Effect of product bed height and air velocity on the drying rate of extruded maize pellets

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Declaration

I hereby declare that the entire content of this dissertation is my own original unaided work, except where specific reference is made by name or in the form of a numbered reference. The work herein has not been submitted for a degree at another university.

Signed: ....
Bartho Pasch

Abstract

In the food processing industry, specifically food drying and cooling, there is still a lack of available information that is based on experiments and reliable data. A specific product that has not been investigated is pure maize extruded pellets used for porridge made for human consumption. In order to use these pellets as porridge, it is finely milled. To ensure that the pellets are properly milled, the pellets must be dried and cooled to ensure that the mill has a good efficiency and that the product has an acceptable shelf life. Therefore, by investigating the drying and cooling kinetics of the product, an improved and more efficient process can be obtained. Two factors that have an influence on the drying kinetics, is the ambient air velocity through the product bed and the product bed height. Through the optimization of the performance of a counterflow bed dryer and cooler, energy costs and time can be saved.

The purpose of this project is to acquire experimental data by investigating the effect that the product bed height and the air velocity through the bed has on the drying and cooling performance in order to ease the design process of a counterflow dryer/cooler with optimized performance. This exploration will include experiments on an experimental drying test bed. In these experiments, ambient air will be used at different air velocities and product bed heights.

Performance parameters such as the total moisture loss, the drying rate, the moisture loss rate and the moisture loss per kilowatt of fan power (kW) will be evaluated in terms of the bed height and the air velocity. Conclusions can be then reached as to what bed height and air velocity deliver an optimum cooling/drying performance. This information will then be presented to ease the design process of the cooler/dryer. A mathematical model is also created to estimate the drying rate at certain specified parameters. Using the drying rate value can aid the designing process by estimating the ideal size of the cooler/dryer for a specified rate of product flow through the cooler/dryer. The model is validated by comparing it to the experimental results.

Research has been done on the mechanical design of a counterflow dryer/cooler to see what factors are involved in drying and cooling. By evaluating the effect of these factors, the researcher concluded that increased air velocity in a counterflow dryer/cooler increases the drying rate; this is due to the mass transfer rate that is increased. However, the air velocity maximum in a continuous counterflow cooler must not exceed the minimum fluidization velocity, as the product will start to mix and will prevent even drying and cooling. The increase in product bed height also increases the drying rate that is caused by a decrease in cooling rate. A decrease in cooling rate results in a longer time for evaporation and mass transfer from the product, due to the difference in partial pressure between the water in the air and the water in the product.

By evaluating the performance, the researcher concluded that the optimum parameters in which to operate the counterflow dryer/cooler, is at a bed depth of 0.4 m and at an air velocity of 1.8 m/s. The best drying rate is obtained at an air velocity of 2.2 m/s, but this velocity causes fluidization and will not fit the application of this dryer. Furthermore the information presented can thus be used to design a counterflow cooler/dryer with minimum inputs.

Keywords: Drying; Cooling; Maize; Counterflow cooler; Food processing; Product bed height; Air velocity; Drying optimization; Drying rate; Extruded maize pellets; Drying performance

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Nomenclature

m_p	Product mass [kg]
M	Moisture [%]
g	Gravitation constant [m/s^2]
F_d	Drag force [N]
F_b	Buoyancy [N]
U_{mf}	Minimum fluidization velocity [m/s]
P_b	Pressure drop over bed [Pa]
W_b	Product bed weight [N]
A_b	Bed cross sectional Area [m^2]
M_p	Moisture in product [kg/kg]
dt	Time interval,[s]
$\dot{m}_a$	Mass flow rate of dry air
W_s	Solid weight [N]
$\dot{m}$	Mass flow rate [kg/s]
$\dot{m}_w$	Mass flow rates of water from surface of a particle, [g water/s]
X	Absolute humidity of air
h_1	Specific enthalpy of inlet drying air [kJ/kg]
h_m	Thermodynamic state of the particle
h_{fg}	Latent heat of vaporization of water [kJ/kg]
C_m	Specific heat [kJ/ kg K]
T_m	Material temperature [°C]
R_c	Product drying rate [kg^2/m^{2}s]
A_p	Surface area of product [m^2]
q	Rate of heat transfer
h_p	Heat transfer coefficient [W/m^{2}K]
BH	Bed Height [m]
V	Air velocity [m/s]
T_g	Temperature of the gas [°C]
ρ_a	Density of air [kg/m$^{3]}$
ρ_b	Bulk density [kg/m^3]
t_R	Residence Time [s]
H_b	Height [m]
W_i	Interval weight [kg]
ε	Voidage
Re	Reynolds number
p	partial pressure [Pa]
$\dot{Q}_{evap}$	Heat transfer rate due to water evaporation [kJ/s]
$\dot{Q}_{loss}$	Heat loss (kJ/s),

Subscripts

cv	Isobaric process

1	Inlet
2	Outlet
v	Vapor
g	Gas
a	Air
p	Product

Chapter 1

Introduction

This chapter includes background studies of counterflow dryer/cooler characterization and design. It also includes the problem statement, where after the objective and research methodology are presented.

1.1. Background

Fluidized bed dryers and coolers are used throughout the food processing industry to dry or cool wet granular foods. Various types of counterflow bed dryers and coolers have been developed; each one optimized for a specific material. In this study, the product that has to be dried and cooled is extruded maize pellets used for human consumption. By analysing the different parameters that have an influence on the performance of the dryer or cooler, information can be revealed that can be used to optimize drying in in a dryer. Various factors such as the product bed height, air velocity through the bed, air temperature, product density, bulk density, product shape, product material etc. influence the dryer performance. Literature [1, 2] has indicated that the drying performance of a dryer is sensitive to the product bed depth and the air velocity.

Maize cereal is produced by cooking maize meal through an extrusion process; this maize product then has to be dried before it can be milled. The cooked maize meal is then mixed with sugar, flavourings and colorants to produce an edible and tasty cereal. Cereal can also be used as it is extruded and since the product must be safe for storage, it must be cooled and dried before packaging. Drying reduces the moisture content in the food product to improve shelf-life and enable storage at ambient temperature [3]. It is important to minimize the moisture in the products to the safe limits that are different for each product [3]. Improper drying can cause mould growth and endanger the safe storage of the product [4]

In order to dry the extruded product, a counterflow cooler/dryer is normally used. In [5], the author states that the efficiency in conventional dryers is usually low, therefore the improvement of the efficiency is very desirable. Due to the ever-increasing costs associated with energy, it is essential to optimise drying and cooling processes [6] in order to keep costs as low as possible. Tests and experiments are usually done on dryers to determine the performance of the dryer under various operating conditions. These conditions include normal operating conditions, maximum capacity of the dryer under typical operating conditions, maximum drying performance, maximum cost effectiveness, and parameters for better product quality and minimum environmental impact [7].

1.2. Problem statement

Selecting or designing the appropriate dryer or cooler to optimize the drying process efficiency can be difficult; therefore to be able to optimize or design a dryer an in depth knowledge about dryers and coolers is needed. Experimental data processed into useful information can provide the estimated dimensions and operating parameter values for a dryer with specified input parameters that can optimize the drying process. In the case of this study, the type of dryer is a counterflow cooler/dryer, cooling and drying a CFAM Extruder TX80 product made from maize. This product has specific characteristics that have an influence on the drying performance. The performance will be analysed and a dryer will be designed accordingly, enabling the optimization of the drying performance for this product.

In literature, very little empirical data is available on the effect that the product bed height and the air velocity have on the extruded maize product. The effects of these operating parameters are considered to be crucial in improving the performance of a counterflow cooler/dryer and they therefore need to be considered in the design process.

1.3. Objective

This study will focus on two of the operating parameters for the extrusion of maize pellets, namely air velocity through the product bed and the product bed height. The study investigates the effect that these two parameters have on the drying rate of the product. The drying process in a dryer bed usually occurs at a high air temperature, but some drying also occurs at an ambient air temperature. If air at ambient temperature can be used rather than heated air, it could decrease production costs considerably.

The objective of this study is to process the collected data in order to design a cooler/dryer. The data is collected from an experimental test bed of which the air velocity and product bed height can be varied while logging the relative humidity and dry-bulb temperature. The effect that these parameters have on the drying rate and eventually the drying performance is investigated.

To accomplish this objective, the following tasks are defined:

- Investigate the relevant literature.
- Experimental investigation into the product.
- Data processing on the experimental results to determine the drying rate and performance from the logged parameters.
- Determine the effect of air velocity and product bed height on the drying rate.
- Implement the results into a preliminary design of a counterflow cooler/dryer.

1.4. Research methodology

1.4.1. Literature overview

A literature study will be done on counterflow coolers/dryers. The overview will include an investigation into the factors that will influence the drying and cooling process. Furthermore, the overview will state how these factors influence the design of a counterflow cooler/dryer.

1.4.2. Experimental investigation

An experimental test bench will be designed and manufactured to produce data on the extruded maize product. The air velocity and product bed height will be varied to obtain results concerning the effect that these parameters have on the drying process.

1.4.3. Data processing

The results obtained from the experimental tests will then be processed. The temperature and relative humidity are used to calculate the moisture loss curve of the extruded maize product during the drying process. By investigating the effect of air velocity and product bed height on the drying rate, the performance can be evaluated by investigating the total moisture loss in the product, moisture loss rate, cooling rate and drying efficiency. A drying rate will be estimated at each varied parameter with the use of a mathematical model and will be verified with the results obtained in the experiments.

1.4.4. Prelimanary design on a counterflow cooler/dryer

By using the obtained data to determine the optimal parameters for dryer performance, a counterflow cooler/dryer will be designed. A model will be created to implement the results into the preliminary design of a counterflow cooler.

1.5. Chapter layout

Chapter 1 provides a background to the study as well as the problem statement, objective of the study, and the research methodology.

Chapter 2 presents a literature overview of the research that has been done on the drying of maize pellets in bed coolers/dryers. It also includes research by numerous authors that describes the effect that air velocity through the bed and the product bed height have on the drying rate of foods and counterflow coolers/dryers. The drying rate analysis and definitions will be provided and investigated.

Chapter 3 illustrates and describes the experimental test bench setup and the methods that were followed to obtain appropriate data on the effect that the air velocity and product bed height have on the drying rate of the extruded maize pellets. The test bench setup will be discussed, the measurement instruments defined, and the application thereof in the experimental tests.

Chapter 4 presents the experimental data that was converted into information that can be used for future designs. The results mainly consist of the effect that the air velocity and product bed height have on the drying rate of extruded maize pellets. The chapter also discusses the effect of the air velocity and the bed height on the drying efficiency and drying rate. Furthermore, this chapter evaluates and discusses the moisture content percentage of the pellets. Thereafter a mathematical model will be created with which the drying rate can be estimated at various input parameters.

Chapter 5 will discuss how the results can be used to design a counterflow cooler/dryer. Critical parameters are identified that must be taken into consideration during the design process. A design is then provided based on the requirements specified by using the obtained results and the mathematical model.

Chapter 6 includes the conclusions drawn from the study. The conclusions will include a discussion of the results and the effect that various parameters has on the drying of extruded maize pellets. The chapter also discusses whether the results can be used to design a counterflow cooler/dryer.

1.6. Conclusion

This chapter presented the background on the study, the problem statement, the objective and the method that will be used to do the study. The next chapter will present some of the literature that is available on the subject of this study.

Chapter 2

Literature study

This section will provide the literature that was collected and processed to retrieve information concerning counterflow dryers and coolers. The goal of this study is to understand the principles concerning moisture loss in food; therefore the literature review will focus on that.

2.1. Counterflow cooling

Patents for counterflow coolers were introduced in 1989 [8] and they are still used in the food industry today. The designs of counterflow coolers presented in the years since then were created using trial and error although the main principle for these dryers stays the same. Hot extruded pellets are cooled in the cooler using a negatively pressured bed. The hot pellets then accumulate or fall onto a bed with a series of orifices letting air through and preventing the product from falling through [8, 9].

To prevent the pellets from thermal shock[1], the pellets are gradually cooled as air from the bottom of the bed increases in temperature as it makes its way to the top of the bed where the incoming hot pellets enters the cooler. A certain quantity of pellets is then released from the bed at small intervals once it has reached its specified moisture content and temperature. It is important to keep the height of the product in the bed as constant as possible throughout the process to ensure a constant residence time. An illustration of a patent of a counterflow cooler is shown in Figure 1 [8].

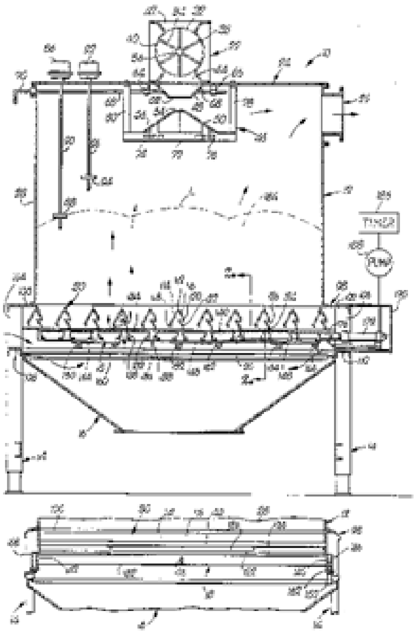

Figure 1: Illustration of a counterflow cooler patent [8]

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[1] Food that is exposed to high temperature can lose nutrients, change in flavour and texture attributes.

Limiting sensors are used to regulate the height of the product in the bed. When the bed floor shifts to let pellets fall into the hopper, air that gradually cools the pellets and warms the air is still moving through the bed [8, 9]. Another illustration of a counterflow cooler model developed by Bliss Industries is shown in Figure 2 [10].

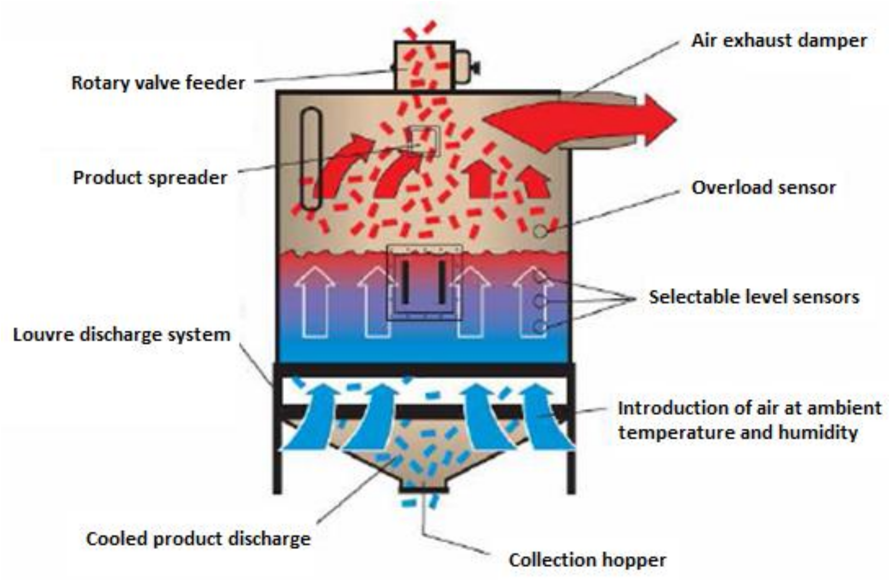

Figure 2: Illustration of a Bliss Industries counterflow cooler [10]

2.2. Counterflow cooler physical phenomena

Some of the advantages of a counterflow cooler include its ability to cover small floor space, its low maintenance and low energy usage [9, 10]. Another advantage is that the cooler can excellently control the final moisture content in the product [9]. The improper drying and cooling of moist solids can cause poor product quality, caking in bags and holding bins, spoilage, and unwanted weight or weight loss. Cooling and drying processes are directly affected by the amount of energy and moisture that the air and pellet contain [10]. The cooler designs that exist are horizontal, vertical, rotary and bunker coolers [9].

Pellets enter the top of the cooler through an airlock valve and fall onto the bed uniformly. Ambient air enters the product bed through small holes and flows into the discharge grid from below. The air and pellets flow in opposite directions and the coolest air first makes contact with the coolest particles and then the warmest air makes contact with the warmest particles. This pattern of counterflowing ensures that the particle cools down at an appropriately gradual rate and it helps to preserve the pellet quality [10]. When particles or pellets cool off too quickly, the surface will become a dry crust preventing moisture transfer from inside the pellet to the surface to be transferred into the air. This will leave the particle moist inside. The pellet will become brittle if the moisture inside reaches equilibrium and this will lead to excess fines [10, 11]. In the Op-Flo[2] cooler, the air flow can be adjusted to control the final temperature and moisture content [12].

The height of the product in the cooler is determined and controlled by the operator using the control of minimum and maximum bed depth sensors [9]. In a counterflow cooler, adjusting the

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[2] Counterflow cooler name developed by Bliss Industries.

valve interval speed alters the bed height and residence time of the product in the cooler [10]. The valve interval speed refers to the time elapsed between openings of the valve. In [9] Maier presents the first study on the experimental and analytical investigation of counterflow coolers. He states that a 0.45 m product height maximizes moisture loss [9]. Bliss industries uses a 1-1.5 [m] product bed depth [10].

Caking can occur if the moisture content distribution in the product bed is wide. Constant rate drying requires a small residence time and enables easy and quick discharge. Multi-deck dryers can be installed when the falling rate period is long and when extended residence time are needed. With a constant floor area, a fluidized bed dryer can handle more product and dry more mass of water than any other dryer, however it requires more headroom. Because of the simplicity of the mechanical operation of the dryer, the labour would be minimal [13].

2.3. Parameters and mathematical modelling

Factors affecting the performance of a pellet cooler are the airflow rate, cooler type, air humidity, air temperature, pellet temperature, pellet flow rate, pellet moisture content, and pellet size [9, 10]. In [9] the author concluded that residence time and product depth are parameters that are most significant in counterflow cooler design. It was also noted that heat and mass transfer are heavily affected by the initial air temperature, but not so much by the relative humidity of the cooling air [10].

Test results indicate that bed depth has a considerable effect on the estimated final moisture content of the granules. Initial product temperature, product flowrate, and air flow rate also have an impact on the estimated final moisture of the product. A very high airflow rate would minimize the moisture loss in the product due to quick cooling [9, 10].

Bliss industries developed a mathematical model to estimate the moisture and temperature profiles in a cooler that depends on variables such as bulk density, pellet density, ambient relative humidity, initial pellet moisture content, ambient air temperature, initial air temperature and cooler bed depth [10].

In [10], Fowler concludes that his model supports the moisture estimation, however the temperature estimation is not entirely accurate. Although it is not entirely accurate, it still provides data and information on how the different parameters influence the moisture and temperature in the bed. Furthermore Fowler concludes that further validating must be done on the model, the drying rate expression must be more appropriate and an investigation must be done to achieve this [10].

Maier's experimental tests on the counterflow cooling of pellets were done on a counterflow cooler model and consisted of several parts that are indicated in Figure 3 [9].

Table 1 [9] provides the results of the experimental tests. One of the parameters that the author used, is the air-to-pellet flow rate ratio that ranged from 0.5 to 2.22. This is a similar ratio to the ratio used in industrial horizontal coolers. Airflow rate varied from 0.149 to 0.697 kg/s per square meter of bed area. The pellet flow rate used was 0.179 and 0.623 kg/s per square meter. The pellets were cooled to within 5°C from the ambient temperature.

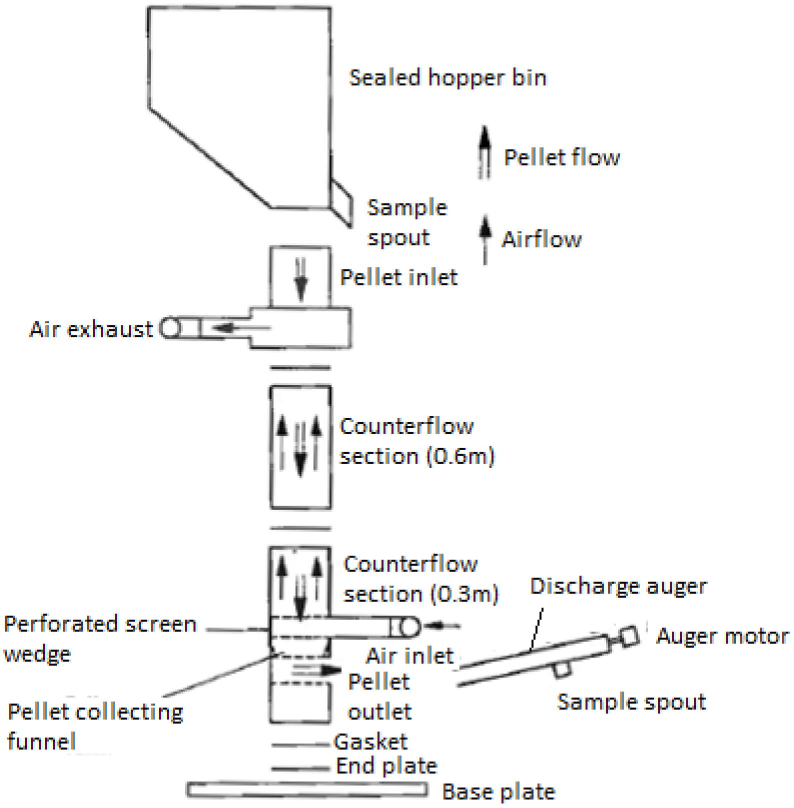

Figure 3: Cross-section view of an experimental counterflow pellet cooler [9]

Table 1: Experimental counterflow cooling results [9]

Results in the experimental counterflow pellet cooler at a bed depth of 0.9 m						
Test	**Air-to-pellet ratio**	**Air flow [kg/s.m²]**	**Pellet flow [kg/s.m²]**	**Moisture loss percentage points [% wet bulb.]**	**Pellet cooling [ΔC°]**	**Cooling effect[Δ°C]**
1	2.22	0.564	0.255	2.37	15.5	-1.9
2	1.87	0.564	0.301	1.54	11.8	2.5
3	1.43	0.697	0.488	1.82	14.6	3.1
4	1.27	0.566	0.448	2.01	17.9	0.5
5	1.16	0.259	0.221	1.68	8.1	-1.9
6	0.92	0.571	0.623	1.75	21.9	6.6
7	0.83	0.149	0.179	1.73	19.2	-1.8
8	0.51	0.153	0.31	1.77	23.1	6.4

In Table 2 [9] below the moisture loss and temperature loss data at different bed heights is indicated.

