Energetic Analysis in a Spray Drying Process

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Abstract: The present work aims to evaluate the installation of an equipment of spray drying by psychrometry technique, analyse the power sources consumption and relate with the productivity of the equipment by energy auditory. This work consists of comparing the evaporation capacity of a 750 kg/h of water spray dryer and the amount of water that comes from atmospheric air, where the equipment consumes 160 kWh and 80 kg of LGP/h. Therefore, this work demonstrates that in order to project a spray dryer, it must be analysed by these water mass values in atmospheric air and be contemplated by a dehumidifier in order to prevent so significant and different losses in different periods of the same day.

Keywords: Energetic resources, Productivity, Psychrometry.

1. INTRODUCTION

Human beings, using their intelligence, have searched ways to win obstacles built by nature. They have developed invented several something else with the objective of overcoming these difficulties. As someone has said before, “necessity is the mother of great technological developments”.

Globally, drying is the most widely used method for preserving foods for use in homes or for sale [1].

Spray drying is a process carried out in a closed chamber, which aims to remove moisture from a product by transferring heat and mass from the water contained in the product to the air that is previously heated.

This process has stages that are very characteristic of it. The liquid feedstock (usually aqueous) is first atomised into a spray of spherical droplets, then contacted with a drying medium (usually air) with results in evaporation of moisture from the droplets. Drying proceeds as the droplets and the air pass through the drying chamber [2].

The micro-capsule content is commonly called in technical literature as active agent, internal phase or core. The material that forms external part is commonly called as covering, membrane, encapsulate agent, carrier, peel or shell. The core material has, in general, 80-85 % of capsules. The encapsulated matter can be released by mechanical action, that is, by shell disruption through pressure or physical-chemical variations of temperature or pH in the element that the capsules are in, acting on the membrane [5].

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Figure **1** shows a microscope picture of micro-capsules and Figure **2** shows two examples of this one.

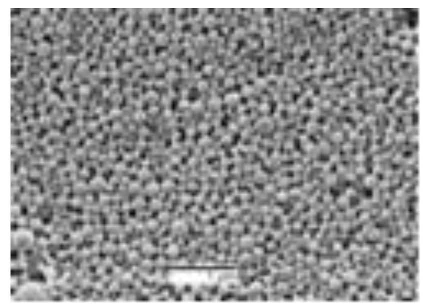

Figure 1: Micro-capsules viewed through a microscope [3].

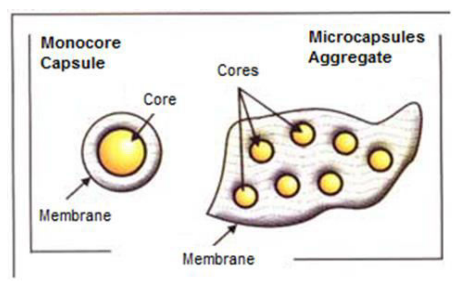

Figure 2: Micro-capsule structure [4].

The food industry uses smell micro-capsules, sauce essence and others. These additives are encapsulated with the intention of enlarging their utile life, reducing the volatilisation and the oxidative degradation. Additional advantages include their easiness of annexation in powder mixes and improved consistency [4].

Below mentioned is a brief description of the process showing the most important stages in order to understand the spray drying process clearly.

The **emulsion preparation** is made previously in a tank under agitation for dissolution and homogenisation of its ingredients.

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The **spray drying equipment**, or reactor, (Figure **3**) is a conical drying chamber that sprays emulsion by atomisation. Its purpose is to evaporate the water from the emulsion and cause the micro-encapsulation effect.

The **product encapsulated** is the micro-encapsulated active principle, which acquires the dust form and, therefore, is the final product of the process.

Figure 3: Spray dryer device [3].

Figure **4** shows a spray drying draft with its air flows and matters internal to the reactor.

