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Industrial Maltodextrin Production and Impacts on Dryer and Product Performance

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Abstract

Maltodextrins are products of partial hydrolysis of starch and have been widely used in many types of processed foods. They are classified according to the degree of hydrolysis of the starch and have several properties such as sweetness, solubility, and viscosity. It also consists of a product with wide applicability, such as energy supplements. The product density is very important, since its variability may not meet the specification of some customer companies. This causes problems in the storage of the final product, causing a possible safety risk in storage. The product will not be positioned on the pallets or there will be damage to the packaging due to due storage, generating financial losses or product returns. The decision to conduct current research on maltodextrin quality control has matured after realizing that the final density has an impact on storage and on the customers' satisfaction. This work aims to verify the influence of spray drying parameters on the apparent density of maltodextrin in six batches. After the evaluation, it was identified that the vacuum variation in the spray dryer caused deviations in the final product density. In addition, the mass and executive energy balance is calculated when drying the maltodextrin batches. The process losses and the thermal efficiency of the spray dryer were calculated in this study for future knowledge and actions. The glass transition temperature was evaluated in the spray dryer operating conditions and considerations were made for studies. The study showed that among the quantified parameters, the vacuum applied in the spray dryer that influenced the apparent density of maltodextrin and the operation of the dryer should operate with an average vacuum of 44 mmCa, since the other drying parameters presented similar values and, therefore, without influence on apparent density. The mean porosity of maltodextrin was 0.7018±0.017. According to manufacturer information (NIRO-GEA), the evaporation capacity is 1200.00 $kg \cdot h^{-1}$ and the average of the evaporated water mass rate in the system is 876.66 $kg \cdot h^{-1}$, which leads to the conclusion that the spray dryer was operating at 73% of the design capacity during the production phase.

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The density of the liquor is 1310.62±2.81 $kg \cdot m^{-3}$. The mean mass rate of maltodextrin not recovered in the process calculated by mass balance is 269.53±122.90 $kg \cdot h^{-1}$. The drying system showed an energy loss rate of 1,792,962 ± 55,349$kJ \cdot h^{-1}$, which consists of a loss of 17%. The thermal efficiency of the system was 0.27±0.01, which means that 27% of the energy is used for drying the product. The value of the glass transition temperature (Tg) calculated for this drying system is between 150.0°C to 151.8°C, the output temperature of the dryer chamber between 106.12°C to 107°C and the air inlet temperature in the dryer between 192.08°C to 196.43°C. The internal operating temperature of the dryer is below the glass transition temperature of the final product. This makes it possible to classify the product as vitreous.

Keywords: Maltodextrin; Mass balance; Energy balance; Glass transition temperature.

1. Introduction

The current research on maltodextrin was motivated by the fact the its density is an important parameter of the final product because it significantly influences the commercial area and the number of its applications.

The objective of this research was to study the operational variables in spray drying for maltodextrin production, considering the evaluation of the quality parameters of both the intermediate liquor, and the maltodextrin. The identification of which variables could have more influence on the apparent density of the product, and the determination of the energy efficiency data for a given drying system were also some of the purposes of this research.

1.1. Starch and Maltodextrin

Chemically, starch consists of a carbohydrate formed by atoms of carbon, hydrogen, and oxygen in the ratio 6: 10: 5 ($C_6H_{10}O_5$), consisting of glucose units linked by the carbon C1 of one of them, to the carbon C4 of the other, called glycosidic bonds [1]. Two types of molecules occur: amylose, formed glucose units joined by α (1→4) glycosidic bonds, whose number can vary from 300 to 2,000; the branched-chain amylopectin, branched at intervals of 15 to 30 glucose units, joined with α-amylose-type bonds (1→4) and α bonds (1→6) [2]. The amylose molecule acquires a helix conformation into which the amylopectin is inserted. The spiral is responsible for the color showed by the complex formed by starch and iodine. The color intensity is related to the chain length associated with the degree of polymerization, GP, as shown in Table 1.

Table 1: Color generated as a function of the polymerization degree (PG) of glucose units [1].

PG	Color
45	blue
35-40	purple
20-30	red
12-15	brown
12	colorless

Maltodextrin is, by definition, a hydrolyzed starch formed by α-D-glucose units linked mainly by glycosidic bonds (1→ 4). Maltodextrin is a hydrolyzed product of starch and consists of a mixture of saccharides, mainly D-glucose, maltose and a series of oligosaccharides and polysaccharides. Therefore, it has a wide molecular mass distribution [3].

The dextrose-equivalent (DE) expresses the number of aldehyde groups with reduced ends in relation to pure glucose. Thus, high dextrose equivalent (DE) indicates high hydrolytic conversion and low molecular weight. Depending on the degree of hydrolysis of the starch molecule, the product obtained is classified as maltodextrin (if the DE value is less than 20) or syrup (DE equal to or greater than 20) [4].

1.2. The Maltodextrin Production Process

The process for producing liquid maltodextrin having a DE between 5 and 20% begins by mixing starch with an amount of water sufficient to provide a starch solution around 50% DS (% dry solid). An amount of α-amylase sufficient to hydrolyze the starch is added to this solution. This starch slurry is evaporated to obtain a starch solution with DE between 0.5 and 5.0%. The enzymatic process involves two steps of α-amylase addition. In the first step, the solution is heated from 120 to 165°C for a period of 30 seconds to 10 minutes. It is then kept at a temperature between 101°C and 115°C, for up to 10 minutes in a pressure vessel. In the second step of adding α amylase, the solution is kept between temperatures of 93°C to 100°C for enough time to obtain the product with DE between 5 and 20% [5]. Figure 1 presents a scheme of the conversion of starch to maltodextrin.