Table 2: Specifications for different bed heights [9]

Product depth in bed [m]	Moisture loss percentage [% wet bulb]	Temperature difference [Δ°C]
0.3	1.54 – 1.77	8-23
0.9	1.73 – 2.37	15-19.2

In [9] the authors' prediction of the temperature profiles varied from 10 to 28% and that of moisture varied from 3 to 60%. The mathematical model did not predict the moisture and temperature profiles precisely, however the authors' model can investigate the performance of the cooler when certain parameters are changed.

The time the air is in contact with the pellets is called the residence time. The residence time in a cooler can be adjusted for a specified bulk density by changing bed depth, adjusting pellet flowrate or a combination of the two. Controlling the residence time in a cooler and dryer is critical in optimizing performance. Being able to change the constant bed depth to a different height and to control residence time, provide great control over the drying and cooling process [10].

In [9] the authors analysed the residence times to cool a product to within 5°C of ambient temperature at specified bed depths. Table 3 [9] present these residence times.

Table 3: Ideal cooling times at different bed depths [9]

Bed depth [m]	**Residence time [min]**
0.15	2.6
0.30	5.3
0.45	7.9
0.60	10.5

By increasing the bed depth from 0.15 m to 0.3 m to 0.45 m, the moisture loss was increased from 0.6 to 0.7 to 0.8 percentage points. The moisture loss reached a maximum after 6 min in a 0.6 m depth bed.

Air-to-pellet mass flow rate can be used as a parameter to estimate residence time. Decreasing air-to-pellet flow rate results in a decrease in residence time. Moisture content and air-to-pellet ratio is inversely proportional to each other as is evident in Figure 4 [9].

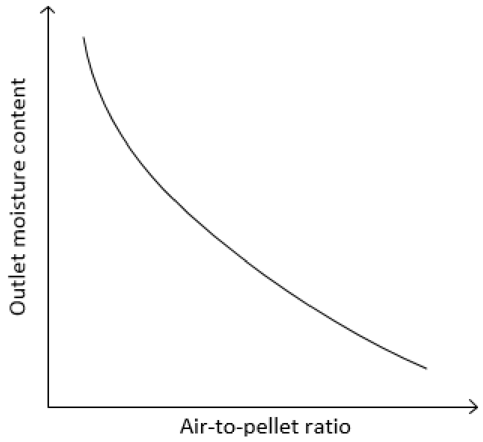

Figure 4: Outlet moisture content versus air-to-pellet ratio in cooling [9]

Large air-to-pellet ratios result in higher moisture outlets and a higher initial drying rate. By increasing the air-to-pellet ratio, the pellets cool of more quickly, thus the drying potential is reduced. There exists an optimum air-to-pellet ratio at a specific bed depth through which a desired final moisture content can be obtained and for which the pellet can be cooled to within 5°C of the ambient temperature [9].

There is little moisture loss beyond a certain bed depth. In fact, moisture and temperature may increase beyond a certain bed depth. Based on their tests, Nonhebel and Moss [9] concluded that smaller pellets dried and cooled at a greater rate than a larger sized pellets. The smaller pellets also lost more moisture than the larger pellets. The authors then concluded that the desired moisture content for a certain size has an optimum residence time. By altering the product bed depth and air-to-pellet flow ratio, the exit moisture content can be controlled. The moisture loss will be more if the pellet is warmer than moderately warm and it will be even more when residence time is increased. Nonhebel and Moss also found that inlet air temperature, relative humidity and initial moisture content have little effect on the performance of the cooler and therefore they did not discuss it in depth in their paper [9]. They concluded that at a bed depth of 0.45 m the moisture loss in a counterflow cooler was maximized. The moisture loss and cooling rate was significantly influenced by the initial pellet temperature and pellet diameter [9].

2.4. Fluidized bed drying

An illustration of a typical continuous fluidized bed dryer can be seen in Figure 5 [14]. Particles rest on an air distributor plate that distributes flowing air uniformly over the bed to ensure uniform drying. Typical components found in a fluidized bed dryer are an air blower, air heater, and a bed column. Different types of fluidized driers have been studied, tested and evaluated [15], however this literature study will only contain information on the counterflow dryer as the design of such a dryer is the goal of the this study.

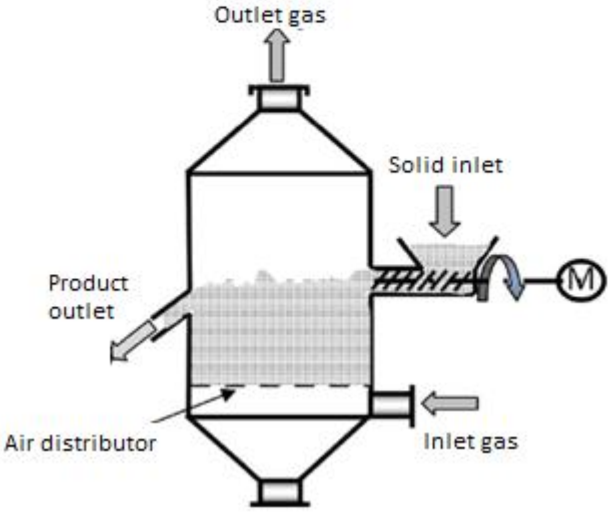

Figure 5: Illustration of a continuous fluidized bed dryer [14]

The main task of drying in the food industry is to reduce the moisture content in the food product so that shelf-life can be improved and storage at ambient temperatures enabled [3]. Uneven moisture distribution in the product cannot be avoided, but can be minimized within the product limits. It is important to minimize moisture in products to the safe limits that are different for each product [3]. Typical products that are processed in these dryers are foodstuff, chemicals, pharmaceuticals in powder or agglomerated form, pesticides, dyestuffs, detergents, surface active agents, biomaterials, ceramics, waste management processes, polymer and resins, fertilizers, beverage products, and carbohydrates [15].

The main advantages of fluidized bed dryers are a high thermal efficiency and a high rate of heat and mass transfer to ensure a short drying time. This offers a wide choice in the ways in which the machine dries [16]. Advantages of these fluidized bed dryers also include easy operation and maintenance, it can be easily automated and can be used to dry, cool, mix and classify products. Typical disadvantages of fluidized bed dryers include high pressure drops over the product bed, attrition of solids, and erosion of the containing surfaces. A full fluidized dryer has a major disadvantage, namely the uneven distribution of residence time in the dryer. Due to the mixing of the solids, it is not possible to predict which solid will leave the bed at what time. This leads to an experimentally proven non-uniform distribution in solid moisture content [14, 16, 17, 18].

The large contact surfaces of the dryer is another advantage of fluidized bed dryers as it shortens the drying time of the product [19]. In addition to all the advantages due to the fluid like product, these dryers can use gravity to transport the product in and out of the dryer by means of pnematical conveying. An undesirable quality of the fluidized bed is a low fluidization quality, giving rise to a lower performance and operation. Improper drying can cause mould growth and endanger the safe storage of a product. Temperatures that are too high can cause grain quality degradation due to increased enzymatic inactivation [4].

2.5. Fluidization

Fluidization occurs when material that is in a packed or stationary state is exposed to flowing air, causing the material bulk to move to its loosest state possible, to form a fluid like bed [20, 21]. This effect of fluidization occurs when the drag (F_d) and buoyancy force (F_b) of the air provided exceeds the gravitational force of the product as is indicated by this equation:

$$m_p \cdot g \leq F_d + F_b \tag{1}$$

A gas, liquid or liquid-gas can be used as the fluidization agent, however only air will be discussed in this study, as the model in this study is used in food drying and cooling [21].

To understand the fluidization concept, it is important to understand the movement of solids in the product bed. Gas hold-up is a term used to characterize the fluidization state of the bed. Gas hold-up is quantified as the volume fraction of air present in the product bed [21]. In [22], experimental results indicated that there is an increase in solids concentration (inverse of gas hold-up) when the product bed depth is increased. This mainly occurs in the middle of the bed, whereas there was no change at the wall of the bed. This is due to the increase of the bubbles in the bed caused by the product bed depth increase [21].

It is important to study and characterize the motion of particles in the bed to ensure an efficient and effective operation. Problems such as hot and cold spots and un-fluidized zones in the bed can be visually observed [23]. Product quality can be decreased as a result of poor fluidization caused by attrition of a wider product distribution. Vigirous mixing in a fluidized bed causes a difference in residence time between the particles and a wider residence time distribution that leads to uneven product qualty and moisture [19].

2.5.1. Minimum fluidization velocity

Minimum fluidization velocity is the velocity at which a packed stationary product bed evolves into the bubble regime of fluidization. This velocity is one of the most important parameters that characterize a fluidized bed. This velocity can be determined experimentally and methods such as the heat transfer method, the pressure drop method and the voidage method are used [20]. The heat transfer method entails the measurement of the wall heat transfer coefficient as the air velocity increases amongst others. The point of minimum fluidization is obtained when there is a drastic increase in the heat transfer coefficient. The cost and high quality experimental setup make this method undesirable. The pressure drop method uses the measurements of the pressure drop over the bed against the air velocity. The minimum fluidization velocity point is reached when the pressure in the correlation between the pressure drop and the air velocity becomes constant. The voidage method entails the determination of the point where the voidage in the bed starts to increase as the velocity increases and the bed expands, as is evident in Figure 6 [24]. Because it is very complex to determine this point, it is not used that often [21].

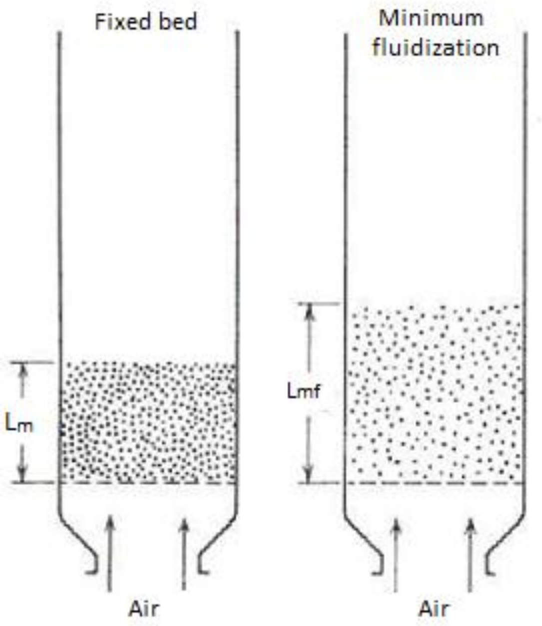

Figure 6: Illustration of bed expanding [24]

In [22], the experimental results obtained for determining the minimal fluidized velocity indicated that using the pressure drop method agrees with results of theoretical calculations such as the Ergun equation and other theoretical models. Material properties, material geometry, gas properties and bed geometry have an influence on minimum fluidization velocity [21, 22]. Hilal *et al*. [25] analysed parameters such as bed diameter and the geometry and type of distributor, and their results showed that both parameters have an influence on the minimum fluidization velocity. The minimum fluidization velocity increased as the number of holes in the distributor increased, and decreased with an increase in bed diameter [21, 25].

In the experiments performed by Escudero [21], it was found that the minimum fluidization velocity increased as the density of the product increased. These tests were performed on materials with three different densities. The mass of the higher density particles is higher when the volume stays constant and thus an increased air velocity is needed to overcome the weight of the particles. Because of this, a larger pressure drop over the bed will be noted [21]. In [21] the authors also concluded that as the height-diameter ratio increased, the minimum velocity stayed more or less constant [21].

2.5.2. Bed distribution

The solid particles and air bubbles distribution in a fluidized dryer is greatly influenced by the air flow supply. Fluidization quality depends highly on the bubble distribution. Good fluidization needs an even distribution of air bubbles through the bed and these air bubbles should be small and their density large [26]. Images were taken during testing to identify air bubble distribution and it was noted that the bubbles are concentrated very close to the distributor and is then distributed over the whole bed to very close to the walls. The bubbles then taper inwards as it move upwards into the product bed and fuse at a certain height. This profile of distribution altered when bed height was changed [23, 26, 27] . In [27] it was found that by experimenting with different bed parameters such as air velocity and bed heights, particles in a fluidized bed tend to rise in the middle of the bed and move downwards at the sides of the bed.

2.5.3. Stages of fluidization

In terms of the types of fluidizing regimes or stages, Yang [28] noted that there are six different stages, namely fixed, bubbling, slugging, turbulent, fast and pneumatic conveying. Figure 7 [29] present a diagram of the different stages of fluidization [21].

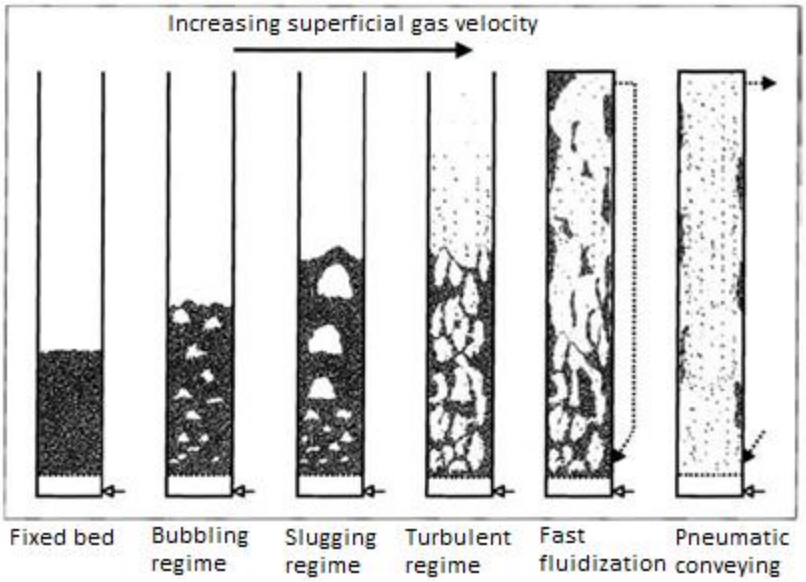

Figure 7: Diagram of fluidization stages [29]

In the fixed bed stage, the air does not have sufficient velocity and thus not sufficient force to move the solids in the bed and only flows through the bed. The bubbling stage is reached when the air velocity is increased and bubbles start to form in the solids and move upwards, mixing the product. This velocity is known as the minimum bubbling velocity [21]. In [28] the authors noted that the slugging fluidized state appears in a product bed which ratio of bed depth to bed diameter is larger than two. The slugging regime starts when the bubble size reaches two thirds of the bed diameter and starts merging into one large bubble [21].

Crowe [29] stated that at the air velocity where one big bubble breaks up into more bubbles, the slugging fluidizing state has been reached. This velocity is determined when the deviations of pressure fluctuations reach a maximum. Turbulent fluidization occurs at an air velocity larger than the bubbling fluidization velocity and smaller than the fast fluidizing velocity [29, 30, 31]. When the air velocity increases and reaches the transport velocity, it is called the fast fluidization velocity. The pneumatic conveying state is reached when the velocity is still increased and the solid particles are then transported out of the bed in a diluted phase [21]. Irregular sizes, shapes and densities can cause a product to fluidize non-uniformly [21].

2.5.4. Pressure drop

Increasing the air velocity brings about an increase in the pressure drop across the product bed. The pressure drop stays relatively constant when the air at a minimum fluidization velocity is further increased [21]. Figure 8 [21] portrays the pressure drop against the velocities reached from fixed bed to fully fluidizing state.

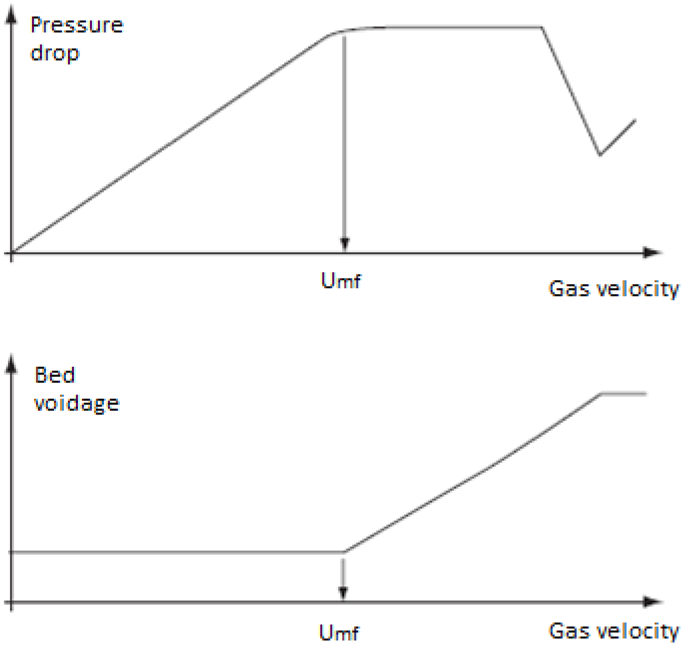

Figure 8: Various regimes of a bed of particles at different gas velocities [21]

Once the fully fluidized state has been reached, the pressure drop is the total weight of the product over the area. Thus, pressure drop over the product bed is proportional to the weight of the product and inversely proportional to the area of the bed [32].

$$P_b \propto \frac{W_b}{A_b} \qquad (2)$$

The gravity force of the particles then equals the buoyancy or drag force that the air exerts [21, 30]. For stable fluidization, the pressure ratio between the distributor and the product bed over a certain area can be determined as indicated in Figure 9 below [33].

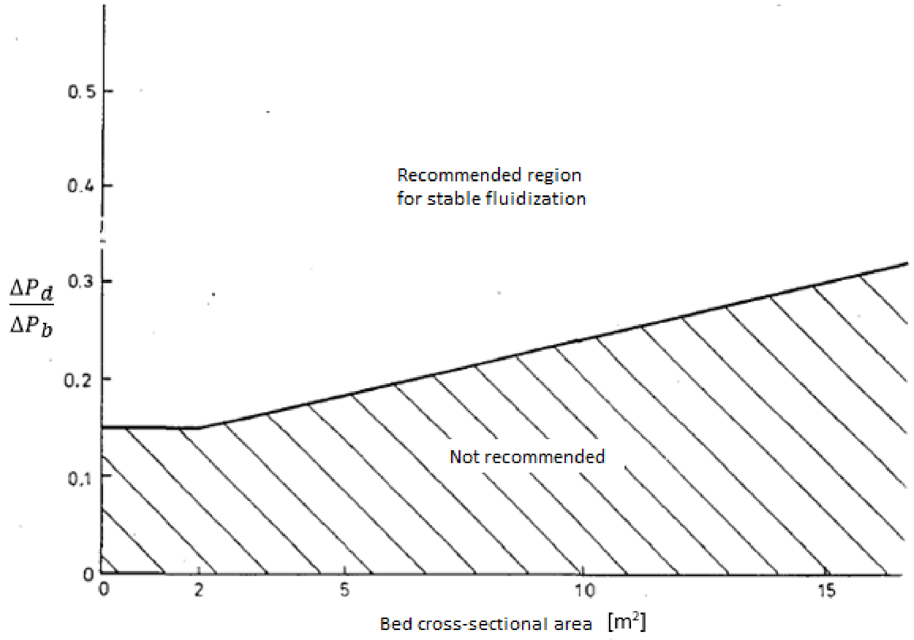

Figure 9: Minimum recommended values of distributor/bed pressure drop ratio [33]

2.5.5. Airflow distributor

The distributor supports the weight of the product and admits air to flow uniformly through the product bed. To ensure good fluidization, air must flow through enough points that are evenly distributed over the bed area and the air must be supplied to the points from a well-designed plenum chamber [33]. When there is a shortage of air distribution points, good fluidization cannot be achieved, bed particles can elutriate, and undesirable air and product flow in the bed, corrosion and erosion of bed surfaces can occur [33]. An oversupply of air distribution points can lead to air starvation in the bed in some parts that also causes bad fluidization, undesirable gas and product flow and erosion and corrosion on bed materials [33]. The air distributor performance is of key importance to the optimized operation of fluidized beds [34].

Types of distributors that are widely available are ordinary, sandwiched, bubble, cap tuyere and sparger distributors. A certain pressure drop is needed to obtain good airflow distribution. As a rule of thumb the pressure difference over the bed must exceed 30% of the pressure difference over the product bed, to ensure good distribution [15, 28].

Wormsbecker [35] studied the influence that different types of distributor plates have on the hydroponics on a fluidized bed. Experiments in which the gas velocities and the bed loading were varied, were performed [35]. The main goal of the distributor is to evenly distribute the air across the area of the bed and to optimize the air/product contact. The heat and mass transfer rates can potentially vary with different distributors. As is evident in study [35], the punched plate provides a higher drying rate of the product than the Dutch weave and perforated plate designs [35].

Perforated plate has the advantages of simplicity, good performance and a design that has been studied extensively [33]. Perforated plate usually has an open area ratio of 25-45% [36]. The advantages of perforated plate are a low installation cost, low pressure drop, good thermal efficiency, no risk of clogging and high contact efficiency [37, 38]. The characteristics of the particles determine the operation and design of a perforated plate distributor fluidized bed. These characteristics include particle size, particle distribution, density and shape [36].

To determine the pressure needed from a fan or blower, the hydronomical resistance of the product bed and the resistance of the distributor is used [39].

If the pressure drop over the distributor plate is high enough and at least equal to the drop over the product bed, good quality fluidization will occur [6]. It is desirable to install fans with automatic control to maintain the pressure balance, and to keep the pressure just below atmospheric pressure above the bed to prevent fines leaking from the dryer [13]. Some suppliers install a distributor perforated plate with holes of about 1 mm in diameter. When air flows through the distributor plate, the flow usually increases in the middle of the bed with little air flow upwards near the walls. This can be improved by dishing the perforated plate in the middle to distribute the air more to the walls.

2.6. Drying rate

In this section, literature on the drying rate of food will be discussed.

