Effect of product distribution geometry on drying of extruded maize pellets

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It all starts here ™

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Abstract

In the drying of foodstuffs it is preferable that the product should be spread out flat and uniformly on the bed in order for the air to pass evenly through the product, ensuring uniform drying. However, many types of dryers distribute the product non-uniformly on the bed. This can cause some of the product to be over-dried or burnt while the rest is still too moist to be packaged.

The problem therefore is to investigate the effect that the geometry of the product on the bed has on the drying of the product and secondly to make recommendations on the preferred floorplate length of a multi-level vertical dryer to dry the product under investigation satisfactorily.

In order to investigate the effect that the product distribution geometry has on drying, two types of tests were done in which extruded maize product was dried under different conditions. For the first type, a non-uniform product bed geometry was dried at various air temperatures and air velocities. For the second type, the geometry was varied while keeping the air temperature and air velocity constant. With each test, samples for moisture analysis were taken before as well as after drying at the bed's ridge, centre and valley.

The experiments showed that drying at a higher temperature produces greater moisture removal from the product compared to drying at lower temperatures. In general the higher the air temperature is, the drier the product will be, provided that case hardening does not occur. The tests conducted showed that the difference in moisture content between the product at the ridge and the product at the valley increases as the air temperature increases. It was found that the higher the air velocity, the lower the product's moisture content will be after drying. The difference in moisture content between the product at the ridge and the product at the valley is less if the product has been dried at a high air velocity compared to when the product has been dried at a lower air velocity. It was found that the further the distance is between the ridge and the valley, that is, the greater the amplitude is, the larger the difference will be between the moisture content at the ridge and the moisture content at the valley. This means that the lower the amplitude, the more uniform the bed geometry is. It was also found, however, that uniform drying can occur even though the geometry of the product on the bed is not uniform, provided that the amplitude is equal to or smaller than the maximum amplitude for uniform drying.

If it is known how the air temperature and air velocity will affect the drying of the product, the dryer can be set up to dry the product successfully within the acceptable tolerance of the desired final moisture content, despite the fact that the product bed geometry is non-uniform. Furthermore, the difference in moisture content is dependent on the floorplate length of the multi-level dryer. This means the floorplate length needed to dry the product to a certain tolerance can be calculated beforehand and the dryer designed accordingly.

Keywords: Dryer bed geometry, Floorplate length, Maize product, Moisture content, Multi-level dryer.

Table of Contents

I. List of figures

II. List of tables

III. Nomenclature

Symbol	Description	Units
Γ	Unaccomplished moisture ratio	-
Δm	Difference in moisture content	%
Δm_{pct}	Difference in moisture content expressed as a percentage of the moisture content before drying	%
θ	Angle of repose	Deg
λ	Wavelength	mm
A	Amplitude	mm
a_w	Water activity	-
$c_{w,\infty}$	Water vapour concentration in the free stream air	kg m^{-3}
$c_{w,sat}$	Water vapour concentration in the air at the surface of the wet bulb thermometer	kg m^{-3}
D_{eff}	Effective moisture transfer diffusion coefficient	m^2/s
H_0	Height of the valley in the bed	mm
H	Height of the product on the bed	mm
l	Floorplate length	mm
L_0	Characteristic half-thickness	m
m_{before}	Moisture content before drying	%
$m_{largest}$	Largest moisture content	%
m_{ridge}	Moisture content at the ridge	%
$m_{smallest}$	Lowest moisture content	%
m_{valley}	Moisture content at the valley	%
p_{sat}	Saturation pressure	kPa
r	Radius of extruded maize pellet	mm
RH	Relative humidity of air	%
R_w	Ideal gas constant for water vapour	J/kg-K
t	Time	s
T_∞	Free stream air temperature	^{o}C
T_{wb}	Wet-bulb temperature	^{o}C
x	Horizontal position in the bed	mm
y	Vertical position	mm

1. Introduction

This chapter provide some background information, the problem statement and discusses the objectives of the project. It also gives the methodology and the scope, discuss the deliverables and finally present the dissertation layout.

1.1. Background

Drying is one of the most commonly used methods of preserving food. Several methods are available to dry various types of food. One of the most common methods is the passing of high-temperature, low-humidity air through a product bed [1]. In doing this, the moisture in the product is taken up by the air passing through, thus leaving the product drier and the exiting air slightly colder and more humid [2].

For this specific method of drying there are numerous types of dryers. One of these is the multi-level vertical dryer. This dryer consists of any number of floors or levels, each containing a specified amount of product to be dried. The product enters from above, thus the top floor. After a pre-set amount of time, each level's bottom opens, allowing the product to fall through to the next level, while the hot, dry air continually flows through the product beds. This process continues until the product reaches the final level.

The point of interest, for this study, is the geometry that the product adopts on the beds upon falling through a floor. For this particular dryer design, each floor consists of a number of floorplates that are aligned next to one another to, together, form the floor. When the time has come for the product to fall through to the next level, each floorplate pivots around its centre, allowing the product to fall through. The result is that, on the next level, the product distribution geometry will not be flat, but will consist of ridges and valleys.

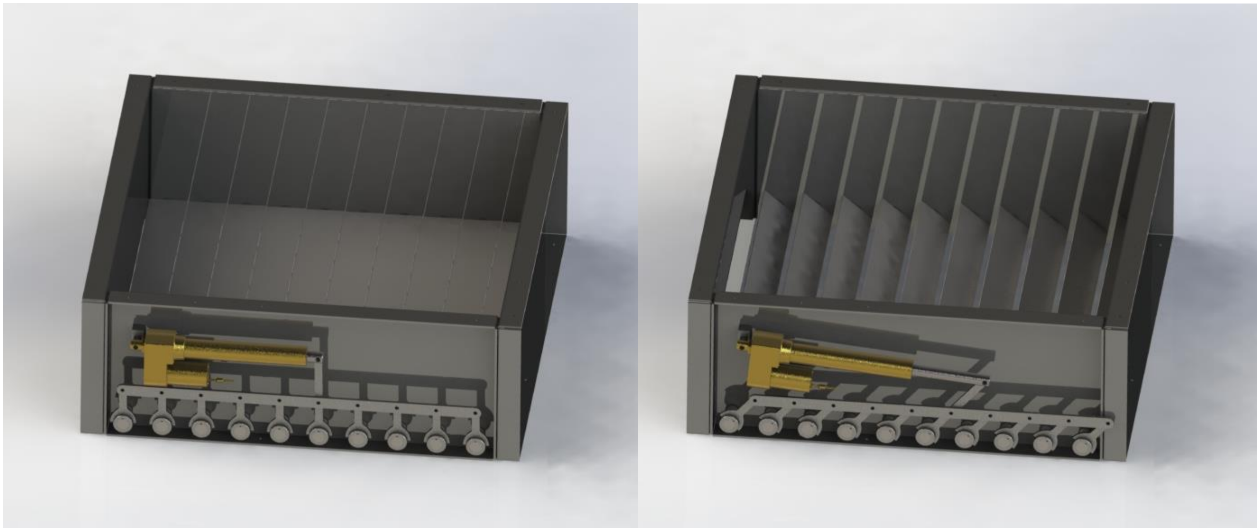

Figure 1 - The proposed floorplate concept with the floor closed (left) and opened (right)

This non-uniform geometry of product on the bed will affect the drying of the product, since not all of the product experiences the same drying conditions.

1.2. Problem statement

When drying food products, it is ideal for the distribution of product on the bed to be flat and uniformly spread to allow the passing air to move evenly through the product, ensuring each bit of product undergoes the same drying conditions and ultimately has the same drying curve. However, many dryers or drying systems make it impossible for the product to be flat and uniformly spread.

Non-uniform distribution of product on the bed might lead to different bits of products experiencing different conditions and ultimately having different drying curves. The variation in the geometry of the product on the bed can have such a large effect on the drying curves that the method of drying may be declared unsatisfactory.

The problem therefore is to investigate the effect that the geometry of the product on the bed has on the drying of the product and secondly to make recommendations on the preferred floorplate length to dry the product under investigation satisfactorily.

1.3. Objective of the project

The objective of this project is to investigate a dryer in which this product, distributed on the product bed, does not have a flat geometry and to investigate the effect of the varying air temperature and air velocity experienced by the product at various positions within the product on the bed. This will then determine whether a typical distribution of product on a multi-level dryer's product bed produces a sufficiently dried product.

To achieve this objective, the following tasks are defined:

- Investigate the relevant literature
- Conduct experimental investigation
- Do data processing on the results obtained
- Determine the effect of the geometry on the drying of the product
- Determine possible floor-plate lengths based on the results presented

The methodology for each of these tasks is discussed below.

1.4. Methodology

The methodology gives an outline of the steps to be taken to achieve the objective of the project described in Section 1.3.

1.4.1. Investigation of the relevant literature

A broad background of the drying industry and all its relevant components needs to be established. Studying the relevant literature gives insight to enable the researcher to provide possible solutions to the problem statement.

1.4.2. Experimental investigation

An experimental investigation is required to confirm or contradict hypotheses made about the drying of the specified product bed geometry.

1.4.3. Data processing of the results obtained

The results obtained during the experimental investigation need to be processed so that a logical and relevant conclusion that addresses the problem statement can be derived.

1.4.4. Determination of the effect of the geometry on the drying of the product

The effect that the geometry of the product bed has on drying can be determined by analysing the processed results. The effect that the air temperature and air velocity have on the different locations, or positions, in the product bed is also presented.

1.4.5. Determination of possible floorplate lengths based on the results presented

A relationship between the difference in moisture content in a single product bed and the floorplate length is determined, making it possible to identify a floorplate length beforehand that will deliver a desired difference in moisture content.

1.5. Scope

Neglecting to consider the effect that the product distribution geometry has on drying kinetics could lead to some product being over-dried after the pre-calculated drying time, while the rest is still too moist to be packaged [3]. Simply assuming the drying kinetics to be the same as for a flat, uniform distribution of product on the bed is erroneous [4]. An over- or under-dried product can influence the quality of the product and the consumer might choose not to purchase this product, leading to financial loss.

This research will focus on the effect of a ridge-and-valley type product distribution geometry. The research does not give a solution to all possible geometries. It will only consider the product distribution geometry explained in Section 4 and conclude whether this typical product geometry for a multi-level dryer dries a maize-based product sufficiently.

Figure 2 - The geometry of the product on the bed

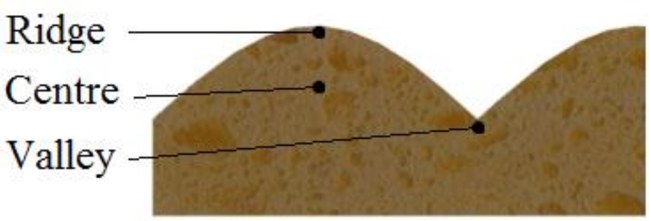

Figure 3 - Positions where samples were taken during testing

The product used during these tests is extruded maize puffs of spherical form. It is assumed that the slight variations in the product size will have a negligible effect on the results presented in this dissertation.

1.6. Deliverables

After completion of this project, the designer of dryers will have a very good guideline as to the effect of the product distribution geometry on drying. It will be easy to identify a floorplate length that will deliver a desired difference in moisture content within the product bed. The air temperature and air velocity needed for the product to have a certain moisture content can also easily be determined.

For an already existing dryer, it can be determined if the parameters of the drying process can simply be altered to still deliver the product as dry as required, or if the product distribution geometry produced by this dryer simply will not dry as the costumer requires.

1.7. Dissertation layout

The first of what may be expected further in this dissertation is the literature study. The literature study looks at relevant literature and builds a background to understand the drying of foodstuffs better.

The literature study provides indicators as to what exactly drying or dehydration is and why food is dried. It explains what problems may be encountered if drying is not done sufficiently and consider the most popular methods of drying. Emanating from the different methods of drying, the literature study discusses numerous types of dryers and their functioning. Bringing the literature closer to the multi-level dryer's product bed geometry, the literature study examines case hardening and then heat and mass transfer during drying. Finally, the effect that the product bed depth has on drying is discussed.

Following the literature study, the test method is explained. The set-up of the test bench is briefly discussed, where after the test procedure is laid out step by step.

The geometry of the product on the bed is thoroughly discussed. The shape is mentioned, the reason why the product has taken on this shape and the equation describing the shape. It is also hypothesised when the height of the ridge relative to the valley is small enough to assume uniform drying throughout the bed.

After the geometry of the product on the bed has been discussed, the results obtained during the experimental investigation are provided. It is firstly explained how the results were processed, where after the measured results are provided. In the next sub-section, the results are interpreted, both regarding various air temperatures and velocities with a constant geometry amplitude, as well as constant air temperatures and velocities with various geometry amplitudes. In the final sub-section, a proposed concept design for a multi-level dryer, designed with careful consideration of observations made from the results, is presented.

In the section on conclusion and recommendations, some conclusions are derived from the work presented and recommendations for future research are made.

1.8. Conclusion

The introduction gave a thorough understanding of the outcome expected of the project and also gave insight into the type of dryer used, along with the product bed geometry it produces. This information is needed to understand the approach used and the results attained later.

Other information that is also crucial in understanding the methodology of the project is the literature study. Chapter 2 gives the findings of other researchers' work in this field.

2. Literature study

This chapter consists of selections of other researchers' work that has previously been published. This work is in the same field and refers to knowledge already available, as well as giving insight into new research.

2.1. What is drying or dehydration?

Drying or dehydration is one of the oldest methods of food processing. At first, only the sun was used to dry food, but later other processes of dehydration, e.g. fire, heated air etc., were also used. Drying is removal of water from the product in an uncontrolled environment. This procedure depends on the availability of sun energy. It is fairly inexpensive, but requires a large space for the product to be spread out and the food can easily be contaminated by insects, birds, animals and humans. Dehydration, on the other hand, is the removal of water from the product in a controlled environment. Conditions such as temperature, air flow, humidity and resident time are carefully monitored [5].

In dehydration, water is removed from the food by hot air dryers, e.g. cabinet, tunnel, conveyer and fluidised bed dryers, or by heated surface dryers, e.g. drum and vacuum shelf dryers. As water on the surface of the product evaporates, it is replaced by water migrating from the inside of the product. This movement of water within the product is achieved by means of several mass transfer mechanisms. Ultimately, the total water content and water activity (a_w) within the product reduces. The drying process not only dehydrates the product, but also reduces its weight and bulk, which reduces packaging and transportation costs. Dehydration also has a great effect on the sensory properties of food, and certain dehydrated foods are reconstructed with water before consumption, such as powdered milk or vegetables in a soup mix.

Sublimating the water inside the food is another method of drying, called freeze-drying. Sublimating means that water goes directly from the solid phase to the gas phase, skipping the liquid phase. Foods that are freeze-dried have superb sensory and nutritive qualities in comparison to products dried by other dehydrating methods [6] because it does not affect the heat labile components of the product.

2.2. Why dry food products?

The search for methods to preserve food has continued since the dawn of human civilization. To survive harsh winters, people would have to find some methods of ensuring that there would be plentiful food in seasons when no fresh fruit or vegetables were available [7].

The purpose of drying food is to prevent microbial growth and chemical deterioration through the removal of water activity (a_w), hence prolonging the food's shelf life, and also to improve ease of storage, packaging and transportation [5].

All food can be spoiled by food microorganisms or through enzymatic reactions within the food itself. A sufficient amount of moisture is required around bacteria, yeast and moulds for them to grow and cause spoilage. By reducing the moisture content of food, these spoilage-causing microorganisms are prevented from growing and the process slows down enzymatic reactions that take place within the food. All these processes help to prevent the spoilage of food [8].

2.3. Problems encountered when drying is not done sufficiently

In dry food, food with a water activity (a_w) < 0.9, bacteria will generally not play an important role in the spoilage of the food. At 0.8 < a_w < 0.85, spoilage is by fungi. With a decrease in a_w, the spoilage is also delayed or retarded. Food can be stored for several years without spoilage with 0.65 < a_w < 0.75. The shrinkage of food during drying, although sometimes desired, can be a problem if it is undesired and the drying is not done correctly. Along with this, browning of food and case hardening due to more rapid evaporation of water at the surface than diffusion from the inside can also occur. This case hardening forms a hard shell on the outer skin of the product that not only reduces the value of the food, but may also trap moisture inside the food that supports the growth of both pathogenic and non-pathogenic bacteria [5].

2.4. Methods of drying

There are various means of dehydrating foods: the sun, a conventional oven, an electric dehydrator or a microwave oven. Like other preservation methods, drying requires energy. The energy related cost of dehydrating food is higher than for canning and often more expensive than freezing, sun-drying excluded [9].

Solar drying is an adaptation of sun drying. The sun's rays are collected in a specialised unit with sufficient ventilation for the removal of moist air. Inside the unit the temperature is usually 20 to 30^{O}C higher than in open sunlight, resulting in a shorter drying time. Although solar drying is already considerably more efficient than sun drying, lack of control over the weather is still a major factor to be kept in mind. Areas with little sunlight through the year are not suitable for sun or solar drying, as it is likely that the food will go sour or mouldy before the drying is completed.

The most practical way to experiment with dehydration is oven-drying. It does not depend on the weather, protects the food from insects and dust and requires little initial investment. Unfortunately, ovens are not very cost-effective, as they require a lot of energy. Food also tends to scorch after a while, as it is difficult to maintain a low drying temperature. Oven-dried food tends to be darker, more brittle and less tasty than food dried in a dehydrator.

An electric dehydrator is a self-contained unit with a heat source and ventilation system. These systems are used for drying indoors, and are not dependent on weather conditions. Initially, it is a high-investment purchase, but it uses less energy than an oven, which saves on monthly expenses. Compared to any other method of drying, the quality of dehydrated foods dried in an electric dehydrator is best [10].

2.5. Different types of dryers

Numerous different types of dryers are available. This section serves to mention and briefly describe a few of the most common ones.

2.5.1. Indirect dryers

Indirect dryers, as described in a definition by Hall [11], are dryers where the medium of heating (e.g. heated gas, steam) does not directly contact the product that is to be dried [12].

2.5.1.1. Batch tray dryers

This basic type of indirect dryer has pans or trays on hollow shelves on which the product is placed. It is heated by a medium, such as high-pressure steam, hot oil or even an electric heater. A vacuum is administered to the drying chamber in order to remove vapour from the chamber.

These types of dryers are extensively used for products that are sensitive to heat or easily oxidised. Batch tray dryers are especially used for products that should be carefully handled in order to minimize material loss. Products that are hygroscopic may be dried satisfactory at low temperatures. The biggest concerns of this type of dryers are the labour costs to load and unload the product and the unit's small holding ability.

2.5.1.2. Indirect-contact rotary dryers

The steam tube dryer is the most common indirect-contact rotary dryer. It is composed of a cylindrical, rotating shell, usually angled slightly (18^{O} to 58^{O}) to the horizontal to facilitate the transportation of the moist product through its shell. Several steam-heated pipes are placed symmetrically around its perimeter. To help agitation, lifting flights are usually added behind the tubes.

Indirect rotary dryers are used when direct-contact rotary dryers are not fit for the task, e.g. when direct contact with heated gases is not acceptable for product quality or fine particles may be present, which can flow with the drying gas stream [13]. This dryer type is ideal for continuous drying of solids that may not be exposed to ordinary atmospheric or combustion gases. Compared to direct-contact dryers, indirect-contact dryers have some benefits, like less deterioration of the product due to extreme exposure of the product to high temperature. Furthermore, absorption of contaminating elements, such as NO_X, is eliminated.

2.5.1.3. Rotating batch vacuum dryers

In essence, the rotating batch vacuum dryer is a vessel that rotates while containing the product to be dried. It is most often used for dryer products such as powders, granules and crystals. It is rarely used for sticky products, as these would stick to the side of the vessel and form lumps.

