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Research Article

Design, Production and Testing of a Dryer Coupled with a Refrigeration Machine for Fruit and Vegetable Preservation

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Abstract

The aim of this project is to design and build a refrigerated dryer for preserving fruit and vegetables. The prototype comprises a refrigeration chamber, a drying chamber and a condensing unit housing. SOLIDWORKS and EES software were used for the design and power calculation of the refrigeration system units, respectively. The dryer is supplied with hot air by the condensing unit. The experimental part will involve characterizing the air in the drying and refrigeration chambers, and the product in the drying chamber. Sizing the refrigeration chamber based on a heat balance gave us a condenser power of 489.24 W and a drying temperature of 48°C. The coefficient of performance being at a temperature of 5°C.

Keywords

Product Drying, Dryer, Refrigeration, Mushroom, Mecycling

1. Introduction

Today, the desire to preserve the sustenance of food is one of the driving forces behind the development and improvement of preservation techniques. These include drying and refrigeration. Drying is an energy-intensive and costly operation, accounting for 10-15% of total industrial energy consumption worldwide [8]. This large share means that we need to find ways of optimizing processes, both economically and ecologically. With the aim of reducing energy losses during a drying

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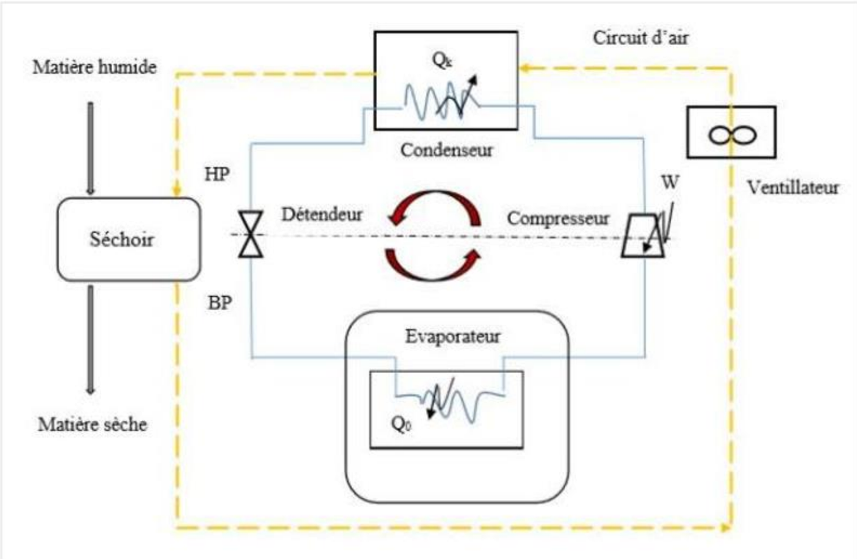
operation, some work has been carried out on product characterization [2, 3, 10]; other researchers have worked on characterizing drying equipment [1, 6, 9, 11]. This is the background to our work. The main objective of our study is to contribute to drying optimization. The aim is to design and characterize a prototype refrigerated dryer.

2. Refrigeration Dryer Design

In this section we will describe, dimension and calculate the parameters of our machine.

2.1. Description of the System

The system works by using waste heat from the refrigeration machine's condenser to heat the air circulating around the mushrooms to be dried. This hot air then evaporates the water from the mushrooms, causing them to dehydrate. This method recycles the heat from the condenser and uses it for a useful process, thus reducing energy costs. This phenomenon is illustrated in Figure 1.



(Heat transfer fluid circuit: —— Moist air circuit: —·—·—)

Figure 1. *Block diagram of the system coupling the dryer to a refrigeration machine.*

2.2. Sizing the Refrigeration Chamber

We evaluated the heat output of the heat exchangers and the compressor and then deduced the power of the fan to be installed.

2.2.1. The Characteristics of Outside Air

The machine we want to build will be installed in the city of Douala, and we have recorded the average air characteristics in Table 1 below.

Table 1. *Outside air characteristics [7].*

Dry temperature (°c)	Moist température (°c)	Relative humidity Hr (%)	Moisture content (g/ kgas)	Enthalpy (kJ/kgas)
32	26	83	25,2	96,72

2.2.2. Sizing Hypotheses

To achieve the objective of this work, it is important for us to set dimensioning assumptions in order to overcome certain difficulties. Our assumptions are as follows:

Overheating temperature 5°C; Undercooling temperature 5°C; The enthalpy of the drying air remains constant during drying to keep the temperature invariant; The walls of the drying unit have uniform and constant temperatures; Heat exchanges by conduction and radiation are negligible.

