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FRUIT AND VEGETABLE DRYING MACHINE WITH ENERGY INDEPENDENCE

Ioan PAVEL[1,*], Gheorghe ȘOVĂIALĂ[1], Gabriela MATACHE[1], Valentin BARBU[1], Kati PAVEL[1], Ana-Maria POPESCU[1]

[1] National Institute of Research & Development for Optoelectronics/INOE 2000, Subsidiary Hydraulics and Pneumatics Research Institute/IHP

* pavel.ihp@fluidas.ro

Abstract: *Drying is one of the ways of long-term preservation of vegetables and fruits for industrialization or direct consumption without added preservatives. Throughout the year, there is a wide availability and diversity of fruits, vegetables, or medicinal plants that can be preserved by drying. To the costs of harvesting and drying one needs to add those of handling and transport, which are sometimes quite high; therefore, it is preferable to move the drying machines to the harvesting site of the products to be dried. Most of the time, these sites are isolated and do not have access to the electricity network; this raises the issue of energy independence of the drying facilities, i.e. the production of thermal and electrical energy from local resources around the harvesting points. The work presents an energy-independent drying machine that uses a Top-Lit-Up-Draft (TLUD) type hot air generator fed with wood chips for the production of thermal energy, and for the automation system the power supply is made from a 12V DC battery charged from photovoltaic panels.*

Keywords: *Energy-independent drying machine, solar PV panel, TLUD module, biomass, gasification*

1. Introduction

Drying is one of the oldest forms of preserving fruits and vegetables. Drying reduces the water content of the product in order to preserve it, but also reduces their mass and volume, which leads to lower packaging, storage and transport costs.
Convective drying is a high energy-consuming technology, which in many situations makes it dependent on cheap, local thermal energy sources.
Because biomass can be stored and used when needed, it remains the most versatile energy source for agricultural farms in various production processes [1,2,3].
By using the Top-Lit-Up-Draft (TLUD) type micro-gasification process, fuel gas and residual vegetable charcoal - commonly called biochar - are produced from biomass. Biochar is a sterile product that can be mixed with compost as an amendment in agricultural soils to increase their production capacity [4,5,6].
Due to the very long half-life of carbon residing in the soil, the incorporation of biochar resulting from the TLUD process achieves a sequestration of atmospheric carbon for very long periods of time and therefore leads to a negative CO_2 balance [4,6].
Compared to the direct combustion or wood gasification processes, the TLUD gasification process is characterized by very low values of the superficial velocity of the gases passing through the pyrolytic front. The slow process maintains a superficial velocity of the produced gas at very low values, which ensures a reduction of free ash being dragged along, as fine particles (PM2.5 - particles less than 2.5 micrometers in diameter), to a maximum value of 5 mg/MJbm at the exit of the burner, value far below the norm imposed in the EU in 2015 for biomass burning processes, which is below 25 mg/MJ [6].
The working principle of the TLUD type gasifier is shown in figure 1. The gas generator consists of a gasifier with an upward gasification air stream, connected to a burner. The biomass is introduced into the reactor and rests on a grate through which the primary air for gasification passes, from bottom to top. The ignition and initiation of the pyrolytic front is done at the upper part of the gas generator, and it advances in the biomass layer. Pyrolysis results in gas, tar and coal. The tars pass through the layer of incandescent coal, are cracked and completely reduced due to the heat

radiated by the pyrolysis front and the flame in the upper part. The resulting gas is mixed with the secondary combustion air that is preheated by the reactor wall and is introduced into the combustion zone through the holes located at the top of the reactor. The highly turbulent mixture burns with a flame at temperatures up to 900ºC.

