

Procedure for conveyer-belt dryer sizing using dehydration-rate curves

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ABSTRACT

The aim of this dissertation is to provide an understanding of the drying phenomena associated with the drying of a selected extruded maize product. Mathematical modelling of drying is complicated and in many cases inaccurate due to the assumption of constants used in the mathematical models. These constants vary for each product and are determined by the nature of the product being dried. Using the assumed values for designing a dryer can lead to energy losses and a decrease in product quality.

Current literature does not provide sufficient data regarding the drying process of extruded maize products. This can lead to faulty and inefficient drying procedures. In the drying industry, products for commercial use need to adhere to strict regulations regarding the moisture content of the food. By failing to comply with these regulations, companies can face legal implications. On the other hand, decreasing the moisture content of the product too much increases the amount of raw material needed to make up the desired weight specified on the packaging. This causes the profit margins to decrease, since the company is using more expensive raw product than cheaper water.

In addition, current literature does not provide adequate data regarding the effects of the process parameters involved, for this reason the influence of selected operating parameters will have to be investigated. To achieve this, drying tests were performed. Tests were conducted through batch samples inserted into a drying chamber. Through accurately logging selected variables, the influence of the process parameters were investigated.

The results of these tests can be used to determine the actual moisture content of the product at a certain time. As a result of this, the product can be dried up to the selected moisture content and no extra moisture is removed. In addition, these results provide data on the quality of the product after drying.

These results can also be used to optimize the energy consumption of the system. From the tests performed, conclusions are reached regarding the selected process parameters as well as the calculated residence time. Considering the abovementioned results, a preliminary sizing design with the chosen parameters is provided.

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Notation

A	the area of the belt that the air flow is applied to [m ²]
a	the area of the test bench the air flow is applied to [m ²]
A_{st}	the area of the heat exchanger exposed to the passing air [m ²]
b_{Belt}	width of the belt [m].
Cp_a	specific heat of the air [kJ/kg K]
Cp_p	specific heat of the product [kJ/kg K]
Cp_s	specific heat of the solid [kJ/kg K]
Cp_w	specific heat of the water [kJ/kg K]
Cp_v	specific heat of water vapour [kJ/kg K]
E_g	energy contained in the air [kW]
E_p	energy contained in the product [kW]
F_{ac}	the mass flow of air [kg/s].
F_{AC}	drying air stream flow rate [kg/s db]
F_S	product stream flow rate [kg/s db]
F_{ST}	steam flow rate [kg/s]
h_A	specific enthalpy of outlet air stream [kJ/kg]
h_{A0}	specific enthalpy of fresh air stream [kJ/kg]
h_s	specific enthalpy of the solid exiting the chamber [kJ/kg]
h_{so}	specific enthalpy of the solid entering the chamber [kJ/kg]
h_g	specific enthalpy of the air stream [kJ/kg]
H_{Bed}	height of the product bed [m].
k_M	drying constant [s ⁻¹]
m_w	mass of water [kg]
m_a	mass of air [kg]
m_s	mass of dry solid [kg]
m_{ss}	mass flow of the solid through the system [kg/s]
m_v	mass of vapour [kg]
m_p	mass of the product [kg]
$\dot{m}_{in}$	moisture flow into the system [kg/s]

$\dot{m}_{out}$	moisture flow out of the system [kg/s]
P_s	pressure at sensor [kPa],
Q	heat exchanged at dryer heat exchangers [kW]
rh	relative humidity ratio of the air [%]
T_A	outlet air stream temperature [°C]
T_{ac}	temperature of the air stream leaving the heat exchanger [°C]
T_{am}	temperature of the mixed air [°C]
T_g	temperature of the gas [°C].
T_p	temperature of the product [°C].
T_S	outlet product stream temperature [°C]
T_{st}	the temperature of the steam [°C]
$T_{smax,}$	outlet product maximum temperature [°C]
t_R	residence time [s]
U_{st}	overall heat transfer coefficient [W/m ² K]
V_A	velocity of the air through the product [m/s].
V_{Belt}	speed of the belt [m/s].
X_A	outlet air stream humidity [kg/kg db]
X_{AC}	drying air stream humidity [kg/kg db]
X_{A0}	fresh air stream humidity [kg/kg db]
X_S	outlet product stream material moisture content [kg/kg db]
X_{SE}	equilibrium product stream material moisture content [kg/kg db]
X_{S0}	inlet product stream material moisture content [kg/kg db]

Symbols

Δ	deviation
Δ_{HS}	latent heat of vaporization of water [kJ/kg]
ΔH	latent heat of evaporation for the moisture in the solid [kJ/kg]
ΔH_{st}	latent heat of evaporation for steam [kJ/kg]
$\Delta \dot{m}$	difference in moisture flow [kg/s]
ω	humidity ratio for air-water gas mixtures [kg _{water} /kg _{dry air}]
ω_1	deviation in humidity ratio for air-water gas mixture [kg _{water} /kg _{dry air}]
$\omega_{original}$	original humidity for ratio air-water gas mixture [kg _{water} /kg _{dry air}]
ω_{out}	humidity ratio for air-water gas mixtures exiting the chamber [kg _{water} /kg _{dry air}]
ρ_A	density of the air [kg/m ³]
$\rho_{Product}$	density of the product [kg/m ³]
λ	rate of water removal [kg _{water} /s]
λ_n	normalized rate [kg _{water removed} /s·%Initial moisture]
β	the amount of water removed per interval [kg]
β_{total}	the total amount of moisture removed [kg]

Abbreviations

db	Dry base
FBD	Fluidized bed dryers
CBD	Conveyor-belt dryer

1 INTRODUCTION

In this chapter insight is provided into the reasons for performing this research. This chapter provides a background to the identified problem and explains the path followed to solve the problem. Furthermore, this chapter explains what will be discussed in the rest of the chapters.

1.1 MOTIVATION FOR THE STUDY

Drying extruded produce is a necessary process in which extruded products are conditioned to the correct moisture content for packaging. Companies striving to improve the post-extrusion processes need accurate information to choose the right type of dryer for optimal efficiency. Efforts to model this field encountered numerous challenges as stated by Kiranoudis et al. [1]: *“However, most design efforts in this field face problems of extreme difficulty related to complex drying conditions that include many interconnected and opposing phenomena, chiefly related to the complicated nature of drying. Although the modelling of drying processes is well developed with adequate understanding of the process itself, most models incorporate a large number of thermophysical properties and transport coefficients, **which in most cases are only imprecisely [determined], producing inaccurate or erroneous results** on large-scale industrial applications.”* Many studies completed assumed constant transfer coefficients, this assumption can produce results that do not concur with reality [2].

Laboratory testing is required to obtain reliable data and limitations for the process. These can be performed on a pilot plant to observe the effect on product composition due to changes in process parameters. The data obtained from the tests can then be used to select appropriate operating parameters in order to increase the efficiency of the drying process.

1.2 PROBLEM STATEMENT

Currently information on the effect that air temperature and retention time has on the drying rate of extruded maize products is insufficient. Thus, the correct sizing of conveyer-belt dryers is problematic. The presented research investigates these parameters for a horizontal conveyer-belt dryer.

The problem therefore is to measure and process relevant data to produce effective conveyer-belt dryer sizing data for extruded low-density maize pellets.

1.3 RESEARCH OBJECTIVES

To complete a **literature study** in which the investigation focuses on drying theory involved in conveyor-belt dryers (CBDs). In addition, the study investigates current **mathematical models** available from literature. One of these models is chosen and discussed in more detail.

To **design and develop a pilot test plant**, since literature fails to provide adequate data on drying. To **investigate the influences** of process parameters on the drying rate of the maize products.

To perform **data processing** on the results obtained in the pilot project in order to be able to **draw conclusions** about the effect that the operating parameters have on the drying rate of the product.

To suggest a **concept design of a CBD** through utilizing the acquired informational conclusions.

1.4 RESEARCH METHODOLOGY

This section illustrates how the previously stated research objectives were achieved.

1.4.1 Literature study

A literature study was performed, investigating current literature regarding dryer types, drying in general, characteristic variables associated with drying and a summary of the mathematical models available in literature.

1.4.2 Pilot plant design and testing

When using the research presented in the literature study to design a pilot plant it is quite straightforward to determine which process variables should be measured and logged. The method to determine the moisture loss in the test plant was validated to ensure that the results obtained from the plant were accurate. This can be done by inserting freshly extruded product into the test bench with various specified parameters. The influence of each parameter on the drying rate is determined from the logged parameters.

1.4.3 Data processing

The processing of the result data was done using mathematical analysis. The processed results were simplified and represented as normalized rates. This rate compensates for deviations in the initial product moisture content. Using this processed results, a conclusion could be made concerning results that achieved optimal drying without decreasing the quality of the product, by utilising the best process parameters. Furthermore, the processed results can be used for the design and sizing of CBDs.

1.4.4 Concept design of a CBD

The concept design was based on the results obtained from the processed results.

1.5 DISSERTATION LAYOUT

Chapter 2 of the dissertation provides an overview of the available relevant literature. The literature investigates the types of dryers available on the market as well as the uses of each type. The literature study focuses on CBDs. In addition, Chapter 2 provides literature on the drying phenomena and the mathematical modelling thereof.

Chapter 3 discusses the developed pilot test plant and the procedure of the tests conducted. In addition, it describes the data processing performed.

In Chapter 4 the data is presented and processed. The processed results are discussed and conclusions are reached from these results.

Chapter 5 presents the design selected and briefly discusses the reasoning behind the selection.

Chapter 6 presents the conclusions reached through the research, as well as recommendations for further work.

2 LITERATURE STUDY

This chapter provides a brief overview of the literature regarding drying and associated terms and principles required to understand drying and in particular convection drying.

2.1 BACKGROUND

The first ever record confirming the drying of vegetables dates back to the 18th century [3]. Drying is commonly described as removing moisture to yield a solid product using thermal energy [4]. One of the most important properties in any food drying process is to decrease the water activity in a food to a specific determined level, since this improves the food stability and minimizes chemical and physical changes taking place during storage [5]. In conveyor-belt dryers, heat transfer is obtained by convection between the product and the heated air stream. The energy required to evaporate the moisture from the product is supplied to the exposed surface of the material via convection, thereafter the evaporated moisture is carried away by moving air [6].

2.2 DRYER TYPES

In this section a brief overview of a few different types of dryers is given. This section provides insight into different methods of drying and describes the inner workings of rotary, fluidised bed, spray and solar dryers as well as CBDs.

2.2.1 Rotary Dryer

The rotary dryer consists of a cylindrical shell that is rotated on bearings slightly inclined above the horizontal level. The wet product is fed into the top of the dryer. The product progresses to the exit due to the rotation of the drum, head effect and the slope at which the drum is inclined. An illustration of a direct heat rotary drum dryer is given in Figure 1.

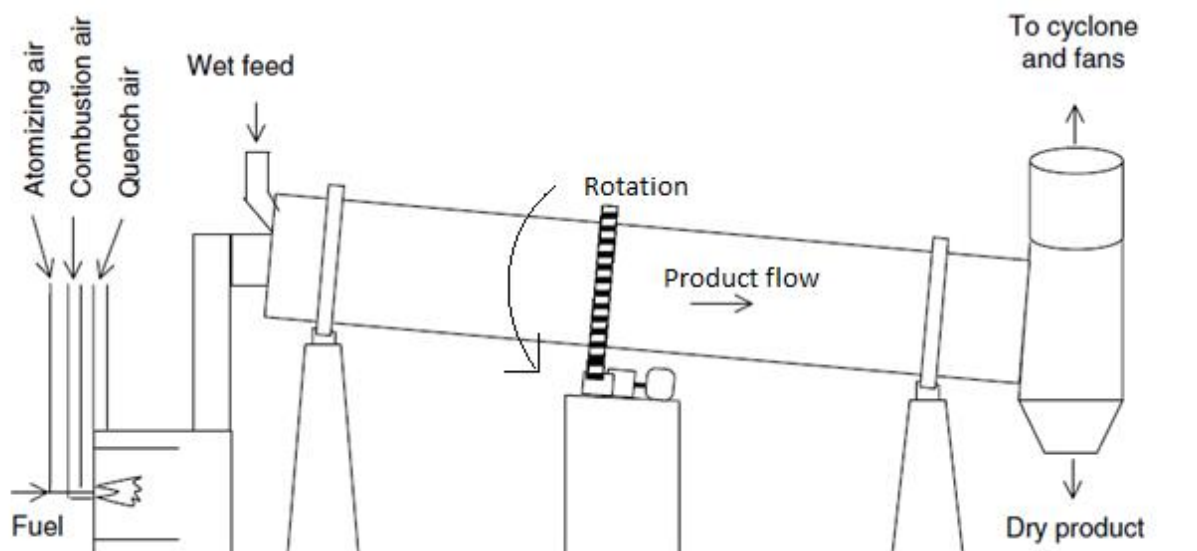


Figure 1: Simplified diagram of a rotary drum dryer [4].

Rotary dryers deliver a discharged product that should be relatively free-flowing and granular. This type of dryer can be used in batch or continuous processes handling large amount of ore and natural minerals [4].

2.2.2 Fluidized bed dryers

Fluidized bed dryers (FBD) work on the principle of air that is being forced through a product that rests on an air distribution plate. The fluidizing air passes through the product and at a certain air velocity the product will become fluidized: this is when the weight of the product is totally supported by the air stream. Figure 2 illustrates the setup of this design and the flow of the product and the air through the dryer. The FBD offers a range of advantages that is desirable in many processes such as good solids mixing, easy material transport and good heat and mass transfer rates [4]. This drying process is continuous [7]. The advantages include high thermal efficiency, high moisture removal rate and low maintenance. Disadvantages include high pressure drop and high electricity consumption [4].

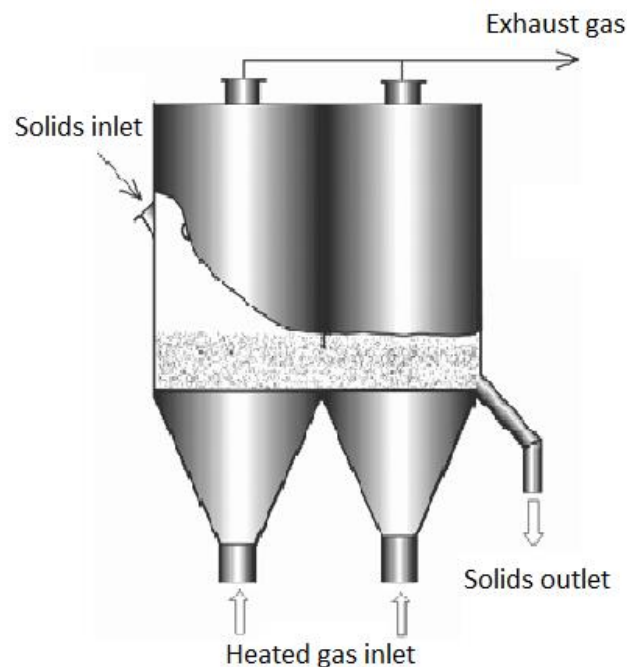


Figure 2: Illustration of a fluidized bed dryer [4].