Rotating batch vacuum dryers have a heated vacuum chamber that rotates about its horizontal axis. Heat for drying is provided by a neighbouring heating jacket. In the last stage, water is commonly used to cool down the product. A limitation to the available heat transfer areas is the foremost disadvantage of this type of dryer.

2.5.1.4. Agitated dryers

Vertical agitated dryers, or batch cone dryers, are conically shaped vessels and are normally operated under vacuum. An internally mounted screw gives an agitated motion to the product. This screw can also be heated, which supplies extra heat to the product. The screw rotates about its own axis and moves around in the vessel on a revolving arm. The screw also enables self-cleaning of the vessel wall as it moves past it. Good sealing bearings must be considered to refrain from product being contaminated [13]. Agitated dryers function with heating mediums of hot water, steam or often hot oil.

In horizontal agitated dryers a shaft, running through the middle of a stationary horizontal cylindrical shell, is lined with numerous agitation blades for mixing and conveying of the product to be dried. Heat for drying is transferred via circulation through the shaft or through an external jacket. Some modern designs also include wall scrapers mounted on springs or breaker bars to handle sticky products better. For a batch dryer the exit hole may be located at its centre, and for a continuous dryer the exit hole may be located at the end of the dryer. The discharge, like the inlet, occurs by means of a screw conveyer, rotary valve or double butterfly valve. Vapour is extracted through the exhaust located at the top of the dryer.

2.5.2. Rotary dryers

Rotary dryers can be classified as direct, indirect-direct, indirect and special types. This classification is based on the method through which heat is transferred to the solids, direct being when heated gas makes contact with the solids and indirect when it is separated by a metal wall or tube [14].

The most common types of rotary dryers include:

- Direct rotary dryer
- Direct rotary kiln
- Indirect steam-tube dryer
- Indirect rotary calciner
- Direct – Roto-Louvre dryer.

The direct-heat dryers are the simplest and most economical. They are always preferable in cases where contact between solids and gases or air is not harmful. If the solids, however, contain extremely fine particles, excessive entrainment losses in the exit gas stream is possible, owing to the large gas volumes and high gas velocities that are required.

For the indirect-heat dryers, only sufficient gas flow through the cylinder to remove vapour is required. It has the advantage of being suitable for processes that require special gas atmospheres and exclusion of outside air.

2.5.3. Fluidised bed dryers

Many types of fluidised bed dryers have been developed for the industrial sector, each according to the particular process, product, operational safety and environmental requirements. Since all types of fluidised beds differ considerably, it is important to take into account what can be achieved with what type and what not, before a decision is made on what type to use.

2.5.4. Drum dryers

Drum dryers are commonly used to dry viscous, concentrated solutions, pastes or slurries on steam-heated drums while rotating.

2.5.4.1. Atmospheric double drum dryer

This type of dryer can dry slurry or paste. It is fed through a pendulum nozzle or through a head that has multiple nozzles on to the nip of two steam-heated drums that counter-rotate towards each other. This forms a boiling pool at the nip. Starch slurries gelatinise in the boiling pool, which form pastes that become more viscous. The slurry or past is spread into two thin sheets by the counter-rotation of the drums. These two sheets consequently dry conductively.

2.5.4.2. Atmospheric single-drum dryers

This type of dryer works in much the same way as the atmospheric double drum dryer, except that it has applicator rolls (feed applicator rolls if the slurry is fed from above and dip applicator rolls if the slurry is fed from beneath via a tray) that apply the slurry that is to be dried to the drum.

2.5.4.3. Atmospheric twin drum dryers

Slurry is applied to the drums by direct dip coating of the twin drums in the feed tray, which is situated at the bottom of the dryer or by splash or spray feeders that literally splash or spray the steam-heated drums with the slurry. The dried sheet is formed by adhesion to the drum's surface and is held up against gravity by its surface tension. Drying is achieved conductively. This type of dryer is ideal for a solution that produces a dusty product.

2.5.4.4. Enclosed drum dryers

In the event that solvent vapour, other than water, released during drying needs to be recovered, or if the product that is dried generates a lot of dust, atmospheric double or twin dryers can be enclosed in vapour- or dust-tight enclosures. This forms enclosed drum dryers. The dust can be removed by using wet scrubbers and the vapour is recovered with a suitable condenser.

2.5.5. Freeze-drying

Freeze-drying is a very useful method when drying solids that may not be heated even to moderate temperatures. The product that must be dried is frozen. The water inside the product is removed by sublimation from the frozen material in a vacuum chamber. Freeze-drying produces the highest quality food product obtainable by any method of drying. The product, during freeze-drying, obtains structural rigidity at the surface where sublimation occurs. This rigidity prevents collapse of the solid matrix after it has been dried. This gives a porous, non-shrunken product that facilitates rapid and almost complete rehydration if water is added again afterwards. There is also little loss of flavour and aroma with the use of freeze-drying. In any food product, bound water will be present during freeze-drying, but there is often a sharp transition temperature for the still wet region during drying [15], below which the quality of the product increases markedly.

Freeze-drying requires very low pressures or high vacuum to achieve an acceptable drying rate. In essence, freeze-drying is a multiple operation in which the material to be stabilised is frozen hard by low-temperature cooling, dried by direct sublimation of the frozen solvent within the product and by desorption of the bound solvent and stored under controlled conditions, in the dry state. If the freeze-drying process is practised correctly, most products can be kept in such a way for an estimated unlimited period of time and still retain all their physical, chemical, biological and majority of organoleptic properties.

2.5.6. Conveyer dryer

The basic concept of the conveyor dryer is very simple. The product is carried through the dryer on conveyors, while hot air is moved through the product on the conveyer. It is one of the most versatile dryers available. There are very few drying technologies that can equal the conveyor dryer’s ability to deal with a wide variety of products.

Although it is a simple concept, improper understanding of the heat and mass transfer process in the conveyor dryer is sure to lead to poor product handling, wasted energy and reduced product quality.

2.5.7. Infrared drying

Infrared (IR) drying is an increasingly popular, but not yet widely accepted, method of supplying heat to the product for drying. Although this type of heat transmission, in the past, was used incidentally, accompanying other types of heat transfer, IR dryers are now designed to use radiant heat as the primary source of heat transfer [16].

The use of IR drying of foodstuffs is not very common. Ginzburg [17] did, however, confirm that IR drying can be successfully applied in the drying of foodstuffs. Sandu [18] mentioned many advantages of IR drying of food, which include the versatility of IR heating, the simplicity of the equipment required, the ease of accommodation of the IR heating with convective, conductive and radial heating, the fast transient response and energy savings. A great advantage of IR heating is that it may be applied continuously or intermittently (both in space and time) to save energy as well as improve the product quality [12].

2.6. Case hardening

In the event that the cells on the outside of the product lose moisture faster than the cells on the inside, case hardening will occur. This will cause the surface to become hard, preventing the escape of moisture from inside the product to the surrounding air [19].

At a low drying rate, that is a low temperature, the moisture gradient within the product is small and internal stresses are low. This means the material shrinks down fully onto a solid core with uniform shrinkage. At a high drying rate, i.e. a higher temperature, the moisture on the surface decreases rapidly, leaving the surface stiff and limiting subsequent shrinkage. This increases pore formation. The permeability and integrity of the crust play a role in maintaining the internal pressure within the geometric boundary.

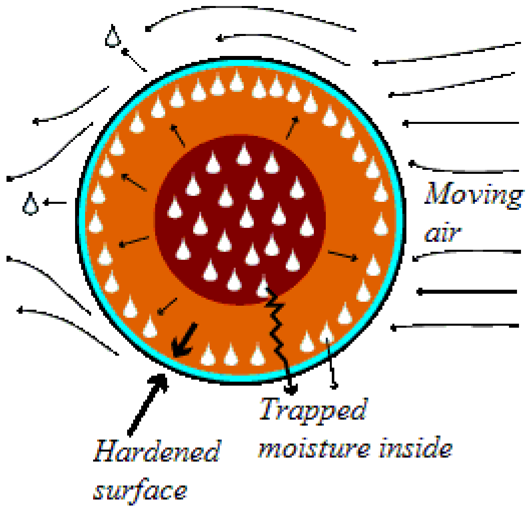

Figure 4 - Case hardening [20]

The concentration of moisture in the outer layer of the product is less than that in the interior during drying, since the outer layer loses moisture before the interior. The resulting surface shrinkage causes checking, cracking and warping. A moisture gradient and resistance near the surface form. The faster the drying rate, the thinner the crust [21]. The drying process should never be hastened by raising the temperature during drying. While the product may appear dry on the outside, it may still be moist on the inside, which will cause mould [22].

2.7. Heat and mass transfer explained

The specific internal energy of a vapour is higher than that of a liquid. Therefore energy is required to evaporate a liquid. The evaporation of a liquid at an interface will thus result in a reduction in temperature if some additional energy is not provided. Significant temperature changes can be expected when considering the combined effect of heat and mass transfer, as well as increased energy transfer rates on wetted surfaces. The theory of simultaneous heat and mass transfer is considered using convection heat transfer correlations together with mass transfer analogy.

A key factor in simultaneous heat and mass transfer is the concept of wet-bulb temperature. A psychrometer, a hygrometer consisting of wet-bulb and dry-bulb thermometers where the difference in the two thermometer readings is used to determine atmospheric humidity, can be used to measure the amount of water in an air-water vapour mixture.

At first, both the wet-bulb and the dry-bulb thermometers will read the same temperature. Over time, as the liquid water in the wick around the wet-bulb thermometer evaporates, the wet-bulb temperature will decrease. The reduction in temperature will continue until the required evaporation energy is provided by convection heat transfer from the surrounding air [23].

The water vapour concentration in the air at the surface of the wet-bulb thermometer can be determined with the aid of the ideal gas law, as seen in equation (1),

$$c_{w,sat} = \frac{p_{sat}(T_{wb})}{R_w T_{wb}} \tag{1}$$

where $p_{sat}(T_{wb})$ is the saturation pressure of water at the wet-bulb temperature, T_{wb}, and R_w is the ideal gas constant for water vapour. For the free stream air, the concentration of water vapour is given in equation (2),

$$c_{w,\infty} = \frac{RHp_{sat}(T_\infty)}{R_w T_\infty} \tag{2}$$

where RH is the relative humidity of the air and T_∞ is the free stream air temperature (dry-bulb).

2.8. Effect of product bed depth on drying

Little literature could be found on the effect of product distribution geometry on drying. A certain product distribution geometry is analogue to a variation of the product depth along the side (3) or sides (4) of the product bed.

$$H(x) = f(x) \tag{3}$$

$$H(x,y) = f(x,y) \tag{4}$$

with *H* the height of the product on the bed at a certain point *x.*

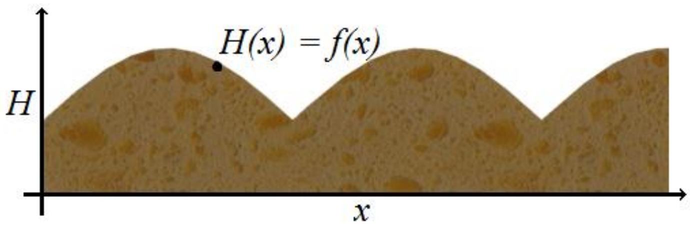

Figure 5 - Geometry along the x-axis of the product bed

Therefore looking at the effect of the product depth is a good starting point in understanding the effect of a non-uniform bed geometry.

Diffusion refers to the process by which molecules intermingle as a result of their kinetic energy of random motion [24]. In this case, the movement of the moisture from within the product to its surface and finally to the air that is flowing through the product bed.

Diffusion in a single particle differs from that through a layer of porous particles. Babbit [25] did a study on the adsorption and desorption of water vapour by wheat kernels at various bed depths ranging from 28 mm – 168 mm. He noted that with an increase in the depth of the bed, the moisture content absorbed during a time period decreased. He stated that this was not due to resistance of moisture movement within the grain itself, but rather due to the diffusion through the air and overlaying layers of kernels.

In another study by Islam and Fink [26], the drying behaviour of potatoes were investigated. For a first test potatoes of various thicknesses were dried in thin layer and for a second test potatoes were dried in deep beds of various depths. Both in thin layer and deep bed drying, the drying time increased with an increase in the bed depths. This was due to the fact that there was more moisture to evaporate from the deeper beds and higher air velocities in the shallower beds. The decrease in air velocity as the bed depth got deeper followed a power law equation that a threefold increase in bed depth would result in halve of the nominal air velocity. Tripling the bed depth led to doubling of the drying time to be dried to a pre-decided moisture ratio.

Upon plotting the moisture diffusion coefficient found from two models of carrot drying in a thin layer against the thickness of the monolayer, a climbing curve with growing carrot slab thickness was delivered for the first model [27]. A straight line was produced by the second model, which levelled off after a certain slab thickness. The difference in these models is that the first model assumed no shrinkage but the second incorporated it. With this in mind, the authors concluded that shrinkage cannot be neglected. No further explanation was, however, given regarding the relationship between the effective diffusion coefficient and the thickness.

When drying glass microsphere beads saturated with water at different bed depths, a poor correlation between the bed depth and D_{eff} was found [28]. It should, however, be understood that drying the wet glass beads is very different from drying biological materials with low moisture content due to different methods of water movement through the product.

In any of these readings, the effect of the bed depth on D_{eff} was not looked at and in the majority of these cases; no effort was done to calculate the diffusion coefficients. The effect of the bed depth on adsorption, desorption or the drying phenomena was only looked at by the effect on the rate or drying time of the process, instead of the diffusion coefficient, assuming a constant diffusion coefficient with depth. It is because of this that numerous researchers studied the relationship between bed depth and the slope of the linear solution of Fick's Law, the slope being the concentration gradient.

Fick's Law:

$$slope\,of\ \ln\Gamma\ vs\,time = \frac{D_{eff}\pi^2}{4L_0^2}t \qquad (5)$$

Theoretically, it is expected from this equation that as the bed depth increases, the slope should decrease, which is the general phenomenon in the literature, while D_{eff} is assumed to be the same. If so, the linear solution for every depth-slope combination must result in the same value of D_{eff} regardless of the slope dependence relationship value. In most cases, however, the D_{eff} is not the same and the error attained by the slope being determined with an assumed constant D_{eff} might be substantial, which would then affect the calculated process time in an undesirable way. This argument can also be valid for D_{eff} values estimated by the use of the non-linear solution. Meskine [29] obtained D_{eff} values of both single particles and a bulk pack of corn flakes at room temperature with the use of the non-linear solution. The value for the bulk was higher compared to that of the single particle. The air entrapped between the particles could have behaved as part of the system, which led to this observation. Since the diffusion of moisture in air yields a very high moisture diffusion coefficient (2.6 x 10^{-5} m^2/s [30,31]) in comparison with the material's moisture diffusion coefficient, the diffusion coefficient of the enclosed air is a contributing factor to the measurement of D_{eff}, which results in higher values for the bulk of material [32].

2.9. Conclusion

The literature study explained what dehydration is, why food needs to be dried and also what problems may be encountered if the food is not sufficiently dried. Different methods of drying were mentioned, and different types of dryers, additional to the multi-level dryer explained in the introduction, were explained. Short yet detailed accounts of case hardening and the phenomena of heat and mass transfer were given before concluding with the crucial literature on the effect of product bed depth on drying.

The following chapter discusses the test method, firstly looking at the test bench set-up, where after the test procedure is explained.

3. Experimental approach

In this chapter a short description of the test bench is given, followed by an explanation of how the tests were conducted. Testing on an actual dryer that is supposed to be used for production purposes would have been too costly. For this reason a test bench was designed and built on which all the required tests were done and accurate measurements were taken. Appendix C presents pictures of the test bench used.

3.1. Test bench set-up

The concept of the test bench is that of heated air flowing through the product bed. A centrifugal fan draws atmospheric air over a gas burner that heats the air. The heated air then flows further, drying the product as it flows through the product bed before it exhausts into the atmosphere.

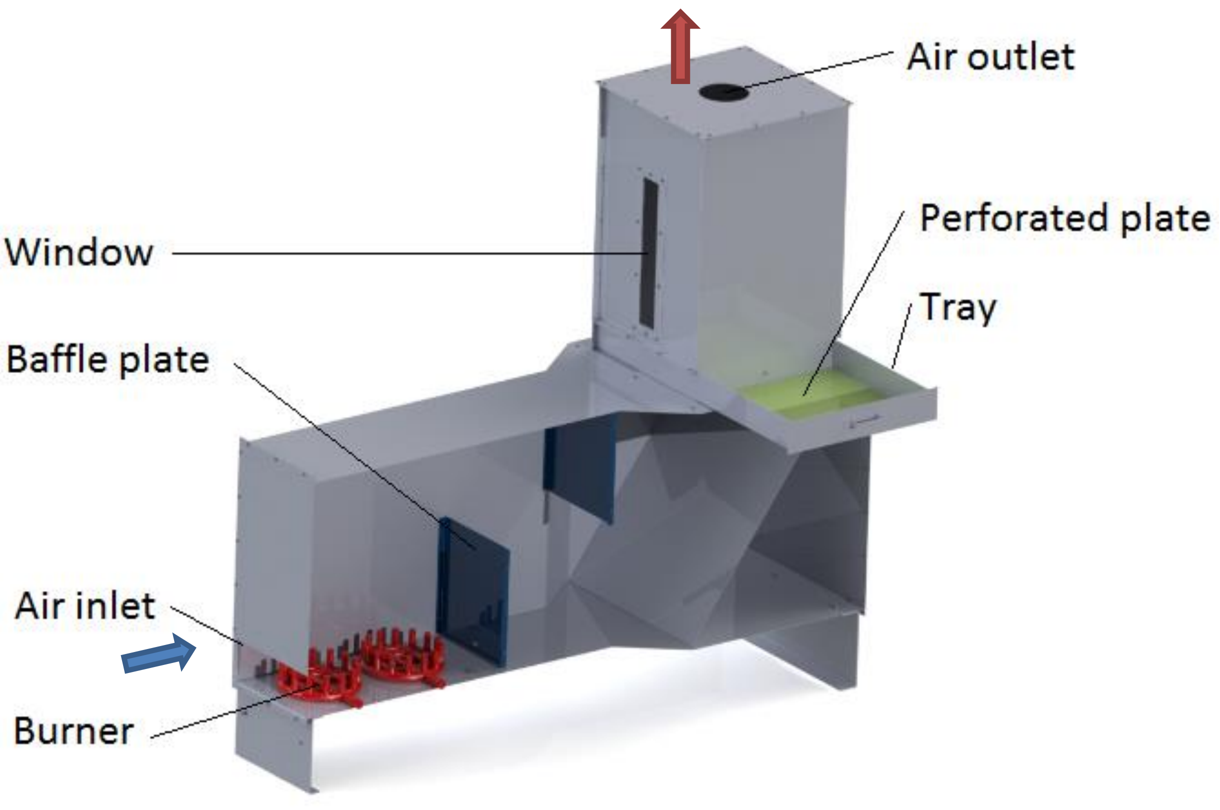

Figure 6 - Test bench set-up (fan not shown)

The burners heating up the air are gas jet burners. These burners burn propane gas, the amount of which is controlled by a needle valve. For this experiment, the temperature was at a minimum of 80^{O}C and a maximum of 150^{O}C. Propane gas was selected because it is not harmful and does not affect the taste or texture of the product. As shown in the chemical reaction (6), the only products formed during combustion are carbon dioxide and water.

$$C_3H_8 + 5O_2 \rightarrow 3\,CO_2 + 4H_2O + heat \quad (6)$$

The product is kept in a tray that slides in and out of the test bench like a drawer. Once the system has reached operating conditions, the drawer is simply slid into the test bench. The bottom plate of the tray is a perforated plate, to allow air to flow through from beneath, while also preventing the product from falling through to the floor of the test bench.