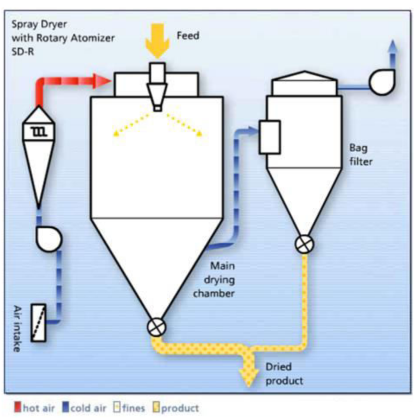

Figure 4: Simplified flow sheet for spray dryer [3].

From Figure **4**:

1. hot air is the hot air flowing in chamber;
2. cold air is the cold air flowing in the chamber;
3. fines are emulsion particles pulverised by atomisation in chamber;
4. product is the final product in powder, encapsulated active principle.

Previously, an emulsion formed basically with water, an encapsulant, and an active ingredient (aroma) was prepared. The emulsion is sprayed by atomisation (Figure **4**, fines) in a drying chamber against a hot air flow (Figure **4**, hot air), water evaporates instantaneously and a thin dust (Figure **4**, product) particle from 10 to 200 micron is collected in cyclone. The aromatic principles are encapsulated in a support matrix formed by encapsulation, being protected from evaporation and oxidation.

A nozzle atomiser spray dryer was empirically modelled by [6], where the effect of several inputs were considered, such as inlet air temperature, feed flow rate, and maltodextrin concentration on the product quality.

A combined supply of heat by convection and infrared radiation, the heat flux density in the infrared radiation device, and the intensity of mixing the gas phase were working parameters considered by [7] in experimental investigations of a spray drying installation.

The aromas inserted in the vast majority of dehydrated products today are produced by this process. The encapsulation technique is applied, mainly, to increase the lifetime in the shelf of an aroma (shelf-life) and still, for reason of process adequacy. For example, in dehydrated mixtures, such as juices and jellies, it would be more difficult or impractical to add a liquid aroma, therefore, the powdered aroma (encapsulated) is used.

The micro-encapsulation of foods uses formularisations the contends the ingredients to be preserved in mixture with the most varied encapsulating agents of amides or its derivatives, proteins, gums, lipids, or combinations between these agents. The drying technology is the second step of choice: atomised drying, drawing, molecular inclusion, co-crystallisation, and many others according to [8].

The micro-capsules are formed by the involvement of the active matter or core with the wall matter or capsule. The micro-capsules can have diameter varying between units of micrometres till millimetres and present diverse forms depending on the materials and methods used for its attainment. The micro-encapsulation of essential oil involves the following stages: choice of wall materials suitable for essential oil for encapsulation preparation of the emulsion, consisting of the solution of the wall matter and the oil, and emulsion homogenisation. Finally, the emulsion drying by atomisation in the dryer will form globules that can contain internal bubbles and smooth or rugous surfaces [8, 9].

The variety of encapsulating, commonly used in micro-encapsulation, is relatively limited and includes natural gums, carbohydrates, proteins, waxes, and some natural polymers that are chemically modified [10, 11]. According to [12], for encapsulation to have an adequate performance, it will have to fulfill the following conditions: to hinder the loss perfuming components, to have the capacity to involve the active material, resulting in a free-draining powder with easy handling and incorporation into dry nutritious mixes and to protect the active matter of the oxidation, light, and humidity during the shelf life.

The micro-encapsulation can be defined as a process in which a membrane involves small particles of solid, liquid or gas with the objective to protect the protect the matter from adverse conditions such as such as light, humidity, oxygen and interactions with other composites, stabilising the product, increasing the useful life and promoting the controlled release of encapsulated in conditions pre-established [8].

The drying by atomisation (spray drying) is one of the most used methods for the micro-encapsulation due to great availability of equipment, low cost of the process, possibility of use of an ample variety of encapsulating agents, good retention of volatile composites, and stability of the end product [13].

The theory of active matter retention explains that this one volatilises a little during the drying, if the wall matter quickly forms a semi-permeable film around the droplets of atomised emulsions, in order to allow the diffusivity of the water while it holds back the active matter [14, 15].

