Local Temperature	
	Boundary - DS_OUTLET1		
	Type	OUTLET	
	Location	DS_OUTLET1	
	Settings		
	Flow Regime	Subsonic	
	Mass And Momentum	Average Static Pressure	
	Pressure Profile Blend	0.05	
	Relative Pressure	1.00	atm.
	Pressure Averaging	Average Over Whole Outlet	
	Thermal Radiation	Local Temperature	
	Boundary - DS_OUTLET2		
	Type	OUTLET	
	Location	DS_OUTLET2	
	Settings		
	Flow Regime	Subsonic	
	Mass And Momentum	Average Static Pressure	
	Pressure Profile Blend	0.05	
	Relative Pressure	1.00	atm.
	Pressure Averaging	Average Over Whole Outlet	
	Thermal Radiation	Local Temperature	
	Boundary - Floor		
	Type	WALL	
	Location	F36.31	
	Settings		
	Heat Transfer	Adiabatic	
	Mass And Momentum	No Slip Wall	
	Thermal Radiation	Opaque	
	Diffuse Fraction	1.00	
	Emissivity	1.00	
	Wall Roughness	Rough Wall	
	Sand Grain Roughness Height	2.00	mm
	Boundary - Wall		
	Type	WALL	
	Location	F32.31, F33.31, F34.31, F35.31, F37.31	
	Settings		
	Heat Transfer	Heat Flux	
	Heat Flux in (March)	768.57	W/m^2
	Mass And Momentum	Free Slip Wall	

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	Thermal Radiation	Opaque	
	Emissivity	1.00	

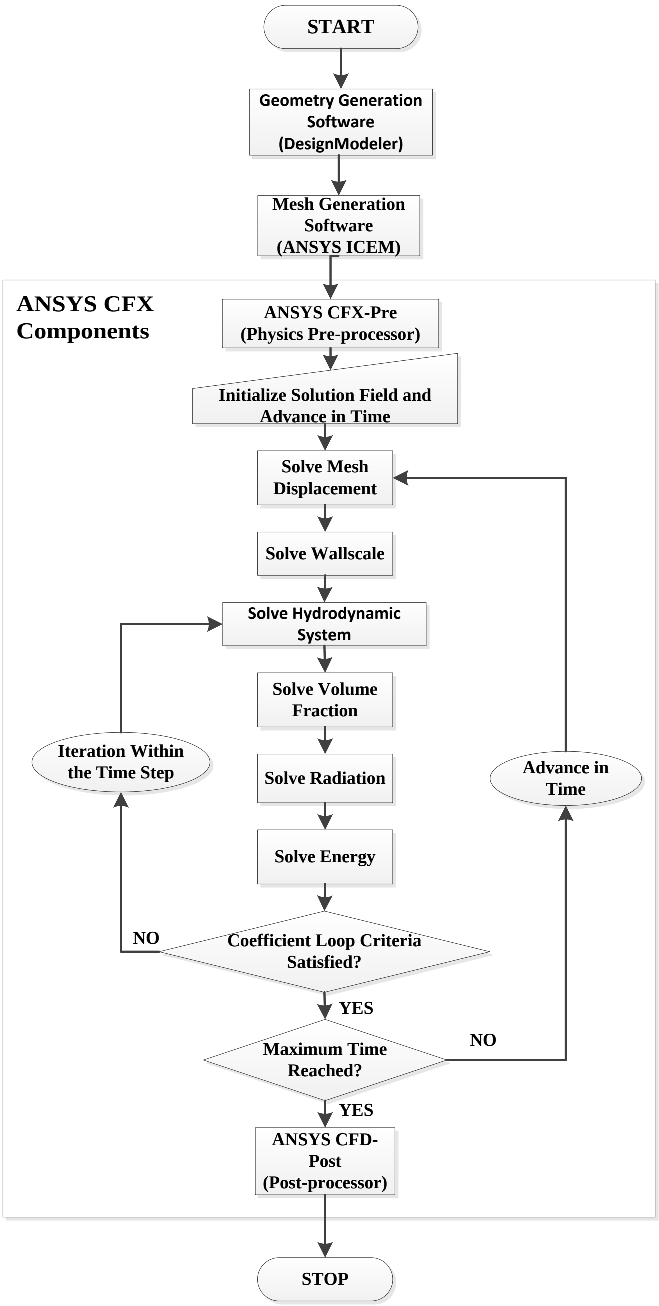

Figure 1: Flow chart of the CFD simulation

Figure 1 is the process flow chart of the computational fluid dynamics simulation.

