UNIVERSITY OF SOUTHERN QUEENSLAND

THE DRYING OF ABATTOIR PAUNCH FOR WASTE-TO-ENERGY CONVERSION

A Thesis submitted by

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Abstract

Abattoir paunch waste has the potential to become a site-specific, viable, waste-to-energy stream for adoption within the red meat processing industry. While the literature suggests numerous end uses for dried paunch, the high initial moisture content makes undried paunch a waste product of little to no value to the industry. Thus, this thesis aims to determine some of the specific properties of paunch to determine its inherent drying behaviour. If the initial moisture content of paunch can be reduced in a cost effective manner it can become a useful biomass for industrial uses such as co-combustion, pyrolysis, or gasification. Thus, the aim of the thesis is to characterise paunch waste and develop predictive equations to enable assessment of its re-use as a biomass. To achieve the aim this thesis determined drying rates, energy content, equilibrium moisture content, bulk density, and the latent heat of vaporisation of paunch to allow predictive equations to be developed to inform the future design and modelling of a paunch drying method.

To enable characterisation of paunch a new thin layer dryer was developed using an environment chamber with purpose built load cells used to record weight changes over time. The results obtained in this study showed that the thin layer drying constant, *k*, varied from 0.0002 to 0.0029 min^{-n} with an average *n* value of 1.42 ± 0.081 for 35 to 55 °C operating air at 40, 50, 60, and 80% relative humidity. The equilibrium moisture content varied from 7.14 to 13.44% moisture content and constants for the Chung-Pfost equation were determined. Calorific values varied from 17 to 20 MJ/kg for grass and grain type paunches respectively. Based on newly derived equations the bulk density for untapped paunch ranged from 106 kg/m^3 (dry) to 504 kg/m^3 (100%) and for tapped 152 kg/m^3(dry) to 862 kg/m^3(100%). The energy density values for paunch varied from 4 865 to −2 110 MJ/m^3. The latent heat of vaporisation for paunch varied from 3 741 to 2 519 kJ/kg for 6 to 15% moisture content. A solution to the Hukill deep-bed drying equation was found with new coefficients specific to paunch determined for the dimensionless time unit.

The paunch drying characteristics in this study are expected to benefit Australian and international red meat processing plants by allowing a fundamental understanding of paunch behaviour. This understanding will inform the design of paunch dryers and the selection of appropriate end uses based on the intrinsic properties of paunch such as the energy content and energy density.

Certification of Thesis

This thesis is entirely the work of Jennifer Spence except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Student and supervisors signatures of endorsement are held at USQ.

Prof. B. Carter

Principal Supervisor

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List of contributions from publication co-authors

This section details contributions by the various authors for each paper included in this thesis.

Appendix D – AMPC technical report

NCEA 2016, *Development of methodologies for characterising paunch waste (PW) to inform dewatering/drying technologies*, Technical report, Australian Red Meat Processor Corporation (AMPC), Sydney, Australia.

This report was written by J. Spence on behalf of NCEA USQ as part of her PhD thesis. This technical report was funded by Australian Red Meat Processor Corporation (AMPC).

Author	Percent Contribution	Tasks Performed
J. Spence	95%	Data collection and analysis, interim, final report and snapshot
NCEA	5%	Editing

Appendix E – Conference paper

Spence, J, Buttsworth, D, McCabe, BK, Baillie, C, Antille, D & Carter, B 2016, 'Abattoir paunch waste as a biomass energy source: investigations into drying rates', *Proceedings Venice2016, Sixth International Symposium on Energy from Biomass and Waste*, CISA Publisher, Venice, Italy.

This paper was presented by J. Spence at the Venice 2016, Sixth International Symposium on Energy from Biomass and Waste. It has been published in the conference proceedings.

Author	**Percent Contribution**	**Tasks Performed**
J. Spence	85%	Data collection and analysis, all drafts of paper.
D. Buttsworth	10%	Data analysis.
Others	5%	Suggested changes to manuscript.

Appendix F – Energy paper

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Author	**Percent Contribution**	**Tasks Performed**
J. Spence	90%	Data collection and analysis, all drafts of paper.
D. Buttsworth B. Carter	10%	Technical advice, Suggested changes to manuscript.

Appendix G – Thin layer drying rates paper

Spence, J, Buttsworth, D, McCabe, BK, Baillie, C, Antille, D & Carter, B 2017, 'Investigation into thin layer drying rates and equilibrium moisture content of abattoir paunch waste', Renewable Energy Journal, https://doi.org/10.1016/j.renene.2017.07.082

This paper is based on the Venice2016, Sixth International Symposium on Energy from Biomass and Waste conference paper presented by J. Spence. It has been accepted and the first revised copy of the abstract has been included in Appendix G.

Author	Percent Contribution	Tasks Performed
J. Spence	85%	Data collection and analysis, all drafts of paper.
D. Buttsworth B. Carter D. Antille	13%	Data analysis, editing, Suggested changes to manuscript.
Others	2%	Editing

Paper collaboration

McCabe, B, Antille, DL, Birt, HWG, Spence, JE, Fernana, JM, Vander Spek, W & Baillie, CP 2016, *An investigation into the fertilizer potential of slaughterhouse cattle paunch*, American Society of Agricultural and Biological Engineers Annual International Meeting, ASABE, USA.

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Abbreviations

AMPC	Australian Red Meat Processor Corporation
BOD	Biochemical oxygen demand
EMC	Equilibrium moisture content
d.b	Dry basis
GHG	Greenhouse gas
HSCW	Hot standard carcass weight
HHV	Higher heating value
LHV	Lower heating value
MC	Moisture content
MLA	Meat and Livestock Australia
MR	Moisture ratio
RH	Relative humidity
RMP	Red meat processing
TS	Total solids
w.b	Wet basis
wb	Wet bulb

Chapter 1 : Introduction

'Climate change is destroying our path to sustainability. Ours is a world of looming challenges and increasingly limited resources. Sustainable development offers the best chance to adjust our course'

(Ban Ki-Moon)

1.0 Renewable energy

As global energy demand rises along with concerns over the use of fossil fuels, organic waste is increasingly seen as a renewable energy source for the future. Some nations routinely use general organic waste on an industrial scale to produce energy; for example, Denmark employing some 30 municipal waste incineration plants to create heating and/ or generate electricity (Ramboll 2006). Associated research, in the use of general organic waste such as municipal solid waste streams for use in gasification, has also attracted much attention in recent years (Morrin et al. 2014). In parallel with these developments there is also an opportunity to research and utilise more industry-specific organic waste streams, given that they are potential sources of on-site renewable energy production. More specifically, this thesis is concerned with the use of paunch, a significant by-product of the red meat processing (RMP) industry globally.

Renewable energy technologies have been integrated into Australian industry to varying degrees. This implementation of renewables has been limited mainly by the higher cost of the renewable energy source compared to the cost of the competing fossil fuel derived energy resulting in long pay-back periods for the renewable alternative. In Australia, until recently, electricity prices remained low and stable which combined with a lack of Australian Government support, funding, and initiatives in the renewable sector made the implementation of renewable technology undesirable. However, recent Australian electricity price increases
and changing government policy on greenhouse gas (GHG) emissions has created a renewed interest in renewable energy technologies as a means of reducing emissions and creating a more sustainable future for Australian industry.

1.1 Australian red meat processing industry

The Australian RMP industry is Australia's largest food manufacturer and exporter (Edge 2012) and is extremely energy and resource intensive. Australia currently has approximately 150 RMP sites operating in all states and territories, ranging from beef only, sheep only, and mixed processing facilities (Primary Industries Standing Committee 2009, AMPC 2015). A large RMP plant is defined by Meat and Livestock Australia (MLA) as processing over 600 head per day of beef which equates to approximately 42 300 tonne hot standard carcass weight (tHSCW) per year with average emissions of 554 kg $CO_{2\text{-}e}$/tHSCW and water consumption of 9.4 kL/tHSCW (GHD 2011). In a study of 15 RMP sites the breakdown of the total energy demand was 31.6% grid electricity, 37% natural gas, 19% coal with 67% of total energy emissions related to electricity use (GHD 2011). To become sustainable the Australian RMP industry must thus look towards renewable energy to reduce their reliance on fossil fuel sources and reduce their environmental footprint.

RMP produces a number of potential waste to energy streams. Animal waste materials and animal byproducts form part of the definition for "renewable biomass" in the Energy Independence and Security Act (2007) (Boundy et al. 2011). RMP waste streams include paunch solids (grass and grain from the first stomach of ruminant animals) and liquids, pen manure, and waste water. The main types of organic solid waste generated during meat processing include manure, paunch contents, solids from primary treatment and biological solids from wastewater treatment (AMPC 2012).

1.2 Paunch as a biofuel

Biomass from paunch represents a promising waste stream to recover energy. So given that paunch currently has little or no value to the Australian RMP industry, any conversion of paunch into a useful biomass will be of benefit to RMP sites. Australian abattoirs currently undertake one of several options to address paunch waste management including i) removing paunch and other solids off site; ii) composting material on-site and used on-site; and iii) composting material on-site and used off-site. Jensen et al. (2014) have investigated paunch wastewater as a possible waste stream for biogas production in Australian abattoirs, however, unlike other countries which use the paunch content of slaughterhouse waste in the production of biogas (Poschl, Ward, & Owende 2010), there has been limited uptake of the solid paunch content in anaerobic digestion for methane production in Australia.

Early studies have provided indications that paunch has the potential to be of benefit to RMP sites including uses in gasification or as a stock feed (e.g. Baumann 1971, Ricci 1977). However, since that time (1970's), little has been done to turn this waste product into a value added commodity. While composting and land/farm disposal does occur (Jensen et a. 2014) it is an otherwise absolute waste product left over from the meat processing with inherent costly disposal/ treatment difficulties such as its high biochemical oxygen demand (BOD) (Ricci 1977). It has comparable energy content to that of other biomass products and when used as an energy source in Australia it has the potential to create greenhouse gas (GHG) and energy credits (Bridle 2011), making it a suitable renewable candidate. It has the potential to become an industry specific renewable energy source for the Australian RMP industry for use in the boiler as a coal replacement, in co-combustion units, or for pyrolysis (eds Witherow & Scaief 1976, Bridle 2011). However, little research has been done on paunch as an energy source which has limited the uptake of this potential waste to energy stream.

The current management and handling of paunch creates no added benefit to the Australian RMP industry. Paunch is potentially better value to the RMP industry as an energy source (e.g. co-combustion) as opposed to composting (a common end use for paunch) due to the GHG reduction and potential energy it could generate. As a RMP by-product paunch accounts for a large amount of GHG emissions, but its impact would be reduced if it was made useful as a biomass for renewable energy. To become sustainable the Australian RMP industry can now look towards renewable energy technology to help lower their operating costs and reduce their environmental footprint.

