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Research paper

Intelligently controlled solar-powered active fruit and vegetable dryer

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Abstract

Due to the impact of consecutive periods of drought recently being experienced in Africa; food storage and shelf life are decreasing rapidly. Food drying increases the shelf and storage life. Electrical dryers are expensive and electricity availability is a challenge in most African countries. To provide high quality and fast drying, a new intelligent automated active solar dryer is proposed in this paper. The dryer mainly operated on a battery system charged by photovoltaic panels. To produce heat in the oven, a heating element was used which was powered by a battery system. Sensors monitored the temperature, humidity and air velocity inside the dryer house and the data was send to a controller which performed automations on the switching of the convection fans and the heating element. The heating element switching was automated to optimise power consumption. Since the main energy source is solar radiation, a backup energy source was needed for worst case situations regarding weather. A port for electrical energy was installed for operations during cloudy and rainy days. From the results obtained, it was observed that the proposed system with temperature control, humidity control, forced hot air convection and forced humidity extraction offered an improved solution in comparison to the already available methods. These improvements observed are in terms of reduced energy usage, faster drying rate and preserved quality in the dried fruits.

Keywords: *Food shortage; Solar powered dryer, Fruit; Vegetable; Intelligent control; Active dryer.*

1. Introduction

Africa is currently facing consecutive seasons of drought and most countries are struggling to come to terms with the impact [1]. This has heavily affected the agricultural sector and has resulted in a high demand for food storage and shelves life. Food drying has been identified as one of the effective methods that provide longer storage and shelve life [2]. Various food drying methods have been implemented but they have side effects which affects production. These available drying methods include electrical dryers, solar passive and active dryers.

The issue with the electrical dryer is that it is expensive and that electricity availability is a challenge in most African countries. In some areas, the passive or active solar drying is implemented. These drying methods are less effective in terms of drying rate and quality production. This is due to exposure to dust, bacterial infection, rain and other species which may feed of the products. Both the active and the passive solar dryers have a slower drying rate since their drying process depends on heat intensity from the sun and natural convection.

Due to the impact of consecutive periods of drought recently experienced in Africa; food storage and shelf life are in high demand. Food drying increases the shelf and storage life. Various food drying methods like electrical dryers, solar passive and active dryers have previously been implemented, but they inherently contain side effects which affect production [3].

Electrical dryers are expensive and electricity availability is a challenge in most African countries. On the other hand, passive or active solar drying methods are slow and lack quality control. To provide high quality and fast drying, the automated-active solar dryer is proposed. The dryer uses photovoltaic panels, an energy storage system and a heating element to enable 24 x 7 day operation. The automation of the system optimizes power consumption and drying rate to maintain constant quality.

There are various existing solar dryers that were invented to counteract this problem [4], but in this project a more effective solar dryer is implemented. The exciting dryers still require more national electricity for effective operation to meet the desired production for commercial demands and the ones which do not use electricity have a lot of side effects which affects the drying process and the quality of the products. The various existing solar dryers include: Passive Solar Dryers, Active Solar Dryers and Greenhouse Dryers.

Passive Solar Dryers are called natural Circulation of natural convention systems [5]. These solar dryers use indirect or direct solar for heating and natural air flow for humidity control. Their operation depends entirely on solar energy. Examples of these are the Tent, Box, Seesaw and Cabinet dryers. Tent dryers are normally made of black and transparent polyethylene, where by the black polyethylene is used only on the wall which is opposite the sun for better heat attraction into the dryer house. The main purpose of the polyethylene is protection from shortcomings caused by dust, rain, predators and dirt which may cause bacterial infections [5]. This dryer uses natural convection for drying. It is cheap but takes long drying time. The box dryers are generally used for less quantity drying. The dryer house is generally made of wooden or steel structure with glass coverings. The dryer house is normally painted black on the inside except the top part, for maximum heat concentration. It has holes on the bottom for air inlet and other holes for air outlet on the top. These dryers also use natural convection but are more effective than the Tent Dryers. They can provide a moderate interior temperature (50-60˚C) and airflow rate [6].The temperature can rise to an excess of about 80 ˚C [7]. A Seesaw Dryer normally has two sections: the pre-heater unit and the dryer house. The pre-heater unit is naturally horizontal, the dryer house is resting on an axis and it can be tilted 30˚ up and down at specific times of the day for maximum heat absorption [5]. Heating inside the dryer house is obtained through the preheater and by directing the top of the dryer house with respect to direction of the sun. A Cabinet dryer is built in a form of a chamber with shelves inside. If the chamber is transparent, it is termed direct or integral-type solar dryer and if the chamber is opaque then it is termed indirect or distributive-type solar dryer. There are also mixed-mode dryers which combines both the direct and indirect types [8]. The operation of Cabinet Solar Dryers is similar to the one of Seesaw Dryers. The difference is that the Cabinet dryer has a chimney or air vents which regulates humidity inside the dryer house. Due to the hot air inlet being at the bottom, the dryer has a tendency of drying the bottom tray first and drying the top one last. That can result in over drying bottom trays. A temperature of about 70-100˚C can be obtained and it is excessive to some of the products [5]. This temperature can result in over heating of the products since natural convection has poor humidity control.

The active Solar Dryers are also termed Hybrid or Forced Convection Dryers. Through these dyers, a prime airflow can be achieved throughout the drying process which provides optimum temperature and moisture control irrespective of the weather condition. Therefore, this increases the capacity and reliability of the dryer and makes it more effective in comparison to the natural convection dryers. Active solar dryers use fans powered by photovoltaic panels (PVPs). These reduce the drying time by three times and decrease the required collector area by 50% [5]. Two types of Active Solar Dryers are: Active Ventilated Cabinet Solar Dryers and Cabinet Dryers with Backup Heating. An Active Ventilated Solar Dryer is designed similarly to a natural convection Cabinet Dryer. The difference between the two is that fans are installed on the Active Cabinet Dryer to provide optimum air flow. PVPs are used to power the fans and also for air flow speed control. Due to the controllability of temperature and moisture in the dryer house, the possibility of overheating is mitigated or abolished. The solar dryers may be cheaper, easy to manufacture and effective but they may not be good enough for industrial use. The challenge rises when it gets rainy and cloudy for days, of which can result in drying time delay and less production. To overcome this challenge there has to be a back-up heating system. There are various back-up heating systems which uses fuels or electricity. These systems are expensive to install and also to maintain.

