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Modeling of Drying Process and Energy Consumption of Onion (*Ex-gidankwano Spp.*) Slices in a Hybrid Crop Dryer

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ABSTRACT: *High consumption of energy in the drying industry has prompted extensive research regarding various aspects of crop drying energy consumption. Specific energy consumption, moisture ratio and thermal efficiency in drying of fresh ex-gidankwano onions variety were determined using a hybrid electric-gas dryer at air temperatures of 50, 60 and 70^{o}C, and at air velocities of 0.5, 1.0 and 1.5m/s. Thin layer models were selected by carrying out statistical analyses to fit the drying rate data to themodels. The Page drying model was found more suitable to describe the drying behaviour of onions slices based on its highest average R^2-values of 0.99 and lowest average RMSE of 3.91for all temperatures and air velocitiesirrespective of the heat source. Records of drying rates and energy consumption were made using electronic weighing balances and the Arduino microprocessor respectively. Results obtained show that the specific energy consumption decreases with increase in air temperature but increases with increase in air velocity in both heat sources. The minimum and maximum specific energies for the electric and gas heat sources were 48.73MJ/kg and 90.21MJ/kg, and 36.83MJ/kg and64.65MJ/kg of moisture evaporated respectively.The thermal efficiency of the heat sources increased proportionally with increasing drying air temperature and decreased with increase in drying air velocity with maximum values of 54.8% and 68.2% for the electric and gas heaters respectively. The gas heat source performed more efficiently in terms of energy consumption and thermal efficiency at different temperatures and air velocities.*

Keywords:*Drying, electrical heater, modeling, energy consumption, hybrid dryer.*

I. INTRODUCTION

Various governments in Nigeria have been making efforts through the adoption of appropriate agricultural policies to achieve the goal of food security in the country. These efforts have been hampered by the inability to process farm produce to increase their shelf life in order to make food available all year round and enhance the economic status of the farmer. Farmers however, produce food in excess of demand for fresh produce by local markets during the peak harvest periods. These food products deteriorate within few days of harvest due to high moisture content of most crops at harvest, inadequate or lack of processing and storage facilities, mechanical and pathogenical damage etc. (Khouzam, 2009; Mu'azu*et al*., 2012; Nwakuba *et al.*, 2016); hence to dry fresh produce at the safest temperatures at minimum energy cost for proper storage of the surplus produce during the off-peak season. The high moisture content of these produce makes them unsafe for keeping over long periods of time, resulting in agricultural product losses.

According to Bennamoun and Belhamri (2003), storage of fresh produce is one of the most important stages of the production process, as it is during this stage that significant quantities of the foodstuff may undergo deterioration. As such, preservation is the key in reducing food loss. Drying has been a major means of preserving agricultural food products especially in developing countries like Nigeria. It is regarded as one of the oldest methods of food preservation processes available to mankind since prehistoric times, and it represents a very important aspect of food processing. Longer shelf-life, product diversity and substantial volume reduction are the reasons for the popularity of dried agricultural produce, including improvements in product quality, preservation of nutritive values, and process applications (Antwi, 2007). Such improvements could lead to an increase in the current acceptance of dehydrated foods in the market (EL-Mesery and Mwithiga, 2012). Drying is defined as the removal of moisture from a product by heat that yields a product at an acceptable moisture level that prevents deterioration within a certain period of time for marketing, safe storage, processing, or transportation (Ekechukwu and Norton, 1999; Nwakuba *et al.*, 2016). It encapsulates the dual process of heat transfer to the product from a heating source, and mass transfer of moisture from the interior of the product to its surface and from the product surface to the surrounding air.

Onion (*Allium cepa L.*) is one of the main crops under Allium family, cultivated in the tropical countries such as it is done in the Northern Nigeria. It has red, white and gold (yellow) colours as common varieties of its species (El-Mesery and Mwithiga, 2012). Onions farmers differentiate them as freshly consumed onions and those for industrial transformation based on the time of planting and method, harvesting time and bulb size among other characteristics (Bonaccorsi*et al.,* 2008; Gouda *et al.,* 2014). Apart from its characteristic smell and flavour (pungency) to food, onion can be used in a wide variety of ways. Its biological compounds and medical functions are mainly due to their high organo-sulphur compounds (Corzo-Martinez *et al.,* 2007). The common preservation technique followed for onion worldwide are mostly sun or solar drying (Stavric, 1997) and hot air drying (Sarsavadia, 2007). However, these methods demand longer drying time, higher processing temperature, affected by daily fluctuation of weather and thereby making it difficult to maintain the product moisture content and quality properly because of air-borne dirt and dust (Sharma and Nath, 1991). Fresh onions usually have an initial moisture content of about 7.3 to 5.99 g of water/g of dry matter, which is equivalent to a moisture content of 85.7 to 88.0% in wet basis (Sharma *et al.,* 2005). Kumar *et al.* (2006) reported an initial moisture content of 85 to 90% (wb). Other researchers such as Sawhney*et al.* (1999) and Sarsavadia (2007) reported that onions are generally dried from an initial moisture content of about 86 to 7% (wb) or less for efficient storage and processing.