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3. COMPUTATIONAL FLUID DYNAMICS SIMULATION RESULTS AND DISCUSSION

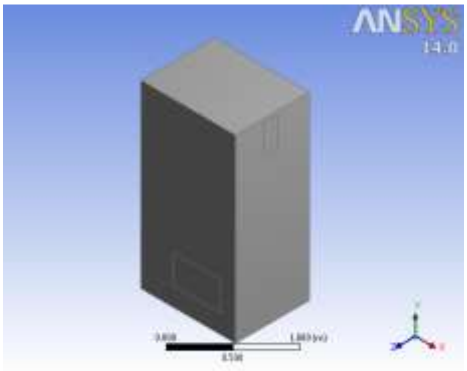

Figure 2: Geometric Model of the Rectangular Passive Greenhouse Dryer

Figure 2 presents the modelled 3-D geometry of the rectangular passive greenhouse dryer in ANSYS Designmodeler beginning with the dimensions of Olokor in [36]. The geometry of the dryer is rectangular in shape with inlet vent situated below while two adjacent outlet vents are located towards the top of the rectangle.

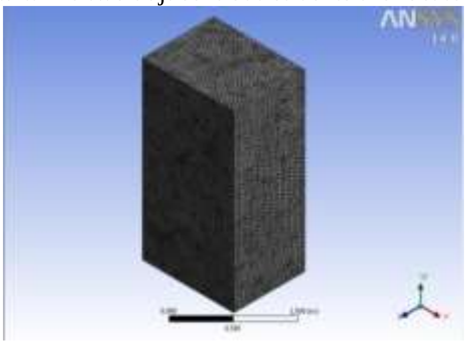

Figure 3: Meshed Rectangular Passive Greenhouse Dryer Geometry

Figure 3 presents the meshed 3-D geometry of the rectangular passive greenhouse dryer in ANSYS 14.0 ICEM CFD. Tetrahedral unstructured mesh was used in this study. Total number of nodes is 19580 and elements are 92628 which have been employed for the analysis of the rectangular passive greenhouse dryer. This resulted in an element to node ratio of approximately 5:1 which is typical of tetrahedral meshing.

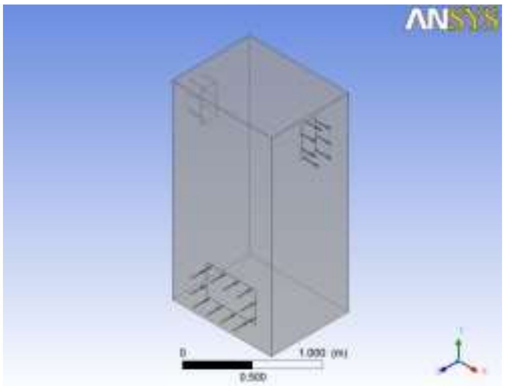

Figure 4: Inlet and Outlets Boundary Setup on Rectangular Passive Greenhouse Dryer Geometry

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Figure 4 is the modelled boundary conditions of the greenhouse dryer in ANSYS 14.0 CFX-Pre with the process parameter specifications as well as constants used for the simulations are shown in Table 1 and Table 2 earlier presented. Table 3 are the define convergence criteria in the simulation process.

Table 3: Definition Convergence Criteria

Convergence Criterial	**Setting**
Minimum coefficient loop	3
Maximum coefficient loop	4
Residual type	Root mean square (RSM)
Residual target	10^{-4}

The residual was observed to be reduced rapidly within the set convergence criteria both for the momentum, mass and heat transfer with attainment of convergence within 50 cumulative Time-step of 150 iterations.

3.1. Transient temperature distribution in rectangular passive greenhouse cavity

The results of the analysis of the scalar quantities (air properties) of using the predicted values of solar energy irradiation of 768.57 kW/ m^2 equivalent to 5.38 kWh/m^2 energy for 7 hours of sunshine duration typical of March, in Kainji for simulating the natural convection batch process in the rectangular passive greenhouse dryer (solar tent) are presented in Figures 5 to 11. In this study streamlines were used in the visualization of the air flow properties in the rectangular passive greenhouse dryer. Streamlines are a family of lines that are everywhere parallel to the velocity which are strictly Eulerian concept and mainly used in analytic work [25], [26], [37], [38].

