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Computational Fluid Dynamics Performance Analysis on Mixed Mode Solar Dryers.

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ABSTRACT.

Four mixed mode solar dryers with different tray arrangement each has been constructed and evaluated at Nsukka (Lat. 6.86°N, Long 7.39°E), Nigeria. The arrangements considered were; 'End-end', 'End-centre', 'centre', and 'mixed'. The evaluation was carried in two phases; Load and No-load Tests. Using cassava (*manihot esculenta*) for the load test. The best result recorded was for the 'End-centre' arrangement with drying temperature range (30.7-49.3℃), moisture content (wet) reduced to 18.96%, weight loss of 1.21kg, with an average drying rate of 35.40 g/hr., and the calculated system drying efficiency was 83.24%.

Computational fluid dynamics (CFD) was used to simulate air flow within the dryers for the no-load test, the result showed a more uniformly distributed temperature, velocity stream lines and higher velocity magnitude in the 'End-centre' than other tray arrangements. This confirms the result of the load phase test.

1. INTRODUCTION

Drying may be required for several reasons. First and most often, water is removed from the fresh crop to extend its useful life. The dried product is later rehydrated prior to use in order to produce a food closely resembling the fresh crops, for example, in the use of dried vegetables. Second a crop may require drying so that it can be further processed. For example, many grains are dried so that they can be ground into flour. Third, fresh crops are sometimes dried so that a new product distinctly different from its original form can be produced. (Chandrakumar and Jiwanlal, 2013)

Traditional open sun drying process, which involves spreading the crop in thin layers of mats, trays or paved grounds is one of the oldest, simplest and widely practiced by local farmers in the rural areas. The process requires relatively low capital investment, large drying area, is time consuming, and is generally unhygienic (Lawrence et al. 2013) also, the process can have a negative impact on dried products' quality mainly due to contamination by windborne dirt and dust, insects etc. (Vlachos et al. 2002). The resulting decrease in quality renders the product less marketable (Tiris et al., 1994). In addition, rainfall and wind can even destroy the whole drying process.

The negative effects of open sun drying are mitigated by the use of solar dryers. A solar dryer is an enclosed unit to keep the food safe from damage from animals, insects, microorganism, pilferage, and unexpected weather condition. The produce is dried using solar thermal energy in a cleaner and healthier fashion. Basically, there are four types of solar dryers; direct, indirect, mixed-mode and hybrid solar dryers

(Chandrakumar and Jiwanlal, 2013). Gallali et al. (2000) compared products dried by solar dryer and natural sun drying. Their study indicated that using solar dryer gives more advantages than natural sun drying especially in terms of drying time. In a solar dryer the temperature of the air surrounding the product is raised above the ambient air temperature (Fuller, 1978). According to Ramana (2009), solar-energy drying, where feasible, often provides the most cost-effective drying technique.

Recently there have been researches and works to improve the efficiency of solar dryers by varying different design parameters. Bennamoun and Belhamri (2003) investigated a solar batch dryer for drying agricultural products. The result shows that increasing the collector surface area and the temperature of the drying air reduces the drying time. Bassey (1991) studied the effect of chimneys and collector air gap height on the performance of indirect natural convection dryers. The result indicated that the performance of the dryer was significantly enhanced by reducing the mean collector air gap height gap from 5 to 4cm. Vidya et al (2013) inculcated a heat exchanger made of copper wire at the exit door of a solar dryer in order to reduce heat wastage and increase the drying temperature of the dryer. Ugwu et al. (2014), constructed a solar kiln dryer with black pebbles. It was found to increase the efficiency, as the pebbles served as heat storage for night periods.