2.6.1. Description

It can be difficult to study the drying rates of a certain product without performing experiments due to the wide variety of the mechanisms involved in internal moisture transport. These mechanisms include thermal diffusion, surface diffusion, capillarity, bulk and modular flow and they depend on the structure and properties of a product [6].

Early experiments on fluidized bed drying show that mass transfer on a single particle occurs in two stages, at constant rate and then at falling rate. Constant rate drying occurs when free moisture on the surface and in the outside pores is constantly withdrawn into the drying agent. The falling rate drying stage is present when diffusion occurs inside the solid, transporting the moisture to the surface due to a temperature rise in the solid. The critical moisture content is the moisture content in the product at the stage when the constant rate drying ends and when the falling rate drying stage starts. Figure 10 [40] below illustrates the characteristic drying curve as function of time and moisture [40].

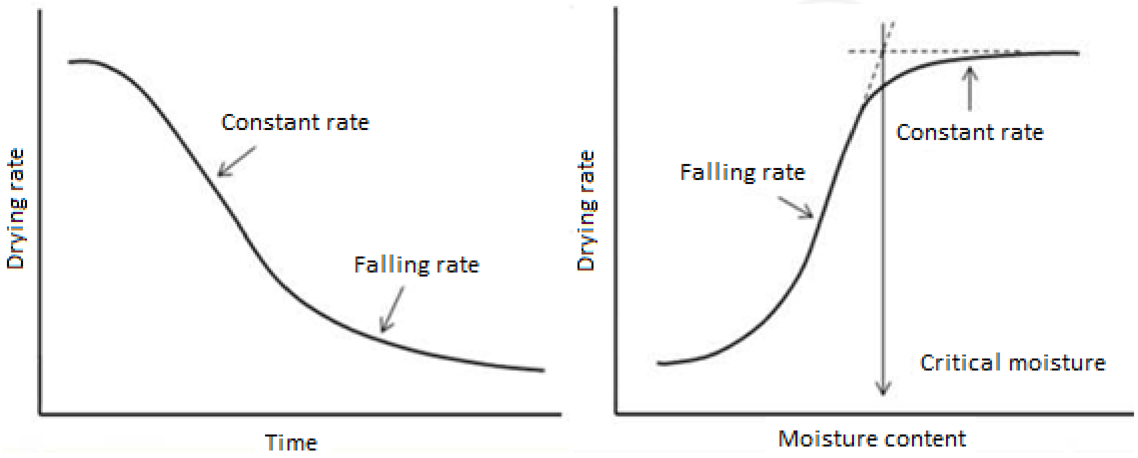

Figure 10: Characteristic drying curves for moist particles [40]

The maximum drying rate occurs in the constant rate period, and lasts until the moisture reaches the critical point[3]. The moisture transfer in the falling rate period is limited by the moisture diffusion to the surface. The size and extent of the two different drying zones depend on the type of material dried and its properties. Sand, for example, has a large constant drying period in comparison with more fibrous materials such as mustard grain or poppy seeds [41, 42].

Despite the simplicity of the operation of the dryer, knowledge of hydronomics combined with mass transfer is still needed to design a bubbling fluidized dryer. The mass transfer coefficient is needed to accurately model and analyse the drying kinetics of a certain product in a certain dryer [40]. External drying factors determine the mass and heat transfer intensity. These factors form the drying conditions characteristics and they provide a good description of a fluidized bed. The heat transfer coefficient is mainly determined by experimentation and the value is only valid for a certain product with a certain size, machine, and conditions. It is then incorporated into different equations. A heat transfer coefficient is not yet determined for the food in this design in any study [39].

Drying consists of heat and mass transfer. Heat is provided to the solid via convection and is needed for evaporation that releases moisture into the airstream, which is the mass flow. The heat further makes its way to the inside of the solid through conduction. Moisture makes its way to the surface of the particle and evaporates into the air stream. Figure 11 illustrates the mass and heat transfer of a food particle [43, 5].

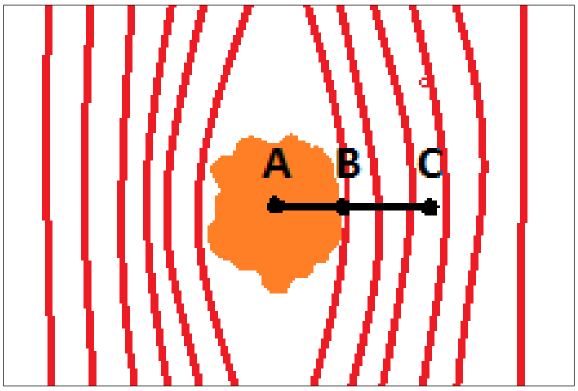

Figure 11: Mass and heat transfer illustration

Through convection, heat is transferred from the surrounding air C to the pellet surface B and then through conduction from B to C. Moisture moves from the inside of the particle A to the surface B as vapour or a liquid, and on the surface it evaporates into the air. The temperature difference between B and C and A and B causes heat transfer. The overarching cause of heat transfer from surrounding air to the inside of the particle is the difference in temperature between A and C. At a moisture temperature lower than evaporation temperatures, mass transfer occurs between B and C due to the difference in partial pressures or concentrations, and between A and B due to the difference in concentration [39]. In the case when the material temperature is close to the moisture boiling point, the liquid evaporates within the particle and moves to the surface and surrounding air [39].

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[3] The point where drying rate goes from constant to falling

A mathematical model of a process is used to represent a real system based on selected features and properties of the real system. Simulation, control and optimization are the essential components in these models, and they fall into three categories: White-box that uses the first principles that are derived from physical and chemical relationships, black-box that is constructed using experimental data, and grey box that uses both [44]. The minimum product bed depth and residence time of the product to reach the necessary moisture content and particle temperature is determined by using the heat transfer coefficient [39]. According to the authors in [39], this calculation is very inaccurate (more than 100%) due to simplified assumptions and the high uncertainty of the heat transfer coefficient estimation.

The authors of [5] state that the efficiency in conventional dryers is usually low, therefore improving the efficiency is very desirable. The recent developments and design modifications done on fluidized bed dryers make that possible. Optimal energy management has to be maintained due to an increase in energy cost and the adoption of a more environmentally friendly operation and strategies [6]. Experiments proved that the drying rate in a fluidized bed is greater than that in packed beds [6]. Drying rate increases as air temperature increases [6]. Water on the surface of the product evaporates in seconds and this is described as the constant rate period.

2.6.2. Characteristics

Fluidized bed drying can occur continuous or batchwise. For small scale production or for the use of drying experiments, a batchwise fluidized bed can be used. Experiments will be performed to determine the drying rate of the specific product for this design. A batchwise operation is ideal for this process due to the constant quality of the product through the bed [14]. In continuous fluidized bed drying, the residence times differ widely as the product dried varies due to the difference in material properties. Drying rates and fluidization are affected by these material properties, such as density and the specific heat value of the product [14].

It was noted that the bed temperature and end of process temperature are lower in the packed bed [6]. The tests and experiments performed by Static *et al*. [6] show that as the inlet air is increased, the drying time decreases [6]. Sinivasakannan [41] used the mean residence time, which increases with an increase in temperature and bed height, to estimate the drying rate in continuous drying. He also found that a continuous bed has a lower drying rate than a batch fluidized bed [41].

2.7. Influence of parameters

The influence of the various parameters on the drying will now be discussed. The outlet moisture decreases as the inlet air temperature increases [16]. The increased air temperature increases the pellet surface temperature, which reduces the humidity and increases the evaporation rate from the pellet surface as is evident from Figure 12 [16].An increase in pellet flow rate increases the moisture outlet because of the lower residence time that is possible. The drying rate of the product decreases as the pellet diameter increases. A larger particle size means that the surface area per unit weight decreases and this reduces the drying rate [16].

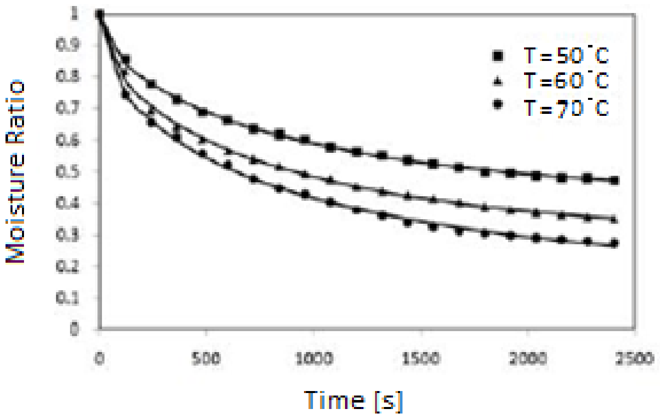


Figure 12: Effect of temperature of drying air [16]

2.7.1. Air velocity

Air velocity has a great effect on the drying rate in the constant drying rate zone and on a product with a low internal resistance to moisture transfer. However, with a product with high resistance to moisture transfer, the air velocity has little effect on the drying rate [15]. Higher bed temperatures lead to higher moisture removal rates and diffusivities. The diffusion effect is complex and depends largely on the significance of internal and external resistance to moisture transfer [15, 42].

An increase in airflow also has an increase on power consumption. Smaller grains have a higher resistance to airflow that causes an increase in moisture removal and a reduced fan output, thus an increase in power efficiency. A fluidized bed can compete with other air dryers when high moisture removal and low energy consumption is needed. This type of dryer is reliable and economical for the drying of light weighted grain [42, 45]. The effect of air velocity on the drying rate of food particles can be clearly seen Figure 13 [6] and Figure 14 [6]. These graphs indicate that the drying rate increased as the air velocity increased even though the temperature differs. T_G presents the inlet air temperature.

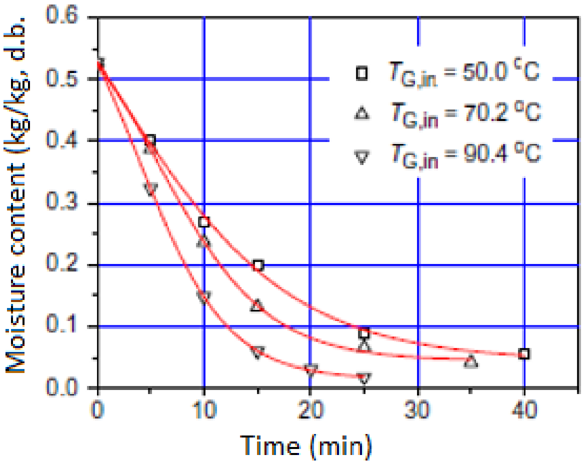


Figure 13: Moisture versus time at 0.19 m/s (packed bed) [6]

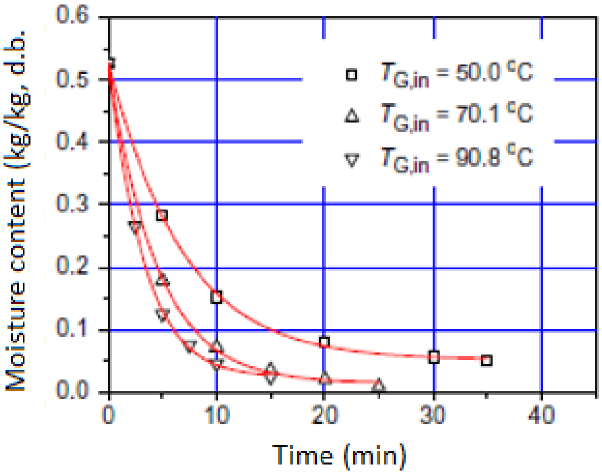


Figure 14: Moisture versus time at 0.59 m/s (fluidized bed) [6]

In rough rice, the constant drying rate stage is very small and it converges to zero. The internal resistance of a product has a great influence on the drying rate and moisture transfer, therefore its temperature has a greater effect on drying rate than on velocity. Thus, it is important to keep the internal resistance to moisture in mind when designing a dryer. An increase in air velocity reduces the external mass transfer resistance and it causes an increase in drying rate. Thus, with no increase in temperature, the only way to increase drying rate is by increasing air velocity and because of the high internal resistance of the product, little diffusion will take place [16, 45].

2.7.2. Bed depth

More evaporization of moisture (mass transfer) takes place when the bed height increases. However, voidage (bed porosity) does not have a significant effect on the drying performance [4].

By using a thin layer drying equation coupled with mass and heat balance equations, a simplified model was developed for a moving bed dryer. In comparing parallel flow and counterflow drying, it is evident that counterflow drying is more effective for drying in terms of drying rate and size of the dryer when air is used as drying agent. At low air temperatures, the difference in effectivity becomes even larger [46].

According to [45], further research must be done on other food products with a different moisture content and weight than wheat and rice.

2.8. Background literature on calculations

The complex process calculations and hydronomics describing the dryer are material specific. Thus, different mathematical models have been created to model the drying kinetics in a dryer. These analytical models are solved with a variety of empirical models and simplified assumptions, mostly developed using existing experimental data [47].

In the case of this study, the drying agent is air and to design the dryer different regimes of fluidization need to be investigated to ensure that drying efficiency is optimized. A fluidized bed dryer consists of the following parts: a blower, heater and drying column. Thermal balance in the drying column is derived by applying energy, entropy and mass balances. In a dryer where there is a single inlet and outlet, the mass rate balance equals [43].

$$\frac{dm_{cv}}{dt} = \dot{m}_{g1} - \dot{m}_{g2} \tag{3}$$

and a balance of air in water equals

$$W_s \cdot \frac{dM_p}{dt} = \dot{m}_a \cdot (X_1 - X_2) \tag{4}$$

where W_s is the mass of the dry solid, M_p is the moisture content of the material (uniform through the bed), X_1 and X_2 are the inlet and outlet absolute humidity of the air and $\dot{m}_a$ is the mass flow rate of dry air.

The previous equation can be rewritten as:

$$\dot{m}_w = \dot{m}_a \cdot \left(X_1 - X_2 \right) \tag{5}$$

The heat transfer due to the heat of evaporation is significant, but there is also heat transfer to the surroundings. The energy rate balance is:

$$\frac{dH_{cv}}{dt} = \dot{Q}_{evap} + (\dot{m}_{a1} \cdot h_1) - (\dot{m}_{a2} \cdot h_2) - \dot{Q}_{loss} \tag{6}$$

Where $\dot{Q}_{evap}$ is heat transfer due to water evaporation in kJ/s, $\dot{Q}_{loss}$ is heat loss in kJ/s, h_1 is inlet air specific enthalpy and h_2 is the outlet air specific enthalpy. As the mass flowrate of the dry air and the mass of dry product stay constant over time, the energy balance can be written as:

$$\frac{W_s \cdot \left(h_{m2} - h_{m1} \right)}{dt} = \dot{Q}_{evap} + \dot{m}_a \cdot \left(h_1 - h_2 \right) - \dot{Q}_{loss} \tag{7}$$

The material enthalpy balance for material flow is:

$$h_{m2} - h_{m1} = C_m \cdot \left(T_{m2} - T_{m1} \right) \tag{8}$$

C_m is the specific heat of the material. The moist air enthalpy h_m is:

$$h = h_a + X \cdot h_V \tag{9}$$

The heat transfer due to the phase change is [43]:

$$\dot{Q}_{evap} = \dot{m}_w \cdot h_{fg} \tag{10}$$

Where h_{fg} is latent heat of the evaporation of water in kJ/kg at the average temperature of the moist material [43].

The energy balance can be used to derive a first law of thermodynamics energy efficiency for a drying system. Thermal efficiency can be written as [43]:

$$\eta = \frac{Energy\ transmitted\ to\ the\ solid}{Energy\ incorporated\ in\ the\ drying\ air}$$

And this is:

$$\eta = \frac{W_s \cdot [h_{fg} \cdot \left(M_{p1} - M_{p2}\right) + c_m \cdot \left(T_{m2} - T_{m1}\right)]}{\dot{m}_{da} \cdot \left(h_1 - h_0\right) \cdot \Delta t} \tag{11}$$

Heat transfer can occur through radiation, convection and conduction, depending on the operation. The contribution that each mechanism delivers to the system depends on the type of distributor, flow condition, particle classification, pressure and operating temperature [15].

Heat transfer through convection between a particle and the air is expressed as:

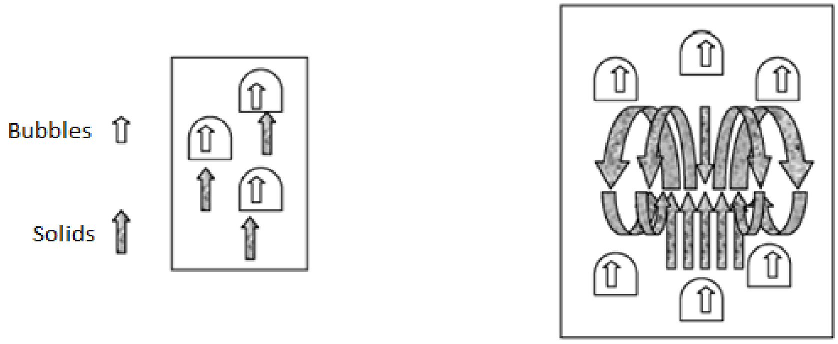
$$q = h_p \cdot A_p \cdot \left(T_p - T_g\right) \tag{12}$$

where q is the rate of heat transfer, h_p is the heat transfer coefficient in W/m^{2}K, A_p is the surface area of a single particle, T_p is the temperature of the particle, and T_g is the temperature of the gas [15].

2.9. Experimental investigations from literature

Tests and experiments are done on dryers to determine their performance under normal operation conditions, maximum capacity of dryer under typical operation conditions, optimized operating parameters for maximum performance, optimum operating parameters for cost effectiveness, product quality, and minimum environmental impact. The test results can then be compared to the design data [7].

A fluidized bed dryer can only be scaled up to a full size industrial dryer by using experimental pilot plot data and not by mathematical models due to the unreliability of these mathematical models for fluidized bed dryers. Hence, experimental pilot plant tests must first be undertaken to estimate the performance of the dryer.The biggest problem of scaling up is the fact that the bubbles in the bed remain the same size although the flow patterns can differ in larger dryers [19]. In smaller equipment, the bubbles push the product upwards as they rise and not much mixing is taking place, wheras in larger dryers vigorous mixing takes place due to large scale flow paterns in the centre and at the wall, as is evident from Figure 15 [19]. This can also happen the other way around [19].



Solids mixing caused by upwards solids motion in rising bubbles

Solids mixing due to large scale toriodal circulation patterns up in center and down at wall

Figure 15: Different solid and bubble flow patterns in small and large fluidized beds [19]

Difusion or dispersion coeffisients increase as the bed diameter increases. Limitations such as these require that the specific material must be tested at a pilot plant and experimentally to ensure that an accurate up-scale procedure is followed to evaulate the operation of a industrial fluidized dryer. Therefore, using only labrotory data and first principles to design and predict the performance of a dryer is difficult [19]. To determine the heat and mass transfer coefficients with appropriate accuracy, is always problematic. Heat transfer coefficients are mostly determined by using the turbulent flow around a sphere, but the flow in a large dryer can vary considerably. An accurate method to determine these coefficients is the Ranz and Marshall correlation [13, 25]. Models for drying in fluidized dryers are often too specific to a certain material and design and it is therefore hard to use other models to simulate performance on another material and design.

2.10. Design processes for dryers

The steps that can be followed to design a dryer or cooler can be seen in the diagram in Figure 16. These steps are described in [15].

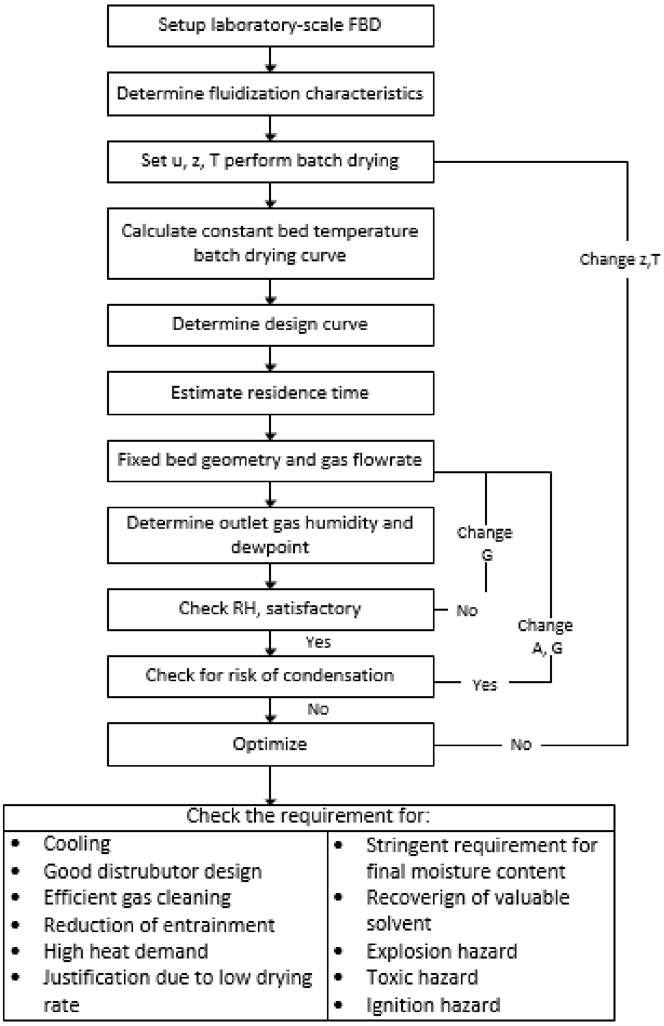


Figure 16: Design steps from experimental tests [15]

Another guide as to what steps can be followed to design a dryer or cooler can be seen in Figure 17. This guide is described in [48].