If this semi-permeable film forms micro-capsules exempt of any superficial deformation, the wall matter effectiveness will be bigger than the one in the active matter retention. Then the evaluation of the wall matter components depends on the concentration of the mixture and of the process parameters that influence in the formation of the superficial structure of the micro-capsules. Therefore, a wall matter is adequate when the final product is constituted of complete micro-capsules, that is, the active matter will be completely involved and protected from the environment by the wall matter. According to [16], the functionality of the micro-capsules is critically dependent on its superficial structure.

The energy performance of an industrial scale spray dryer was explored through its energy efficiency and energy saving calculation based on a comprehensive mathematical model, such as the response surface methodology (RSM), considering the effect of process parameters on energy performance using a space-filling design [17]. A comparison between two spray drying techniques was presented by [18] in order to obtain the best energy consumption and quality of the final product. The performance of the spray drying process and the drying system were evaluated through energy and exergy analyses by [19].

A laboratory-scale spray dryer was used to determine the most suitable drying conditions for the manufacture of sugarcane juice powder. After that, an industrial-scale spray dryer was developed to corroborate the results obtained in the laboratory [20].

The reduction of energy consumption in spray drying through the generation of mono-disperse droplets was evaluated by [21] based on the heat and mass balances and the dynamics of droplet displacement in a single flow spray dryer, where correlations were established for the drying gas temperatures that satisfy certain moisture content of the output product for droplet flows of different diameters.

The influence of spray drying conditions on the energy required, on the production cost, and on the physical and chemical characteristics of the product was investigated by [22], where the inlet air temperature (180-220 ^{o}C), the outlet air temperature (80-100 ^{o}C), and silica and maltodextrin (DE-10) as additives were the factors investigated.

The study by [23] had proposed to estimate a safe drying temperature for a spray drying system, as well as the specific energy consumption.

A closed-loop cycle dryer system was introduced by [24] to reduce energy consumption during its use, where the system is based on a mono-dispersed droplet atomiser that reduces the amount of fines in the exhaust air and allows dehumidification and air recirculation by the dryer.

An educational module based on Excel© Visual Basic for Applications (VBA) was developed by [25] in order to simulate the operation of the spray drying process with a focus on its use in the chemical, ceramic, food and pharmaceutical industries for the production of high volume and high value particulate products.

More energy efficient techniques are being used OR suddenly being used to reduce energy consumption in spray drying processes, such as pre-concentration of feed liquids through membrane reactors or falling film evaporators [26].

Psychrometry is the study of the air and water vapour mixtures, that is, the study of humid air – in the limit, study of binary mixtures in which one of the components is a condensable vapour [27].

The psychrometry can be applied in [27]:

- climate control, especially in air conditioning for thermal comfort.
- condensation on cold surfaces (dew on the grass on a cold morning the water on the external surface of a beer cup), etc.
- the evaporative cooling.
- the white tracks left by the turbines of the air-planes.

The psychrometrics properties are [27]:

- temperature of dry bulb,
- temperature of humid bulb,
- relative humidity,
- absolute humidity,
- specific enthalpy, and
- specific volume.

As psychrometrics processes there are [27]:

- heating,
- humidification,
- cooling and dehumidification,
- mixture of two air flows, and
- insufflations in the environment.

This work presents an analysis of a drying technology known as spray drying that nowadays is considered the most useful and important drying technology, overcoming the freeze-drying technology, which is a drying process of products under temperature and pressure conditions in which the water that is previously frozen, passes from the solid phase directly to the gas phase (sublimation) [28, 29].

The present work aims to evaluate the installation of an equipment of spray drying by psychrometry technique, analyse the power sources consumption and relates with the productivity of the equipment by energy auditory. Therefore, to apply the psychrometry in order to calculate how much water is coming from the air humidity, it can be deposited on the equipment, compromising its production capacity, and then assessing whether energy resources such as liquefied petroleum gas (LPG) and electricity are in fact the best used in this industrial process.In such a way the work will be able to contribute as a source of information for future installations of spray dryer devices in any facility.

2. MATERIALS AND METHODS

This work consists in comparing the evaporation capacity of a 750 kg/h of water spray dryer and the amount of water that comes from atmospheric air [30-32].