Nowadays, given the increase in computing power, the application of Computational Fluid Dynamics (CFD) can be a valuable tool for engineering design and analysis of solving complex fluid flow, addressing heat and mass transfer phenomena, aiding in the better design of solar dryers and produce high quality of dried product. CFD simulation is used extensively because of its capability to solve equations for the conservation of mass, momentum, and energy using numerical methods to predict the temperature, velocity, and pressure profiles in the drying chamber (Suhaimi et al., 2013). Christiana et al. (2012) presented a numerical simulation of the airflow inside a hybrid solar-electrical dryer, using a commercial CFD (ANSYS-CFX Code) package. Numerical results were compared with experimental data obtained in a prototype. The dryer was tested without the trays and without any load. Suhaimi et al (2013) predicted the drying uniformity of a newly designed solar tray dryer. Misha et al (2013) investigated the airflow distribution throughout the drying chamber by using Computational Fluid Dynamics simulation for kenaf core drying. The experimental and simulation data exhibited very good agreement.

In the previous studies conducted on drying with solar dryers, there have been little or no information on the effects the trays arrangements would have on the performance of a solar dryer. This work is an improvement of previous work by Akubue et al. (2015) as more trays were include and the incorporation of simulation CFD for the no-load test, using cassava *(Manihot esculenta Crantz)* as the product to be dried for the load test.

2. Materials and Methods

2.1 Experimental set up

The different tray arrangements are shown in the figures 1,2,3 and 4 below

Fig 1; 'Mixed tray arrangement'

Fig 2;'End-centre arrangement'

Fig 3' End-end tray arrangement'

Fig 4; 'Centre tray arrangement'

Fig 5; Pictorial view of the dryers

The dryer is a mixed mode passive solar dryer, it combines both aspects of direct and indirect dryers. A separate collector below preheats an incoming airflow through a rectangular inlet of 10cm by 12cm and

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then direct sunlight adds heat to the airflow and the product as well, the heated air is then directed (by buoyancy) to the products placed in the chamber. After heating, the air leaves the dryer through the chimney. The dryer consists of an insulated (7 cm thick foam) wooden material casing painted black to minimize heat loss. Mild steel sheet of 1mm thickness (dimension 108 cm × 54 cm) painted black, acts as the collector - for absorption of solar radiation. Plain transparent glass (4 mm thick) serves as the glazing material for the solar collector inclined at the local latitude (Nsukka, Lat. 6.86°N) and the front cover of the drying chamber. Wooden frames and wire net were used in the construction of the trays, having a vertical distance of 18.56 cm between each tray. The wider trays were 46 cm by 40 cm, while the smaller trays were 23 cm by 40 cm each.

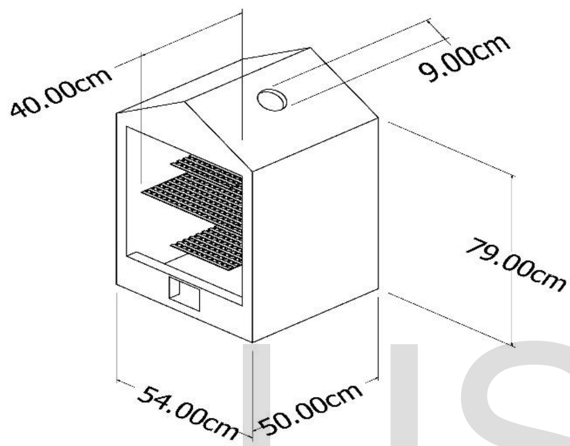

Fig.6 (a) side view of the 'mixed' arrangement

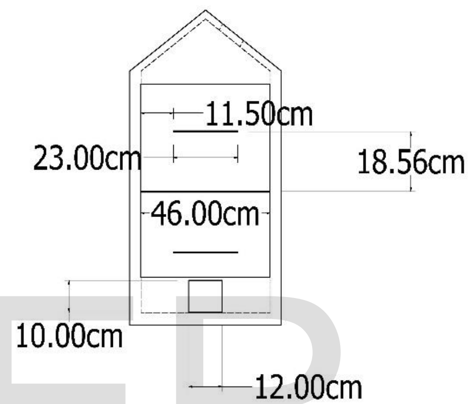

Fig.6(b) Front view of the 'mixed' arrangement

Figures 6(a) and 6(b) above generalizes the dimensioning of the solar chamber. The tray is 0.25cm thick.