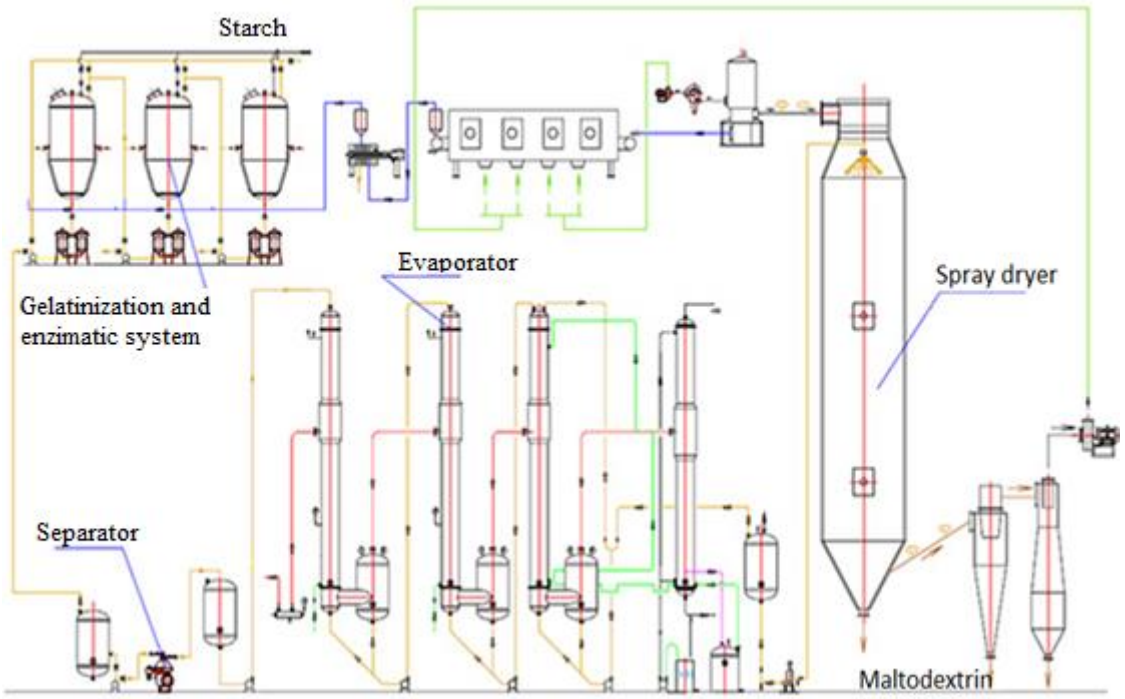

Figure 1: Schematic representation of the process of converting starch into maltodextrin [6].

1.3. Spray dryer

Spray drying is one of the types of drying technology, which is suitable for processing solutions, suspensions, and slurry-like materials. The feeding liquid can become fog droplet in micron dimension, then they are rapidly dried into particles with a diameter about 30 to 500 μm by hot air within 5~30 s. Spray drying has been widely used in chemical industry, biological and food processing, pharmaceutical manufacture, and other fields due to its continuous and automatic operation, instant dry, low labour intensity, and good working environment. However, spray drying is a kind of unit operation with high energy consumption and relatively low energy utilization. The hot air is used as the drying medium in spray dryer. It was reported that the heat efficiency of spray dryer is about 25% to 60%, and some are below 20% [7].

Spray drying is a unit operation by which a liquid-phase material is atomized into a stream of hot gas to instantly obtain a powder. The initial liquid that feeds the sprayer consists of a solution. The production of dry maltodextrin and other materials must conform to the desired physical and chemical properties of the product. The characteristics of the final product depend on spray drying conditions, including drying aid concentration, inlet air temperature and feed mass [8]. Figure 2 illustrates the drying operation [9].

The spray drying process is widely used in food and chemical industry to produce a large variety of powders. Prediction of particle stickiness as a function of operating conditions of spray drying could help minimizing operational problems or could be used to perform agglomeration to modify final powder properties. At the beginning of the spray drying process, liquid drops (20–40 μm) are formed by the atomizer and are put in contact with the hot drying medium. Temperature and water vapor pressure differences between drops and hot drying air are high. Consequently, fast evaporation from each drop surface occurs and, during the drying phase, very rapidly the particles behave as a moisture core with a dry surface. The water content of the particles decreases strongly in some seconds [10].

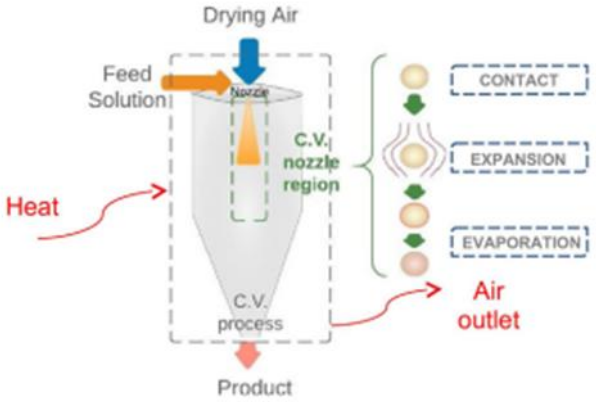

Figure 2: Flows in an atomization dryer under vacuum operation [9].

1.4. Glass transition temperature

The glass transition temperature (Tg) is the center of a range around 20 °C or higher in which transformation occurs. Below Tg, a material is in a glassy state that is characterized by a rigid, although friable, solid with viscosity on the order of 1012 Pa.s. In the vitreous states, the mobility or diffusion of molecules is practically

non-existent. When the temperature of the material is above the glass transition temperature, the glassy material becomes sticky and presents a considerable decrease in viscosity and an increase in mobility [11].

During the spray drying process, in presence of specific components as carbohydrates, the surface viscosity increases up to a critical value for which the particles surface can be considered as sticky. Sticky behavior depends on composition, temperature, and water content, in relation to the glass transition phenomenon. The surface of each particle surface will be sticky for temperatures between 10°C and 30°C, higher than the glass transition temperatures. Below glass transition, particles will be like to a stable glass [10].

Depending on the kind of the processed material, and on the type of dryer, there are several phenomenological aspects mentioned by BUCEK and his colleagues [15].