Greenhouse dryers are forms of dryers used for large scale drying. The roof and walls of the dryer house can be made transparent materials such as glass, fibre glass, UV stabilized plastic or polycarbonate sheets and surface is rather black to enhance solar radiation absorption. The transparent materials are fixed on steal or wooden structure with bolts and nuts and rubber sealing to prevent rain and humid air leaking into the dryer house other than the ones on the inlet and outlet openings. Depending on the quality of the design, greenhouse dryers can allow greater degree of control over drying process than the cabinet dryers [9]. The dryer operates from direct striking of solar energy onto the product inside the dryer. Types of Greenhouse Dryers include Natural Convection Greenhouse Dryers, Greenhouse Dryers with Forced Convection and Continuous Production Greenhouse Dryers. The natural Convection Greenhouse dryer operates on natural air circulation and direct solar energy striking. These dryers are cheap and easier to build but they take longer drying time. The dryer house generally consists of parallel row of drying platforms of galvanised iron wire mash surface mounted on wooden structure. The house is generally orientated is such a way that the inlet opening is facing east while the outlet chimney is placed on the western side for optimum heating. A greenhouse dryer with forced convection is designed similarly to a natural convection greenhouse dryer, the difference between the two is that in forced convection dryer a fan is placed inside the chimney. The fans are powered by photovoltaic panels and they used to provide optimum airflow and temperature control. A Continuous Production Greenhouse Dryer is designed in a form of a drying tunnel with walls made of transparent material. On the inside of the dryer house there is a rail for carts with several stacks of trays containing the product to be dried. The dryer house temperature is provided by direct solar radiation and heat collectors. Electric fans are also installed for optimum temperature and humidity control. This design is implemented for continuous production where products are pushed in and out continuously for drying.

The primary objective of this project was to design and implement an automated-active solar fruits and vegetables dryer. The dryer should mainly operate on battery system charged by photovoltaic panel. To produce heat in the oven, a heating element must be used which was powered by a battery system. Sensors should be used to monitor the temperature, humidity and air velocity inside the dryer house and the data should be send in a controller which must perform automations on the switching of the convection fans and the heating element. The heating element switching must be automated to optimise power consumption.

2. Proposed solution

A preliminary design of the proposed solution is shown in figure 1. This diagram shows an overview of the concept design and the correlation between the components. This system consists of controller, heating unit, renewable energy source, fans and sensors. Since photovoltaic panel produces limited energy, a drying system which maintains an effective production while using less power and has fast drying must be implemented. The dryer is to be implemented using the components in figure 1. The sensors must be placed inside the dryer house to monitor the progress and operation.

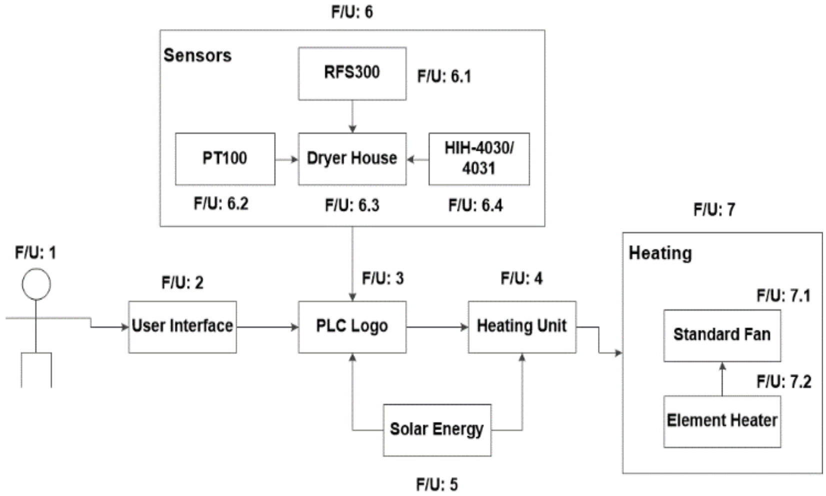

Fig. 1: Conceptual Design.

During the various times in the day, there is a variation in solar radiation which may result in process delay due to varying energy. To solve this problem a battery system is need that was charged by photovoltaic panels (PVPs) and used for operation to maintain constant energy distribution. The sensors are used to monitor the temperature, humidity and air flow rate. The data is then send to the controller where switching automation on the fans and heating element was performed based on the drying conditions defined by the user.

When starting the drying process, the user should first define the drying temperature, required humidity level and the drying air flow rate of the fruit or vegetable to be dehydrated. Once the operation is started the sensors will monitor the temperature, humidity and airflow rate inside the dryer house and send the data to the controller which will perform automations on the heater and the fans with respect to the values defined by the user. The functional unit of each component are described in table 1.

Table 1: Functional Units Descriptions

Functional Unit (F/U)	Description
1: User	The user will interact with the control interface.
2: User Interface	On this interface, the temperature, humidity and airflow rate was displayed. This is also a link between the user and the controller.
3: Controller	The controller receives data from the sensors and performs automation on the switching of the heating element and convection fans. The automation will adhere to an algorithm conditions and activities, which was defined by the designer.
4: Heating Unit	The heating unit was automated by the controller. In this unit, heating and air circulation are implemented.
5: Renewable Energy	The renewable energy is used to power the controller, heating element and the convection fans. The use of renewable energy makes it possible for application in places where there is no electricity.
6: Sensing	The sensors are used to monitor the temperature, humidity and airflow rate. This data is then send to the controller and is also displayed on the user interface.
6.1: Airflow rate probe	This probe is used to monitor the airflow rate in the oven.
6.2: Temperature probe	This probe is sued to monitor the temperature change in the oven.
6.3: Dryer house	The dryer house is the whole system including the oven and the heating unit. The drying process is performed in the oven. The goods to be dried placed in the oven where they get dehydrated by circulating hot dry air around them.
6.4: Humidity probe	This probe is used to monitor the humidity level in the oven.
7: Heating	The heating unit is used to warm up the cold air in the oven to a temperature required for drying
7.1: Fans	Fans was used for to produce forced convection and humidity control. A number fans was controlled by the controller to maintain the required drying air velocity and humidity level.
7.2: Heating Element	A heating element was used to produce the required temperature for drying. The switching of this element was automated by the controller.

3. Design overview

The operational flow of the system is illustrated is figure 2, also in figure 3, the design architecture is presented. Firstly, the user should switch the system on, select the type of fruit to be dried and select how dry they should be; between half or fully dry. The temperature and airflow rate inside the dryer house as well as the on one from the exterior are measured and displayed. The measured values are the compared to the drying set values of the specified product.

After comparing the values and the combined temperature is less than the set value, the heating element is switched on; if the combined temperature is higher than the set value, the fans are switched on; otherwise nothing is done.

Next, the Humidity level in the dryer house is measured and compared to the set value and all measured values are displayed. If the humidity level is more than the set value, the humidity control fans are switched on and if the humidity level is low, the fans are switched off or nothing is done if they are not on. Lastly the time s checked, if the time is less than the set value, the cycle repeats itself but is the timer is equal to the set value the system rings an alarm and switch off.