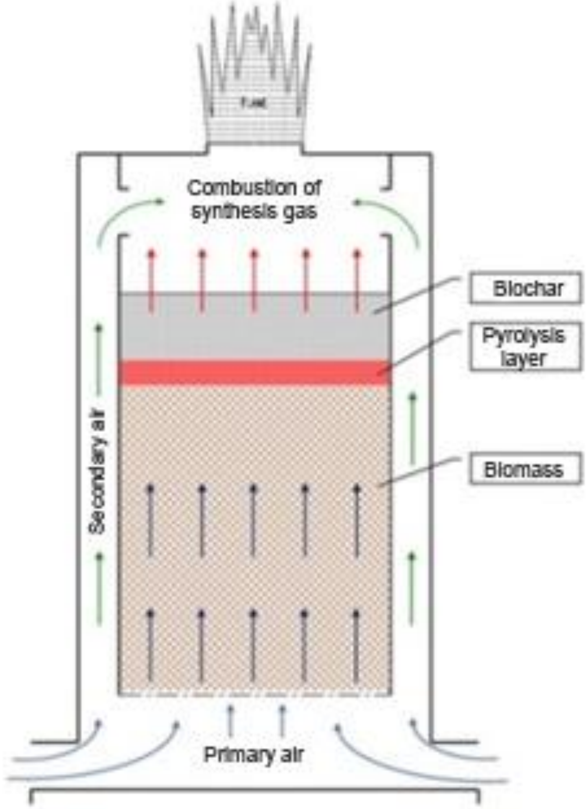


Fig. 1. Functional diagram of the TLUD energy module [7]

Removing excess water from the raw material is conditioned by heat transmission and the state and movement of water vapour. Heat transmission is based on the temperature difference between the material subjected to dehydration (fruits, vegetables, etc.) and the heat carrier (hot air).
During the dehydration of fruits and vegetables in an air stream, the free water is carried away immediately by evaporation. This rapid evaporation depends on the total surface of the fruits (or vegetables), the speed of air circulation and the difference between the surface tension of the vapours on the surface of the material and the surface tension of the vapours in the air stream. During the drying of fruits and vegetables, the water from the cell juice diffuses to the surface, due to internal diffusion, and evaporates. It is important that only the water evaporates during the drying process, not the aromas that give the fruit its taste and flavour.
The movement of water from inside the product to the outside is a result of the internal diffusion process and is the direct consequence of the difference in osmotic pressure determined by a different concentration in soluble substances of the liquid inside and at the periphery of the product particle.
The movement of water takes place from points with a higher water content to those with a lower content, resulting from the evaporation of water through the phenomenon of external diffusion. Thanks to the internal diffusion, the humidity is finally equalized in all the layers of the product subjected to dehydration.
The optimal development of the process (figure 2) occurs when the rate of water evaporation from the surface of fruits and vegetables is equal to the rate of moisture migration from the inside to their surface.