2.2.3 Spray drying

This process converts a fluid into a dried product in single process. The fluid is usually sprayed into moving medium hot air. The water in the droplets evaporates to yield a dry product. The energy absorbed due to the evaporation of the water keeps the temperature of the droplets low, thus a high air temperature can be applied. Spray drying can be used to dry a pumpable suspension of fine solids [7]. The drying time of this process is very short when compared to alternative drying methods. This drying technique can be used for heat sensitive products. Spray drying is used to dry food, dairy products, pharmaceutical chemicals and ceramic powders [4]. Spray drying is used as a continuous drying process [7]. Advantages include effective property and quality control, high production volumes with relatively basic equipment. The disadvantages of this system includes that it cannot be used for high bulk density products and the financial investment are greater than that of other types of continues dryers [4].

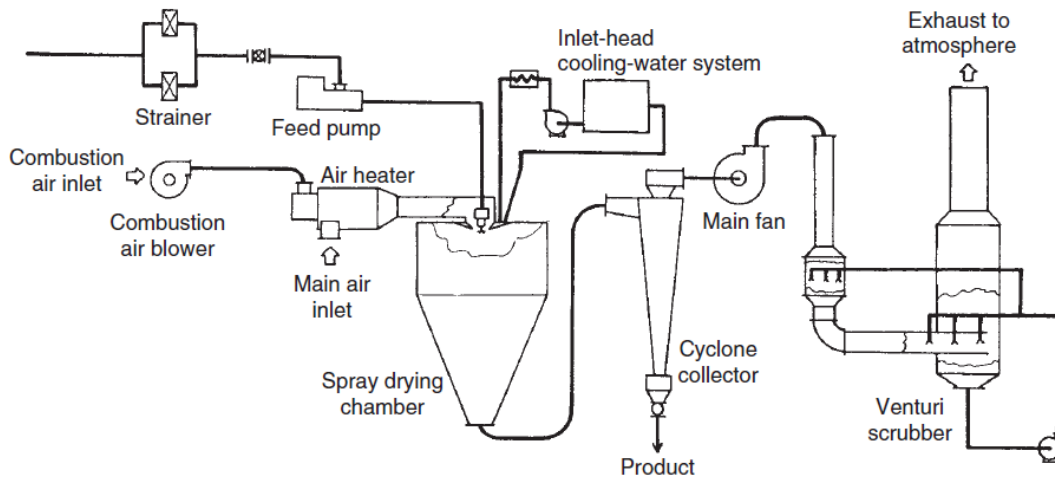


Figure 3: Schematic of a spray dryer process plant [4].

2.2.4 Solar drying

Solar drying refers to the collecting of solar energy to dry a product. Solar dryers can be divided into four main types, namely direct, indirect, mixed mode and hybrid dryers [8]. Open-air solar dryers are widely used in developing countries where grid-connected electricity and the supply of other energy sources are too expensive, unavailable or unreliable. The traditional open-air dryer poses many disadvantages - high amounts of crop losses due to insufficient drying, exposure to rodents and birds, unexpected weather conditions - because the efficiency of an open-air dryer is dependent on climatic conditions [9], and fungal infestations. Solar dryers can be used to dry handle a continuous material flow with the use of flat-plate collectors to provide the energy needed [4]. Cabinet dryers can provide a semi-continuous drying process [2]. High temperature solar dryers are used when relatively high drying rates are required, this drying can be done in either batch or continuous flow drying [10]. The main advantage of solar drying include the use of a free and renewable energy resource. Disadvantages include the unavailability of this resource, storage methods can be used to store energy for low radiation periods [4].

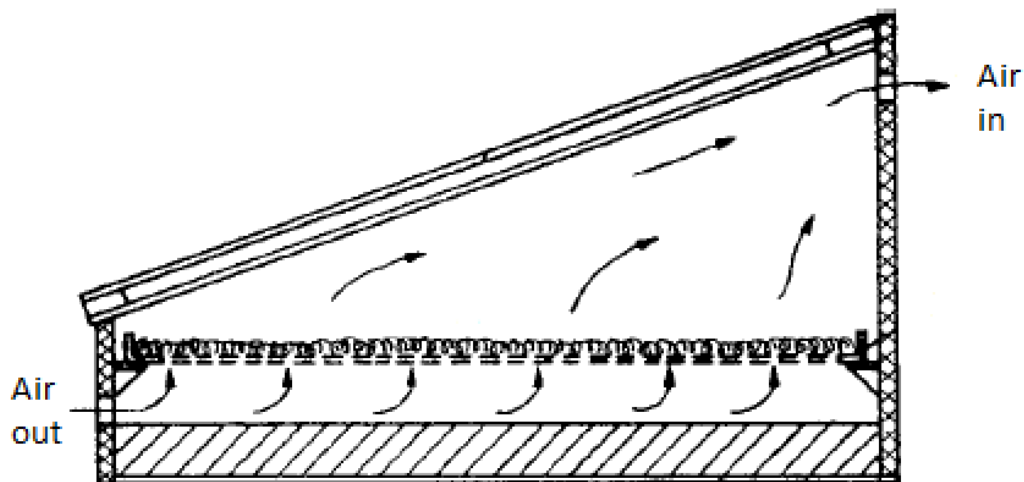


Figure 4: Solar cabinet dryer [4].

2.2.5 Conveyor-belt dryers

The principle of a conveyor-belt dryer (CBD) is illustrated in Figure 5; the product is dropped onto a perforated conveyor belt, on which the product is transported through drying chambers. Hot air is forced through the product bed in order for the water to evaporate from the product and to transport the vapour away from the product. [4]. In conveyor-belt dryers the manipulated variable will typically be the temperature of the hot air [6]. Additional variables include the bed depth and retention time. Since this research focuses on conveyor-belt dryers the next section explains some of the detail theory behind conveyor-belt dryers

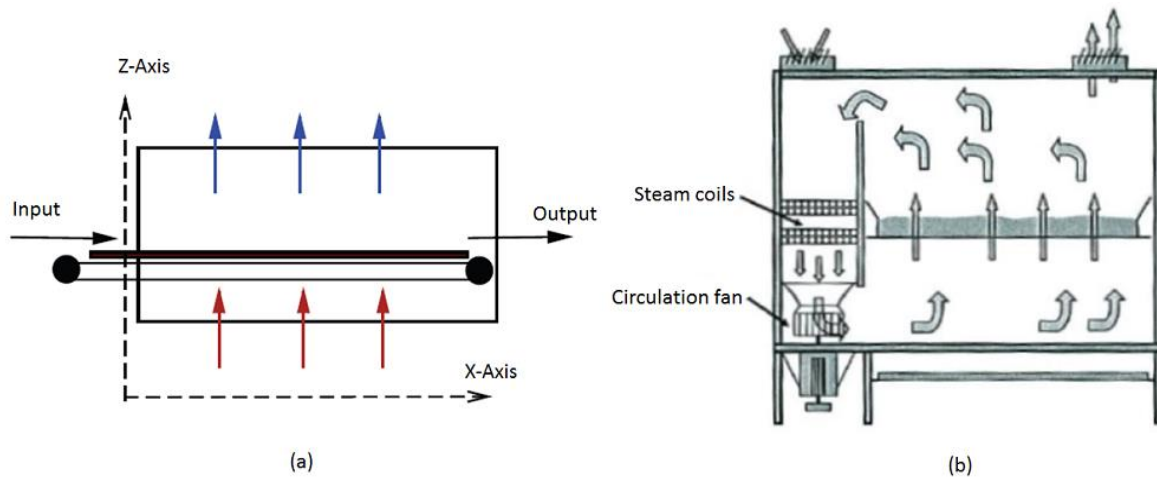


Figure 5: Illustration of drying chamber - side view (a) and section view (b) [6].

2.3 DETAIL ON CONVEYOR-BELT DRYERS

The next section will investigate CBD configurations, since this document focuses on CBSs

2.3.1 Single pass, single stage dryer

This is the most basic CBD. The product is fed onto the conveyor belt, which then transports the product while hot air is forced through the product bed. The product bed, airflow and temperature are constant throughout the whole chamber [6]. This configuration is illustrated in Figure 5 (a).

2.3.2 Single pass, multiple stage dryer

Two or more single pass dryers are placed in series as illustrated in Figure 6. This provides the ability to vary the bed depth between chambers. The product can progressively be packed with an increasing depth as the moisture content is reduced. The temperature of each stage can be altered to optimize the efficiency of each stage [6].

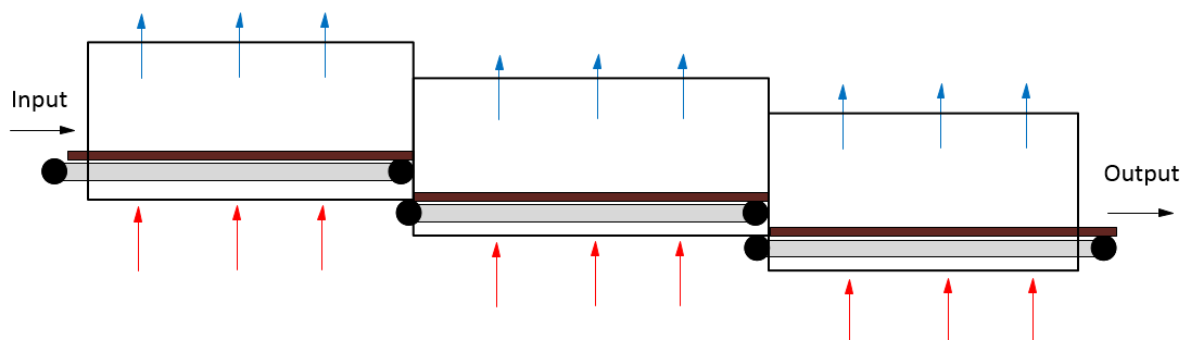


Figure 6: Illustration of a single pass multi-stage dryer [6].

2.3.3 Multiple pass dryer

The multiple pass dryer is very similar to the single pass multi-stage dryer, but with the multiple pass dryer the conveyor beds are arranged on top of another as illustrated in Figure 7. The benefit of a multiple pass dryer is the reduction of floor space needed for the same capacity. Furthermore, the benefits include the same ability to vary the bed depth as in the case of a single-pass, multi-stage configuration. The product enters the dryer at the top and the product then makes its way downwards to the lower beds. This is the most popular configuration found in industry [4].

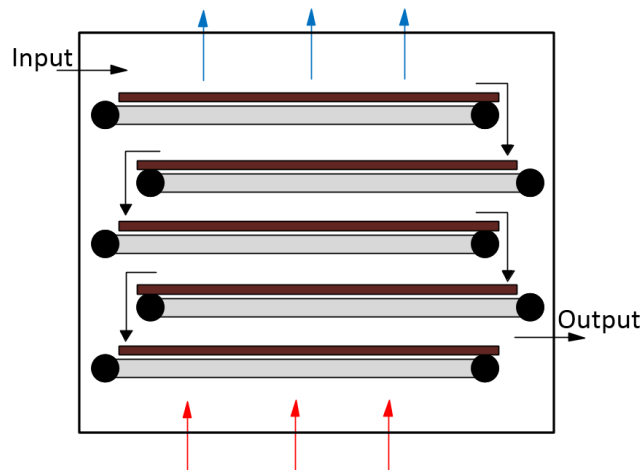


Figure 7: Illustration of a multi-pass dryer

2.4 AIRFLOW

Airflow through the product bed should be even to ensure uniform moisture content in the product [11]. Convective heat and mass transfer are proportional to airflow velocity through the product. As is evident in Figure 8, there will be preferential air flow through the shallower areas, which present a lower resistance than the deeper areas, resulting in a non-uniform final dried moisture content [4]. Specially designed feeders/spreaders are installed in a dryer to ensure uniform spreading [12]. The product can be spread in a number of ways to ensure uniformity. Oscillating feeders consist of an inclined chute which oscillates from side to side. Vibratory spreaders consist of a vibrating belt narrowing to the dispensing end; allowing the product to fall onto the belt below. If clumping is not an issue with the product, a simple hopper with an adjustable opening can be used. The spreading process can also be done after the product has been placed on the belt by means of rotating paddles or a reciprocating spreader which “combs” the product evenly over the bed [4].

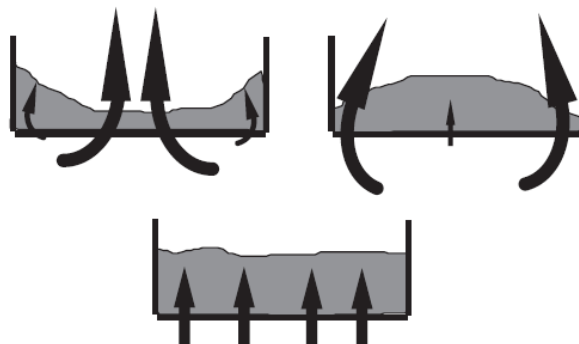


Figure 8: Illustration of the airflow pattern through packed product bed [4]

In the dryer, air is passed through the drying bed at velocities varying between 0.4-1.4 m/s. Modern dryers make use of partially recirculated air. This is done to decrease the amount of power needed to operate the dryer. Air will be exhausted to maintain a predetermined humidity level in the dryer. By utilizing this state, the design can use the energy supplied by the air more effectively. Only the necessary amount of fresh air is added to keep the humidity of recirculating air at desired levels [13]. The typical amount of exhausted air is 20%, but it can range between 10-40% of the total heated air flow [14] [4].

2.5 DRYING THEORY AND MODELS

This section will investigate the theory and principles used in the drying process in order to provide an insight into the drying process as well as defining the modelling of the complex process.

Convection can be defined as a process of heat transfer from a hotter medium to a colder medium in which one of the mediums is a gas or liquid [15]. Every moving fluid contains energy and this movement of energy allows heat to be transferred from one point to another. This implies that when a cold fluid is brought into contact with a solid that is at a greater temperature, the solid will transfer energy in the form of heat to the fluid. The fluid can in turn deliver the heat obtained to the next solid that is at a lower temperature than the fluid. This movement of energy can be divided into two main categories, namely: forced or natural convection. Forced convection is the process through which mechanical energy is added to the fluid to create the movement needed. Natural convection is the process through which no mechanical energy is added, and the movement is caused by density differences, which in turn are caused by temperature differences [16].

2.5.1 Drying theory

It is necessary to explain the theory and terminology used in drying to understand drying. The following section discusses the drying process as well as terms used in the process. The literature presented also discusses the effects of the different process parameters used in drying.

2.5.1.1 Drying

In thermal drying, two processes take place simultaneously in the product. These processes will be explained as stated in [6]:

When a product is extruded there is surface moisture on and internal moisture in the product. The processes taking place are:

- (i) In the first process, the heat transfer, supplied by convection energy, causes the evaporation of the surface moisture. The water vapour is then carried away from the solid by the moving air. In the first process, the removal of water vapour is influenced by external conditions, namely:
 - Heat assists the evaporation: by increasing the amount of heat in the hot air it increases the ability of the air to absorb the surface moisture of the product.
 - Humidity of air: when the relative humidity of the air is low, the air has a greater ability to absorb more water vapour into the air stream.
 - Airflow: the movement of the air transports the water vapour away from the product, increasing the movement of the air that in its turn increases the removal rate of the water vapour.