The test bench contains baffle plates between the burners and the tray that contains the product. These baffle plates create turbulence, ensuring a better mixture of warmer and colder air. By the time the air reaches the product, it is thoroughly mixed and has a uniform temperature.

The movement of the air through the test bench was achieved by the use of a centrifugal fan. Instead of blowing, the fan draws atmospheric air and exhausts the air back into the atmosphere after it has been heated and drawn through the product bed. The velocity at which the fan drew the air was controlled by a variable speed drive (VSD). The VSD enabled the fan speed to be altered through variation of the input frequency. The relationship of the VSD frequency to the velocity of the air through the test bench tray, with an area of 0.025m^2, is shown in Figure 7.

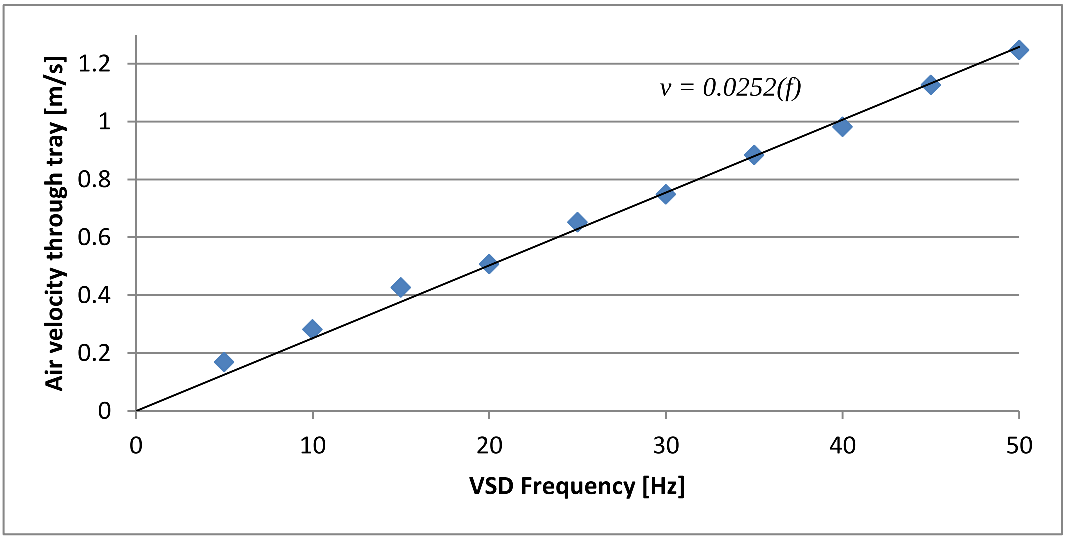

Figure 7 – Relationship between the air velocity through the tray and the VSD frequency

3.2. Test procedure

The product that has to be dried needs to be fresh in order to prevent any unaccounted for moisture loss or clumping. For this reason, the first step in the test procedure is to run an extruder. As soon as the extruder is ready and steadily running, the extruded product can be brought to the test bench.

The test bench's burners should be lit first and the needle valve adjusted until the desired temperature is achieved.

Next the VSD should be set to the desired frequency. If the VSD is set before the burners are lit, the air stream will be too strong for the gas to ignite.

The temperature should again be monitored, as the air velocity affects the air temperature.

While the process parameters stabilise, the product, fresh from the extruder, can be inserted into the tray and combed or raked so that the product bed geometry is as prescribed. A product sample for moisture analysis of the product before drying must now be taken.

Once the process parameters are as desired and stable, the tray with the product on can be slid into the dryer – gently, so as not to disturb the product bed geometry. As soon as the tray is slid in, the timer starts.

After the prescribed residence time, for these experiments 5 minutes, the tray may be slid open and samples for moisture analysis taken at respectively the ridge, the valley and the centre.

The tray may be cleaned and the required steps of the procedure repeated for different parameters.

The tests reported in Table 2 are all at a constant temperature of 20^{O}C and a constant air velocity of 7 m/s. These parameters were chosen with care. Since the air temperature and air velocity evidently have an effect on the drying, the parameters at which the amplitude tests were done were carefully selected. For the temperature, the tests were done at room temperature. To determine the air velocity at which these tests were to be done, the air velocity was slowly and continuously increased until an air velocity was reached were a measurable change in the moisture content was observed while still not fluidising the product, which was at 7 m/s.

3.3. Conclusion

Chapter 3 provided a detailed description of the test bench used to attain the results presented in Chapter 5. The physical structure of the test bench was explained, as well as the variable parameters that affect the drying of the product.

The geometry that the product on the bed takes on subsequent to falling through the floorplates is explained in the following chapter. This geometry is the key aspect of this research and greatly influences the drying of the product, which is why attention is given to detail in this chapter.

4. Geometric distribution of the product

This chapter describes the product bed geometry typically formed when using a multi-level dryer. The chapter also presents a simplified mathematical representation of this geometry.

4.1. Natural geometry of the product on the bed

The geometry of the product on the bed, previously shown in Figure 2, is shown in Figure 8.

Figure 8 - Typical geometry of the product on the bed produced by a multi-level dryer

The product falls from one level of the multi-level dryer to the next due to gravity. On the level on to which the product falls, it only heaps up until it reaches a certain angle. Once this angle is reached, the additional product slides off the heap, keeping the heap's geometry. This angle is called the angle of repose, shown in Figure 9.

Figure 9 - Illustration showing the angle of repose

The angle of repose, a basic property of granular materials, is the maximum slope angle where the material is at rest. Above the slope angle, the material will start to flow and below the angle, the material will stop moving and become stable [33].

For extruded maize puffs the angle of repose is typically between 30^{O} and 40^{O}. The more the amount of moisture in the pellet increases, the larger the angle will be, as moisture exhibits a binding effect holding the puffs together.

4.2. Geometry approximated as a sine wave

For this dissertation, a 30° angle of repose was used in all calculations. The natural geometry that the product on the bed takes on subsequent to falling to a next level has very much the same shape as a sine wave of all positive values, that is the absolute value. For this reason the geometry of the product on the bed has been approximated as the absolute values of a sine wave, as displayed in Figure 10, for the calculations in this dissertation.

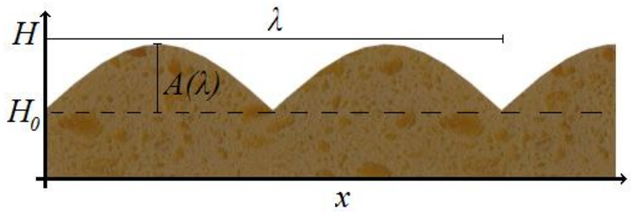

Figure 10 - The sine wave geometry the product takes on subsequent to falling to a next level

$$H(x) = \left| A \cdot \sin\left(f \cdot x \right) \right| + H_0 \qquad (7)$$

Note that in equation (7), the vertical value is expressed by y and not H, as this equation is not applicable below the valley in the product bed.

The dryer is required to deliver uniform drying. This means that the moisture content of the product at any given point in the product bed should not differ from that of any other point in the same batch. The further the distance between the ridge and the valley (henceforth referred to as the amplitude), the larger the difference is between the moisture content at the ridge and the moisture content at the valley. With this in mind, it can be derived that the shorter the amplitude, the closer the bed geometry is to uniform.

$$\lim_{A \to 0} H(x) = H_0 \qquad (8)$$

The amplitude is a function of the wavelength and the wavelength, for the geometry produced by a multi-level dryer, is double the length of the floorplate:

$$\lambda = 2 \cdot l \qquad (9)$$

The proposed design for the multi-level dryer has a floorplate length of 100 mm. This means the wavelength for the curve representing its geometry is 200 mm. The angle of repose is fixed in these calculations, and therefore, with the wavelength known, the amplitude can be calculated with simple trigonometry.

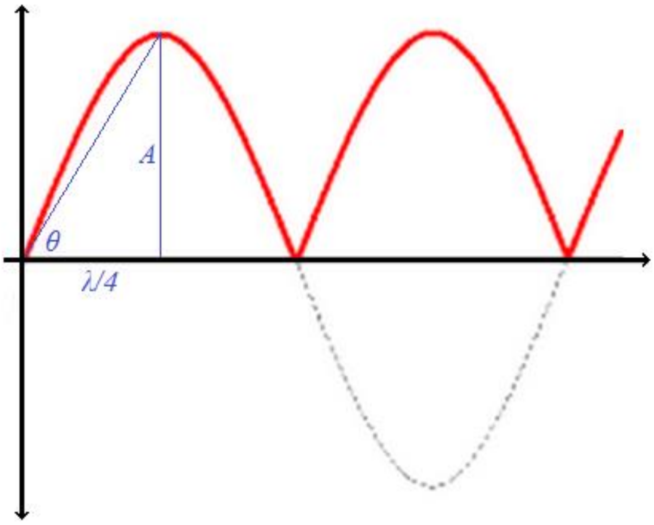

Figure 11 - Trigonometric relations used to determine the amplitude

Note from Figure 11 that the angle of repose is taken straight from the ridge to the valley and not tangent to the sine wave. From this figure, the equation for the amplitude is:

$$A = \frac{\tan(\theta)\cdot\lambda}{4} \quad . \tag{10}$$

With the angle of repose and the wavelength as defined earlier, the equation for the sine wave representing the geometry that the multi-level dryer produces is:

$$y = \left|28.87\cdot\sin(0.03142\cdot x)\right| + H_0 \quad . \tag{11}$$

A single product puff is approximated as a sphere of diameter 10 mm. The product geometry sine wave in relation to the product puffs is illustrated in Figure 12.

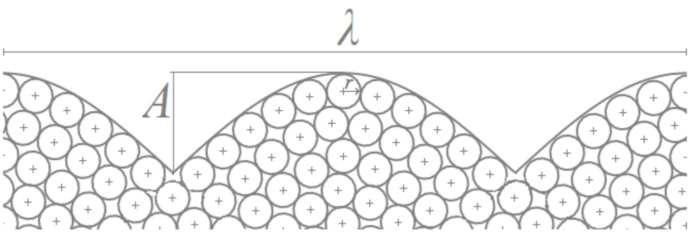

Figure 12 – Illustration of simplified product packing for a product geometry sine wave with *l* = 100 mm and *r* = 5 mm

In order for the bed geometry to be considered relatively flat, $A \le r$.

With the angle of repose kept constant, the relationship between the amplitude and the wavelength is:

$$A = 0.144\cdot\lambda \quad . \tag{12}$$

From equation (9), the same can be derived about the relationship between the amplitude and the floorplate length, l, as shown in Figure 13.

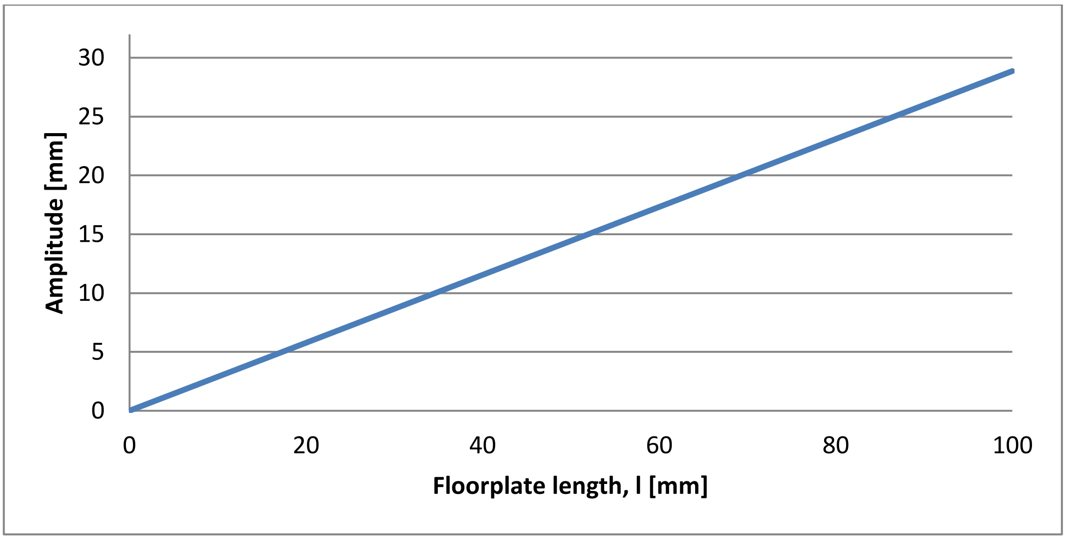

Figure 13 - The relationship between the amplitude and the floorplate length

The amplitude value nearest to $r = 5\,mm$ for a floorplate length that is a round number (for ease of manufacturing), is $A = 5.05\,mm$, with $l = 17.5\,mm$.

The equation for the sine wave representing the geometry that the multi-level dryer produces is now:

$$y = \left|5.05 \cdot \sin\left(0.17952 \cdot x\right)\right| + H_0 \ . \quad (13)$$

Again, the product geometry sine wave with relation to the product puffs is illustrated in Figure 14.

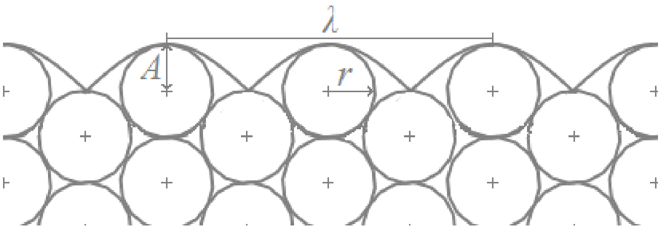

Figure 14 - Product geometry sine wave with *l* = 17.5mm and *r* = 5mm

When Figure 14 is compared to Figure 12, it is seen that the geometry in Figure 14 is much closer to uniform than that in Figure 12. However, the geometry of the product on the bed does not need to be completely flat for uniform drying to occur. It was found that a non-uniform product geometry can still provide uniform drying as shown in Section 5.3.2.

4.3. Conclusion

In this chapter it was concluded that the natural geometry that the product on the bed takes after falling on a next level is simplified or approximated as a sine wave of all positive values, i.e. the absolute value. The type of product will determine the angle of repose, which will in turn determine the amplitude of the wave. It is also noted that just as the difference in moisture content is proportional to the amplitude, the amplitude is proportional to the floorplate length.

Chapter 5 presents the results attained. The processing of the results is briefly discussed, where after the measured results are given and interpreted. The knowledge acquired from the results is then used to make recommendations on the design of a multi-level dryer.

5. Experimental results and concept design

The results obtained after running the desired tests on the test bench are provided and explained in this chapter, followed by a proposed concept design derived from the results.

5.1. Processing of results

The first step is identifying the position in the product bed where the product contains most moisture after drying, as well as the position that contains least moisture. Figure 15 shows the positions where the samples were taken, previously indicated in Figure 3.

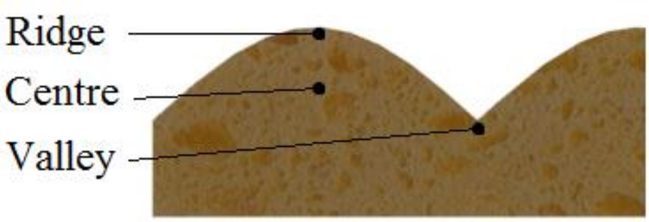

Figure 15 - Positions where samples were taken during testing

These two moisture values are cardinal, because for all following calculations and, in fact, the key element of this dissertation, the difference in moisture, Δm, is required.

$$\Delta m = m_{largest} - m_{smallest} \tag{14}$$

Illustrated in Figure 16, the moisture content of the three positions in the product bed is given for various tests. i.e. tests with different air temperatures and air velocities.

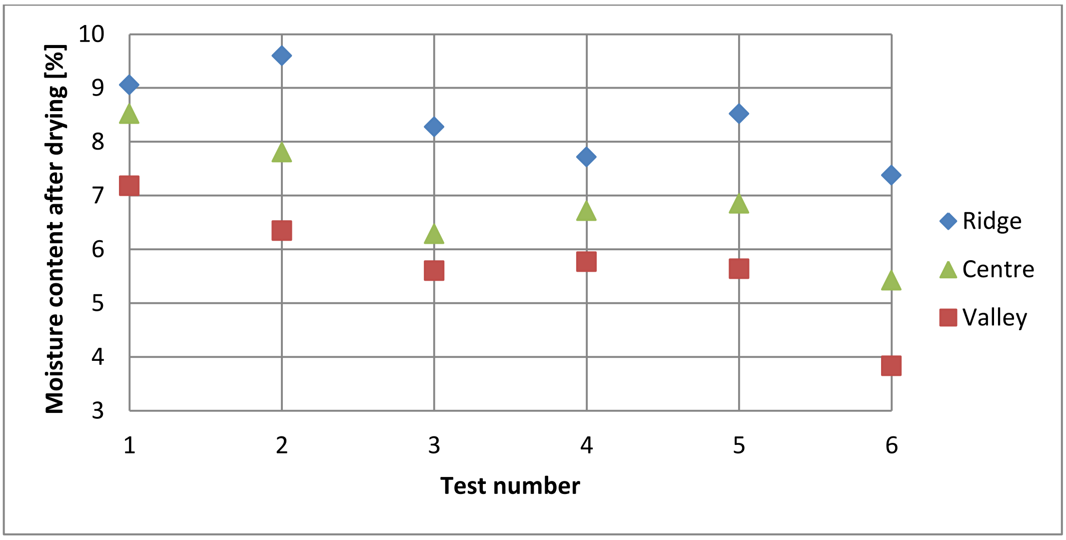

Figure 16 – The percentage moisture of the centre persistently between that of the ridge and the valley

It is evident that the valley experienced the highest moisture loss, the centre the second highest and the ridge the lowest. It is clearly noted that the percentage moisture content of the product at the centre is persistently between that of the ridge and the valley. This means the percentage moisture content of the centre has no effect on Δm. Since it has no effect, it will not influence the conclusion of this dissertation. It is thus irrelevant for the purpose of this study and needn't be measured for any further calculations.

Airflow will inevitably follow the path of least resistance. This means that the flow will follow the shortest, most unrestricted path that is available [34]. When the air approaches the product on the bed, it will much rather flow through the valley, than through the centre and ridge, as there is less resistance. Therefore the valley will be over-dried compared to the rest of the product bed [35]. The product at the centre and ridge is stacked higher than at the valley. This creates a denser path for the air to flow through, thus higher pressure. The resistance pressure increases with an increase in the percentage of fines in the product [36], or in other words an increase in bulk density, as is the case at the centre and ridge. This causes an increase in the airflow resistance per unit bed depth of the product [37].

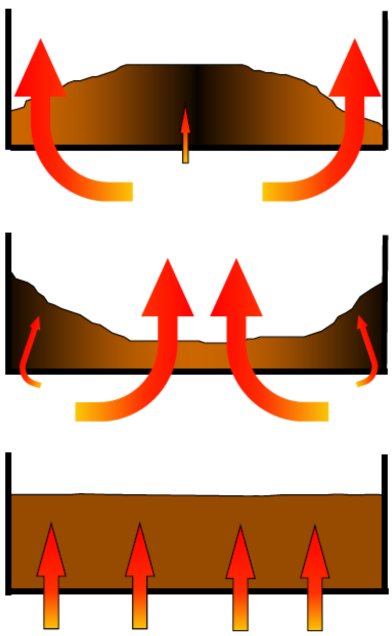

Figure 17 - Path of least resistance of air flowing through the product [35]

Also noted in Figure 16 is that the moisture content of the ridge is always greater than that of the valley, without exception. With these two observations in mind, equation (14) can be written more relevantly as:

$$\Delta m = m_{ridge} - m_{valley} \tag{15}$$

Although the differences in moisture at the specified parameters give a good indication of the drying kinetics at that given air temperature and air velocity, it is important to note that the moisture content of the product before it is dried is not always the same. In most cases these moisture values differ only slightly, but this difference is sufficient to influence the drying rate. Typical values of the moisture content of the product before it is dried can be found in Table 1 and Table 2. To overcome this, the difference in moisture content can be normalised by representing it as a percentage of the moisture content of the product before it was dried:

$$\Delta m_{pct} = \left(\frac{m_{ridge} - m_{valley}}{m_{before}} \right) \cdot 100 \tag{16}$$

5.2. Measured results

Table 1 shows the percentage moisture content of the product before drying and after drying, both at the ridge and at the valley, as well as the difference in moisture content for various air temperatures and air velocities. Note that the values given are the averages for each test, since numerous tests were done to eliminate any outliers.