In order to analyze the drying behaviour of an agricultural product, it is essential to study its drying kinetics, which in turn has led to the study of technological variables involved in the drying process. According to El-Mesery and Mwithiga (2012), for a realistic techno-economic evaluation of a dryer installation, certain performance factors such as energy efficiency, thermal efficiency, adiabatic thermal efficiency, specific heat energy consumption, specific electric energy consumption, specific volume of dryer and specific fuel consumption are often used (Pakowski and Mujumdar, 1995; Arinze*et al.,* 1996).). Modelling of the thin-layer drying process is also of paramount importance in the design and optimization of dryers (Brook and Bakker-Arkema, 1978; Bertin and Blazquez, 1986; Vagenas and Marinos-Kouris, 1991). Thin layer drying however, is a common method widely used for agricultural products to prolong their shelf life (Hossain *et al*., 2009). It is a layer of material exposed fully to an airstream during drying. There is a wide range of thin layer drying models, which have found wide application because of their ease of use and often describe drying phenomena in a unified manner regardless of the control mechanism. Several mathematical models such as the Midilli*et al*., Page model, Newton model, Fick's diffusion model, Logarithmic model, Henderson and Pabis model, etc. have been used to describe the thin layer drying process of agricultural products. Most researchers describe their thin layer drying experiments with suitable mathematical models which can be theoretical, semi-empirical or purely empirical. Thin layer drying equations are used to estimate the drying time of several products and also to generalize drying curves. A considerable amount of data has been reported in the literature regarding the thin layer drying models of various agricultural products.

Similarly, crops consume varying quantities of energy for optimum drying due to their different biological characteristics, since crop drying energy consumption has been identified to be dependent upon its initial and desired moisture contents, drying air temperature, relative humidity, dryer design and air velocity (Nwakuba *et al.,* 2016). High moisture-laden crops such as onion, tomatoes, sweet potato, banana, okra, pineapples, pepper, carrots, garlic, cabbage, etc. require high heat energy for safe drying (El-Mesery and Mwithiga, 2012). Many of these agricultural products require relatively long drying times (ranging between 5 minutes to73 hours) with optimum drying air temperatures ranging between 50 - 85°C (Tiwari, 2012; Ehiem *et al*., 2009), which is above the temperature range in which Photo Voltaic Cells (PVC) can be collected most efficiently and cheaply for solar energy dryers. Due to this high energy requirement, the overhead drying cost of most crops is usually high resulting in high price of dried food products (Antwi, 2007). The objective of this study was to compare the performance thermal efficiency of the electrical and gas heaters on a sliced local onion variety (Kano species), and to estimate the energy consumption of the drying process for each of the two heat sources of the dryer.

II. MATERIALS AND METHODS

2.1 Dryer description

The choice of heat source for drying of produce is a function of many factors including the initial moisture content, product type, availability of energy to power the heat source, and the required drying time for the product before deterioration sets in. The drying experiments were conducted with both the electrical and gas-fired heat sources of the hybrid dryer as shown in Figure 1. The hybrid dryer consists of four major integral components: suction and expeller fans that provide the required drying air velocity; heating units (resistance wire and butane gas); the drying chamber having two layers of drying racks made of wire mesh on which the sliced crops are placed for drying; and the control unit. Other components of the dryer system include: gas cylinder (butane gas), DC battery (75Amps, 12V), liquid crystal display (LCD), temperature and relative humidity sensors (LM-35 transducers), keypad, weighing balance, a-1500W heating element, frame support, and rollers.

The heart of the dryer comprises an Arduino microprocessor which controls the overall operation of the system and automates tasks such as temperature and humidity control, electriccurrent flowing through the entire system as well as automatically switching between the heat sources when there is sudden outage of any of the heat sources. The system also contains a heating element powered by AC mains powerwhich when detected, the control unit automatically switches on the heating elementand continuously measures the temperature and humidity of the drying chamber and switches the heater off or on accordingly. When AC mains is no longer detected, the system sounds an alarm prompting the user to switch on the gas. Transducers (for recording both temperature and relative humidity) were placed at four strategic points in the dryer namely: chimney, two drying racks, and inlet fan, where measurements were taken automatically by the microprocessor unit and displayed on the LCDof the control unit. Different drying temperatures and air speeds can be selected by the use of a 4 x 4 matrix keypad for input and LCD for displaying the current state of the system. The energy consumption from the accumulator and AC were measured and recorded by the control unit. When the control unit is connected to the computer, a specialized software, SCADA (supervisory control and data acquisition) was used to log the readings at 30 minutes interval and the results, stored in a database for immediate or future analyses. A universal serial board (USB) cable was connected to the Arduino microprocessor to transfer temporarily stored data in the Arduino to a micro-computer for further analysis, thus the system is fully automated.

2.2 Experimental procedure

Fresh ex-gidankwano, a red skinned local variety of onions were purchased from a local market and kept in an open-airenvironment where the experiment was carried out. Equal sized product samples were selected, hand-peeled and cut into slices (1cm) using a sharp stainless steel knife, with the direction of cutting perpendicular to the vertical axis of the onions bulb. The slicedsamples were accurately made with the aid of a digital vernier caliper and were evenly spread on the drying tray to cover the entire tray area, hence thin-layer drying.In each selected heat source, three different preset air temperatures of 50, 60 and 70^{o}C at three varying air velocities (0.5, 1.0 and 1.5m/s) were used and inputted through the use of the keypad panel.A high and low temperature threshold were inputted as well as the air flow velocity with the use of a 4 x 4 matrix keypad to determine the temperature at which the drying chamber must be maintained. This lasted for a maximum time of 25 minutes (depending on the temperature and air flow velocity). When the optimum temperature was attained, the Arduino microprocessor automatically switches off the heating element (for the electrical system) or the gas solenoid valve, and triggered off an alarm signal and turns the heat source on again when the drying chamber temperature falls one degree below the preset temperature (± 0.1^{O}C accuracy), thereby establishing a steady-state condition in the drying chamber before the freshly cut sliced onions samples weighing approximately 300g were spread on the tray in a single layer and inserted into the drying chamber.Drying runs at each experimental setting of air temperature, and air flow velocity were repeated three times, and the average values recorded. Since there were three temperature and three air velocity settings for the two heat sources, a total of 18 runs were obtained. The weight loss of the samples were taken in 30 minutes interval until the final desired moisture content of 7% wet basis (wb) was achieved (Sarsavadia, 2007; Antwi, 2007; El-Mesery and Mwithiga, 2012). For every 10 minutes, the Arduino microprocessor recordsthe amount of current flowing into the electrical heater and fans with which a constant known value of 220V was used to determine the energy consumption, whilstfor the gas, the difference in mass of the gas cylinder before and after every batch of drying was taken and converted to energy consumed (kJ).