- Area of exposed surface: increasing the contact area will increase the evaporation rate.
- Vapour pressure: if the of the outside environmental pressure is increased the vapour would be forced to stay confined in the product, e.g. a pressure cooker [17].

(ii) In the second process the internal moisture is transferred from the inside of the product to the surface where it is exposed to the convection heat, resulting in the evaporation as discussed above.

During this process the movement of the moisture from the core of the solid to the surface depends on:

- The temperature of the air
- Moisture content of the air
- Physical nature of the solid

When the solid product is saturated with moisture the surface is covered with water. The internal moisture migration is sufficient to sustain this surface of the solid with enough moisture to ensure it is covered [6]. This flow of moisture can be caused by one or more of the following mechanisms:

- Diffusion
- Capillary flow
- Internal pressure caused by shrinkages

2.5.1.2 *Dehydration rate*

Dehydration rate or drying rate can be defined as the rate at which moisture evaporates from the surface of the product into the air [18]. The drying rate can also be described as a function of the humidity of the product. Considering Figure 9 the drying rate consists of two periods: the constant-rate drying period and the falling-rate drying period [18]. In the constant drying rate period the 1st process dominates. The surface is completely covered by water and the drying rate is independent of the internal moisture content. As the moisture content of the product decreases, process 2 increasingly start to dominates the drying rate. This is where dry spots on the surface start to appear and at the same time the temperature of the product starts to increase due to the fact that the moisture evaporation present on the surface is not sufficient to absorb the energy supplied to the solid. This is the falling-rate drying period. The moisture content at which this second period starts is known as the critical moisture content [6].

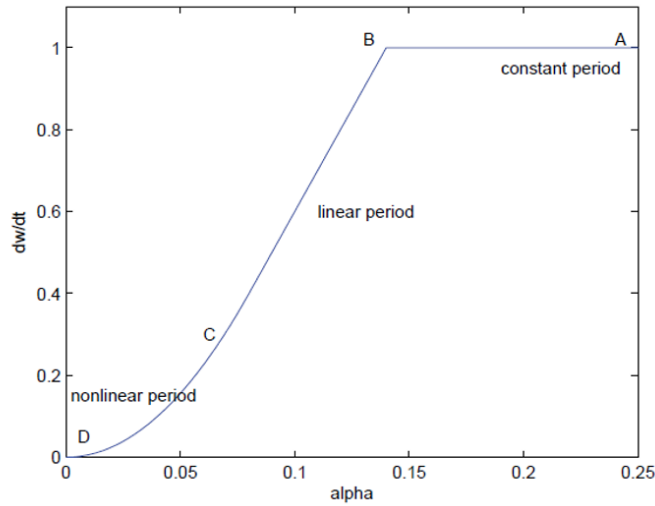


Figure 9: Drying rate as a function of the humidity [6]

2.5.1.3 Humidity ratio

The humidity ratio or absolute humidity is the ratio of the mass of the vapour to the mass of the dry air [4]. The humidity ratio X_a for unit water vapour per unit dry air is defined as shown in Equation (2.1)

$$X_a = \frac{m_v}{m_a} \quad (2.1)$$

where m_v is the total mass of vapour and m_a is the total mass of dry air (air not including vapour) [kg]. Equation (2.2) describes the humidity ratio for a solid as

$$X_s = \frac{m_w}{m_s} \quad (2.2)$$

where m_w is total mass of water and m_s is the total mass of the dry solid (the weight of the water is not included)[kg] [6].

2.5.1.4 Relative humidity

Relative humidity is the relation between the amount of water that is contained in the air and the amount of vapour that the air could contain if it was at saturation conditions. This can be described as the ratio of water vapour pressure to saturation pressure [4] [16].

2.5.1.5 Dew point temperature

Dew point temperature is the temperature at which the air vapour mixture would become saturated and condensation would occur [4]. This is where relative humidity is 100%. The temperature of the product will increase to the dew point temperature where-after the temperature of the product will stay constant at this temperature whilst the moisture is above the critical moisture content. Once the moisture content has fallen beneath the critical moisture point, the temperature will start to increase towards the temperature of the air [19].

2.5.1.6 Wet-bulb temperature

Wet-bulb temperature is also called the humid temperature [16]. Wet-bulb temperature is a temperature that is reached when a small amount of liquid evaporates into a large amount of moving unsaturated air. When air circulates across a water surface a heat transfer will take place, this transfer will cause the water to evaporate. This evaporation will cause a decrease in water temperature, whereas air approaches saturation conditions. An equilibrium will be reached once the system has stabilized. The temperature at which this stabilization will take place is known as the wet-bulb temperature [20].

2.5.1.7 Case hardening (crust formation)

Case hardening can be described as the hardening of the outer case of the product that is caused by dehydration on the surface of the product that happens quicker than the transfer of internal moisture to the surface [21]. Case hardening is also known as crust formation. Case hardening may be required in certain processes such as the puffing of extruded products [22]. Decreasing the temperature of the drying air decreases the rate of dehydration, thus by decreasing the temperature of the air stream, case hardening can be prevented [2]. Trying to increase the rate of drying by increasing the air stream temperature can result in case hardening [23].

2.5.2 Energy theory

In this section, the energy processes of a dryer are discussed and theoretically explained. The section will also discuss the energy changes in the product and the gas mixture energy as discussed by Van Delft [6].

2.5.2.1 Enthalpy

Enthalpy is the heat content of humid air [4]. The enthalpy of air is the sum of the enthalpy of the air plus the enthalpy of the water vapour that is contained in the air [20].

2.5.2.2 Latent heat of evaporation

The latent heat of evaporation can be defined as the amount of heat required to vaporize a unit mass of a liquid. Liquid boils at different temperatures when the atmospheric pressure is changed, which implies that the amount of heat needed is dependent on the atmospheric pressure at which the liquid evaporates [24].

2.5.2.3 Specific heat

The humid specific heat can be described as the amount of heat needed to increase the temperature of one unit mass of air by 1 degree Celsius ($^{\circ}\text{C}$). This unit mass includes the water vapour it contains [16].

2.5.2.4 Product energy

The product energy involved in the running of a dryer can be complex to determine. To accurately determine the energy balance in the dryer, the latent heat and specific heat must be taken into consideration [25]. The energy needed can be described as the energy used to increase the temperature of the product (including the moisture present) and the latent heat of evaporation of the moisture that has been removed.

The energy contained in the product can be given as:

$$E_p = m_p C p_p T_p \quad (2.3)$$

where m_p is the mass of the product [kg]. T_p is described as the temperature of the product [°C]. The bulk specific heat of the product is $C p_p$ [kJ/kg K]. This specific heat cannot be directly determined, thus it can be assumed that the specific heat of the product can be calculated as a combination of the dry solid and the water. The energy in the product can thus be calculated as the sum of the energy of the dry solid and the water. This can be written as:

$$E_p = (m_s C p_s + m_w C p_w) T_p \quad (2.4)$$

where E_p is the energy of the product [kJ/s], m_s is the mass of the solid [kg]. The specific heat of the solid is represented by $C p_s$ [kJ/kg K]. The mass of the water in the solid is given by m_w [kg], and the specific heat of the water is $C p_w$ [kJ/kg K]. Considering that:

$$m_w = m_s X_{so} \quad (2.5)$$

where X_{so} is the product inlet moisture content [kg_{water}/kg_{solid}], researchers can conclude that

$$E_p = m_s (C p_s + X_{so} C p_w) T_p \quad (2.6)$$

$$E_p = m_s h_s \quad (2.7)$$

where h_s is defined as the enthalpy of the solid:

$$h_s = (C p_s + X_{so} C p_w) T_p \quad (2.8)$$

In order to understand the energy balance it is necessary to examine the change in energy in the product. The change in energy can be described as the difference between the inlet and outlet energies.

$$\Delta E_p = [m_{ss} (C p_s + X_{so} C p_w) T_p]_{in} - [m_{ss} (C p_s + X_s C p_w) T_p]_{out} \quad (2.9)$$

where m_{ss} is the mass flow of the solid through the system [kg/s] and where X_s is the product outlet moisture content [kg_{water}/kg_{solid}].

This concludes the calculation of the energy within the product. The energy of the air, E_g [kJ/s] can be calculated in the same manner. The energy of the air can be described in almost the same manner than the energy in the product. It is a combination of the specific heat of the air and the specific heat of the moisture contained in the air. When considering the moisture in the air, it is important to consider the latent heat of evaporation contained in the air ΔH_s [kJ/kg], then the calculation of the energy of the air can be formulated as follows:

$$E_g = (m_a C p_a + m_v C p_v) T_g + \Delta H_s m_v \quad (2.10)$$

where m_a can be described as the mass of the air [kg]. $C p_a$ and $C p_v$ are the specific heat of the air and the specific heat of vapour [kJ/kg K]. T_g is the temperature of the gas. The mass of the vapour in the air is represented by m_v [kg].

Considering that:

$$m_v = m_a X_a \quad (2.11)$$

where X_a is the outlet air stream humidity [$\text{kg}_{\text{water}}/\text{kg}_{\text{air}}$], the equation can be simplified to:

$$E_g = m_a h_g \quad (2.12)$$

with h_g being the enthalpy of the air stream defined as:

$$h_g = (Cp_a + X_a Cp_v)T_g + X_a \Delta H_s$$

Once again the energy transferred is the difference between the inlet and outlet energy. The change of energy can be given as:

$$\Delta E_g = F_{ac} \left((Cp_a + X_a Cp_v)T_g + X_a \Delta H_s \right)_{in} - \left((Cp_a + X_a Cp_v)T_g + X_a \Delta H_s \right)_{out} \quad (2.13)$$

where F_{ac} is the mass flow of air [kg/s] and Cp_v is the specific heat of the water vapour (kJ/kg K).

2.5.3 Cooling zone

It is common for a product to exit a dryer at below 88 °C. The product must then be properly cooled. If an extruded product is packaged at a high temperature, moisture will condensate in the packaging, wetting the outer surface of the extruded product, and this will allow mould growth. When cooling is added to the dryer, 20-25% of the total retention time in the unit is needed for adequate cooling. A well cooled product temperature is generally between 5.5-8.3°C higher than the ambient storage temperature [13].

2.5.4 Mathematical models

In this section mathematical modelling will be performed using the terms explained in the previous section. This division will focus on calculating the power needed, residence time and the air flow required.

Mujumdar [4] presents a model that considers the various aspects of a dryer such as the type of dryer and the shrinkage of the dryer. This model is viewed as a sound model that delivers efficient solutions, however, little data is available regarding the properties of the finished product. This generates the need for gathering experimental data.

Helge Didreksen [26] presents a dynamic model for the transfer of heat, momentum and mass in a rotatory dryer. This model displays a good ability to predict changes in the product quality with changes in operating parameters.

Lais Koop et al. [27] developed a dynamic two-dimensional model that involves a set of four differential equations obtained from mass and energy balances, derived from the deep-bed drying of mate leaves.

The mathematical model chosen for this research is the one explained by Kiranoudis et al. [1]. The selection of this model is attributed to the fact that only one constant is present in the model, namely k_M , known as the drying constant. The mathematical modelling will be done for one chamber, taking the whole dryer as one segment. This will be done to simplify the modelling of the dryer, seeing that

the modelling of the dryer is a highly challenging task. This complexity is confirmed by Mujumdar, A.S [4]. This author states that it is very difficult to predict many of the effects experienced in a conveyor-belt dryer. These effects can include the permeability of the product bed, case hardening and product clumping. In many cases, laboratory testing is required to determine the limiting temperatures for food products to maintain the required characteristic and quality.

In general, conveyor dryer manufacturers make use of simple empirical models to determine the size of the dryer. Their calculations are limited to determining the size of the dryer.

The mathematical model will involve the heat and mass transfer in the dryer, as well as the product and air stream involved in the drying process. The dryer arrangement is shown in Figure 10 that displays the flow of air through the system as well as the flow of product (green) and the energy input (yellow).

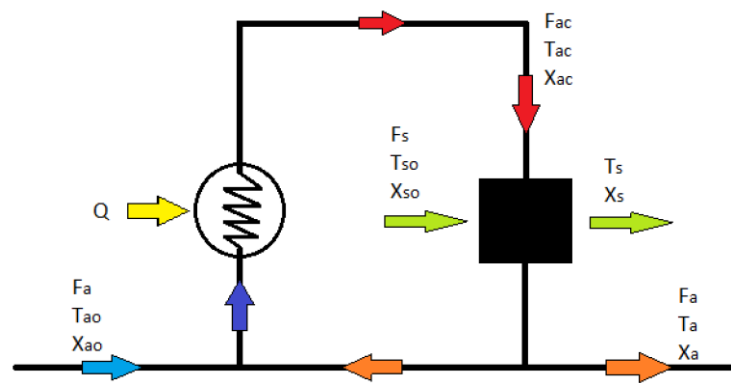


Figure 10: Schematic arrangement of product and air streams in a dryer

Figure 11 provides an illustration of the side view of a drying chamber as the product moves through the chamber.

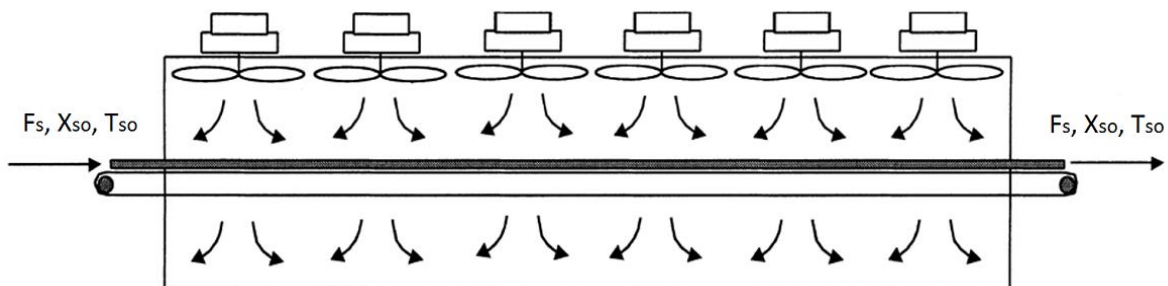


Figure 11: Side view of drying chamber

The overall mass balance of the dryer is given as:

$$F_A(X_A - X_{A0}) = F_S(X_{S0} - X_S) \quad (2.14)$$

where F_A is the flow rate of the fresh air stream added to the drying chamber [kg/s dry basis]. X_A is defined as the absolute humidity of the rejected air stream [kg/kg dry basis]. The absolute humidity of the fresh air stream X_{A0} [kg/kg dry basis] is the ambient air humidity, this air is mixed with the recirculation air to reduce the humidity of the recirculation air before being forced through the product bed again. F_S is the flow rate of the product stream through the drying chamber [kg/s dry basis], while the moisture content of the product on entering the chamber is X_{S0} [kg/kg dry basis],

and the moisture content of the product when exiting the dryer can be described as X_s [kg/kg dry basis].