2.2 Experimental procedure

2.2.3 Load Test.

Cassava was purchased at Ogige market in Nsukka, Nigeria. The cassava husk was peeled off and washed in slightly warm water. It was later sliced to a circular shape of approximately 0.4 cm thick and 2.5 cm in diameter. The measured parameters were; temperatures, solar intensity and weight of the dried product. The entire experiments were carried outdoors for two weeks in May-June 2015 at the National Center for Energy Research and Development, University of Nigeria, Nsukka from 10 am to 6 pm.

Equal mass of product were placed in each dryer. The experimental readings were taken at interval of two hours which was later increased to three hours immediately when we noticed infinitesimal change in weight of the previous and present readings during the end stages of the experiment. When taking readings, the mass of each specimen on the shelves was measured simultaneously. The different temperatures (ambient, inlet, chamber and product) were measured with a microprocessor digital thermometer (k-type), manufactured by Rubber holster –with a test range of -50℃-1300℃, resolution of 0.1℃, and accuracy of $\pm$0.1℃ $\pm$0.4℃. Three holes of 1cm diameter were made by the sides of the drying cabinet so as to allow for measurement of chamber temperature using thermocouple probes.

The weight of the product was measured with a digital analytical weighing balance (Adventurer-Ohaus, China), with sensitivity of 0.001g. Ohaus Solar-meter was used to measure the solar insolation. The initial moisture content was analyzed with Ohaus moisture Analyzer and found to be 73.6% (wet basis). Digital stop watch with accuracy of 0.01sec was used to measure the time.

2.2.4 No-load simulation.

Autodesk simulation CFD,2016 edition was used in the simulation for the no-load test. The pattern of air stream in the drying chamber is important and since there was no variable condition in this study, the simulation was carried out in a steady state condition. The z-plane was chosen to study and analyse the velocity and temperature in the drying chamber. The z-Plane is considered the weak zone compared to others areas in the drying chamber. The set-up of boundary conditions were defined as followings:

- Inlet: air mass flow rate of 0.23kg/s, air temperature of 45℃, air velocity of 0.6m/s normal to air inlet.
- Outlet: Assuming a gauge pressure of zero

The wall was assumed adiabatic, turbulent flow type and 20 iterations.

2.3 Performance Evaluation

Evaluation of thermal performance in drying applications is considered as a means of assessing how well (or poorly) a dryer operates under a certain condition (Walid et al. 2014). The performance of the system and the drying characteristics is calculated using the following expression:

The moisture content (M_c) is expressed as a percentage of moisture present in the product. The instantaneous moisture content at any given time on wet basis is calculated using the following expression.

$$M_c(wet) = \left(\frac{M_i - M_d}{M_i}\right) \times 100 \quad (1)$$

where M_i, is the initial mass of the sample in kg and M_d is the final mass of the sample in kg.

Drying rate (R_d) is formed by a decrease of the water concentration during the time interval between two subsequent measurements divided by the time interval

$$R_d = \left(\frac{M_i - M_d}{t} \right) \quad (2)$$

where 't' is the time of drying in sec.

Efficiency of drying (η_d) is a measure of the overall effectiveness of a drying system (with respect to the drying chamber). It is the ratio of energy required to evaporate the moisture from the product to the energy supplied to the solar dryer; the drying efficiency at any time period was calculated using the following expression (Thanvi and Pande, 1987). Assuming that the loss of heat from the dryer to the ambient air is negligible and there is heat utilized to increase the temperature of the product.

$$\eta_d = \left(\frac{W_w L + m_p c_p \Delta T}{A I_t t_h} \right) \quad (3)$$

Latent heat of vaporization is usually expressed as a function of temperature (Pelegrina *et al*. 1999). So, the latent heat of vaporization (J/kg) in this study was calculated at the drying air temperature according to ASAE standard of moisture content determination of 1992 as follows

$$L = 2502535259 - 2385.76424(T_d - 273.16) \quad (3.1)$$

where η_d is drying efficiency (%), t_h is desired time period (7200 sec) in this study, 'A' is the surface area of air heater (m^2), W_w is water evaporated during a time period (kg), m_p is mass of cassava samples at a time period (kg), C_p is specific heat of cassava (El-Awady *et al*. 1993), ΔT is temperature difference between air temperature inside the drying chamber and ambient air temperature (°C), I_t is total solar intensity on horizontal surface (W/m^2) and T_d is drying air temperature, (°K).