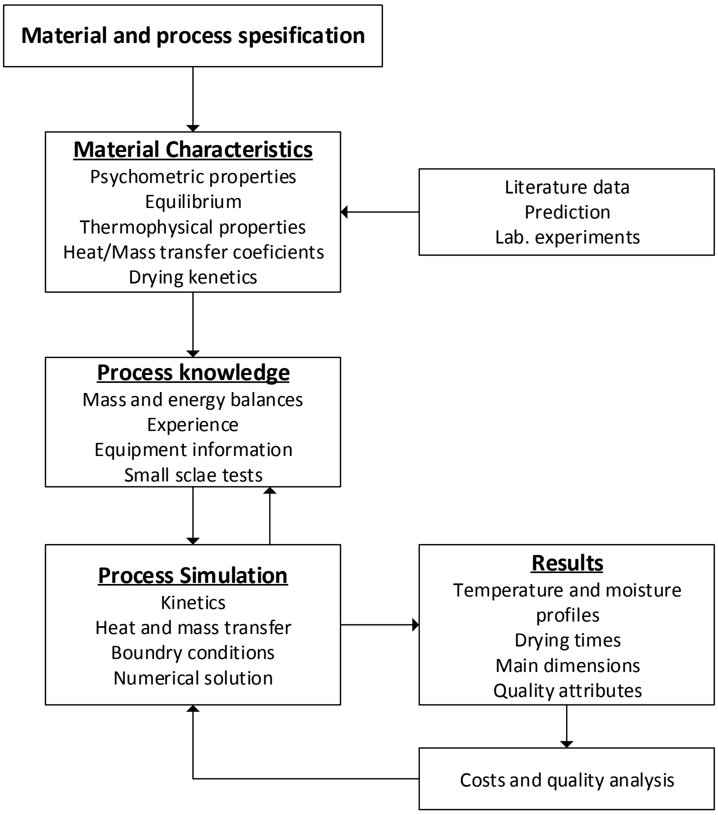


Figure 17: Fluidized bed dryer design steps [48]

2.11. Conclusion

This chapter presented a literature overview of the research that has been done on the drying of maize pellets in bed coolers/dryers. It also includes research by numerous authors that describes the effect that air velocity through the bed and the product bed height have on the drying rate of foods and counterflow coolers/dryers.

The next chapter will discuss the experimental method and the instruments used to collect data on the study subject.

Chapter 3

Experimental setup

This chapter will discuss the experimental testing performed in this project. This includes the instruments used, description of the material tested and the method followed. These tests are done to determine how the process parameters influence the drying process of extruded maize pellets

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The product used in the experiments is pure maize meal. The maize was extrusion cooked at a rate of 80 kg/h. The extruder used was a CFAM Technologies extruder named the TX32. The dosing water used in the extrusion process was fed at a rate of 10 l/h. The maize was extruded through a die at the end of the barrel that contains holes with a 3 mm diameter. The properties of the product are shown in Table 4.

Table 4: Initial product properties

Pellet Property	Description
Diameter	8-10 mm
Shape	Spherical
Material	Extrusion cooked maize
Initial temperature	50°C
Bulk density	250 kg.m^{-3}
Initial average moisture	0.12 kg.kg^{-1}

3.1. Testing bench design and setup

The experimental setup consists of a rectangular tube made from Perspex that contain the product that must be dried. The tube container is 750 mm high and has a cross section of 250 mm by 250 mm. A distribution perforated plate with holes that are 3 mm in diameter was assembled onto the bottom of the tube container. This allowed the product to rest on the plate and let the air through from the bottom. A relative humidity sensor was installed at the top part of the tube where the air exits the tube. The illustration of the testing tube can be seen in Figure 18.

The testing tube was placed on the ducting that will direct the air to the bottom of the tube and through the product. A fan that supplies the air was connected to the ducting. An airflow meter was installed into the ducting, downstream from the fan. The airflow meter from a straight piece of ducting was placed 500 mm downstream to ensure laminar flow as it reaches the airflow meter. An illustration of the entire experimental setup can be seen in Figure 19.

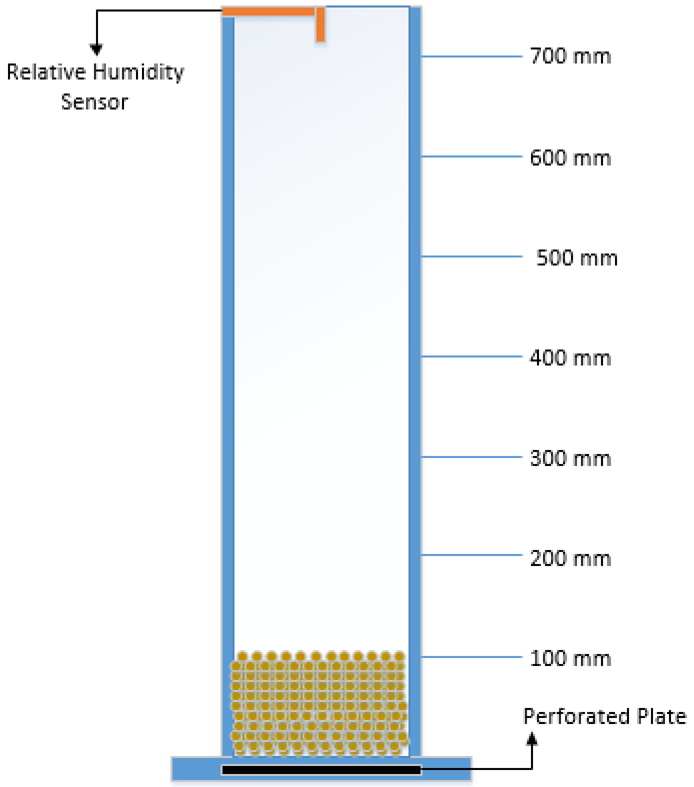

Figure 18: Illustration of experimental test tube

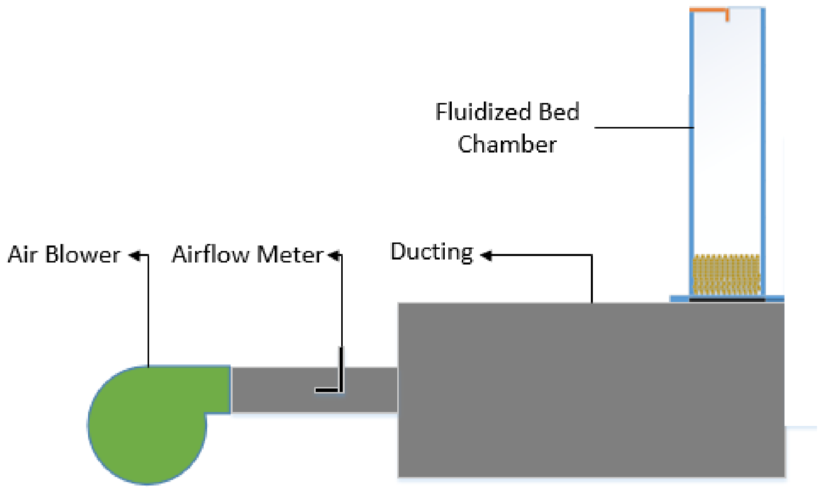

Figure 19: Illustration of entire experimental setup

3.2. Instrumentation and equipment

In order to determine the drying characteristics of the extruded maize product, various measurements are required. These measurements include among others, the temperature, the relative humidity and the air-flow velocity. More details on these measurements are provided below:

3.2.1. Temperature and relative humidity logger

This logger logs the relative humidity and the dry bulb temperature of the air exiting in the tube after it flowed through the product. A bracket was made to support the logger. The logged data was then processed in a computer program called Data Logger Graph.

3.2.2. Airflow meter

This meter measures the velocity and total pressure of the supplying air. It was installed into the ducting, downstream from the air blower.

3.2.3. Scale

A digital scale was used to weigh the initial product that will be placed into the testing tube. For the verification of the calculation of the moisture loss, the product is also weighed after the test.

3.2.4. Product moisture analyser

A product moisture tester was used to measure the moisture content of the product before and after each test. This was also used to verify the moisture loss calculation.

3.2.5. Blower

An air blower was used to supply air to the product bed.

3.2.6. Variable speed drive

The variable speed drive (VSD) was used to control the blower speed, which in turn controls the air velocity by means of altering the frequency of the blower motor.

3.3. Experimental process

Immediately after the extrusion process took place, the product was placed inside the testing tube onto the perforated plate. Testing was done at 4 different air flow speeds, namely 1, 1.4; 1.8 and 2.2 m/s. To specify the air velocity testing parameter values, testing was done at a bed height of 0.4 m and the air velocity was increased to the point where the product bed was in the fluidized state. This velocity value was then chosen to be the highest testing air velocity parameter, which was 2.2 m/s. Three other values derived from the highest testing parameter at an interval of 0.4 m/s were chosen, to ensure that the values represent the range of values used in the industry.

The values of the bed height were chosen to best represent the conditions in industry and according to the available resources and finances. This lowest value chosen was 0.1 m and it was increased to 0.4 m in 0.1 m intervals. Testing was then done at each combination of bed height and air velocity to obtain 16 data points.

3.4. Recapitulation

A custom manufactured experimental test bed setup enabled the investigation to determine the influence that the air velocity and product bed height had on the drying process of the extruded maize pellets. The instruments used were an airflow meter, scale, moisture meter and a relative humidity sensor. Testing was performed at air velocities of 1; 1.4; 1.8; 2.2 m/s in combination with product bed heights of 0.1; 0.2; 0.3 and 0.4 m.

The next chapter will present the results that were obtained in the experimental tests. It will include the processing of the results and the presentation of useable information concerning the cooling/drying performance of extruded maize pellets.

Chapter 4

Experimental results

In this chapter, the results that have been obtained in the experimental tests are processed into useful information and are then discussed. The drying performance at various air velocities and product bed heights is evaluated. Furthermore, the drying performance is measured through the following parameters: total moisture loss, moisture loss rate and process efficiency.

In Figure 20 a flow diagram that illustrates the steps that were followed to process the results into useful information is presented.

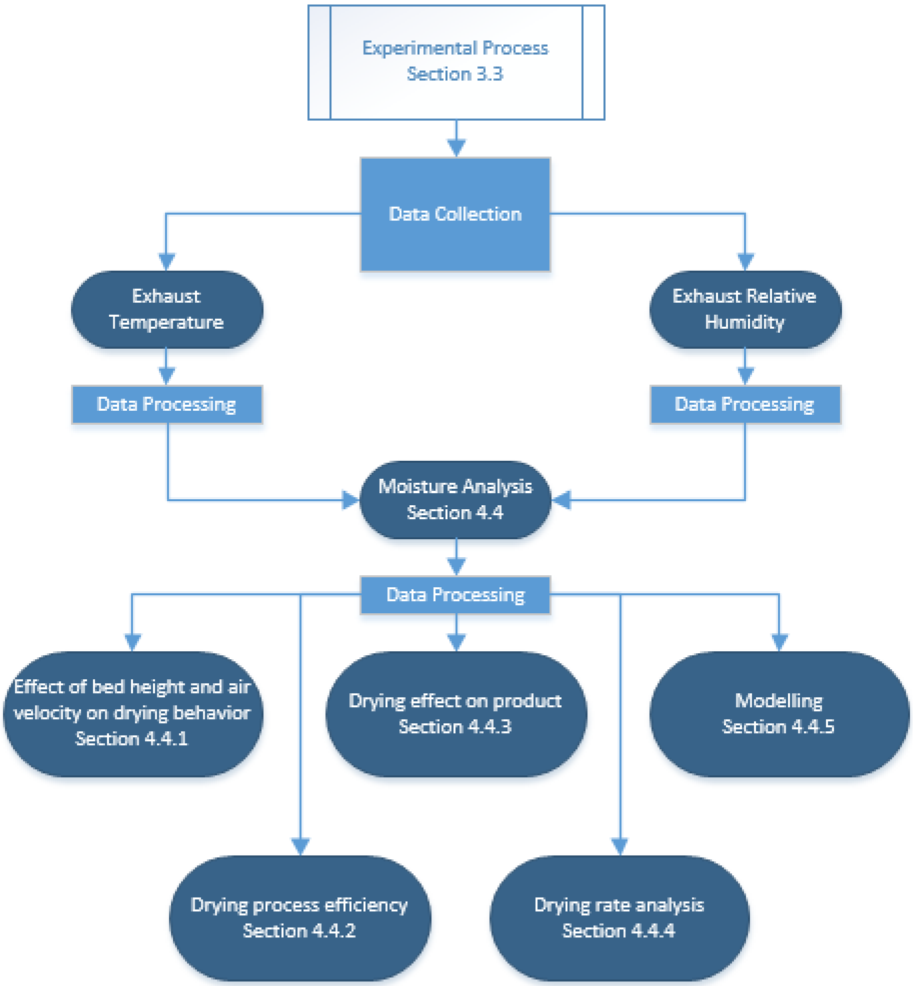

Figure 20: Data processing flow diagram

The raw data obtained in the experimental tests was firstly processed by analysing the temperature and relative humidity change during the drying process. Secondly, the moisture loss in the product was analysed by calculating the total moisture loss in the product, the drying efficiency and the moisture loss rate. After calculating these values the following was discussed:

the effect the bed height and air velocity have on the drying behaviour, the drying process efficiency, the drying effect on the product, drying rate analysis and lastly the mathematical modelling. These processed results were used to specify the optimal drying process parameters to dry the extruded maize product.

4.1. Assumptions

The assumptions made during the processing of results are that the:

- Dryer is ideally insulated.
- Solids are uniform in size, spherical and homogeneous.
- Physical properties of the product remain constant over time.
- Shrinkage of the solids and temperature gradient inside the pellets are neglected.

The assumptions made have a relatively small effect on the results, while if they were to be included it would have a dramatic effect on the model complexity. The author in [41] stated that models are developed to predict drying kinetics; these models include from analytical models with simplified assumptions to only empirical models based on experimental data [41].

4.2. Captured data

Measurements of the exiting air after it moved through the wet extruded product were taken during experimental testing. The logger took a reading of the relative humidity and dry-bulb temperature at a two second interval. The logger's readings were plotted on a graph, as indicated in Figure 21. This figure represents the temperature and the relative humidity over time. Similar graphs for the 0.2, 0.3 and 0.4 m bed heights can be found in Appendix A. The graph below presents a curve that has the same form than the curves at other bed heights. This data was processed into sensible information from which good conclusions could be drawn of the effect of bed height and air velocity on the drying process of extruded maize pellets.

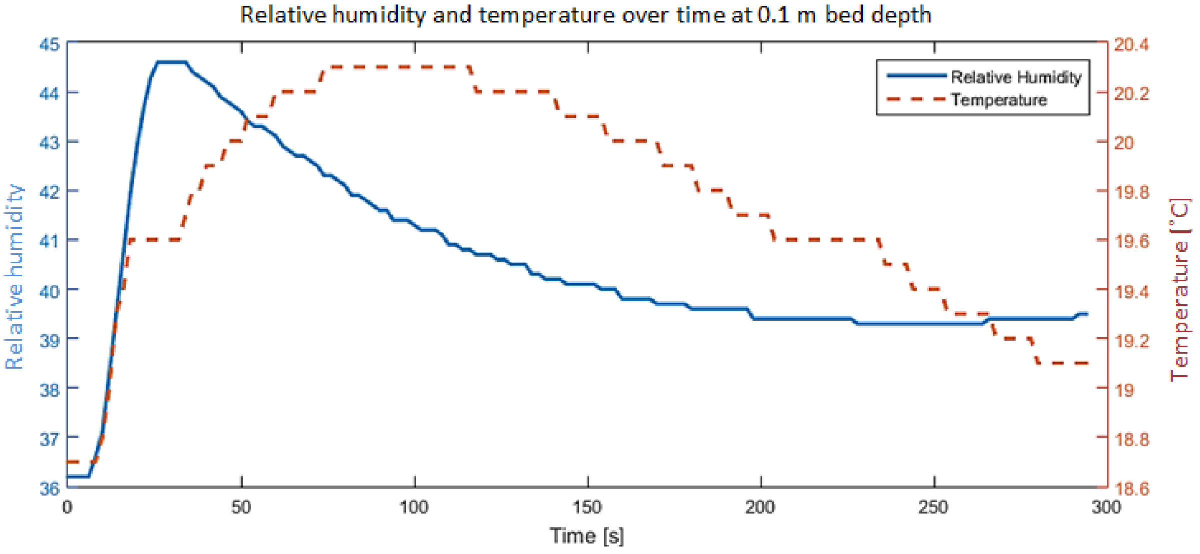

Figure 21: Temperature and relative humidity over time at a 0.1 m bed depth

4.3. Result processing reasoning

The reason why a model based on empirical data was created, especially for the drying of a food product that has not been experimentally tested, is the following:

The mass transfer in foods is based on empirical operation and design due to the lack of mass transfer properties available for various foods. [39] Process calculations and the intricate hydronomics are dryer and material specific. Models are developed to predict drying kinetics; these models include from analytical models with simplified assumptions to only empirical models based on experimental data [41].

According to [39], the drying of porous foods is rather complex. This is due to the interaction between heat and mass transfer and the interaction between the airflow and the product. Solutions for these problems are complex and present complicated computational problems. Limited progress has been made to predict drying behaviour, which is due to the lack in data of the thermodynamic properties of foods. The mathematical theoretical calculation model solutions that are developed still need time to replace the regularly used empirical data in the design of dryers. A lot of work is still needed to predict drying behaviour and to obtain analytical solutions for the drying of foods [39].

The author in [9] did experimental tests and developed a model to estimate the moisture content and temperature of the pellets in a counterflow cooler. The model he developed, predicted the moisture content of the pellets at 3% to 60%. He concluded that the model can only be used to predict the behaviour of different parameters. Additional research must be done to increase the accuracy of the single pellet equation for drying rate in order to generate more accurate output results. This author states that the temperature he predicted was lower than the temperature obtained in the experiments. This can be attributed to the increased equilibrium moisture content that then predicted an increased cooling effect of the evaporation [9].

4.4. Moisture analysis

In this section the moisture loss from the product into the air is analysed by means of different performance parameters. The temperature and relative humidity readings were processed into a moisture loss rate value. To achieve this, the moisture ratio content of the incoming air and the outgoing air was calculated. The difference equals the moisture loss in the product. Air density was estimated by using the EES built-in function. The mass flow of the moisture loss of the product is calculated by using the following equation:

$$\dot{m}_a = \rho_a \cdot V_a \cdot A_b \tag{13}$$

Where $\dot{m}$ is the mass flow rate of the air in kilogram per second and A_b the section area of the product bed. Moisture loss is multiplied by the mass flow of the air to obtain the rate of moisture loss.

The moisture loss calculations were verified by measuring the moisture in the pellets using a moisture analyser. Further verification was obtained by weighing the pellets before and after each test to calculate the moisture loss.

4.4.1. Effect of bed height and air velocity on moisture loss

This section will discuss the moisture loss behaviour in the product bed at different bed heights and drying air velocities. The bed height and air velocity have an effect on the temperature. This will be discussed first and then the moisture loss behaviour in the bed for both of these parameters.

4.4.1.1. Effect of bed height on drying behaviour

In Figure 22, the behaviour of the temperature of the exiting air at a constant air velocity of 1.8 m/s and at different bed heights (BH) can be seen. The curve is more or less the same for all the air velocities and this graph illustrates the typical curve. This is indicating the effect that the product bed height had on the temperature change of the exiting air. The bed heights were changed from 0.1 m to 0.4 m in 0.1 m increments. The graph illustrates the temperature difference between the ambient air and the exiting air that passed through the product. The velocity was kept constant even though there would have been a pressure difference over the bed as the bed height changed.

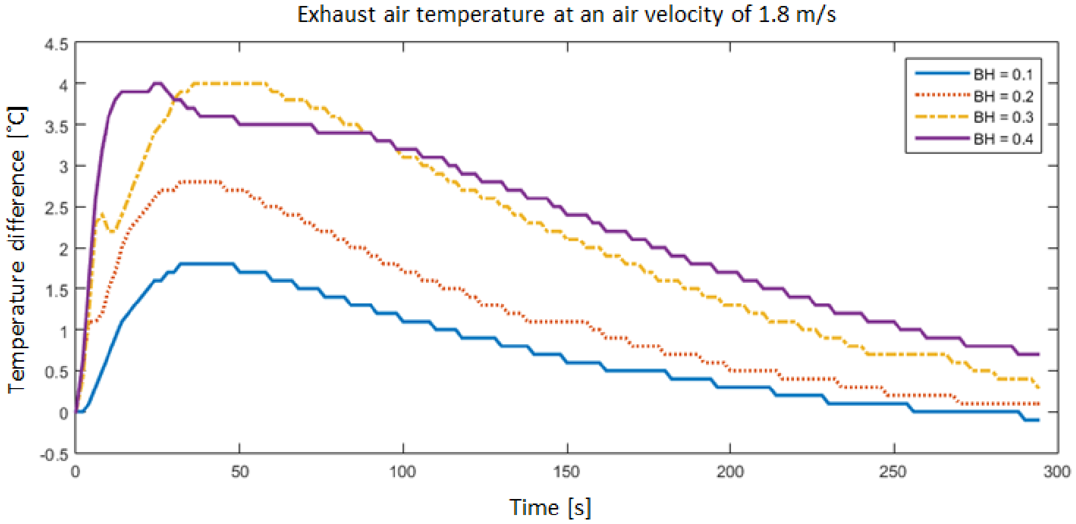

Figure 22: Air temperature difference over time at 1.8 m/s at various product bed heights

Figure 23 shows the percentage of moisture loss in the product over 300 s at various bed heights at an air velocity of 1.8 m/s. This percentage is the ratio between the weight of the moisture lost and the dry product.