The mass balance over the dryer is given as:

$$F_{AC}(X_A - X_{AC}) = F_S(X_{SO} - X_S) \quad (2.15)$$

where the flow rate and absolute humidity of the heated drying air stream is F_{AC} [kg/s] and X_{AC} [kg/kg dry basis]. If negligible heat loss is assumed, the overall heat balance in the drying chamber can be stated by the following equation:

$$Q = F_A(h_A - h_{AO}) + F_S(h_S - h_{SO}) \quad (2.16)$$

where Q is the exchanged heat [W]. The enthalpy of the air stream entering the chamber and the air stream exiting the chamber is given by h_{AO} and h_A [kJ/kg]. The specific enthalpy of the product on entering the chamber and on exiting the chamber is given by h_S and h_{SO} [kJ/kg].

The overall heat balance in the drying compartment is given by the equation:

$$F_{AC}(h_{AO} - h_A) = F_S(h_S - h_{SO}) \quad (2.17)$$

where h_{AO} is the specific enthalpy of the air stream entering the compartment [kJ/kg].

Determining the required residence time in the dryer is a complicated process. However, it can be determined by using a simplified model. The empirical model used in this study, has an exponential form that contains a mass transferral constant of a phenomenological nature, which is called the drying constant. This constant accounts for many factors influencing the residence time, including the mass diffusion and the boundary layer phenomena. When taking the above mentioned into account the mass transfer is expressed by the following equation:

$$X_S = X_{SE} + (X_{SO} - X_{SE}) \exp(-k_M * t_R) \quad (2.18)$$

where k_M is the drying constant [s^{-1}] and t_R is the residence time [s] and the equilibrium moisture is X_{SE} [kg/kg dry base]. In this model it is assumed that the heat transfer coefficient takes a adequate value to ensure that the product stream leaving the chamber is in thermal equilibrium with the air stream leaving the chamber. This assumption simplifies the model and eliminates the use of differential equations that would not play a great role in improving the accuracy of the model. Based on the above mentioned, the following equation can be derived:

$$T_S = T_A \quad (2.19)$$

with T_S being the outlet product stream temperature [$^{\circ}C$], and T_A the outlet air stream temperature [$^{\circ}C$]. This equation also indicates that thermodynamics determines that the product moisture content on leaving X_s [kg/kg dry base] should be greater than the equilibrium moisture X_{se} [kg/kg dry base] of the product stream, thus it can be stated in (2.20) that:

$$X_s \geq X_{se} \quad (2.20)$$

Furthermore, the air velocity through the product involved is computed as:

$$V_A = \frac{F_{AC}(1 + X_{AC})}{A \rho_A} \quad (2.21)$$

where V_A is the velocity of the air through the product [m/s]. A is the area of the belt that the air flow is applied to [m²], and ρ_A is the density of the air [kg/m³]. To prevent physical changes to the product, an upper temperature limit T_{smax} is set to ensure that no thermal degradation occurs during the drying process. Thus it can be stated that:

$$T_s \leq T_{smax} \quad (2.22)$$

The specific enthalpy of an air stream can be calculated as a function of its temperature and moisture and is given by the following equation:

$$h_A = C_{pA} T_A + X_A(\Delta H + C_{pV} T_A) \quad (2.23)$$

where C_{pA} and C_{pV} are the specific heat constants of the air and vapour contained in the air [kJ/kg K] and ΔH is the latent heat of evaporation for the moisture in the solid [kJ/kg]. The amount of heat gained by the air in the heat exchanger can be approximated by the following heat balance equations:

$$Q = F_{st} \Delta H_{st} \quad (2.24)$$

$$Q = A_{st} U_{st} ((T_{st} - T_{am}) - (T_{st} - T_{ac})) / \ln\left(\frac{T_{st} - T_{am}}{T_{st} - T_{ac}}\right) \quad (2.25)$$

The authenticity of equation (2.25) is confirmed by W.S. Janna [28]. In equation (2.24) F_{st} is the flow rate of the steam [kg/s] and ΔH_{st} is the latent heat of evaporation of the steam [kJ/kg]. In equation (2.25) A_{st} is the area of the heat exchanger exposed to the passing air [m²], U_{st} is the overall heat transfer coefficient [W/m² K], and the temperature of the steam is T_{st} [°C]. T_{am} is the temperature of the mixed air stream entering the heat exchanger consisting of recirculation and fresh air streams [°C]. T_{ac} is the temperature of the air stream leaving the heat exchanger [°C].

This section explained the chosen mathematical model and other models as well as heat and mass transfers occurring in a drying chamber. These equations can be used to calculate basic design parameters. Many of the phenomena present in the drying process cannot be accurately predicted. The mathematical modelling can be simplified, but the final design parameters should be obtained from laboratory tests.

2.6 CONCLUSION

In this chapter a summary of the relevant literature was provided, and a mathematical model obtained from literature was presented. This chapter provided an improved understanding of the theory involved in the convection drying process, in particular for the purpose of convection drying in the conveyor-belt dryer.

The next chapter will discuss the tests performed to determine the effects of various process parameters. It will explain the steps that were followed to obtain reliable results. The chapter will give a short summary of the results as well as a brief discussion of the results obtained in the test setup.

3 TEST PROCEDURE

This chapter describes the pilot test plant and the testing procedure used for the experimental investigation. Later in this chapter the data processing done on the results obtained will be discussed. The chapter also describes a test done to validate the data processing.

3.1 TEST SETUP

The test bench (TB) assembled consisted of a heating unit to increase the temperature of the airstream, a product bed tray (PBT) that has a perforated bottom plate to allow the air through and a centrifugal fan that provided airflow.

The heating unit consisted of two gas jet burners and burning propane gas that can increase the temperature of the passing air stream to the desired temperature. For the purpose of the test the maximum air temperature was set at 150°C. The temperature was controlled by means of a needle valve. The burners are situated at the inlet of the test bench as indicated by A in Figure 12.

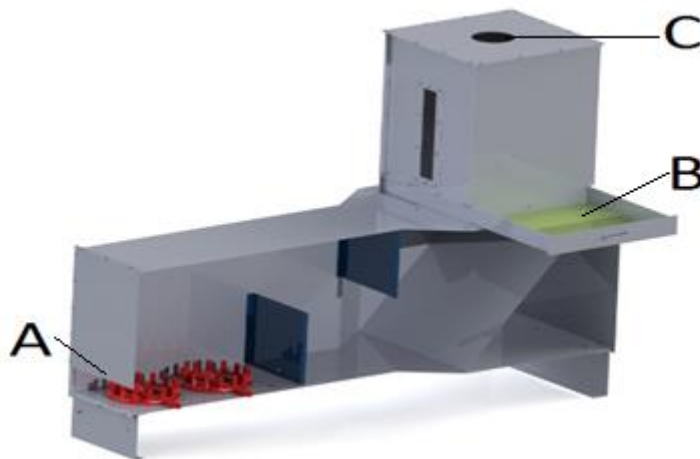


Figure 12: Test bench assembly

The PBT is situated at B in Figure 12. The bottom plate is perforated to allow airflow through the product stacked on top. The tray mechanism allows the process parameters to equalize in the TB, therefore the product can then be inserted into the airstream in the same way it would have been inserted in an actual CBD. This mechanism also allowed the product to be extruded after the TB was activated and stabilized, which increased the ability to insert the product directly from the extruder.

During the setup of the test bench, the temperature distribution across the bed width was measured within a 5% accuracy range, at an operating temperature of 100°C. The airspeed variation through the bed was measured and it was found that a speed variation of 6% is present at an average wind speed of 0.5 m/s. The airflow rate through the setup was controlled by means of a variable speed drive (VSD) that allowed the fan to be set at various frequencies, thus delivering various airflow rates. The desired airflow rates are associated with a specified frequency.

3.2 PROCEDURE

During the tests the process parameters were set. The TB was then run dry to ensure that the transients stabilize and that uniformity is reached in the system. Freshly extruded maize product was then placed on the product tray, thereafter a sample was taken for moisture analysis. The product was then inserted into the air stream by means of the sliding tray. The product was then dried until a specified time limit was reached. During the tests, the relative humidity and dry-bulb temperature were logged. Figure 13 illustrates a typical relative humidity curve (solid line), and the dry-bulb temperature curve (dotted line). After the product was dried to reach the specified time limit, the PBT was removed from the airstream and another sample was taken for moisture analysis.

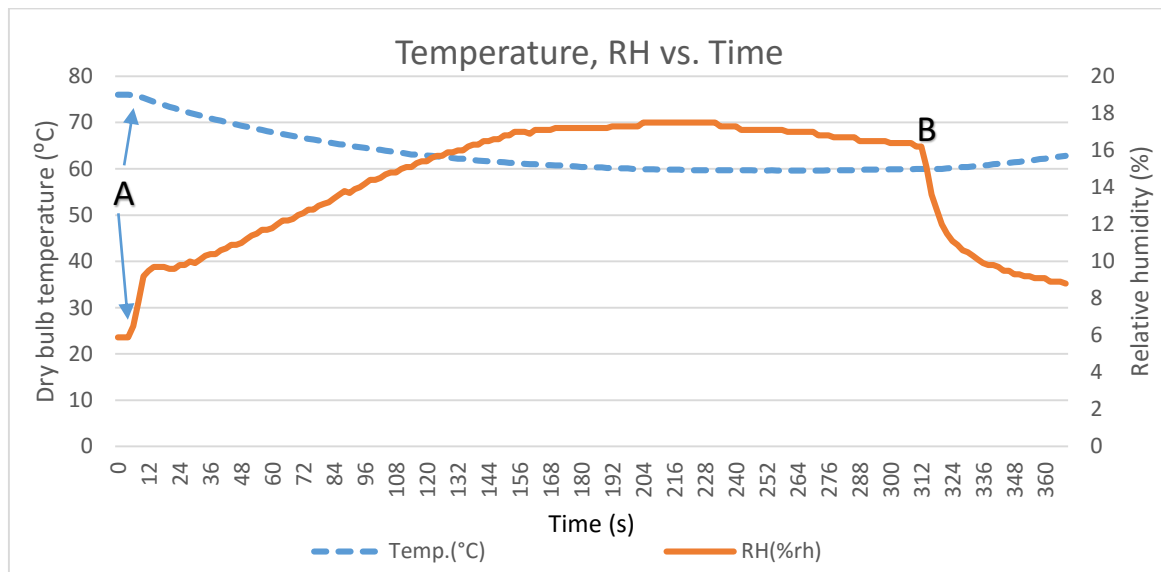


Figure 13: Typical Humidity and temperature curve

When examining Figure 13 it is clear that at point A there is a sudden increase in relative humidity and a sudden decrease in temperature that indicate that the wet product was inserted. The moisture that evaporated from the wet product increased the relative humidity. The decrease in temperature is attributed to the fact that energy from the airstream was used to evaporate moisture from the surface of the product. The point B the dried product was removed from the TB.

3.3 DATA PROCESSING

This section provides an explanation of the data processing that was performed to obtain useful results from the measured data. It provides insight into the results that will be discussed, and confirms the assumptions made.

3.3.1 Assumptions

For the purpose of these tests the following assumptions were made:

- The system is isolated, no leakages are present.
- The atmospheric humidity remains constant for the duration of the test.
- Pressure remains constant throughout the test.
- Atmospheric conditions were taken as standard for Potchefstroom.
- Altitude is taken as 1369 m [29].

- The temperature and airflow distribution over the tray are uniform.
- The initial moisture distribution inside the product is constant.

3.3.2 Total amount of moisture removed

In the processing of the data the noisy data was filtered using Savitzky-Golay filtering in Matlab as this smoothens the data. This smoother data was then used for further processing. By using the relative humidity and dry-bulb temperature values in EES (Engineering Equation Solver) as arguments and adding the atmospheric pressure of the atmosphere at the location of the sensor, P_s [kPa], to the equation, the absolute humidity of the air can be calculated. EES returns a value for the humidity ratio, ω , for air-water gas mixtures [kg_{water}/kg_{dry air}] [30]:

$$\omega = \text{HumRat}(\text{AirH2O}; T = T_g; r = \text{rh}; P = P_s) \quad (3.1)$$

where rh is the relative humidity of the air measured [%]. Using Equation (3.1) the difference in the humidity ratio of the original air stream and the air stream after the wet product is inserted [kg_{water}/kg_{dry air}] can be determined:

$$\omega_1 = \omega_{out} - \omega_{original} \quad (3.2)$$

where ω_1 is the deviation in humidity ratio, ω_{out} is the humidity ratio exiting the chamber and $\omega_{original}$ is the original humidity ratio of the air before entering the chamber. Then the mass flow of the air, $\dot{m}$, can be calculated as follows [kg_{dry air}/s]:

$$\dot{m} = \rho_A * V_A * A \quad (3.3)$$

where ρ_A is the density of the air [kg/m³]. Multiplying the difference in humidity ratio [kg_{water}/kg_{dry air}] with the amount of air put through the system will provide the amount of water removed per second (λ) [kg_{water}/s]:

$$\lambda = \omega_1 * \dot{m} \quad (3.4)$$

The relative humidity logger logs the data in 2 second intervals therefore it can be assumed that λ is the average for each 2 second interval. By multiplying λ with the amount of time in one interval (2 seconds), the average amount of water for each interval β can be obtained [kg]:

$$\beta = \lambda * 2 \quad (3.5)$$

The average amount of water removed per second varies, thus it was necessary to set up a parametric table in EES to calculate the average amount of water removed for each time interval. The total moisture removed can be determined by accumulating all these values:

$$\beta_{total} = \sum \beta \quad (3.6)$$

where β_{total} is the total amount of moisture removed from the product [kg]. The EES code for these calculations can be seen in Appendix 0.

3.3.3 Normalized rate

Due to the nature of extruded products, the moisture content of the product varies slightly when entering the TB. To obtain accurate results, it is important to ensure that the initial condition of the product is constant. To ensure this constant initial condition, the removal rate (λ) is divided by the percentage moisture in the product initially (X_{so}) [%]. This value is defined as the normalized rate λ_n that can be described as the rate of water removal per percentage moisture in the product initially [kg water removed/s·%initial moisture] that is calculated as follow:

$$\lambda(t)_n = \frac{\lambda(t)}{X_{so}} \quad (3.7)$$

This factor accounts for the amount of initial moisture present in the product. For the purpose of this study, the normalized rate will be investigated. Calculations and conclusions will be made on the basis of the investigated normalized rate.

3.4 CONCLUSION

In this chapter the process is described which will be used to compile data required for the design process. The chapter gives insight into the test bench used and the assumptions made. The calculations used are explained and the validation is given for the data processing. Lastly the chapter described the value that will be used for further interpretation namely: the normalized rate.

4 RESULTS AND DISCUSSION

In this chapter, the results obtained will be presented systematically. The results will be discussed to provide an understanding of the reasons for the specific way in which the results behaved.

4.1 VERIFICATION OF DATA PROCESSING

This section discusses the verification of the moisture loss calculation performed with physical tests. Secondly the moisture loss curve obtained is verified with the mathematical model discussed. This is done to ensure that the calculations performed and the conclusions reached are based on a reliable data processing method.