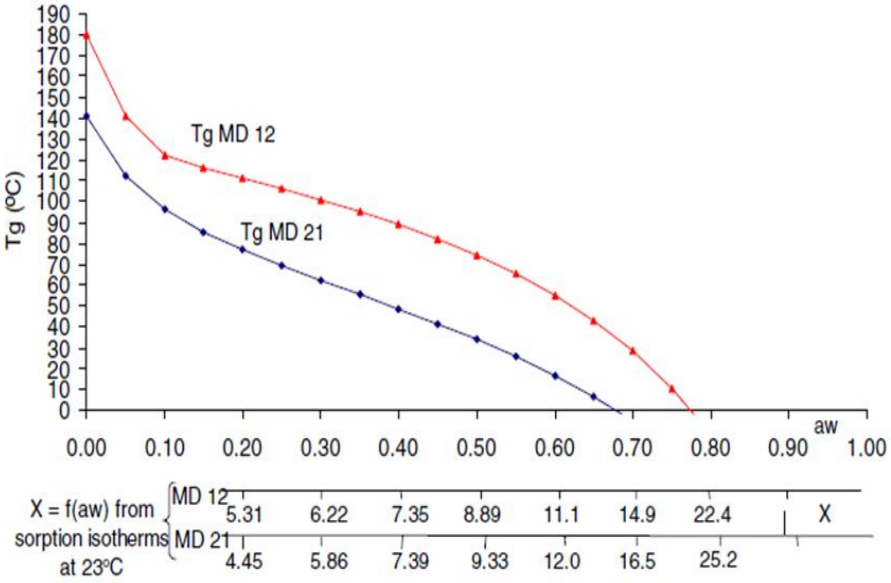

Figure 3: Evolution of glass transition temperatures of maltodextrin DE12 and DE21 as a function of water content and water activity [10].

2. Material and methods

To carry out the analysis of the maltodextrin liquor and the final product, the internal methods of the Cargill factory were used.

In the analysis of pH in liquor and maltodextrin, 10 g of sample is weighed in a beaker, adding 90 mL of distilled water. This solution is stirred until becoming completely dissolved. The pH reading is carried out, using the Gehaka equipment, Model PG200, Sensor from Digimed DME-CV2.

In the method of analysis of iodine in liquor, the determination of hydrolyzed starch is based on the reaction of a complex of iodine with starch that results in the production of the blue color. A solution of 0.02 N of iodine is added to a solution prepared with product and deionized water, cooled between 2.0°C to 4.0°C. Then, it is

necessary to wait two minutes to assess the color of the solution. In the technique, 50 mL of undiluted starch hydrolysate and 25 mL of deionized water are added. It is necessary to stir until complete dissolution is achieved. The sample is placed in a refrigerator to be cooled from 2.0°C to 4.0°C, and 0.02 N of iodine dropwise is added until a slight color is obtained. While shaking the sample, exactly 1.0 mL of 0.02 N iodine must be added. Note the initial blue or purple color. The final reading is taken after two minutes of reaction time. The colors evaluated in this method are: Blue (A), and Brown (RB). The Osmometer (Advanced Instruments, Inc. Model: 3250) is an instrument for measuring the freezing point depression. The sugars present in the starch hydrolysate decrease the freezing point in direct proportion to the dextrose equivalence. By preparing a sample of known concentration and measuring the freezing point depression, the dextrose equivalence can be easily calculated. The method consists of weigh 12 to 13 g of sample, dilute the sample to 13% solids, pipette 25 µL of the sample into the osmometer and read. The dextrose equivalence value is calculated by Equation (1).

$$DE = 0.14 \cdot mOSm - 1,18 \quad (1)$$

DE = Dextrose equivalence (%).

The determination of bulk density is carried out by adding the sample to a calibrated 100 mL beaker in the "magnetic feeder" equipment. Then, the beaker with the product is weighed on an analytical balance. Equation (2) allows the calculation of the apparent density.

$$\rho_{r\ mtx} = (m_2 - m_1) \cdot 1000 / 100\ mL \quad (2)$$

$\rho_{r\ mtx}$= Bulk density of solid product ($kg \cdot m^{-3}$); m_2 = Sample and beaker mass (g); m_1= Mass of the beaker (g)

This method of Baumé determination uses the refractive index reading. The refractive index reading is obtained using the refractometer (brand: Antoon Paar; model: ABBEMAT). For the Baumé determination, a conversion table is used relating refractive index, % dry solid (% DS), and Baumé for this product, when the chemical composition and the sample temperature are known. To determine the moisture (U) in the maltodextrin sample, a 5 g sample was placed in a forced-air oven at 130ºC for 1 hour. The sample needs to be cooled in a desiccator for 30 minutes. Equation (3) is used to calculate the moisture of the dry product.

$$U\ (\%) = (m_5 - m_3) / (m_4 - m_3) \cdot 100 \quad (3)$$

m_3= Mass of crucible (g); m_4 = Mass of sample and crucible (g); m_5= Mass of crucible and dry sample (g)

2.1. Specific heat and Specific density

The relation by VAN BEEK (1976), cited by Souza [16] consists of a more general model for calculating the specific heat of food. The model indicates that the specific heat can be established by knowing the composition and specific heat of each component, Equation (4).

$$c_p = \sum (c_{pi} \cdot X_i) \quad (4)$$

c_p = Specific heat ($kJ \cdot kg^{-1} \cdot ºC^{-1}$); X_i = Mass fraction of component i; c_{pi} = Specific heat of component i ($kJ \cdot kg^{-1} \cdot ºC^{-1}$).

To calculate the specific heat of the Maltodextrin components, data published by CHOI and OKUS (1986), cited by Souza [16], were used. Table 2 presents the equations relating the calculation of specific heat of food components and temperature.