2.3 Energy consumption

The energy consumed by the electrical heater (EH) was indirectly determinedby the Arduino microprocessor in the control unit.This measuring device was connected in such that it could measure all the electric current flowing into the heating element. Having known the supply voltage and time of flow, the energy is thus calculated using Equation (1).

$$\mathbf{E=IVT} \quad 1$$

Where: I = current (Amps.); V = voltage (V); T = time (seconds).

The total energy (kJ) consumed per batch of drying operationfor each treatment combination was determined by summing all the current flowing into the heating element and the fan as recorded by the Arduino control unit until the drying samplesreach a moisture content of 7% (wb) and applying equation (1). The energy consumption in using the butane gas was determined by weighing the gas cylinder using a balance that had a precision of ± 0.1 g. The mass of the gas cylinder was measured just before the samples were inserted into the drying chamber, and again immediately after terminating the drying process. The difference in mass was then converted into gas consumed energy (Q_G)by the use of Equation (2).

$$Q_G = M_G H \quad (2)$$

Where: M_G = mass of consumed butane gas (kg); H = lower heating value of butane gas = 45600 kJ/kg (Demirbas, 2006). The specific energy consumption used in evaporating sample moisture by both heat sources is given by Equation (3) (Jindarat*et al.*, 2011).

$$SEC = \frac{\text{Total electrical or gas energy}}{\text{Mass of water removed during drying}} \quad (3)$$

2.4 Thermal efficiency

Thermal efficiency of a heat source is the ratio of the actual heat used to effect drying to the total heat supplied by the heat source. Water at 0^oC has latent of heat vaporization of about 2500KJ/kg when evaporating from an open surface under atmospheric pressure (El-Mesery and Mwithiga, 2012). The energy consumption for moisture evaporation of agricultural products during drying is usually higher than that for open-surface due to the intra-particle resistance to moisture migration from food matrix (Nwakuba *et al.*, 2016). Therefore, the latent heat of vaporization of water at temperatures of 50, 60 and 70^oC was taken to be 2382.7, 2358.5 and 2333.8kJ/kg respectively (Jindal and Reyes, 1987; El-Mesery and Mwithiga, 2012; Ekpunobi*et al.*, 2014).The energy consumed in evaporating moisture from a given batch of sample is given by Equation (4).

$$Q_m = M_m L \quad (4)$$

Where: Q_m = total energy consumed in evaporating product moisture (kJ); M_m = mass of moisture removed during drying (kg); L = latent heat of vaporization of water at each drying air temperature (kJ/kg). The thermal efficiency of the dryer (T_e) is therefore expressed as Equations (5) and (6).

$$T_e = \frac{\text{Actual energy used in evaporating moisture}}{\text{Energy consumed}} \quad (5)$$

$$T_e = \left(\frac{Q_m}{Q_G}\right) * 100 \quad (6)$$

Where:Q_m and Q_G = actual energy used and energy consumed (kJ) respectively.

2.5 Modelling of the drying curves

Thin-layer modeling of the drying behavior is important for investigation of the drying characteristics of onion slices. For mathematical modeling, the thin-layer drying equations in Table 1 were tested in order to select the best model for describing the drying behavior of onion slices during drying (Ayensu, 1997; Ozdemir and Davis, 1999; Hossain *et al.*, 2009; Midilli*et al.*, 2002). The moisture ratio (MR) of onion slices during drying was calculated using Equation (7):

$$MR = \frac{(M - M_e)}{(M_o - M_e)} \quad (7)$$

Where: M = moisture content of the sample at any time (%wb); M_o = initial moisture content and M_e is the equilibrium moisture content (%wb). Since the values ofM_e are relatively insignificant when compared with M or M_o,it can therefore be set to zero for air drying temperatures such as those used in this study (Kiranoudis*et al.*, 1992; Bennamoun and Belhamri, 2003; Akgun and Doymaz, 2005; Mitra*et al.*, 2012). Thus, the moisture ratio can be simplified to Equation (8) as:

$$MR = \frac{M}{M_o} \quad (8)$$

However, the suitability (goodness of fit) of the tested models to the experimental data was evaluated and compared using the following statistical parameters such as: coefficient of determination (R^2) and root mean square error(RMSE) (Kiranoudis*et al.*, 1992; El-Mesery and Mwithiga, 2012; Darvishi, 2012; Kaveh and Chayjan, 2014) as given in Equations (9) and (10) respectively.

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp} - MR_{pred}\right)^2}{\sqrt{\left[\sum_{i=1}^{N}\left(MR_{exp} - MR_{pred}\right)^2\right] * \left[\sum_{i=1}^{N}\left(MR_{exp} - MR_{pred}\right)^2\right]}} \quad 9$$

$$RMSE = \frac{\sqrt{\sum_{i=1}^{N}\left(MR_{exp} - MR_{pred}\right)^2}}{N-1} \quad 10$$

Where: $MR_{exp,}$ = experimental moisture ratio determined in the measurements, MR_{pred} = predicted moisture ratio for this measurement, and N = number of observations.