2.3 Results and discussions.

2.3.1 Analysis of drying temperature

The result of the average drying temperature of the different tray arrangements during the Load-test experiment is as in Fig.7.0. The graph indicates a high drying temperature between 12:00pm and 4:00pm, with its peak values at 2:00pm. The drying temperature in the chamber of the different tray arrangement ranges from (31.53 - 41.87℃) for the "End-Center" arrangement followed by (30.9-40.90℃), for the "Centre" arrangement, (30.39-38.32℃) for "Mixed" and (29.67-37.10℃) for the "End-end" arrangement.

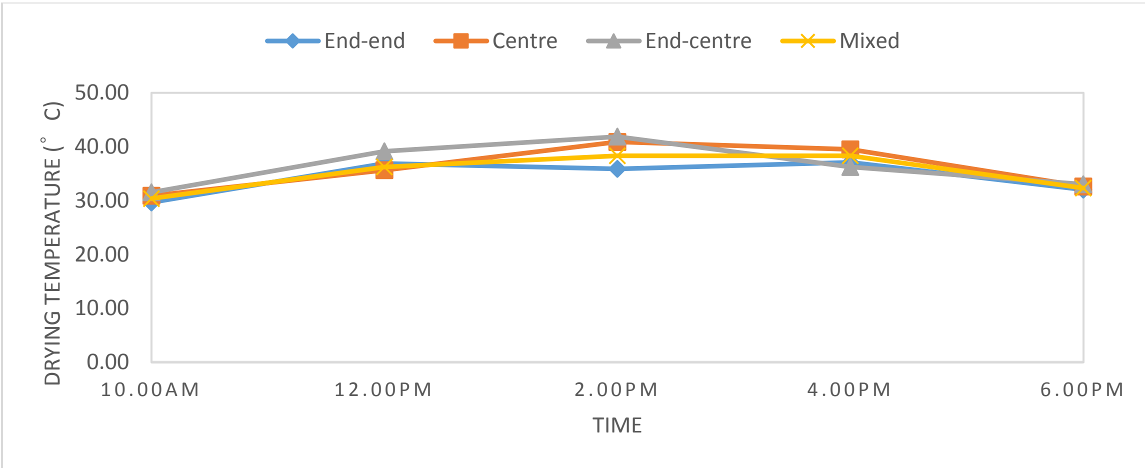

Fig. 7.0 showing drying temperature during load test.

2.3.2 Analysis of the moisture content (wet)

The variation of moisture content (wet basis, as gotten from equations 1) with drying time is illustrated in Fig. 8.0 Similar to that obtained by Mohanraj (2009). The average moisture content was reduced from 73.60% to 20.39% for the four trays.

