Energy and exergy analyses of convective drying of green bell pepper in a cabinet tray dryer

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Abstract: This paper presents Computational Fluid Dynamics (CFD) in the drying process of green bell pepper in a cabinet tray dryer using three drying temperatures (50 °C, 55 °C and 60 °C). Engineering simulation software ANSYS 14.5 was used to simulate the model of the dryer in 2 Dimensional (2D). The ANSYS Design Modeler modeled the 2D representation of the dryer and ANSYS ICEM was used for mesh analysis. Thereafter, the derived data from the simulation was used in the calculation of the energy and exergy analyses of the dryer based on the thermal efficiency with respect to the varied drying temperatures in order to assess the performance of the system in terms of energy utilization (EU), energy utilization ratio (EUR), energy efficiency, exergy inflow and outflow, exergy loss and exergetic efficiency. The results indicated that EU and EUR decreased from 0.02401 to 0.01975 J s^{-1} and 0.01441 to 0.00299 respectively as the drying air temperature increased from 50 to 60 °C. Energy efficiency decreased from 0.196% to 0.115%. Exergetic efficiency increased with increase in drying air temperature from 0.9903% to 0.9928%. Model equations that could be used to express the energy and exergy parameters as a function of drying temperature were established from this study.

Keywords: Ansysfluent, CFD, drying temperature, energy, exergy

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1 Introduction

Drying is one of the most important processes in food processing and preservation and has been generally defined as the removal of moisture from a material to a predetermined level (Kumar et al., 2012). This ensures foods are stored for longer periods in ambient temperature than fresh foods due to the fact that microbiological activity have become reduced with minimal physical and chemical changes (Ozgur et al., 2011). Drying can be accomplished by several methods such as hot air, microwave and vacuum drying (Lam et al., 2014). The recent advances in drying technology has brought about increase in the development of computer programs that have the great capacity in evaluating the drying parameters and high efficiency which gives high impact to the cost of energy used during the operation. Besides experimental testing, computational work nowadays is becoming more important due to lower cost and acceptable accuracy with minimum error. It has been

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adjudged that Computational Fluid Dynamics (CFD) software reduces a lot of trial and error on experimental work (Amanlou and Zomorodian, 2010) in that it gives detailed account of the stringent parameters that cannot be observed analytically since it is capable of presenting visualized results. CFD techniques have been integrated to dryer designs in order to solve the complexity in drying phenomenon.

Energy and exergy in drying process deals with the thermodynamic process which is being governed by the first and second laws of thermodynamics. The first law laid emphasis on the quantity of energy in a system without consideration for the energy quality in the system while exergy deals with the second law of thermodynamics, which involves the reversibility and irreversibility of thermal processes as a result of entropy generation (Chemmala and Dinesh, 2014). Energy and exergy analyses in drying processes had drawn interest from researchers where different approaches and methodologies were employed. To mention few, exergy and energy effect was studied in a drying of a native cassava starch (Aviara et al., 2014), and tomato slices in a mixed mode natural convective solar dryer (Arepally et al., 2017). Since there is few information on the energy and exergy analyses of green bell pepper drying in the scientific literatures, the main objective of this study was to investigate the energetics and exergetics of green bell pepper drying in a cabinet tray dryer and establish the variation of the efficiencies with the drying conditions of inlet and outlet temperatures by varying the drying temperature using the obtained data from CFD analysis.