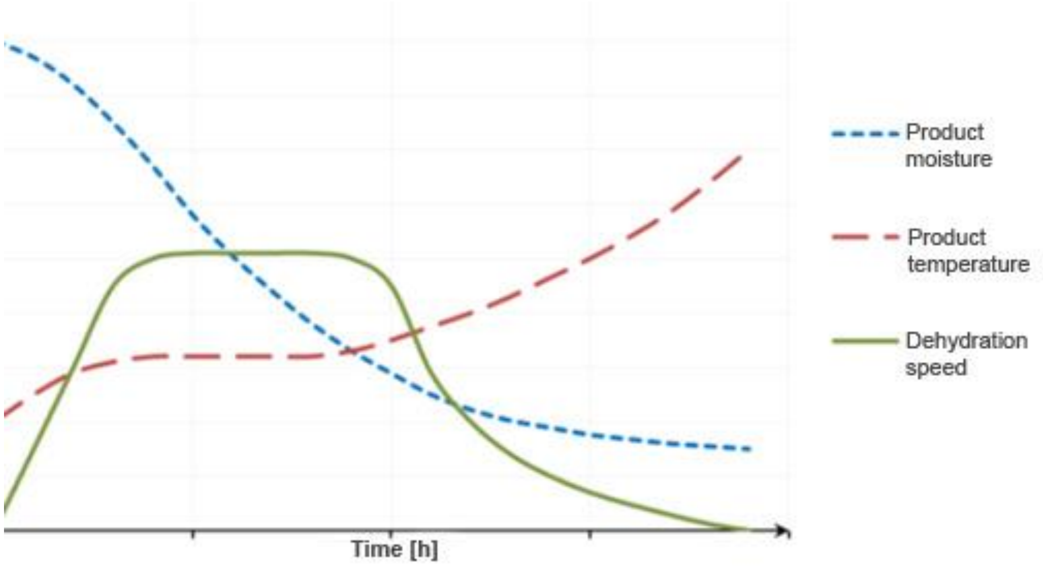
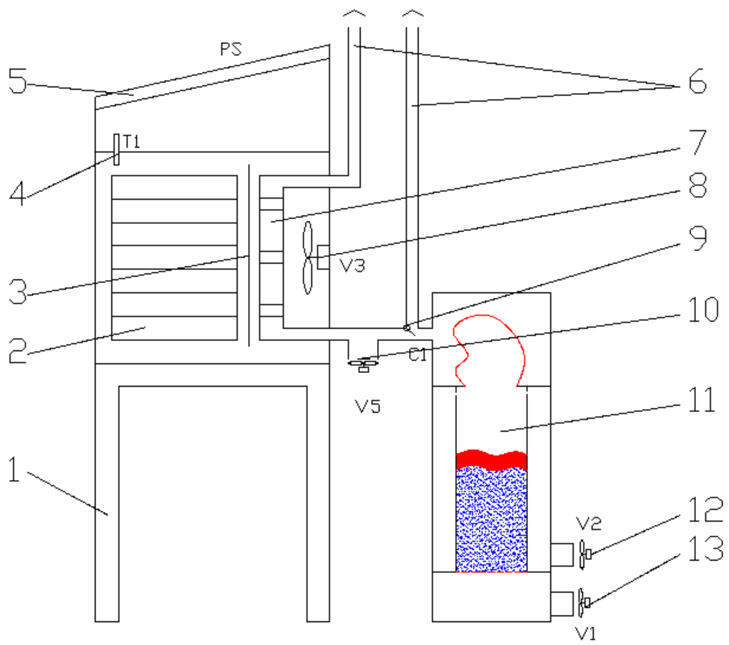


Fig. 2. Theoretical chart of the drying process

2. Materials and methods

2.1 Structure of the drying machine

The fruit and vegetable drying machine has three major subassemblies: a drying chamber with trays, a hot air generator based on the TLUD principle, and a control module.



1- Frame
2- Drying trays
3- Deflector
4- Thermometer
5- Solar PV panel
6- Natural draft tubing
7- Heat exchanger
8- Hot air fan
9- Smoke flap valve
10- Cooling fan
11- TLUD hot air generator
12- Combustion air fan
13- Gasification air fan

Fig. 3. Energy-independent vegetable and fruit drying machine - components

The drying machine shown in figure 3 consists of a frame (1) on which a drying chamber is placed, in which there is, next to the drying trays (2), a smoke-to-air heat exchanger (7) that is ventilated by the fan (8) and directs the hot air flow through a deflector (3) - that evens out the temperature and speed of the hot air in the chamber - towards the trays with material to be dried.

The temperature in the chamber is controlled by the thermocouple (4) which controls the flap valve (9) and directs the flow of hot smoke to the exchanger (7) in the chamber or to the atmosphere through the tubing (6) depending on the temperature requirements of the drying program. If the desired temperature is accidentally exceeded or the drying process requires the temperature in the chamber to decrease, the flap valve (9) closes the direction to the exchanger, and the fan (10) introduces cold air from the atmosphere into the exchanger, cooling it. The control signals for running the drying program (figure 4) are generated with the help of a PLC which is supplied with electricity from a battery pack charged from the photovoltaic panel (5). The power of the hot air generator (11) can be controlled by controlling the speed of the fans (12,13), keeping the optimal 1/3 ratio of gasification air/combustion air.

2.2 Sizing of the drying machine

Energy characteristics of energy-independent drying machines [8] are listed in Table 1 below.