3.1. Heating element design

A parallel element design using the Fr-Nr RD 100/4 wire was adopted for the heating element. The following are the specification of the wire: Resistance: 3.90 Ohm/ m, Current rating: 1.34 A, AWG: 0.4 mm. The element was made of parallel connection of several coils. A single coil-wire strand can handle only up to 1.3 A, therefore a single coil wire maximum current is set to 1.2 A. Based on the literature study and trial-runs done using a tapped heating coil, it was identified that to obtain the target drying time for the size of the drying compartment and amount of fruits pieces that can be loaded, the heating coil needs to dissipate 160 W

Since the PLC operates at 24 V, to make the system integration more effective, reliable, cost-effective and space-saving by avoiding DC-DC converters, the whole system was designed around a 24 V power source. To calculate the resistance of the heating element, Ohm's law is used:

$$P = \frac{V^2}{R_{Element}} \tag{1}$$

$$R_{Element} = \frac{V^2}{P} = \frac{(24)^2}{160} = 3.2\ \Omega \tag{2}$$

As mentioned earlier, since each parallel coil – single strand can only handle a maximum of 1.34 A, set the maximum allocated current in each strand to be 10 % less than the datasheet maximum current. A 10 % safety margin was chosen to increase the reliability and improve the service life of the final product.

$$I_{max\_allowed} = 1.34 \times \frac{90}{100} = 1.2\ A \tag{3}$$

Hence the requested minimum resistance of each coil strand can be calculated as:

$$R_{Single-coil\_min} = \frac{24}{1.2} = 20\ \Omega \tag{4}$$

Now, the number of required parallel coil strands can be calculated as,

$$n = \frac{R_{single\_coil}}{R_{Element}} = \frac{20}{3.2} = 6.25 \tag{5}$$

Which means the heating element needs to consist of 7-parallel single-strand coils. With seven parallel coils, each single – strand coil will handle a current of.

$$P = VI \tag{6}$$

$$I_{Element} = \frac{P}{V} = \frac{160}{24} = 6.7\ A \tag{7}$$

Which means $I_{Coil} = \frac{6.7}{7} = 0.957\ A$

3.2. PT-100 Temperature probe

The PT 100 probe is a temperature probe which was used to sense the temperature inside the drying chamber, the heat produced by the heating element and the heat collector. The information from the temperature probe was used by the controller to automate the switching of the heating element and the convection fans.

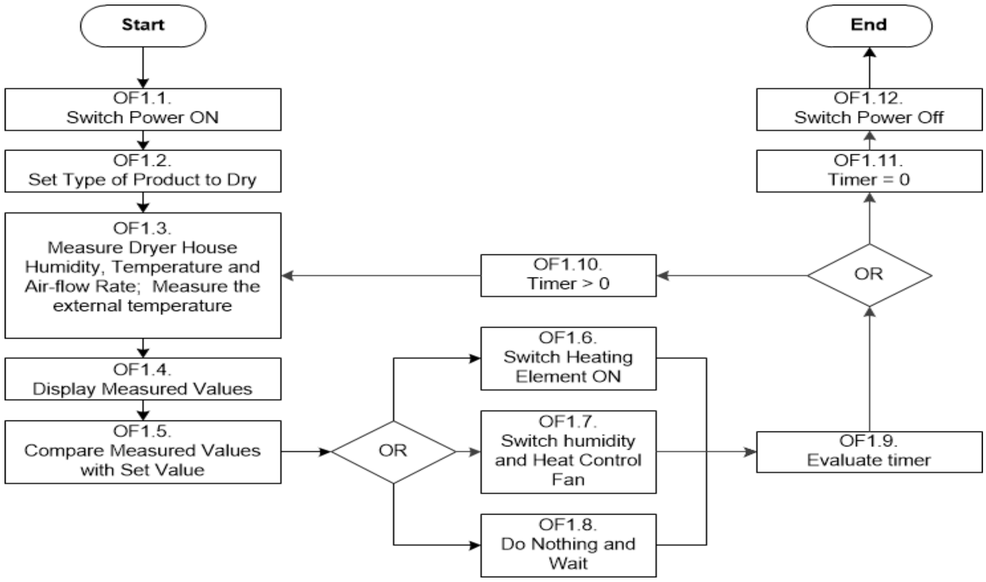

Fig. 2: System Operational Flow

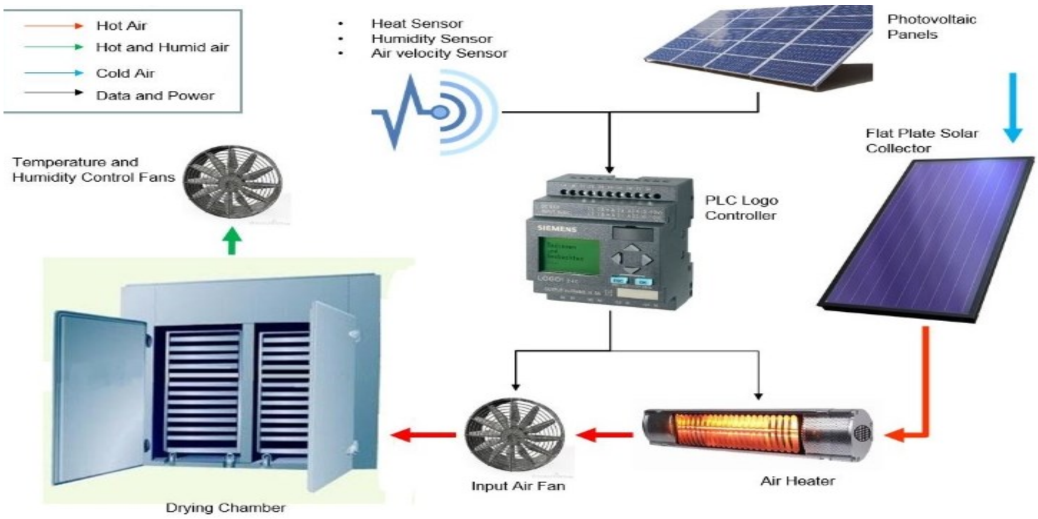

Fig. 3 : Design architecture

The complete system requires three temperature probes in total. One probe is placed in the heating unit, outside the oven to measure the exterior temperature and the last, one inside the oven. The probe that is placed in the heating unit is for monitoring the temperature of the air in the heating unit before it is passed to the oven so that the heat send to the dryer house can be regulated to avoid overheating. The second probe is placed at the output of the solar-heat collector for monitoring the hot air from the surrounding the user can be aware of the atmospheric temperature since it may affect the interior temperature.

The third temperature probe is placed inside the oven. This probe monitors the temperature within the oven to ensure that the internal temperature does not exceed the specified level. If the temperature within the oven is too high, that may result in over drying or burning the fruits. Furthermore, drying at a high temperature may degrade or completely remove the nutritional value of the product.

3.3. HIH 4031 Humidity probe

The humidity probe is a sensing device used to monitor the humidity change in a specific area. As mentioned in the previous chapters, the humidity probe is going to be installed inside the oven. For this project, only one humidity probe is required. The probe is connected to the PLC controller for the automation of the humidity control fan.

When heat is applied to the fruit pieces inside the drying chamber, the moisture evaporates and gets collected inside the oven and if not extracted, condensation will occur will disturb the drying process. Therefore, it is essential to monitor the humidity change in the oven, for the dehydration process to be successful and effective.

The humidity probe must be mounted at the top of the oven. That is because the fans force forces hot air upwards and since the moisture openings are at the top, which means the humid-hot air will move upwards. For that reason, the top of the drying compartment is the best position for mounting the humidity probe.