The best model describing the drying kinetics of the sample was chosen based on the higher value of R^2 and lower values of RMSE, and the better was the goodness of fit of the model (Babalis and Belessiotis, 2004;Ertekin and Yaldiz, 2004; El-Mesery and Mwithiga, 2012).

III. RESULTS AND DISCUSSION

3.1 Drying kinetics of onion slices (*ex-gidankwano spp*.)

The drying curve of the *ex-gidankwano spp*. slices dried with either the electric and gas heat sources are as presented in Figures 2 and 3 respectively. Increasing the drying air temperature resulted in an increase in the drying rate of the sample slices, and this was true for both heat sources.Increasing the air velocity at constant air temperature resulted in a corresponding decrease in the drying time for both the electric and gas heaters. The time required to reduce the moisture content to 7%(w.b)using the electrical heater when the air velocity was set at 0.5 m/s and when drying at air temperatures of 50, 60 and 70°C were 425, 400 and 320 minutes, respectively. For the electrical dryer, these drying times decreased to 350, 310 and 200 minutes, and to 260, 235, and 155 minutes, when the air velocity was increased to 1.0 and 1.5 m/s respectively. The drying times for the gas heater were close to those of the electrical heater for each setting of air temperature and velocity. These trends are similar to theresult findings ofDemir*et al.*(2004);Menges and Ertekin (2005); Kumar *et al.* (2006); and El-Mesery and Mwithiga (2012).

3.2 Modeling of drying curves

Statistical analyses were carried out to fit the drying rate data to the four selected drying models presented in Table 1. The results of the analyses are presented in Tables 2 and 3 for the electric and gas heaters respectively. From the tables, all the selected drying models gave consistently high coefficient of determination (R^2), which means that all the models could describe the drying behavior of onion slicesamples well. However, among the four models, the Page model had the highest average R^2-values and lowest average RMSE values for all temperatures and air velocities. Other researchers like Wang (2002), Kumar *et al.* (2006), El-Mesery and Mwithiga (2012) amongst others have found the Page model more suitable to describe the drying behavior of onion slices irrespective of the heat source and sample species.

3.3 Specific energy consumption

Specific energy consumption (SEC) is referred to as the amount of heat required to eliminate 1kg of water (moisture) from a wet agricultural product during heated-air drying. The SEC for drying of sliced onion samples using the electric and gas heaters at different air temperatures and air velocities are illustrated in Figure 4. The SEC decreases with increase in air temperature but increases with increase in air velocity in both heat sources. With the electric heater, the temperature of the drying air was increased from 50 to 70°C at constant air velocity (0.5 m/s), the specific energy consumption decreased from 70.42 to 48.73 MJ/kg of moisture evaporated. At constant air velocities of 1.0 and 1.5m/s and for the same air temperature range of 50 to70°C, the specific energy consumption of the electricheater decreased from 80.46 to 63.67MJ/kg and 90.21 to 75.47MJ/kg of moisture evaporated. These values imply that less energy isconsumed when a highair temperature atlow air velocity is used. The SEC values also compare to the value of 84MJ/kg obtained by El-Mesery and Mwithiga (2012) for onion slices of 100g with the same temperature range; 64 MJ/kg determined by Jindarat*et al. (*2011) for hot air drying at 70°C. Sharma and Prasad (2006) found values that ranged from 140 to 215 MJ/kg while drying garlic and their values showed a decreasing trend with increase in temperature within the range of 40 to 70°C, although the SEC values are decidedly higher. For the gas heater, increasing the drying air temperature from 50 to 70°C at a constant air velocity of 0.5 m/s resulted in a decrease of the specific energy consumption from 47.82 to 36.83MJ/kg of evaporated moisture. At constantair velocities of 1.0 and 1.5 m/s, the specific energy consumption in the gas heater decreased from 54.37 to 47.41MJ/kg and 64.65 to 52.53MJ/kg of moisture evaporated respectively, when the air temperature was increased from 50 to 70°C. Similar trends have also been reported by Khoshtaghaza*et al*. (2007) and Aghbashlo*et al.* (2008). Generally, the SEC of the gas heater is lower than that of the electric at all conditions of air temperature and air velocity settings. This could be as a result of the longer periods of the electrical heating element when compared to the gas burner and the fact that the heating element retained high thermal mass even when it was switched off.

3.4 Thermal efficiency

The thermal efficiencies of both heat sources for different drying air temperatures and air velocities are illustrated in Figure 5. The thermal efficiency of the heat sources increased proportionally with increasing drying air temperature and decreased with increase in drying air velocity. This is as a result of low thermal conductivity of agricultural products as more energy in form of heat are lost at higher air velocities during drying, hence low thermal efficiency of the dryer heat source. Similar trends were reported by Jindal and Reyes (1987), EL-Mesery (2008) and EL-Mesery and Mwithiga (2012). Varying the air temperature of the electric heater from 50 to 70°C at constant air velocity of 0.5 m/s resulted in the thermal efficiency increasing from 36.52 to 54.81%; while for the gas heat source, it ranges between 59.8 to 68.2% at the same air velocity. Similarly, for higher air velocities at different air temperatures, the thermal efficiency of the LPG heater was higher than that of the electric heater.