4.1.1 Verification of moisture loss calculations

The verification of the moisture loss calculations was determined by using a cotton cloth that covered the product tray. The cloth was soaked in water and dried to such an extent that no water was lost due to dripping. The cloth was weighed and placed in the drying chamber. After the specified time elapsed, the cloth was removed and weighed again. The loss in weight indicated the amount of moisture that was lost. The weighed moisture loss was then compared to the amount of moisture lost according to the calculations stated above. For validation reasons, the test was repeated three times.

Table 1: Verification results

Test	Moisture loss calculated (g)	Moisture loss weighed (g)	Difference (g)	Difference (%)
1	321	301	20	6.6
2	285	273	12	4.4
3	351	334	17	4.8
Average	313.3	308.3	16.3	5.3

From Table 1 it is seen that the maximum difference in between the moisture loss weighed and the moisture loss calculated is 6.6 %. The average difference is 5.3%.

4.1.2 Verification of moisture loss curve in extruded maize products

Figure 14 illustrates the moisture content of the drying product at various time intervals. The solid line indicates the moisture content of the product at the given time intervals by using the test setup and data processing method as presented in Chapter 3.

The dotted line indicates the moisture content of the product by using the mathematical model as presented in Section 2.5.4, from this it is seen that the form of the moisture curve is very similar, however, the measured moisture content was altered by twelve seconds. This was done to ensure that the measurements reached transient conditions. The non-transient conditions are caused by the imperfections of the testing procedure such as the opening and closing of the product tray and leakages of the system. When using the mathematical model no leakages are taken into consideration and the system is considered as a closed system.

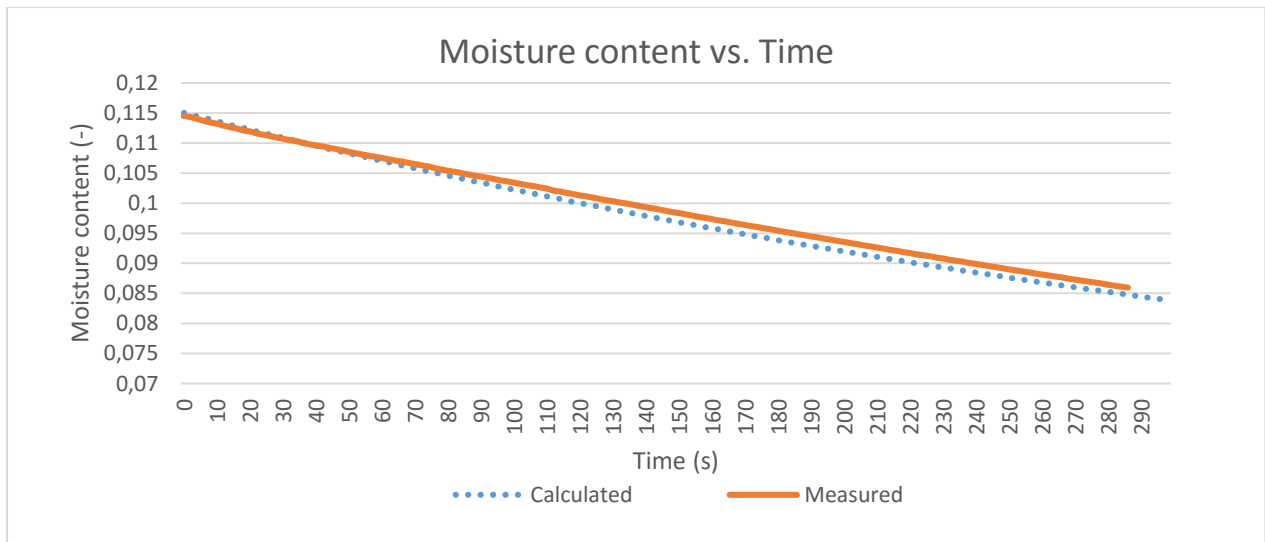


Figure 14: Moisture content vs. time

From Figure 14 it is seen that the curves of the calculated and measured values correlates well. At 284 seconds there is a 1.37 % difference in moisture content.

4.2 THE INFLUENCE OF TEMPERATURE AND AIR SPEED ON PRODUCT QUALITY

Figure 15 displays the typical results obtained for the tests performed at 100°C and 150°C , each test was also performed at 15 Hz and 25 Hz.

From Figure 15 it was evident that a change in airflow rate or temperature caused a change in the normalized rate curve of this extruded maize product. The most significant impact on the normalized rate curve was caused by temperature increase. In addition it was clear that the temperature alters the shape of the curve when comparing the test performed at 100°C and 15 Hz (T_{100 F₁₅}) to the curve for the test performed at 150° and 15Hz (T_{150 F₁₅}).

By comparing the tests performed at the same temperature but with different airflow rates, it was evident that the increased airflow rate increased the normalized rate slightly, as well as shifting the curve to the left. The normalized rate curve can be divided into three regions as indicated in Figure 15.

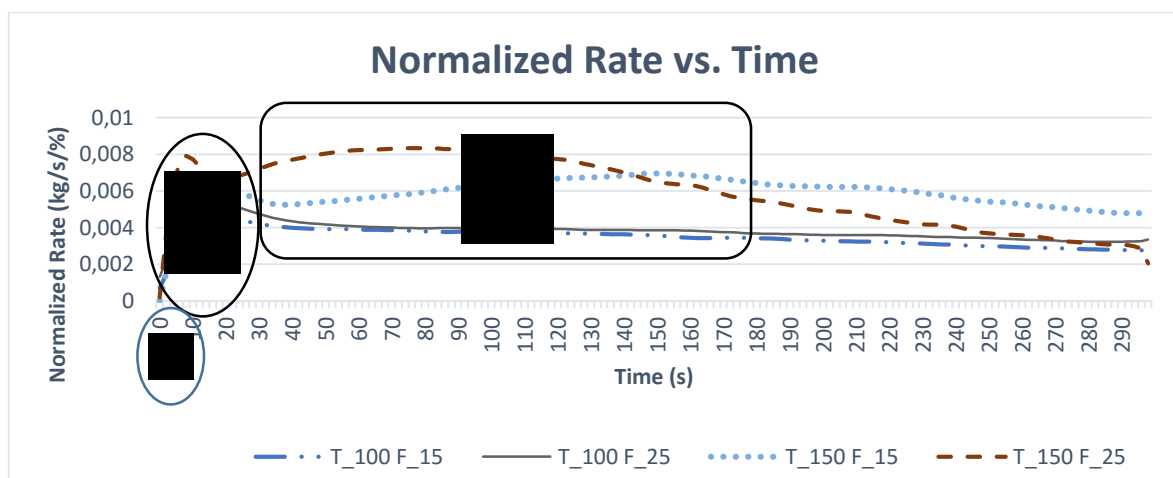


Figure 15: Normalized rate vs. time (showing the three regions)

Due to the change in the parameters, the moisture distribution in the product differed at each region. Figure 16 provides an illustration of the moisture distribution inside the product at each region during the drying process. The initial moisture distribution of the product was uniform as is indicated in Figure 16 (A). Considering the test performed at 100°C and 25Hz , it was evident that a sudden increase in normalized rate in region B indicated that a relatively large amount of moisture was removed from the product. This sudden increase was attributed to the available surface moisture that had evaporated the moment it was brought into contact with the air stream. The peak of the increase was reached after 20 seconds of exposure to the airstream. The decrease in normalized rate indicated that the evaporable surface moisture was removed. The core of the product still contained a high moisture content value, evident from Figure 16 (B). Considering region C, the normalized rate curve nears linearity. This linearity of the curve was reached 50 seconds after testing commenced and indicated that a steady state transfer was reached. This transfer is described as the diffusion of moisture from the inside of the product to the surface, and the evaporation of the moisture. It can be said that the rate at which the diffusion took place was in effect the same than the evaporation rate. In Figure 16 (C) it is clear that the difference between the surface moisture content and the core moisture content became insignificant when approaching a uniform distribution.

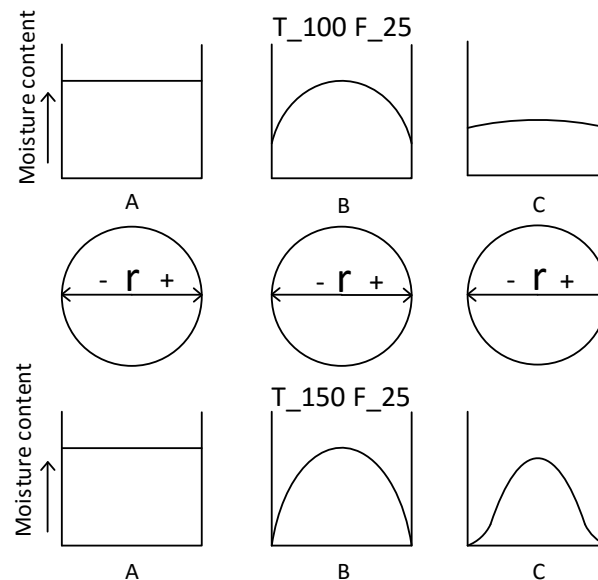


Figure 16: Moisture distribution

Considering the test performed at 150°C and 25Hz , a sudden increase in normalized rate appeared, as was described for the test that was performed at 100°C and 25Hz . This increase is due to the rapid evaporation of surface moisture. However, the magnitude of the increase indicated that considerably more moisture was removed, which can be attributed to the fact that at high temperatures the capability of the air to carry moisture increases, that causes a rapid dehydration near the surface of the product. The surface moisture at region B is noticeably lower compared to the same region for the test done at 100°C and 25Hz . The internal moisture of the product remained high due to the gradual diffusion of moisture to the surface. When looking at region C it is evident that the normalized rate curve decreases linearly from this region. This is caused by case hardening of the outer surface. As indicated in Figure 16 (C) for the second test, the moisture near the surface of the product remained low whilst the internal moisture of the product was still high. Figure 17 displays the effect that air

temperature had on the normalized drying rate at a constant airflow rate. In this case an airflow associated with a 15Hz frequency was investigated.

4.3 INFLUENCE OF TEMPERATURE ON NORMALIZED RATE

Firstly, as shown in Figure 17, the increase in temperature changed the shape of the drying curve. Secondly, it is clear that by increasing the temperature of the air, the normalized rate also increased. At all the temperatures tested, sudden increases were apparent. The sudden increase can be attributed to the rapid removal of surface moisture, and can be described as the potential of the airstream to evaporate moisture from the surface of the product. At a higher temperature, the potential is considerably higher. It was noted that up to 100°C this increase produced a near linear normalized rate. At 100°C the linear rate was near constant, indicating that the diffusion rate of the moisture in effect was the same than the rate at which moisture was removed from the surface of the product. At 60°C, the normalized rate decreased linearly, which indicated that the air stream did not contain the potential to fuel the transfer of internal moisture to the surface at the rate at which the surface moisture was removed, however no case hardening was observed at this temperature.

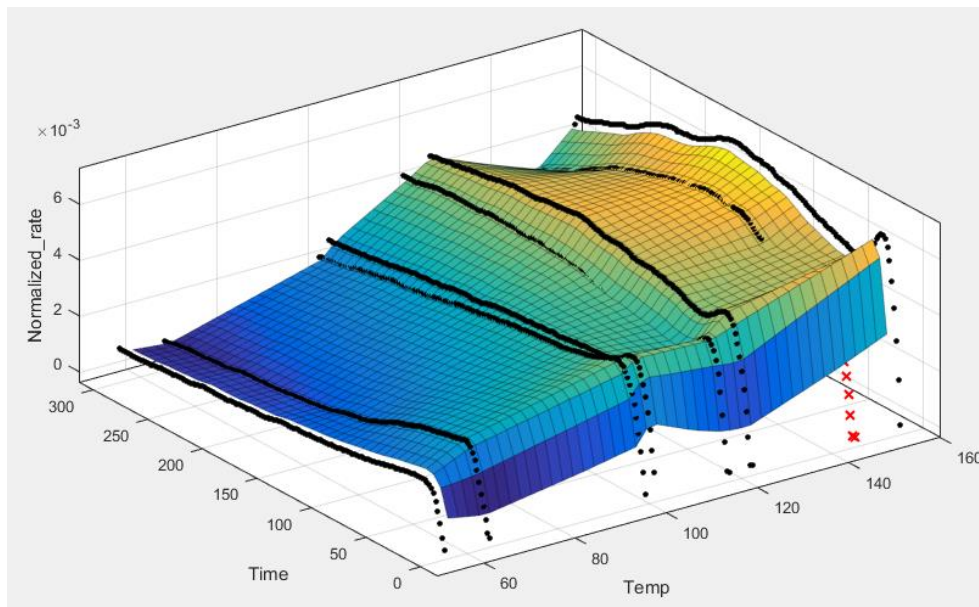


Figure 17: 3D normalized rate vs. time, temp (15 Hz)

When the temperature was increased to above 100°C, it resulted in a non-linear curve following the initial increase. This increase in normalized rate is attributed to the fact that at temperatures above 100°C the air stream has the potential to fuel the transfer of moisture from the core of the product to the surface. However, it was observed that beyond 150 seconds of testing performed at 150°C, this increase reached a maximum followed by a steep drop, indicating case hardening.

4.4 INFLUENCE OF AIR SPEED ON NORMALIZED RATE

Figure 18 displays the normalized rate measured at an airflow rate at 25Hz and different air temperatures. At the elevated airflow rate it was evident that the initial increase of the normalized rate was slightly higher. At temperatures above 100°C, the same phenomenon was observed, namely that the normalized rate increased after the initial increase. However, as indicated in Figure 18, the maximum was reached after only 100 seconds, which indicated that case hardening occurred earlier

than when compared to an airflow associated with 15Hz. At 150°C the case hardening influenced the normalized rate to such an extent that the normalized rate decreased to 0.002 [kg/s·%] after 300 seconds, which is the same than the normalized rate achieved when testing was performed at 60°C.