Table 1: Energy characteristics of energy-independent drying machines

Parameter	Unit	Value
Positioning surface on trays	m^2	5.00
Specific thermal power	kW/m^2.cas	2.00
Rated thermal power	kW	10.00
Specific drying agent flow rate	$(Nm^3/h)/m^2$.cas	300.00
Drying agent flow rate	Nm^3/h	1500.00
Pressure drop across the drying machine	Pa	80.00
Minimum total fan efficiency		0.40
Fan electric power	W	83.33
PLC supply electric power	W	10.00
Power consumed by a transducer	W	5.00
Power consumed by a servomotor	W	5.00
No. of transducers	-	2.00
No. of servomotors	-	2.00
Automation electric power	W	30.00
Required electric power	W	113.33
Hours of daily use	h	12.00
Daily required electricity	kWh/day	1.36

Parameters related to thermal energy supply to the drying machine [8] are presented in Table 2.

Table 2: Thermal energy supply - related parameters

Parameter	Unit	Value
Positioning surface on trays	m^2	5.00
Specific thermal power	kW/m^2.cas	2.00
Rated thermal power	kW	10.00
Shredded local biomass - dimensions	mm	10...50
Shredded local biomass - moisture	%	<20
Shredded biomass layer medium density	kg/m^3	250

No. of TLUD energy modules	pcs	1
Flue gas/air minimum efficiency	-	0.85
Maximum required thermal power	kW	11.76
TLUD energy module rated power	kW	15
Shredded biomass PCI (Pouvoir Calorifique Inférieur)	MJ/kg	15.00
Share of biochar produced from biomass	%	15
Fully gasified biomass PCI	MJ/kg	14.00
Maximum hourly biomass consumption	kg/h	4.46
Average hourly biomass consumption (75%)	kg/h	3.34
Average drying time/batch	h	6.00
Biomass consumption in one batch	kg/batch	20.06
No. of batches per day	batch/day	2.00
No. of biomass loads/batch		2.00
Mass of fuel loaded into the reactor	kg	10.03
Reactor volume for shredded biomass	dm^3	40.12
Daily biomass consumption	kg/day	40.12
Daily consumed volume of shredded biomass	dm^3/day	160.50
Daily produced biochar mass	kg.ch/day	6.02
CO_2 equivalent mass sequestered in biochar	kg.CO_2/day	22.07

The photovoltaic panel for the production of electricity has a surface area of about 2 m² and is connected to a 50 Ah battery pack. This constrictive variant ensures total energy independence, which makes it possible to reside continuously in isolated locations for longer periods of time.
The electricity requirement - related parameters [8] are shown in Table 3 below.

Table 3: Electricity requirement - related parameters

Parameter	Unit	Value
Power supply only from a 12V DC battery		
Charging / discharging energy yield	-	0.87
Battery discharge limit	%	20
Minimum required battery capacity	Ah	**162.84**
Power supply with PV panel + battery		
Lighting hours in an average summer day	h/day	**9.00**
PV panel lighting level	%	66
Specific rated electric power	W/m²	150
Daily produced electricity	Wh	1469.20
Minimum required PV panel area	m²	1.649
PV panel area	m²	2
Power supply safety factor		1.2
Required battery capacity	Ah	**48.85**

The drying machines can be used in stationary mode at the farm premises; the electricity supply is made from the single-phase 220V AC electrical network with a 220V AC/12V DC power supply connected to the battery pack with which the continuity of the drying process can be ensured even during periods of network failure.

2.3 Drying rules

The drying process is considered to be carried out normally when the mass of the product dries uniformly and when, in a dry state, the vegetables meet the qualitative conditions required by the internal standards and norms in force.
The hot air must enter the drying machine at a maximum temperature of 80°C - in principle, as much as the product can withstand - and a relative humidity of about 25%, so that the product can be dried at a minimum of 8% humidity. This air leaves the drying machine at a temperature of 40-45°C (rarely 50°C) with a relative humidity of 60-80% to avoid condensation.
When the product heats up too much and dries unevenly, partial frying or softening occurs, acquiring a foreign smell. Such drying is considered defective.
Drying vegetables and fruits at sub-optimal temperatures inevitably leads to longer drying times, which leads to transient softening of the raw material and a change in its colour.
The softening of the product is also caused by the poor air circulation in the drying machine and is directly caused by the microbiological changes that can occur in this case, changes that consist in the appearance of sour taste, dark colour, loss of nutritional quality.
In order to prevent partial frying or softening of the product, it is necessary to systematically monitor the air temperature variations in the drying machine during the drying process and to adjust in advance both the entry of fresh air and the exit of moist air.
To accelerate the drying process, it is necessary that the relative humidity of the hot air be reduced, and its circulation speed be increased. The decrease in the relative humidity of the thermal agent is obtained by raising its temperature; this decrease translates into an increase in its absorption capacity.
Excessively raising the air temperature above the established limit can adversely influence the process. For example, it is possible that a crust may form on the surface of the product, especially in the case of fruits, which prevents the evaporation of water from the deeper layers.
In the first part of the drying, the air speed has an important influence, since in addition to the function of a heating agent, the air also has the function of taking over and conveying the water vapours resulting from evaporation. The faster the removal of water vapours will be, the better conditions will be created for other quantities of water to migrate to the surface of the products. In the second phase of drying, when vaporization occurs inside the product, the air speed has a much smaller influence on the drying speed.