This evaluation was carried out on Friday, 06/19/ 2020 and the measurements of temperature and relative humidity for the schedules of 09h00, 15h00, and 21h00.

After that the amount of water, in g/kg of dry air, can be identified in psychrometric chart. The specific volume of water is determined through interpolation, in m^3/kg of dry air.

From the compressor air flow of 27,000 m^3/h that the device consumes, it is possible to evaluate the mass flow of air, in kg/h, by dividing this value by the specific volume of air (v) at process inlet, in this case v = 0.91 [m^3/kg].

The amount of water deriving from atmospheric air is evaluated dividing the value of amount expressed in g of water per kg of dry air for each scheduled hour (09h00, 15h00, and 21h00) over the mass flow. The result must be converted from g to kg by dividing the value per 1,000.

The equipment consumes 160 kWh and 80 kg of LGP/h.

In order to obtain the results listed in section 3, Eqs. (1) and (3) are used to determine the LPG consumption. Eq. (1) is used to determine LPG's volumetric mass.

$$\dot{m}_{LPG} = \frac{LHV_{LPG}}{\dot{Q}} \quad (1)$$

Where,

$\dot{m}_{LPG}$ is LPG flow mass [kg/h]

LHV_{LPG} is lower heating value of LPG [49,030 kJ/kg]

$\dot{Q}$ is the burner energy [GJ/h]

The burner energy is calculated by Eq. (2).

$$\dot{Q} = \dot{m}_{air} \cdot \left(h_{burner.out} - h_{burner.in}\right) \quad (2)$$

Where,

$\dot{Q}$ is the burner energy [GJ/h]

$\dot{m}_{air}$ is air flow mass [kg/h]

$h_{burner\cdot out}$ is burner's output specific enthalpy [kJ/kg]

$h_{burner\cdot in}$ is burner's input specific enthalpy [kJ/kg]

The total water mass is calculated only for the current process, in order to determine the water evaporation capacity of the spray drying through Eq. (3).

$$\dot{m}_{water} = \dot{m}_{air} \cdot \left(w_{out} - w_{in}\right) \quad (3)$$

$\dot{m}_{water}$ is water flow mass [kg/h]

$\dot{m}_{air}$ is air flow mass [kg/h]

w_{out} is chamber's output absolute humidity [$kg_{water}/kg_{dry\cdot air}$]

w_{in} is chamber's input absolute humidity [$kg_{water}/kg_{dry\cdot air}$]

The dew point of the air at the outlet of the dehumidifier will be determined as 3 °C in the refrigeration process [33] and - 40 °C in the adsorption process [34], which are based on the ISO 7183 standard [35].

Also, a mass and energy balance is made in order to validate all calculations presented, according to Eqs. (4) to (8).

$$\sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out} \quad (4)$$

$\dot{m}_{in}$ is total mass flow in the inlet [kg/h]

h_{in} is total specific enthalpy in the inlet [kJ/kg]

$\dot{m}_{out}$ is total mass flow in the outlet [kg/h]

h_{out} is total specific enthalpy in the outlet [kJ/kg]

By replacing the parcels for each by-product of the spray drying system, Eq. (5) is obtained.

$$\dot{m}_{air.in} h_{air.in} + \dot{m}_{product.in} h_{product.in} + \dot{m}_{water.in} h_{water.in} =$$
$$\dot{m}_{air.out} h_{air.out} + \dot{m}_{product.out} h_{product.out} + \dot{m}_{water.out} h_{water.out} \quad (5)$$

$\dot{m}_{air\cdot in}$ is flow mass in the air inlet [kg/h]

$h_{air\cdot in}$ is specific enthalpy in the air inlet [kJ/kg]

$\dot{m}_{product\cdot in}$ is flow mass in the product inlet [kg/h]

$h_{product\cdot in}$ is specific enthalpy in the product inlet [kJ/k

$\dot{m}_{water\cdot in}$ is flow mass in the water inlet [kg/h]

$h_{water\cdot in}$ is specific enthalpy in the water inlet [kJ/kg]