3.4. RFS300 Air velocity probe

The velocity sensor is a probe used to monitor air flow. The air velocity probe in this project was installed inside the oven to monitor the air flow rate. The probe was connected to the PLC controller to control the speed of the input fan. For an effective dehydration to be achieved, air circulation is essential. To circulate the air effectively, the air velocity must be monitored and this is realised through the air velocity probe. In this project, two air velocity probes were required. One probe was mounted at the air input and the other was place in the middle of the oven. These two probes will assist with monitoring the changing air velocity inside the oven.

3.5. Axial fan

There are three fans which are used in this project. The first two are placed at the air inlet of the heating unit chamber and the other one at the roof top of the drying chamber. 120 mm or 80 mm diameter fans may be used since the oven is smaller and less convection was required. For effective dehydration to occur the fan should produce an air flow rate of 0.31 m/s -1.5 m/s as discussed in the literature study.

The inlet fans are used to push the inlet air through the heating element into the drying chamber. They are also used to extract the hot-dry air from the heat collector into the oven. The other fan is used to extract humid air out of the drying chamber.

3.6. Controller

The PLC logo was chosen to be used as the controller for this project. The controller is to receive data from the PT100, HIH-4031, RFS300 and from the user defined inputs. Then the data is processed by encoded algorithms to determine the switching of the fans and the heating element in the system. The PLC's algorithm is shown in figure 4. The list of abbreviations used in the connection and flow diagram of figure 4, with their descriptions is shown in table 2.

Table 2: PLC Flow Chart Abbreviations

Abbreviation	Description
T1	PT100 probe placed at the output of the heat collector
T2	PT100 probe placed in the drying chamber
T3	PT100 probe placed in the heating element unit
H	HIH-4031 probe placed inside the drying chamber
V1	RFS300 probe on the input of the heating unit
V2	RFS300 probe on inside the drying chamber
t	timer
F1	Input fan 1
F2	Input fan 2
F3	Humidity Extraction Fan

The basic operation of the system is that when the system switches on, the temperature inside the heat collector is measured. If the heat collector temperature is less than 65 ℃ the heating element must be switched on, if it is greater or equal to 65 ℃ the heating element must remain off. Next the humidity inside the drying chamber is measured and if the moisture content in the drying chamber is greater than 45 %, humidity control fan must be activated. This process must repeat until the moisture content is less than or equal to 13 %.

The PLC will have two AM2 RTD resistance temperature detector expansion module which is specially designed for the PT 100 sensor and an AM2 which in a normal analogue expansion module. This makes the implementation of the sensors easier. Some of the components were connected directly on the output ports of the PLC, but the sensors was connected on the expansion modules.

3.7. Solar power and battery system

The power source for the dryer is been specified as solar energy from the trade-offs in the previous chapter. Solar panels, charge controller and battery system are sued. The amount of power from the supply is determined by the power consumption of the system. The power consumption of the system included sum of the power consumption three fans, the PLC and the heating element.

$$Power = Fans + PLC + Heating\ Element = 167.2\ W \quad (8)$$

The sizes and total number of photovoltaic panel, charge controller and batteries are determined in throughout this section. The connection diagram of the power system is also discussed at the end of this section.

Assume that a total load of 167.2 W was operated for 24 hours per day, therefore 4,012.8 Wh per day is required. Due to energy losses may occur, they must be account for and therefor 20% has to be added to the load. The total load is then:

With reference to weather conditions in Africa, a daily peak sunshine period of 6.6 hours is available [10]. To determine the total solar panel input, the total load must be divided by the peak sunshine period which is 729.6 W assuming a 6.6-hour sunshine period. According to the calculated panels input, a combination of panels must be selected to provide at least 729.6 W. If three 300 W photovoltaic panels are chosen, they will generate 900 W. Each panel will provide an output of 300 W (P_{max}) and 8.36 A (optimum operating current) [11]. Note that any choice of panels can be applicable if it will provide enough energy.

A charge controller is rated by the capacity of current it can tolerate from the solar panel. This makes the short circuit current of the panel an important aspect when selecting a charge controller. These panels selected above, each has a short circuit current of 8.83 A. Therefore, the total short current of the system is: 26.49 A.

Due to the inconsistency of solar radiation, the output of the photovoltaic panels may vary. Therefore 25 % tolerance must be added to the short circuit current to get 33.11 A.

$$Total\ load + 20\%\ energy\ losses = 4815.36\ Wh/day \quad (9)$$

This implies that charge controller with minimum current rating of 33.11 A may be used, but due to standard sizes a 33.11 A charge controller is not available and therefore a 40 A charge controller