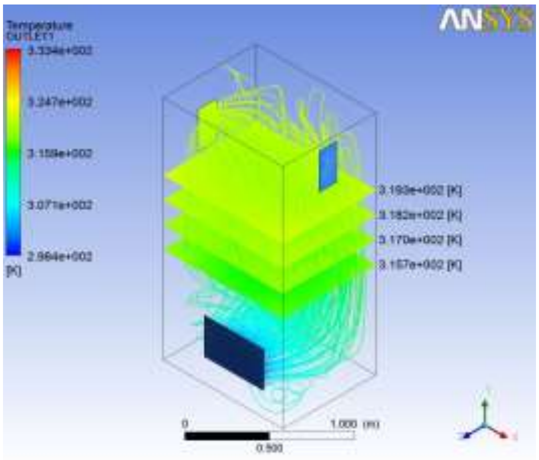

Figure 5: Temperature Streamlines of the Drying Medium (air) in Rectangular Passive Greenhouse Dryer for the Month of March

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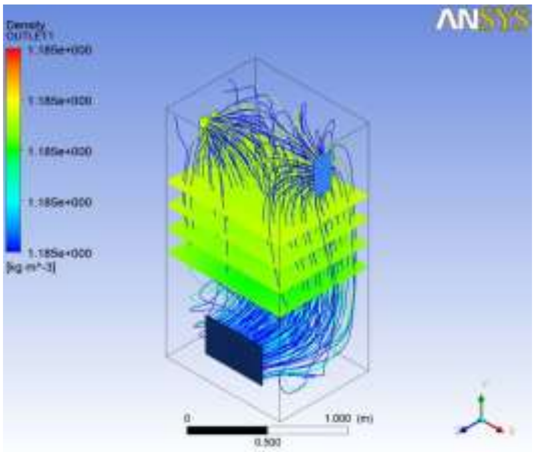

Figure 6: Density Streamlines of the Drying Medium (air) in Rectangular Passive Greenhouse Dryer for the Months of March

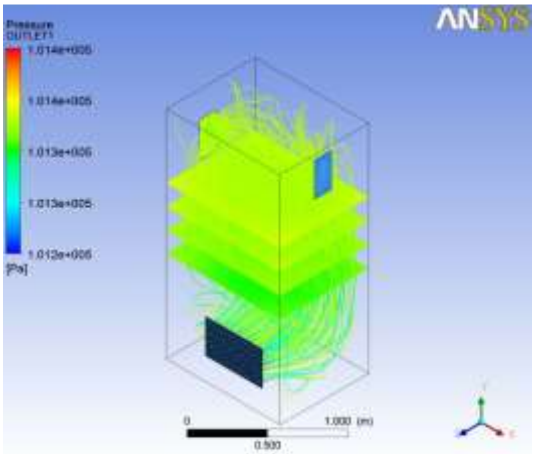

Figure 7: Pressure Streamlines of the Drying Medium (air) in Rectangular Passive Greenhouse Dryer for the Months of March

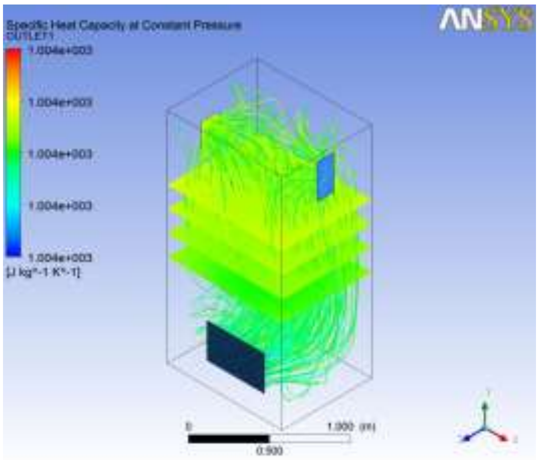

Figure 8: Specific Heat Capacity Streamlines of the Drying Medium (air) in Rectangular Passive Greenhouse Dryer for the Months of March