Table 2: Equations for determining specific heats for food components

Component	Temperature Relationship	Standard Deviation	Standard Deviation (%)
Protein	$c_p = 1.9842 + 1.4733 \times 10^{-3}T - 4.8008 \times 10^{-6}T^2$	0,1147	5,57
Carbohydrate	$c_p = 1.54884 + 1.9625 \times 10^{-3}T - 5.9399 \times 10^{-6}T^2$	0,0986	5,96
Fat	$c_p = 1.9842 + 1.4733 \times 10^{-3}T - 4.8008 \times 10^{-6}T^2$	0,0236	1,16
Ash	$c_p = 1.0926 + 1.8896 \times 10^{-3}T - 3.6817 \times 10^{-6}T^2$	0,0296	2,47
Water (<0ºC)	$c_p = 4.0817 - 5.3062 \times 10^{-3}T + 9.9516 \times 10^{-4}T^2$	0,0988	2,15
Water (>0ºC)	$c_p = 4.1762 - 9.0864 \times 10^{-5}T + 5.4731 \times 10^{-6}T^2$	0,0159	0,38
Ice	$c_p = 2.0623 + 6.0769 \times 10^{-3}T$	0,0014	0,07

For the determination of density, the mass fraction and density of food components are used. The food components are protein, fat, carbohydrate, ash, and water. In this study, as the mass fractions of fat, protein and ash are very small, they were not used to calculate the specific heat of liquor or maltodextrin. Equation (5) presents the calculation of density.

$$\rho = 1/ \sum(X_i/\rho_i) \quad (5)$$

ρ = Density ($kg \cdot m^{-3}$); X_i = Mass Fraction of component i; ρ_i = Component i density ($kg \cdot m^{-3}$).

The density values of each food component are obtained by the equations of CHOI and OKUS (1986), cited by Souza [16] and presented in Table 3, which relates density to temperature.

Table 3: Equations for the determination of density for food components.

Component	Temperature relationship	Standard error	Standard error (%)
Protein	$\rho = 1.3299 \times 10^3 - 5.184 \times 10^{-1}T$	39,9501	3,07
Carbohydrate	$\rho = 1.59919 \times 10^3 - 3.1046 \times 10^{-1}T$	93,1249	5,98
Fat	$\rho = 9.2559 \times 10^2 - 4.1757 \times 10^{-1}T$	1,2554	0,47
Ash	$\rho = 2.4238 \times 10^3 - 2.8063 \times 10^{-1}T$	2,2315	0,09
Water	$\rho = 9.9718 \times 10^2 + 3.1439 \times 10^{-3}T - 3.7574 \times 10^{-3}T^2$	2,1044	0,22
Ice	$\rho = 9.1689 \times 10^2 - 1.3071 \times 10^{-1}T$	0,5382	0,06

2.2. Mass Balance

At the entrance of the spray dryer, there are the mass flow rate of the feed solution ($\dot{m}_{lr}$), and the mass flow rate of the atomization air in the inlet of the dryer ($\dot{m}_{a\ u\ e}$). At the outlet, there are the mass flow rate of the atomization air in the outlet of the dryer ($\dot{m}_{ar\ u\ s}$), and the mass flow rate of the dry product ($\dot{m}_{mtx}$), as shown in the vacuum spray dryer system (Figure 2). In this model, it is considered that there is no chemical reaction of the product. Furthermore, the mass of the product accumulated in the control volume is neglected (dm/dt=0). Therefore, the mass balance in a vacuum spray dryer can be written as RAMOS and his colleagues [9], Equation (6):

$$(\dot{m}_{lr} + \dot{m}_{ar\ u\ e}) = (\dot{m}_{mtx} + \dot{m}_{ar\ u\ s}) \qquad (6)$$

$\dot{m}_{lr}$= Mass flow rate of the feed solution (liquor) ($kg \cdot h^{-1}$); $\dot{m}_{ar\ u\ e}$ = Mass flow rate of atomization air in the inlet of the dryer ($kg \cdot h^{-1}$); $\dot{m}_{mtx}$ = Mass flow rate of the dry product (maltodextrin) ($kg \cdot h^{-1}$); $\dot{m}_{ar\ u\ s}$ = Mass flow rate of atomization air in the outlet of the dryer (transport the evaporated water) ($kg \cdot h^{-1}$).

Inside the spray dryer chamber, the solid (s), the liquid (l), and the gas (g) phases are present. The wet air mass rate ($m_{ar\ u}$) consists of water vapor and dry air. The rates of dry air ($\dot{m}_{ar\ e}$) at the inlet (e), and at the outlet (s) of the dryer are equal. Therefore, the mass balance of the water component, on the wet basis, is described as in Equation (7)

$$(\dot{m}_{lr} \cdot X_{a\ lr} + \dot{m}_{ar\ e} \cdot Y_e) = (\dot{m}_{mtx} \cdot X_{a\ mtx} + \dot{m}_{ar\ s} \cdot Y_s) \qquad (7)$$

$X_{a\ lr}$ = Mass fraction of water in the liquor (kg water$\cdot kg^{-1}$wet product); Y_e = Absolut humidity of the atomization air in the inlet of the dryer (kg water$\cdot kg^{-1}$dry air); X_{amtx} = Mass fraction of water in the maltodextrin (kg water$\cdot kg^{-1}$wet product); Y_s = Absolut humidity of the atomization air in the outlet of the dryer (kg water. kg^{-1}air dry); $\dot{m}_{lr}$= Mass flow rate of the liquor ($kg \cdot h^{-1}$); $\dot{m}_{mtx}$ = Mass flow rate of maltodextrin ($kg \cdot h^{-1}$); $\dot{m}_{ar\ e}$ = Mass flow rate of atomization air in the inlet of the dryer ($kg \cdot h^{-1}$);$\dot{m}_{ar\ s}$ = Mass flow rate of atomization air in the outlet of the dryer ($kg \cdot h^{-1}$).