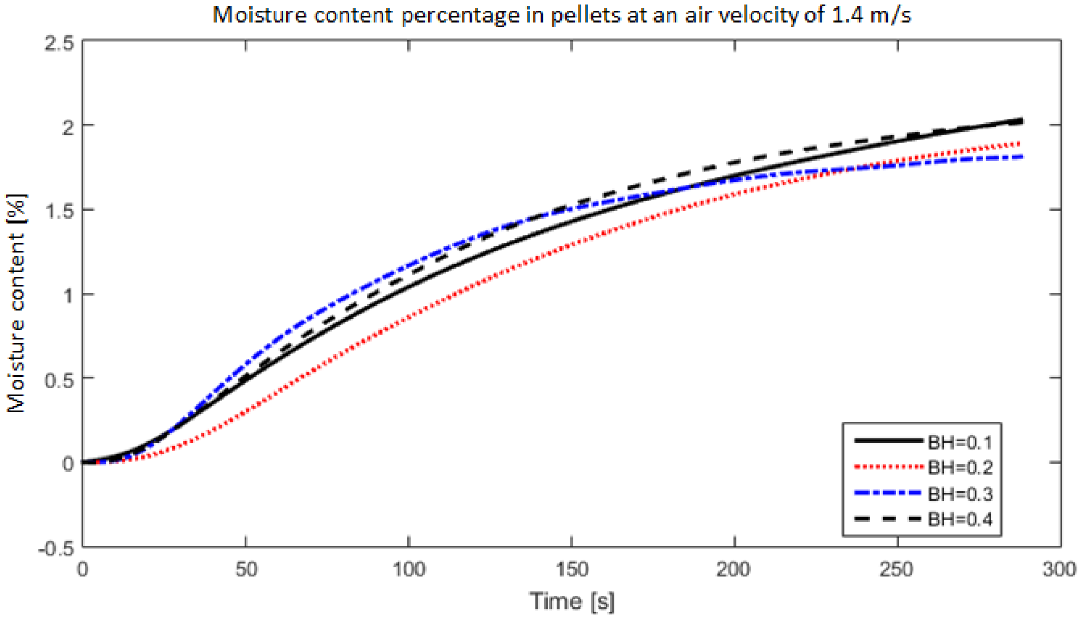

Figure 23: Cumulative sum of moisture in exiting air over time

Figure 22 shows the temperature difference between the ambient air and the exiting air over time at an air velocity of 1.8 m/s. Evaporation of the moisture on the surface of the pellets increased the temperature of the air, due to the heat of the moisture on the surface of the pellet. It can be concluded from equation (14) that the larger the contact area between the pellets and the air for a constant heat transfer rate, the more the outgoing temperature increases.

$$Q = h \cdot A_p \cdot (T_i - T_o) \tag{14}$$

In Figure 22 it is portrayed that the temperature change rate at the start of the test was the same at all bed heights. However, the time period of the temperature change rate at the start was larger for a 0.4 m bed height than a 0.1 m bed height. This caused a higher temperature difference at the start of the test and increased the time for the product to reach ambient temperature. This is due to the increased product bed area and bulk volume of the product. The larger the volume of the product in the bed, the more heat is available.

An increase in temperature of the surface moisture leads to a decrease in the vapour pressure of the moisture. This increases the difference between the vapour pressure of the moisture on the pellet surface and the partial pressure of the moisture in the air, which in turn leads to an increase in mass transfer. The equation below illustrates the mass transfer of the moisture from the pellet into the air:

$$m_w \cdot \frac{dM_m}{dt} = -k_g \cdot A_p \cdot (p_{vs} - p_{vg}) \tag{15}$$

Where m_w is the moisture mass flow, dM_m/dt is the moisture loss rate, p_{vs} is the partial pressure of the solid surface and p_{vg} the partial pressure of the drying air. When the wet and warm pellets entered the drying chamber, the moisture on the pellets' surface evaporated due to the difference in partial pressure mentioned above. When the pellets were subjected to ambient temperature airflow, it cooled off and gradually lost the ability to evaporate moisture. Therefore, the slower the cooling rate of the pellet, the longer the time that moisture has to escape by means of evaporation. The temperature will reach ambient temperature and the product will stop evaporating when the wet bulb temperature of the air equals the pellet surface temperature, when no energy is exchanged and there is no difference in partial pressure.

To obtain the total percentage moisture that has been removed by the air, it is necessary to calculate the area under the moisture loss rate over time. By using the equation below, the total moisture lost can be determined.

$$\sum M = \int \frac{dM}{dt} \tag{16}$$

Where M is the moisture in the exiting air, dM the moisture difference and dt the time difference. To obtain the total percentage moisture lost in the product bed, the following calculation is used:

$$\%M = \frac{\sum M}{W_p} \tag{17}$$

Figure 23 shows that the bed height had a small effect on the percentage of moisture lost, and had a total moisture difference of about 0.5% of moisture at various bed heights over 300 s.

To explain this behaviour, it is necessary to calculate the average temperature of each kilogram of product, to draw the conclusion that the heat distribution at different bed heights stays constant. In investigating the amount of heat each pellet received, the amount of product per kilogram of product is divided by the average temperature difference, as illustrated in Table 5. This will help to understand the effect that the temperature has on the moisture loss and the effect the bed height has on the cooling rate and moisture loss.

Table 5: Ratio of temperature and mass of product

Bed height (m)	Weight of product (kg)	Average temperature difference between ambient and exiting air (°C)	Ratio [°C/kg]
0.1	0.8	0.6	0.75
0.2	1.6	1.25	0.81
0.3	2.4	2.1	0.88
0.4	3.2	2.4	0.75

The ratio stays more or less constant, which indicates that at each bed height the product per kilogram receives more or less the same heat. This explains the small difference in moisture loss at different bed heights. Furthermore, the natural ambient air physical properties changes can also cause an uneven effect on the moisture loss. This can be due to ambient temperature and relative humidity fluctuations that affect the evaporation. Although the bed height did not have a constant correlation with the moisture loss, it can predict the moisture loss to a certain extent.

To conclude, the results obtained show that the final moisture content of the exiting air did not change as the product bed changed. To verify this result, the author in [2] did a study on the drying rate of solids in a batch fluidized bed and found that the drying rate is marginally influenced by the bed height at a height over 50 mm. As holdup increases and air velocity stays the same, the drying rate decreases due to the decrease in input enthalpy per unit mass [2].

4.4.1.2. Air Velocity

In this section, the moisture loss in the product will be analysed in terms of the air velocity value through the product bed. To analyse the moisture loss, the temperature curve will be analysed at different air velocities where after the percentage moisture loss will be analysed and discussed. Finally, the total percentage moisture lost after 300 s will be plotted on a 3D axis. This will give an idea of the behaviour of the moisture loss at different bed heights and air velocities.

Figure 24 presents the temperature difference of the exiting air and the ambient air over time at a product bed depth of 0.4 m and various specified air velocities. Figure 24 shows that the change in air velocity does not have a constant effect on the temperature change rate of the exiting air. Thus, it is making the cooling performance very unsteady with the change in air velocity.

The equation below explains the temperature behaviour in terms of the heat transfer coefficient in the product bed [10, 49].

$$h = A_p \cdot C_A \cdot G_a \cdot \left(\frac{d_p \cdot G_a}{\mu_a} \right)^B \tag{18}$$

where G_a is the air flow rate and d_p the pellet diameter. It can be concluded from this equation that an increase in air flow means an increased heat transfer coefficient. However, it does not support the results of the experimental tests. Therefore, the small difference in temperature behaviour at different velocities may be attributed to the difference in flow patterns through the bed as the velocities changed. This was noticed while the experiments were done. The unstable behaviour can also be attributed to the random packing of the pellets. A velocity change can affect the area of the pellets reached by the air. If the area stays constant, the heat transfer coefficient stays constant although the air velocity varies. Thus, the heat transfer coefficient remains relatively similar at all air velocities.

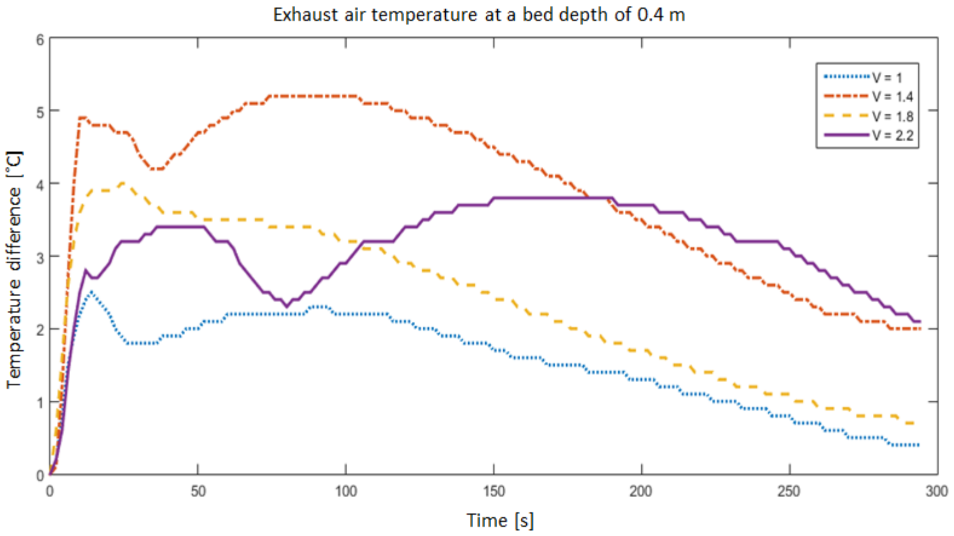

Figure 24: Exhaust air temperature over time at a 0.4 m bed depth at various air velocities

Figure 25 presents the total moisture lost from the product at a bed depth of 0.4 m at different specified air velocities.

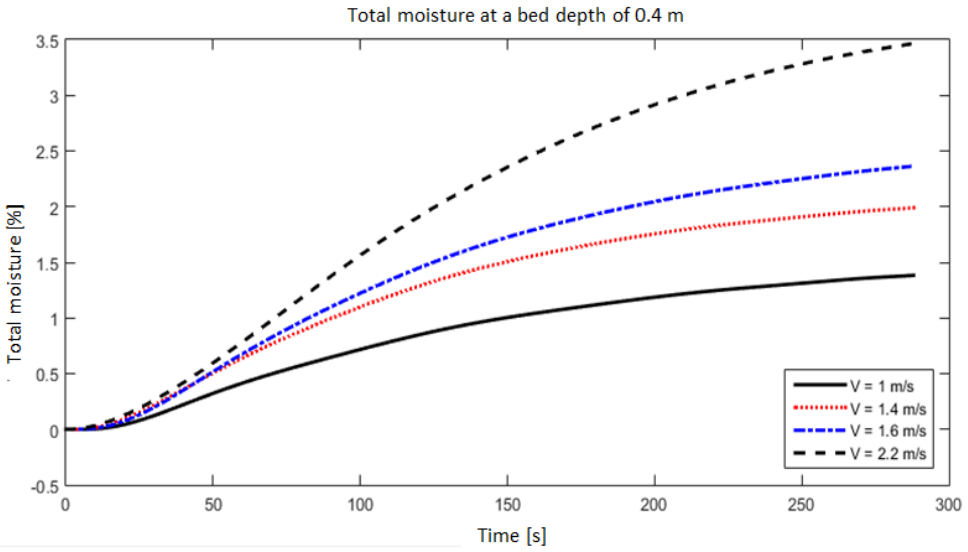

Figure 25: Total moisture lost at 0.4 m bed depth

Figure 26 presents the effect that the air velocity and the bed depth have on the total moisture loss percentage of the product.

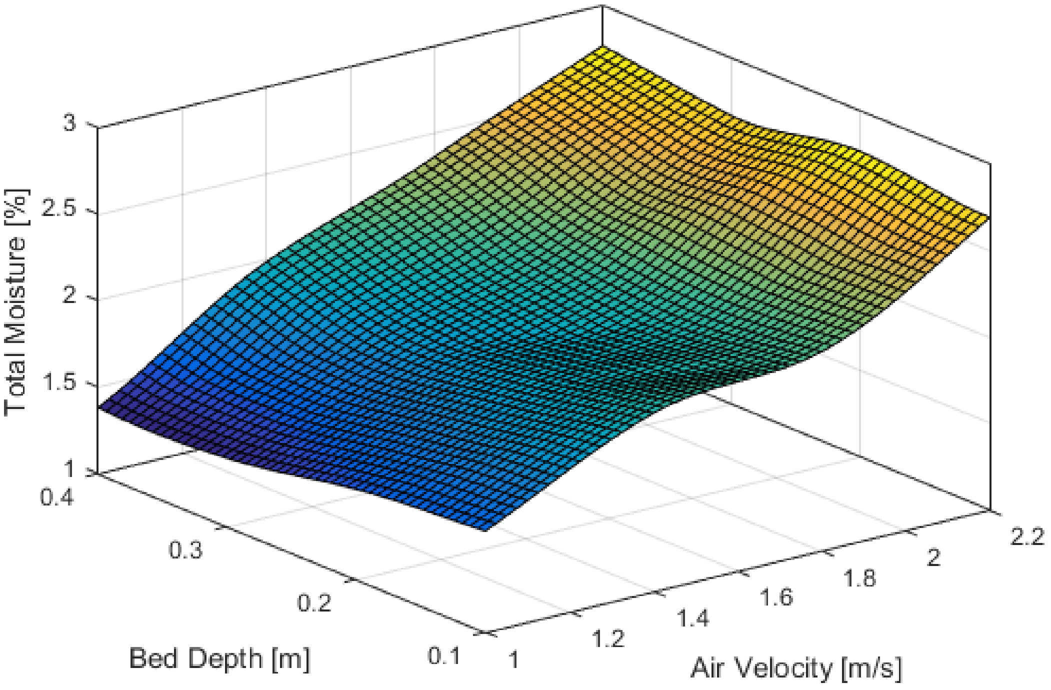

Figure 26: Effect of air velocity and bed depth on percentage of total moisture lost

It is clear that the total percentage moisture loss increases as the air velocity through the bed increases. This can be attributed to the mass transfer equation below [2].

$$K = \frac{V_a}{3} + \left[\frac{4 \cdot D_p \cdot \varepsilon_{mf} \cdot V_a}{\pi \cdot d_p} \right] \tag{19}$$

Where V is the air velocity and K the mass transfer coefficient. As the mass flow rate of the air increases, the potential of the air to carry the moisture out of the bed at an increased rate also increases. As seen in a previous discussion, the air velocity did not have a great impact on the temperature change rate. Therefore, it can be concluded that the reason for the total moisture difference is the result of the mass transfer rate that has increased. It is therefore concluded that the big difference in total percentage moisture loss can be attributed to the increased mass transfer rate and evaporation rate. Furthermore, more moisture is lost due to the increased air velocity. The higher the air velocity, the more moisture mass can be lifted out of the bed.

Calculating or predicting the mass transfer coefficient is very complex due to the change it undergoes while drying occurs. Mass transfer, as is evident from the results, comes mostly from the surface, but while surface moisture is removed mass transfer also occurs inside the product. The product is dependent on both heat and mass transfer [2]. For the purpose of these experiments, it was assumed that only mass transfer will be taken into account, since no diffusion was taking place inside the product. There is no diffusion on the surface due to the low temperature of the air.

The air velocity has a similar effect on moisture loss at different product bed heights. It shows that at a higher bed height, there is a more constant correlation between the air velocity and the total moisture loss in the product. Figure 26 shows the effect that the air velocity and the bed depth have on the moisture loss percentage.

It was evident that air velocity had a significant effect on the drying rate in terms of total moisture loss in the product bed. The results of this investigation are presented in Figure 25. The percentage moisture loss represents the percentage of total water per product mass in kg/kg. Figure 25 indicates that the air velocity has a great effect on the moisture loss percentage per hour. As the air enters the product from below, the air temperature increases as it moves upwards through the product, gradually cooling the product from the bottom to the top of the product bed. Therefore, a low bed depth will increase the cooling rate; thereby increasing the possibility for thermal shock. As for the effect of the air velocity, more moisture is removed when the air velocity is high, as this increases the mass transfer rate.

In the results obtained the temperature of the exiting air did not change as the velocity of the air changed. In a deep bed there is a change in axial air velocity near the wall of the bed as the porosity changes. The author in [50] states that there is a change of velocity and a pressure drop along the bed. This velocity behaviour has an influence on the heat and mass transfer coefficient in a deep bed and the effect seems to increase as the bed height increases [50].

In the results obtained, the moisture content of the exiting air increased as the velocity of the air increased. This author states that as mass flow increased, so did the mass transfer coefficient and this resulted in a faster evaporation rate. As the velocity increased, so did the static pressure over the bed [51]. According to [1], the increase in gas flow rate in the bed dryer decreases the final moisture content in the food. The author also found that the heat transfer and evaporation coefficient increased as the velocity increased [1]. Furthermore, the drying rate is increased as the airflow rate is increased, and the drying rate is decreased when the inlet humidity increases [2]. According to [2], an increase in air velocity increases the drying rate in the constant drying rate period and this has a small impact on the falling rate period [2].

4.4.2. Drying process efficiency

In this section, the drying efficiency will be investigated when the air velocity and bed heights are altered. The drying efficiency is measured by the total moisture lost in 5 minutes per kilowatt of blower power. Figure 27 shows the mass of moisture, in grams, that is lost from the product per kilowatt power used by the air blower.

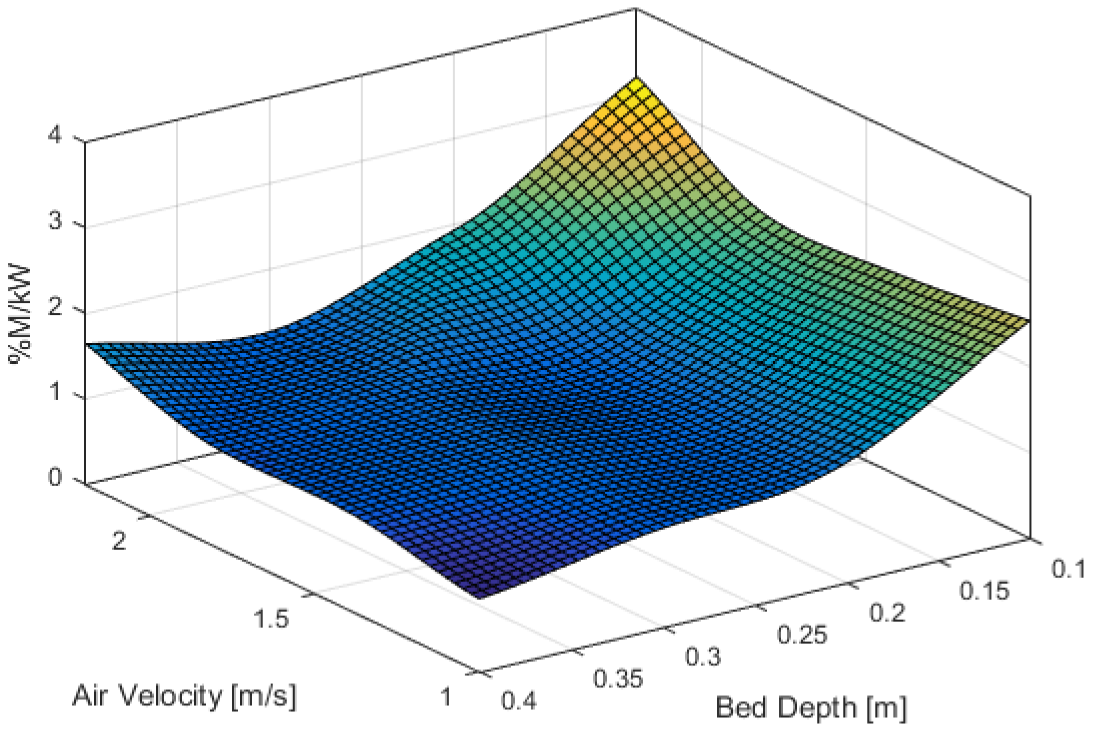

Figure 27: Effect of air velocity and bed depth on the moisture lost per kilowatt

The graph indicates that as the air velocity is increased, the moisture loss efficiency increases. As the air velocity increases through a fixed bed, the pressure drop increases linearly, thereby increasing the power needed by the air blower. When the fluidization state is reached, the pressure drop remains constant and the moisture loss rate increases, thereby increasing the moisture loss efficiency of the drying process.

At an air velocity of 2.2 m/s, all specified bed depths have reached the bubbling fluidization state. This high velocity was specified to investigate the effect of fluidization on the drying rate of the maize pellets. Evaluating fluidization in terms of the energy usage is a sensible approach in terms of optimizing the energy efficiency in a dryer.

Another efficiency that is important to take account for is the bed height and bed area ratio to ensure even airflow. The airflow at a 0.1 m bed height on an area of 0.04 m^2 is sufficient for even airflow. Even distribution is guaranteed at a bed height of 0.2 m and an area of 0.04 m^2 as witnessed during experimental testing. Thus, there is a ratio of 0.2 between area and height, so A = 0.2H.

4.4.3. Drying effect on product

The product moisture loss refers to the moisture loss in reference to the initial moisture content of the product and the effect the moisture loss has on the product quality.

As the product exits the dryer, steam is blown from the product due to the pressure drop and high temperature as the product exits the hole. The product then has to be transported to the cooler/dryer, and in the process more moisture is lost. At the inlet of the cooler/dryer, the average moisture content measured in kilogram water per kilogram product of the maize pellet is 12%. To achieve this moisture content after extrusion and to ensure the moisture content stays constant all the time, the product flow and water flow rate in the extruder must be kept constant.

Table 6 indicates the parameters that the TX32 extruder must be operated at to ensure the correct pellet moisture content.

Table 6: Extruder operating parameters

Parameter	Value
Product flowrate	80 kg/h
Dosing water flowrate	11 l/h
In-barrel moisture content	13.75%
Screw speed	700 rpm
Die hole size	3 mm
Amount of die holes	3

The final moisture content is also be influenced by the screw configuration, size of the barrel, and the size of the screws. So the parameters mentioned above will just give an indication of the parameter values and cannot be followed precisely. Other factors that will also influence the drying rate are the product density, area and volume of the product.

As mentioned earlier, the total moisture content of the maize pellet is 12% when it reaches the cooler/dryer. As stated by a food extrusion expert [52], when the maize pellet reaches a moisture content of below 10%, the pellets are safe to store and can be shelved for a reasonable time. This value is considered to be acceptable in the food industry. So to evaluate the drying of maize in terms of safe moisture content, graphs will be used to indicate whether the product reaches the acceptable moisture content in five minutes.

As the batch bed depth does not have a great influence on the drying rate of the pellets, the air velocity will be evaluated to determine at which velocity the 10% moisture content will be reached and the time it will take to reach that moisture content.