Given its intrinsic properties, paunch may be a viable RMP industry renewable energy fuel source. Early energy measurements done with a Parr Oxygen Bomb Calorimeter showed that paunch has an average energy content of 16.7 MJ/kg (Ricci 1977). This energy content is comparable to switch grass (a renewable biomass crop) which has an energy content of 18.4 MJ/kg, as shown in Table 1.1 (McLaughlin et al. 1999). However, the energy content for paunch is variable due to the different feed rations fed to the livestock. Approximately 23–25 kg of paunch is produced per head of cattle (wet weight) or roughly 3.8 kg dry weight (Ricci 1977, eds Witherow & Scaief 1976, Doyle & Lant 2001). Based on dry weight, a large processing plant (600 head of cattle per day), would produce approximately 2.3 tonnes of paunch per day. A study done by Bridle (2011) states that each tonne of paunch used as an energy source could generate GHG credits of up to 1 tonne $CO_{2\text{-}e}$ and gain energy credits up to 3.2 gigajoules depending on current and future emission reduction policy. These energy credit benefits combined with its high energy content make paunch a suitable biomass candidate.

Table 1-1. Comparison of (dry) energy contents for paunch, switch grass, coal, and wood. Paunch appears to have a lower energy content than coal but is comparable to switch grass and wood in energy content.

Biomass type	Energy content (MJ/kg)	Reference
Paunch	16.7	Ricci (1977)
Switch grass	18.4	McLaughlin et al. (1999)
Coal	27.4	McLaughlin et al. (1999)
Wood	19.6	McLaughlin et al. (1999)

1.3 Barriers to the implementation of paunch as a renewable energy source

Paunch as a biofuel could enable a problematic organic waste product to become a useful energy source for abattoirs. Why then is paunch yet to be implemented into the Australian RMP industry as a renewable energy source? Literature would suggest that the lack of progress is due to the high initial moisture content (MC) of paunch (around 80–85% when dewatered of surface water (Ricci 1977, eds Witherow & Scaief 1976)). Paunch has a self-sustaining flame when the total solids are ≥ 30% (eds Witherow &

Scaief 1976, Bridle 2011). However, as stated by Bridle (2011), burning paunch with 70% MC would only be suitable as a waste disposal method with the paunch itself providing little or no energy. If paunch were to be used as a coal substitute or for co-combustion for efficient boiler output, the paunch would need a substantially lower MC than 70% (w.b) as water content impacts boiler output and is boiler specific. Hatt (1997) states that boiler efficiency loss is approximately 0.1% for each 1% increase in MC. Coal ranges in MC from 2.2–39% depending on the type of coal. If boiler output drops due to MC it is possible to increase the feed rate of the boiler to increase the output but a more efficient way is to decrease the initial MC of the feedstock, in this case paunch. In addition, Bridle (2011) found that for use in pyrolysis the paunch needs to be reduced to 20% MC. These MC values reveal that some form of drying is required to lower the initial MC in order for paunch to become a biofuel. *Therefore, it appears that the drying of paunch is the major drawback in implementing paunch as a renewable energy source.*

Sun drying of paunch (spreading a thin layer of product over an area to dry in the sun) is not an appropriate drying method for most Australian abattoirs due to the large surface area required for drying and potential for wet days, flooding and other environmental concerns of runoff and pest infestation. While most Australian abattoirs do have access to vacant land it is generally reserved for wastewater treatment ponds which are then irrigated onto crops growing on adjacent land. This demonstrates a clear need to design a suitable method for paunch drying to create an effective product to be integrated into industry.

1.4 Research Aim

The aim is to physically characterise abattoir paunch waste and develop predictive equations to facilitate assessment of paunch as a useful biomass.

The objectives are:

- Characterise the physical properties of paunch for use as a biomass,
- Develop predictive models for paunch drying.

1.5 Thesis overview

To achieve its aim this thesis investigates drying rates, energy content, equilibrium moisture content, latent heat of vaporisation and effectiveness by empirically simulating the conditions expected for a drying facility on-site at an abattoir. This empirical study is then followed by forecasting paunch drying behaviour using physical and mathematical modelling that accurately reproduces the observed drying behaviour results. The thesis then concludes by discussing and interpreting the paunch characteristics directed at assisting the transformation of paunch from an unwanted waste stream into a viable future source of renewable energy for the RMP industry.

Chapter 2 : Literature Review

2.0 Introduction

Any form of air drying relies on three key conditions. These are; (1) the rate of water removal is dependent on the condition of the air, (2) the properties of the product, and (3) the design of the dryer (Earle 1983). Therefore, there are a number of factors to be considered before an effective procedure for drying a product can be developed. In particular the drying of any material requires knowledge of the materials' specific drying properties (specific to certain air conditions), the materials' composition, and an understanding of drying processes to enable informed choices regarding an appropriate drying method.

2.1 Paunch characteristics

Before a suitable drying method for paunch can be designed there are a number of specific drying properties and paunch characteristics that need to be determined. Table 2.1 demonstrates the limited previous research into the composition of paunch. This table demonstrates variation in the composition of paunch but does not provide detailed information into whether the paunches were predominantly grass fed, grain fed, or a mixture of both (apart from the specified grass fed paunch used in the Bridle (2011) study). The largest variation appears in the carbohydrate value which ranges from 40.8 to 72.9% total solids (TS). This variation in paunch composition is expected due to the large variation in cattle finishing procedures and the types of feed used.

Table 2-1. Previous research done on the composition of paunch. Values show some variation between studies.

Composition %				
Moisture	**Protein**	**Ash**	**Carbohydrate**	**References**
6.8	12.7	7.2	40.8	Witherow & Scaief (eds) (1976), Baumann (1971)
15.3	10.3	6.7	42	Ricci (1977)
13.3	8.1	13.5, 7.02, 7.7	72.9	Bridle (2010, 2011a,b)

There are a number of finishing procedures for cattle being prepared for slaughter. These procedures are used to increase the weight and quality of the end product. Finishing procedures include pasture finishing, lotfeeding and intensive finishing (including opportunity feedlots used to fatten stock when feed prices are low and fat prices high (Seirer 1995)), supplementary feeding, and drought feeding (MLA 2012). Feedlot rations should contain roughage, grain, and minerals with 70–80% of the ration being grain (DPI 2011). Table 2.2 demonstrates the finishing ration percentages that should be used for feedlot cattle. The roughage is generally hay or silage (fermented, high moisture fodder) but 50% of the roughage can be comprised of poor quality feed such as straw (DPI 2011). The grain component can be comprised of barley, wheat, triticale, sorghum, maize, lupins, or oats. Growth promoters, protein supplements, and minerals are also fed to improve the quality of the end product (DPI 2011). The possible variation in finishing procedures demonstrates the difficulty in precisely classifying the composition of paunch.

Table 2-2. The finishing ration percentages that should be used for feedlot cattle (DPI 2011).

Finishing ration	Ration if protein of hay roughage is adequate in %	Ration if protein of hay roughage is inadequate in %
Grain	75	70
Roughage	20	20
Protein concentrate	-	5
Minerals/vitamins	5	5
Total	**100**	**100**

As well as the variation in finishing procedures there is also variation in the paunch composition due to whether the cattle are slaughtered on the day they arrive at the abattoir or whether they are held over due to a delay such as a weekend. In either case the cattle are most likely to be given hay or grazed in a holding paddock and this alters the paunch composition.

2.2 Ruminant digestive tract

It takes cattle between 1–3 days for food to pass through the digestive tract (Rounds & Herd n.d). The ruminant digestive system differs from monogastric digestive tracts in that instead of one stomach as seen in monogastric, the ruminant stomach is comprised of four compartments: the rumen (produces the paunch waste stream at abattoirs), reticulum, omasum, and abomasum (Rounds & Herd n.d). The rumen is the largest compartment, contains 50% of the total digestive tract capacity, is constantly mixing the contents, contains billions of bacteria, protozoa, and fungus, has a ph ranging from 5.5–7.0, and a temperature between 37–40 °C (Rounds & Herd n.d, Hall & Silver 2009, De Mulder et al. 2016). The delay of up to three days digestive time clearly shows paunch contents are highly dependent on the type of feed given during the finishing process and time of slaughter.

2.3 Current paunch management and handling in Australian abattoirs

The current best practice for paunch handling includes dry dumping instead of wet dumping (Doyle & Lant 2001, MIRINZ 1996), the separation of the solids from the liquid followed by land disposal of the solids for uses such as composting or worm feed. In essence, this means that the paunch is first dry dumped, the contents are dumped out without the addition of water and then the emptied rumen is umbrella washed. The paunch then passes through some form of dewaterer such as a screw press separator or contra shear screen which is situated above a holding area (Figure 2.1). The separator dewaters the paunch of most of its surface water, thus separating the liquid from the solid. The resulting liquid waste stream, once separated from the solids, passes to holding ponds while the solid waste is collected for landfill, as compost, or spread on fields (Spence 2012). Currently there is very little benefit being gained from the paunch solids produced at Australian RMP sites, with paunch having negative value to those sites having to pay disposal fees for landfill (AMPC & MLA 2012).

Figure 2-1. Paunch on site at an Australian RMP plant passes from a screw press to fall into a pile in the cement holding area.

For paunch to become a useful biomass several paunch properties and characteristics need to be developed to allow informative paunch drying times to be developed specifically for grass, grain, or mixed type paunches. Energy content and energy density are required to determine the end viability of paunch for use as a biomass. Drying curves/ rates along with equilibrium moisture contents (EMC) for each type of paunch need to be determined to allow drying time predictions (and modelling of paunch drying) to be made. Also knowledge of the bulk density and latent heat of vaporisation of the paunch will be required to help develop a suitable dryer design.

2.4 Drying principles — Surface drying

There are a number of external, general factors that affect paunch drying. These factors can be divided into two groups, depending on the different stages of drying. The first stage of drying is the evaporative stage which has a constant drying period and is mostly affected by temperature and relative humidity (RH). The second stage is the internal migration of water to the surface which has a falling rate drying period and is mostly affected by temperature and particle size (Brenndorfer et al. 1985).

The factors that affect the two different drying stages are shown in Table 2.3. For surface evaporation, higher temperature and lower RH will produce faster drying rates. In addition higher air velocity also creates faster drying rates, however this effect is limited above certain velocities and once reached will no longer increase the drying rate. RH is a percentage of how much water is in the air compared to how much water the air can hold. Warmer air can hold more water and therefore, has a lower RH than cooler air (BOM 2011). RH is important when it comes to drying as it acts as a medium to remove moisture from the surface of a product.