Equation (8) describes de mass rate for the solid component.

$$\dot{m}_{lr} \cdot (1 - X_{a\ lr}) = \dot{m}_{mtx} \cdot (1 - X_{a\ mtx}) \qquad (8)$$

2.3. General energy balance and thermal efficiency

The general energy balance of the vacuum spray dryer can be obtained by an enthalpy balance of the system inlet and outlet flows Equation (9):

$$\dot{m}_{lr} \cdot q_{lr} + \dot{m}_{ar\ e} \cdot H_{ar\ e} = \dot{m}_{mtx} \cdot q_{mtx} + \dot{m}_{ar\ s} \cdot H_{ars} \qquad (9)$$

However, this system is not adiabatic, so an enthalpy gain or loss term is added, as described in Equation (10) [9]:

$$\dot{m}_{lr} \cdot q_{lr} + \dot{m}_{ar\ e} \cdot H_{ar\ e} + Q = \dot{m}_{mtx} \cdot q_{mtx} + \dot{m}_{ar\ s} \cdot H_{ar\ s} \quad (10)$$

$\dot{m}_{are}$= Mass flow rate of atomization air in the inlet of the dryer (kg dry air·h^{-1}); $\dot{m}_{ars}$ = Mass flow rate of atomization air in the outlet of the dryer (kg dry air·h^{-1}); q_{lr} = Mass enthalpy of the liquor in the inlet of the dryer (kJ·kg^{-1}); H_{are} = Specific enthalpy of the atomization air in the inlet of the dryer (kJ·kg air^{-1}); q_{mtx} = Specific enthalpy of the maltodextrin in the outlet of the dryer (kJ·kg^{-1}); $\dot{m}_{mtx}$ = Mass flow rate of maltodextrin (kg·h^{-1}); $\dot{m}_{lr}$ = Mass flow rate of liquor (kg·h^{-1}); $H_{ar\ s}$ = Specific enthalpy of the atomization air in the outlet of the dryer (kJ·kg air^{-1}); Q = Heat flow from the system to the environmental (kJ·h^{-1}).

The thermal efficiency (η) of the spray dryer can be determined by the ratio between the sum of the energy of the dry product and the evaporated water, which is the rate of the mass flow rate of the evaporated water ($\dot{m}_{ma\ ev}$), multiplied by the latent heat of water vaporization at the temperature of the chamber, λ_a, by the heat of the feed solution and the air in the inlet of the dryer, as in Equation (11), described by CHENG et.al [7].

$$\eta = (\dot{m}_{mtx} \cdot q_{mtx} + \dot{m}_{ma\ ev} \cdot \lambda_a)/(\dot{m}_{lr} \cdot q_{lr} + \dot{m}_{ar\ e} \cdot H_{ar\ e}) \quad (11)$$

λ_a = Latent heat of the water vaporization (kJ·h^{-1}).

Equation for calculating the atmospheric pressure of Uberlândia where the dryer is installed. To calculate the atmospheric pressure in Uberlândia, Equation (12) was used:

$$P_{at} = a + b \cdot h \quad (12)$$

h = < 1120m (McQUISTON e PARKER, 1994); P_{at}= Atmospheric pressure (kPa); a = 101,325; b= - 0,01153; h = Altitute (m).

2.4. Calculation of absolute humidity and mass flow rate of atomization air

The absolute humidity of the atomization air (Y) and mass flow rate of the atomization air ($\dot{m}_{ar}$) are calculated using Equations (13). It is applied for an adiabatic system, considering the added water in a system with wet air, knowing that the inlet air rate plus the evaporated water rate is equal to the outlet air rate.

$$\dot{m}_{ar} \cdot Y_e + \dot{m}_{a\ ev} = \dot{m}_{ar} \cdot Y_s \quad (13)$$

$\dot{m}_{ar}$ = Mass flow rate of dry air in the inlet and outlet of the dryer (kg·h^{-1}); $\dot{m}_{a\ ev}$ = Mass flow rate of evaporated water (kg · h^{-1}); Y_e e Y_s = Absolute humidity of the air in the inlet and outlet of the dryer (kg water· kg^{-1} de dry air).

2.5. Specific Volume

The specific volume is the ratio between the volume flow rate of the air at the outlet of the dryer and the mass flow rate of the air, described in Equation (14).

$$v = V/(\dot{m}_{ar}) \quad (14)$$

v = Specific volume ($m^3 \cdot kg^{-1}$ar seco); $\dot{m}_{ar}$= Mass flow rate of dry air in the dryer ($kg \cdot h^{-1}$); V = Volume flow rate of the air in the outlet of the dryer ($m^3 \cdot h^{-1}$).

The specific volume is determined by Equation (15) (TREYBAL, 1981)[17].

$$v = [(Y_s)/M_v + 1/M_{ar}] \cdot R \cdot (T_{kv})/(P_{at}) \quad (15)$$

v = Specific volume ($m^3 \cdot kg^{-1}$ar seco); M_v = Molecular weight of vapor of water ($kg \cdot kmol^{-1}$); M_{ar} = Molecular weight of air($kg \cdot kmol^{-1}$); T_{kv} = Temperature (º K); P_{at}= Atmospheric pressure (Pa); R = Constant of gases ($J \cdot kmol^{-1} \cdot {}^oK^{-1}$); Ys= Absolut humidity of the air (kg water$\cdot kg^{-1}$dry air).

2.6. Equation for energy calculation

Equation (16) presents the calculation of the heat flow rate of the air from the system to the environmental:

$$Q_{ar} = \dot{m}_{ar} \cdot H_{ar} \quad (16)$$

Qar= Heat flow from the system to the environmental ($kJ \cdot h^{-1}$); $\dot{m}_{ar}$ = Mass flow rate of dry air ($kg \cdot h^{-1}$); H_{ar} = Enthalpy of the atomized air ($kJ \cdot kg^{-1}$dry air).

2.7. Equations for the enthalpy calculation

Equation (17) presents the relationship between the enthalpy of humid air (H_{ar}) with the absolute humidity of the air (Y) and the temperature (T), (ASHRAE,2001)[18].

$$H_{ar} = 1{,}005 \cdot T + (2051 + 1{,}805 \cdot T) \cdot Y \quad (17)$$

H_{ar} = Enthalpy of the wet air ($kJ \cdot kg^{-1}$dry air); T = Temperature (ºC); Y = Absolute moisture of the air (kg water$\cdot kg^{-1}$ dry air).