2.4 Operating principle

To control the temperature of the hot air in the drying machine, a temperature sensor T1 (figure 4) is used, which is fixed in the place where the hot air passes to the products to be dried.
The temperature control is done with a PLC that controls the C1 flap valve for hot air access to the exchanger or its evacuation into the atmosphere. If the temperature in the drying machine is too high, flap valve C1 closes the access of hot air to the exchanger, directing it to the atmosphere, and the cooling fan V5 turns on and introduces cold air from the atmosphere into the heat exchanger, reducing its temperature. The PLC also controls the speed of the V3 fan, obtaining the variation of hot air flow and the variation of the amount of heat extracted from the heat exchanger.

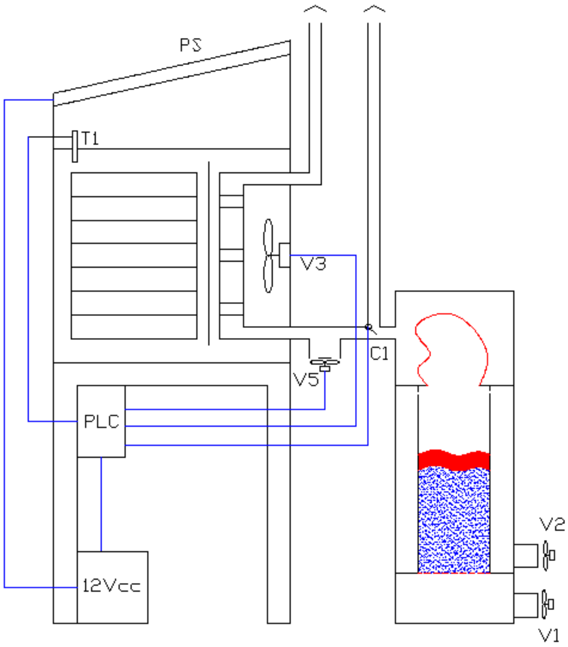


Fig. 4. Control module (wiring diagram)

The power of the TLUD generator can be adjusted manually depending on the requirements of the drying process, from the flow of gasification air and combustion air supplied by the V1 and V2 fans. It should be noted that varying the temperature in the drying machine is done with a relatively large hysteresis, which requires a flexibility of the drying mode programmed in the PLC.

3. Conclusions

This article presents a solution for a convective drying installation with total energy independence intended for isolated areas which uses a mixed system for the production of the necessary energy: thermal energy - produced with a hot air generator based on the TLUD principle, in which shredded local biomass is used, and electricity - produced with photovoltaic panels connected to a battery pack.
The hot air generator on the TLUD principle is characterized by high energy conversion efficiency, biochar production and very low CO and particulate matter (PM) pollutant emissions; it is easy to use and safe in operation; it is tolerant to variations in the properties of the biomass, both chemical and dimensional, which ensures great adaptability to the variety of local biomass resources.
In order to carry out the dehydration process in optimal conditions, the maximum temperature that each product to be dried can withstand must be determined, as well as the temperature entering the drying machine and the temperature at which the moisture-laden air must exit, in order to avoid its condensation.
The automation scheme meets the requirements for temperature control (increase and decrease) and the variation of air speed in the drying machine corresponding to the drying process of vegetables and fruits.

Acknowledgments

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