Table 2-3. Factors that affect the evaporative and internal moisture migration stages of drying (Brenndorfer et al. 1985).

Surface evaporation	Internal migration
Temperature; Warmer air greater evaporation rate	Temperature is important
More humid slower evaporation rate	Humidity not important (apart from where it affects the evaporation from the surface).
Velocity (movement of air) greater evaporation rate but the gain is limited above certain velocities	Air velocity is no longer important
Unaffected by particle size of the sample to be dried	Size of particle is important
Heat conduction and radiation of drying chamber can also add to rate	Physical structure of the solid, solid porosity. Moisture content.

2.4.1 Surface drying

Evaporation from a wet surface (as long as the surface remains wet) can be considered the same as for evaporation from a free water surface and is mostly affected by temperature and humidity (Brenndorfer et al. 1985). The reduced Penman equation demonstrates some of the factors that influence drying rates.

$$E = AR_n + B(a+bW)D; \qquad (2.1)$$

where E is the evaporation rate, R_n, is the net radiation, W is the wind speed, A and B are coefficients that contain physical properties of air and water vapour, a and b are empirically determined values, and D is the saturation deficit of the air (Mason & Hughes 2001).

The evaporative rate, E, can be broken into two terms, a radiation term, AR_n, and an aerodynamic term, $B(a + bW)D$. These terms are dependent on: the amount of radiation available for evaporation, temperature and RH as related to the saturation deficit, and wind speed. Large D and W terms are generated by hot, dry air and these are therefore, large contributors to the potential evaporative rate (Mason & Hughes 2001).

2.4.2 Subsurface drying

For moisture to migrate from the interior of a product to the surface there are two underlying principles, diffusion and capillary flow (Brenndorfer et al. 1985). The equation for diffusion of a liquid through a solid tells us that the moisture rate decreases with bigger particle sizes (Brenndorfer et al. 1985). Therefore, this second drying stage is the limiting factor in drying times, as when there is sufficient moisture (moisture gradient) in the material there is a constant flow of moisture to the surface which is then evaporated. However, once the material starts to dry this rate drops and then tends to zero once EMC has been reached (Brenndorfer et al. 1985). Temperature and the physical structure and porosity of the product are also important in the second stage of drying.

2.5 Experience with drying times and techniques

A number of studies have been published regarding the possible benefits of dried paunch. As early as 1971 it was suggested that paunch be dried using a gas-fired dehydrator and then used as a feed additive (Baumann 1971). Of the papers produced that specifically relate to paunch drying, the drying constants produced from these papers are of little value due to the constants either being specific to that studies' particular dryer or only done for one temperature (35 °C). However, the earlier findings associated with the performance of paunch drying are beneficial to the field of knowledge into paunch behaviour. For example, a study by Farmer, Brusewitz & Moustafa (1979) revealed that drying times were increased from 7 to 10 to 12 days if the crust was not agitated during drying. In some cases where the second stage of drying is predominant, a hard impermeable skin is formed on top of a product. The material is then called casehardened and such behaviour is characteristic of paunch. Paunch forms an outer crust that acts to seal the paunch and significantly reduce the migration of moisture from the interior (De Baerdemaeker & Horsfield 1976, cited by Farmer, Farouk, Brusewitz 1980). This can be seen on site as paunch left in a pile will develop a dry outer layer while the inside will start to compost after 24 hours. A possible method for dealing with casehardening is to retard evaporation and keep it in phase with the internal migration of moisture from the interior thereby not allowing a crust to form. This improvement could be achieved by increasing the RH and therefore lowering the evaporative rate, while not affecting the second stage of drying (Mujumdar 2007). Another method is to agitate the paunch during drying as per the Farmer, Brusewitz and Moustafa (1979) study and Yin and Farmer (as cited in eds Witherow & Scaief 1976) who built a solar dryer with mechanical agitation after trying to sun dry paunch (spreading a 10cm layer out in the sun). They built the solar still to combat problems encountered with sun drying such as rain rewetting the paunch, hand agitation, fly, and odour problems. Their study dried paunch to 16–20% MC in a week.

Drying constants characterise the rate of drying by combining all the transport properties of drying (i.e. thermal conductivity, moisture diffusivity, interface heat, and mass transfer coefficient) into a simple exponential function (Mujumdar 2007). Drying constants are applicable to constant air conditions and are themselves a function of MC, material temperature and thickness, air humidity, temperature, and velocity (Mujumdar 2007). The results of Farmer, Farouk, and Brusewitz's (1980) study showed that their average drying rate is only relevant to their specific solar dryer design. The measurements in their study were performed over a 24 hour period in a pilot sized solar dryer, and therefore are not a true value for average drying rates of paunch as it included large variations in temperature such as those experienced between day and night when the dryer would have been inactive. Farmer, Farouk, and Brusewitz (1980) had ambient temperatures between 10–25 °C, with operating temperatures of 15–50 °C at the high end of their dryer and 15–35 °C at the low end. The drying times were also restricted by the temperatures reachable by the dryer design (higher operating temperatures may have given much higher drying rates) and impacted by climatic conditions such as the daily maximum ambient temperature and RH. Notwithstanding this, the benefits of the study lies in the demonstration of a working solar dryer able to dry paunch from 80–30% MC (w.b) in five days.

Griffith and Brusewitz (1980) conducted a study using a tunnel dryer to determine the drying rate of paunch. The study was based on their assumption that air temperature is not controllable in a dryer whereas RH is. Therefore, the study investigated drying rates at 35 °C air temperature with 20, 50, 80% RH at a depth of 2.5–10.2 cm.

Spence (2012) did a comparison study to the Griffith and Brusewitz (1980) study using a similar tunnel dryer design. The results in the Spence (2012) study were analysed using Griffith and Brusewitz (1980) and Farmer, Farouk, and Brusewitz (1980) equations. Griffith and Brusewitz (1980) measured a drying rate constant, *k*, of 0.005 to 0.108 /hr for their preliminary results and an average rate of 1.17 and 1.14 /hr for their main experiment. It is interesting to note the range of more than an order of magnitude in the drying constant values provided by Griffith and Brusewitz (1980). In comparison, the Spence (2012) experimental *k* values varied from 0.0643 to 0.1703 /hr. While these fall within the range given by Griffith and Brusewitz (1980) caution should be exercised in making direct comparisons with the results from the Spence (2012) study. This is because while both experiments had similar designs, Griffith and Brusewitz's (1980) experiment used a lower temperature of 35 °C, and used RH that ranged higher, up to 80%. Griffith and Brusewitz's (1980) results also used paunch from just three different cows whereas the Spence (2012) experimental results used paunch obtained from a screw press, for each separate run, with the paunch being either grass or grain fed in origin, or a mixture of both, from many cows. The drying rates obtained in the past studies appear to have limited application in future work (such as being specific to a certain dryer) or show discrepancies between *k* values.

The literature demonstrates a clear lack of understanding of inherent paunch characteristics. As stated by Brenndorfer et.al. (1985), the failings of most solar dryer designs is that a dryer is designed and then an application sought, there is a lack of appreciation of the environment for which the dryer is intended, and the final design is frequently inappropriate which restricts the uptake of the new technology. Paunch characteristics need to be understood before an optimum dyer can be designed. Optimum dryer design is reliant on information such as drying rates under set conditions, the initial and desired final MC of a product, and the drying characteristics such as maximum drying temperature (Brenndorfer et. al 1985). Without this information, it is not possible to design a suitable dryer or to determine whether a dryer is operating under optimum conditions.

2.6 Conclusion

Changes need to be made in regards to current paunch treatment methods used by the RMP industry as paunch is currently viewed as a waste product of little, zero, or negative economic value by industry. On the other hand, the research done to date shows that paunch is a promising by-product suited to a waste-to-energy conversion stream for industry to adopt. The problem remains however that there is no consensus as to the best method to dry paunch effectively for use as a biomass energy product. Thus, a physical characterisation of the paunch drying process is needed, to allow a systematic approach to the effective design of a paunch dryer. An understanding of paunch drying behaviour can therefore help enable a problematic waste stream to become a value adding commodity for the RMP industry in Australia and globally.

Chapter 3 : Overview of paunch characterisation

3.0 Paunch characterisation introduction

The literature regarding paunch drying studies suggests that some form of drying will be required to lower the initial MC of paunch to allow implementation into industry as a waste-to-energy stream (e.g. Ricci 1977, eds Witherow & Scaief 1976, Bridle 2011). However, sun drying is not a viable option due to the large amount of land required and pilot dryers have been trialled with only slightly better drying rates than sun drying. Therefore, a systematic characterisation and approach is needed to allow understanding of the specific properties of paunch to help in the development of paunch as a biomass. The initial work includes the need to identify and calculate:

- type of paunch
- initial MC
- thin layer drying rates
- equilibrium MC
- energy content
- bulk density
- latent heat of vaporisation

As a result of this information, a depth drying model will be developed that will provide varying parameters to be used to assist in future dryer design and testing of drying equipment.

3.1 Experimental equipment

The main objective of this study is to measure some of the fundamental characteristics of paunch. The experimental equipment for determining paunch characteristics comprised of several components:

- moisture balance, OHAUS MB45 (USA)
- psychrometer
- environmental chamber, Steridium (Brisbane)
- wind speed indicator, Davis instruments Turbo Meter
- load cell, 50 g
- load cell, 500 g
- microcontroller and software, Picaxe
- oxygen bomb calorimeter, XRY-1A (China)
- Benzoic acid one gram pellets (Parr instrument Co., USA)
- digital scales
- various measuring cylinders

3.2 Sample collection and preparation

Currently there is no standard for sampling or testing paunch. The methodology used to obtain paunch samples was based on the Australian Standard Guide to Sampling of Particulate Materials (1997) (more information is provided in Appendix D). This standard ensures that all particles in the paunch stream have an equal chance of being selected and used in the final analysis. It also includes ways to eliminate bias by using appropriate handling techniques such as eliminating sample contamination and not changing the samples' MC during collection. The best practice for the preparation of the paunch samples was based on the Australian Standard Guide part 2: Preparation of Samples (1997) with the main aim being to keep the properties of the test samples the same as the original sample (Appendix D). This is important as it reduces collection and preparation error and creates a consistent and repeatable methodology.

Paunch samples were obtained from two separate abattoirs located in South East Queensland, Australia. The paunch was collected directly from a screw press or a contra shear screen depending on the abattoir. A screw press or contra shear screen dewaters the paunch of much of its surface water thus separating the liquid from the solids. The liquid passes to holding ponds while the solid waste is collected for landfill, compost, or spread on fields.