Equation (18) is used for calculating the enthalpy of maltodextrin and liquor.

$$q = 1 \cdot c_p \cdot \Delta T \quad (18)$$

q = Enthalpy ($kJ \cdot kg^{-1}$); c_p = Specific heat ($kJ \cdot kg^{-1} \cdot {}^oC^{-1}$); ΔT = Temperature difference (ºC).

2.8. Equation for calculating porosity

Porosity (ε) is determined by Equation (19). It is defined as the relationship between the empty volume of a substance (v_{va}) and the total volume (v_{total}), ARAUJO, (2013)[19].

$$\varepsilon = v_{va}/v_{total} \quad (19)$$

ε= Porosity; v_{va} = Empty volume (m^{-3}); v_{total} = Total volume (m^{-3}).

2.9. Equation for determining the glass transition temperature

Equation (20) by BUSIN cited by Collares [20] describes a relationship between DE and the glass transition temperature (Tg) for maltodextrin.

$$Tg = -1{,}4 \cdot DE + 176{,}4 \quad (20)$$

DE = Dextrose equivalence (%); Tg = Glass transition temperature (°C).

2.10. Statistical treatment of data

The results were statistically treated using the mean values, and the standard deviation and are presented as M±σ throughout this work.

2.11. Plant Characteristics

The spray dryer used in this study is a NIRO-GEA, with a nominal evaporation capacity of 1200.00 $kg.h^{-1}$, and outlet air flow of 46,400 $m^3.h^{-1}$. The dimensions of this equipment are 9600 mm in height, and 6800 mm in diameter.

3. Experimental Results

3.1. Evaluation of the results of the six batches of maltodextrin final product

Industrial batches of maltodextrin were sampled and analyzed to verify the quality control parameters. The parameters of moisture (U), pH, total solids (%DS), dextrose equivalent (%DE), and bulk density ($\rho_{r\ mtx}$) were analyzed. The results are shown in Table 4.

Table 4: Data analysis of moisture, pH, total solids (%DS), dextrose equivalent (%DE) and bulk density of the six batches of maltodextrin.

	Specification	Batch $_{mtx\ 1}$	Batch $_{mtx\ 2}$	Batch $_{mtx\ 3}$	Batch $_{mtx\ 4}$	Batch $_{mtx\ 5}$	Batch $_{mtx\ 6}$
Moisture (%)	< 5%	4,93	4,48	4,22	4,75	4,24	4,37
pH (1:9)	4,5 - 5,5	4,94	4,8	4,9	4,97	4,92	4,91
Dry Solids (% DS)	> 95%	95,07	95,52	95,78	95,25	95,76	95,63
Dextrose equivalent (% DE)	17 - 19,9	17,86	18,56	18,84	17,72	17,58	17,86
Apparent density ($kg.m^{-3}$)	470 (Expected value)	446	419	434,1	482	477	469

The results for moisture (U), pH, total solids (%DS), and dextrose equivalent (DE) are within the range established by the product specification. The results for the bulk density of batches 1, 2 and 3 are below the target. On the hand, the data for the batches 4, 5, and 6 are close to the target value of 470 $kg \cdot m^{-3}$. The calculation of DS (%) is done by subtracting 100 from the moisture value. The liquor tanks that supply the spray dryer to carry out the drying process of maltodextrin are analyzed, and the results are shown in Table 5. They demonstrate that the dextrose equivalent is less than 20.

Table 5: Mean values of DE (%), pH, DS (%) and Iodine in liquor tanks (batch lr mtx) at the inlet of the spray dryer.

Batch $_{lq\ mtx}$	DE (%)	pH	DS (%)	Iodine
1	17.81	4.9	69.3	RB
2	18.65	5.1	70.2	RB
3	19.12	5.0	69.0	RB
4	18.00	5.0	69.8	RB
5	18.14	4.9	69.8	RB
6	18.05	4.9	70.3	RB

The operating conditions of the spray dryer were monitored every hour during the drying of each batch of maltodextrin. The data collected in the study are: T_{ek} the temperature in the inlet of the spray dryer chamber (ºC); V_{elr} the volume flow rate of liquor in the inlet of the spray dryer ($m^3 \cdot h^{-1}$); $T_{e\ lr}$ the liquor temperature in the inlet of the spray dryer (ºC); R the rotation of the spray dryer atomizer (rpm); V_k the vacuum in the spray dryer chamber (mmCa); T_{sk} the air temperature in the outlet of the spray dryer chamber (ºC). The calculation of the air temperature average in the inlet, and in the outlet of the spray dryer, and the volume flow rate of the liquor in the spray dryer showed that the variation in 25 hours, quantified every hour, was situated around an average value with low dispersion as described in Table 6.

Table 6: The mean values and standard deviation of the spray dryer control parameters for the six batches of maltodextrin (M is the mean value; σ is the standard deviation).

	$Batch_{mtx}1$	Batch $_{mtx}2$	Batch $_{mtx}3$	Batch $_{mtx}4$	Batch $_{mtx}5$	Batch $_{mtx}6$
	M±σ	M±σ	M±σ	M±σ	M±σ	M±σ
T_{ek} (ºC)	192,08±16,64	195,4±3,77	196,43±3,09	193,35±2,52	194,5±1,54	194,85±1,67
V_{elr} ($m^3.h^{-1}$)	2,39±0,18	2,35±0,2	2,47±0,07	2,47±0,04	2,51±0,06	2,47±0,06
T_{elr} (ºC)	109,43±3,31	108,6±7,27	104,95±20,59	109,06±4,71	109,82±2,26	110,05±2,08
R (rpm)	11598±38	11480±0	11535±67	11480±0	11442±59	11480±0
V_k (mmCa)	-34,72±5,4	-30,21±4,26	-33,57±2,57	-42,61±3,76	-44,45±3,04	-43,35±4,13
T_{sk} (ºC)	106,66±2,13	106,52±1,13	107,05±0,74	106,23±0,97	106,4±0,66	106,12±0,63

The vacuum applied for batches 1 to 6 were: -34.72; -30.21; -33.57; -42.61; -44.45 and -43.35 mmCa, respectively. When a more pronounced vacuum is applied, keeping the flow rate and air temperature constant, as well as the other average parameters, the droplets moisture is eliminated more quickly and the particles contract

more and, therefore, have less internal porosity and greater apparent density. Despite the tendency to lower internal porosity, which makes rehydration difficult in terms of instantaneity, volumetric contraction (shrinkage) was probably dominant.