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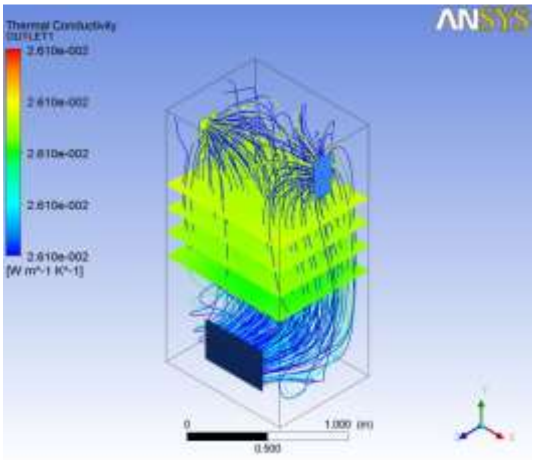

Figure 9: Thermal Conductivity Streamline of the Drying Medium (air) in Rectangular Passive Greenhouse Dryer for the Months of March

The temperature streamlines of the air in the rectangular passive greenhouse dryer for the month of March as well as the mean temperature on the plane of each rack are presented in Figures 5. Figures 6 present the density streamlines for the month of March, Figures 7 present the pressure streamlines for March. The results of other thermo-physical properties of the drying medium (air) were also obtained and presented by Figure 8 (specific heat capacity at constant pressure) and Figure 9 (thermal conductivity). These results indicate the variation of the different properties of the air as it transit from the inlet to the outlets across the racks. They also indicate the direction of flow of the drying medium (air) to be against gravity hence, buoyancy driven. The mean temperature on the plane of each rack are observed from the simulation to be 42.52 °C, 43.82 °C, 45.02 °C and 46.12 °C respectively. Hence, the results of the simulation show that there are variations in the drying medium (air) temperature across the racks from the inlet towards the outlets. The results further show that air density, the pressure, the specific heat capacity and thermal conductivity of the drying medium within the greenhouse dryer appeared relatively constant during the simulation with these values being $1.185 kgm^{-3}$, $1.01335 \times 10^5 Pa$ (approximately 1 Atmosphere), $1004.4\, Jkg^{-1}K^{-1}$ and $0.0261\, Wm^{-1}K^{-1}$ respectively. These values of the thermo-physical properties of humid air within the temperature range studied agree with those of [39] and data generated by Engineering Equation Solver software [40] reported in [19] for air.

Figure 4 shows that there is temperature variation in the direction of air flow as well with time which indicates spatial and temporal variation of process temperature. This suggests the transient nature of the batch process in rectangular passive greenhouse dryer [1]. The racks for drying products are normally situated between the inlet vent and the outlet vents. The air temperature variation between the vents was observed to be $25 \leq T \leq 49.18$ (ºC) for March. As the humid air flow through the dryer the temperature increases across the racks as a result of solar radiation energy gain. As observed in the experimental study, such temperature increase is accompanied by decrease in the relative humidity. The implication of this is the increase in the drying potency of the air by widening the difference between the vapour pressure of the air and the saturation vapour pressure which is temperature dependent [19], [41].

The density of the fluid is constant within the dryer as shown in Figure 5. This is typical of the Boussinesq model which uses a constant density fluid model, but applies a local gravitational body force throughout the fluid that is a linear function of fluid thermal expansivity β, and the local temperature difference with reference to a datum called the Buoyancy Reference Temperature[35]. Hence, the change in density over the expected range of conditions is considered to be relatively small and negligible. Figures 8 shows that the pressure within the dryer appears to be constant at $1.01335 \times 10^5 Pa$ with a little increase at the inlet vent and a little drop in pressure at the outlet vents consequently, the air flow is primarily as a result of temperature variation in the drying chamber as opposed to pressure variation.

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3.2. Comparison of experimental results with numerical simulation results

To ensure the match between the simulated results and real physics, validations were conducted. The temperature distribution at the different rack levels (R_{18}, R_{36}, R_{54} and R_{72}) representing the rack at 18cm, 36cm, 54cm and 72cm respectively measured from the inlet vent of the experiments and corresponding to temperature distribution at different level of XZ-plane in the simulations (see Figure 5) were compared in Figure 10.