Due to the variation in paunch content, samples were categorized as either grass or grain type paunches. Grass type paunches consisted of only roughage type feed such as grass or hay. Paunches were classified as grain type if there was obvious grain present in the sample. This can be determined visually, based on the particle size and shape of the paunch. Figure 3.1 shows the difference between a predominantly grass type and grain type paunch. Grass type paunches appear as thin rectangular particles while predominantly grain type paunches display thin rectangular particles (as per the grass type paunch) mixed with a variety of possible shapes such as round or ellipsoid particles. The grain type paunch will also feel and look grittier than the grass type paunch.

Figure 3-1. An example of dried grass (left), rectangular particles and grain (right) type paunches, rectangular with round/ovoid particles.

3.3 Moisture content

All paunch samples tested had the initial MC and in most cases, a final MC calculated. MC is the amount of water contained in a material and is given as a ratio or percentage, where 0 is completely dry, and 1 (or 100%) is completely saturated. The MC can be given as a wet or dry moisture basis. The below equations were used to convert between wet (w.b) and dry (d.b) basis MC.

Wet basis is a ratio of the weight of water to the wet weight of the product (Teter 1987) given by:

$$MC_{w.b} = 100 \times \frac{W - D}{W}; \tag{3.1}$$

where $MC_{w.b}$ is the wet basis MC percentage, W is the wet weight, and D is the dry weight.

Dry basis is the ratio of the weight of water to the dry weight of the product (Teter 1987) given by:

$$MC_{d.b} = 100 \times \frac{W - D}{D}; \tag{3.2}$$

where $MC_{d.b}$ is the dry basis MC percentage, W is the wet weight, and D is the dry weight. To convert between wet and dry basis:

$$MC_{w.b} = \frac{100 \times MC_{d.b}}{100 + MC_{d.b}}; \tag{3.3}$$

and

$$MC_{d.b} = \frac{100 \times MC_{w.b}}{100 - MC_{w.b}}; \tag{3.4}$$

where $MC_{w.b}$ is the wet basis MC (%), $MC_{d.b}$ is the dry basis MC (%) (IRRI n.d).

3.4 Moisture content procedure

The moisture content of the paunch was measured in an OHAUS MB45 (USA) moisture balance (Figure 3.2) before (and after when needed) any experimental procedures. The initial MC drying profile for the balance was a step profile, with step 1 set at 200 °C for 10 minutes, step 2 set at 150 °C for 10 minutes, and step 3 set at 105 °C for 25 minutes, for a total run time of 45 minutes. This profile was based on the operation manuals' suggested setting for wet vegetables and tested for repeatability for paunch. The final moisture content and EMC used a standard drying profile set at 100 °C for 45 minutes.

Figure 3-2. Ohaus MB45 moisture balance used to determine initial, final, and equilibrium moisture content.

3.5 Overview conclusion

Sample collection was a standard procedure for all paunch samples and MC measurement was required across a number of experiments. For ease of readability the following chapters contain individual procedures relating to their specific topic.

Chapter 4 : Thin layer drying

4.0 Introduction

A thin layer dryer provides valuable drying information that can be used for product characterization, product quality management and evaluation, product drying computer simulation (using the products specific drying constant), selection and performance testing of drying equipment, and for obtaining a products optimum drying temperature and humidity (ASAE Standards 1999).

Thin layer dryers expose a product to constant air flow (generally about 1 m/s with a minimum flow of 0.3 m/s), temperature, and RH. The definition of a thin layer being a 'layer of material exposed fully to an airstream during drying. The depth (thickness) of the layer should be uniform and should not exceed three layers of particles' (ASAE Standards 1999). During drying the product weight is measured nearly continuously with a required accuracy of 0.2% of the sample mass. Temperature sensors need an accuracy of ± 1 °C, RH needs an accuracy of ± 3%, and air velocity needs an accuracy of ± 5% (ASAE Standards 1999). Having consistent and reliable control over drying conditions is necessary for the accurate quantification of drying parameters. A thin layer dryer is one such way to determine these fundamental parameters.

The concept of using an environment chamber to produce controlled temperature and RH conditions for a thin layer dryer was investigated. Oven and microwave methods have been used to determine thin layer drying models (e.g. Hemis, Singh & Jayas 2011, Omolola, Jideani & Kapila 2015, Hii, Law & Cloke 2008). However, control of RH is difficult or not achievable in these systems. Therefore, this project attempted to create a novel thin layer dryer using a Steridium (Brisbane) environmental chamber to produce consistent air conditions. Initial moisture contents were acquired using an OHAUS MB45 (USA) moisture balance for each sample before being placed inside the chamber. Each sample was weighed every hour by taking the sample out of the chamber, weighing on a digital balance and then placed back inside the dryer. Final moisture contents were obtained at the end of each run using the moisture balance. A number of uncertainties were introduced using this method. This included the temperature and humidity changing each time the door was opened and the chamber needing to restabilise.

In the final design, a load cell (wired into a custom built data logger) was used to record changing weight over time inside the dryer, which removed the need to open and close the chamber door to record weight. Figure 4.1 shows the load cell incorporated into a tray holder which is wired into the data logger. The tray holder and data logger casing were printed using a 3D laser printer located at USQ (Toowoomba). Initial and final MC were obtained for each run using the moisture balance. Samples were placed inside the environment chamber (Figure 4.2) and left until equilibrium MC was achieved. The data obtained was then converted into MC for use in the drying equations.

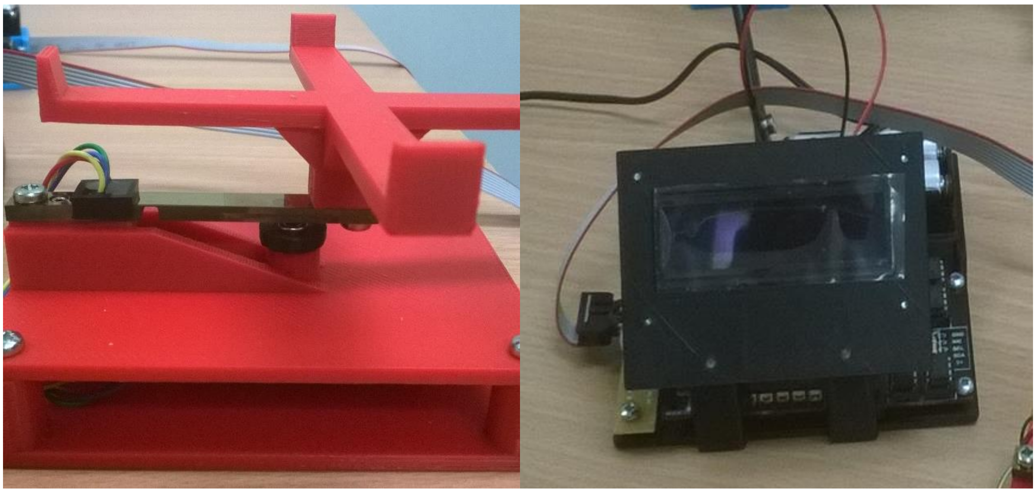

Figure 4-1. A 50 gram load cell and tray holder (left) wired into a custom built data logger (using a Picaxe microcontroller) (right).

Figure 4-2. The Steridium Environmental chamber used to control temperature and relative humidity to allow the determination of thin layer drying rates (load cells were placed on shelves inside the chamber).

4.1 Thin layer equipment calibration

A purpose built thin layer dryer was designed and tested for stability and suitability. The load cells measured a change in resistance with changing weight and this resistance was digitised. Figure 4.3 demonstrates a calibration test using calibrated weights (5 and 10 grams). Combinations of the 5 and 10 gram weights were added and taken off the load cells to check the repeatability of the digitisation. Some error was introduced by placing the weights and taking them off the load cell which caused some fluctuation of the digitisation units however these were within ± 5 channels of the stabilised channel number and stabilised within a couple of readings.

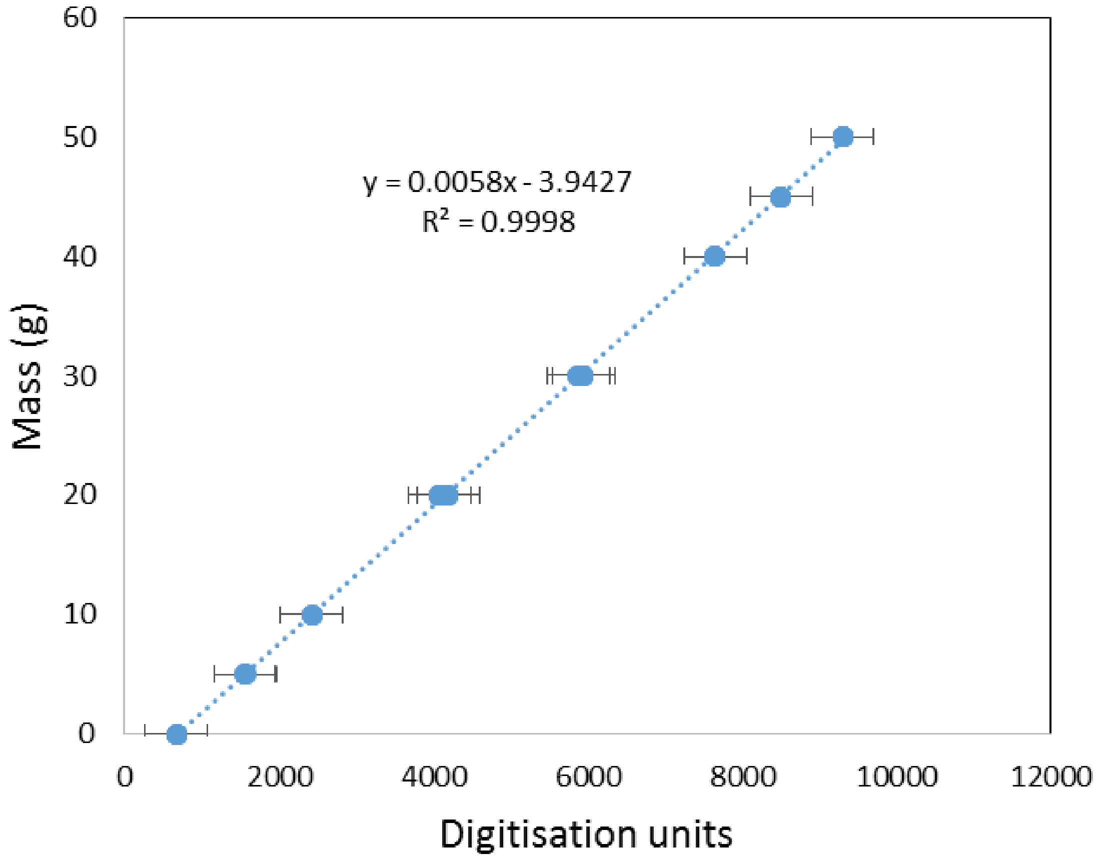

Figure 4-3. Calibration mass versus digitisation units from the load cell and data logger system.