2 Materials and methods

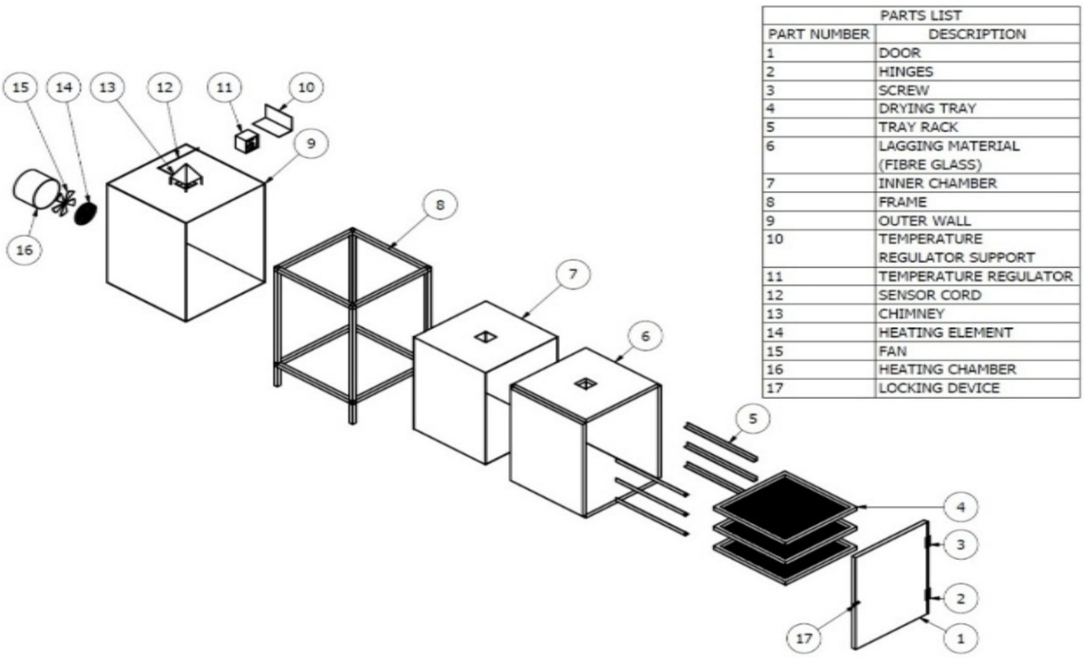


Figure 1 Assembly drawing of the dryer

2.1 Description of the dryer

The cabinet tray dryer was designed and constructed (Figure 1). The dryer has three major sections; these are the drying chamber, the cylindrical heating chamber which houses the heater and the blower (axial fan) and the temperature controlling unit. The drying chamber has a rectangular cross-section, and it is double walled (25 mm thick) insulated with fibre glass to minimize heat loss through the chamber walls to the surroundings. The drying chamber walls were made of 1.5 mm gauge galvanized steel sheet. The external dimension is 600 mm (width) × 600 mm (length) × 750 mm (height), while the internal dimension is 550 mm (width) × 550 mm (length) × 700 mm (height). It has three trays which were stacked with a distance of 150 mm to one another in a vertical arrangement to ensure optimum exposure to drying air and to help improve airflow distribution throughout the drying chamber. Each tray has an area of 530 mm × 530 mm and was made from 20 mm square pipe. It has heating chamber of a cylindrical configuration of length 150 mm and diameter 200 mm which houses the fan and the heating element. Heat is supplied by an electrical heating coil of 1800 W and hot air is blown from the heater housing to the drying chamber with the aid of an axial flow fan. The dryer also consists of a digital temperature regulator for varying the drying temperatures. Also, provision was made for air outlet in order to disallow moisture condensation at the top of the drying chamber; a duct of 80 mm by 80 mm was made at the top of the drying chamber. The green bell peppers were loaded on the drying trays, the cabinet is closed and heated air is blown across.

2.2 Experimental materials and procedures

The green bell pepper was procured from central market in Ilorin, Kwara State, Nigeria. The total weight of the samples in all trays was approximately 1.5 kg. The pepper was sliced to thickness of 3 mm and dried without the seeds. The initial moisture content was determined by oven-drying method to approximately 85% wet basis. All samples passed through osmotic dehydration pretreatment process - in hypertonic salt (NaCl) solutions under the following conditions: osmotic solution concentration (5% (w w^{-1}), 10% (w w^{-1}), 15% (w w^{-1}), 20% (w w^{-1}) and 25% (w w^{-1})) and osmotic process duration of 60 min, 90 min, 120 min, 150 min and 180 min. Osmotic dehydration was done as means of improving the sensory (colour, flavour, odour and texture) and nutritional qualities (vitamins, minerals and others) of the products after drying. All samples were arranged in the dryer after the osmotic dehydration pretreatment process.