2.2.3. Refrigeration Machine Power Balance

The aim is to determine the energy consumption of the machine's main components. The EES (Engineering Equation Solver) software is used to calculate the compressor, condenser, expansion valve and evaporator capacities using the following equations:

The compressor

$$P_{cp} = \dot{m}(h_2 - h_5) \tag{1}$$

The condenser

We report that the amount of heat per unit mass of fluid circulating in the plant is deduced from examination of the enthalpy diagram:

$$P_{cd} = \dot{m}(h_{2\prime} - h_{3\prime}) \tag{2}$$

The expansion valve

The expansion of the fluid is isenthalpic. The enthalpy diagram shows that this is the case:

$$h_4 = h_{3\prime} \tag{3}$$

Evaporator

$$P_e = \dot{m}(h_5 - h_4) \tag{4}$$

Since the condenser capacity is a known value, the mass flow m˙ of the refrigerant is calculated as follows:

$$\dot{m} = \frac{P_{cd}}{h_{2\prime} - h_{3\prime}} \tag{5}$$

Coefficient of performance

The COP is defined as the ratio between the need and the resource. In our case, this machine will have two aspects of this coefficient:

$$COP_i = \frac{P_i}{P_{cp}} \tag{6}$$

Index i=f for cold production and i=cd for heat production. In this study, it is the heat production vocation that is valued.

Ventilator sizing

The useful power of the fan capable of conveying the quantity of air proportional to the drying chamber.

$$P_u = Q_a \times \Delta P \tag{7}$$

2.3. Calculation of Drying Chamber Parameters

For our project, we'll be drying 1 kg of mushroom (oyster mushroom) with an initial moisture content of 85% and a final moisture content of between 10 and 12%. The drying method used will be convection drying at 45°C through a thermal dryer. The mathematical equations used for sizing our plant are as follows:

Quantity of water to extract [4]:

$$Q_e = \frac{X_i - X_f}{100 - X_f} \times Q_f \tag{8}$$

Moisture content [1]

$$X_r = \frac{m(t)}{m_i} \tag{9}$$

Required evaporation capacity in kg/h [4]:

$$\frac{CE}{h} = \frac{Q_e}{Ideal\ \ drying\ \ time} \tag{10}$$

Required Dry air flow in m³/h air [5]:

$$Q_a = \frac{CE/h \times 1000}{PE\ \ medium} \tag{11}$$

2.4. Drying Chamber Energy Balance

This assessment will consist of evaluating the various losses from the drying chamber.

Energy dissipated by walls

$$Q = K.S.\Delta T \tag{12}$$

As our wall is made of wood panel and aluminum sheet, the thickness of the sheet will be neglected. The interior convection coefficient is given by the following equations [13]:

$$Re = \frac{U.d}{\upsilon} \tag{13}$$

$$Nu = 0{,}0366\ \ Re^{0.75} Pr^{0.333} \tag{14}$$

$$h = \frac{Nu \times \lambda}{d} \tag{15}$$

The overall heat exchange surface is given by the following relationship:

$$S = 4 * S_1 + 2 * S_2 \tag{16}$$

Energy required to dry products

$$P = \rho_{air} \times Q_a \times C_{pair} \times \Delta t \tag{17}$$

The latent heat of vaporization of the water contained in the product

$$Q_l = (Q_e \times L_{lib} \times 90\% + Q_e \times L_{lie} \times 10\%) \times \frac{1}{t_s} \tag{18}$$

Provisional power balance

$$Q_{pr} = Q_p + Q_l + P_s \tag{19}$$

Total balance (Q_T)

The total balance sheet is the sum of the provisional balance sheet and non-quantifiable losses. It is expressed by the relationship below.

$$Q_T = Q_{pr} + Q_n \tag{20}$$

Dryer efficiency calculation

$$\eta = \frac{P}{Q_T} \tag{21}$$

Refrigerant selection

The refrigerant used here is R134a with a mass flow rate of $\dot{m} = 0{,}0026 kg/s$.

3. Results and Discussion

This section presents the results of the sizing, characterization and realization of the machine.

3.1. Presentation of Sizing Results

Le tableau 2 ci-dessous nous présente le récapitulatif des résultats issus du dimensionnement. Ces données ont permis de choisir les équipements nécessaires pour la réalisation du prototype.

Table 2. *Sizing results.*

Designations	Results	Designations	Results
Compressor capacity	P_{cp} = 113,11W	Air flow required	Q_a = 103,6875 m^3/h
Condenser capacity	P_{cd} = 489,24 W	Power required for drying	P_s = 453W
Cooling capacity	Pf = 376,13 W	Energy dissipated by the walls	Q_p = 26,64 W
Coefficient of performance	COP heat = 4,325 COP cold =3,32	Latent heat of vaporization of the water contained in the product	Q_l = 0,0429 W
Quantity of water to be extracted	Q_e = 0,8295 kg	Provisional power balance	Q_{pr} = 479,64 W
Evaporation capacity required	CE/h = 0,207375 kg/h	Dryer efficiency	η=92,59%

3.2. Refrigeration Machine Performance

To satisfy the cooling and/or heating requirement, the mass flow rate circulating in the system must be equal to 2.68 g/s.