3.2. Performance of the spray dryer

The Table 7 summarizes the mass flow rate of the liquor ($\dot{m}_{lr}$) and maltodextrin ($\dot{m}_{mtx}$), mass fractions of water in liquor (X_{alr}) and maltodextrin (X_{amtx}) and the mass flow rate of evaporated water ($\dot{m}_{aev}$) in the system for each batch of maltodextrin produced.

Table 7: Mass flow ratio of liquor ($\dot{m}_{lr}$), and maltodextrin ($\dot{m}_{mtx}$); Mass fractions of water in liquor ($X_{a\ lr}$), and in maltodextrin ($X_{a\ mtx}$); Mass flow rate of evaporated water ($\dot{m}_{aev}$) in the system for each batch of maltodextrin produced.

Batch $_{mtx}$	$\dot{m}_{lr}$ (kg.h^{-1})	$X_{a\ lr}$	$\dot{m}_{a,lr}$ (kg.h^{-1})	$\dot{m}_{mtx}$ (kg.h^{-1})	X_{amtx}	$\dot{m}_{a,mtx}$ (kg.h^{-1})	$\dot{m}_{aev}$ (kg.h^{-1})
1	3.130,81	0,31	960,22	2.097,92	0,05	103,43	856,79
2	3.079,96	0,30	918,75	2.009,58	0,04	90,03	828,72
3	3.237,23	0,31	1.003,54	2.235,42	0,04	94,33	909,21
4	3.237,23	0,30	976,67	2.046,25	0,05	97,20	879,48
5	3.289,66	0,30	995,12	1.972,92	0,04	83,65	911,47
6	3.237,23	0,30	960,49	1.972,92	0,04	86,22	874,27
						M	876,66
						σ	31,55

The average of the mass flow rate of water evaporated in the spray dryer is 876.66±31.55kg·h^{-1}, (see Table 7), and the moisture content of the maltodextrin produced was at the desired value < 0.05 kg water/kg DS.

Table 8: The mass flow rate of maltodextrin ($\dot{m}_{mtx}$) and of the liquor ($\dot{m}_{lr}$); Mass fractions of maltodextrin in liquor (1- $X_{a\ lr}$), and in maltodextrin (1-X_{amtx}); Loss rate of maltodextrin ($\dot{m}_{mtxp}$) in the drying and bagging system for each batch of maltodextrin produced.

Batch $_{mtx}$	$\dot{m}_{lr}$ (kg.h^{-1})	1- $X_{a\ lr}$	$\dot{m}_{e\ mtx}$ (kg.h^{-1})	$\dot{m}_{mtx}$ (kg.h^{-1})	1-X_{amtx}	$\dot{m}_{s\ mtx}$ (kg.h^{-1})	$\dot{m}_{per\ mtx}$ (kg.h^{-1})
1	3.130,81	0,69	2.170,59	2.097,92	0,95	1.994,49	176,10
2	3.079,96	0,70	2.161,21	2.009,58	0,96	1.919,55	241,65
3	3.237,23	0,69	2.233,69	2.235,42	0,96	2.141,08	92,61
4	3.237,23	0,70	2.260,56	2.046,25	0,95	1.949,05	311,51
5	3.289,66	0,70	2.294,54	1.972,92	0,96	1.889,27	405,27
6	3.237,23	0,70	2.276,74	1.972,92	0,96	1.886,70	390,04
						M	269,53
						σ	122,90

3.3. Thermal efficiency of the dryer

The calculation of the heat flow transferred from the system to the environment and the thermal efficiency of the spray dryer is presented in Tables 9 and 10, respectively. The porosity of maltodextrin is shown in Table 11.

Table 9: Mass flow rate data (ṁ); Enthalpy data (q) of liquor and maltodextrin; Enthalpy data (H) of humid air at the inlet, and outlet; Calculation of heat flow (Q) in the drying system for each batch of maltodextrin produced.

Batch $_{mtx}$	$\dot{m}_{lr}$ (kg.h^{-1})	q_{lr} (kJ/kg^{-1})	$\dot{m}_{are}$ (kg.h^{-1})	H_{are} (kJ/kg^{-1})	Q (kJ.h^{-1})	q_{mtx} (kJ/kg^{-1})	$\dot{m}_{ars}$(kg.h^{-1})	H_{ars} (kJ/kg^{-1})	$\dot{m}_{mtx}$ (kg.h^{-1})
1	3.130,81	269,25	38.357,81	206,23	-1.691.158	192,48	38.357,81	172,70	2274,02
2	3.079,96	267,21	38.357,81	209,58	-1.808.942	192,28	38.357,81	172,59	2251,24
3	3.237,23	258,23	38.357,81	210,64	-1.825.619	193,19	38.357,81	173,12	2328,02
4	3.237,23	268,34	38.357,81	207,52	-1.769.464	191,71	38.357,81	172,25	2357,76
5	3.289,66	270,21	38.357,81	208,68	-1.822.910	192,01	38.357,81	172,43	2378,19
6	3.237,23	270,78	38.357,81	209,04	-1.839.679	191,51	38.357,81	172,13	2362,96
							M	-1.792.962	
							σ	55.349	

Table 10: Enthalpy data (Har e) of the inlet air of the dryer; Enthalpy data (q) of liquor and maltodextrin; Latent heat of water (λ_a) and mass flow rate (ṁ) of maltodextrin; Liquor, and evaporated water for the calculation of the thermal efficiency (η).