2.3 CFD simulation setup

ANSYS FLUENT CFD solver was used overtime since it is the best in analyzing CFD simulation (Erguvan and MacPhee, 2018; Kumar and Ranjan, 2018). The 2-dimensional analysis of the flow pattern in the dryer in ANSYS FLUENT solver is as follows: the geometry of the dryer was modeled in ANSYS Design Modeler to depict the dryer in 2-dimensions; ANSYS ICEM was used for mesh analysis. The fluid flow inside the dryer was defined by using a 2D solver with steady state condition, mass conservation, momentum equations and energy equations were solved iteratively using the commercial CFD code ANSYS Fluent. The code uses a pressure-based solver with SIMPLE method for velocity-pressure coupling. The relaxation factors were 0.3 for pressure, 0.7 for momentum, 1 for density, 1 for body force and 0.8 for turbulent kinetic energy. In the advanced solution control, Gauss- Seidel smoother type was used. The velocity and temperature fields were discretized with a second order upwind scheme, whereas the pressure field was discretized with a PRESTO (Pressure discretization schemes) Scheme. The convergence criteria for residuals of continuity and momentum equations were 10^{-4} and 10^{-6} for energy and radiation equations standard $k-\varepsilon$ model with enhanced wall temperature treatment. The initialization of all the boundary conditions was done in order for the software to solve the numerical equations. The number of iterations and the reporting levels were set to 600 and 10 respectively in which the result converged at the 470th iteration.

In this study, a comprehensive thermodynamic investigation through energy and exergy analyses was conducted to assess the performance of a cabinet tray dryer during the drying process of a green bell pepper and study how its operating conditions and efficiency can be improved further by varying the drying air temperature. Some of the data utilized in the calculations were taken from computer generated results during the CFD simulation carried out with ANSYS FLUENT 14.5 by varying the drying air temperature in order to converse materials and energy that would be needed to run the experiments in replicates.

2.4 Energy usage by the dryer

The detailed account of the behaviour of the drying air and the change in energy with respect to the components in the dryer are being governed by some thermodynamics parameters. These parameters are described using Equations 1-5;

The conservation of mass for dry air

$$\sum \dot{m}_i = \sum \dot{m}_o \tag{1}$$

The conservation of mass for humidity is given by:

$$\sum(\dot{m}_i\omega_i + \dot{m}_z) = \sum \dot{m}_o\omega_o \quad (2)$$

The conservation of energy

$$\dot{Q} - \dot{W} = \sum \dot{m}_o\left(h_0 + \frac{V_o^2}{2}\right) - \sum \dot{m}_i\left(h_i + \frac{V_i^2}{2}\right) \quad (3)$$

where, $\dot{m}_i$ and $\dot{m}_o$ are the mass flow rate at the inlet and outlet respectively, kg s^{-1}; $\dot{m}_z$ is the mass flow rate of moisture of the product, kg s^{-1}; ω_i and ω_o are the inflow and outflow specific humidity respectively, g kg^{-1}; $\dot{Q}$ is heat energy inflow, kJ s^{-1}; $\dot{W}$is rate of mechanical work output, J s^{-1}; h_i and h_o are the enthalpies of air at the dryer inlet and outlet temperature, J kg^{-1}; V_i and V_o are air velocities at dryer inlet and outlet respectively, m s^{-1}.

Since there is no resultant motion in the drying process as shown in Equation 3; the momentum components $\frac{V_o^2}{2}$ and $\frac{V_i^2}{2}$ were eliminated and is reduced to the Equation 4.

$$\dot{Q} = \sum \dot{m}_o h_0 - \sum \dot{m}_i h_i \quad (4)$$

Considering the mass flow rate of the air to be uniform (i.e. $\dot{m}_a = \dot{m}_i = \dot{m}_o$), Equation 4 is reduced to Equation 5

$$\dot{Q} = \dot{m}_a(h_0 - h_i) \quad (5)$$

where, m_a is the mass of air, kg s^{-1}.

2.5 Thermodynamic parameters

Some thermodynamic parameters such as relative and specific humidities, enthalpy of air was considered as shown in Equations 6 - 8.