IV. CONCLUSION

The performance of the hybrid electric-gas dryer has be evaluated at different drying temperatures of 50, 60, and 70^{o}C and at air velocities of 0.5, 1.0 and 1.5m/s using a uniform sliced thickness of 1cm of a local variety onion sample. In both heat sources, the drying time decreased with corresponding increase in the air temperature and air velocities. The page drying model was found more suitable to describe the drying behaviour of onions slices based on its highest average R^2-values (0.99) and lowest average RMSE values (3.91) for all temperatures and air velocities irrespective of the heat source. The specific energy consumption of the gas heater was lower than that of the electric heat source with minimum and maximum values of 48.73MJ/kg and 90.21MJ/kg, and 36.83MJ/kg and 64.65MJ/kg of moisture evaporated for the electric and gas heat sources respectively. The thermal efficiencyof the gas heater was higher than the electrically heated source.The thermal efficiency of the heat sources increased proportionally with increasing drying air temperature and decreased with increase in drying air velocity with maximum values of 54.81% and 68.2% for the electric and gas heaters respectively. The onion slices dried in both heat sources for all drying conditions were of good quality in terms of visual appearance and nutritive content. However, this type of design suggests that drying with gas performs better than the electric heat source given its performance in terms of energy consumption and thermal efficiency at all varying parameters in relation to the electric heater.

V. TABLES AND FIGURES

Table 1: Thin-layer drying models

No.	Model	Equation	References
1	Newton	MR = exp (-Kt)	Zarein*et al.*, 2013; Sahari and Driscoll, 2013
2	Henderson and Pabis	MR = a.exp (-Kt)	Zarein*et al.*, 2013, Darvishi, 2012.
3	Page	MR = exp ($-Kt^n$)	Zarein*et al.*, 2013; Darvishi, 2012
4	Modified Page	MR = exp [$-(Kt)^n$]	Waewsak*et al.*, 2006

Table 2: Results of statistical analysis of four different thin-layer drying models for sliced onion hot air drying using electric heat source.

No.	Air velocity (m/s)	Air temperature (°C)	Constant		R^2	RMSE
1		50	k=0.0072		0.997	5.41
	0.5	60	k=0.0080		0.995	9.09
		70	k=0.0099		0.991	9.18
		50	k=0.0083		0.997	8.63
	1	60	k=0.0101		0.993	8.20
		70	k=0.0131		0.984	9.97
		50	k=0.0090		0.993	4.98
	1.5	60	k=0.0121		0.991	6.73
		70	k=0.0160		0.990	9.30
	Average				0.991	7.92
2		50	k=0.0073	a=0.963	0.998	5.20
		60	k=0.0078	a=0.819	0.993	8.28
	0.5	70	k=0.0089	a=0.706	0.981	9.91
		50	k=0.0078	a=0.836	0.994	8.95
		60	k=0.0096	a=0.762	0.986	9.81
	1	70	k=0.0121	a=0.708	0.974	9.74
		50	k=0.0095	a=1.033	0.998	5.32
	1.5	60	k=0.0119	a=0.931	0.994	6.94
		70	k=0.0153	a=0.774	0.995	7.12

	Average				0.990	7.92
3		50	k=0.0053	n=1.057	0.999	3.91
		60	k=0.0083	n=1.004	0.999	5.04
	0.5	70	k=0.0136	n=0.954	0.998	7.66
		50	k=0.0082	n=1.007	0.999	5.05
		60	k=0.0124	n=0.978	0.998	6.42
	1	70	k=0.0236	n=0.903	0.998	5.02
		50	k=0.0063	n=1.072	0.999	4.51
	1.5	60	k=0.0094	n=1.049	0.998	5.31
		70	k=0.0157	n=1.011	0.999	6.10
	Average				0.998	5.44
		50	k=0.0082	n=1.057	0.993	8.44
4	0.5	60	k=0.0096	n=1.004	0.997	9.58
		70	k=0.0129	n=0.954	0.991	7.62
		50	k=0.0065	n=1.007	0.981	8.63
	1	60	k=0.0084	n=0.978	0.969	9.32
		70	k=0.0101	n=0.903	0.934	9.95
		50	k=0.0088	n=1.072	0.996	7.63
	1.5	60	k=0.0124	n=1.049	0.997	8.63
		70	k=0.0167	n=1.012	0.997	7.20
	Average				0.983	8.54

Table 3: Results of statistical analysis of four different thin-layer drying models for sliced onion hot air drying using butane gas heat source.

No.	**Air velocity (m/s)**	**Air temperature (°C)**	**Constant**		**R^2**	**RMSE**
1		50	k=0.0071		0.998	7.53
	0.5	60	k=0.0083		0.996	9.23
		70	k=0.0097		0.994	10.01
		50	k=0.0081		0.996	8.63
	1	60	k=0.0102		0.996	7.98
		70	k=0.0131		0.997	10.22
		50	k=0.0100		0.991	9.39
	1.5	60	k=0.0121		0.983	7.21
		70	k=0.0162		0.981	6.87
	Average				0.995	8.75
2		50	k=0.0074	a=1.015	0.996	8.61
		60	k=0.0077	a=0.812	0.999	9.10
	0.5	70	k=0.0088	a=0.694	0.994	9.93
		50	k=0.0077	a=0.850	0.993	8.97
		60	k=0.0098	a=0.805	0.991	9.80
	1	70	k=0.0120	a=0.705	0.978	9.72
		50	k=0.0099	a=0.832	0.996	8.86
	1.5	60	k=0.0110	a=0.756	0.984	9.36
		70	k=0.0140	a=0.700	0.978	9.53
	Average				0.991	9.31
3		50	k=0.0049	n=1.064	0.999	3.16
		60	k=0.0087	n=0.991	0.999	5.62
	0.5	70	k=0.0140	n=0.949	0.999	4.21
		50	k=0.0083	n=0.992	0.999	8.40
		60	k=0.0110	n=0.989	0.998	4.52
	1	70	k=0.0260	n=0.883	0.998	6.13
		50	k=0.0011	n=0.996	0.999	8.90
	1.5	60	k=0.0191	n=0.817	0.998	5.01
		70	k=0.0253	n=0.766	0.999	3.92
	Average				0.999	5.43
		50	k=0.0068	n=1.066	0.993	9.88
4		60	k=0.0085	n=0.994	0.997	9.58
	0.5	70	k=0.0110	n=0.947	0.998	9.36
		50	k=0.0085	n=0.993	0.981	8.63
		60	k=0.0100	n=0.989	0.969	10.63
	1	70	k=0.0160	n=0.881	0.987	9.95
		50	k=0.0100	n=0.996	0.991	7.65
	1.5	60	k=0.0160	n=0.818	0.997	10.99
		70	k=0.0210	n=0.768	0.998	7.22
	Average				0.990	9.32