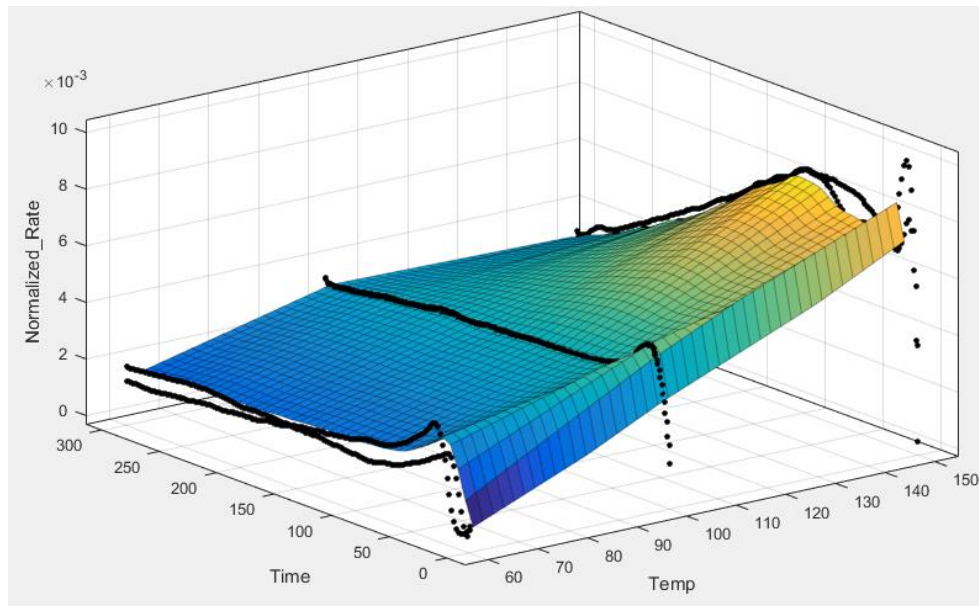


Figure 18: 3D normalized rate vs. time, temp (25 Hz)

The case hardening that occurred earlier was an indication that the evaporation rate at the surface of the product was considerably higher than the diffusion rate of the internal moisture. At 100°C a linear and almost constant normalized rate was observed. The normalized rate was slightly higher than the one obtained in the test performed at 15Hz.

4.5 COMBINED INFLUENCE OF TEMPERATURE AND AIRSPEED ON THE AVERAGE NORMALIZED RATE

In Figure 16 the data is graphically compared and simplified providing the average normalized rates at given parameters. From Figure 19 it can be clearly seen that the effect of the air temperature was more significant than that of the airflow rate. This is evident from the inappreciable increase from region A, 60°C and 15Hz, to region B, 60°C and 25Hz, compared to the substantial increase from region A, 60°C and 15Hz to region C, 150°C and 15Hz. One can also observe that the influence of the airflow rate was more significant at elevated temperatures, when comparing the noticeable increase from region C to region D, to the small increase from region A to region B.

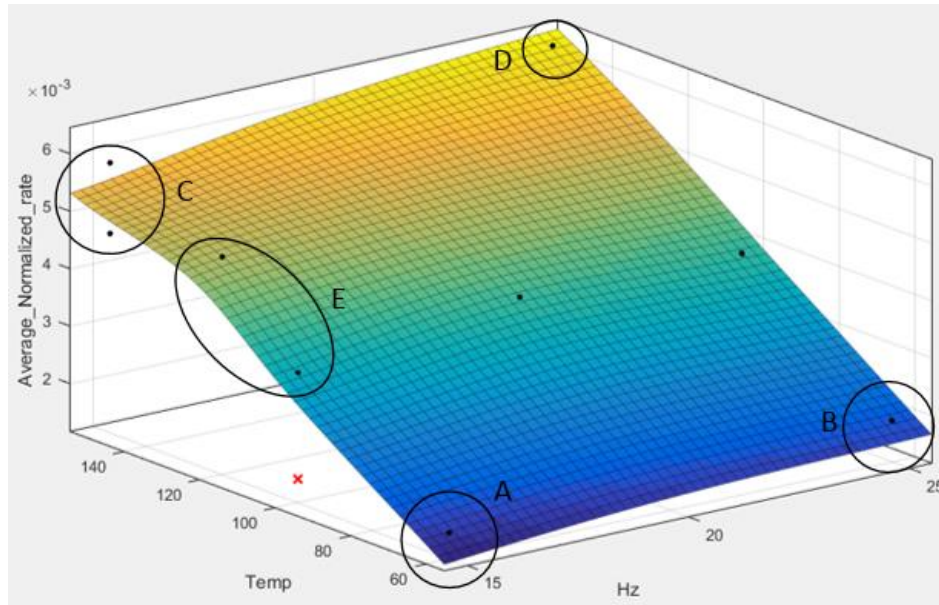


Figure 19: Average normalized rate vs. time, temp

The increase of airflow rate caused a $0.00036[\text{kg/s}\cdot\%]$ increase in the normalized rate. This insignificant increase can be attributed to the fact that the airstream does not possess the potential to increase the rate of diffusion of moisture to the surface of the product, as well as a relatively high relative humidity slowing down the rate of evaporation from the surface. Considering the same increase in airflow rate at 150°C , a noticeable increase of $0.00087[\text{kg/s}\cdot\%]$ was observed. This increase is ascribed to the fact that the airstream contains enough potential to encourage moisture diffusion to the surface of the product. The increased temperature decreased the relative humidity of the airstream, thus increasing the potential of the air to absorb moisture, which in its turn increased the evaporation rate.

From Figure 19 it is evident that there is a linear increase with the increase of air temperature at a constant airflow rate. This linearity is lost in region E, where this decrease in the normalized rate slope is ascribed to the fact that the relative humidity of the air around the product increased. The increase in relative humidity dampened the ability of the air to remove moisture from the product surface. By increasing the airflow rate at 150°C , it increased the amount of air through the product, this lowered the relative humidity that improved the ability of the air to absorb moisture, thus increasing the evaporation rate from the surface of the product.

When comparing region B to region D, a near linear curve is observed, which can be attributed to the fact that the airflow through the product was sufficient to keep the relative humidity at desired levels.

4.6 INFLUENCE OF PARAMETERS ON ENERGY REQUIREMENTS OF SYSTEM

Figure 20 indicates the energy required to increase the temperature of the air. By using the data obtained in Figure 19 and Figure 20, the most efficient parameters could be selected. Taking 60°C and 15Hz as the base values, the increase in normalized rate could be compared with the increase in energy required, thus also the increase in cost.

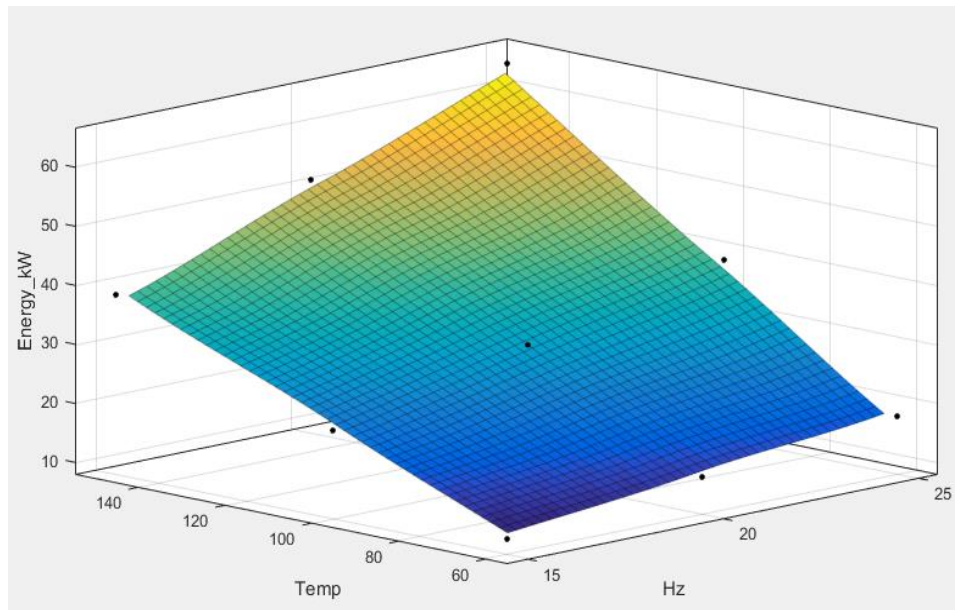


Figure 20: Energy vs. Temp, Hz

When graphically comparing Figure 19 and Figure 20, both display a smaller increase with the increase in airflow rate, than the increase associated with the increase in temperature. Due to the nonlinear behaviour seen at region E in Figure 19, region E does not represent viable operating parameters when compared to the linear increase in energy.

The rest of the data collected will now be analysed analytically for improved understanding.

Table 2: Energy increase vs. Normalized rate increase

Hz	Temp	% Energy increase	% Normalized Rate increase
15	60	0	0
25	60	66,67	23,62
15	100	114,34	125,61
20	100	185,75	143,00
25	100	257,17	149,93
15	150	257,17	243,72
25	150	495,34	300,70

From Table 2 it can be observed that from all the sets of parameters tested, the only set of parameters that increased the normalized rate more than it increased the energy required, is found at 100°C and 15Hz, with a positive difference in increase of 11.27%.

4.7 CONCLUSION

From the data presented it can be concluded that a change in both airflow rate and air temperature influence the normalized rate. The influences of the parameters can be summarized in the following way:

- (i) The temperature of the air stream exerts the biggest influence on the normalized rate curve, which is evident from the curves presented in Figure 15, when comparing the test performed at 100°C and 15Hz to the test done at 150°C and 25Hz .
- (ii) Secondly, the temperature changes the shape of the curve. At elevated temperatures the initial increase is followed by a non-linear curve.
- (iii) The airflow rate affects the time at which the drying regions occur. The airflow rate increases the normalized rate slightly, without changing the shape of the curve. The curve seems to be compressed at higher airflow rates.

From Figure 17 and 16 it is evident that drying performed at above 100°C should be avoided due to the nonlinear normalized rate curve obtained. The fact that case hardening was present at the test performed at 150°C as observed in Figure 18 confirms this.

From Figure 19 it can firstly be concluded that region E should be avoided to ensure optimum efficiency. Figure 19 secondly validates the statement that the airflow rate has a more significant impact at elevated temperatures.

With regards to Figure 19 and Figure 20 it can be concluded that increasing the temperature delivers a bigger increase in normalized rate than the increase in energy cost, when compared to an increase in airflow rate. From Table 2 it is clear that evaluating each set of parameters from the test performed at 100°C and 15Hz , the parameters delivered a bigger increase in normalized rate than the increase in energy required.

Ultimately it can be concluded that drying of this type of extruded maize product should be performed at 100°C and 15Hz . In the first place, this set of parameters avoids case hardening of the product and secondly it optimizes the efficiency of the drying phenomena. These parameters provide a normalized rate, λ_n , of $0.00252 \text{ [kg}_{\text{water removed}}/\text{s} \cdot \% \text{Initial moisture}]$.

In the next chapter the preliminary design procedure is given. The chapter gives the path followed to determine the selected design parameters.

5 PRELIMINARY DESIGN PROCEDURE

This chapter explains the processing of the conclusions obtained and it also indicates the calculations performed to calculate factors considered in the preliminary design. This chapter further illustrates the preliminary design suggested. In addition this chapter discusses the reasoning behind the design.

5.1 SIZING

To determine the size of the dryer, a calculation needs to be done using the normalized rate. At the selected parameters, a normalized rate of 0.00252 [kg_{water removed}/s·%Initial moisture] was achieved. Using this normalized rate and assuming an initial average moisture content of 13%, the size can be calculated. The flow rate of the moisture to and from the dryer can be calculated as:

$$m_{in} = F_s \cdot X_{SO} \quad (3.8)$$

$$m_{out} = F_s \cdot X_s \quad (3.9)$$

where $\dot{m}_{in}$ is the moisture flow rate in [kg/s] and $\dot{m}_{out}$ is the moisture flow rate out [kg/s]. The flow rate of the product is F_s [kg/s]. The amount of moisture that must be removed is obtained by calculating the difference between the inlet moisture flow and the outlet moisture flow.

$$\Delta m = m_{in} - m_{out} \quad (3.10)$$

where $\Delta \dot{m}$ is the difference between the inlet and outlet moisture [kg/s]. By multiplying the normalized rate with the percentage initial moisture present in the product, the average moisture removal rate can be obtained λ [kg/s]:

$$\lambda = \lambda_n \cdot X_{so} \quad (3.11)$$

The moisture removal rate achieved by the chosen parameters, is λ [kg/s]. Due to mass balance, the moisture removed from the drying chamber should be the same than the rate at which moisture was inserted into the dryer. Assuming that the normalized rate chosen was achieved for a product tray size of 0.25m² (a), the size of the area exposed to the airflow can be determined by:

$$A = \frac{a \cdot \Delta m}{\lambda} \quad (3.12)$$

where A is the total area exposed to the airflow [m²], and a is the area of the area exposed to the airflow during the pilot plant test [m²].

5.2 BELT SPEED

The belt speed of the dryer is calculated on the principles of the conservation of mass:

$$F_s = V_{Belt} \cdot b_{Belt} \cdot H_{Bed} \cdot \rho_{Product} \quad (3.13)$$

By using the following values the speed of the belt can be calculated.

Table 3: Selected design values

Symbol	Description	Value	Unit
F_s	Product flow rate	0,033	kg/s
b_{belt}	Width of the belt	0,5	M
H_{bed}	Height of the bed	0,5	M
$\rho_{product}$	Density of the product	250	kg/m ³

The size of the exposed area and the speed at which the belt should move is calculated from this. From these performed calculations, the design could be concluded.

5.3 PROPOSED PRELIMINARY CONCEPT

Considering the above mentioned calculations and using the research presented in the previous chapters the preliminary design is illustrated in Figure 21.

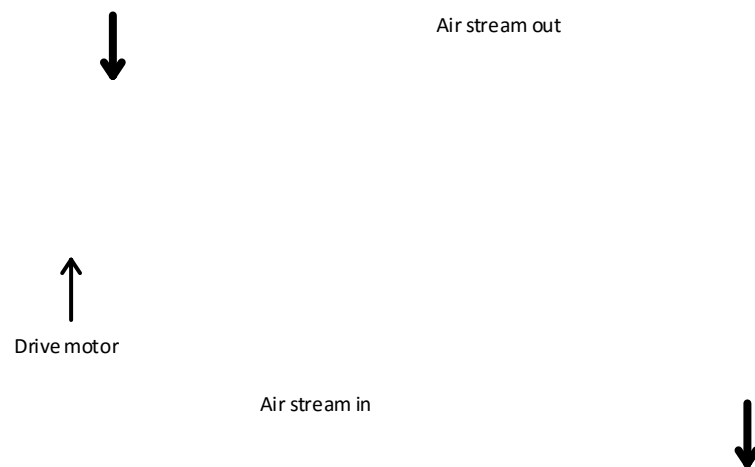


Figure 21: Concept design of CBD

Figure 21 displays the preliminary concept that operates on the principle of wet product being dropped onto a perforated conveyor belt. Directly beneath the belt is a plenum that allows air to be distributed uniformly through the product. The air forced through the product will be at 100°C and at an airflow associated with 15Hz . Performing the calculations for an average product moisture inlet content of 13% and an exit moisture content of 10% and using Equation(3.12), the area exposed to the airflow was calculated as 0.7631 m^2 . By using the belt width specified in Table 3, a belt length of 1.53 m was calculated. The speed of the belt is controlled by the drive motor situated on the roller of the conveyor belt and the speed of the belt was calculated as 0.004 m/s . The dry product was then ejected from the drying chamber for further processing.

5.4 CONCLUSION

In this chapter the proposed preliminary concept procedure is given. This procedure can be used to determine the sizing of a conveyor-belt dryer for increased or decreased product flow rate. In the next chapter the final conclusions are given. Some recommendations are made for future research and the final thoughts of the dissertation is given.

6 CONCLUSIONS AND RECOMMENDATIONS

From the research presented in this dissertation a few conclusions and recommendations can be made. These conclusions are discussed in this chapter. The chapter is concluded with a few final thoughts of the research presented.