2.5.1 Relative humidity

It is defined as the ratio between the partial vapour pressure of water in the mixture at a given temperature (P_v,T), and the saturated vapour pressure at the same temperature (P_{sat},T):

$$\emptyset = \frac{P_{v@T}}{P_{sat@T}} \times 100\ \% \quad (6)$$

where, $\emptyset$ is the relative humidity, %; $P_{v@T}$ vapour pressure at time - T, Pa; and $P_{sat@T}$ saturated vapour pressure at time – T, Pa.

2.5.2 Specific humidity

This is defined as the water vapour mass per drying air unit mass.

$$w = \frac{m_v}{m_a} = 0.622\frac{P_{v@T}}{P - P_{v@T}} \quad (7)$$

where, w is the specific humidity, kg kg^{-1}dry air; m_v is the mass of vapour, kg s^{-1}; m_a - is the mass of air, kg s^{-1}; $P_{v@T}$ - is the vapour pressure at temperature T; Pa; and P is the total pressure, Pa.

2.5.3 Enthalpy of the drying air

The enthalpy of the drying air is given in the Equation 8:

$$h_{da} = c_{pda}T_{da} + wh_{sat@T} \quad (8)$$

where, h_{da} is the enthalpy of the drying air, kJ kg^{-1} c_{pda} is the specific heat of drying air, kJ kg^{-1}; T_{da} is the drying air temperature; w is the specific humidity, kg kg^{-1} Dry air; and $h_{sat@T}$ is the enthalpy of the saturated vapour kJ kg^{-1}. The mass-energy model for the drying experiment is shown in Figure 2.

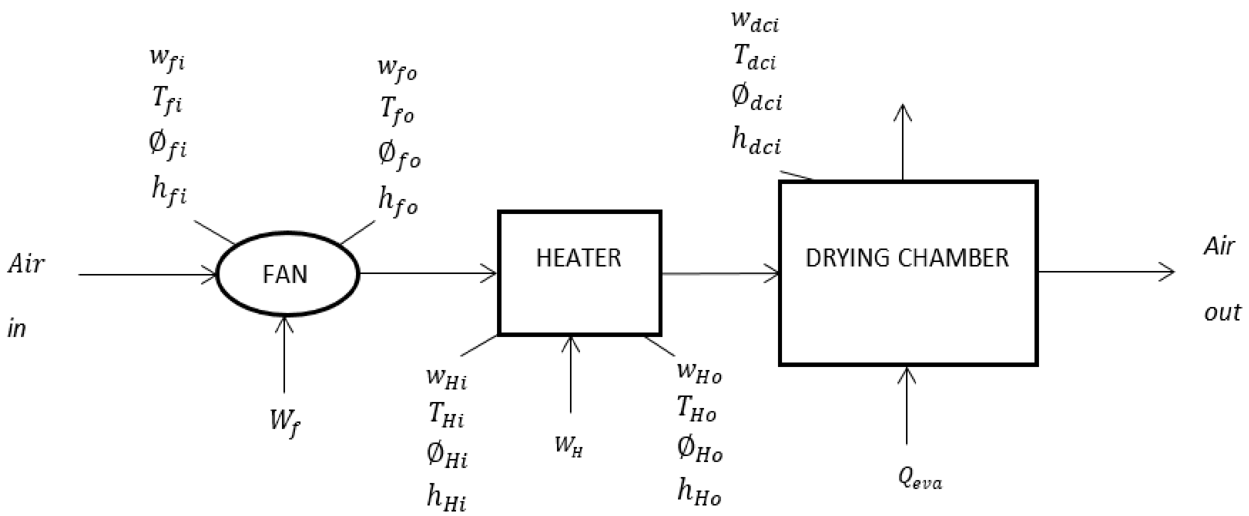


Figure 2 The mass-energy model for the drying experiment in respect to the components

where, w is the specific humidity of dry air, kg kg^{-1}; T is the air temperature, K; $\emptyset$ is the relative humidity,%; h is the enthalpy of air, kJ kg^{-1}; fi and fo are the air conditions at the fan inlet and outlet Hi and Ho are the air conditions at the inlet and outlet of the heater, Q_{eva} is the thermal power obtained from evaporation, kJ s^{-1}; Q_{loss} is the thermal power loss, kJ s^{-1}.