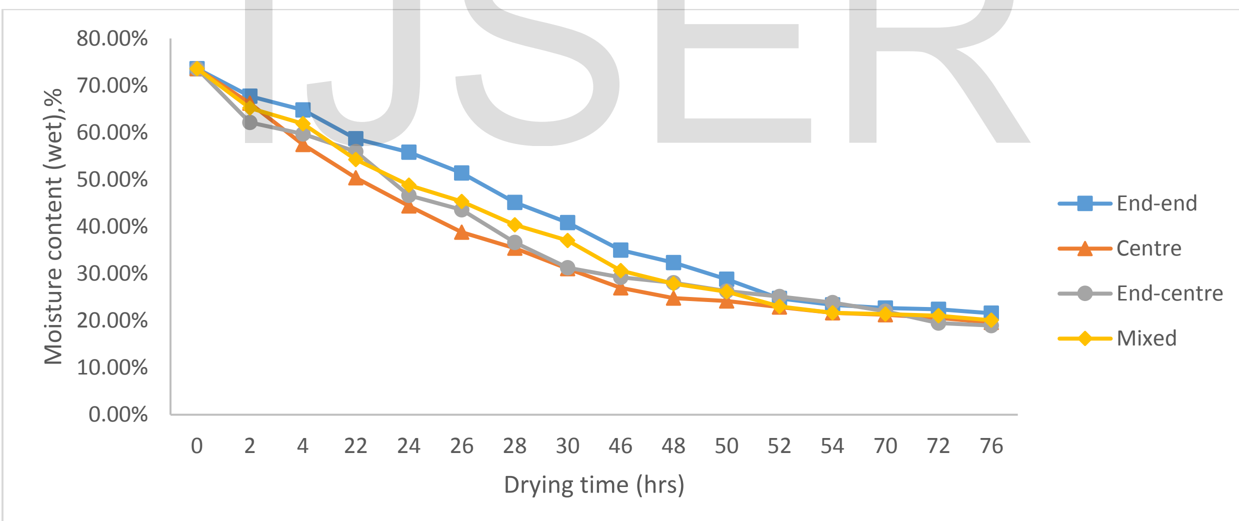

Fig.8.0 Showing the variation of moisture content with total drying time.

It is observed from the graph above that at the end of the drying experiment, the moisture content of the "End-center" tray arrangement is lowest (18.96%) and highest for the "End-end" arrangement (21.58%) compared to the other tray arrangements. For most of the drying period, the moisture content of the "center" arrangement is lowest.

A possible explanation would be that since drying air temperature is the most important parameter in drying (Ndukwu, 2009), and from the temperature measurements, "end-center" and "center" gave the highest temperature when compared to other arrangements. So the higher the drying temperature the lesser the moisture content.

2.3.3 Analysis of drying rate

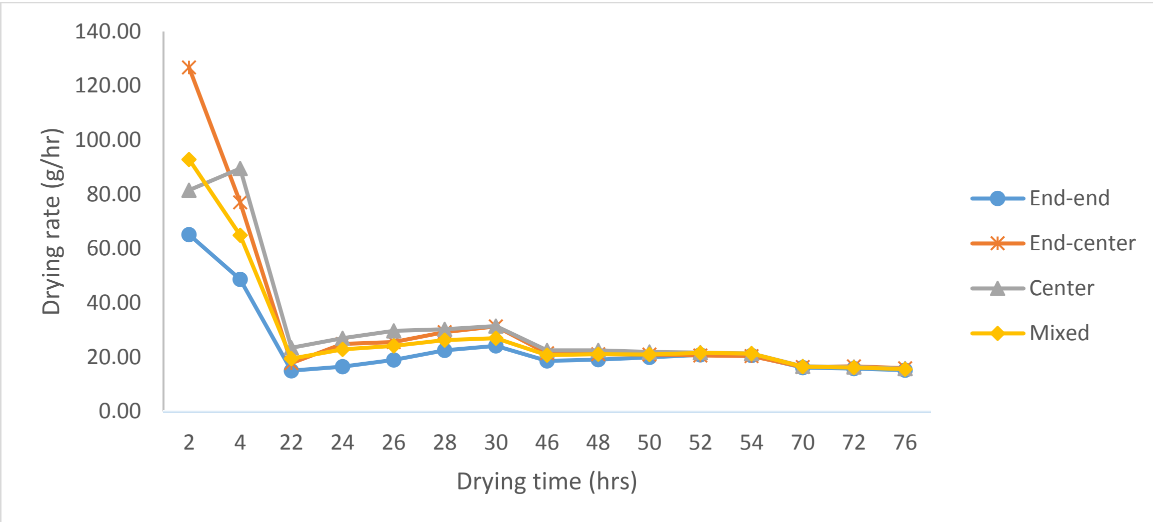

Fig. 9.0 showing the cumulative drying rates with time.

Figure 9.0 shows the cumulative drying rate with time, with reference to the initial weight of the product with total drying time at a given instant (equation 2). It shows that the drying rate of the “end-center” arrangement is initially the highest (126.75g/hr.) and least for the ‘end-end’ arrangement (65.17g/hr.). But for most of the drying periods, the “center” arrangement gives a higher drying rate, with an average rate of 31.43g/hr. with the least drying rate seen for the “end-end” arrangement (23.80g/hr., average).
It is observed that a steep slope is seen at the beginning of the drying, which agrees with Fred (2002), that during the initial stages of drying, the drying rate is fastest because more moisture is at the surface of the product, having little distance to travel from the core of the drying product to the surface, therefore there is more transfer of energy at the early stages of drying.