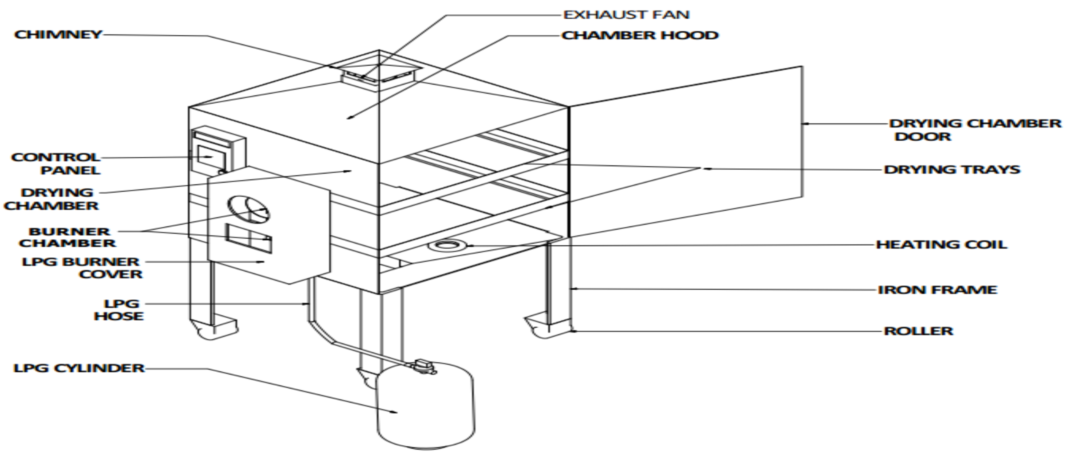

FIGURE 1: Isometric drawing of the hybrid electric-gas dryer.