2.6 Fan

Fan outlet conditions was determined using Equation 9

$$\dot{Q} - \dot{W}_f = \sum \dot{m}_{da}\left[(h_{fo} - h_{fi}) + \left(\frac{V_{fo}{}^2 - V_{fi}{}^2}{2\times1000}\right)\right] \quad (9)$$

$\dot{Q} = 0$ since there is no heat transfer and also since we are considering only the outlet conditions, $V_{fi} = 0$

$$h_{fo} = \left[\left(\dot{W}_f - \frac{V_{fo}{}^2}{2\times1000}\right)\left(\frac{1}{\dot{m}_{da}}\right)\right] + h_{fi} \quad (10)$$

where, h_{fi} and h_{fo} are the enthalpies of air at the inlet and outlet of the fan, kJ kg^{-1}; V_{fi} and V_{fo} are the air velocities at the inlet and outlet of the fan, m s^{-1}; $\dot{W}_f$ is the power of the fan, kJ kg^{-1}; $\dot{m}_{da}$ is the mass flow rate of dry air, kJ kg^{-1}.

2.7 Heater inlet and outlet conditions

The operating conditions for the heater was determined using Equation 11.

$$Q_{usable} = \dot{m}_{da}c_{pda}(T_{Hi} - T_{Ho}) \quad (11)$$

where, Q_{usable} is the useable heat, kJ; $\dot{m}_{da}$ is the mass of dry air, kg; c_{pda} is the specific heat of drying air, kJ kg K^{-1}.

2.8 Energy utilization (EU) and energy utilization ratio (EUR)

Energy utilization (EU) and energy utilization ratio (EUR) was determined by applying the first law of thermodynamics using Equations 12 and 13:

$$EU = \dot{m}_a(h_0 - h_i) \quad (12)$$

The EUR during the drying process was given as

$$EUR_{dc} = \frac{\dot{m}_a(h_{dci\,@\,T} - h_{dco\,@\,T})}{\dot{m}_a(h_{dci\,@\,T} - h_{a\infty})} \quad (13)$$

where, EUR_{dc} is the EUR for the drying chamber; m_{da} is the mass of dry air, kg; $h_{dci\,@\,T}$ is the enthalpy of air at the inlet of the drying chamber at temperature T, kJ kg^{-1}; $h_{dco\,@\,T}$ is the enthalpy of air at the outlet of the drying chamber at temperature T, kJ kg^{-1}; $h_{a\infty}$ is the enthalpy of air at ambient temperature T, kJ kg^{-1}.

2.9 Energy efficiency

This was evaluated as the ratio of the energy used and the input energy using Equation 14.

$$\eta_E = \frac{E_i - E_o}{E_i} = \frac{\dot{m}_a(h_{dci\,@\,T} - h_{dco\,@\,T})}{\dot{m}_a h_{dci\,@\,T}} \times 100\ \% \quad (14)$$

where, η_E is the energy efficiency, %; E_i and E_o are the input and output energies respectively, kJ s^{-1}.

2.10 Exergy analysis

In the scope of the second law analysis of thermodynamics, total exergy of inflow, outflow and losses of the drying chamber were estimated. The basic procedure for exergy analysis of the chamber is to determine the exergy values at steady-state points and the reason of exergy variation for the process. The exergy values were calculated by using the characteristics of the working medium from first law energy balance. For this purpose, mathematical formulations were used to carry out the exergy balance (Ahern, 1980) following the reference conditions for the system (Table 1).

The exergy was determined using Equation 15

$$\dot{Ex} = \dot{m}_{da}c_{pda}\left[(T - T_\infty) - T_\infty\, In\, \frac{T}{T_\infty}\right] \quad (15)$$

The inlet and outlet exergies were determined according to the drying chamber inlet and outlet temperatures using Equations 16 and 17.

$$Ex_{dci} = c_{pda}\left[(T_{dci} - T_a) - T_a \ln\frac{T_{dci}}{T_a}\right] \quad (16)$$

$$Ex_{dco} = c_{pda}\left[(T_{dco} - T_a) - T_a \ln\frac{T_{dco}}{T_a}\right] \quad (17)$$

where, Ex_{dci} and Ex_{dco} are the exergy at the inlet and outlet of the drying chamber respectively, kJ s^{-1}.