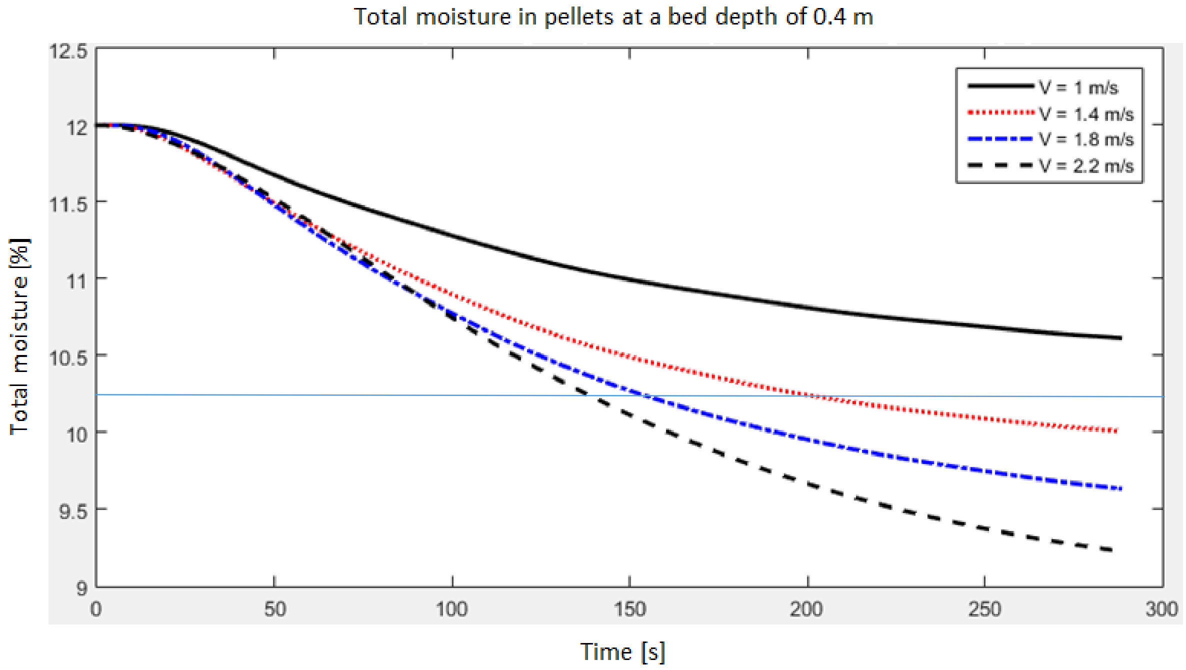

Figure 28: Specified moisture content at various air velocities

The results in Figure 28 indicate that at 10% product moisture content is reached at different times with a change in air velocity. This means, with an increase in air velocity through the bed, the product will dry faster. As shown in Figure 28, an air velocity of larger than 1.4 m/s reached the designated moisture loss in five minutes. However, between the velocities of 1.8 and 2.2 m/s, the velocity reached a minimum fluidization velocity. Therefore, such a high velocity is not preferable as this will cause uneven drying if used in a continuous process dryer.

For further investigation the ratio between the different air flows per volume product can be analysed. This information can be used to see how much airflow is needed to dry a certain amount of product. Another factor that must also be investigated is the effect that the product density, area and volume has on the drying rate. To represent this ratio, a graph will present the moisture content over time at different ratios. Figure 29 illustrates the moisture loss over time at different airflows and volumes of product ratio, RA. RA has a unit measured in volume flow rate of air to the volume of product in the bed.

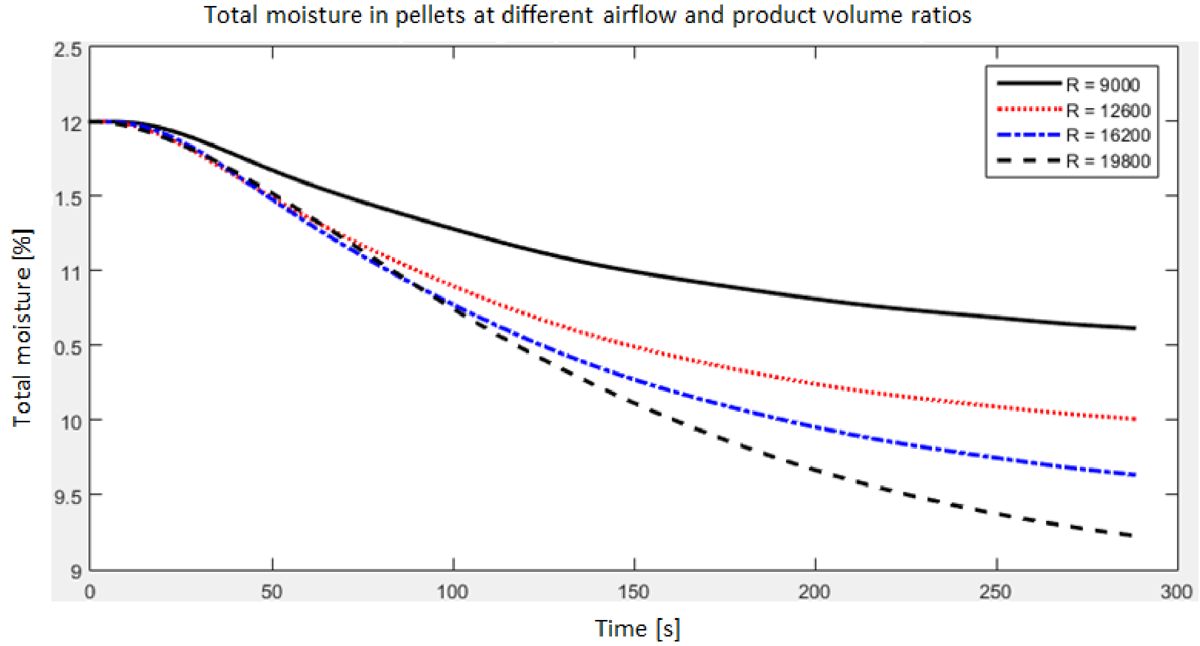

Figure 29: Moisture content percentage at air flow and product volume ratio

It is evident that the higher the ratio, the quicker the moisture reached the accepted content. However, such a high volume of airflow is not always possible due to financial and floor area constraints. This graph can then be used to determine what airflow is needed to dry a certain amount of product to the acceptable moisture content in a certain time.

4.4.4. Drying rate analysis

To analyse the drying rate of the product after the temperature and relative humidity in the exiting air results were processed, the moisture loss rate over time can be calculated and plotted. The moisture loss rate refers to the rate of moisture that leaves the product bed, while the drying rate refers to the moisture loss at a certain product density and surface area.

The theoretical drying rate R_c in a constant drying rate period is given by [53]:

$$R_c = -\left(\frac{W_p}{A_p} \cdot \frac{dM}{dt} \right) \tag{20}$$

Where R_c is the theoretical drying rate with unit kg^2/m^{2}s, W is the mass of the product, A_p is the drying surface area of the product and dM/dt is the moisture loss rate in kg/s. The graph in Figure 30 indicates the drying rate over time. The drying rate represents the rate at which moisture will be lost at a certain product density, product surface area and volume. These results are needed when the same material is used, but the density and the diameter differs. The drying rate at different air velocities can be seen in Figure 30.

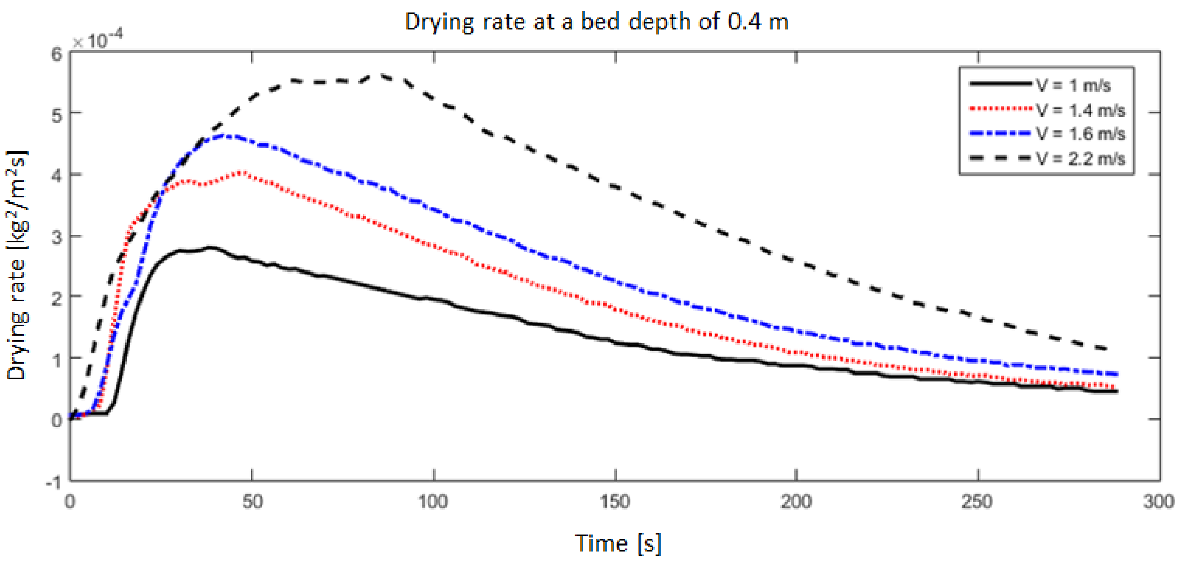

Figure 30: Drying rate at 0.4 m at different air velocities

In the figure above it is evident that this curve is similar to the moisture loss rate curve, since the drying rate is only multiplied by constants to account for the density, area and volume of the product.

As the pellet is exposed to higher air velocities, the moisture loss rates are higher than when the pellets are exposed to low air velocities. Thus, a high air velocity is needed during the evaporation phase to achieve a high moisture loss before the product temperature is too low to evaporate any more moisture. The higher drying rate is due to the reduction of the external mass transfer resistance caused by an increase in air velocity in the product bed.

This graph clearly indicates that, after the curve reached an early peak, the rate changes constantly as the moisture is lost. This is due to the fact that only surface moisture is removed and no diffusion is taking place in the pellet. As the velocity increases, the rate of moisture loss decreases at a slower rate in the same way than with a lower velocity. This is due to the larger amount of moisture that is lost. To predict the moisture loss or moisture content in a product at different product bed heights and air velocities, a drying rate function is needed.

4.4.5. Modelling

This section will discuss the created mathematical model used to estimate the moisture loss and the residence time at different bed heights and air velocities. The model will be created using the data obtained from the experiments, thus it is empirical in nature. Equation (20) will be used to calculate the drying rate for each product bed height and air velocity. These values of R_c will be plotted on a surface, as represented in Figure 31. To obtain a mathematical model to represent the drying rates at a certain product bed height and air velocity, a curve fit will be executed to obtain a function.

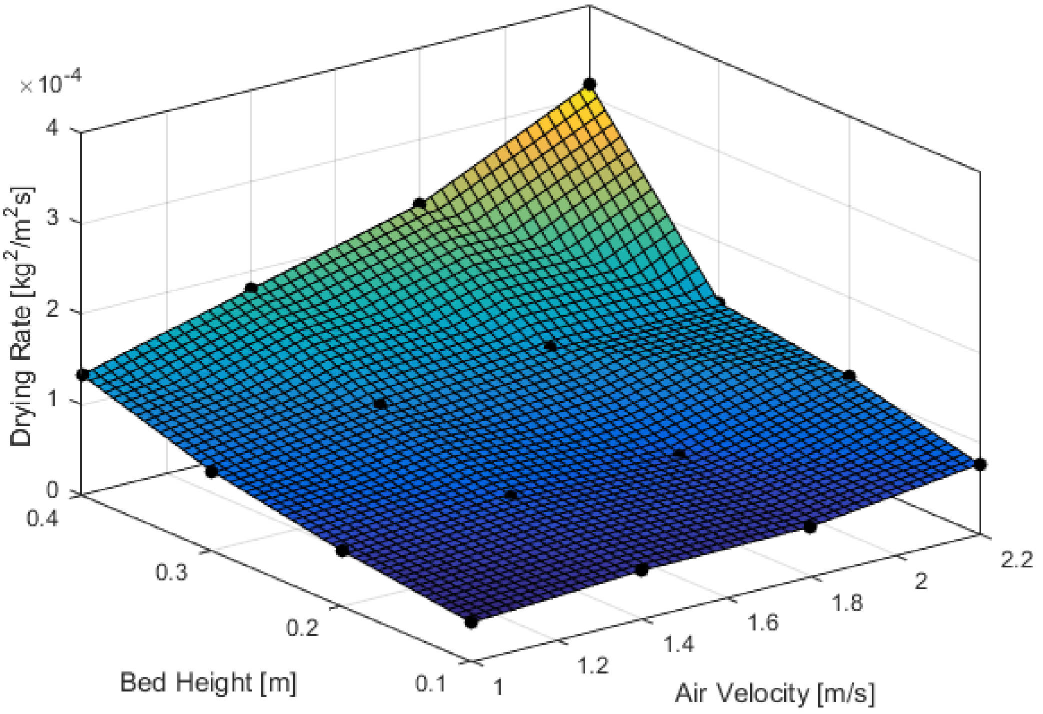

Figure 31: Surface plot of the drying rate

To estimate the drying rate R_c at a certain bed height and air velocity value, a curve fit was done on the 3D plotted surface obtained from the experimental data, shown in Figure 32.

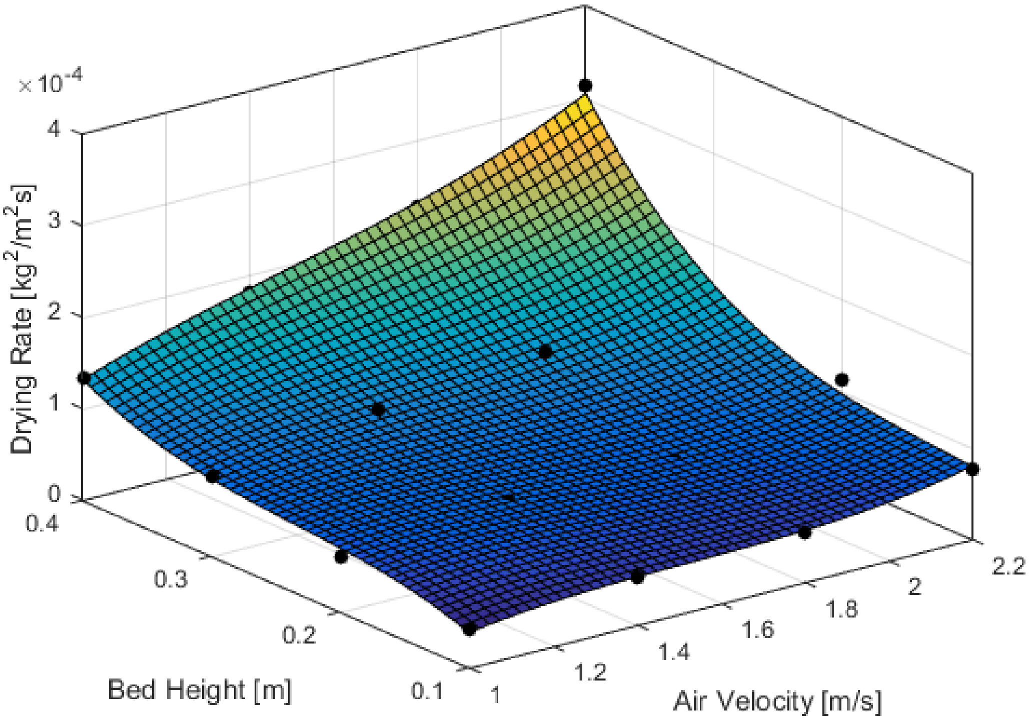

Figure 32: Drying rate fitted surface plot

The function obtained from the surface plot with air velocity on the x-axis and bed height on the y-axis was:

$$R_C = \begin{pmatrix} -(407.8)-(633.3)\cdot V+(2441)\cdot BH+(364.4)\cdot V^2-(989.4)\cdot V\cdot BH- \\ (8314)\cdot BH^2+(78.12)\cdot V^3+(43.75)\cdot V^2\cdot BH+(2426)\cdot V\cdot BH^2+8392\cdot BH^3 \end{pmatrix}\cdot 10^6 \quad (21)$$

This function can then be used to estimate the drying rate, which can then in turn be used to estimate the amount of moisture lost after a certain time passed. The third degree polynomial fit has a 95% coefficient confident bound and an R-square goodness fit of 0.9847.

To verify this model, it will be evaluated and compared to the experimental data. The moisture loss over a certain time period will be calculated using the fitted function and then compared to the experimental moisture loss. Table 7 presents the difference in results between the experimental moisture loss and the moisture loss determined by using the drying rate function in the constant drying period.

Table 7: Moisture loss calculation

Bed height [m]	Air velocity [m/s]	Theoretical drying rate [kg^2/m^{2}s]	Theoretical moisture loss [g]	Experimental moisture loss [g]	% error [%]
0.1	1	3.82E-05	14.60	15.80	8
0.1	1.4	5.23E-05	19.98	20.30	2
0.1	1.8	5.63E-05	21.47	21.50	0
0.1	2.2	8.00E-05	30.52	30.80	1
0.2	1	6.98E-05	26.66	24.30	-10
0.2	1.4	7.77E-05	29.65	27.50	-8
0.2	1.8	7.67E-05	29.29	30.30	3
0.2	2.2	9.70E-05	37.01	44.30	16
0.3	1	8.44E-05	32.20	33.50	4
0.3	1.4	1.05E-04	40.21	43.50	8
0.3	1.8	1.19E-04	45.40	51.70	12
0.3	2.2	1.55E-04	59.22	53.40	-11
0.4	1	1.32E-04	50.45	49.80	-1
0.4	1.4	1.86E-04	70.89	71.70	1
0.4	1.8	2.33E-04	89.04	85.10	-5
0.4	2.2	3.05E-04	116.36	124.70	7

From Table 7 it is evident that the largest percentage error is 16%, which is acceptable for this application as some accuracy was sacrificed to simplify the function. The model that the author in [9] developed, predicted the moisture content of the pellets at 3 to 60%. The model in this study therefore is more accurate in terms of moisture loss estimation.

To calculate the residence time for a specified moisture loss, the following equation is used. M_1 and M_2 are the initial and final moisture contents, and by using this equation the residence time t_R can then be solved:

$$t_R = \frac{W_p}{A_p \cdot R_c} \cdot (M_1 - M_2) \tag{22}$$

So to conclude, the mathematical model was created and can be implemented to calculate the drying rate at bed heights between 0.1 and 0.4 m and air velocities of between 1 and 2.2 m/s.

4.5. Conclusion

Estimates of the residence time to dry the weight of the moisture that was recorded in the experiments were made to see whether the constant drying rate can be applied to the drying that takes place in ambient air. Looking at the error percentage, it can be concluded that the drying rates can be used for this application. The constant drying rate can be used due to the fact that the drying only occurs in the constant rate, since only surface moisture is removed. It is assumed that no drying takes place during the falling rate period and if the air was hotter than the inside of the pellet, the moisture will go over into the falling drying rate stage. Furthermore the model the author in [9] created predicted a moisture content accuracy of between 3 to 60%, thus it can be said that the model created in this study performs better.

This model can then be used, as will be evident from the next chapter, to design a counterflow bed cooler/dryer. The drying rate can be estimated for different parameters and further calculations can then be done to design a dryer with dimensions for optimum drying.

The results were verified with literature, which indicated that the results are in line with previous literature in terms of the influence the different parameters has on the drying performance.

Chapter 5

Model based preliminary design

In this chapter, the system specification and design of the dryer will be discussed. This will include a discussion of the design parameters, dryer dimensions and the drying process design. The information that was collected from the results will be used to design a counterflow cooler.

5.1. Design parameters

In order to start to design a cooler/dryer, certain requirements and parameters must be specified. To specify these parameters, they must be understood and specified according to realistic limits. In this section, the design parameters are going to be discussed and the influence each has on the design of the dryer/cooler.

5.1.1. Percentage moisture loss required

The percentage moisture required can be specified to attain a certain final percentage of moisture content, or it can be specified to maximum moisture loss in five minutes. The moisture loss depends on the bed depth, air velocity, residence time, bed area and various material properties.

The results obtained illustrated the percentage moisture loss at various air velocities and product bed heights. These results can be used to predict at what bed depth or velocity the required moisture is optimized. However, other factors must also be taken into account and these factors will be discussed in the following sections.

5.1.2. Residence time

Residence time is the period of time that the product spends in the cooler/dryer bed. The specification of residence time is closely linked to the product flow of the process. An increased product flow rate at a constant bed area and bed height means a decrease in residence time, if the cooler/dryer operates at a continuous rate. If the bed area is increased at a constant product flow rate and bed height, the residence time will decrease. If the bed height is increased at a constant bed area and product flow rate, the residence time will increase.

To calculate the residence time for a certain moisture percentage loss at a specific bed height and air velocity, equation (22) can be used. After using this equation, a plot can be drawn at specific parameters and then a polynomial curve fit can be performed.

Another design factor to consider is the fact that the increase in bed depth decreases the cooling rate of the product. However, the product in all bed depths was cooled to within 5°C of ambient temperature at 300 s. Therefore it can be assumed that the temperature will not be considered after 300 s and that the bed depth will only vary between 0.1 m and 0.4 m.

5.1.3. Air velocity

As seen before, when the air velocity is increased, the rate and total of percentage of moisture loss increase. Air velocity can be a determining requirement if the plant only has a certain amount of air. However, if a certain velocity is not required, it is wise to use the velocity just below the minimum fluidization velocity, because this will ensure maximum drying performance and no mixing of the product. When a certain air flow is specified, a balance between area and height must be kept so that the velocity and power needed are the same.