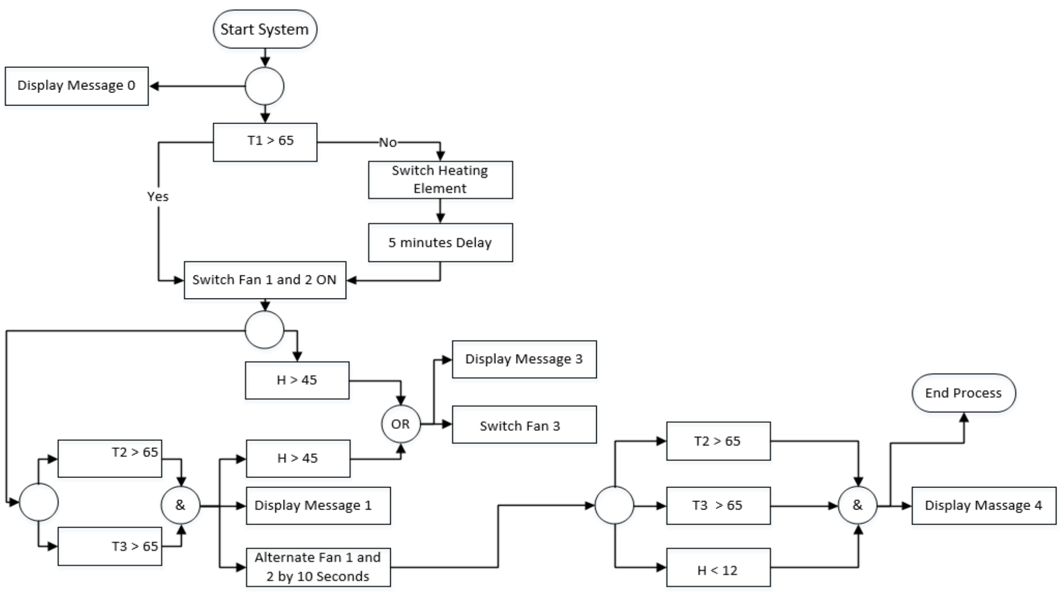

Fig. 4: Controller Diagram

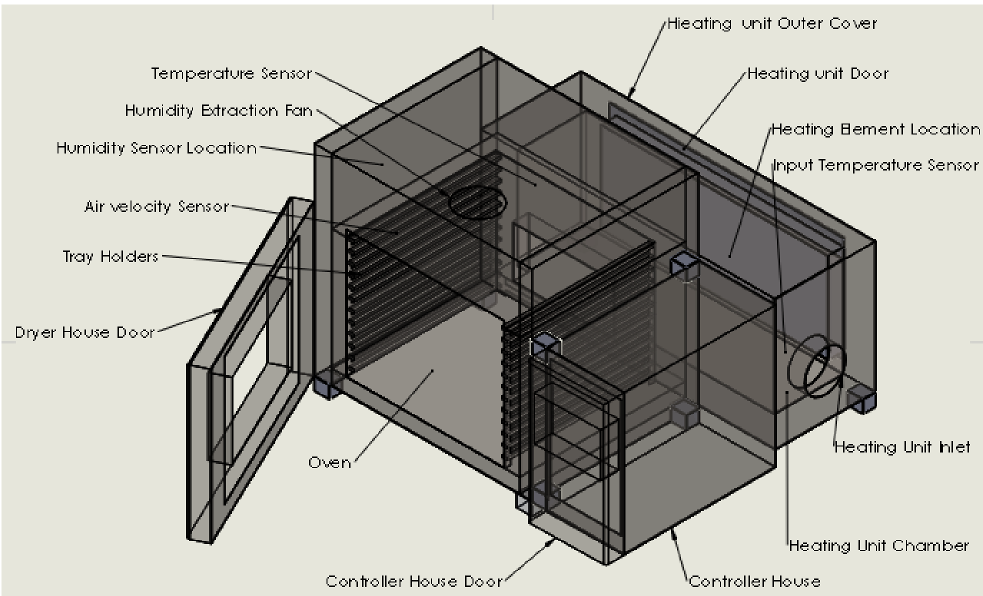

Fig. 5: Dryer House.

may be used. The charge controller must also have a voltage rating of 24 V since the PLC and the heating element requires 24 V.

It is recommended that a battery should discharge only 20% so that it may last longer. The total battery amp hours required are determined based on the daily watt hours required and the number of days to operate from a single charge while assuming that the battery will not discharge beyond 20%. The average amp-hours per day are calculated as:

$$Average\ Ah/day = \frac{4815.36\ Wh}{24\ V} = 200.64\ Ah/day \quad (10)$$

The number of batteries required is directly proportional to the product of the amp-hours required and the number of days to operate from a single charge; and is inversely proportional to the product of the current capacity of the chosen batteries and the discharge limit. According to the specifications, the system is supposed to operate for two days from a single charge. If a battery of 12 V – 100 Ah is chosen, then the total number of batteries is calculated as follows:

$$Total\ number\ of\ batteries = \frac{(200.64\ Ah\ per\ day)(2\ days)}{(100)(0.8)} = 5.016 \approx 6\ batteries \quad (11)$$

Since the system requires an input of 24 V, this means three parallel sets of two batteries.

3.8. Dryer house

The dryer is designed and simulated with SolidWorks® 2016-2017. These simulations are done using the flow simulation library. This is done to analyse the air flow inside the dryer house. Figure 5 shows the full design of dryer house with the location of all probes, fans and heating element. Three simulations of various humidity extraction fans configuration are done to study the effect of the fans on the system air flow. The considered configurations are: two extraction fans at the top back of the dryer house, one extraction fans at the top back of the dryer house and one extraction fan at the top of the dryer house.

The standard air flow rate and temperature for food dehydration is 0.31 m/s and 60 ℃ - 80 ℃ respectively as mentioned in the literature study. The standard humidity for dehydrated products which are crunchy is less than 12% and 15% for rubbery; but this can differ depending on the type of product. The air flow and humidity rate calculations are out of scope of this project, only their flow simulations are considered.

Figure 6 shows the dual-extraction fans configuration. The arrows show the direction of flow. In this simulation, rotation parts are used to simulate the fans and the air flow. The simulations are done at the air temperature of 60 ℃, 70 ℃, 80 ℃, 90 ℃ and 100 ℃ to model the thermal flow in the dryer house at various temperatures. Through simulations it was found that the air flow is similar for all temperatures, therefore only simulations at 75 ℃ are used for all configurations. The velocity of the fans is kept constant throughout the simulations at 0.4 m/s.

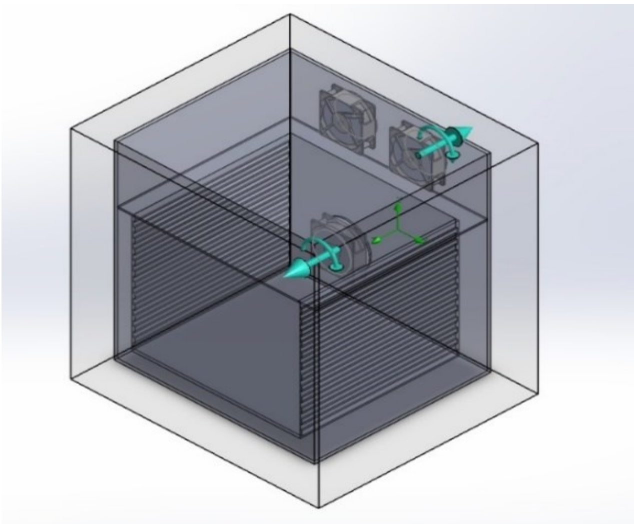

Fig. 6: Thermal Simulation Design.

Figure 7 show the thermal flow analyses at temperature of 75 ℃ when all fans are being active. The temperature in the simulations is measure in Kelvins and it can be converted to degrees Celsius by the following equation:

$$T_C = T_K - 273.2 \quad (12)$$

T_C is the temperature in degrees Celsius and T_K is the temperature in Kelvins. From figure 7 it is found that when both output fans are active, too much air is extracted. This affects the temperature in the drying chamber. It also shows that this results in insufficient air distribution whereby the air does not reach some parts of the oven.

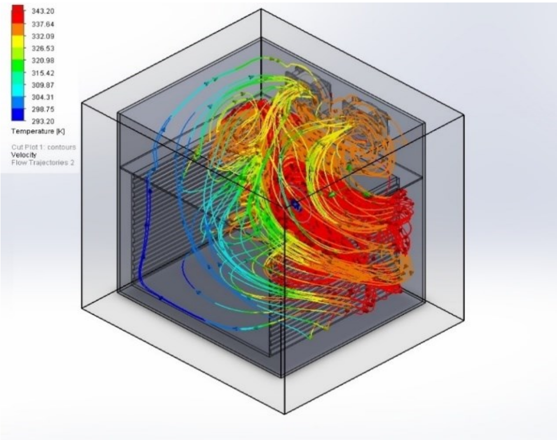

Fig. 7: Simulations with All Fans Active.

3.8.1. Single top-back humidity extraction fan configuration

Figure 8 shows the thermal flow simulation when only one humidity extraction fan is active. In this configuration, there occurs better air circulation but there is still much space which does not receive air circulation. This is because the extraction fan pulls the air to the back while leaving the front with insufficient air circulation. There is also some air which leave through the other fan which is not active, this is because the fan area is normally open.