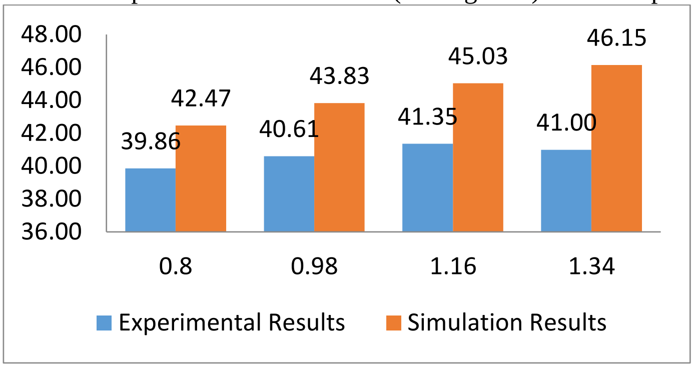

Figure 10: Comparison of Temperature Distribution for Experiments and Simulations

Table 4: Summary of ANOVA for Temperature Distribution in Rectangular Passive Greenhouse Dryer

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	26.89707	1	26.8971	18.4730	0.0051	5.9874
Within Groups	8.73612	6	1.456			
Total	35.63319	7				

Figure 10 closely assessed with the analysis of variance (ANOVA) for temperature distribution in rectangular passive greenhouse dryer of Table 4 show that there are observable differences in the temperature distribution between experimental and simulation results. Consequently, the analysis of variance (ANOVA) at a significance level of $\propto= 0.05$, $F_{cal} = 18.4730$ is greater than $F_{crit} = 5.9874$ in Table 4. In summary, $F(1,6) = 18.4730, p > 0.05$. Hence, there is significant difference between the experimental and simulation results at the different levels of the racks. However, since it appears that a linear relationship exists between the experiment and simulation, the Pearson correlation coefficient was used to further measure the strength of the relationship to be 0.8577. This indicate that 85.77% of the variation of the experimental result can be accounted for by the simulation (considered excellent according to Ricardo and Ferran in [42]) which implies that the simulations predicts the experimental results with degree of accuracy across the different rack levels.

3.3. Comparison of thermo-physical properties with those in accredited literatures

Table 5 presents the comparison of other thermo-physical properties of moist air in the rectangular passive greenhouse dryer (see Figures 6, 8 and 9) with those obtained from numerical evaluation of moist air properties within the same temperature range in accredited literatures [40], [43].

Table 5: Comparison of Simulation Results of the Thermo-Physical Properties of Moist Air with those of [40], [43] EES within the Temperature Regime

Thermo-physical Properties	**Present Study**	**ASHRAE**	**EES**	**% Deviation in Properties (ASHRAE)**	**% Deviation in Properties (EES)**
Density (kg/m^3)	1.185	1.130	1.126	-4.867	-5.240
Specific heat capacity (J/kg.K)	1004	1007	1007	0.298	0.298
Thermal conductivity (W/m.K)	0.0261	0.0270	0.0267	3.333	2.250
Prandtl number	0.705	-	0.725	-	2.759

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The comparisons of density, specific heat capacity, thermal conductivity and Prandtl show that observable variations also exist among the values. However, [40] tend to be closer to the simulation results. These results show that the simulation model can predict the temperature, density, heat capacity, thermal conductivity within average deviation of 12.57%, 5.24%, 0.3% and 2.25% respectively. The model is therefore able to account for the effect of heating due to solar radiation, as well as the natural convection heat transfer within the dryer. Hence, the model can be used to understand the performance of different dryer design based on different energy sources and weather conditions.

4. CONCLUSION

System dynamics have provided insight into the behaviour of the thermodynamics properties and exergy of the drying medium (air) in a multi-racks rectangular passive drying system. In computer-aided engineering analysis of the proposed mechanistic model, the numerical simulation results predicted the range of transient temperature within the rectangular passive greenhouse dryer's cavity as $25^0C \leq T \leq 49.18^0C$ increasing in the direction of buoyancy from the inlet vent towards the outlet vents. The buoyancy air flow as a medium of heat and moisture transfer in the gravitational field of the rectangular passive greenhouse dryer is primarily as a result of temperature variations in the drying chamber as opposed to pressure variations. The thermo-physical properties (specific heat capacity, thermal conductivity and density) of the drying medium (air) were also found to be relatively constant in the batch process of the passive greenhouse dryer. The computational fluid dynamics (CFD) simulation in the computer-aided engineering analysis approach therefore, enabled the prediction of the batch process parameter as well as the digital prototyping of the rectangular passive greenhouse dryer and will form the basis for future research in related fields.

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