To obtain the minimum fluidization velocity, the bed height value is needed. A chart can be drawn up to present the pressure drop, bed height and air velocity.

$$U_{mf} = \sqrt{\frac{4 \cdot d_p \cdot (\rho_s - \rho_a)}{3 \cdot \rho_a} + \frac{1}{0.4 + {}^{24}\!/_{\mathrm{Re}} + {}^{4}\!/_{\sqrt{\mathrm{Re}}}}} \tag{23}$$

$$\mathrm{Re} = \frac{V_{ai} \cdot \rho_a \cdot d_p}{\mu_a} \tag{24}$$

The pressure drop over the product bed can be attained by:

$$\Delta P_b = H_b \cdot (1 - \varepsilon) \cdot (\rho_s - \rho_a) \cdot \mathrm{g} \tag{25}$$

With

$$\varepsilon = 1 - \frac{W_p}{\rho_s \cdot A_b \cdot H_b} \tag{26}$$

as the bed height increases, the pressure also increases, while the air velocity decreases. Therefore, to ensure even air distribution one should rather increase the bed height to ensure an even airflow than to have a high velocity with an uneven airflow. Therefore it is most important to keep the air velocity below the fluidization velocity. Through the whole process, efficiency should always be kept in mind.

5.1.4. Bed height

As pointed out before, the product bed height does not have a significant impact on the drying rate and total moisture loss at a constant air velocity. Therefore, the consideration that must be kept in mind with bed height is that it influences the area. The higher the bed, the smaller the area needs to be to accommodate the needed residence time. As the bed height increases, the pressure drop increases. Therefore, more power is needed by the fan to produce the same speed making it more expensive. The bed height does however affect the efficiency of the process, because the higher the bed, the lower the efficiency. So the bed height can be optimized by examining the area and the efficiency.

An important consideration that must be taken into account is the fact that a large area with a low bed has much more potential for uneven air flow due to the small pressure drop. Therefore, it is wiser to choose a higher bed height, even though it affects the efficiency.

To summarize, the bed depth can be obtained by the area to height ratio. If area is not provided, the product flow will determine the bed height by using the residence time. A ratio of between 3 and 4 is used in the industry to determine bed depth and area.

5.1.5. Bed area

The bed area has no impact on the drying rate, but it does determine the bed height that is needed for a specific residence time. As the bed area increases, it can also have a negative impact on even airflow through the bed. To obtain even air distribution the pressure drop must be as high as possible. A good bed area to height ratio ensures a good airflow distribution over the bed. A ratio of 2-3 is usually used in the industry and has proven to achieve a good airflow distribution. Bed area can be calculated with the area to height ratio and the product flow will determine the area.

5.1.6. Other parameters

Other parameters such as the bulk density, particle density, and product rate have a significant impact on the drying rate. These parameters must be considered in the calculations and the percentage moisture loss rate.

5.2. Dryer dimensions

To obtain the appropriate bed area, the drying rate will be used to calculate the amount of product that can be dried to specification. The experimental results indicated that a 0.4 m bed height is ideal. The specification for drying might be 1% or 2% moisture loss according to the application of the maize pellets. The drying of the maize pellets to a certain specification depends on the bed depth and air velocity. The calculations were done in Microsoft Excel with input values from Matlab, these calculations can be seen in Appendix A.

Table 8 can be used as input parameters to determine what floor space area are needed to dry the product at a certain bed depth, air velocity and moisture content. However, the design for this study is based on only one bed depth and one air velocity. The design will adhere to the following specifications: (these specifications are for wet product entering the dryer).

Table 8: System specification

Specification	Value
Initial moisture content	12% kg moisture/kg dry product
Bed height	0.4 m
Air velocity	1.8 m/s
Material density	524 kg/m^3
Bulk density	200 kg/m^3
Pellet diameter	9 mm (±1 mm)

According to the specification, the area needed for optimum moisture loss is 2.083 m^2; which will be rounded down to 2.0 m^2 for ease of design. In order to simplify the design, it is best to design the dryer in a square cross section, as it will keep the manufacturing simpler and easier. By doing so, the side length will be 1.4 m.

5.3. Drying process

In this section the drying process will be specified according to the area, product flow, bulk density and residence time. The cooler was designed using a swivel valve bed that allows the product to be released at intervals in order to ensure even drying of the total product. This interval product height must be calculated when the timer is pre-set at 15 seconds on the valve to ensure even product flow though the dryer. A 15 second interval is used as this is an interval that was tried and tested by experienced process engineers and that is used in industry. 15 Seconds is enough to ensure even drying and gradual product flow.

The amount of product that must be dumped in each interval of 15 seconds to ensure a total product flow of 2 ton/h, must be calculated. By calculating this value, the researchers know how long the valve must be open at each interval. To evaluate whether the same amount of product is dropped each time, one must ensure that the height of the bed must be lowered by a certain value each time. Calculating this value is important to evaluate the amount of product dumped in each interval. The following equation is used:

$$W_i = \dot{m}_p t_i \tag{27}$$

Where W_i is the interval weight to be dumped, $\dot{m}_p$ is the product mass flow in kg/s and t_i is the interval time. To calculate the interval height, the following equation is used:

$$h_i = \frac{W_i \cdot A_b}{\rho_b} \tag{28}$$

Where h_i is the height of the product that must be dumped in each interval, A_b is the area of the bed and ρ_b the bulk density of the product. The interval height is calculated as 0.02 m and the weight of the product is 8.33 kg per interval.

The ideal air velocity will be just below fluidization air velocity, which is between 1.8 m/s and 2 m/s for a 0.4 m bed .The maximum optimum air flow is calculated using the following equation:

$$Q_a = V_a \cdot A_b \tag{29}$$

To conclude, the final process specification will be shown in Table 9.

Table 9: Final process specifications

Parameter	Value
Bed height	0.4 m
Air velocity	1.8 m/s
Interval time	15 sec
Weight per interval	8.33 kg
Height per interval	20 mm
Air flow rate	13500 m^3/h
Efficiency	41.72 g/kW
Total moisture loss	85.1 g/s
Kg/h/m^2	25 kg moisture/h/m^2
Drying rate	2.28E-04 kg/s or 820 g/h

5.4. Mechanical design

In this section, the mechanical design of the counterflow dryer/cooler will be discussed. This includes the final dimensions, materials and mechanism design.

It is important to ensure that airflow is at a relative constant speed through all the openings and ducts in order to reduce losses and friction in the dryer. Therefore, the air inlets, hopper inlets, product bed and air exits must be designed accordingly. As the bed that consists of perforated plate and has 3 mm diameter holes has an area of 2 m^2, the bed open area is 30% of the total area. This area was obtained in accordance with literature and previous designs. This equals an open area of 0.6 m^2. Thus the air inlets, hopper inlets and air outlet must be as close to this value as possible.

The dryer/cooler will consist mainly of sheet metal, as it has the necessary strength for the application of the dryer. It must be corrosion resistant, thus it should be made from stainless steel such as SS304, or it can be made with powder coated mild steel. The powder coated mild steel is the cheaper option that will be used for every component except the bed grid plate on which the product is loaded. The grid will be of SS304 that reduces the risk of corrosion and friction wear. A section view of the bed assembly can be seen in Figure 33.

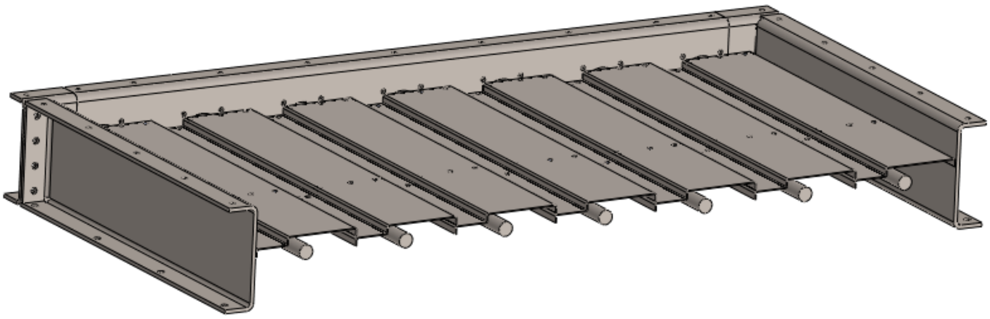

Figure 33: Cross section of the valve bed

The height of the shell in which the product is situated, is 1.2 m. Figure 34 illustrates a CAD rendering of a preliminary design of a counterflow cooler/dryer.

Figure 34: Final preliminary counterflow cooler/dryer design

5.5. Conclusion

As shown in this chapter, a complete process design can be done based on the results that were obtained. The main parameters that influence the operation and performance of the dryer/cooler and the way in which they were implemented in the design process, was discussed. The chapter also discussed how the performance is affected by a change in the main parameters.

The next chapter will discuss the conclusions derived from this study and recommendations for future study will be presented.

Chapter 6

Conclusions and recommendations

This chapter will include the conclusions obtained in this study and will make recommendations for further research. The conclusions are based on the results that were obtained and on whether or in what way these results solved the problem.

6.1. Conclusion

It can be concluded that the air velocity through the product bed and the product bed height do have an effect on the drying and moisture loss rate of extruded maize pellets. Furthermore this information can aid in the design of a counterflow cooler/dryer. The following information will describe the conclusions made on different subjects which all forms part of the solution to the problem.

6.1.1. Moisture loss rate

The total moisture lost from the product to the atmosphere increased as the bed depth increased due to the decreased cooling rate of the pellets and the increased amount of product in the bed.

The total moisture lost from the product to the atmosphere increased as the air velocity through the product bed increased. Moisture loss with increasing air velocity is mainly increased due to the increase in mass flow rate. Therefore, by increasing the air velocity, the moisture can leave the pellets faster. However, a faster air velocity does not influence the cooling rate of the pellet. This can be due to different flow patterns as the speed increases or because the velocity did not increase the heat transfer coefficient.

6.1.2. Drying efficiency

The efficiency measured in grams of moisture lost per kW of fan power increased as the product bed height and air velocity through the product bed increases.

6.1.3. Decreases temperature rate.

An increase in product bed height led to a decreased cooling rate of the pellets that allowed a longer time in which moisture could evaporate from the pellet surface. Moisture loss is mainly influenced by the decreased temperature cooling rate that allowed an increase in moisture lost in the process, resulting in increased evaporation.

Therefore, the conclusion that can be made is that the bed must stay warm for as long as possible to increase the moisture loss. This can take place when the bed depth is increased.

6.1.4. Experiments and research

By doing experiments, the drying rate has been obtained at various bed depths and air velocities, for only one time of 300 seconds. Thus, this research can only be used for these specifications presented in Table 10:

Table 10: Research limits

Parameter	Description
Residence time	300 s
Bed depth	0.1 to 0.4 m
Air velocity	1 to 2.2 m/s
Product	Maize extruded product
Ambient air temperature	18°C to 25°C

This research can account for different product densities and diameters of the same material than that used in the experiments. All tests were done at an ambient temperature of 18°C to 25°C. The results indicate that the ambient temperature for each test varies too little to draw conclusions on the effect the inlet temperature has on the drying and cooling process. The obvious effect that the air temperature is going to have is that as the temperature decreases, the pellets will cool down quicker. A speculation can be made that this will decrease the drying rate due to a lack of an evaporation period.

6.1.5. Modelling

This drying rate model can be used to ease the design process by using a simple function to estimate the drying rate at different bed heights and different air velocities. As many food machinery designers use their expert experience to design dryers, the information obtained in this study can help the designer to optimize the design for performance. The model, as indicated earlier, has a maximum error percentage of 16%, which is acceptable for this application. The error percentage is a result of the simplification that sacrifices the accuracy of the information.

The author in [9] did experimental tests and developed a model to estimate the moisture content and temperature of the pellets in a counterflow cooler. The model he developed, predicted the moisture content of the pellets at 3% to 60%. The model in this study has estimated moisture loss to 16% accuracy; therefore this model performs better than the model in [9].

6.1.6. Model based preliminary design

The results can be used for a preliminary design of a counterflow cooler, mainly based on the model created from the experimental data. A fully specified counterflow cooler has been designed and can be used in the industry. The information presented in the study can also predict the influence of parameter changes on the drying performance of a design cooler/dryer.

6.2. Recommendations for further work

Performing further experiments at higher air speeds and higher bed depths can provide more options for the parameters of the dryer that can increase the efficiency and drying rate even more. To perform tests at a higher test bed, additional financial assistance, that was not available during the experiments that were performed for this study, is needed. It is recommended that further tests must be done to investigate the effect that the perforated plate holes has on the drying rate of the maize pellets. The effect that different air temperatures have on this type of dryer should also be examined.

The model used can be improved by accounting for mass and heat transfer that will increase the complexity of the model, but also the accuracy.

The experimental method accuracy can be increased by using more accurate and faster processing equipment and instruments.

6.3. Closure

Experimental tests were done to obtain data for the effect air velocity and bed height has on the drying rate of extruded maize pellets. The data was then processed and presented into information can aid the design of a counterflow cooler/dryer. The information includes the optimum parameters for optimum drying rate and the drying rate model at various air velocities and bed heights. Thus this information can help to design a counterflow cooler and dryer for optimum energy efficiency at several parameters. If a cooler/ dryer is already manufactured this information can help to improve efficiency and estimate the drying rate of the extruded maize pellets.

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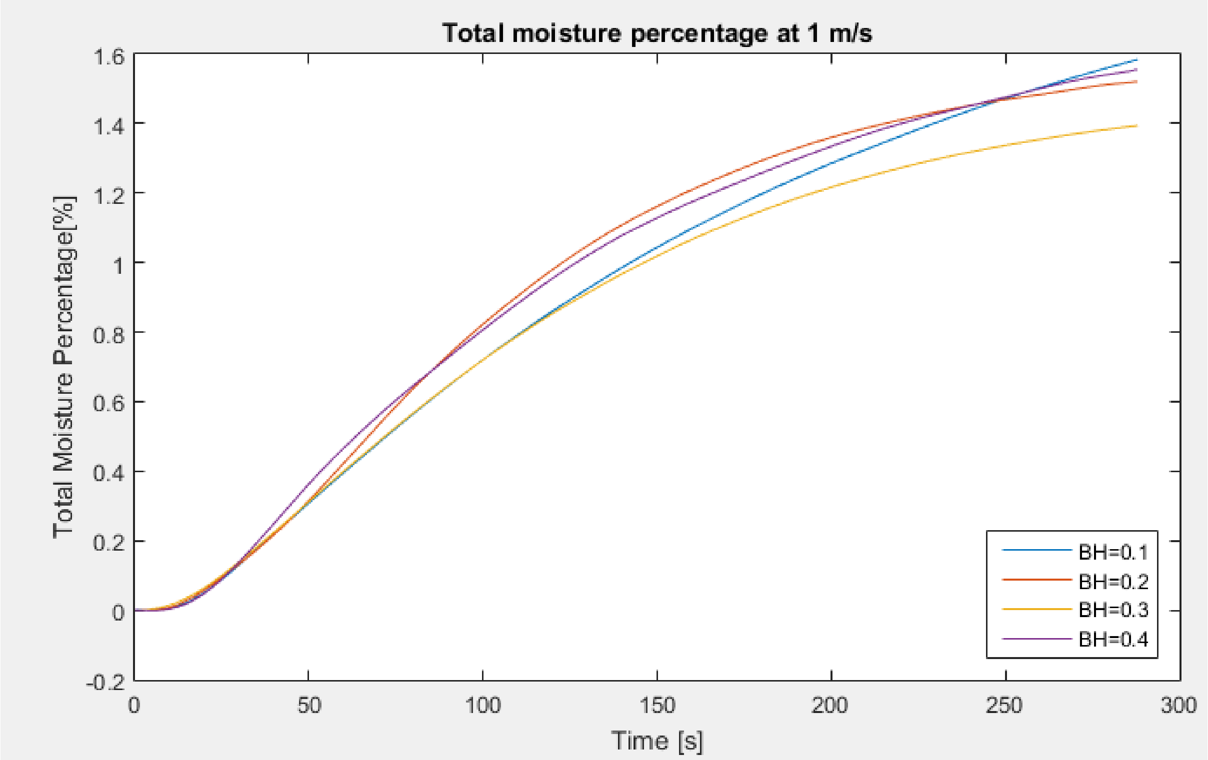
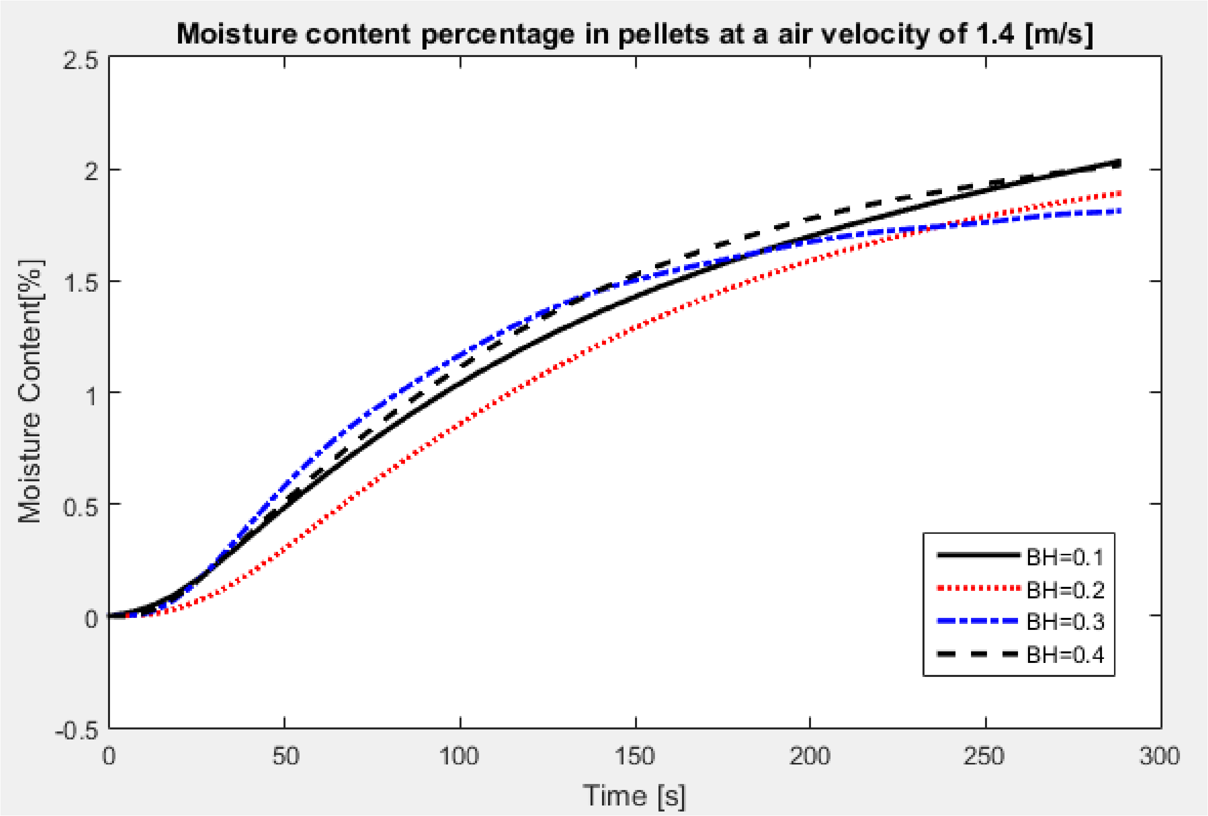
Appendices

Not all information is given, this is just part of the calculations done to present an idea what calculations have been done and what software was used.