6.1 CONCLUSIONS

In Chapter 2 it was indicated by means of a literature study that based on the problems associated with the selection of a dryer as well as drying parameters, it can be concluded that the modelling and prediction of drying is a complicated phenomenon and without sufficient knowledge on and understanding of the process, the prediction of the outcomes of the process can be inaccurate and deliver non-realistic results. This necessitates the performance of tests for different products. The results presented in this dissertation are only applicable to the specific extruded maize product with the specified geometry and composition.

With regards to Chapter 3, and in particular referring to Section 4, it was clear that the process parameters influenced the drying phenomena differently. From the results presented it was also evident that the parameters affected the energy consumption of the dryer differently. By comparing the increase in energy to the increase in normalized rate, the conclusion could be reached that the most efficient operating parameters for this extruded maize product are at 100°C and 15Hz .

Chapter 0 discussed the design considerations and the calculations associated with it. From the calculations it can be concluded that the area exposed to the air stream should be 0.7631 m^2 . The associated belt speed was calculated as 0.004 m/s .

6.2 RECOMMENDATIONS

During the investigation a few problems were identified. These problems should be addressed in future work. A few of the recommendations are:

1. To improve the fit of the curve and thus to increase the insight into the drying phenomena, more tests are recommended close to the selected parameters. Table 4 displays the parameters where tests are recommended. The recommended VSD frequencies controls the speed of the fan, thus it represents a specified airflow rate through the product bed.

Table 4: Recommended parameters

Test	Airflow (Hz)	Temp $^{\circ}\text{C}$
1	15	80
2	20	60
3	20	80
4	20	120
5	20	150
6	25	80
7	25	120

By performing tests at the above mentioned parameters, the linearity of the surface can be investigated, which will provide the ability to investigate the further optimization of the drying process. Performing these tests can assist in the prediction of the results at increased airflow rates and temperatures.

2. In the research presented the atmospheric conditions were assumed to be constant, but in the food processing industry dryers operate throughout the year. This can lead to changes in the drying rate under different atmospheric conditions. Tests are recommended at higher and lower atmospheric pressures. This will be possible by changing the location where the tests are performed. Performing tests during all the seasons will also provide insight into the influences that the day to day conditions have on the drying rate and will investigate the possibility of energy saving in the preferable months.
3. In the procedure followed, hot air was forced through the product only once, but in modern dryers air recirculation is used to improve the efficiency of the system and decrease energy losses. It is recommended that the influence of the recycling of the air to pass through the product more than once must be investigated. Furthermore, utilizing the maximum amount of exhaust air that can be reintroduced to the air stream to be forced through the product, is recommended to decrease the amount of energy lost.

These tests can be performed by altering the setup to allow the air to pass through the product again whilst only a predetermined volume of air is exhausted. The relative humidity of the air should be measured before entering it into the product bed and at the position where the air is exhausted.

4. During the tests performed, a uniform product geometry was used. However, changing the product geometry increases or decreases the surface area of the product that is exposed to the air stream, thus increasing or decreasing the drying rate. For this reason research is recommended on the relation between product geometry and the associated drying rate. These test results can provide a preferred shape for drying that can enable the drying process to be accelerated.
5. All the tests performed used a specific maize extruded product. An investigation into the influence that the product composition has on the drying rate is also recommended.

6.3 CLOSURE

The drying of extruded products remains a complex and undiscovered field. Very little information is available for the use in designs. This can be attributed to the fact that companies performing the test keep the information confidential to be competitive in the market place. Developing a basic model in the sizing of a CBD can help a company to select the right sized dryer for the accurate drying of their product. However much more testing is needed to compile an adequate database. The ultimate solution can be described as where a simple test on the product can determine a process variable e.g. normalized rate, which can be used in a mathematical model.

However, the smallest change in product geometry or composition can alter or influence the rate at which the product is dried. For this reason testing on a pilot plant remains the most reliable source.

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APPENDICES

A. PHOTOS



Figure 22: Pilot plant test setup



Figure 23: Calibration of thermocouples

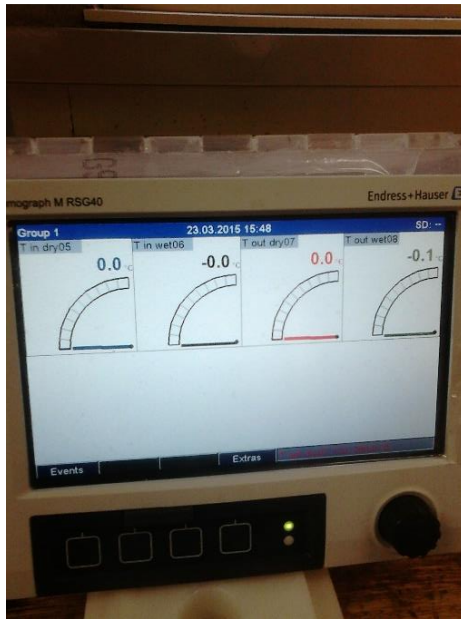


Figure 24: Thermocouple temperature logger display



Figure 25: Airflow distribution

B. ENGINEERING EQUATION SOLVER CODE

B.1 Water content calculations

```
//Measured values
T_atm
=61,42

rh_atm = 0,079
//T_F = 25
//rh_F = 0,25
P1 = 87 [kPa]

//Air moisture ratio
omega_in=HumRat(AirH2O;T=T_atm;r=rh_atm;P=P1)
omega_meter=HumRat(AirH2O;T=T_F;r=rh_F/100;P=P1)
rho=Density(Air;T=T_F;P=P1)

//Calculations
Delta_omega = omega_meter - omega_in
D = 0,16 [m]
area =(3,14/4) * D^2
V = 5,68 [m/s]
m_dot = rho * area* V

Moisture_dot = delta_omega *m_dot
Moisture_kg = Moisture_dot * 2
```

B.2 Sizing

```
F_product = 120 [kg/h]
S_per_uur =3600 [s/h]
m_dot_product = F_product/S_per_uur
x_product_in = 0,13
x_product_uit = 0,10
Lamda = 0,00252 [kg/(s*m^2)]
Lamda_a = Lamda * x_product_in
opp = 0,25 [m^2]
B_belt = 0,5 [m]
H_bed = 0,06 [m]
rho_product = 250 [kg/m^3]

m_dot_vog_in = m_dot_product * x_product_in
m_dot_vog_uit = m_dot_product * x_product_uit
m_dot_delta = m_dot_vog_in-m_dot_vog_uit

// Belt length
area = (opp * m_dot_delta)/Lamda_a
Area = L_belt * B_belt

// Belt speed
m_dot_product = v_belt * B_belt * H_bed*rho_product

// Time
Time = L_belt/v_belt
```

B.3 Verification

//Variables

T_ac = 273,15+100

Delta_t = 20

[k]

X_so = 0,115

[-]

X_se = 0,055

[-]

X_atm_abs = 0,002313

X_atm = X_atm_abs /

rho_a

F_s = 100

[kg/h]

Delta_t = T_ac - T_a

F_a = F_ac

T_atm = 273,15+25

T_so = 273,15+70

T_a =

T_s

k_m_h = 7,87

[1/h]

k_m = k_m_h / S_per_uur

P = 101,3

[kPa]

rho_a = Density(Air_ha; T=T_a; P=P)

DELTA_Ho = Enthalpy_vaporization(Water; P=P)

Cp_a = 1,005

[kJ/kg*K]

Cp_v = 1,8

[kJ/kg*K]

Cp_w = 4,185

[kJ/kg*K]

Cp_s = 3

[kJ/kg*K]

//Energy balances

h_a_Ta = Cp_a * T_a + X_a * (Delta_Ho + Cp_v * T_a)

h_s_Ts = Cp_s * T_s + X_s * Cp_w * T_s

h_a_Tatm = Cp_a * T_atm + X_atm * (Delta_Ho + Cp_v * T_atm)

h_s_Tso = Cp_s * T_so + X_so * Cp_w * T_so

h_a_Tac = Cp_a * T_ac + X_ac * (Delta_Ho + Cp_v * T_ac)

F_ac * (h_a_Tac - h_a_Ta) = F_s * (h_s_Ts - h_s_Tso)

S_per_uur = 3600

[s/h]

//Mass balances

F_a * (X_a - X_atm) = F_s * (X_so - X_s)

F_ac * (X_a - X_ac) = F_s * (X_so - X_s)

//Residence time

X_s = X_se + (X_so - X_se) * exp(-k_m * t_res)

B.4 Sizing results

Unit Settings: SI C kPa kJ mass deg

area = 0,7631 [m²]

H_{bed} = 0,06 [m]

L_{belt} = 1,526 [m]

$\dot{m}_{\text{vog,in}}$ = 0,004333 [kg/s]

p_{product} = 250 [kg/m³]

v_{belt} = 0,004444 [m/s]

B_{belt} = 0,5 [m]

Lamda = 0,00252 [kg/(s*m²)]

$\dot{m}_s$ = 0,001 [kg/s]

$\dot{m}_{\text{vog,uit}}$ = 0,003333 [kg/s]

S_{per,uur} = 3600 [s/h]

x_{product,in} = 0,13

F_{product} = 120 [kg/h]

Lamda_a = 0,0003276 [kg/(s*m²)]

$\dot{m}_{\text{product}}$ = 0,03333 [kg/s]

opp = 0,25 [m²]

Time = 343,4 [s]

x_{product,uit} = 0,1

C PILOT PLANT DESIGN

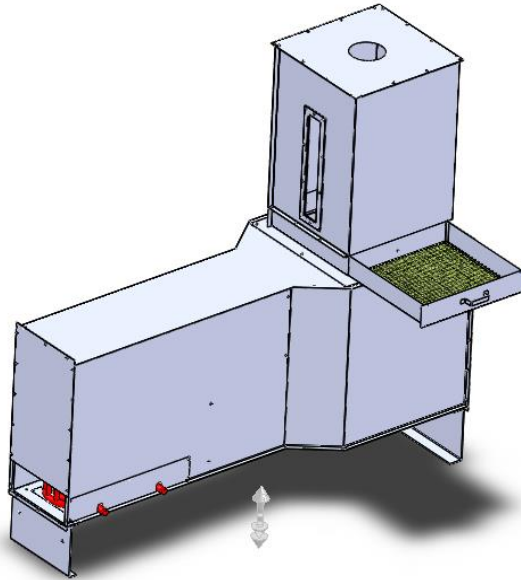


Figure 26: Pilot plant design view (1)

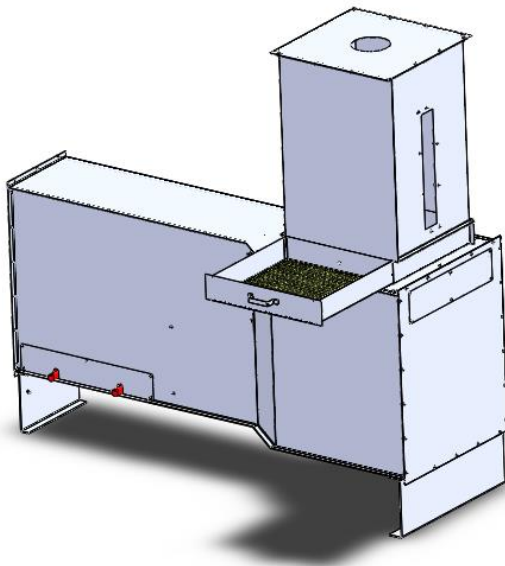


Figure 27: Pilot plant design view (2)

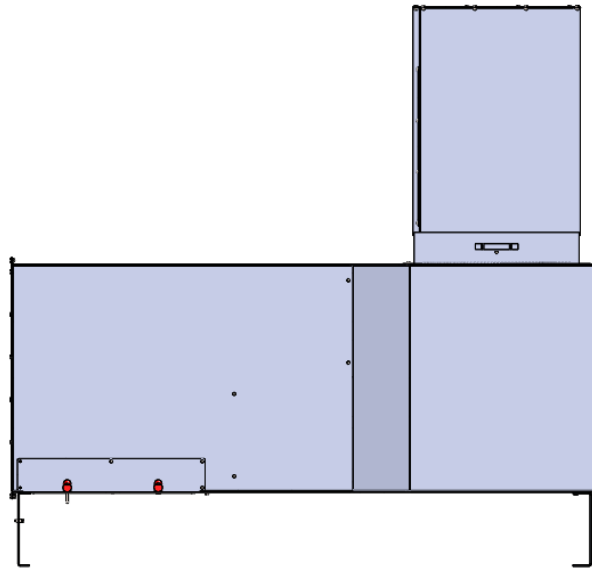


Figure 28: Pilot plant design side view

D PAPER

Influence of airflow rate and air temperature associated with drying of an extruded maize product.

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Abstract

The aim of this paper is to provide an understanding of the drying phenomena and the associated parameters. A change in operation parameters influences the product's moisture and the energy consumption of the system. Current literature does not provide ample data regarding the drying process of extruded maize products. It also does not clarify the effects that the parameters have on the drying process. Tests were done to measure the influence of these parameters. The data produced during these tests can be used to optimize the drying process by maximising the drying rate while still producing good quality product. Furthermore, the energy used to heat the air at various airflow rates is investigated.

Introduction

When extruding, drying the extruded product is an essential process to improve food stability and decrease the physical changes during storage [1]. The drying process is a complicated phenomenon and without sufficient understanding and data mathematical modelling can lead to inaccurate results [2] [3]. In numerous studies, transfer coefficients are assumed constant producing inaccurate results [4]. Conveyor belt dryers work on the principle of wet product being dropped on to a moving perforated belt. Hot air is then forced through the product. This allows the moisture to evaporate and to be transferred away from the product [5]. In conveyor belt dryers, the typical controlled variable is the temperature of the air [6]. If dehydration takes place too rapidly, case hardening can occur. Case hardening can be described as the outer shell of the product losing moisture faster than the inside of the product can diffuse moisture to the surface of the product. Case hardening results in hardening of the outer shell preventing moisture to diffuse from the inside. A high air temperature and low relative humidity of the air will result in rapid dehydration [7]. Case hardening can be prevented by decreasing the temperature of the air stream [8].

Test procedure

For the purpose of the research, a test bench was used. The test bench consists of a heating unit, product tray and a circulation fan. During the test procedure batches of extruded product was placed on the product tray. The product tray is perforated, to allow airflow. Hot air was forced through the product on this tray. The moisture of the air exiting the test bench is used together with the initial relative humidity of the system, with no product inside, to determine the amount of moisture removed from the product. By accurately logging the moisture content of the air, the rate at which moisture is removed from the product can be determined, this is known as the drying rate [9]. The

airflow rate and air temperature was varied to examine the influence of each parameter on the drying rate of the product. To determine the moisture content of the air exiting the setup a humidity sensor was installed. The sensor logs the relative humidity and the air temperature. The static pressure at the location of the sensor is measured using a pitot meter. The temperature, relative humidity and the pressure then serves as the arguments needed to calculate humidity ratio of the air. The humidity ratio is defined as the mass of water vapour per mass of dry air [10]. A thermocouple is inserted directly below the perforated bed to ensure the air entering the product bed is at the desired temperature. The air speed is varied using a Variable Speed Drive (VSD). The setup is run dry until the initial transients of the system stabilizes. After the transients stabilizes the tray is inserted into the air stream.