Table 1 – Difference in percentage moisture content at various air temperatures and air velocities at constant amplitude (A = 80 mm)

Temp	Air velocity	Averages:	After:		Difference in moisture content [%]	
[C]	[m/s]	Before	Ridge	Valley	Δm	Δm_{pct}
80	0.28 (10 Hz)	11.325	9.432	6.258	3.174	28.026
	0.43 (15 Hz)	11.116	9.057	7.181	1.876	16.877
	0.51 (20 Hz)	12.038	9.812	8.188	1.624	13.491
	0.65 (25 Hz)	12.621	7.647	6.153	1.494	11.833
100	0.28 (10 Hz)	11.286	9.603	6.349	3.254	28.833
	0.43 (15 Hz)	11.467	8.281	5.604	2.677	23.346
	0.51 (20 Hz)	11.747	7.718	5.773	1.945	16.558
	0.65 (25 Hz)	11.589	6.147	4.623	1.524	13.146
115	0.28 (10 Hz)	11.137	7.833	4.565	3.268	29.344
	0.43 (15 Hz)	10.925	8.523	5.644	2.879	26.352
	0.51 (20 Hz)	10.757	5.336	3.026	2.310	21.474
	0.65 (25 Hz)	10.945	4.956	3.268	1.689	15.427
150	0.28 (10 Hz)	10.395	6.499	2.246	4.253	40.909
	0.43 (15 Hz)	11.969	7.380	3.839	3.541	29.586
	0.51 (20 Hz)	10.000	3.388	1.195	2.194	21.935
	0.65 (25 Hz)	9.944	2.359	0.971	1.389	13.963

Table 2 shows the percentage moisture content of the product before drying, as well as after drying, both at the ridge and at the valley for various amplitudes. Although the height of the product bed was changed with each test in order to change the amplitude, the amount of product (weight) was kept the same for every test to ensure accurate results.

Table 2 – Difference in percentage moisture content at 20 ^{O}C, 7 m/s and differing amplitudes

Bed depth [mm]			Moisture content [%]			Difference in moisture content [%]	
Ridge	Valley	$\Delta H = A$ (Amplitude)	Before	Ridge	Valley	Δm	Δm_{pct}
325	25	300	9.697	9.250	8.135	1.115	11.498
300	50	250	9.276	9.181	8.289	0.892	9.616
275	75	200	9.666	9.097	8.392	0.705	7.294
250	100	150	9.229	8.953	8.511	0.442	4.789
225	125	100	9.441	8.931	8.693	0.238	2.521
200	150	50	8.981	8.782	8.737	0.045	0.501

5.3. Interpretation of results

The two different sets of results will be interpreted separately, firstly the results of the tests done at various air velocities and temperatures with a constant amplitude and secondly the results of the tests done at constant air velocity of 7 m/s and temperature of 20 ^{O}C, but with various amplitudes.

5.3.1. Various air velocities and temperatures, constant amplitude

All the product is required to dry at a uniform rate to prevent some of the product in the bed from being over-dried while the rest in the same bed is still too moist. The smaller the difference in moisture content between the two extreme points, the closer the geometry of the bed is to being uniform, which yields a uniform drying rate.

The difference in the moisture content of the product tends to be smaller as the air velocity increases, as shown in Figure 18.

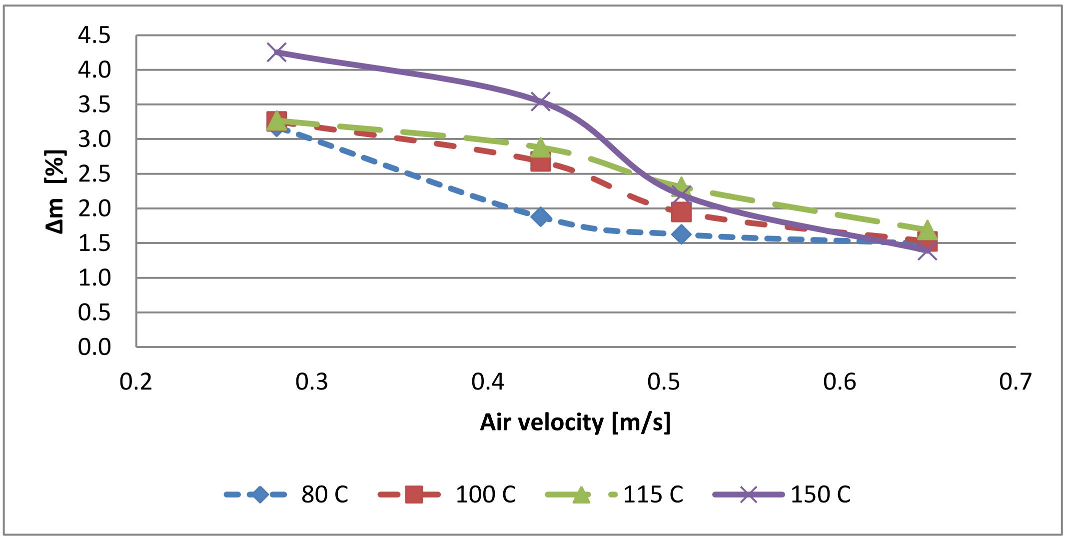

Figure 18 - Effect of air velocity on difference in moisture content at various air temperatures

The difference in the moisture content of the product tends to be larger as the air temperature increases, as shown in Figure 19.

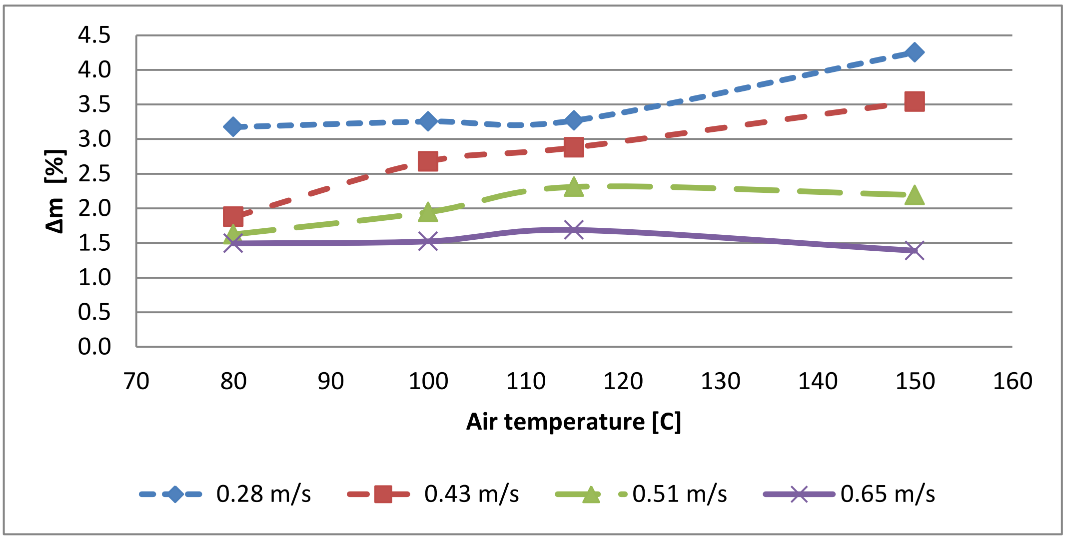

Figure 19 - Effect of air temperature on difference in moisture content at various air velocities

These two observations are seen clearly when combined on a single surface graph, as shown in Figure 20.

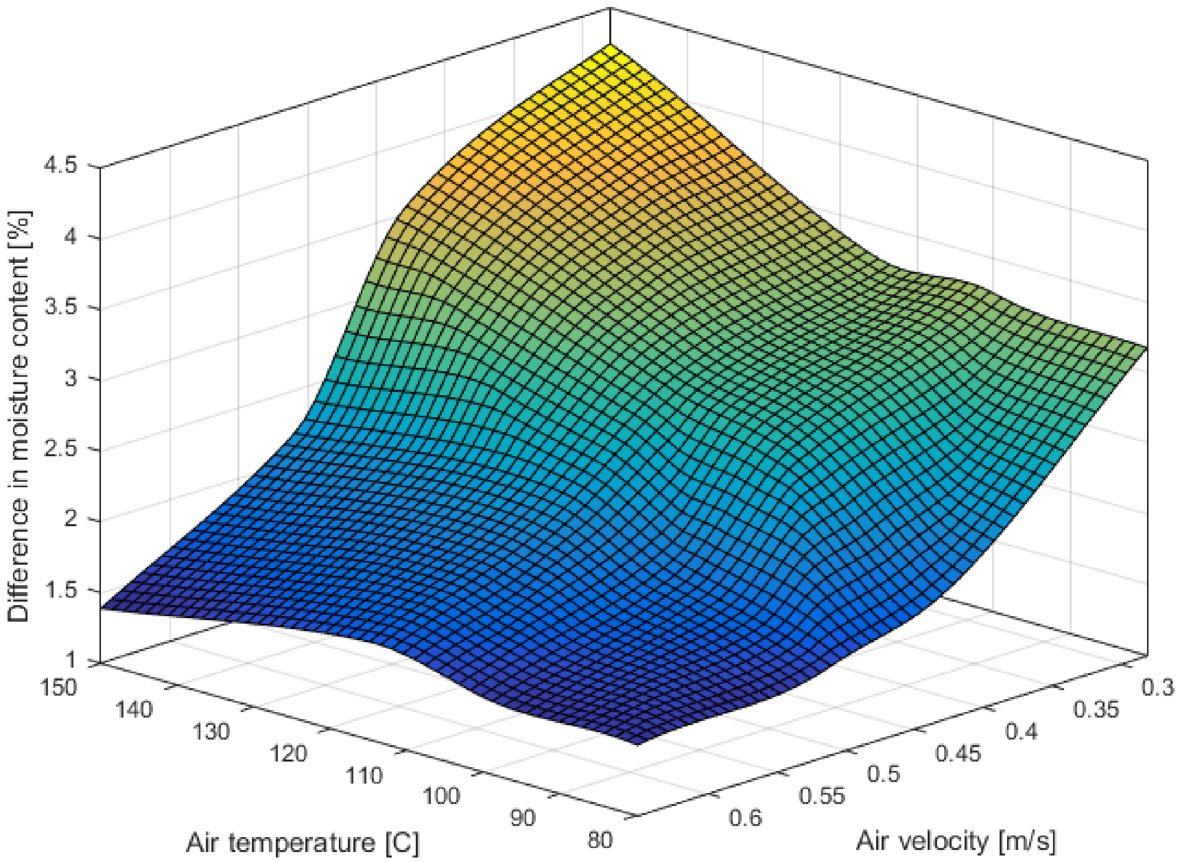

Figure 20 - Surface graph illustrating the difference in moisture content at various parameters

Since the moisture content of the product is not always the same before drying, the normalised values of the difference in moisture content, represented as a percentage of the moisture content before drying, gives a more accurate approach.

The difference in the normalised moisture content of the product tends to be smaller as the air velocity increases, as shown in Figure 21.

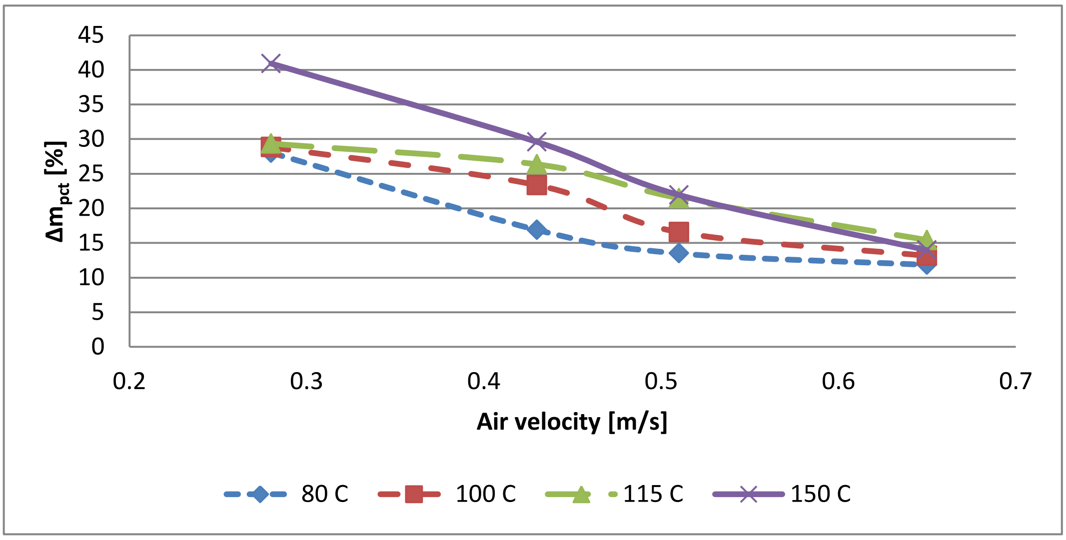

Figure 21 - Effect of air velocity on the normalised difference in moisture content at various air temperatures

The difference in the normalised moisture content of the product tends to be larger as the air temperature increases, as shown in Figure 22.

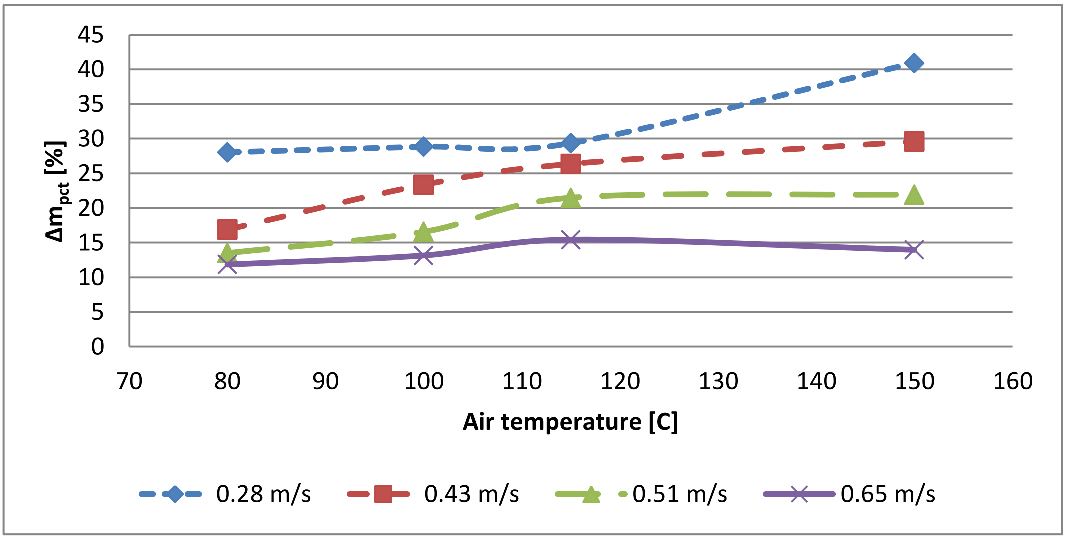

Figure 22 - Effect of air temperature on the normalised difference in moisture content at various air velocities

These two observations are seen clearly when combined on a single surface graph, as shown in Figure 23.

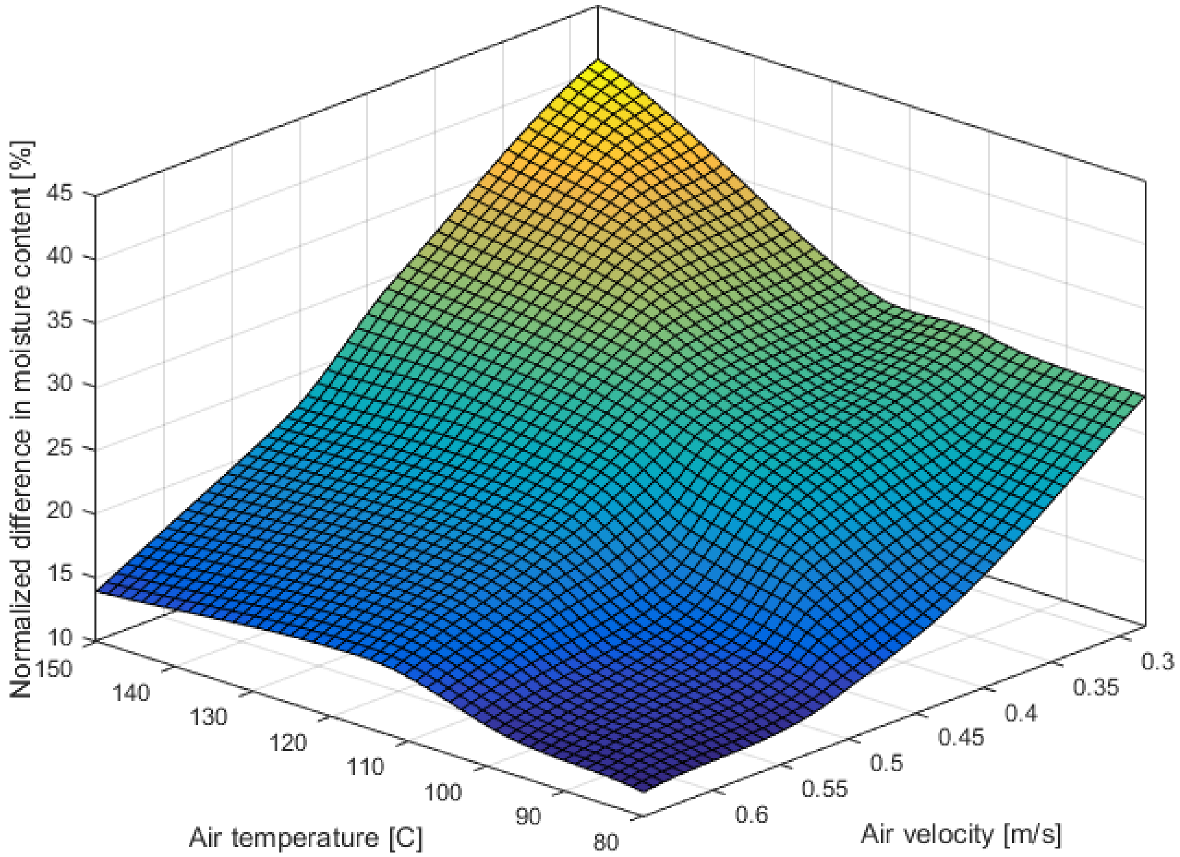

Figure 23 - Surface graph illustrating the normalised difference in moisture content at various parameters

5.3.2. Constant air velocity and temperature, various amplitudes

In Chapter 4 it was hypothesised that the further the distance is between the ridge and the valley (amplitude), the larger the difference will be between the moisture content at the ridge and the moisture content at the valley. The results in Table 2 show that this is in fact the case.

As the amplitude increases, so does the difference in moisture content.