A. Matlab results




Moisture content percentage in pellets at a air velocity of 1.4 [m/s]
Moisture Content[%]
2.5
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
Time [s]
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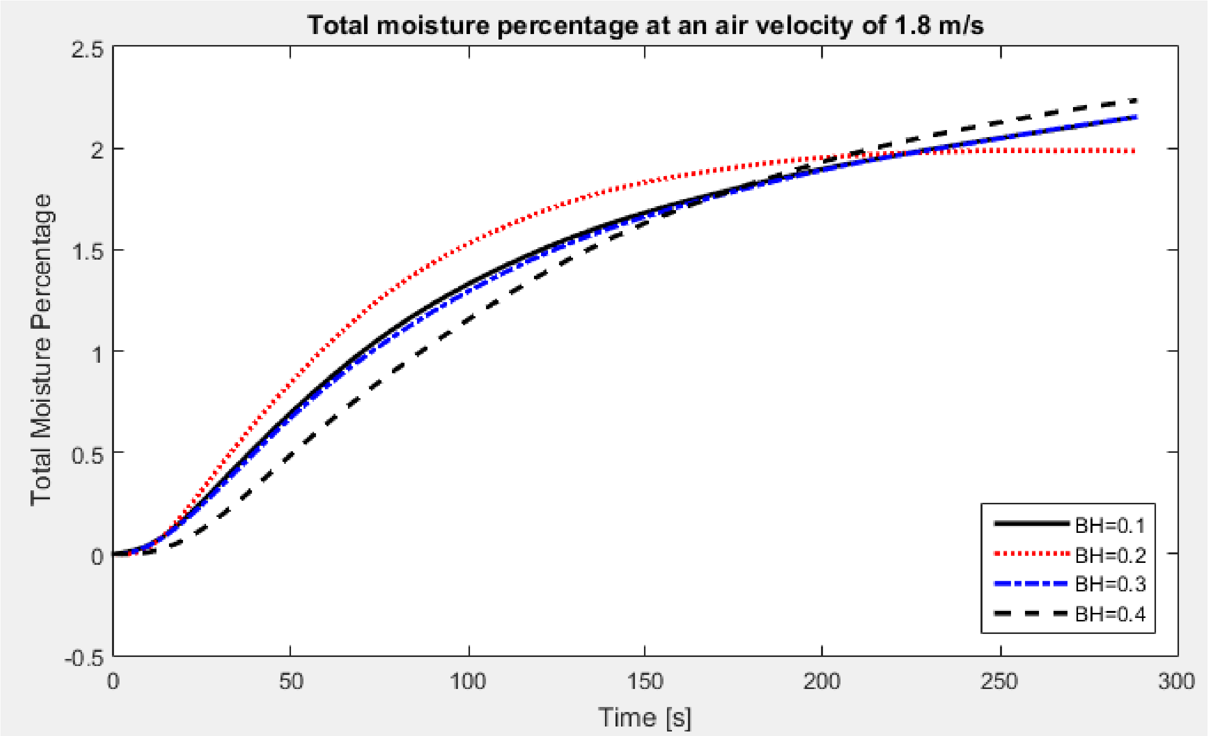
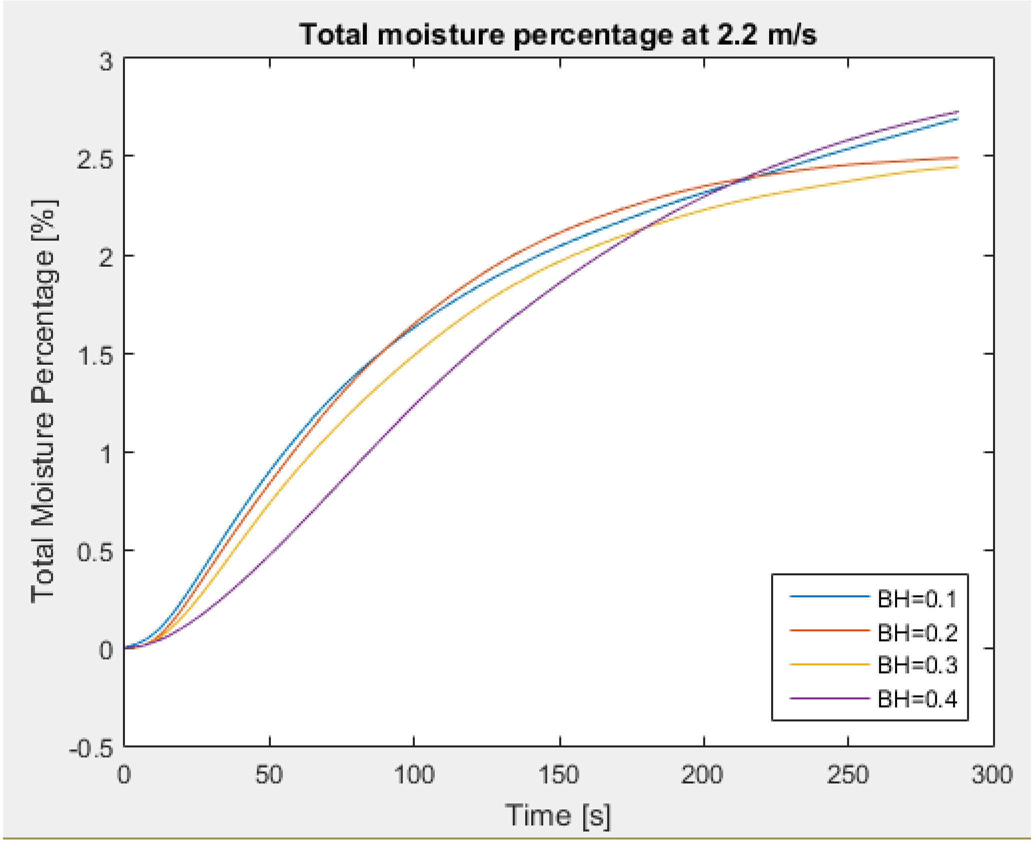
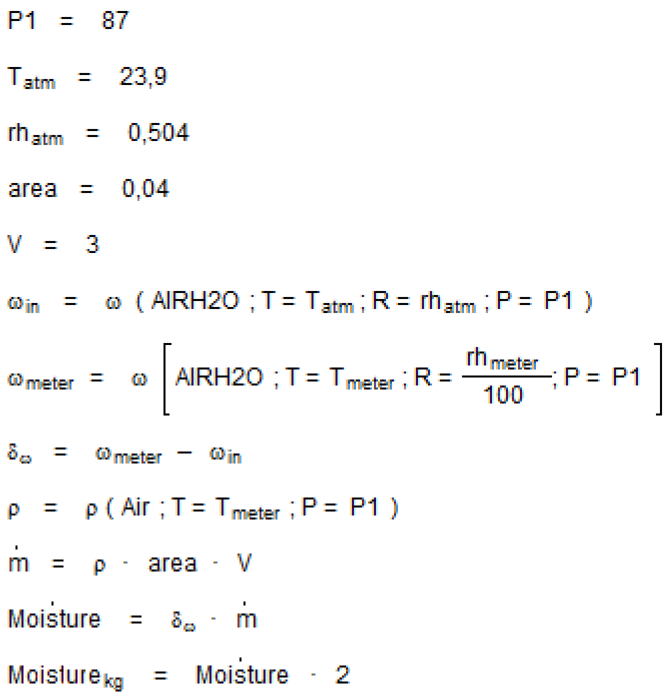
BH=0.2
BH=0.3
BH=0.4


Total moisture percentage at an air velocity of 1.8 m/s
Total Moisture Percentage
2.5
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
Time [s]
BH=0.1
BH=0.2
BH=0.3
BH=0.4


Total moisture percentage at 2.2 m/s
Total Moisture Percentage [%]
3
2.5
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
Time [s]
BH=0.1
BH=0.2
BH=0.3
BH=0.4

B. Engineering Equation Solver (EES) results processing



$P1 = 87$

$T_{atm} = 23{,}9$

$rh_{atm} = 0{,}504$

$area = 0{,}04$

$V = 3$

$\omega_{in} = \omega\ (\ AIRH2O\ ;T = T_{atm}\ ;R = rh_{atm}\ ;P = P1\ )$

$\omega_{meter} = \omega \left[AIRH2O\ ;T = T_{meter}\ ;R = \frac{rh_{meter}}{100};P = P1 \right]$

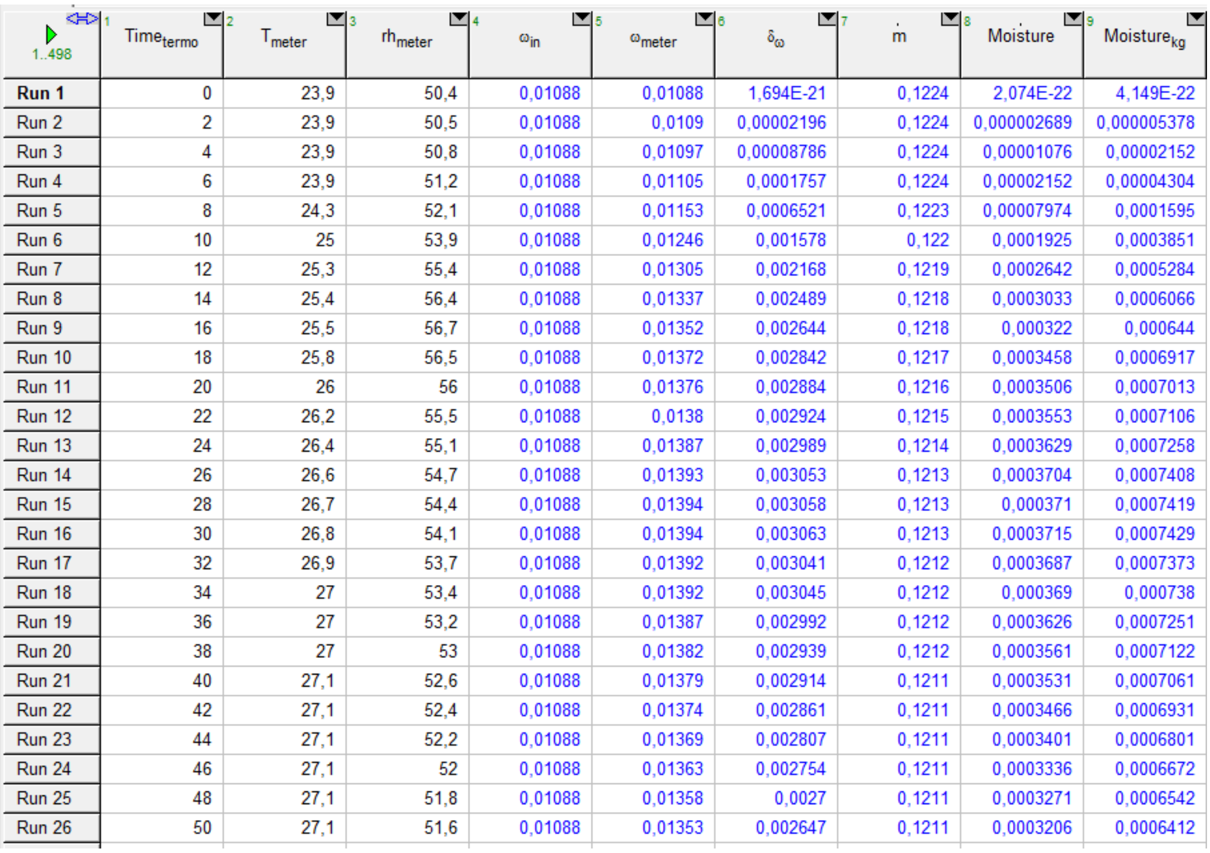
$\delta_\omega = \omega_{meter} - \omega_{in}$

$\rho = \rho\ (\ Air\ ;T = T_{meter}\ ;P = P1\ )$

$\dot{m} = \rho \cdot area \cdot V$

$\dot{Moisture} = \delta_\omega \cdot \dot{m}$

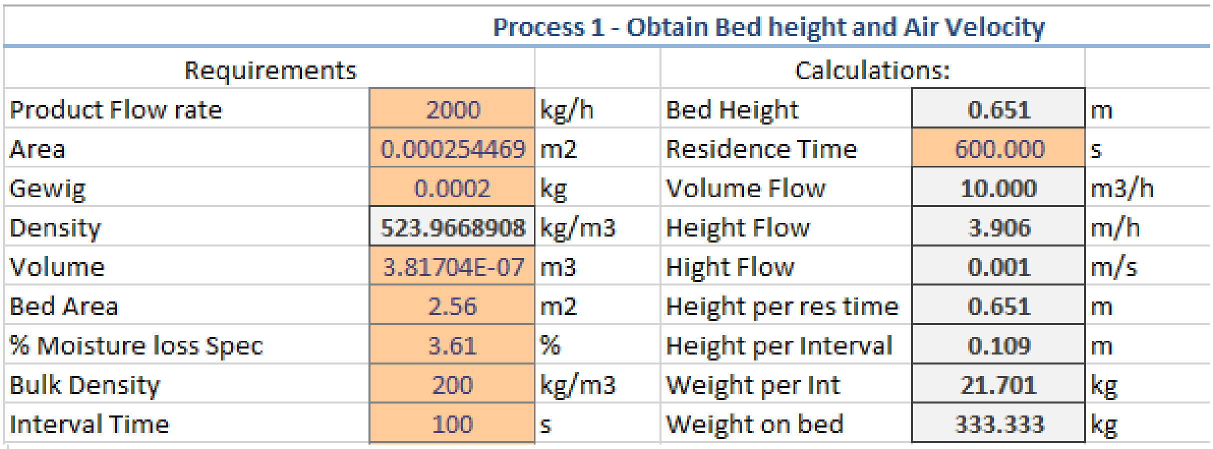
$Moisture_{kg} = \dot{Moisture} \cdot 2$



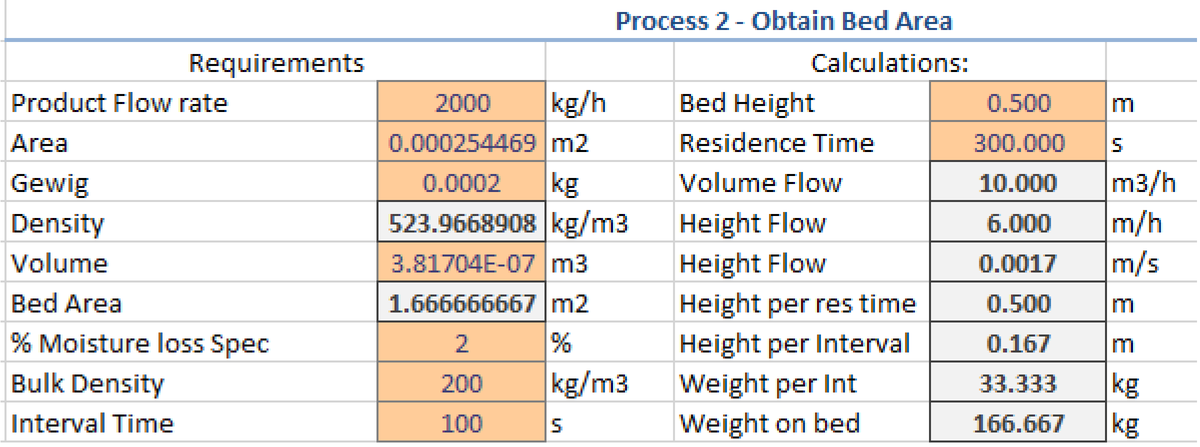
1..498	$Time_{termo}$	T_{meter}	rh_{meter}	ω_{in}	ω_{meter}	δ_ω	$\dot{m}$	$\dot{Moisture}$	$Moisture_{kg}$
Run 1	0	23,9	50,4	0,01088	0,01088	1,694E-21	0,1224	2,074E-22	4,149E-22
Run 2	2	23,9	50,5	0,01088	0,0109	0,00002196	0,1224	0,000002689	0,000005378
Run 3	4	23,9	50,8	0,01088	0,01097	0,00008786	0,1224	0,00001076	0,00002152
Run 4	6	23,9	51,2	0,01088	0,01105	0,0001757	0,1224	0,00002152	0,00004304
Run 5	8	24,3	52,1	0,01088	0,01153	0,0006521	0,1223	0,00007974	0,0001595
Run 6	10	25	53,9	0,01088	0,01246	0,001578	0,122	0,0001925	0,0003851
Run 7	12	25,3	55,4	0,01088	0,01305	0,002168	0,1219	0,0002642	0,0005284
Run 8	14	25,4	56,4	0,01088	0,01337	0,002489	0,1218	0,0003033	0,0006066
Run 9	16	25,5	56,7	0,01088	0,01352	0,002644	0,1218	0,000322	0,000644
Run 10	18	25,8	56,5	0,01088	0,01372	0,002842	0,1217	0,0003458	0,0006917
Run 11	20	26	56	0,01088	0,01376	0,002884	0,1216	0,0003506	0,0007013
Run 12	22	26,2	55,5	0,01088	0,0138	0,002924	0,1215	0,0003553	0,0007106
Run 13	24	26,4	55,1	0,01088	0,01387	0,002989	0,1214	0,0003629	0,0007258
Run 14	26	26,6	54,7	0,01088	0,01393	0,003053	0,1213	0,0003704	0,0007408
Run 15	28	26,7	54,4	0,01088	0,01394	0,003058	0,1213	0,000371	0,0007419
Run 16	30	26,8	54,1	0,01088	0,01394	0,003063	0,1213	0,0003715	0,0007429
Run 17	32	26,9	53,7	0,01088	0,01392	0,003041	0,1212	0,0003687	0,0007373
Run 18	34	27	53,4	0,01088	0,01392	0,003045	0,1212	0,000369	0,000738
Run 19	36	27	53,2	0,01088	0,01387	0,002992	0,1212	0,0003626	0,0007251
Run 20	38	27	53	0,01088	0,01382	0,002939	0,1212	0,0003561	0,0007122
Run 21	40	27,1	52,6	0,01088	0,01379	0,002914	0,1211	0,0003531	0,0007061
Run 22	42	27,1	52,4	0,01088	0,01374	0,002861	0,1211	0,0003466	0,0006931
Run 23	44	27,1	52,2	0,01088	0,01369	0,002807	0,1211	0,0003401	0,0006801
Run 24	46	27,1	52	0,01088	0,01363	0,002754	0,1211	0,0003336	0,0006672
Run 25	48	27,1	51,8	0,01088	0,01358	0,0027	0,1211	0,0003271	0,0006542
Run 26	50	27,1	51,6	0,01088	0,01353	0,002647	0,1211	0,0003206	0,0006412

C. Excel result processing

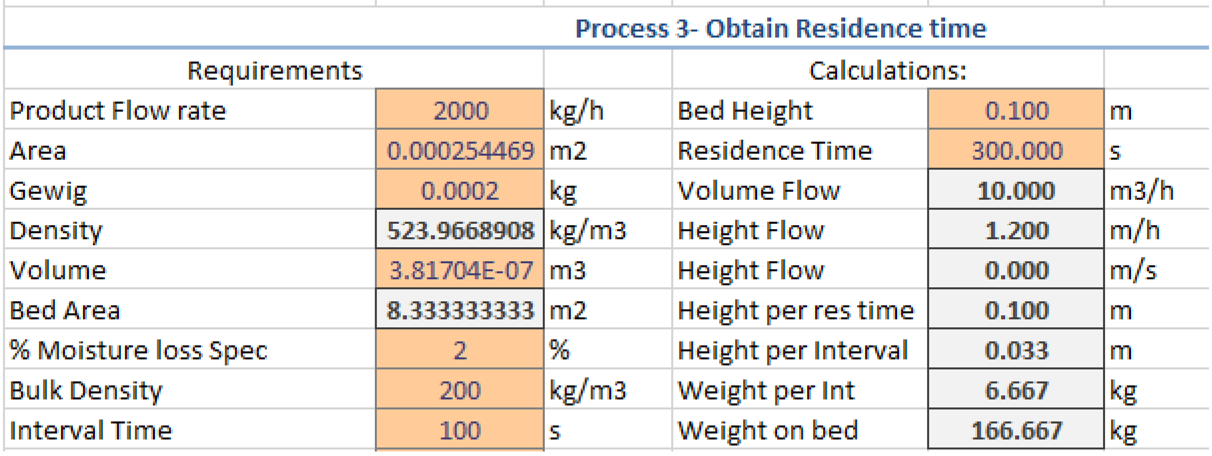
Bed Height [m]	Air velocity [m/s]	Drying rate [kgM/s]	Moisture lost in 5min [gM]	Moisture loss in hour [gM/h]	Max % moistur	kgM/h/n	Min Area needed [m2] for 2%	Min Area needed [m2] for 1%	Area for max Moisture lo	kgProdu	2% Moistur	Ty	kgProduct/ h/m2
0.1	1	3.82E-05	15.80	189.60	1.98%	4.74		4.219409283	8.333333333	0.8	16	303.8	237
0.1	1.4	5.23E-05	20.30	243.60	2.54%	6.09	6.568	3.28407225	8.333333333	0.8	16	236.45	304.5
0.1	1.8	5.63E-05	21.50	258.00	2.69%	6.45	6.202	3.100775194	8.333333333	0.8	16	223.26	322.5
0.1	2.2	8.00E-05	30.80	369.60	3.85%	9.24	4.329	2.164502165	8.333333333	0.8	16	155.84	462
0.2	1	6.98E-05	24.30	291.60	1.52%	7.29	5.487	2.743484225	4.166666667	1.6	32	395.06	364.5
0.2	1.4	7.77E-05	27.50	330.00	1.72%	8.25	4.848	2.424242424	4.166666667	1.6	32	349.09	412.5
0.2	1.8	7.67E-05	30.30	363.60	1.89%	9.09	4.400	2.200220022	4.166666667	1.6	32	316.83	454.5
0.2	2.2	9.70E-05	44.30	531.60	2.77%	13.29	3.010	1.504890895	4.166666667	1.6	32	216.7	664.5
0.3	1	8.44E-05	33.50	402.00	1.40%	10.05	3.980	1.990049751	2.777777778	2.4	48	429.85	502.5
0.3	1.4	1.05E-04	43.50	522.00	1.81%	13.05	3.065	1.53256705	2.777777778	2.4	48	331.03	652.5
0.3	1.8	1.19E-04	51.70	620.40	2.15%	15.51	2.579	1.289490651	2.777777778	2.4	48	278.53	775.5
0.3	2.2	1.55E-04	53.40	640.80	2.23%	16.02	2.497	1.248439451	2.777777778	2.4	48	269.66	801
0.4	1	1.32E-04	49.80	597.60	1.56%	14.94	2.677	1.338688086	2.083333333	3.2	64	385.54	747
0.4	1.4	1.86E-04	71.70	860.40	2.24%	21.51	1.860	0.929800093	2.083333333	3.2	64	267.78	1075.5
0.4	1.8	2.33E-04	85.10	1021.20	2.66%	25.53	1.567	0.783392088	2.083333333	3.2	64	225.62	1276.5
0.4	2.2	3.05E-04	124.70	1496.40	3.90%	37.41	1.069	0.534616413	2.083333333	3.2	64	153.97	1870.5



Process 1 - Obtain Bed height and Air Velocity					
Requirements			Calculations:		
Product Flow rate	2000	kg/h	Bed Height	0.651	m
Area	0.000254469	m2	Residence Time	600.000	s
Gewig	0.0002	kg	Volume Flow	10.000	m3/h
Density	523.9668908	kg/m3	Height Flow	3.906	m/h
Volume	3.81704E-07	m3	Hight Flow	0.001	m/s
Bed Area	2.56	m2	Height per res time	0.651	m
% Moisture loss Spec	3.61	%	Height per Interval	0.109	m
Bulk Density	200	kg/m3	Weight per Int	21.701	kg
Interval Time	100	s	Weight on bed	333.333	kg



Process 2 - Obtain Bed Area					
Requirements			Calculations:		
Product Flow rate	2000	kg/h	Bed Height	0.500	m
Area	0.000254469	m2	Residence Time	300.000	s
Gewig	0.0002	kg	Volume Flow	10.000	m3/h
Density	523.9668908	kg/m3	Height Flow	6.000	m/h
Volume	3.81704E-07	m3	Height Flow	0.0017	m/s
Bed Area	1.666666667	m2	Height per res time	0.500	m
% Moisture loss Spec	2	%	Height per Interval	0.167	m
Bulk Density	200	kg/m3	Weight per Int	33.333	kg
Interval Time	100	s	Weight on bed	166.667	kg



Process 3- Obtain Residence time					
Requirements			Calculations:		
Product Flow rate	2000	kg/h	Bed Height	0.100	m
Area	0.000254469	m2	Residence Time	300.000	s
Gewig	0.0002	kg	Volume Flow	10.000	m3/h
Density	523.9668908	kg/m3	Height Flow	1.200	m/h
Volume	3.81704E-07	m3	Height Flow	0.000	m/s
Bed Area	8.333333333	m2	Height per res time	0.100	m
% Moisture loss Spec	2	%	Height per Interval	0.033	m
Bulk Density	200	kg/m3	Weight per Int	6.667	kg
Interval Time	100	s	Weight on bed	166.667	kg