Further tests were done to check the stability of the load cells under increased temperature and RH. Figure 4.4 demonstrates the change in weight over time (recorded every minute) for a temperature of 35 °C with 40% RH. The graph shows the load cell maintained accuracy and precision, and showed an expected plateau around 15 grams when equilibrium was reached. The load cell recorded the correct change in weight and consistently assigned it to the correct digitisation value. The environment chamber maintained temperature within ± 0.2 °C and ± 1% RH. The airflow was determined as 1.3 m/s using a Turbo meter. These values were within the temperature, RH, and airflow guidelines for a thin layer dryer.

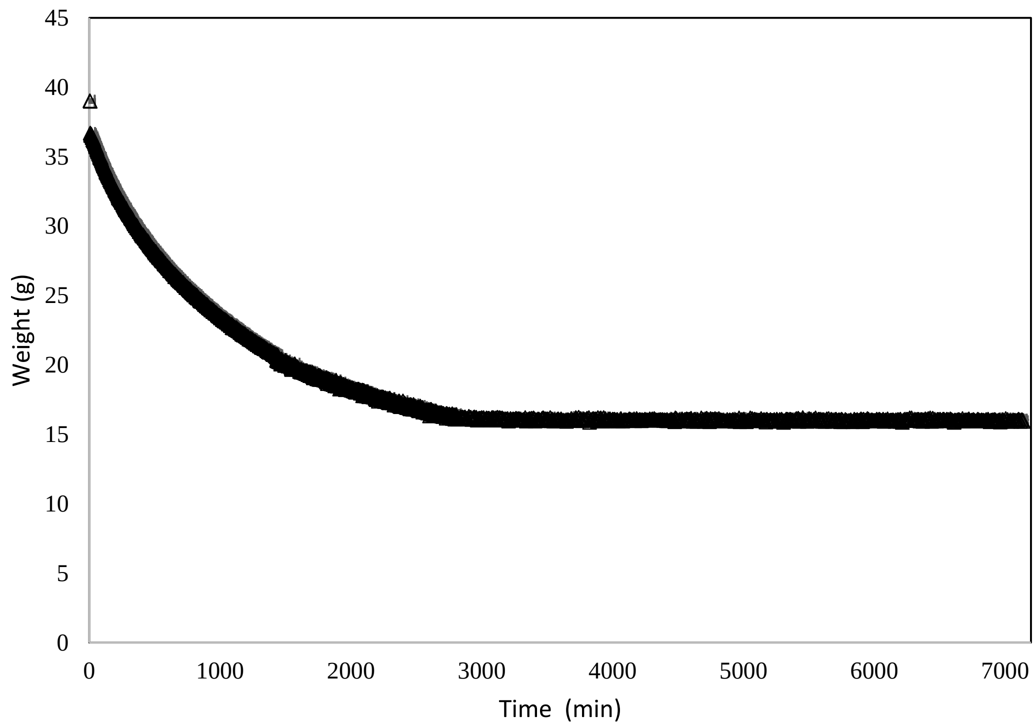

Figure 4-4. Weight (g) versus time (mins) for 35 °C temperature and 40% relative humidity. The load cell precisely maintained accuracy over time and showed an expected plateau once EMC was met.

4.2 Thin layer drying procedure

Initial MC of the bulk sample was measured in the moisture balance. Samples were then placed, in a thin layer, in pre-weighed metal trays and the initial total weight was measured. The trays were placed on the load cell holders inside the preheated environment chamber. All tests ran for a minimum of 72 hours to allow EMC to be reached. Picaxe software was used to record the weight every 5 minutes. Initial tests had the weight recorded every minute but this was changed to 5 minutes as the overall trend and fine detail was not affected by the longer time period. At the end of the test, final total weights were taken of the samples and a final MC was obtained using the moisture balance. The final MC was also the EMC. Drying rates for 35, 45 and 55 °C air each with RH of 40, 50, 60, and 80% were obtained (apart from 55 °C at 80% RH).

As per the (2014) ASAE Standard thin layer drying data was reported in the form of the Page equation:

$$MR = \frac{M - M_e}{M_i - M_e} = \mathrm{e}^{-\mathrm{k}t^n}; \qquad (4.1)$$

where MR is the moisture ratio, M is the MC, M_e is the equilibrium MC, M_i is the initial MC, k is the drying constant, and t is time with the time exponent n. Matlab software was used to fit a least squares curve to the log of the moisture ratio (MR) which was applied to the data for $0.95 > MR > 0.05$ (to avoid the extremity where log is undefined) and graphed to define the drying constant k and the exponent n.

4.3 Drying rates, k values – thin layer results

Using the ASAE Standard (2014) for reporting thin layer drying, k and n values were obtained for 35 and 45 °C temperature air each at 40, 50, 60, and 80% RH. Drying constants were also obtained for 55 °C air at 40, 50, and 60% RH. Figures 4.5–4.7 demonstrate the MR versus time for all humidities at each temperature setting. They show an expected increase in time for increasing humidity. Figures 4.8–4.10 demonstrate Page's equation as applied to the measured data with R^2 values all ≥ 0.9 (Appendices A & G supply further graphs demonstrating the Page Eqn. and more information). The drying constant, k, varied from 0.0002 to 0.0029 min^{-n} with an average n value of 1.42 with a standard deviation of 0.081 (Table 4.1).

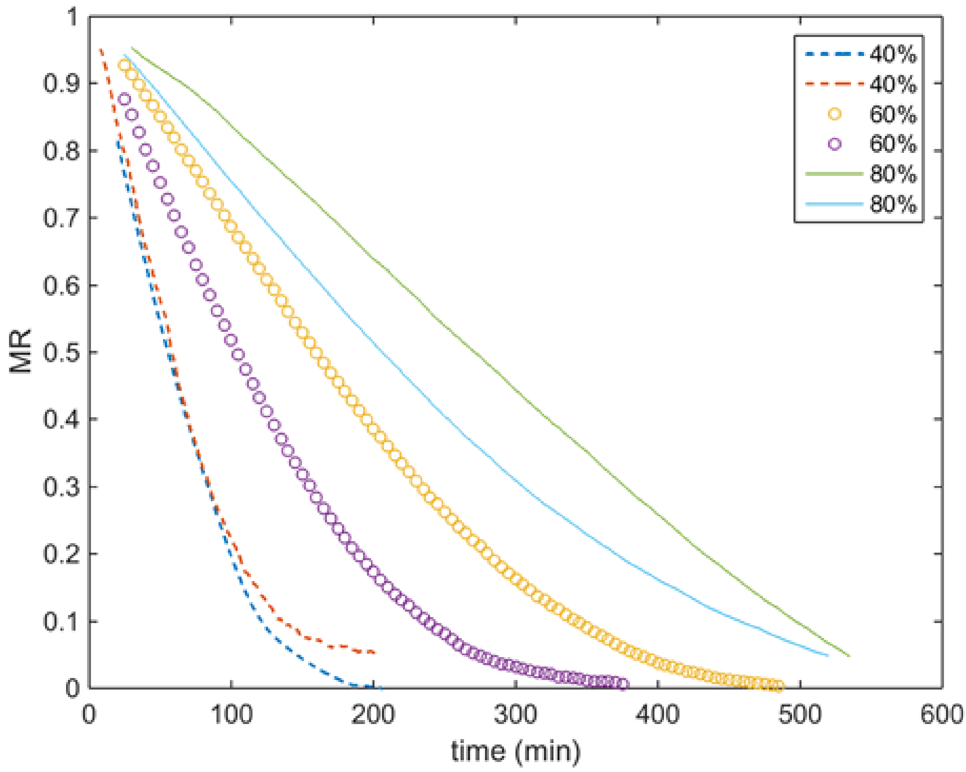

Figure 4-5. The MR over time (min) for 35 °C air at 40, 60, and 80% RH.

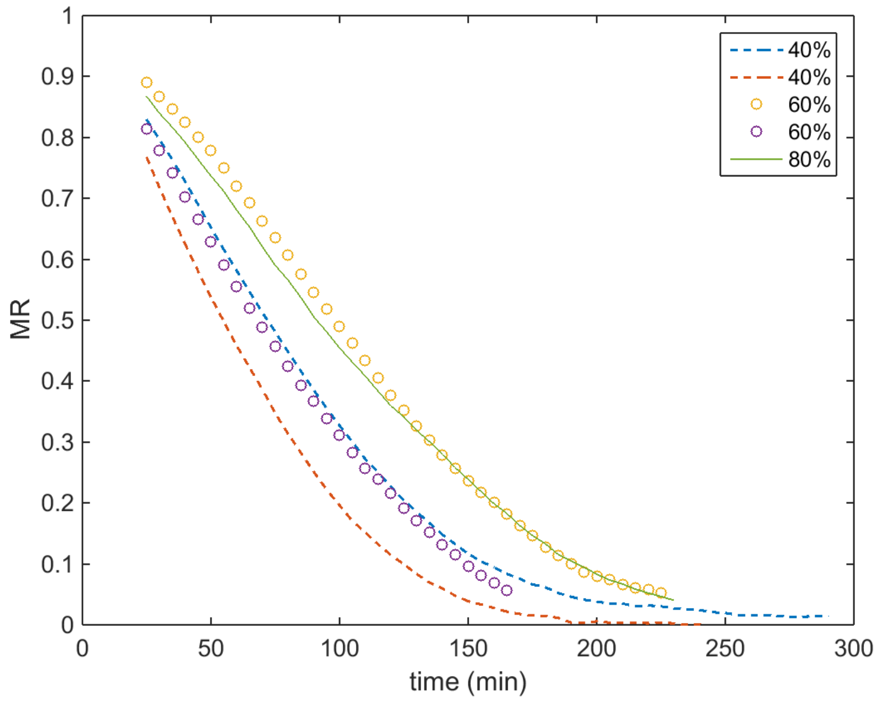

Figure 4-6. The MR over time (min) for 45 °C air at 40, 60, and 80% RH.