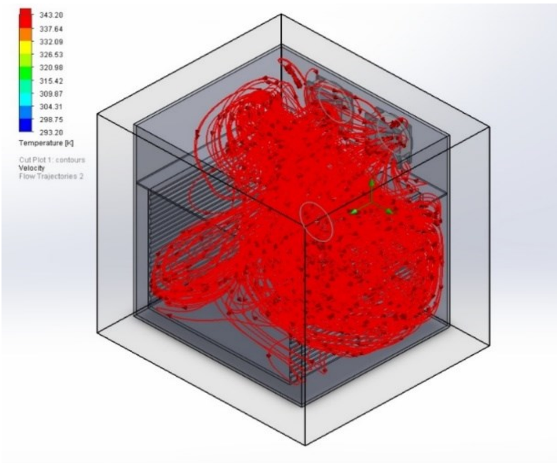

Fig. 8: Simulations with One Output Fan Active.

3.8.2. Single top humidity extraction fan

To determine the best position for the top fan, the simulations where compiled. In this configuration only one extraction fan is used and the inlet is estimated to a size of two input fans. This configuration is shown in figure 9.

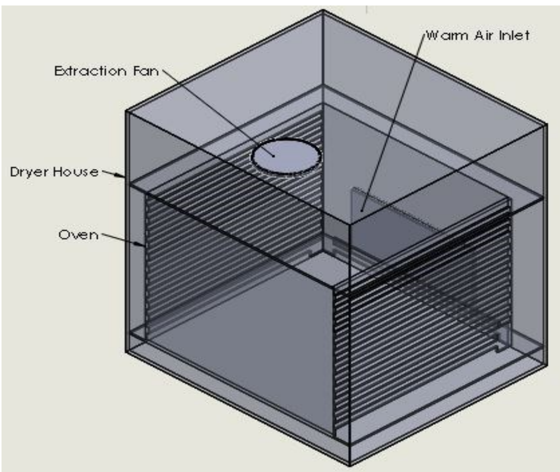

Fig. 9: Single Top Humidity Extraction Fan Assembly.

Through this simulation it can be concluded that the single top humidity extraction fan configuration is the best configuration for the implementation of the dryer house. Figure 10 shows the temperature scale which was used in this configuration. This temperature scale is in Kelvins (K). The minimum temperature is 19℃ and the maximum is 70℃.

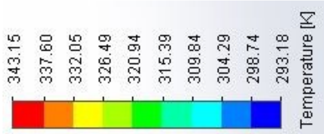

Fig. 10: Temperature Scale.

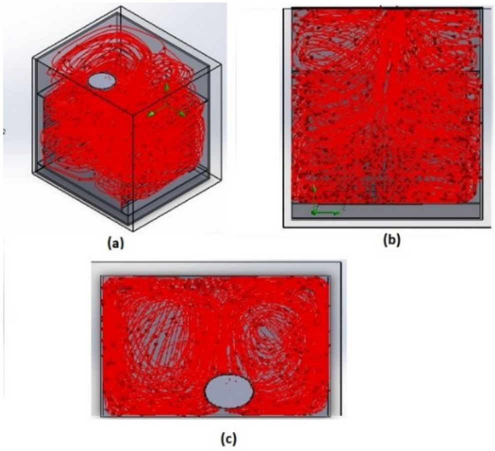

Fig. 11: (A) Flow Viewed in 3D, (B) Flow Viewed from Front and (C) Flow Viewed from Top.

3.8.3. Oven capacity

The oven has a volume of 20 litres. There are 11 trays of 312 mm ($\boldsymbol{x}$) x 296 mm ($\boldsymbol{y}$) area each. To calculate the capacity of the oven, the following assumptions are made:

a) A rectangular fruit piece of 30 mm x 30 mm x 3 mm is used.
b) The horizontal (Δx) and vertical (Δy) spacing between the pieces are 5mm.
c) n_x and n_y are the number of pieces in the x and y directions respectively.

The total number of fruit pieces in the x and y direction are:

$$x = (\Delta x + 30)n_x + \Delta x \quad (13)$$

$$n_x = \frac{312-5}{5+30} \approx 9 \quad (14)$$

$$y = (\Delta y + 30)n_y + \Delta y \quad (15)$$

$$n_y = \frac{296-5}{5+30} \approx 8 \quad (16)$$

$$Fruits\ volume = \left(\frac{vol.}{piece}\right) \times \left(n_x \times n_y\right) \times 11 = 21.384\ cm^3 \quad (17)$$

The percentage of volume occupied by fruits in the oven is:

$$\%\ Fruits\ volume = \frac{\sum Fruits\ volume}{Oven\ volume} \times 100 = 1\% \quad (18)$$

From the calculations, it is found that the fruits occupy only one percent of the volume in the oven. The other volume is occupied by the trays and the rest is left for air circulation

3.8.4. Dryer house

The dryer house is designed using the single top humidity extraction fan configuration. From figure 11, (a) shows the details from the front, (b) shows the details from the back and (c) shows the details from the top. For insulation, the fiberglass wool insulator was used. The choice of this insulator is based on the point that this insulator is easier to remove and reinstall when changes or maintenance is required.

3.8.5. Controller

The controller is designed to be mounted on the righted side on the dryer house. The mounting of the controller house onto the dryer house, allows cold air to flow between this two housing. This is to insulate the warm temperature from the dryer house since the temperature inside the controller house must remain at room temperature.

3.8.6. Heating unit

The heating unit is the housing where the heating element and the input fans are installed. This unit is mounted at the back on the dryer house. The outlet of the heating unit is connected to the inlet of the dryer house. The inlet of the heating unit can be connected to the outlet of the evacuated heat collector or it can be left open in the absence of the heat collector and it will serve as an inlet for cold dry air.

4. Implementation and results

The oven that was bought from the pawn shop is a 1040 x 315 x 390 mm (exterior size) with an interior of 350 x 245 x 240 mm, which gives an interior volume of 21 litres. It came with two trays and two tray holders. The oven was then modified to be able load two more trays so that is can load four trays in total. Three M16 holes were also drilled on the top for humidity extraction and the humidity extraction fan is mounted on top of them. The heating element, wiring and other parts which came with the oven were removed to create space for implementation of the design of this project. The interior of the oven is made of stainless steel sheet metal and the exterior is made of mild steel sheet metal. Figure 12 and 13 shows the modified outlook of the oven and an overview of the integrated system. All wiring inside the oven is done using silicon covered wires to avoid overheating and melting of connections.

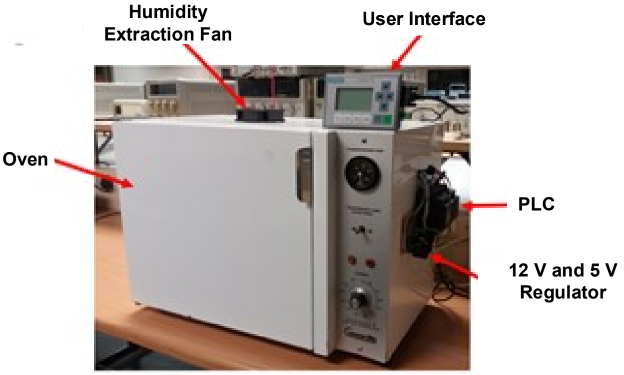

Fig. 12: Oven Outlook.