2.3.4 Analysis of drying efficiency

For the drying efficiency, two typical days were chosen to calculate the efficiency of the drying system, 10th of June was chosen, because at this day the solar intensity was observed to be lowest. Substituting the measured parameters into equation (3), the efficiency of the ‘End-Centre’ was calculated to be 83.24% (0.20 kg moisture evaporated at an average temperature of 5.15°K),’centre’ gave an efficiency of 67.6% (0.09607 kg moisture removed at an average temperature of 5.05K),’end-end’ efficiency was 63.09% (0.09 kg moisture evaporated, average temperature of 4.1K) while ‘Mixed’ efficiency was 52.48% (0.074 kg moisture evaporated at an average temperature of 4.5°K) within two hours period. 11th of June was also chosen, because the solar intensity was highest, using same equation (3), the efficiency of the ‘End-Centre’ calculated was 4.12% (0.038 kg moisture evaporated at an average temperature of 9.2°K), ‘centre’ was 1.79% (0.014kg moisture evaporated at this time, at an average of 8.5K), ‘end-end’s efficiency was

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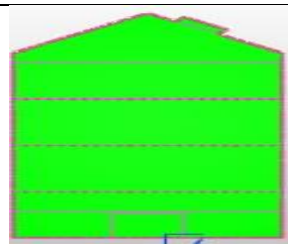
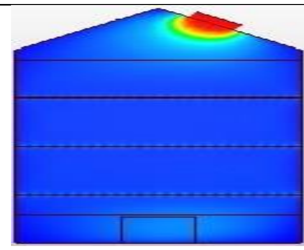
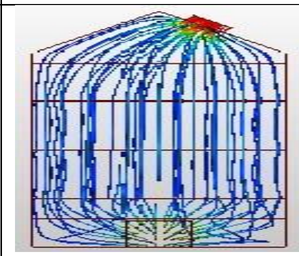
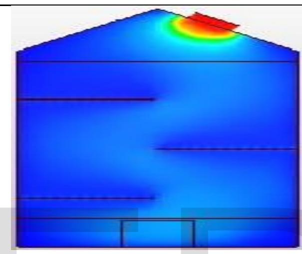
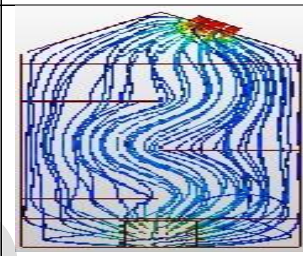
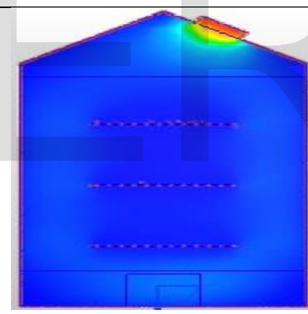
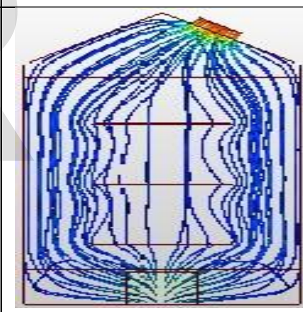
calculated also to be 7.9% (0.08kg weight of moisture removed at an average of 4.65K) while 'Mixed' efficiency was 3.89% (0.036 kg moisture evaporated at an average temperature 6.5^{o}K) within two hours period.