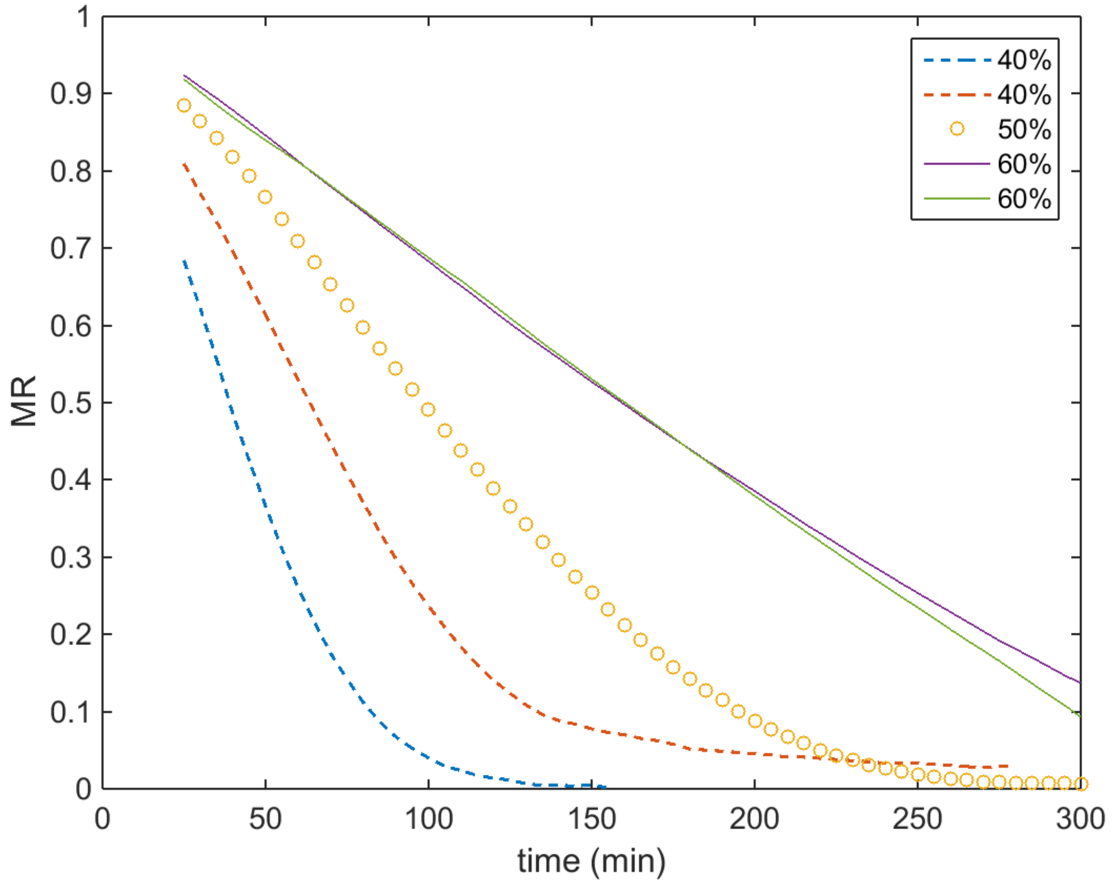

Figure 4-7. The MR over time (min) for 55 °C air at 40, 50, and 60% RH.

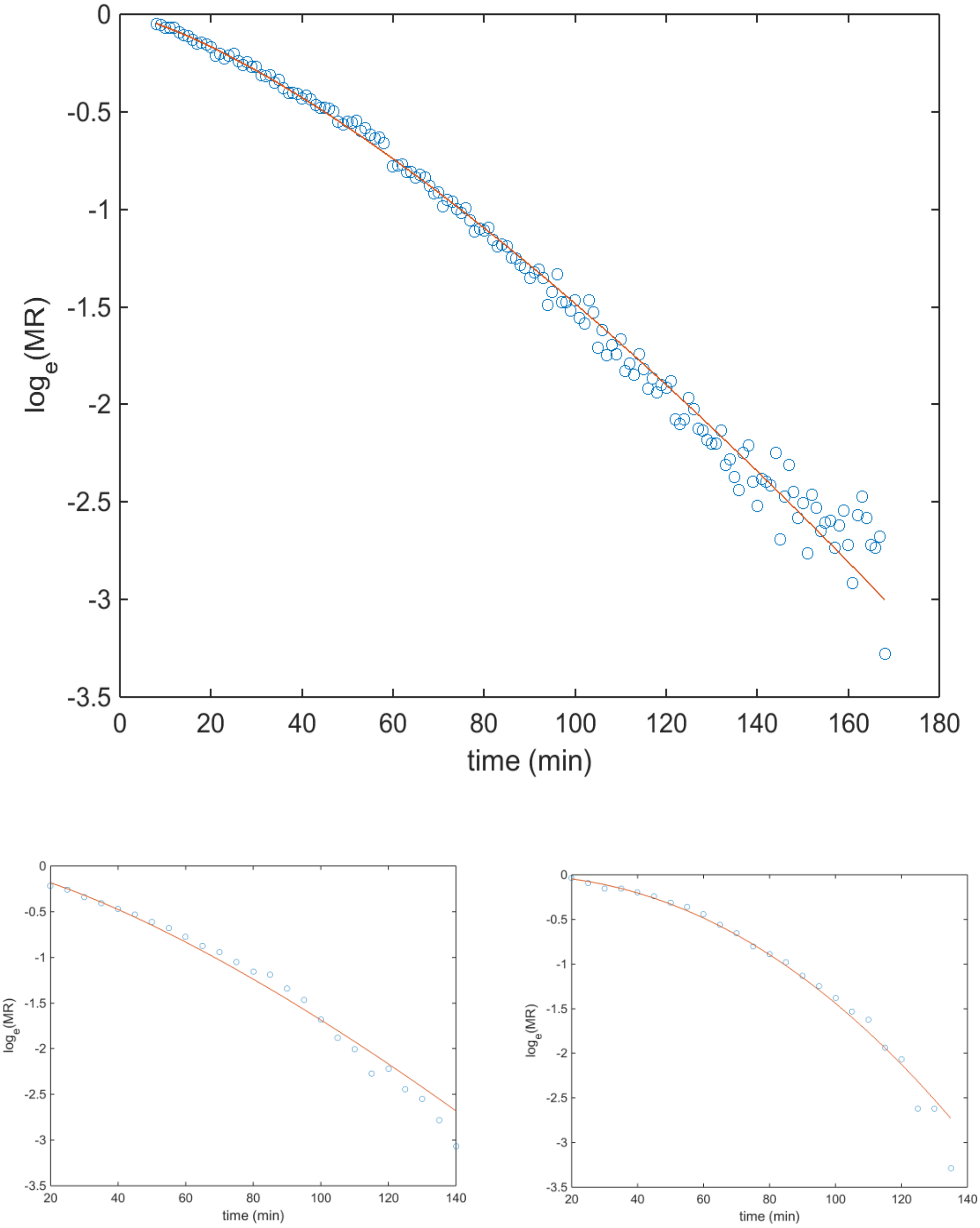

Figure 4-8. Page equation fit for 35 °C, 40% relative humidity thin layer grain type sample (top) and two grass type samples (bottom).

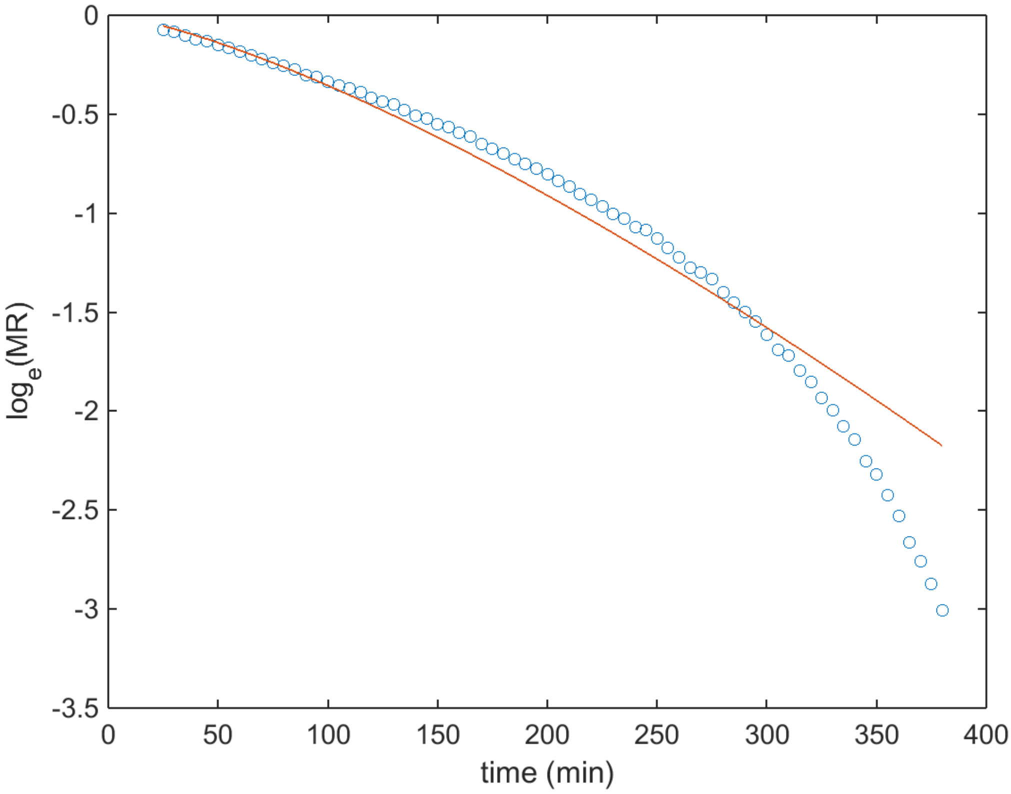

Figure 4-9. Page equation fit for 35 °C, 50% relative humidity thin layer grass type sample.

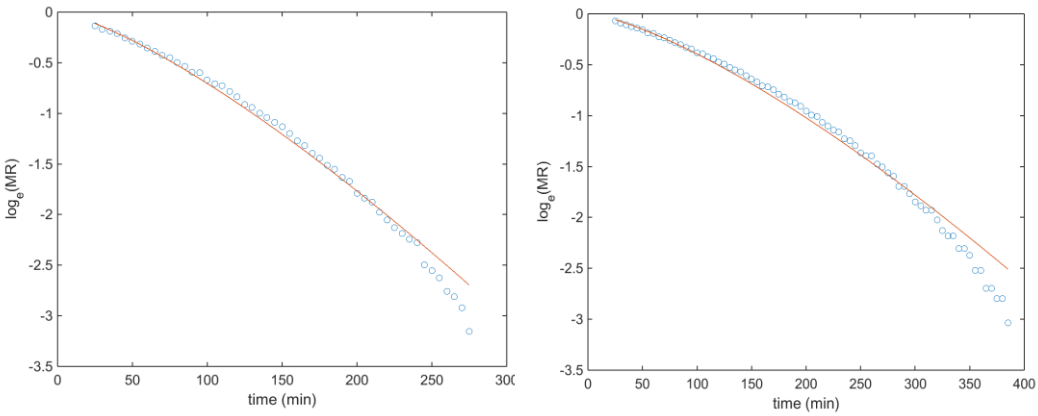

Figure 4-10. Page equation fit for 35 °C, 60% relative humidity thin layer grain type samples.