Fig. 13: Complete Integrated System.

The dehydration test model the drying rate of the system. This test was used to investigate the moisture reduction profile. Through this test, it was concluded if the system has a faster drying rate while retaining the quality of the fruits or vegetables which are dried. The fruits or vegetable was dried till the sensed moisture content in the oven is 12 %. To measure the moisture counted of the dried fruits or vegetables, these products must be weighed before drying and after drying and the moisture content of the dehydrated product can be calculated as,

$$H_d = 1 - \frac{W_w(1-H_w)}{W_d} \tag{19}$$

Where H_d is the estimated moisture content of the product when dry, H_w is the average moisture of the product before dehydration, W_d is the weight of the product when dehydrated and W_w is the weight before dehydration. Figure 14 illustrates the steps which are followed to dehydrate the fruits and the fruits used for the tests in this project are apples since they are one of the fruits with higher moisture content, availability and are cheaper.

- Step 1: Get fresh fruits and wash them.
- Step 2: peal the fruits and cut into 3 – 5 mm thick slice.
- Step 3: Align the slice on the stray with a space difference of 3 – 7 mm in between them.
- Step 4: Stack the trays in the oven, set up the drying conditions and start the PLC program.
- Step 5: Once the drying conditions are accomplished, remove the trays from the oven and leave the fruits to cool.
- Step 6: Once the fruits are cool, they may be package and stored.

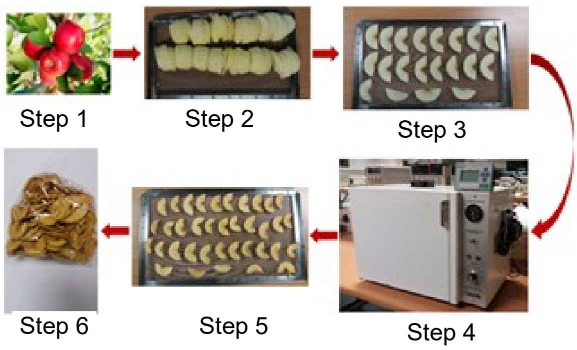

Fig. 14: Steps Followed for Dehydration.

4.1. Heating test

The purpose of this test to determine the period in which the interior temperature reaches the specified temperature for drying and determine if the heating element can heat up the oven to the required temperature. This test is done for no-load and full load. Full load means all trays are loaded with 3 mm thick slices of apples. The power consumption of the system is also tested in this section. With the power consumption test, the power efficiency of the system was evaluated.

4.1.1. No humidity extraction fan

In this section, the system runs without the humidity extraction fan. The purpose of this test is to monitor the temperature change with respect to time when the trays are fully loaded. The power used to produce this temperature is also monitored. Figure 15 illustrates the temperature profile of the system at controlled temperatures of 80 ℃, 75 ℃, 70 ℃ and without temperature control.
The results illustrated in figure 15 shows that when the temperature is not controlled, heat accumulates continuously in a linear direction. When the temperature is controlled at 80 ℃, heat accumulates consciously until it reaches 80 ℃ , the element is switched off until the temperature drops to 76 ℃. This controlled switching continues until the product’s dry condition in met. The first 80 ℃, is detected

after 4 hours. The controlled 75 °C and 70 °C, have the same switching condition as the controlled 80 °C. The first 75 °C and 70 °C are detected after 3hours – 30 minutes and after 1hour – 40 minutes respectively. When the set temperature is detected the element switches off until a temperature of 70 °C and 65 °C is detected for the controlled temperature of 75 °C and 70 °C respectively.

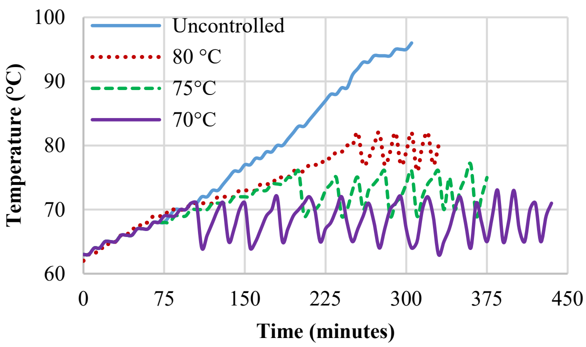

Fig. 15: No Humidity Extraction Fan Temperature Profile.

4.1.2. Including humidity extraction fan

The purpose of this test is to evaluate the influence of the humidity extraction fan on the temperature inside the oven. This test is done only on controlled temperatures of 80 °C, 75 °C, 70 °C. The uncontrolled temperature test in not included since the temperature accumulates beyond the recommended drying temperature which will cause fruits burning deteriorating the dried fruit quality.
The results illustrated in figure 16 shows that when the temperature is controlled at 80 °C, it accumulates linearly until it reaches 80 °C the element is switched off until the temperature drops to 76 °C. This controlled switching continues until the product's dry condition in met. The first 80 °C, is detected after 220 minutes. The controlled 75 °C and 70 °C, have the same switching condition as the controlled 80 °C. The first 75 °C and 70 °C are detected after 205 minutes and after 165 minutes respectively. When the set temperature is detected the element switches off until a temperature of 70 °C and 65 °C is detected for the controlled temperature of 75 °C and 70 °C respectively.

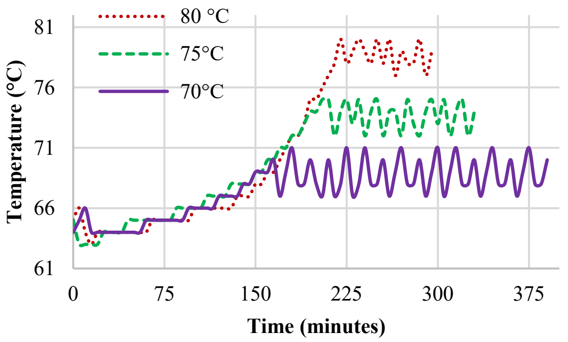

Fig. 16: Temperature Profile when Humidity Extraction Fan Is Included.

4.2. Dehydration test

The purpose of this test is to evaluate the drying rate of the system at various temperatures. Through this test, it was concluded on which temperature has the fastest drying rate while retaining the quality of the product and better power efficiency.

4.2.1. No humidity extraction fan

The purpose of this test is to determine the dehydration rate when the humidity extraction is not included. In this test air convection will only be achieved with the through the interior fans only. Therefor the moisture inside the oven is expected to be pushed out by the interior fans as they circulate the warm air inside the oven. Figure 17 illustrates the humidity profile at controlled temperatures of 80 °C, 75 °C, 70 °C and at uncontrolled temperature.
The result in figure 17 shows that for all four conditions, the moisture reduction rate is similar for a period of 210 minutes. After 210 minutes, the rate of moisture reduction of the 70 °C condition starts to decrease, followed by the 75 °C condition which starts to decrease after 235 minutes. The moisture reduction rate of the uncontrolled temperature starts increasing after 240 °C. The uncontrolled temperature and the controlled temperatures of 80 °C, 75 °C, 70 °C drying conditions, reach a moisture contented of 12 % after 305, 330, 375 and 435 minutes respectively.