$\dot{m}_{air\cdot out}$ is flow mass in the air outlet [kg/h]

$h_{air\cdot out}$ is specific enthalpy in the air outlet [kJ/kg]

$\dot{m}_{product\cdot out}$ is flow mass in the product outlet [kg/h]

$h_{product\cdot out}$ is specific enthalpy in the product outlet [kJ/kg]

$\dot{m}_{water\cdot out}$ is flow mass in the water outlet [kg/h]

$h_{water\cdot out}$ is specific enthalpy in the water outlet [kJ/kg]

Considering $\dot{m}_{product.in} = \dot{m}_{product.out} = \dot{m}_{product}$ and rearranging Eq. (5) gives (6).

$$\dot{m}_{air.in} h_{air.in} + \dot{m}_{product} \cdot \left(h_{product.in} - h_{product.out}\right) =$$
$$\dot{m}_{air.out} h_{air.out} + \dot{m}_{water.out} h_{water.out} - \dot{m}_{water.in} h_{water.in} \quad (6)$$

The enthalpy difference can be represented by Eq. (7).

$$\left(h_{product.in} - h_{product.out}\right) = Cp \cdot \left(T_{product.in} - T_{product.out}\right) \quad (7)$$

Where,

Cp is the specific heat of product at constant pressure [kJ/kg.°C]

Using Eq. (7) in Eq. (6), Eq. (8) is obtained.

$$\dot{m}_{air.in} h_{air.in} + \dot{m}_{product} \cdot Cp \cdot \left(T_{product.in} - T_{product.out}\right) =$$
$$\dot{m}_{air.out} h_{air.out} + \dot{m}_{water.out} h_{water.out} - \dot{m}_{water.in} h_{water.in} \quad (8)$$

Where,

$T_{product\cdot in}$ is the product temperature in the inlet [°C]

$T_{product\cdot out}$ is the product temperature in the outlet [°C]

3. RESULTS AND DISCUSSION

The temperature and relative humidity data were tajen on 06/19/2020, a psychrometric chart was plotted based on the psychrometric chart of Figure **5**.

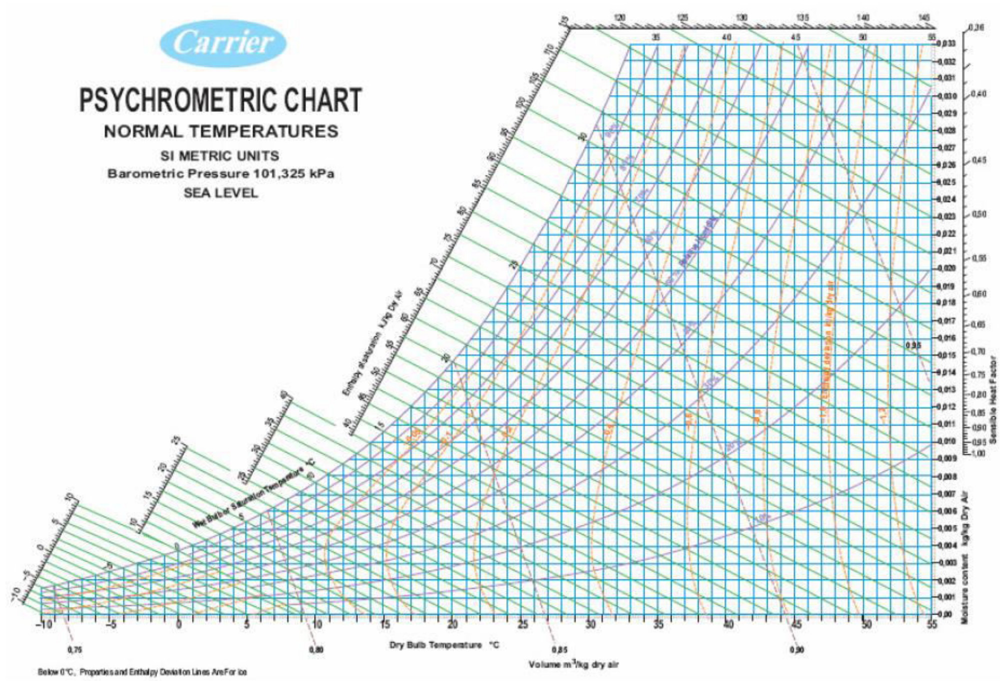

Figure 5: Carrier's psychrometric chart for normal temperatures in SI metric units [3].