Table 4-1. Thin layer drying constant, *k*, values with *n* exponent data for grass and grain type paunch.

Temperature (°C)	Relative humidity %	k (min^{-n})	n	type
35	40	0.0029	1.36	grain
	40	0.0029	1.38	grass
	50	0.0007	1.36	grass
	60	0.0007	1.37	grain
	60	0.0016	1.33	grain
	80	0.0007	1.32	grass
	80	0.0002	1.45	grain
45	40	0.0014	1.46	grass
	40	0.0028	1.39	grass
	50	0.0006	1.43	grass
	60	0.0006	1.57	grass
	60	0.0020	1.39	grass
	80	0.0011	1.45	grass
55	40	0.0020	1.61	grass
	40	0.0017	1.46	grass
	50	0.0007	1.53	grain
	60	0.0007	1.39	grass
	60	0.0008	1.35	grass

Using the drying constant, *k*, and time exponent, *n*, from the Page equation the drying equations based on temperature give:

- $MR_{35\,°C} = e^{-0.0023t^{1.37}}$ (4.2)
- $MR_{45\,°C} = e^{-0.0014t^{1.45}}$ (4.3)
- $MR_{55\,°C} = e^{-0.0012t^{1.47}}$ (4.4)

There is only slight variation between equations for different temperatures, using the average values for all temperatures gives an overriding drying equation for paunch of;

$$MR = e^{-0.0013t^{1.42}}. \tag{4.5}$$

Using the drying constant, *k*, and time exponent, *n*, from the Page equation the drying equations based on humidity are:

- $MR_{40\%} = e^{-0.0023t^{1.44}}$ (4.6)

- $MR_{60\%} = e^{-0.0012t^{1.40}}$ (4.7)

- $MR_{80\%} = e^{-0.00066t^{1.41}}$ (4.8)

The greatest effect on drying rates appears to be due to humidity. Statistical software was used to perform an analysis of variance (ANOVA) to test if there was a statistical difference between temperature or relative humidity drying constants. The ANOVA demonstrated a significant difference in the drying constants for relative humidity with a p value of 0.003, temperature did not demonstrate a significant difference between drying constants with a p value of 0.906. The difference between the humidity equations show the variation in drying rates and are expected to be appropriate equations for predicting paunch behaviour and drying times.

A check was also performed on the found Page equations to see if they demonstrated known drying behavior. Theory predicts three stages of drying, an initial period, a constant rate period, and a falling rate period. Figure 4-11 is an example of a drying rate versus time graph for the previously determined 45°C Page equation. In it are the expected three stages of drying. The initial stage shows where heat is transferred to the product and the rate increases due to evaporation of free water (which paunch has demonstrated to have), the constant rate period is due to evaporation on the surface and doesn't start dropping until the limiting falling rate period which is restricted by internal moisture migration as discussed in section 2.4.

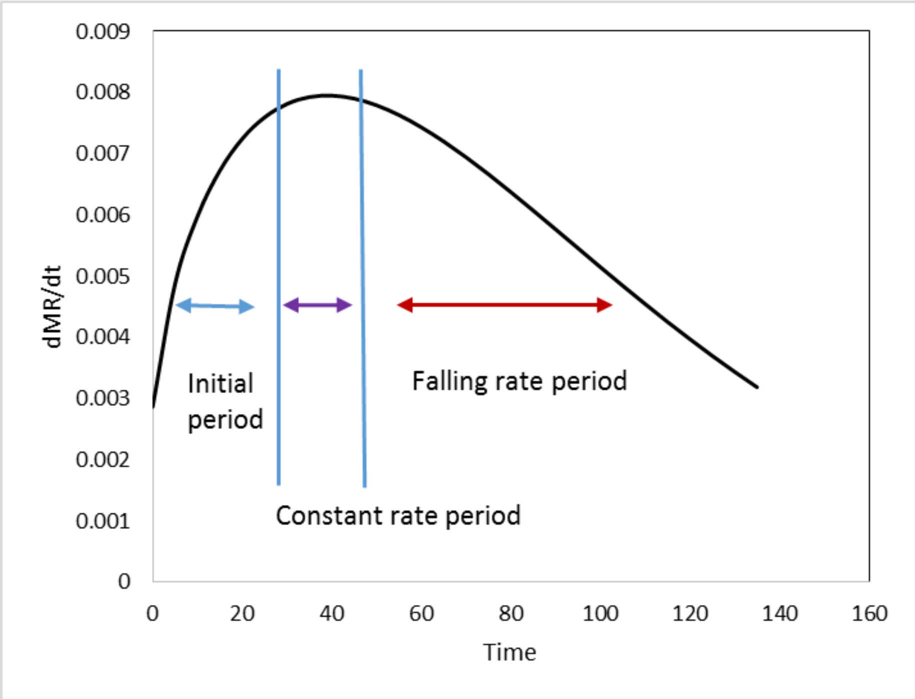

Figure 4-11. An example of the drying rate versus time graph using the Page equation for 45°C operating temperature shows the expected stages of drying.

4.4 Drying rates – thin layer discussion

Thin layer drying rates give the "best" (fastest) case drying times and are an innate property of the paunch. Thin layer constants are the foundation of many deep layer drying models that are based on the principle of starting at depth equals zero (thin layer) and building up. Currently, there are no thin layer drying constants available in the literature for abattoir paunch waste.

The Page equation was fitted to the paunch data and the drying constant *k* calculated. The drying constant, *k*, determined in this study for thin layer drying of paunch ranged from 0.0002 to 0.0029 min^{-n} with an average *n* value of 1.42 ± 0.081. The time exponent *n* showed little variation across both temperature and humidity ranges and therefore the average *n* value was used in an overriding Page equation for temperature. The final drying constants, k, and the time exponent, n, were calculated for paunch as a whole and not separated into grass, grain, or mixed type and therefore, demonstrate the variation in temperature and humidity for all paunch types.

Variation was seen in the drying rates for the same temperature and humidity range and between replicates. This was expected due to the large variation in the paunch samples. As a consequence of the uncontrolled feeding regime of the cattle before slaughter, the ratio of grain and roughage was variable between samples. One of the problems with measuring any value for paunch relates to the statistical fundamental error which is due to the heterogeneity of a sample. The fundamental error will be inherent in all sample measurements because of the large difference in the particle composition of paunch. Therefore, paunch types were not differentiated between for analysis. This variation should be anticipated to occur due to normal industry practices and the drying rates should therefore produce more realistic expectations of paunch drying times.

The fastest drying rates for all temperatures belonged to 40% RH grass type paunch with drying rates decreasing with increased humidity. The descriptive statistics in Table 4.2 show that lower humidity (40%) has faster drying rates for both the minimum (0.0014 min^{-n}) and maximum (0.0029 min^{-n}) values compared to the 60% and 80% RH rates for all temperatures. Temperature does not show the same trend, with less significant difference between maximum and minimum values, with 55 °C demonstrating little difference in maximum value compared to that of 35 and 45 °C which was unexpected. The lowest rate of 0.0002 min^{-n} belonged to 35 °C at 80% RH grain type paunch.

Table 4-2. Descriptive statistics for temperature and humidity minimum and maximum *k* values.

	Minimum (min^{-n})	Maximum (min^{-n})	Mean (min^{-n})	Std. Deviation
35°C	0.0002	0.0029	0.001381	±0.0011
45°C	0.0006	0.0028	0.001420	±0.00089
55°C	0.0007	0.0020	0.001179	±0.00062
40% RH	0.0014	0.0029	0.002297	±0.00066
60% RH	0.0006	0.0020	0.001064	±0.000599
80% RH	0.0002	0.0011	0.000657	±0.00041

As there are no thin layer drying rates for paunch available in the literature, comparison was performed using the Griffith and Brusewitz (1980) study and the Spence (2012) study. The current study gives k ranges between 0.0002 – 0.0029 min^{-n} (with an average n value of 1.42 min^{-1}), this is comparable to (although higher) than the Griffith and Brusewitz (1980) preliminary drying constant, k, of 0.005 to 0.108 hr^{-1} which equates to 0.000083 – 0.0018 min^{-1} and to the Spence (2012) experimental k values of 0.0643–0.1703 hr^{-1}. The faster rate compared to the Griffith and Brusewitz (1980) study is expected, due to the thin layer used, in the current study (as opposed to 2.5 cm minimum depth in Griffith & Brusewitz (1980) and Spence (2012) study).

The Spence (2012) values appear within the same range as the current study but caution must be used in comparison, as the Spence (2012) used a tunnel dryer with a depth of 2.5 cm to allow comparison to the simulated tunnel dryer used in the Griffith and Brusewitz (1980) study. The Spence (2012) study used higher temperatures with lower humidity and the results showed a lot of variation in individual drying runs. This was due to each test run being terminated at the end of each hour test block, as measuring the moisture content destroyed the sample. Therefore, there was a mixture of both grass and grain samples used in the one test. There was also poor control of temperature and humidity, with ambient air conditions impacting temperature and humidity stability. However, variation included the Spence (2012) results verified that lower humidity, higher temperatures would produce faster paunch drying times.

In comparison to the Griffith and Brusewitz (1980) main experiment drying constant, *k*, of 1.17 ± 0.41hr^{-1}, it is significantly (an order of magnitude) different to the rates in the current study. This therefore, indicates there is either some fundamental difference between their study and the current study; or based on their reported preliminary results and perusal of their published data, a possible typographical error in the reporting of the main experiment result (Spence 2012). The type of paunch used may also be a reason for the variation between results as previous literature suggests that there can be an increase in drying times up to five times greater for grain fed cattle as opposed to grass fed (Farmer, Brusewitz & Moustafa 1979). However, this seems less likely to be the cause as grass type paunches were used for all temperature ranges in the current study.