We have considered an isentropic efficiency of 85%, for an evaporation temperature of -2°C and a condensation temperature of 48°C.

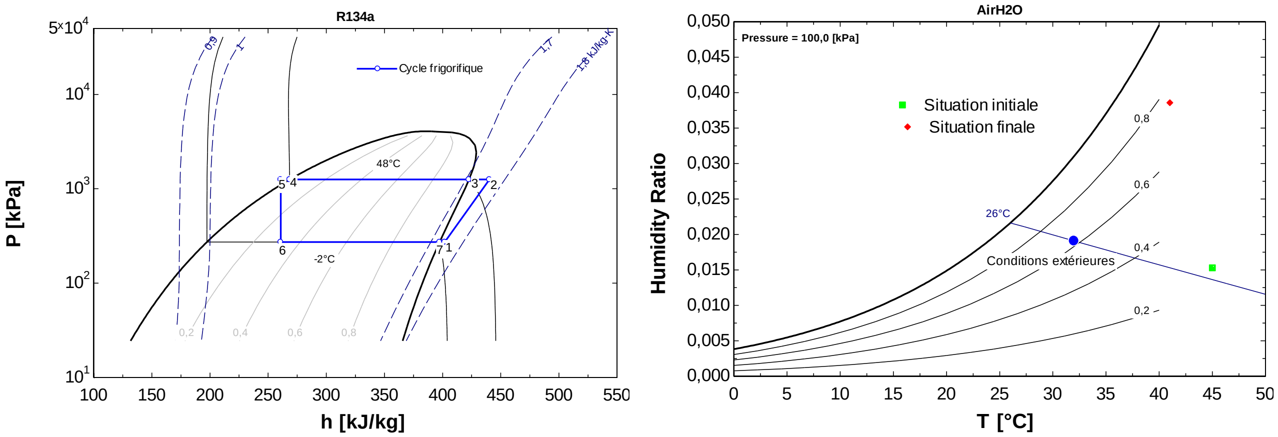


Figure 2. *Refrigeration cycle and Humidity diagrams.*

3.3. Presentation of Digital and Realized Prototypes

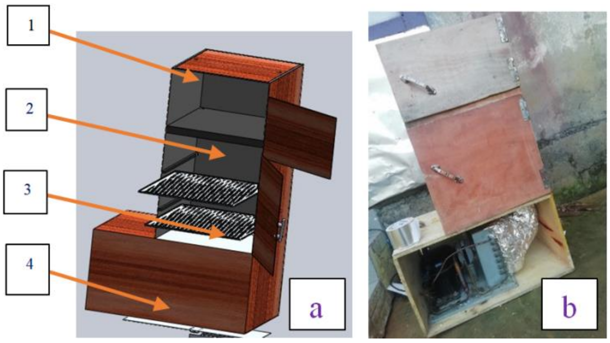


Figure 3. 3D representation of the prototype: a-digital; b-realized.

(1-Refrigeration chamber; 2- Drying chamber; 3- Rack; 4-Heat production chamber)

3.4. Prototype Characterization

3.4.1. Characterization of the Drying Chamber

Figure 4 shows the air temperature inside the vacuum dryer as a function of time in relation to the heat source.

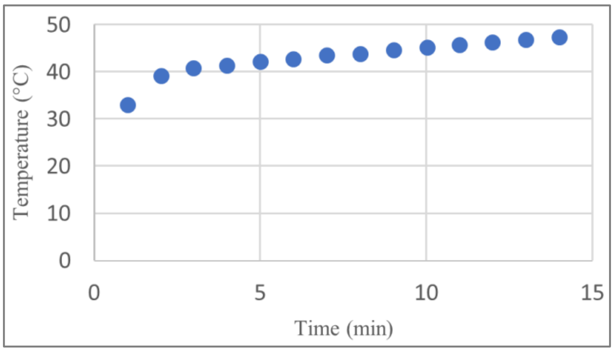


Figure 4. Profile of air temperature as a function of time.

The curve increases. This shows that the air in the dryer heats up with increasing time. It can also be seen that, in the absence of racks, the air temperature in the dryer is homogeneous. This observation has also been made by [1, 12-14].

3.4.2. Product Characterization in the Dryer

Figure 5 shows the evolution of the reduced water content of the mushroom as a function of time for through-flow drying for two racks in the dryer.

The curves show the same pattern, with rack 1 below rack 2 from the start to the end of drying. To reach a water content reduced by 0.1, the curves for racks 1 and 2 take 150 minutes and 180 minutes respectively. It can be said that the products on the racks reach their equilibrium water content one after the other, as the thermal energy expended by water evaporation is accompanied by air cooling. Similar results have been obtained by [2, 13, 14].