In Figure 24 it is evident that the difference in moisture content is directly proportional to the magnitude of the amplitude, that is:

$$\Delta m \propto A \ . \qquad (17)$$

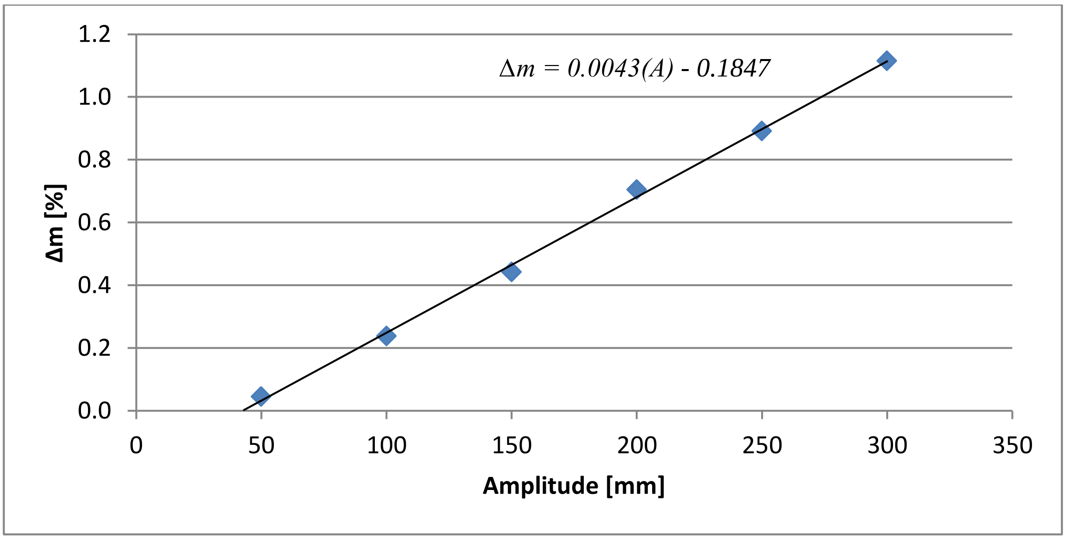

Figure 24 - Relationship between the amplitude and the difference in moisture content

However, careful attention should be paid to the fact that the line in Figure 24 does not go through the origin. This means that for some positive value of the amplitude, the difference in moisture content is zero. In other words, the geometry of the product on the bed need not be perfectly uniform to deliver uniform drying. In order to determine the maximum amplitude where drying is uniform, for the conditions specified in these tests, Δm needs to be set to zero in the equation derived from Figure 24, that is:

$$\Delta m = 0.0043(A) - 0.1847 \,. \tag{18}$$

Solving for A in equation (18) with Δm=0, gives A=42.95 mm.

Figure 13 depicted that that the magnitude of the amplitude is directly proportional to the floorplate length. Combining the results of Figure 13 and Figure 24, the relationship between the floorplate length and the difference in moisture content can be found.

The maximum floorplate length that yields the maximum amplitude for uniform drying can simply be read off the vertical axis of Figure 25, or Δm can be set to zero in the equation derived from Figure 25, i.e.:

$$l = 798.93(\Delta m) + 148.57 \,. \tag{19}$$

For the specific conditions of these tests, the maximum floorplate length that will yield uniform drying is l=148.57 mm. This finding is very important because money can be saved if larger floorplate lengths can be used. Larger floorplate lengths would imply less laser cutting, fewer shafts, fewer bushes or bearings, etc. (see Appendix B).

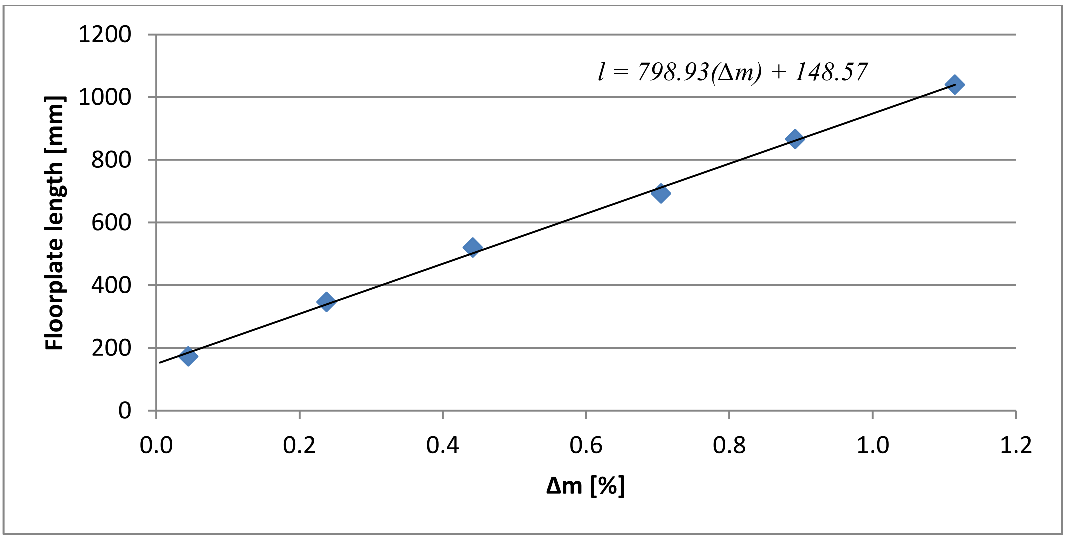

Figure 25 - Relationship between the floorplate length and the difference in moisture content

Again, using the normalised value for the difference in moisture content (Δm_{pct}) gives a more accurate representation. The relationship shown in Figure 24 can now be illustrated as:

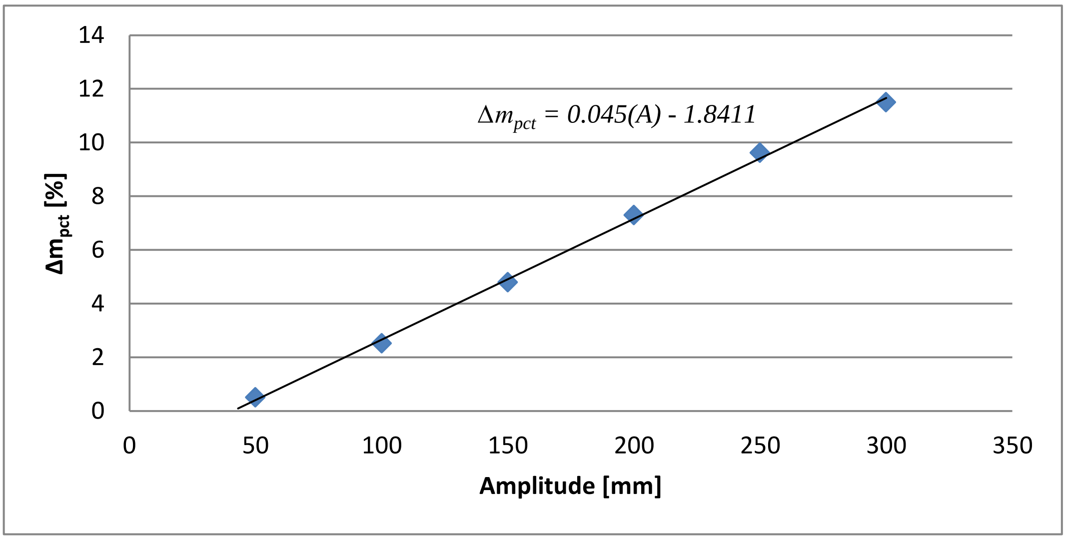

Figure 26 - Relationship between the amplitude and the difference in moisture content

Using the same steps as in equation (18), it is found that the maximum allowable amplitude for uniform drying is now A=40.91 mm. This is less than the previously found 42.95 mm. The normalised value is more trustworthy than the value that is not normalised, which is evident since the normalised value is the smaller one. Ultimately, the maximum amplitude for uniform drying, giving these conditions, is A=40.91 mm.

The normalised relationship is shown in Figure 27. The maximum floorplate length for uniform drying corresponding with the amplitude of A=40.91 mm is l=142.35 mm.

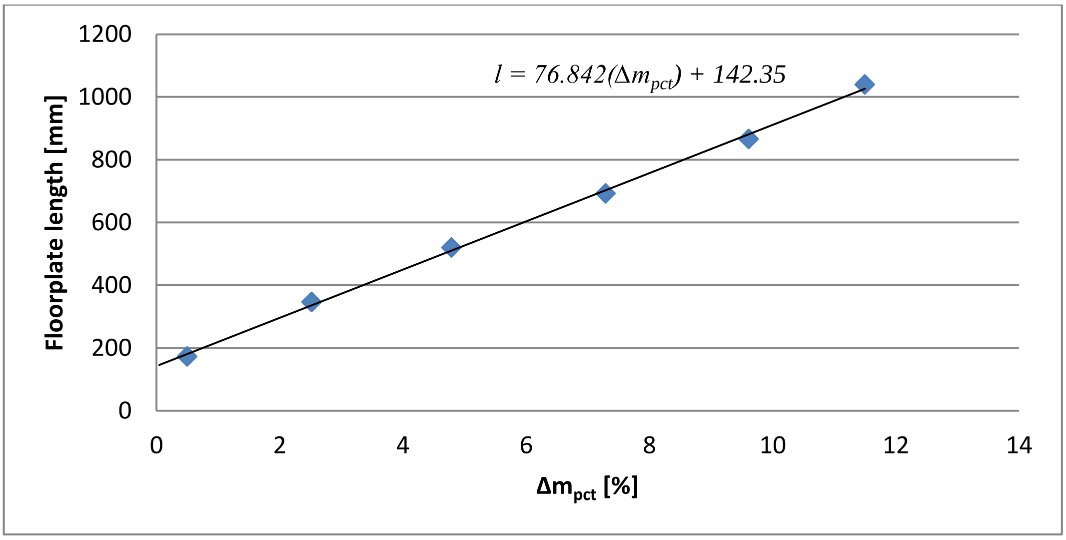

Figure 27 - Relationship between the floorplate length and the difference in moisture content

According to the results, the drying parameters undeniably have an effect on the drying of the product as well as on each other. The trends observed can be implemented in the design of the dryer, to ensure the product is dried exactly as required.

5.4. Using the results to design a modular multi-level dryer

In this section, a proposed design of a single- and multi-level dryer is briefly discussed. The general concept is explained, and how the results presented influence the design. Further information about the concept design is given in Appendix C and the design process followed is laid out in Appendix A.

5.4.1. Single level

Examining a single level gives a thorough understanding of the dryer, which aids in understanding the geometry of the product on the bed subsequent to falling through the floorplates and the drying thereof.

After extrusion the product is conveyed to the dryer. The product is uniformly spread by a spreader on the floorplates of the dryer. The length of the floorplates is determined from the results previously given in this chapter, since a clear relationship between the floorplate length and the difference in moisture content was found in Figure 25.

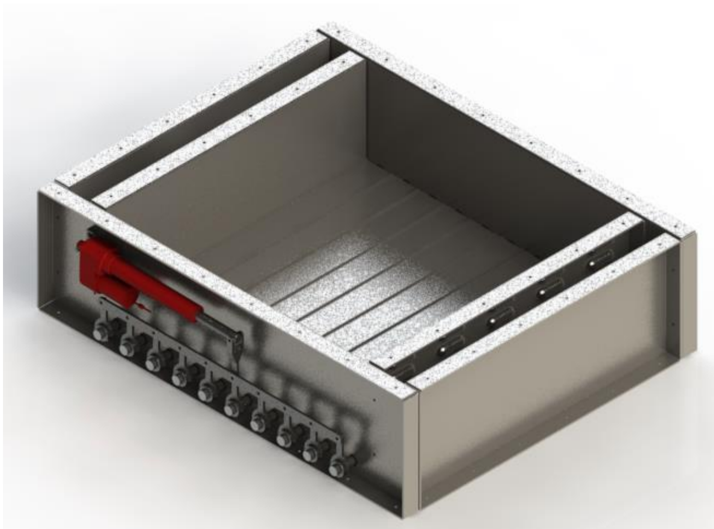

Figure 28 - Isometric view with floorplates closed

After a pre-set amount of time, an actuator extends, opening the floorplates and allowing the product to fall through. The height of the floor is carefully selected to allow for enough space for the product bed with its specific amplitude, as stated in Table 2 of this chapter (also see equation (7)), without the floorplates disturbing the product when rotating.

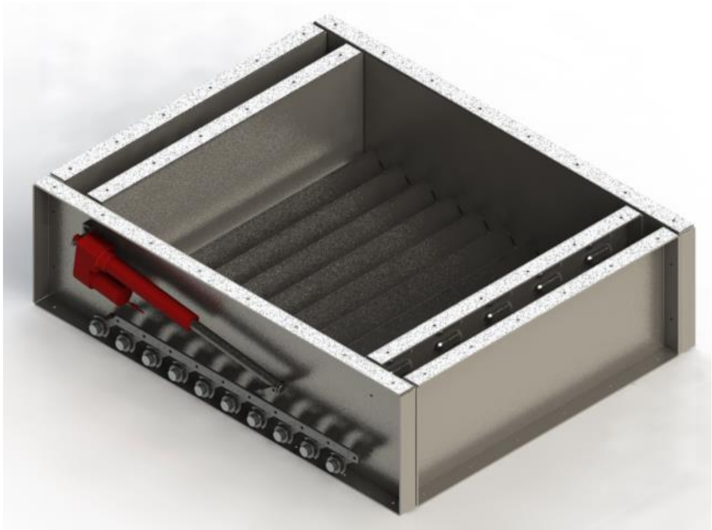

Figure 29 - Isometric view with floorplates open

Airflow chambers on the opposite sides of the dryer allow the passage of air; the air enters and exits the dyer through them. Louvres on one side of the bin allow air to flow through the product, removing moisture from the product as it passes through.

Figure 30 - Isometric view (first angle orthographic projection) with floorplates open

The module is mounted on a stand and exports the dried product through a chute or conveyance pipe on to the next stage.

5.4.2. Multiple levels

As mentioned, the multi-level dryer is modular. Several of these modules can be stacked on top of one another to form the total dryer. There is no theoretical limit to the number of modules that can be stacked; the number is dependent on product quantity, final moisture content, available vertical height, etc.

Not included in Figure 31 are the dryer stand and the spreader. The stand is below the dryer, keeping it off the floor of the facility. It has a chute or conveyance pipe that exports the dried product to the next stage. The spreader is on the top module of the dryer, uniformly spreading the moist product that arrives from the extruder on the top level of the dryer.

Figure 31 - Modules stacked on top of one another forming the multi-level dryer

Every second level is angled 180^{O} to its prior level. This is so that the louvres are opposite one another, forcing the airflow through the product bed. Another advantage of this orientation is that the actuators open in the opposite direction on every second level, resulting in proper agitation of the product.

5.5. Conclusion

In this chapter the measured results obtained from all the tests that were run on the test bench were presented and discussed. Observations and derivations made from the results were used to make critical design considerations, presented in Section 5.4.

The air temperature, air velocity and amplitude of the product on the bed had an immense effect on the drying of the product. This effect is discussed in the following chapter.

6. Conclusion and recommendations

In this chapter the observations that were noted from the results are presented and discussed, along with verification. Recommendations for future research in this field are also given.

6.1. Conclusions

Six distinct conclusions have been made from the experimental results:

1. The air temperature has an effect on the final moisture content of the product.
2. The air temperature has an effect on the difference in moisture content between the product at the ridge and the product at the valley.
3. The air velocity has an effect on the final moisture content of the product.
4. The air velocity has an effect on the difference in moisture content between the product at the ridge and the product at the valley.
5. The floorplate length has an effect on the difference in moisture content between the product at the ridge and the product at the valley.
6. Uniform drying can be achieved with a non-uniform bed geometry.

The conclusions mentioned above, indicate that if the trends for air temperature and air velocity are combined, the product will be driest when dried at a high air temperature and a high air velocity. To dry the product most accurately to a specified moisture content, i.e. with the smallest possible tolerance, it needs to be dried at a low temperature and a high air velocity. A range of temperatures for each specific application can now be identified that will yield satisfactory drying, i.e. temperatures where the product is sufficiently dried and also has a small enough tolerance.

It is interesting to note that an increase in air temperature increases the difference in final moisture content, but an increase in air velocity decreases the difference in final moisture content. This can be accredited to the air preferring the path of least resistance, as well as the saturation of the air. As described in Section 5.1, air will always prefer to flow along the path of least resistance. At a low air velocity, the air does not have enough kinetic energy to move through the product bed at its thickest parts (ridges) and most air moves through the thinner parts (valleys), leaving them drier.

Enhancing this, if the air moves through the product bed where there is only a thin layer of product, there will be little moisture for the air to absorb. If the air moves through the product bed where there is a thick layer of product, there is a lot of moisture for the air to absorb and it may become saturated before leaving the product bed. This will leave the ridge considerably moister than the valley.

When looking at the last two points mentioned, the two points concerning the floorplate length, it is noted that the longer the floorplate length is, the larger the difference is between the moisture content of the product at the ridge and that of the product at the valley, unless the floorplate length is equal to or less than the maximum allowed floorplate length for uniform drying. For a floorplate length of value equal to or less than this specified value, drying is uniform.

These conclusions are described in more detail in the following sections.

6.1.1. The air temperature has an effect on the final moisture content of the product

Drying at a higher temperature produces greater moisture removal from the product compared to drying at lower temperatures. In general, the higher the air temperature is, the lower the product's moisture content will be after drying, given that case hardening does not occur.

This is a verification of the observation made by Lewicki and Lenart [38] while dehydrating fruit and vegetables. According to their research, the dehydration of apples in the range of 30°C to 90°C produced a graph (shown in Figure 32) that clearly indicated less moisture content in the apple pieces after a certain time than drying in the same conditions, except for a lower temperature.

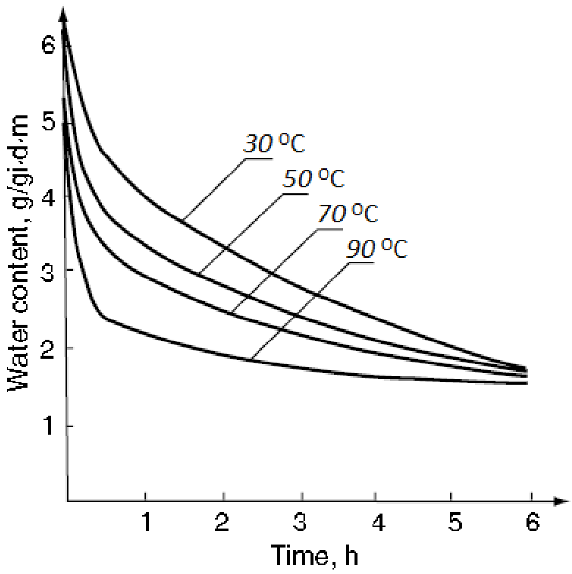

Figure 32 - The effect of temperature on the course of osmotic dehydration of apples at different temperatures [38]

6.1.2. The air temperature has an effect on the difference in moisture content

When considering the difference in moisture content between the product at the ridge and the product at the valley, it is seen that as the air temperature increases, so does the difference in moisture content between the product at the ridge and the product at the valley. As mentioned in Chapter 4, the dryer is required to dry the product uniformly. This means that the moisture content of the product at any given point in the product bed should not differ from that of any other point in the same batch.

Every product to be dried has a specified moisture content to which it is to be dried for long-term storage. It also has an acceptable tolerance; it may be slightly drier or soggier than that specified moisture content. If this tolerance is wide, the product can be dried at a higher air temperature than if the product has a small tolerance. It may be possible that a product needs to be dried to a moisture content so low that a high air temperature is required, but with a tolerance so small that only a low temperature would do. In such a case, the other drying parameters may be varied to ensure the desired drying conditions – one example is extending the residence time.

6.1.3. The air velocity has an effect on the final moisture content of the product

When considering the air velocity, it can be seen that the product's moisture content is lower after drying at high air velocities than it is after drying at low air velocities. In general, the higher the air velocity, the lower the product's moisture content will be after drying.

Kozlova et al [39] reached the same conclusion. In the field of the regularities of the drying of lactulose solutions, they investigated the dependencies of the product output on the airflow rate, among other parameters. The figure below, from their research, illustrates that the moisture content of the product after drying is less when dried at a high air velocity in comparison with drying at a low air velocity. This verifies the observation made in this section.