2.3.5 No-load simulation

Tray arrangements	Temperatures	Velocity magnitude	Velocity streamlines
End-end			
End-centre			
Centre			

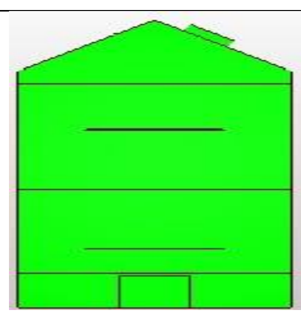
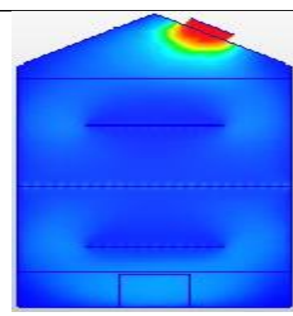
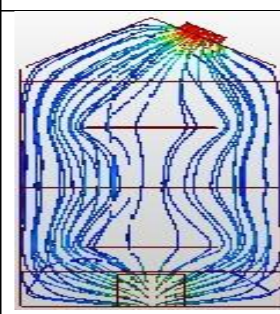
Tray arrangement	Temperature	Velocity magnitude	Velocity streamline
Mixed			

Fig 10. Showing the simulation results of the no-load test for temperatures, velocity magnitude and velocity streamlines.

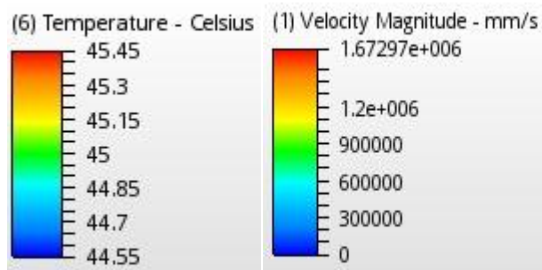


Fig.11 showing the keys used in the simulation of fig.10

The simulation was carried out with the aid of Autodesk simulation CFD, 2016 edition. As seen from fig.10, the temperatures were uniformly distributed in the four dryers at 45 °C. Also, there were more areas of high velocity within the chamber of the ‘end-centre’ arrangements of approximately 600000mm/s followed by the ‘centre’ arrangements, ‘mixed’ arrangement and least velocity portion is observed for the ‘end-end’ arrangement. At 60 percent moisture content, the drying rate increases with increasing air velocity, Fred (2002). Since the moisture content of product being dried is 76%, therefore the tray arrangement with the highest velocity magnitude, in this case, the ‘end-centre’, drying would be fastest.

It is assumed that The product dried in the “end-center” arrangement is exposed to the zig-zag motion of the drying air as seen in the velocity streamline (Flow path of the air), which agrees to the drying rate. Also the drying air experiences little encumbrances in its path as compared to the “end-end” arrangement (with low velocity magnitude areas), which agrees to the theory of Dircy and Weisbach, as both lift forces due to vortices and losses are reduced.

3.0 Conclusion.

In this study, effect of tray arrangements on the performance of a typical solar dryer using cassava (*manihotesculenta*) as the drying product has been investigated. From the results, it has been indicated that cassava drying process occurred in the falling rate period, starting from the initial moisture content of (73.6%, wet) to specific final moisture content depending on the arrangement such as End-Centre (18.96%), centre (19.60%) Mixed (20.07%) and end-end (21.58%). The drying temperatures recorded are highest in the ‘End-Centre’ arrangement as seen by the load experiments and no-load simulations followed by the ‘centre’, ‘Mixed’ and ‘end-end’ arrangement. Similarly, the drying rate of the solar dryer with the ‘End-Centre’ is highest when compared to the other arrangement. The system drying efficiency (average) of the ‘End-Centre’ arrangement is equally highest with about 43.7%, and least for the mixed tray (28.35%).

For the four tray arrangements considered, the experimental and simulation results suggested that the End-Centre arrangement should be considered while designing future dryers for better performance.

A.S.A.E (American society of Agricultural Engineers). (1992). Standard moisture measurement of grain and seeds (S 358.2) 37th Edition

Bassey, M. (1991). Improving the Performance of Indirect Natural Convection Solar Dryers. International Development Research Centre (Canada). Final Report 3-A-90-2069.

Bennamoun, L. and Belhamri, A. (2003). Design and simulation of a solar dryer for agriculture products. *Journal of Food Engineering*. Vol 59 pp: 259-266.