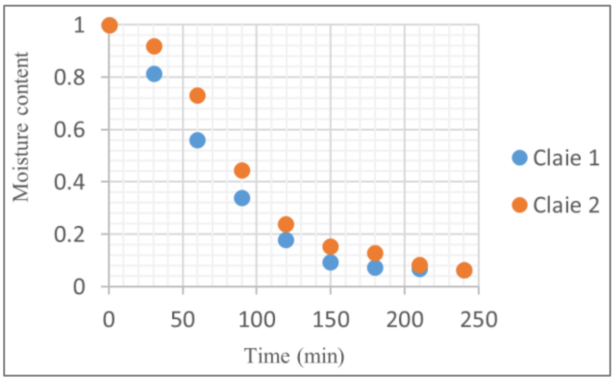


Figure 5. Evolution of reduced water content with time.

3.5. Characterization in the Refrigeration Chamber

Figure 6 shows the temperature trend in the refrigeration chamber as a function of time.

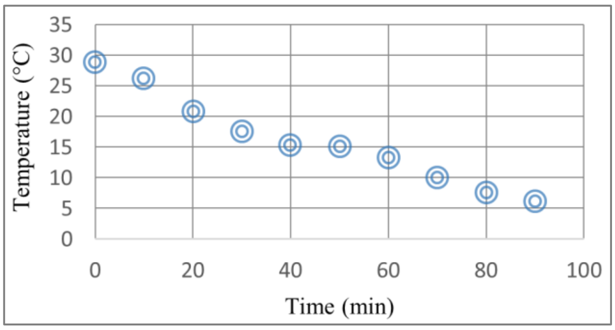


Figure 6. Evolution of the refrigeration temperature as a function of time.

The curve decreases with increasing time. We can see that the curve reaches a temperature of 5°C after 90 minutes. We can see that cold is being produced in our appliance.

4. Conclusions

At the end of this work, the aim was to design and build a system enabling fruit and vegetables to be preserved simultaneously by drying and refrigeration. A prototype thermal dryer coupled with a refrigeration machine was designed to meet this need. The drying cabin has a drying area of around 0.74 $m^2$for a capacity of 1 kg of fresh produce, and the refrigeration chamber is around 0.42 m^2 The resulting condenser power of 489.24W produces a drying temperature of 48°C. Our refrigeration machine produces cold at a temperature of 5°C.

Latin symbols

Symbol	Name	unit
Cp	Specific heat	J kg $^{-1}$ K $^{-1}$
d	Distance	m
e	Thickness	m
h	Enthalpy	J/kg
h	Convective coefficient	W m^{-2} K^{-1}
K	Exchange coefficient	W/m ^{2} ℃
L	Latent heat	J/kg
m	Mass	kg
P	Power	W
P	Pressure	Pa
Q	Heat quantity	J
S	Surface	m ^{2}
t	Time	s
T	Temperature	℃
U	Speed	m s $^{-1}$
X	moisture content	

Greek symbols

Symbol	Name	unit
υ	Viscosity	m ^{2} s $^{-1}$
λ	Thermal conductivity	W m $^{-1}$ K $^{-1}$

Subscripts

Symbol	Name
u	Useful
lib	Free
li é	Linked
e	Water, evaporator
i	Initial
f	Fresh, final
cp	Compressor
cd	Condenser
a	Air
T	Total

Figure 7. *Nomenclature.*

Abbreviations

COP	Coefficient of Performance
Cp	Specific Heat, J kg^{-1} K^{-1}
d	Distance, m
e	Thickness, m
h	Enthalpy, J/kg
h	Convective Coefficient, W m^{-2} K^{-1}
K	Exchange Coefficient, W/m²°C
L	Latent heat, J/kg
m	Mass, Kg
P	Power, W
P	Pressure, Pa
Q	Heat Quantity, J
S	Surface, m²
t	Time, s
T	Temperature, °C
U	Speed, m s^{-1}
X	Moisture content
υ	Viscosity m^2 s^{-1}
λ	Thermal Conductivity W m^{-1} K^{-1}
u	Useful
lib	Free
lié	Linked
e	Water, Evaporator
i	Initial
f	Fresh, Final
cp	Compressor
cd	Condenser
a	Air
T	Total

Author Contributions

Roger Yannick Ekani: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing

Rutheel Brunda Kenvo Lemdjo: Conceptualization, Data curation, Software, Validation, Writing – review & editing

Serge Kewou: Visualization, Supervision, Software

Marcel Edoun: Visualization, Validation, Supervision, Investigation

Conflicts of Interest

The authors declare no conflicts of interest.

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