2.11 Exergy efficiency

Exergy efficiency is defined as the ratio of the exergy use in the drying of the product exergy to energy inflow from the drying chamber. However, it can be explained to be the ratio of the exergy outflow to the exergy inflow for the drying chamber (Akbulut and Durmuş, 2010). Thus, the general form of the exergetic efficiency was determined using Equations 18 and 19:

$$Ex_{loss} = Ex_{dci} - Ex_{dco} \quad (18)$$

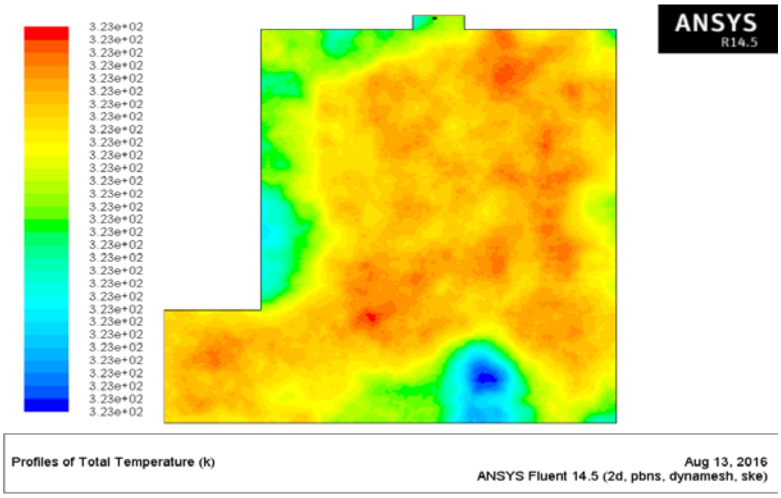
$$\eta_{Ex} = \frac{Ex_{dco}}{Ex_{dci}} \quad (19)$$

where, Ex_{dci} and Ex_{dco} are the exergy at the drying chamber inlet and outlet respectively, kJ s^{-1}; c_{pa} is the specific heat of the air, kJ kg^{-1}; T_{dci} and T_{dco} are the temperatures at the air inlet and outlet of the drying chamber respectively; T_a is the temperature of the environment; and, η_{Ex} is the exergy loss,%.