Chandrakumar, B.P and Jiwanlal, L.B. (2013). Development and performance evaluation of mixed-mode solar dryer with forced convection. *International Journal of Energy and Environmental Engineering*, vol.4, pp:23

Cristiana, B.M; André, G.F; Luben, C.G; Sérgio de Morais, Hanriot and Tiago de Oliveira, M (2012). Simulation of the Airflow inside a Hybrid Dryer. *Ijrras.* Brazil. vol 10 (3).

El-Awady, M.N, Mohamed, S.A. El-Sayed A.S. and Hassanain A.A. (1993). Utilization of solar energy for drying processes of agricultural products. *Misr J. Ag. Eng*., 10(4), pp 794-804.

Fred M. L. (2002). The Importance of Air Velocity in Drying, how air speed through the kiln affects lumber seasoning. See more at http://i.sharethis.com.

Fuller,R.J (1978). Solar drying- A technology for sustainable agriculture and food production. Encyclopedia of life support system.

Gallali,Y.M; Abujnah, Y.K; Bannani, F.K (2000). Preservation of fruits and vegetables using solar drier, a comparative study of natural and solar drying; chemical analysis and sensory evaluation of the dried samples (grapes, figs, tomatoes and onions). *Journal of Renewable Energy*. 19: pp; 203-212.

Lawrence, D; Folayan, C. O: Pam, G. Y. (2013). Design, Construction and Performance Evaluation of a Mixed- Mode Solar Dryer. *The International Journal of Engineering and Science.* Vol. 2 (8), pp;08-16.

Misha, S; Mat, S; Rosli, M.A.M; Ruslan, M. H; Sopian, K; Salleh, E. (2013) Simulation of Air Flow Distribution in a Tray Dryer by CFD. *Applied Sciences Journal World*, Vol. 22 (3). pp;29-34.

Pelegrina, A.H., Elustondo, M.P and Urbicain, M.J. (1999). Rotary semi-continuous drier for vegetables: effect of air recycling. *Journal of Food Engineering*, vol. 41 pp: 215-219.

Ramana, M.V (2009). A review of new technologies, models and experimental investigations of solar driers. *Journal of Renewable and Sustainable Energy*. Vol. 13(4), pp;835–844.

Suhaimi, M; Sohif, M; Mohd, H.R; Kamaruzzaman, S; Elias, S (2013). The Prediction of Drying Uniformity in Tray Dryer System using CFD Simulation. *International Journal of Machine Learning and Computing*, Malaysia. Vol. 3 (5). pp;419-423.

Thanvi, K.P. and. Pande, P.C (1987). Development of a low-cost solar agricultural dryer for arid regions of India. *Energy in Agriculture*, 6(1): 35-40.

Thanvi, K.P. and. Pande, P.C (1987). Development of a low-cost solar agricultural dryer for arid regions of India. *Energy in Agriculture*, 6(1): 35-40.

Tiris, C.; Ozbalta, N.; Tiris, M.; Dincer, I. (1994). Experimental Testing of a New Solar Dryer. *International Journal of Energy Research*. Vol. 18, pp;483–491

Ugwu S.N; Ugwuishiwu, B.O ;Ekechukwu, O.V; Njoku, H ;Ani, A.O (2014).Design, construction, and evaluation of a mixed mode solar kiln with black-painted pebble bed for timber seasoning in a tropical setting. *Journal of renewable and sustainable energy, review.* Nigeria. Vol (41). pp;1404-1412.

Vidya, S.R; Meenakshi, R; Siva, R (2013). Design and Fabrication of Efficient Solar Dryer. *International Journal of Engineering Research*, Vol. 3 (6), pp;1445-1458.

Vlachos, N. A.; Karapantsios, T. D.; Balouktsis, A. I.; Chassapis D. (2002). Design and testing of a new solar tray dryer. *Drying technology*, vol. 20(5), pp;1239–1267.

Walid, A., Mostafa, S. and Ahmed, E. (2014). Performance of Solar Dryer Chamber Used for Convective Drying of Sponge-Cotton. *Thermal Science Journal*. Vol. 18, Suppl. 2, pp; 451 – 462.