Table **1**: relates absolute humidity (g of water over kg of dry air).

Table 1: Absolute Humidity (*w*)

Schedule	Temp. [°C]	RH[a] [%]	*w* [g/kg]
09h00	23	87	15.5
15h00	27	48	11
21h00	13	55	5

[a] RH = Relative humidity.

The intersection points of temperature and relative humidity do not find the straight lines of specific volume; therefore, there was a need to make an interpolation with the points above and below. Table **2** shows these interpolations.

Specific volume was determined by interpolation so that air mass flow can be calculated based on the volumetric mass flow, as related in Table **3**.

Table 2: Interpolations

	Ref #1	Ideal	Ref #2
Interpolation at 09h00			
Specific volume [m³/kg]	0.85	0.8600	0.9
Temperature [°C]	19.5	23	37
Interpolation at 15h00			
Specific volume [m³/kg]	0.85	0.8651	0.9
Temperature [°C]	21.8	27	39
Interpolation at 21h00			
Specific volume [m³/kg]	0.8	0.8171	0.85
Temperature [°C]	7	13	24.5

With these calculations, it is possible to observe that in the same day, there was a great variation in the mass flow, being that this amount of water reduces the projected productivity for an equipment that supports up to 750 kg/h of evaporated water to values that are deducted from mass flow of water from atmospheric air.

Table 3: Air Mass Flow

Schedule [h]	Temp. [°C]	RH [%]	*w* [g/kg]	*v* [m³/kg]	$\dot{m}_{air}$ [m³/h]	$\dot{m}_{air}$ [kg/h]	$\dot{m}_{w}$ [kg/h]
09h00	23	87	15.5	0.8600	27,000	31,395.35	486.63
15h00	27	48	11	0.8651	27,000	31,209.68	343.31
21h00	13	55	5	0.8171	27,000	33,041.96	165.21

Table 4: Real Productivity

Schedule [h]	Temp. [°C]	RH [%]	$\dot{m}_w$ [kg/h]	Productivity [kg/h]
09h00	23	87	486.63	263.37
15h00	27	48	343.31	406.69
21h00	13	55	165.21	584.79

This productivity reduction demonstrates the bad use of the energy resources for the operation of the equipment.

The equipment was projected to evaporate water to evaporate water at a rate of 750 kg/h, consume 80 kg/h of LPG to heat air at a rate of 27,000 m^3/h, and to demand 160 kWh of electrical energy.

However, it can be seen in Table **3** that during the same day, in different schedules, same rate of LPG and electricity is consumed, evaporating a lower rate of water thus limiting productivity.

4. CONCLUSIONS

The following conclusions with regard to the energy resources use has been drawn during June 19th, 2020 according to the results obtained:

- At 09h00, with temperature of 23 °C and relative humidity of 87 %, a real water evaporation capacity of 263.37 kg/h was observed which is equivalent to 64.88 % of wastefulness.
- At 15h00, with temperature of 27 °C and relative humidity of 48 %, a real water evaporation capacity of 406.69 kg/h was observed which is equivalent to 45.77 % of wastefulness.
- At 21h00, with temperature of 13 °C and relative humidity of 55 %, a real water evaporation capacity of 584.79 kg/h was observed which is equivalent to 22.03 % of wastefulness.

For these percentages of productivity losses, LPG and electricity consumption are the same. Then part of these energy resources is wasted with the water excess that comes from atmospheric air. That is, part of the time, LPG and electricity are being used to evaporate water of atmospheric air and not water of the product that desires to dehydrate.

Therefore, this work demonstrates that to project a spray dryer, it must be the values of water mass in the atmospheric air must be analysed and contemplated in a dehumidifier dehumidifier in order to prevent significant losses in different periods in different periods of the same day.

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