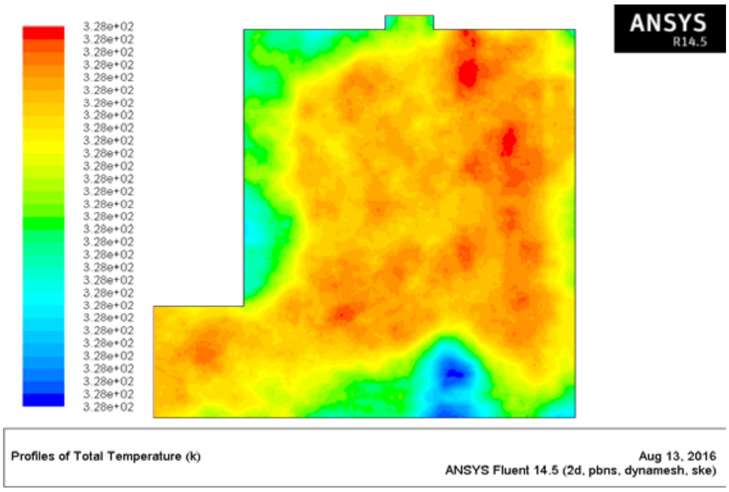
3 Results and discussion

3.1 Temperature profile

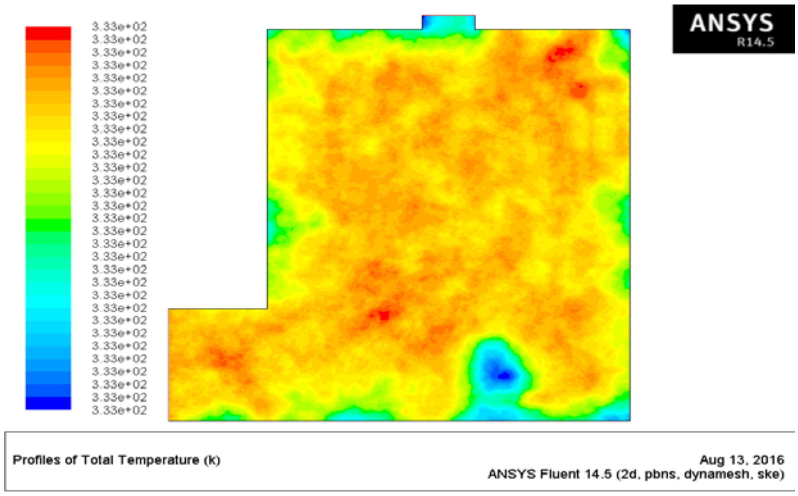
From the visual representation of the temperature field in the dryer, it could be observed from the profile cut plots that as the temperature increases, the uniformity of temperature also increases; which is responsible for the increase in the exergy of the dryer as shown in Figure 3(a, b, c).



(a) 50 °C



(b) 55 °C



(c) 60 °C

Figure 3 CFD post processing of temperature distribution at different drying air temperature.

Table 1 Some of the parameters used for the energy and exergy analysis

Parameters	Symbols	Values	Units
Ambient Temperature	T_a	273	K
Total pressure	P_a	101.325	kPa
Specific heat capacity of air	c_{pda}	1.005	kJ kg^{-1}
Inlet air velocity	v	3.02	m s^{-1}
Enthalpy of the air	$h_{a\infty}$	21.612165	kJ kg^{-1}
Specific humidity of the air	w	0.002008	kg kg^{-1} Dry air
Mass flow rate	$\dot{m}_{da}$	0.490001	kg s^{-1}

The inlet and outlet temperatures calculated from the ANSYS FLUENT solver were used for the exergy analysis as shown in Table 2.

Table 2 Obtained data from the CFD simulation and used for the energy and exergy analysis

Drying temperature (˚C)	$T_{dci@T}$ (K)	$T_{dco@T}$ (K)	$h_{dci@T}$ (kJ kg^{-1})	$h_{dco@T}$ (kJ kg^{-1})
50	323.1500	322.9992	25.0137	25.0627
55	328.1500	327.9991	30.0457	30.0968
60	333.1500	332.9991	35.0804	35.1207

3.2 Energy efficiency, EU and EUR

The energy efficiency of green bell pepper drying in a cabinet dryer decreased from 0.196% to 0.115% as the drying air temperature increased from 50 ˚C to 60 ˚C as shown in Figure 4.