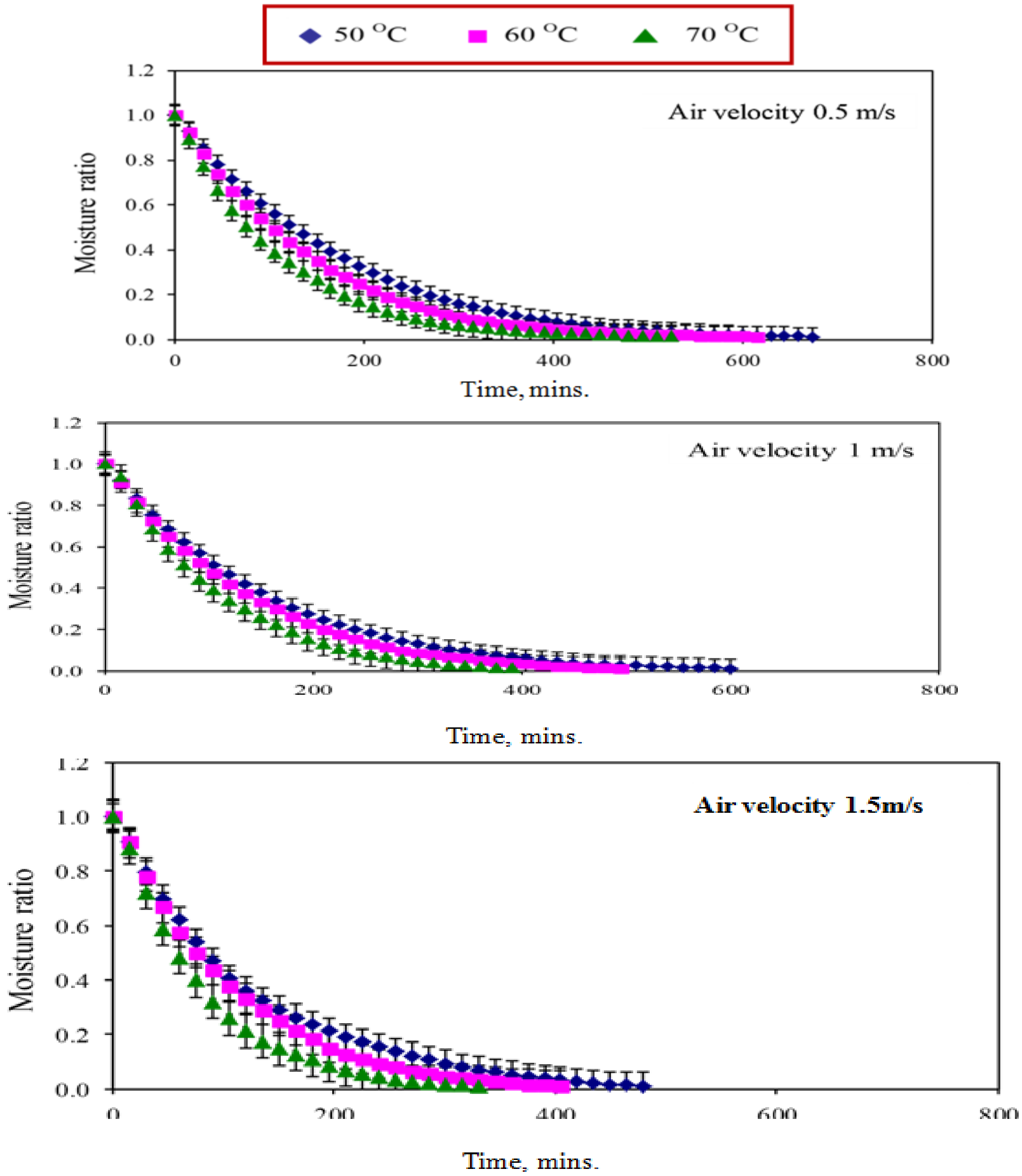

Figure 2: Moisture ratio as a function average drying time, different air temperatures and air velocities for electric heater.

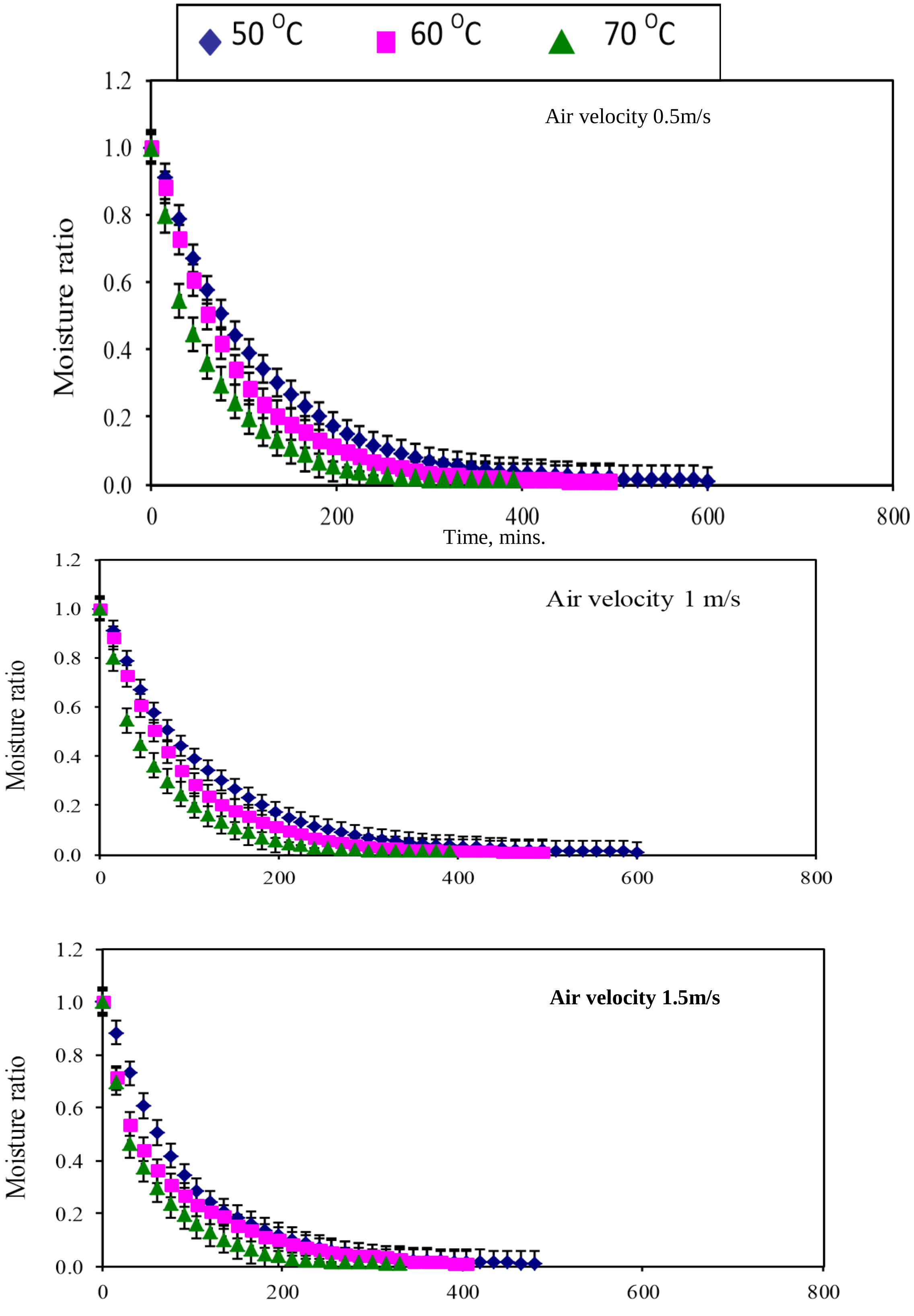

Figure 3: Moisture ratio as a function average drying time, different air temperatures and air velocities for gas heater.