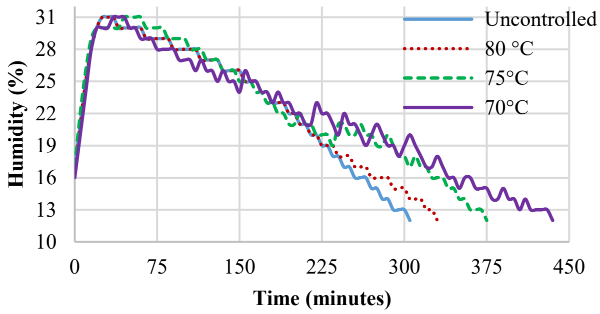

Fig. 17: Humidity Profile without Humidity Extraction Fan.

4.2.2. Including humidity extraction fan

The purpose of this test is to evaluate the influence of the humidity extraction fan on the moisture reduction rate and the drying rate. This test is done only on controlled temperatures of 80 °C, 75 °C, 70 °C. The uncontrolled temperature test in not included since the temperature accumulates beyond the recommended drying temperature.

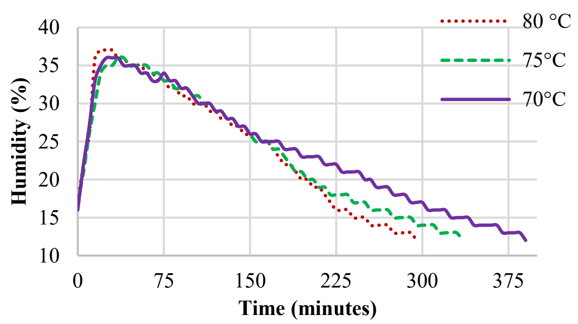

Fig. 18: Humidity Profile with the Extraction Fan Included.

The results in figure 18 show that for all three conditions, the moisture reduction rate is similar for a period of 160 minutes. After 160 minutes, the rate of moisture reduction of the 70 °C condition starts to decrease, followed by the 75 °C condition which starts to decrease after 215 minutes. The moisture reduction of the two temperatures 75 °C and 70 °C is analysed relative to the moisture reduction of the 80 °C condition the controlled temperatures of 80 °C, 75 °C, 70 °C drying conditions, reach a moisture contented of 12 % after 295, 330 and 395 minutes respectively.

4.3. Efficiency

In this section, the efficiency of the system in analysed in term of drying time reduction and reduction in energy usage. The both temperature and drying time are analysed with respect to the 70 °C test condition. This section is divided into two subsections which is the state where humidity extraction fan is not included and when it is included. The system uses an operating power of 166 W without the humidity fan and 167.4 W when the humidity extraction fan is included.

The following equations describe the parameters used to assess the system performance, where h is total drying period and W is operating power:

$$\text{Energy consumed per drying session} = \text{h} \times \text{W} \quad (20)$$

$$\gamma_E \text{ (\% Energy reduction)} = \frac{E_{70} - E_c}{E_{70}} \times 100\% \quad (21)$$

$$\gamma_T \text{ (\% Time reduction)} = \frac{T_{70} - T_c}{T_{70}} \times 100\% \quad (22)$$

Where E_c is the energy at controlled temperature, E_{70} is the energy at 70 ℃, T_c is the time at controlled temperature and T_{70} is the time at 70 ℃ drying condition?

For the maximum system efficiency, the total energy used should be reduced to the possible minimum value and the drying process should take minimum possible time. Hence both γ_E and γ_T should be maximised. Therefore, the efficiency, ɳ for optimum operation is calculated as:

$$ɳ = \gamma_E \times \gamma_T \quad (23)$$

4.3.1. No humidity extraction fan

Table 3 illustrates the calculation of the optimum operation efficiency. In these calculations, the operating power is at 166 W since the humidity extraction fan is not active.

Table 3: Efficiency in the Absence of Humidity Extraction Fan

Temperature	80 ℃	75 ℃	70 ℃
Total drying period (hours)	5.50	6.25	7.42
Total element off period (minutes)	25.00	45.00	95.00
Total energy Consumed (Wh per session)	813.00	880.00	933.87
% Energy reduction	12.00	5.77	X
% Time reduction	25.00	15.00	X
Optimum operation Efficiency	3.00	0.87	X

The optimum operation is found to be 3 % and approximately 1 % for drying at a temperature of 80 ℃ and 75 ℃ respectively with respect the test at 70 ℃.

4.3.2. Including humidity extraction fan

Table 4 illustrates the calculation of the optimum operation efficiency. In these calculations, the operating power is at 167.4 W since the humidity extraction fan is active.

Table 4: Efficiency when Humidity Extracting Fan Is Included

Temperature	80 ℃	75 ℃	70 ℃
Total drying period (hours)	5.0	5.5	6.5
Total element off period (minutes)	40.0	50.0	110.0
Total energy Consumed (Wh per session)	725.4	781.2	781.2
% Energy reduction	7.0	0	X
% Time reduction	23.0	15.0	X
Optimum operation Efficiency	1.6	0	X

The optimum operation is found to be 1.6 and 0 for drying at a temperature of 80 ℃ and 75 ℃ respectively with respect the test at 70 ℃.

5. Conclusion

The results show that when the temperature in the system is uncontrolled, heat keeps accumulating inside the drying chamber, reaching a very high temperature above the recommended temperature for drying and that may affect the quality of dried product. Under uncontrolled drying condition, the drying is faster, but the final product is not of good quality and the power consumption is also high. The tests were only done using apples as it represents the general wide variety of available fruits. Other tests may be conducted to analyse the drying rate and temperature of the required product. The drying rate may slightly vary depending on the moisture content the type of the product to be dehydrated.

When controlling the temperature of the system, it was found that more energy is saved. Therefore, controlling the temperature increases the efficiency of the system. When the temperature is controlled without activating the humidity extraction fan, it is found that the most efficient drying temperature in terms of drying time and power consumption is 80 ℃ in comparison to a temperature of 75 ℃ and 70 ℃ respectively. Even when the humidity extraction fan is activated, drying 80 ℃ is still the most efficient drying condition. These conclusions were made based on the analytical formula for optimum operations efficiency, ɳ.

Regardless of the humidity extraction technique, 80 ℃ controlled temperature drying process, provides the best drying condition in terms of drying time and power usage. A temperature higher would result in faster drying but the quality of the resulting product is affected negatively. 75 ℃ is the most widely used drying temperature according to literature. The results obtained through the project do not verify the information available in literature, but the changes can be caused due to the designed systems;

- Capacity of 600 g which is a smaller scale in comparison to available commercial drying systems,
- Forced convection heating air flow rate is above the commercially used air flow rate
- Forced humidity extraction method is not available in the commercially available products.

Therefore, it can be concluded that the proposed system with temperature control, humidity control, forced hot air convection and forced humidity extraction offers an improved solution in comparison to the already available methods. The improvements are in terms of reduced energy usage, faster drying rate and preserved quality in the dried fruits.

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