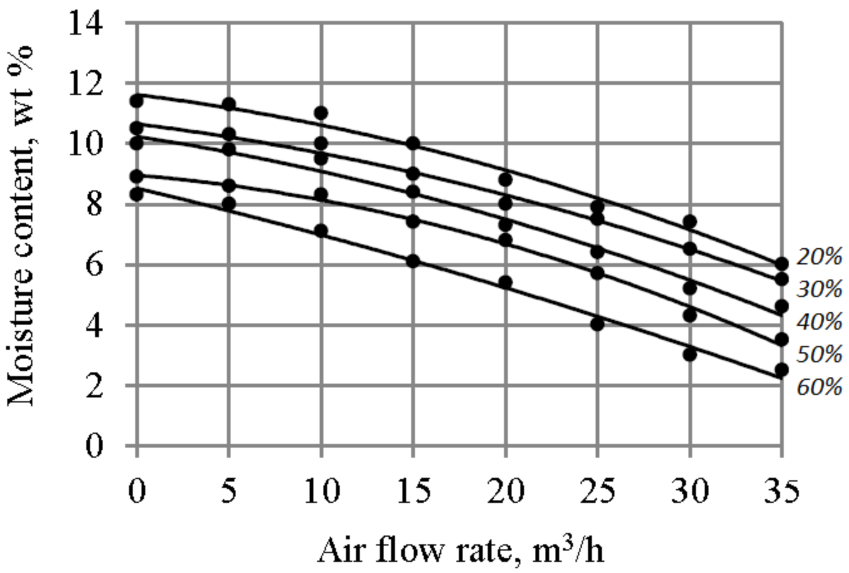

Figure 33 - Moisture content vs. airflow rate at different mass fractions of lactulose [39]

6.1.4. The air velocity has an effect on the difference in moisture content

The same tendency is observed when looking at the difference in moisture content between the product at the ridge and the product at the valley. The difference in moisture content between the product at the ridge and the product at the valley is less if the product was dried at a high air velocity than if the product was dried at a lower air velocity. Other than the temperature, this means that an increase in air velocity will deliver a product with less moisture content after drying, while simultaneously narrowing the tolerance at which the product moisture content will deviate from the specified moisture content. Unfortunately, the magnitude of the air velocity has a maximum value, as fluidisation may occur as the air velocity increases. A product may be required to be dried to a relatively high moisture content, in other words a low air velocity, but with a small tolerance, which requires a high air velocity. In such a case the other drying parameters may again be varied to ensure the desired drying conditions.

6.1.5. The floorplate length has an effect on the difference in moisture content

The amplitude tests confirmed the hypothesis made in Chapter 4. The further the distance is between the ridge and the valley (amplitude), the larger the difference between the moisture content at the ridge and the moisture content at the valley.

Levy et al [40] found that the drying of coal has the same inclination, verifying this observation. In their research they dried coal at various bed depths, keeping the other drying parameters the same. Different beds of different depths are a simplification of one bed with various depths, as in this research. The figure below shows that a shallow bed is dried to a certain moisture content a lot faster than a deep bed is dried to that same moisture content. Consequently, if these two depths were in the same bed, the shallow depth could be denoted the valley, while the deep depth could be denoted the ridge and, according to their research, after a specific amount of time the difference between the moisture content at the ridge and the moisture content at the valley will be less, as the difference between the bed depths is smaller.

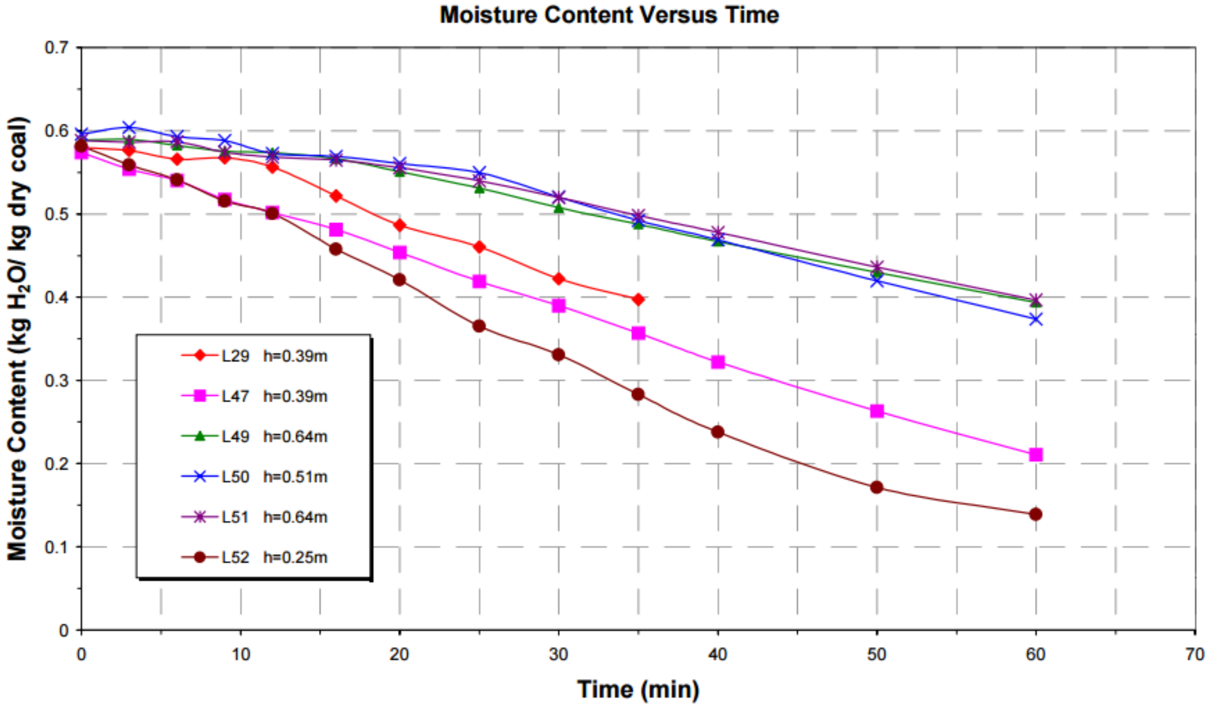

Figure 34 - Drying curves of coal for different bed depths [40]

This means that the lower the amplitude, the closer the bed geometry is to uniform. Just as the difference in moisture content is proportional to the amplitude, the amplitude is proportional to the floorplate length. This is so because of the relationship between the floorplate length and the wavelength of the sine wave that the product bed geometry takes on subsequent to falling through to a next level. Ultimately, to reduce the difference in moisture content, the floorplate length of the multi-level dryer needs to be reduced.

The effect that the length of the floorplates has on the moisture content of the product at different positions in the product bed can be used to predict the difference in moisture content for different floorplate lengths (Figure 27 is an example of this). When designing a multi-level dryer, and with the desired difference in moisture content known, the appropriate floorplate length can be selected in order to achieve the desired output.

6.1.6. Uniform drying can be achieved with a non-uniform bed geometry

In Figure 24 to Figure 27 it was found that the geometry of the product on the bed need not be completely flat for uniform drying to occur. If the amplitude of the product on the bed is small enough, the product at the ridge and the product at the valley will experience similar drying conditions. The steps to be taken to determine the amplitude value that would still allow uniform drying is shown in Section 5.3.2. Note that this value will differ with different drying parameters and product geometry. This maximum amplitude can be used to determine a maximum floorplate length that would still provide uniform drying of the product.

Being able to identify the maximum length of a floorplate is a great advantage, since the manufacturing cost of a dryer can be reduced. Longer floorplate lengths would imply less laser cutting, fewer shafts, fewer bushes or bearings, etc. (see Appendix B).

6.2. Recommendations for future research

All the drying parameters have a specific effect on the drying of the product. These parameters also have an interrelating effect on one another. For example, if a product is dried to a certain moisture content at a certain temperature, the same moisture content can be reached at a different temperature by adjusting any of the other parameters accordingly. In this research, the effect that air temperature and air velocity have on each other was investigated, but the simultaneous interrelation effects of all the other parameters was not investigated. The effect that the amplitude of the product bed geometry has on the drying has only been investigated individually, keeping all other parameters constant.

Important future work will be to investigate the effect that each parameter has on drying under all possible conditions, with respect to the other drying parameters. Doing this will make it possible to create a matrix consisting of the drying parameters to which the system is most sensitive. The difference in moisture content between the valley and the ridge, or moisture content of the product after drying, whatever is selected as the dependent variable of the matrix, can then simply be read off the matrix for the relevant drying conditions.

The most significant drying parameters that may be investigated include:

- Air temperature
- Air velocity
- Geometry of the product on the bed (for a multi-level dryer that delivers a sine wave-like geometry as investigated in this dissertation, this point may be simplified to the magnitude of the amplitude, i.e. floorplate length)
- Residence time
- Type of product to be dried.

Using the results obtained from future investigations suggested above, an improved approach to selecting the correct drying parameters to achieve the desired drying outputs can be determined and implemented.

6.3. Closure

The effect of the product distribution geometry on the drying of extruded maize pellets was closely examined in this dissertation. It has been confirmed that a non-uniform product bed geometry does in fact have an effect on the drying of the product.

For the specific geometry examined in this dissertation, there is often a considerable difference between the moisture content of the product at the ridge and the moisture content of the product at the valley.

If, in industry, the specific application requires all of the product in the batch to be dried to the same final moisture content, the acceptability of the use of this type of dryer is dependent on the amplitude of the product on the bed. If the amplitude of the product on the bed is small enough, the product at the ridge and the product at the valley will experience drying conditions that differ so little that the entire batch of product will have the same moisture content after drying. If the amplitude is larger than the maximum amplitude for uniform drying, this type of dryer is not an acceptable option.

However, if there is an acceptable tolerance with respect to the final moisture content to which the product is to be dried, this type of dryer can be used, provided that it is designed utilising the research presented.

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Appendix A

Concept design process

Many different concepts could have been used and a dryer that still satisfies the requirements would have been delivered. The other possibilities, however, have all been decided against for one reason or another. This appendix shows the design path followed and the criteria used in the selection of concepts.

A.1. Design tree

The design tree shows the different possible concepts that have been considered and the concept that was selected. The chosen path is indicated in red.

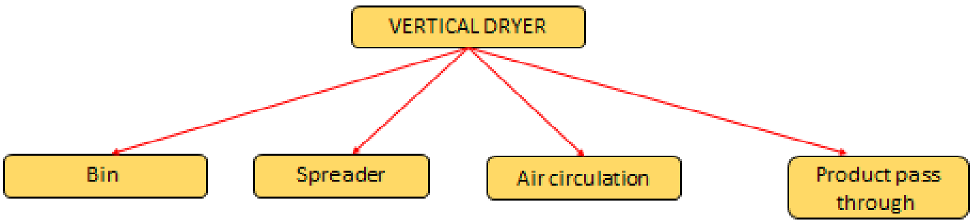

Figure A-1: Different divisions of the dryer to design

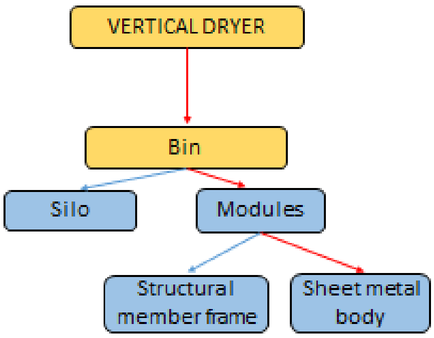

Figure A-2: Concepts to consider for the bin

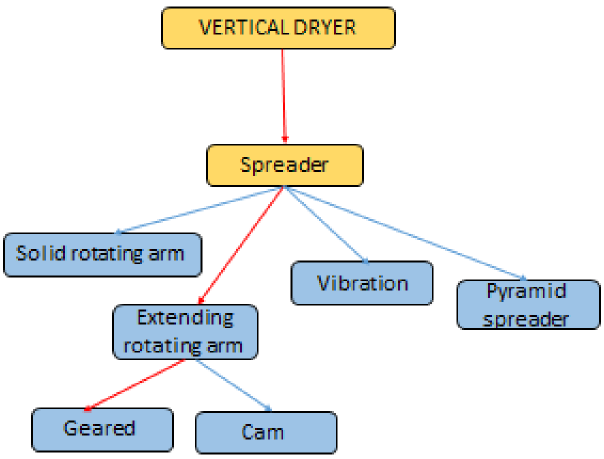

Figure A-3: Concepts to consider for the spreader

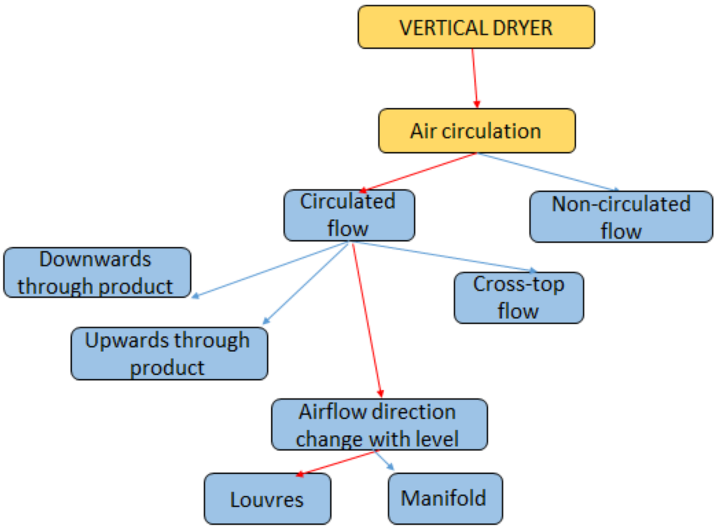

Figure A-4: Concepts to consider for the air circulation

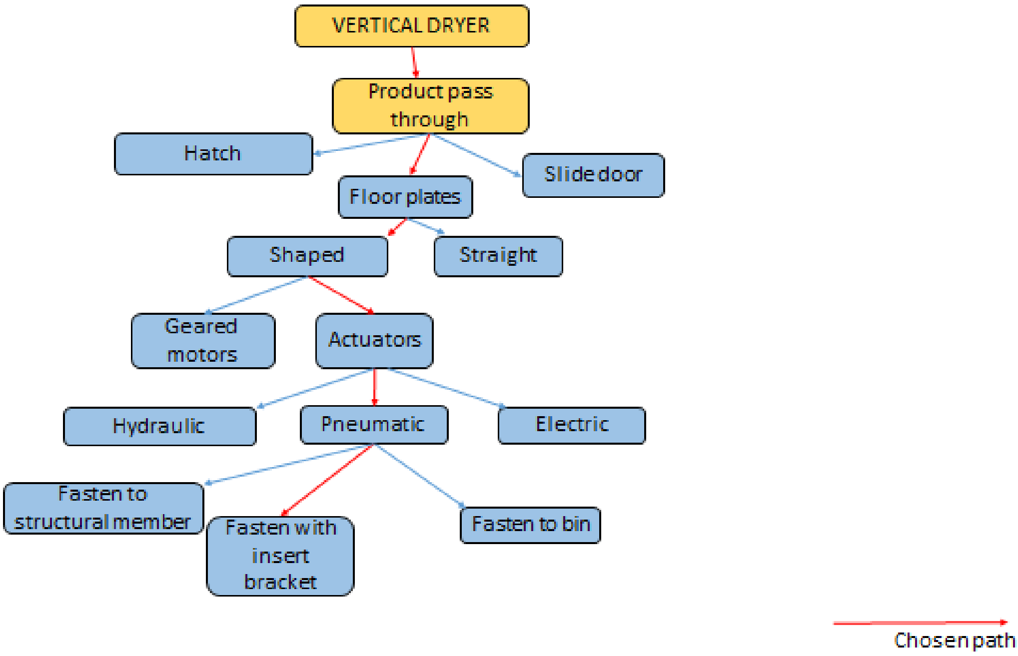

Figure A-5: Concepts to consider for the product pass-through

A.2. Evaluation of concepts

A.2.1. Bin

The bin constitutes the physical sides of the dryer.

A.2.1.1. Silo/module

A silo would mean the entire dryer, in its length, is one part. If the dryer is modular, it is compiled of vertical sections, identical to one another, that stack on top of one another.

Table A-1: Advantages and disadvantages table 1

	Advantages	Disadvantages
Silo	• Sturdy	• Large • Size unchangeable
Module	• Size of the dryer can be changed • Easy to maintain in hard to reach places	• Many fasteners required

Table A-2: Criteria evaluation table 1

Criteria	Weighted percentage	Maximum	Silo	Module
Ease of maintenance	50.00%	10	2	8
Ease of manufacturing	20.00%	10	8	3
Tendency to leak	10.00%	10	5	7
Cost	20.00%	10	5	6
Total		10	4.1	6.5
Total percentage	100.00%		41.00%	**65.00%**

According to this criteria evaluation, the better option is a modular dryer.

A.2.1.2. Structural member frame/sheet metal body

A structural member frame would consist of numerous structural members welded or bolted together with panels in between, whereas a sheet metal body consists only of sheet metal parts with holes etc. cut out with a laser cutter.

Table A-3: Advantages and disadvantages table 2

	Advantages	Disadvantages
Structural member frame	• Less expensive	• Labour-intensive to manufacture • Heavy
Sheet metal body	• Easily manufactured • Relatively light weight	• More expensive

Table A-4: Criteria evaluation table 2

Criteria	Weighted percentage	Maximum	Structural member frame	Sheet metal body
Transportability	30.00%	10	2	4
Ease of manufacturing	40.00%	10	3	8
Ease of assembly	10.00%	10	3	5
Cost	20.00%	10	7	5
Total		10	3.5	5.9
Total percentage	100.00%		35.00%	**59.00%**

According to this criteria evaluation, the better option is a sheet metal body.

A.2.2. Spreader

The spreader is at the top of the dryer. It spreads incoming product from the extruder uniformly on the first level of the dryer.

A.2.2.1. Solid rotating arm/ extending rotating arm/ vibration/ pyramid spreader

The solid rotating arm is a steel rod, simply rotating a pre-set distance above the level on which the product falls. As the product heaps up past this point, the rod knocks it off. The extending rotating arm does exactly the same, except that it extends into the corners of the bin, covering the whole area. For vibration, the top level vibrates, spreading the product heap. A pyramid spreader has many stationary rods perpendicular to the direction in which the product falls. The product falling through hits these crossbars and ends up falling more uniformly.

Table A-5: Advantages and disadvantages table 3

	Advantages	Disadvantages
Solid rotating arm	• Less expensive	• Does not spread in corners of bin • May form clods
Extending rotating arm	• Spreads effectively	• More expensive • More moving parts
Vibration	• Spreads entire area	• Expensive • Will increase fatigue tension
Pyramid spreader	• Inexpensive • Easily maintained	• Large • Does not spread as effectively

Table A-6: Criteria evaluation table 3

Criteria	Weighted percentage	Maximum	Solid rotating arm	Extending rotating arm	Vibration	Pyramid spreader
Effective spreading	35.00%	10	3	8	4	4
Ease of manufacturing	35.00%	10	5	4	3	6
Maintenance	10.00%	10	6	5	5	6
Cost	20.00%	10	7	5	2	7
Total		10	4.8	5.7	3.35	5.5
Total percentage	100.00%		48.00%	**57.00%**	33.50%	55.00%

According to this criteria evaluation, the better option is the extending rotating arm.

A.2.2.2. Geared/cam

Geared refers to the rotating arm being extended with gears, while cam refers to the arm's movement induced by a cam.