Batch $_{mtx}$	$\dot{m}_{mtx}$ .q_{mtx} (kJ.h^{-1})	$\dot{m}_{aev}$ ·λ (kJ.h^{-1})	$\dot{m}_{lr}$. q_{lr} (kJ.h^{-1})	$\dot{m}_{are}$.H_{are} (kJ.h^{-1})	η	λ_a (kJ.h^{-1})	P_{at} (kPa)	$\dot{m}_{aev}$ (kg.h^{-1})
1	437.710,65	1.889.294,56	7.910.445,78	842.975,13	0,27	2.205,08	90,76	856,79
2	432.878,58	1.827.381,38	8.038.916,09	822.993,22	0,26	2.205,06	90,80	828,72
3	449.744,60	2.004.865,41	8.079.793,00	835.945,51	0,28	2.205,07	90,77	909,21
4	451.999,28	1.939.340,97	7.959.887,38	868.682,39	0,27	2.205,11	90,68	879,48
5	456.645,72	2.009.899,26	8.004.657,34	888.901,69	0,28	2.205,12	90,66	911,47
6	452.528,18	1.927.870,48	8.018.282,98	876.567,92	0,27	2.205,12	90,67	874,27

The average of thermal efficiency of the spray dryer was 0.27±0.01 (see Table 10), which means that only 27% of the heat is used to evaporate water from the maltodextrin. According to Cheng [7], the value of the thermal efficiency of the spray dryer varies from 20 to 60%, and the value obtained is within the reported range. Therefore, the big challenge in the spray dryer stage is energy recovery, since it is an operation with high energy consumption and low energy use.

In Table 11, to determine the porosity, 1000 kg of maltodextrin was used as a basis and Equation (19) was applied for the calculation.

Table 11: Data on empty volume (v_{va}), total volume (v_{total}), and product porosity (ε).

Batch $_{mtx}$	m (kg)	$\rho_{r\ m}$ (kg.m^{-3})	$\rho_{\ m\ t\ x}$ (kg.m^{-3})	V_k (m³)	V_{va} (m³)	V_{total} (m³)	ε
1	1000	446,00	1522,30	0,6569	1,5853	2,2422	0,7070
2	1000	419,00	1522,30	0,6569	1,7297	2,3866	0,7248
3	1000	431,10	1522,30	0,6569	1,6627	2,3196	0,7168
4	1000	482,00	1522,30	0,6569	1,4178	2,0747	0,6834
5	1000	477,00	1522,30	0,6569	1,4395	2,0964	0,6867
6	1000	469,00	1522,30	0,6569	1,4753	2,1322	0,6919
						M	0,7018
						σ	0,0170

The mean porosity value of maltodextrin is 0.7018±0.017 (see Table 11). This data is a new information about the product. The porosity values of batches 4, 5, and 6 are smaller when compared to batches 1, 2, and 3, considering that the bulk densities of these batches are higher.

3.4. Glass transition temperature

Applying Equation (20) and using the dextrose equivalent value of the dry product, the glass transition temperature in the system is determined for each batch produced (Table 12). The value of the glass transition temperature (Tg) is between 150.0 and 151.8°C, but the outlet temperature of maltodextrin in the dryer chamber is between 106.12 and 107.05°C. On the other hand, the inlet air temperature in the dryer is between 192.08 and 196.43°C (Table 6).

Thus, the internal operating temperature of the dryer is below the glass transition temperature of the final product. Furthermore, because of reducing the temperature of the particles by the evaporation of water, their temperature will always be lower than Tg. This makes it possible to classify the product as vitreous and there is no sticky behavior inside the dryer. At lower temperatures, when maltodextrin has low moisture and after cooling, the product at the storage temperature behaves below the Tg of maltodextrin, without the occurrence of agglomeration in the packaging phase.

Figure 3 presents a plot of the glass transition temperature versus the water activity for maltodextrin of DE12, and DE21. It shows that the product under study has DE between 17.58 and 18.84%, and the glass transition temperature between 150,0 and 151.8°C, which is similar to the study presented by GIANFRANCESCO [10].

Table 12: Dextrose equivalent (DE), and glass transition temperature (Tg) data for maltodextrin batches.

$Batch_{mtx}$	DE (%)	T_g (°C)
1	17,86	151,4
2	18,56	150,4
3	18,84	150,0
4	17,72	151,6
5	17,58	151,8
6	17,86	151,4

4. Conclusion

The study showed that, among the quantified parameters, the vacuum applied in the spray dryer influenced the apparent density of maltodextrin. Therefore, in the dryer operation, considering the available data from the study, it must operate with an average vacuum of 44 mmCa, which made it possible to obtain the product at the specified bulk density. Bulk density values such as 433 $kg \cdot m^{-3}$ turned out to be below the standard specification value of 470 $kg \cdot m^{-3}$.

This work showed that the mean porosity value of maltodextrin was 0.7018 ± 0.017. Then, comparing it to the desired standard for the product, we can conclude that porosity can be used as an additional parameter for evaluating the quality of the final product, considering its storage. This is a new data for the product under study.

According to the manufacturer's information (NIRO-GEA), the evaporation capacity is 1200.00 $kg \cdot h^{-1}$ and the mass rate of evaporated water, on average in the system, is 876.66 $kg \cdot h^{-1}$ which leads to the conclusion of that the spray dryer was operating at 73% of design capacity during production.

The drying system presented an energy loss rate of 1,792,962.0 ± 55,349.0 $kJ \cdot h^{-1}$, which consists of a loss of 17% of energy to the environment. The thermal efficiency of the system was 0.27±0.01, which means that 27% of the energy is used for drying the product. The output air energy is not computed in the efficiency calculation.

The value of the glass transition temperature (Tg), calculated for this drying system, is from 150°C to 151.8°C, the dryer chamber outlet temperature is from 106.12°C to 107°C, and, at the dryer inlet air, the temperature is between 192.08°C and 196.43°C. Therefore, the product obtained is at a temperature value below the glass transition, and then, in the glassy state, not adhering on the internal surfaces of the dryer, due to this condition.

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