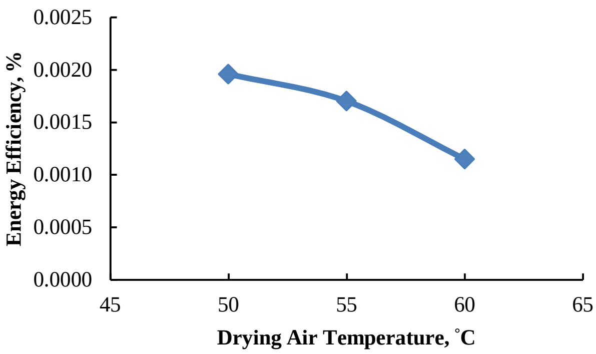


Figure 4 Variation of the energy efficiency with drying air temperature

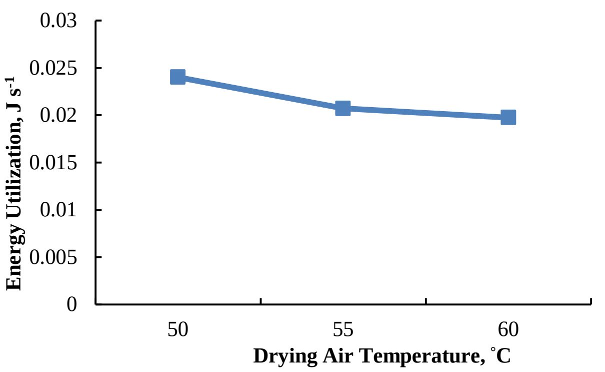


Figure 5 Variation of the EU with drying air temperature

The EU decreased from 0.02401 to 0.01975 J s^{-1} as the temperature increased from 50 ˚C to 60 ˚C as shown in Figure 5. Also, EUR was varied with the drying air temperature during the simulation process of green bell pepper drying as shown in Figure 6. It can be deduced from the plotted graph that the EUR decreased from 0.01441 to 0.0029 as the temperature of the drying air increased from 50 ˚C to 60 ˚C.

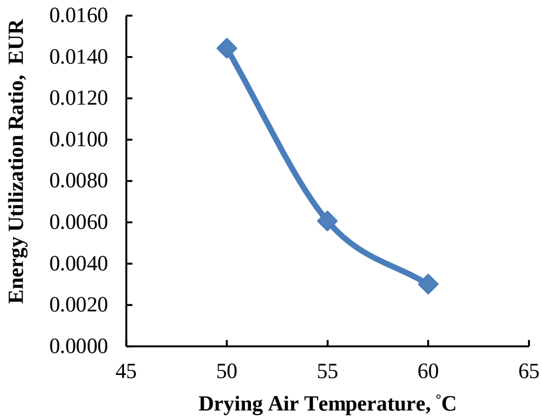


Figure 6 EUR at different drying air temperature

The trend of EUR is advantageous because the energy used was minimal. The relationship that exists between EUR and drying air temperature as discovered in this work is a second order polynomial and can be represented in Equation 21:

$$EUR = 0.0001T^2 - 0.0128T + 0.3881,\ R^2 = 0.9989 \quad (21)$$

3.3 Relationship between the exergetic efficiency with drying temperature

The variations of exergetic efficiency of the cabinet dryer with drying air temperature is shown in Figure 7. It showed that exergetic efficiency increased with increase in drying air temperature.

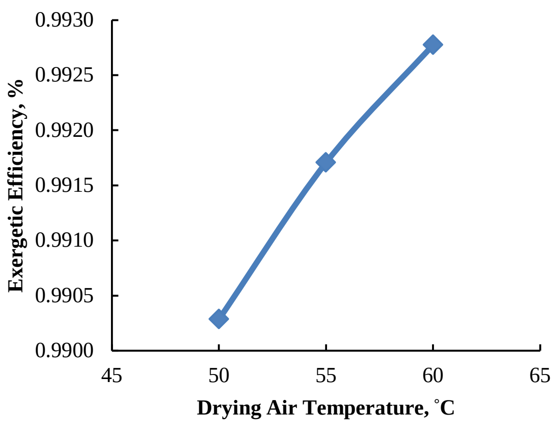


Figure 7 Variation of exergetic efficiency with drying temperature

With respect to the temperature range, the exergetic efficiency varies directly to the behavior of the energy efficiency. The relationship existing between exergetic efficiency and drying air temperature was found to be linear which is expressed in Equation 22:

$$\eta_{Ex} = 0.0002T + 0.9779, \quad R^2 = 0.9934 \qquad (22)$$

where, η_{Ex} is the exergetic efficiency,%; T is the dry air temperature, K; and R^2 is the coefficient of determination

4 Conclusions

Based on the data derived from CFD simulation in computing the energy and exergy analysis, it can be said that ANSYS FLUENT solver is capable of analysing the energy and exergy accounting of a typical drying process using thermal analysis. With these set of results, there is a linear relationship between the EU and the drying air temperature and the best trend between EUR and drying air temperature was found to be polynomial of second order. Also, ANSYS CFD software can be used to account for the energy and exergy of a drying process to ease the analytical evaluation. Considering the overall results, drying air temperature is directly proportional to exergy inflow, exergy outflow and exergy loss since an increase in the drying air temperature brought about increase in the exergy analysis.

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