Figure 1 shows a typical curve obtained when logging relative humidity (orange) and dry bulb temperature of the air (blue line) of a single batch test. At point A, the sudden rise in relative humidity and decrease in temperature indicated that the wet product was inserted. The air temperature decreases at this point, due to the fact energy is being absorbed to evaporate the water from the product surface into the airstream.

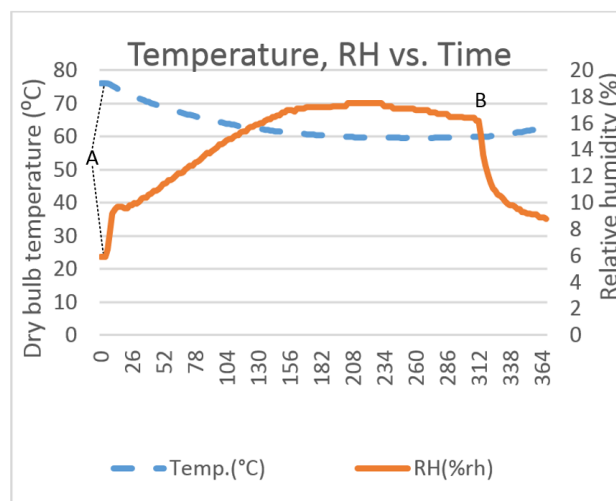


Figure 1: Humidity and Temperature Logging

Results and Discussion

Due to the nature of extruded products the moisture content of the product varied slightly on entering the test this initial moisture content of the product cannot be ignored, due to the fact that if more water is present in the batch the drying rate will be increased and vice versa. The drying rate is divided by the percentage moisture in the product initially ($X_{initial}$) to obtain a value that accounts for initial moisture

content variations in the product. This value is defined as the normalized rate, λ_n [kg/s · %], and is used for further discussion. The normalized rate can be determined as:

$$\lambda_n = \frac{\lambda}{X_{Initial}} \quad (1)$$

where λ is defined as the drying rate measured [kg/s], $X_{Initial}$ is the initial moisture content of the product [%]. The results discussed will investigate the effect of airflow rate and air temperature on the drying rate of the product. For the tests the VSD will be set at specified frequencies and these frequencies delivers a specified fan speed which in turn delivers different air flow rates. Figure 2 displays the result obtained of tests done at 100 °C and 150 °C, and each test was performed at 15 Hz and 25 Hz.

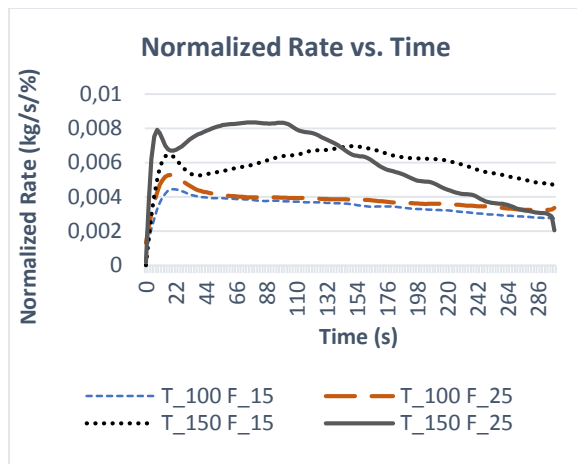


Figure 2: 2D Normalized rate vs. Time

From Figure 2 it is seen that the airflow rate and the temperature of the air changes the characteristic normalized rate curve of this extruded maize product. Refer to Figure 2, the temperature of the air changes the shape of the curve as seen when comparing T_100 F_15 and T_150 F_15. Secondly by referring to curve T_150 F_15 and T_150 F_25 in Figure 2, it is shown that increasing the airflow rate shifts the curve to the left. The normalized rate curves can be divided into three regions as displayed in Figure 3.

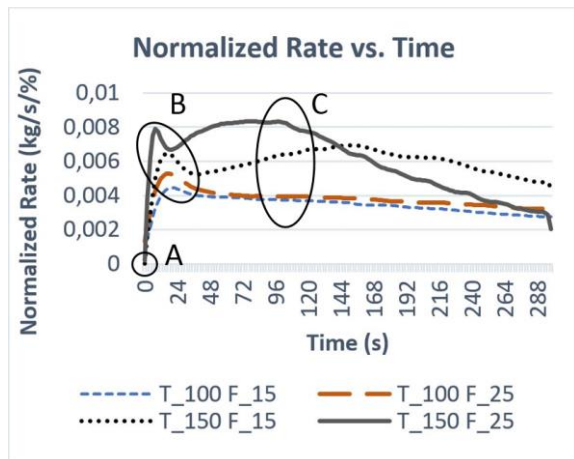


Figure 3: Drying Regions

At each of the regions the moisture distribution in the product differ, Figure 4 illustrates the moisture content at intervals from the centre core of the product. It is seen that at region A the moisture distribution throughout the product is uniform, this is the freshly extruded product and the moisture distribution is in equilibrium. At region B the sudden increase in normalized rate indicates the surface moisture is evaporated into the airstream, comparing the test done at 100 °C and 25 Hz to the test at 150 °C and 25 Hz, it is seen that at the test at the higher temperature removes more surface moisture. The moisture distribution in the product takes a parabolic shape, however the surface moisture at 150 °C is significantly lower. This is attributed to the higher energy content of the airstream at 150 °C, allowing the airstream to deliver a ‘shockwave’ of energy to the surface moisture. The internal moisture of the product remains high at this region, due to gradual diffusion of internal moisture to the surface.

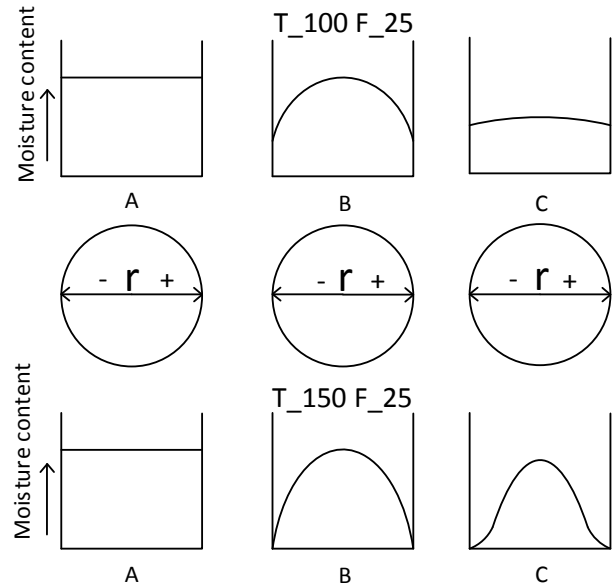


Figure 4: Moisture distribution

At region C for the test done at 100 °C and 25 Hz the internal moisture and the surface moisture are near equilibrium this is seen from the near linear normalized rate achieved, with an insignificant change in normalized rate. The constant normalized rate for the test done at 100 °C and 25 Hz indicate that the rate of the diffusion of moisture to the surface is in effect the same as the rate of the surface moisture evaporation. From region C for the test done at 150 °C and 25 Hz, a near linear normalized rate is achieved, but with a noticeable decline in the normalized rate. The sharp increase in normalized rate and the sudden drop is a characteristic of case hardening, as described earlier this is where the outer surface of the product loses moisture faster than the inside can deliver. This causes the outer case of the product to harden, and thus preventing further moisture diffusion. Sketch C for the test done at 150 °C and 25 Hz in Figure 4 illustrates the moisture distribution in such a case. The moisture at the surface is very low whilst the internal moisture remains high.

Figure 5 illustrates the changes in the normalized rate at the same airflow rate (15Hz) but with the temperature being varied. At 145°C a few data outliers is ignored. The outliers can be attributed to various factors including heat lost to the atmosphere.

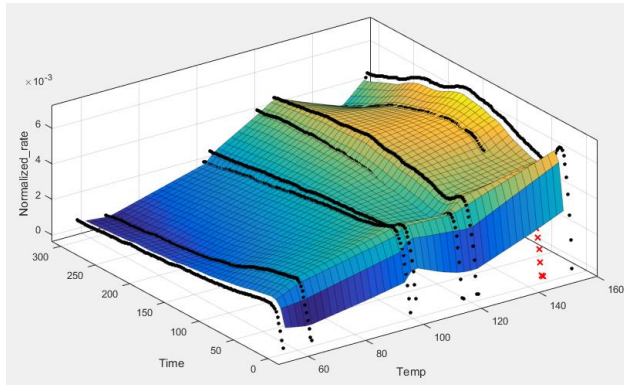


Figure 5: 3D Normalized rate vs. Time, Temp (15 Hz)

It is seen that by increasing the temperature of the air the normalized rate is also increased. In addition, it is seen that at 100 °C an almost constant normalized rate is achieved. Above 100 °C, a decline in normalized rate is observed after 150 seconds. Figure 6 illustrates the changes in the normalized rate at an elevated airflow rate (25Hz) at various temperatures.

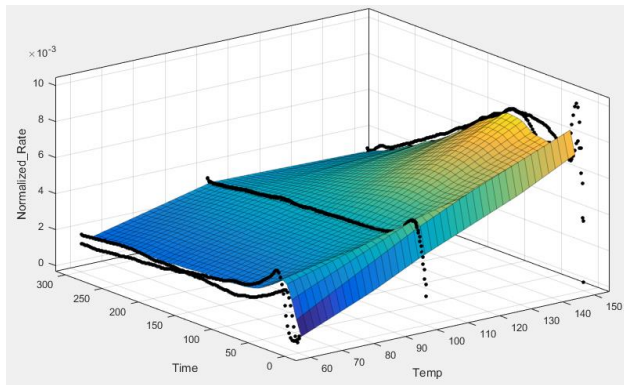


Figure 6: 3D Normalized rate vs. Time, Temp (25 Hz)

From Figure 6 a constant rise in normalized rate is observed with the rise in temperature, however at temperatures above 100 °C a decline is noticed after 80 seconds, at 150 °C the normalized rate is declined up to 0.002 (kg/s/%) after 300 seconds. This value is near the normalized rate achieved when the test is run at 60 °C at the same time interval.

Comparing Figure 5 and Figure 6 it is seen that at both airflow rates the temperature changes the shape of the curve. It is also seen that at the higher airflow rate the decline in normalized rate observed occurs earlier, after only 80 seconds, than that of the lower airflow rates, 150 seconds. To simplify the results presented, and graphically compare the effect of each parameter, Figure 7 illustrates the average normalized rate at given parameters.

Figure 7 shows that the influence of the airflow rate is not as significant as the effect of air temperature. It is also seen

that the airflow rate has a bigger impact on the normalized rate at elevated temperatures. This is seen from comparing the slight increase from region A to region B to the noticeable increase from region C to region D

The increase in airflow rate causes an increase of 0.00036[kg/s·%] at 60 °C in the normalized rate. This is attributed by the lack of energy in the airstream to diffuse water from the core of the product to the surface. The same increase in airflow rate at 150 °C produces a significant increase, 0.00087[kg/s·%]. This increase can be attributed to the fact that the air stream's relative humidity is lower and the potential for absorbing moisture into the airstream is bigger.

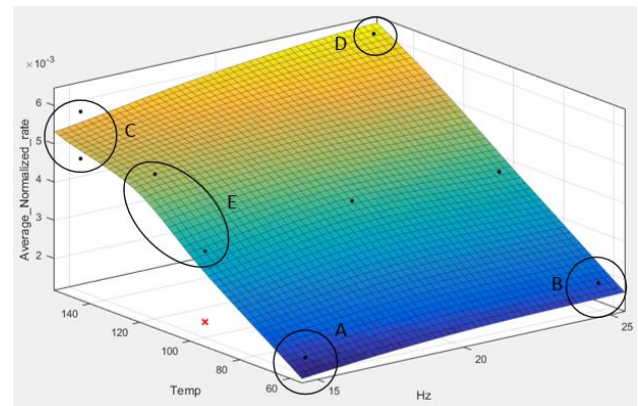


Figure 7: Average Normalized rate vs. Time, Temp

Observing Figure 7 at region A, a linear increase of averaged normalized rate is seen with temperature increase up to region E. At region E this linearity is lost. The non-linear behaviour is caused by the slow movement of air through the product causing the saturation of the air due to rapid evaporation of surface moisture. Increasing the airflow rate increases the amount of air through the system thus, the saturation of the air with moisture decreases. Following the 25Hz curve a near linear curve is seen. The linearity is an indication that the airflow rate through the system is high enough to prevent the saturation of the air.

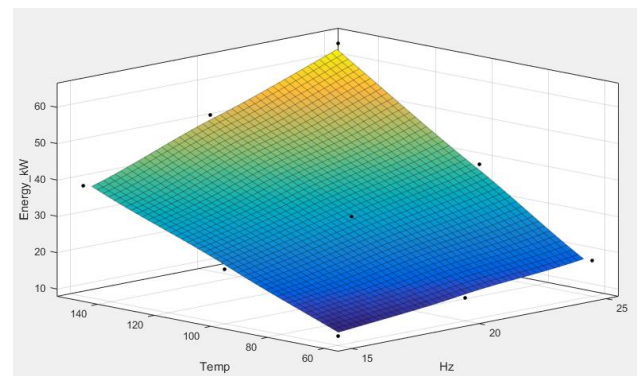


Figure 8: Energy vs. Temp, Hz

Figure 8 displays the energy required to heat the airstream to various parameters selections. Comparing this curve to the average normalized rate surface, Figure 7, the most efficient parameter can be chosen. When comparing the increases at each point, it is seen that the energy required

at 15Hz and 100°, 114.38%, is justified with a sufficient increase in normalized rate achieved, 125.6%.

This delivers the most efficient results of all the data analysed.

Conclusion

From the literature presented it is can be concluded that the normalized rate is effected by both airflow rate and the temperature of the air stream. It can be summarised as follow:

- The temperature of the air stream alters the shape of the drying curve, also this parameter produces the biggest change in drying rate, as seen in Figure 7.
- The airflow rate alters the speed at which the drying regions occur. Higher airflow rates accelerates drying phenomena, without altering the shape of the curve although the curve is compressed when the airflow is increased, whilst increasing the normalized rate slightly.

Considering the case hardening observed at high dehydration rates, high temperature paired with high airflow rate should be avoided. Tests done at 100 °C provides a relative constant normalized rate at all airflow rates.

Considering Figure 4 it can be concluded that for drying done above 100 °C the airflow rate should be chosen carefully, if drying is chosen to be performed above 100 °C it is necessary to test the quality of the product after drying.

Ultimately it is concluded from the research presented that for the conditions tested, 100 °C air temperature and an airflow rate associated with 15Hz is preferable for this extruded maize product, due to the high drying rate that can be achieved. Increasing the airflow rate further would increase the energy consumption of the system greatly and the increase in normalized rate would not justify the increase in energy costs.

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