Table A-7: Advantages and disadvantages table 4

	Advantages	Disadvantages
Geared	• Sturdier	• Likely to get stuck • More expensive
Cam	• Easy to maintain • Will not break easily	• Takes up larger area

Table A-8: Criteria evaluation table 4

Criteria	Weighted percentage	Maximum	Geared	Cam
Effective spreading	35.00%	10	7	5
Sturdiness	30.00%	10	6	4
Maintenance	15.00%	10	4	7
Cost	20.00%	10	5	5
Total		10	5.85	5
Total percentage	100.00%		**58.50%**	50.00%

According to this criteria evaluation, the better option is geared.

A.2.3. Air circulation

The air circulation is the circulation of air both through the product beds as well as outside of the dryer itself.

A.2.3.1. Circulated flow/non-circulated flow

Circulated flow means some of the heated air exiting the dryer is recycled and reused. With non-circulated air, all is exhausted from the system after going through the product beds once.

Table A-9: Advantages and disadvantages table 5

	Advantages	Disadvantages
Circulated flow	• Air already pre-heated • Saves energy	• Air may be moist • Extra ducting for air movement
Non-circulated flow	• Less ducting for air flow • Air completely dry	• Wastes energy

Table A-10: Criteria evaluation table 5

Criteria	Weighted percentage	Maximum	Circulated flow	Non-circulated flow
Energy efficiency	40.00%	10	7	3
Humidity ratio	30.00%	10	4	5
Maintenance	10.00%	10	4	6
Cost	20.00%	10	5	6
Total		10	5.4	4.5
Total percentage	100.00%		**54.00%**	45.00%

According to this criteria evaluation, the better option is circulated flow.

A.2.3.2. Downwards through product/upwards through product/airflow direction change with level/cross-top flow

Air circulation downwards through the product would mean that the air enters above and moves down, going through each bed. Air circulation upwards through the product is the same movement, except that the air enters from underneath and goes through each bed on the way up. Either way, the product still enters from above and goes down as it dries, therefore the air flow direction has a great impact on drying. For air flow direction changing with level, the air moves up through the bed on one level and down through the bed on another level, continuously alternating. Cross-top air flow means the air flows parallel to the product bed, entering on one side and leaving on the other.

Table A-11: Advantages and disadvantages table 6

	Advantages	Disadvantages
Downward through product	• Hot air meets hot product and colder air meets colder product	• Air may become saturated before it exists the dryer
Upwards through product	• Dust particles can be exhausted before reaching other product beds	• Hot air meets colder product and colder air meets hot product
Airflow direction changes with level	• All parts of the bed get flow through them	• Air might be reused when this is not wanted
Cross-top flow	• Air flow easily controlled	• Very little air flow through the bed

Table A-12: Criteria evaluation table 6

Criteria	Weighted percentage	Maximum	Downward through product	Upward through product	Airflow direction changes with level	Cross-top flow
Drying efficiency	45.00%	10	5	4	7	1
Entire bed reached	30.00%	10	5	5	7	4
Possibility to fluidise	5.00%	10	7	2	4	7
Cost	20.00%	10	5	5	4	6
Total		10	5.1	4.4	6.25	3.2
Total percentage	100.00%		51.00%	44.00%	**62.50%**	32.00%

According to this criteria evaluation, the better option is for the airflow to change direction with each level.

A.2.3.3. Louvres/manifold

If the dryer uses the louvre concept, extra sheet metal panels will be added on opposite sides of the product beds and the entire space will serve as an airflow channel, with the air able to enter the product beds through louvres. If manifolds are used, a pipe or ducting system from level to level will be added in which the air can flow.

Table A-13: Advantages and disadvantages table 7

	Advantages	Disadvantages
Louvres	• Simple to manufacture • Easy to insert	• More prone to air leakage
Manifold	• Aesthetically good	• Time-consuming to assemble • More expensive

Table A-14: Criteria evaluation table 7

Criteria	Weighted percentage	Maximum	Louvres	Manifold
Easy to manufacture	35.00%	10	8	4
Prone to air leakage	35.00%	10	4	5
Aesthetics	10.00%	10	5	6
Cost	20.00%	10	6	4
Total		10	5.9	4.55
Total percentage	100.00%		**59.00%**	45.50%

According to this criteria evaluation, the better option is the louvre.

A.2.4. Product pass-through

Product pass-through refers to the concept according to which the product is displaced from one level to the next.

A.2.4.1. Hatch/floorplates/sliding door

When using a hatch, the entire floor of a level is a single plate that falls open when needed. The floorplates are the plates in each section that, orientated horizontally, form a floor for that section and, orientated vertically, allow the product to fall through to the next section. A sliding door is also a single plate, but slides sideways for the product to fall through.

Table A-15: Advantages and disadvantages table 8

	Advantages	Disadvantages
Hatch	• Easy to manufacture • Easy to replace	• Space-consuming • Does not disperse evenly
Floorplates	• Takes little space • Disperses relatively evenly	• Many moving parts
Sliding door	• Easy to manufacture	• Space-consuming • Does not disperse evenly

Table A-16: Criteria evaluation table 8

Criteria	Weighted percentage	Maximum	Hatch	Floorplates	Sliding door
Easy to manufacture	20.00%	10	8	4	7
Disperses evenly	35.00%	10	3	8	6
Space-efficient	25.00%	10	3	8	3
Cost	20.00%	10	8	4	7
Total		10	5	6.4	5.65
Total percentage	100.00%		50.00%	**64.00%**	56.50%

According to this criteria evaluation, the better option is the floorplates.

A.2.4.2. Shaped/straight

Shaped floorplates are lipped while straight floorplates are simply flat, perforated sheet metal.

Table A-17: Advantages and disadvantages table 9

	Advantages	Disadvantages
Straight	• Easy to manufacture • Cost-effective	• Flaccid
Shaped	• Rigid	• More expensive to manufacture

Table A-18: Criteria evaluation table 9

Criteria	Weighted percentage	Maximum	Straight	Shaped
Stiffness	50.00%	10	2	8
Ease of manufacturing	14.00%	10	8	3
Minimising product fall-through	16.00%	10	6	5
Cost	20.00%	10	8	5
Total		10	4.68	6.22
Total percentage	100.00%		46.80%	**62.20%**

According to this criteria evaluation, the better option is the shaped floorplates.

A.2.4.3. Geared motors/actuators

Each floorplate of the dryer rotates around its axis. This rotation is either effected by geared motors, connected with gears, or actuators, connected with connecting arms.

Table A-19: Advantages and disadvantages table 10

	Advantages	Disadvantages
Geared motors	• Accurate	• Many moving parts • Can seize more easily
Actuators	• Longevity • Fewer moving parts	• May contaminate product

Table A-20: Criteria evaluation table 10

Criteria	Weighted percentage	Maximum	Geared motors	Actuators
Longevity	40.00%	10	5	8
Leakage	30.00%	10	0	3
Moving parts	10.00%	10	3	5
Cost	20.00%	10	5	4
Total		10	3.3	5.4
Total percentage	100.00%		33.00%	**54.00%**

According to this criteria evaluation, the better option is the use of actuators.

A.2.4.4. Hydraulic/pneumatic/electric

The actuators are required to open and close the floorplates. Different types of actuators will give different results in achieving this.

Table A-21: Advantages and disadvantages table 11

	Advantages	Disadvantages
Pneumatic	• Clean system • Rapid movement • Physically smaller	• Less power output
Hydraulic	• Larger power output	• Risk of oil contamination
Electric	• Low operational cost	• High component cost

Table A-22: Criteria evaluation table 11

Criteria	Weighted percentage	Maximum	Pneumatic	Hydraulic	Electric
Cleanliness	50.00%	10	8	2	6
Rapid movement	14.00%	10	8	3	5
Power output	16.00%	10	2	8	5
Weight	10.00%	10	6	3	4
Cost	10.00%	10	5	6	4
Total		10	6.54	3.6	5.3
Total percentage	100.00%		**65.40%**	36.00%	53.00%

According to this criteria evaluation, the better option is the use of pneumatic actuators.

A.2.4.5. Fasten to structural member/fasten with insert bracket/fasten to bin

The actuators will have different outcomes if fastened in different ways. The optimum way to fasten the actuators has to be determined.

Table A-23: Advantages and disadvantages table 12

	Advantages	Disadvantages
To sheet metal (bin)	• Very simple	• Might damage bin
To structural member	• Strong	• Aesthetically poor • Difficult to assemble
With insert bracket	• Rigid • Aesthetically good • Strengthens bin	• Expensive

Table A-24: Criteria evaluation table 12

Criteria	Weighted percentage	Maximum	To sheet metal (bin)	To structural member	With insert bracket
Easy to manufacture	14.00%	10	8	2	5
Aesthetics	20.00%	10	8	3	8
Rigidness	50.00%	10	3	8	6
Allows free movement	6.00%	10	5	4	5
Cost	10.00%	10	6	3	9
Total		10	5.12	5.42	6.5
Total percentage	100.00%		51.20%	54.20%	**65.00%**

According to this criteria evaluation, the better option is to fasten the actuator with an insert bracket.

Appendix B

Proposed concept design

This appendix gives a layout of the proposed concept design. The multi-level dryer is a modular dryer. This means it consists of several segments, or levels, that are identical to one another. Understanding a single level is critical in understanding the entire dryer.

B.1. Single level

Examining a single level gives a thorough understanding of the dryer, which aids in understanding the geometry of the product on the bed subsequent to falling through the floorplates and the drying thereof.

B.1.1. Representative illustrations

The series of figures given below are of a single level of the multi-level dryer.

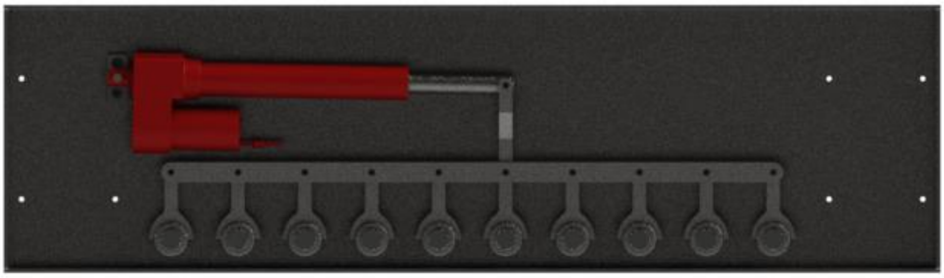

Figure B-1: Front view

Figure B-2: Left view

Figure B-3: Right view

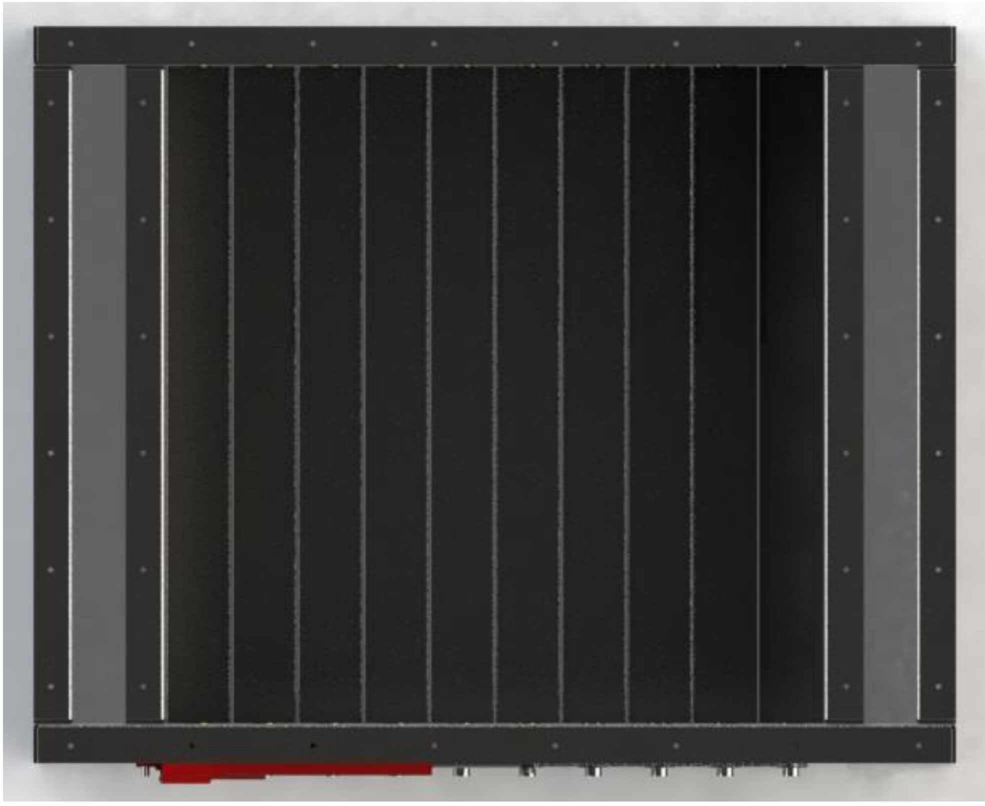

Figure B-4: Top view

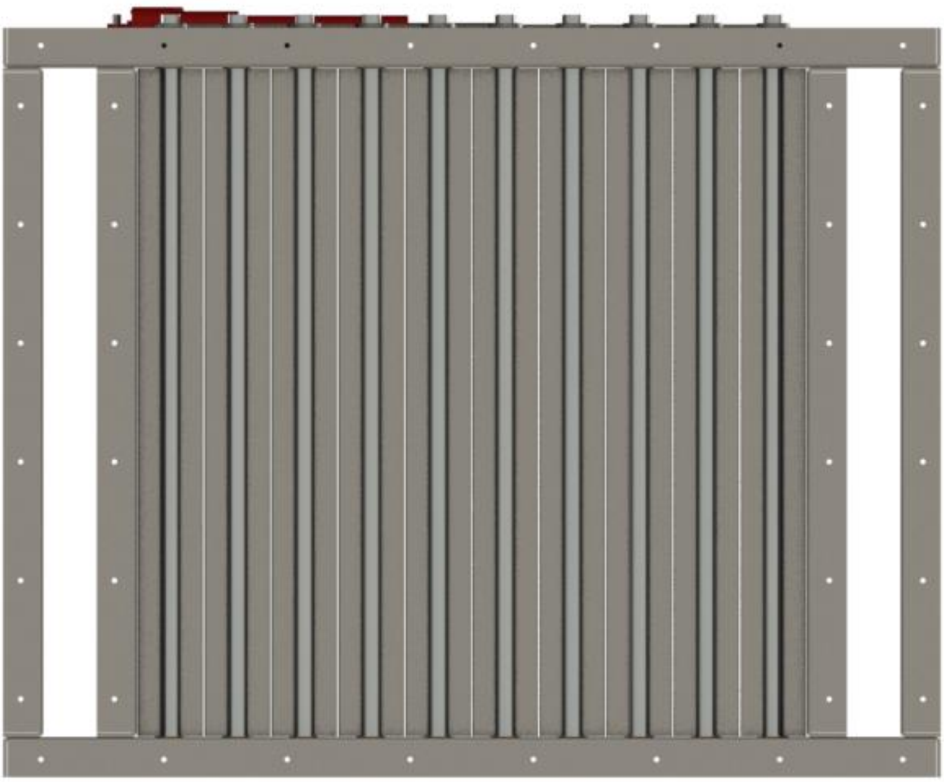

Figure B-5: Bottom view

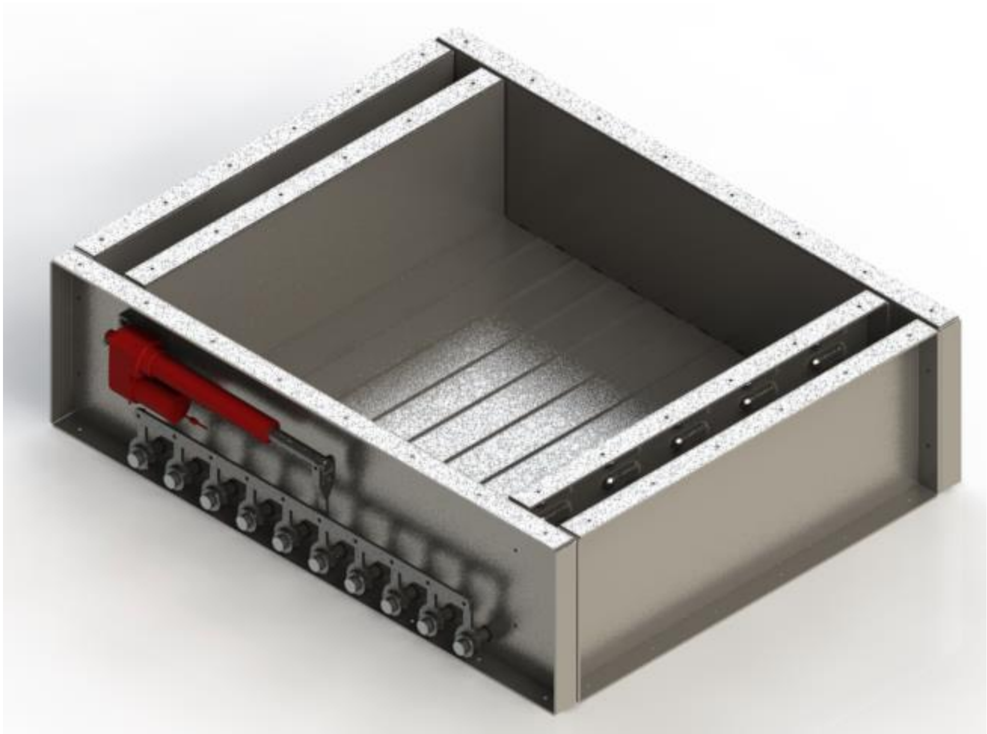

Figure B-6: Isometric view with floorplates closed

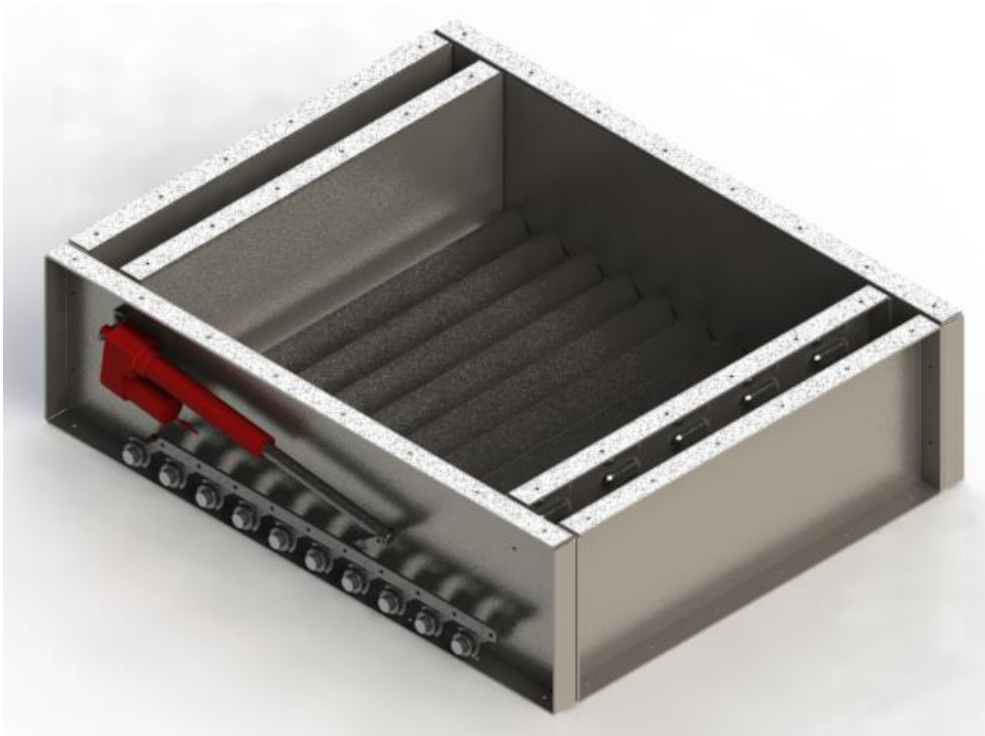

Figure B-7: Isometric view with floorplates open

Figure B-8: Isometric view (first angle orthographic projection) with floorplates closed