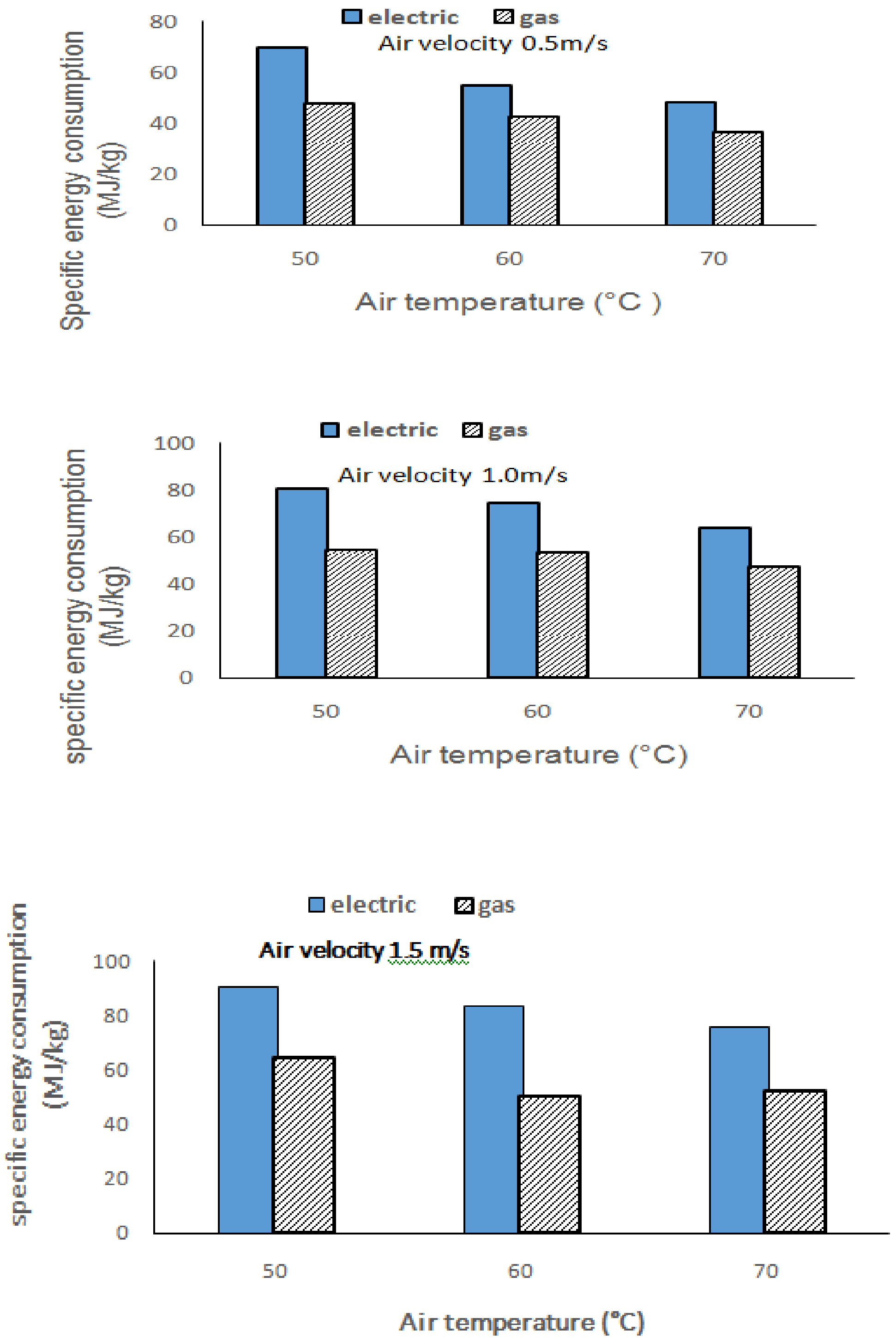

Figure 4: Specific energy consumption at different drying air temperatures and air velocities for both heat sources.

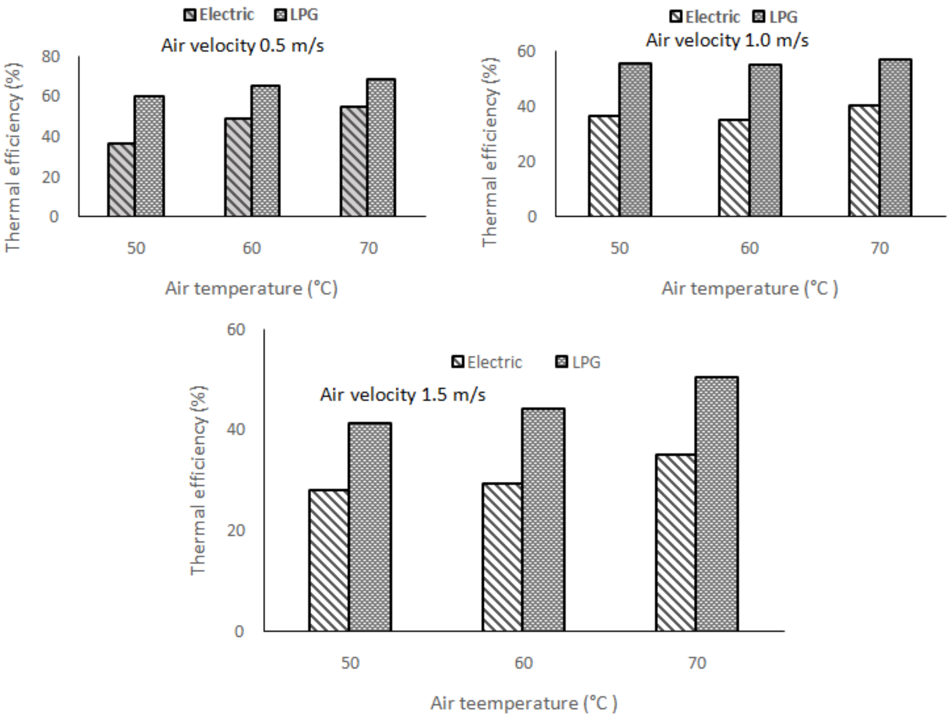

Figure 5: Thermal efficiency of electric and gas heat sources at different air velocities and drying temperatures.

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