Figure B-9: Isometric view (first angle orthographic projection) with floorplates open

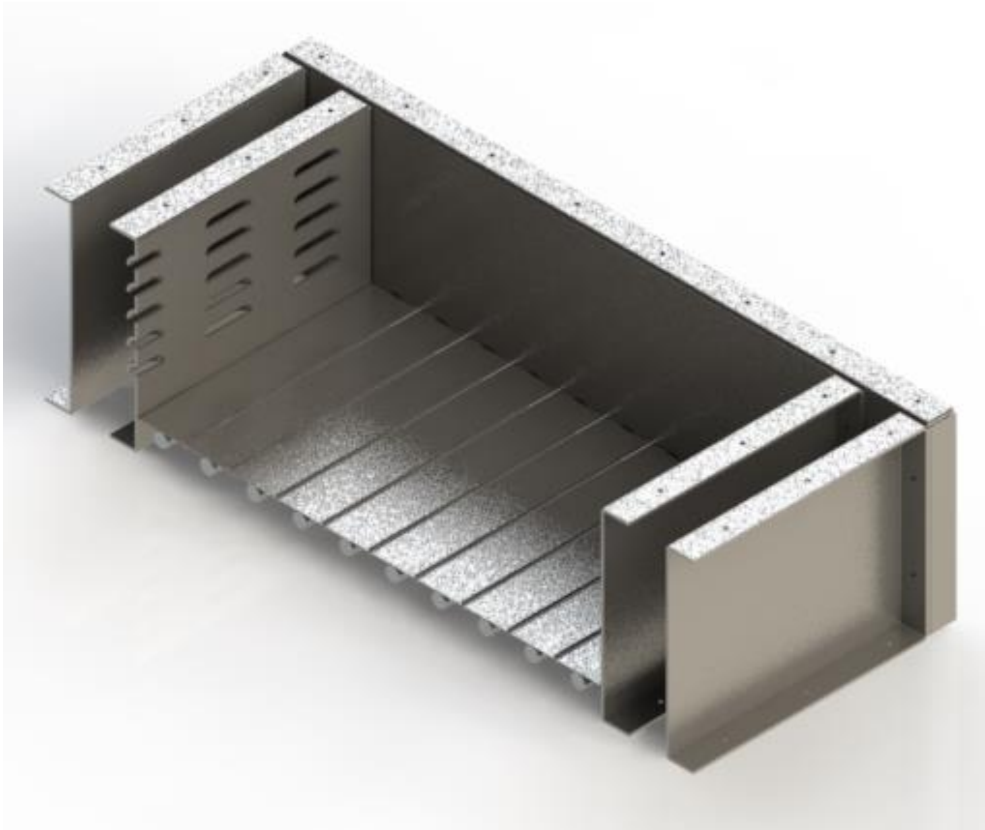

Figure B-10: Section view

B.1.2. Bin

The dryer's bin is manufactured with several sheet metal parts. Each sheet metal part is bent at all four edges to increase its strength, as well as to form a lip by which different levels of the dryer can be bolted together. One of the sheet metal parts has many louvres in it for the desired airflow. Section C.3. describes the airflow.

Figure B-11: Isometric view of one of the sheet metal parts

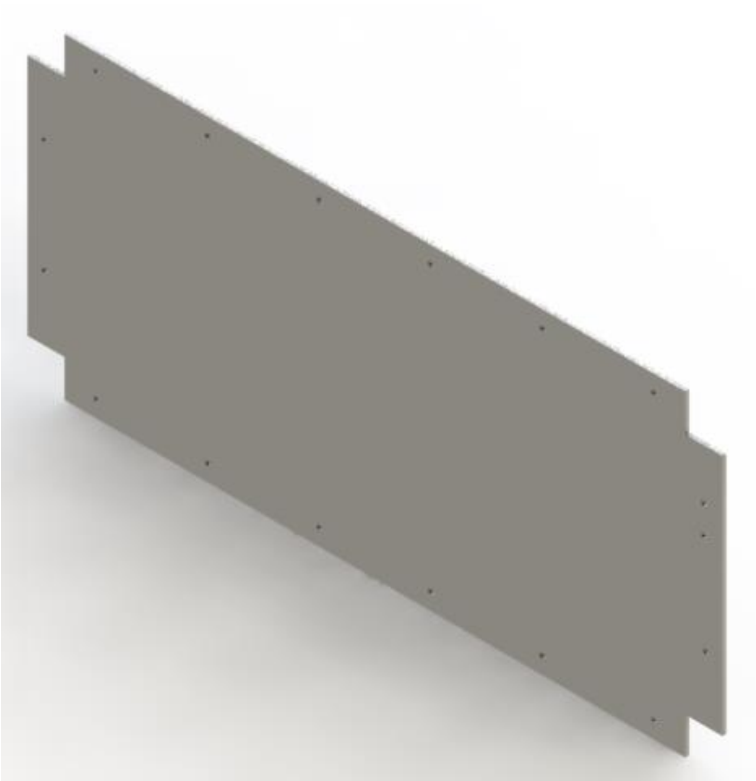

Figure B-12: Isometric view of a flat pattern of one of the sheet metal parts

Figure B-13: Isometric view of a sheet metal part with holes where the shafts that rotate the floorplates are supported

Figure B-14: Isometric view of the louvred sheet metal part

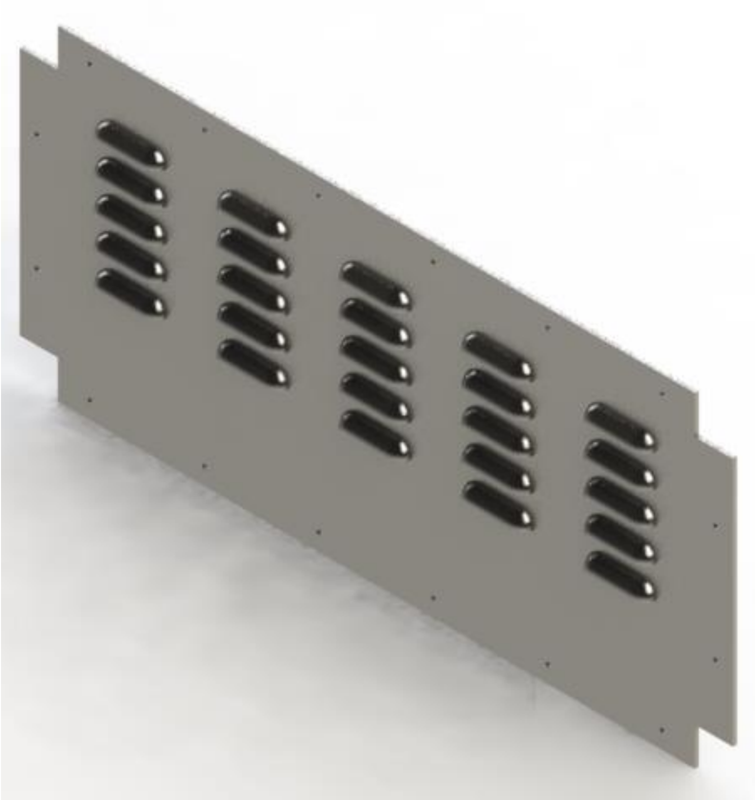

Figure B-15: Isometric view of a flat pattern of the louvred sheet metal part

B.1.3. Perforated floorplates

The floorplates are several pieces of sheet metal that lie next to one another to form a floor on which the product rests. When the shafts rotate, the floorplates fixed to it rotate and the product falls through to the next level. It is manufactured of perforated plate to allow for sufficient airflow through the product and the edges are lipped to increase its strength and prevent deformation. A bush ensures minimum friction between the shafts and the bin.

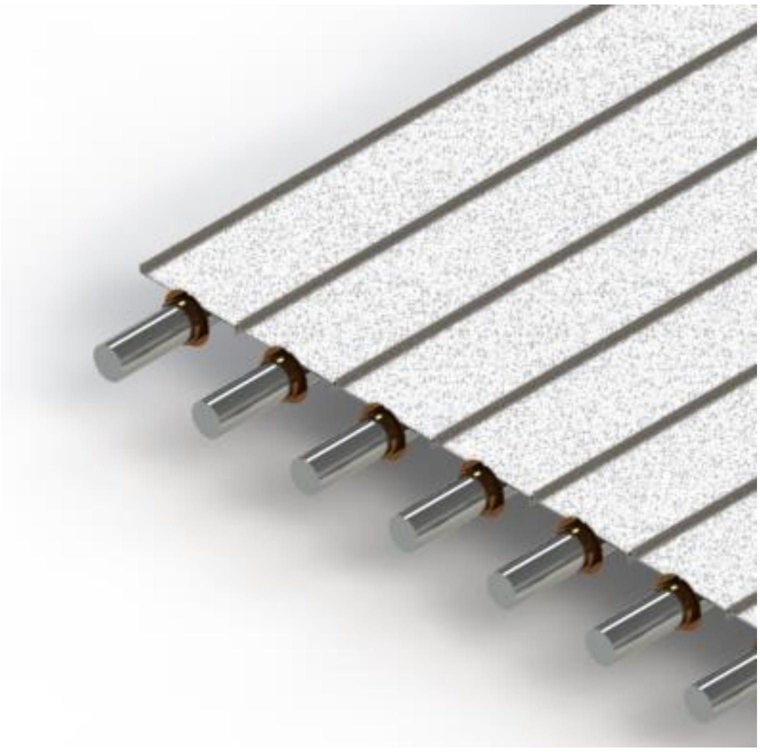

Figure B-16: Floor with floorplates in closed position

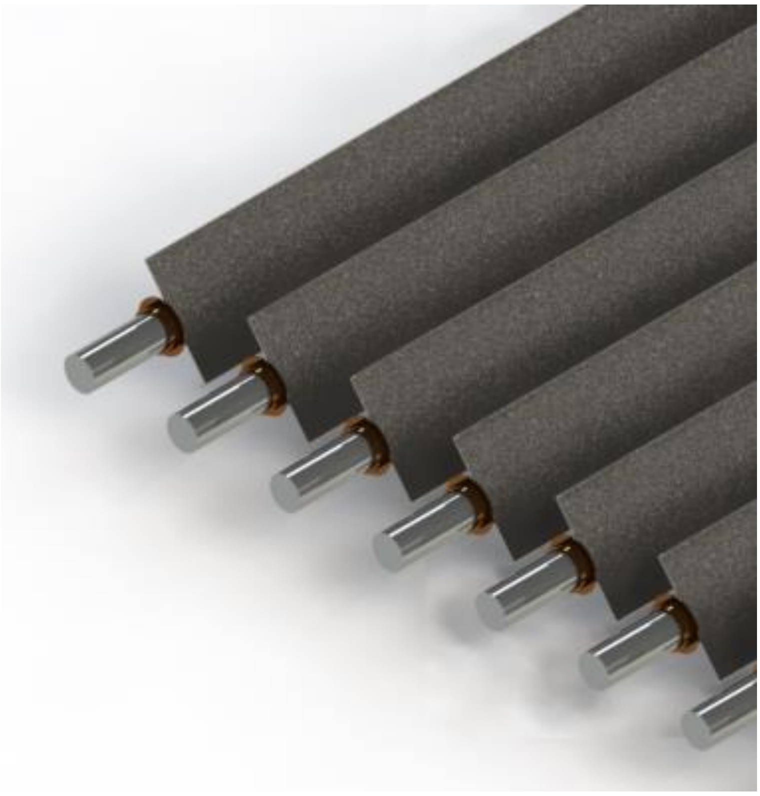

Figure B-17: Floor with floorplates in open position

Figure B-18: Shape in which floorplates are bent

B.1.4. Actuator and actuator mechanism

The actuator is used to open and close the floorplates. During drying the product falls on the floor and after a pre-set amount of time the actuator extends, opening the floorplates, and retracts, closing the floorplates.

Figure B-19: Actuator

The actuator is fastened to the bin of the dryer by bolting an insert-bracket on which the actuator is free to pivot to the bin and securing it with a lock nut.

Figure B-20: Actuator's insert bracket

The actuator is fixed to the mechanism with a pin through the forked arm that is connected to all the other connecting arms.

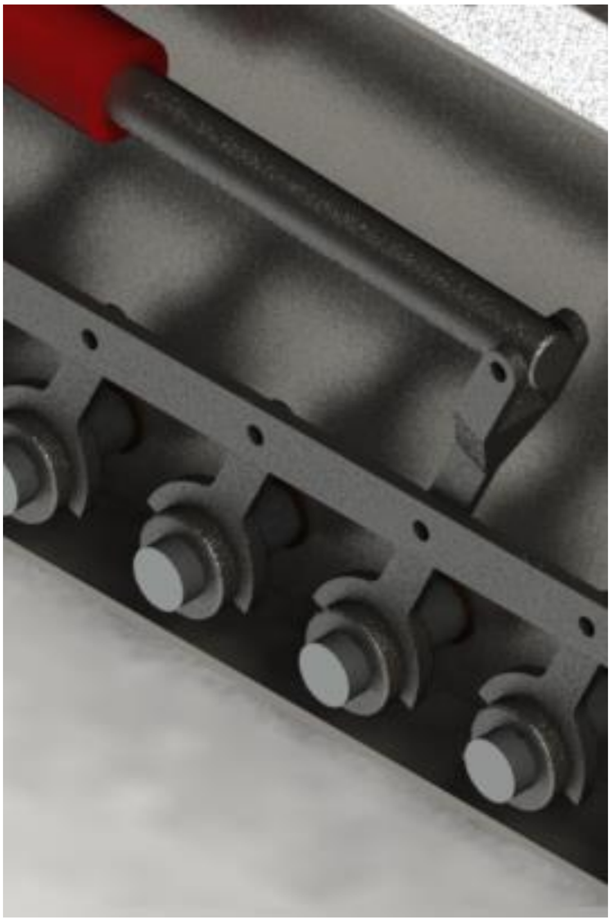

Figure B-21: Forked arm connection

A series of connecting arms transfers the linear motion of the actuator as rotational motion to the shafts, ultimately opening or closing the floorplates.

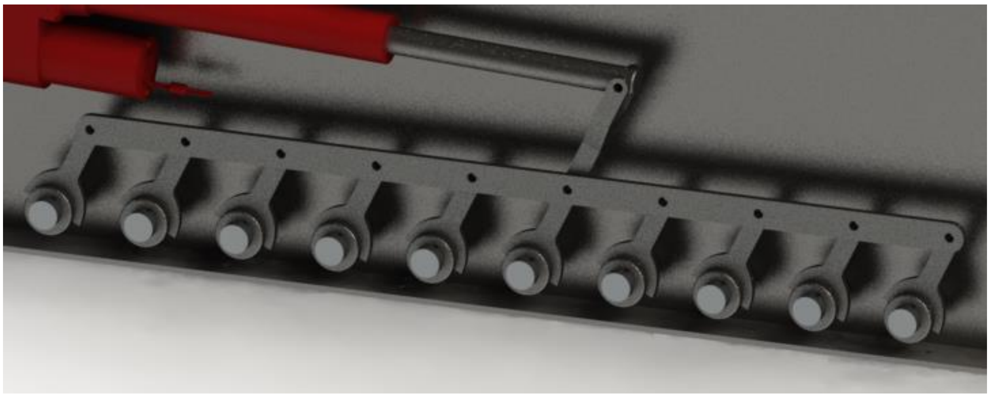

Figure B-22: Connecting arms

The connecting arms, laser cut from sheet metal, are welded onto a weld-on hub, which is fixed to the shaft with a key.

Figure B-23: Weld-on hub

B.2. Multiple levels

As mentioned, the multi-level dryer is modular. Several of these modules discussed above can be stacked on top of one another to form the dryer. There is no limit to the number of modules that can be stacked on one another; the number is dependent on product quantity, final moisture content, available vertical height, etc.

Not included in figures B-24 through B-26 are the dryer stand and the spreader. The stand is below the dryer, keeping it off the floor of the facility, and has a chute or conveyance pipe that exports the dried product to the next stage. The spreader is on top of the dryer, uniformly spreading the moist product that comes from the extruder on the top level of the dryer.

Figure B-24: Modules stacked on top of one another forming the multi-level dryer

Every second level is angled 180^{O} to its prior level. This is so that the louvres are opposite one another, forcing the airflow through the product bed. Another advantage of this orientation is that the actuators open in the opposite direction on every second level, resulting in proper agitation of the product.

B.3. Airflow through the multi-level dryer

Note the chambers that form on the opposite sides of the dryer. These are airflow chambers, through which the air enters and exits.

Figure B-25: Section view with all floorplates closed

The air flows through one of these airflow chambers, through the louvres (at different levels), through the product, through the louvres on the opposite side and into the other airflow chamber.

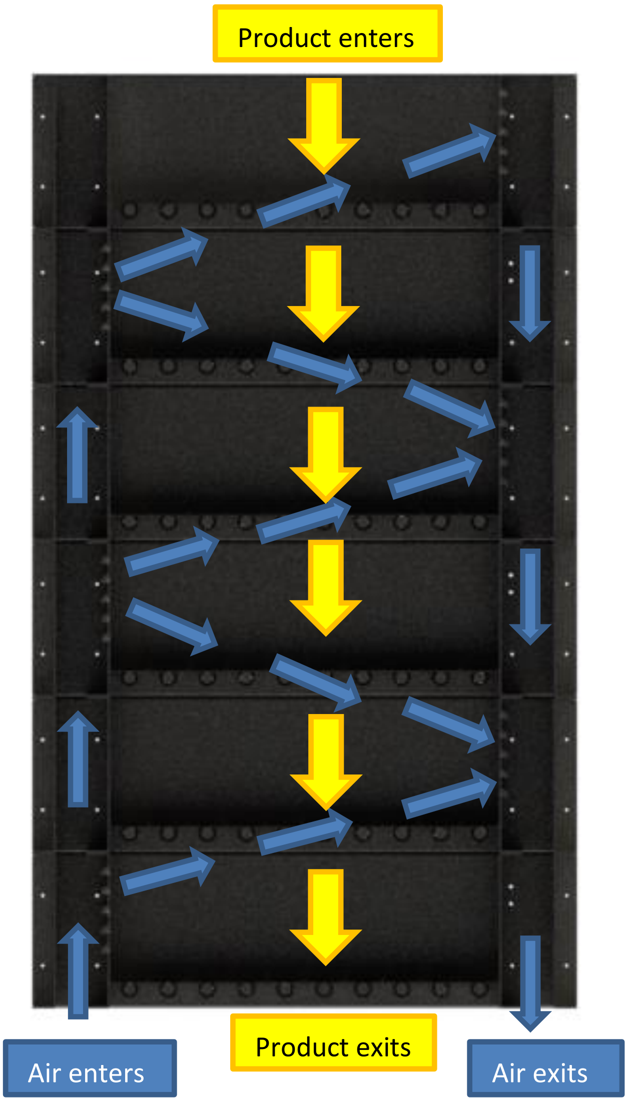

Figure B-26: Airflow through the multi-level dryer

The air enters at the bottom of the dryer and follows the arrowed path to where it exits. This means that some air goes through all the product beds, while other air only goes through one or two product beds. Less air on the top floors, where the product is still hot and moist, as well as the fact that once the air reaches the top it is slightly colder, will minimise case hardening.

Appendix C

Test bench photos

This appendix contains photos taken of the test bench explained in Section 3.1. This is to understand exactly how the tests were done to obtain the results presented in this dissertation.

Figure C-1: Finished test bench

Figure C-2: Test bench during construction A

Figure C-3: Test bench during construction B

Figure C-4: Inside test bench (baffle plates visible)