On the assumption that it is a typographical error in the Griffith and Brusewitz (1980) study then their main experiment drying constant would be comparable to the current study. The comparison between studies would support the faster drying times found in the current study. The current study expands on the Griffith and Brusewitz (1980) study by determining thin layer drying rates at various temperatures. The drying constants determined for shallow depth in the Griffith and Brusewitz (1980) study demonstrated relationships for paunch such as that between; age, depth and humidity. The current study developed thin layer drying rates, for various temperature and humidity, which are fundamental characteristic of paunch and will allow the development of models for paunch drying at depth.

The MR equations determined in this study for paunch thin layer drying demonstrate the importance of humidity control in a dryer. While theory shows that temperature plays an important role in increasing drying rates, lack of humidity control will hinder the process and slow the drying. The MR equations will also benefit future studies by allowing predictive paunch drying models for both thin and deep layer paunch to be produced which will aid in the modeling and testing of future dryer designs.

Chapter 5 : Equilibrium moisture content & Latent heat of vaporisation

5.0 Equilibrium moisture content introduction

Drying rate data for drying equations need to be obtained on an apparatus such as a thin layer dryer. However the EMC's are also needed for determining the moisture ratio (MR) and for complete product characterisation. EMC is easily obtained at the end of a drying run as equilibrium is the final stage of drying. EMC provides the minimum MC that a substance can be dried to, under set drying conditions. Equilibrium is met when the rate of evaporation equals the rate of condensation of a substance. EMC is important, in terms of drying, in that once it has been reached, no further drying is possible at those conditions. Equilibrium is determined during the drying run once there is no longer any change in weight of the sample.

Equilibrium can be met by either adsorption (gaining moisture from the environment) or desorption (losing moisture to the environment). Desorption EMC is always higher than adsorption (Brooker, Bakker-Arkema & Hall 1992). Therefore, calculating the desorption EMC allows 'worst case' MC information to be available for situations such as storage after the paunch has been dried.

5.1 Equilibrium procedure

The EMC was measured at the end of each thin layer drying run. Multiple samples were measured to test for variation and repeatability. The average MC and the standard deviation was calculated for each temperature/RH combination. Desorption isotherms were determined from plotting the EMC versus equilibrium RH.

The Chung-Pfost equation (Chung & Pfost 1967) can be used to develop a predictive model for a products EMC by determining the products constants A and B in:

$$\ln\left\{\frac{P}{P_o}\right\} = -\frac{A}{RT}e^{-Bm}; \tag{5.1}$$

(where P is the water vapour pressure of the product, P_o is the saturated vapour pressure at the equilibrium temperature, A and B are constants, m is MC, R is the universal gas constant, and T is temperature). The Chung-Pfost equation in the format cited by Hutchinson and Otten (1984):

$$MC_e = (\ln A - \ln(T + C) - \ln(-\ln(RH)))\frac{1}{B}; \tag{5.2}$$

(where MC_e is the EMC, A, B and C are constants, T is temperature, and RH is the relative humidity), was used to fit the data to allow a predictive EMC model to be determined for paunch. A non-linear regression using statistical software (IBM SPSS version 23) was used to find the coefficients for the Chung-Pfost equation and an analysis of variance (ANOVA) was used to determine the coefficient of determination, R^2 and the standard error.

5.2 Equilibrium moisture content - results

EMC were measured at the end of a drying run once there was no longer any change in weight recorded by the load cells. The EMC was measured for 35, 45, 55 °C air each at 40, 50, 60, 80% RH (apart from 55 °C at 80% RH due to equipment instability at this level). The EMC varied from 7.14–13.44% MC as shown in Table 5.1. The Chung-Pfost equation [Eqn. 5.2] was fitted to the data (Figure 5.1).

Table 5-1. Average equilibrium moisture content values for 35–55 °C air at 40–80% relative humidity.

	Relative humidity							
Temperature (°C)	40%	Std dev	50%	Std dev	60%	Std dev	80%	Std dev
35	7.998	±0.19	9.51	±0.25	10.84	±0.08	13.44	±0.45
45	7.94	±0.02	8.88	±0.26	9.595	±0.36	13.12	±0.52
55	7.14	±0.12	8.39	na	9.434	±0.30		

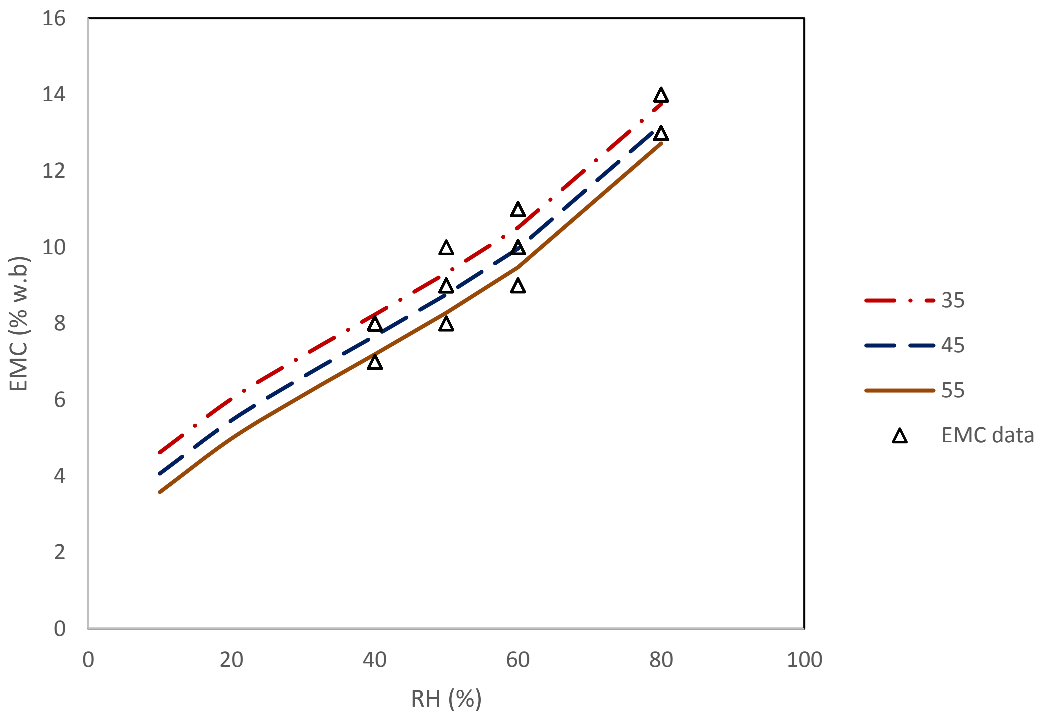

Figure 5-1. Desorption moisture equilibrium isotherms predicted for 35, 45, and 55 °C using Chung-Pfost equation with acquired data for 40, 50, 60, 80% RH (EMC data points indicated above are average values for EMC to allow visual comparison to model).

A non-linear regression was performed using statistical software and the constants *A*, *B*, and *C* were found for the Chung-Pfost equation (as rearranged in Hutchinson & Otten 1984). The constant *A* was found to be 492.88, *B* was 25.550, and *C* was 30.751 with a standard error of 0.0041 (Table 5.2).

Table 5-2. Constants determined for the Chung-Pfost equation.

Type	A	B	C	Standard error
Paunch	492.88	25.550	30.751	0.0041

Therefore, the equation for predicting the EMC of paunch is:

$$MC_e = (\ln 492.88 - \ln(T + 25.550) - \ln(-\ln(RH)))\frac{1}{30.751}; \qquad (5.3)$$

where MC_e is the EMC (decimal), T is temperature (°C), RH is relative humidity (decimal).

5.3 Equilibrium moisture content - discussion

EMC is an important characteristic as it sets the limit to drying under certain conditions and provides storage information for a product once it has been dried. The desorption EMC isotherms are always higher than adsorption isotherms and therefore give a worst-case scenario as to the minimum MC reachable by a product under set conditions. Currently there are no published EMC values for paunch. The EMC for paunch in this study varied from 7.14–13.44% MC with the highest temperature, lowest humidity having the lowest EMC.

The data for the 10, 20, and 30% EMC were extrapolated from the Chung-Pfost model in the format cited by Hutchinson and Otten (1984). The Chung-Pfost model showed a good fit for the data with an R^2 of 0.964 and a standard error of 0.0041. The constants *A*, *B*, and *C* are comparable to the reported values for wheat (soft and hard) and barley (Table 5.3) with an acceptable standard error. The new equation for predicting paunch EMC values will be extremely beneficial for use in MR calculations and storage information.

Table 5-3. Constants for the Chung-Pfost equation and published constants for wheat (soft and hard) and barley.

Type	A	B	C	Standard error	Reference
Paunch	492.88	25.550	30.751	0.0041	
Wheat, soft	726.49	23.607	35.662	0.0147	ASAE D245.4
Wheat, hard	529.43	17.609	50.998	0.0061	ASAE D245.4
Barley	761.66	19.889	91.323	0.0055	ASAE D245.4

5.4 Latent heat of vaporisation- Introduction

Through the process of evaporation, a liquid can be turned into a vapour through a phase change that takes place at constant temperature. The latent heat of vaporisation is the energy (in the form of heat) required to vaporise a liquid mass. The latent heat is given by:

$$Q = mL; \qquad (5.4)$$

where Q is the energy required in kilojoules, m is the mass of the liquid in kilograms, and L is the specific latent heat of vaporisation in kilojoules per kilogram. The specific latent heat for water is 2260 kJ/kg.

The latent heat of vaporisation of a product can be found using the Clausius – Clapeyron equation (Othmer 1940):

$$\frac{dP}{dT} = \frac{LP}{RT^2}; \qquad (5.5)$$

where P is vapour pressure, T is absolute temperature (K), L is latent heat of vaporisation, and R is the universal gas constant.

This can be integrated to give (Othmer 1940):

$$\ln(P) = \frac{L}{RT} + \text{Constant}; \tag{5.6}$$

Therefore, a plot of $\ln(P)$ versus $\frac{1}{T}$ will give a slope equal to the latent heat (L) divided by the universal gas constant. P can be calculated using the equilibrium RH times by the saturation vapour pressure of water at the same temperature (Rodriguez-Arias, Hall & Bakker-Arkema 1959). The equilibrium RH is for a specific temperature and MC obtained from the desorption isotherm, which is in turn determined from plotting the EMC versus RH.

5.5 Heat of vaporisation - results

The latent heat of vaporisation for paunch was calculated by multiplying the saturation vapour pressure of water with the equilibrium RH (found on the EMC isotherm graph Figure 5.1 developed from the Chung-Pfost equation) to find *P* (the vapour pressure). Taking the natural log of the vapour pressure, *P*, and graphing against the reciprocal of temperature produces a slope equal to the latent heat divided by the universal gas constant (Figure 5.2). Therefore, the slope times the universal gas constant will equal the latent heat of vaporisation for paunch.

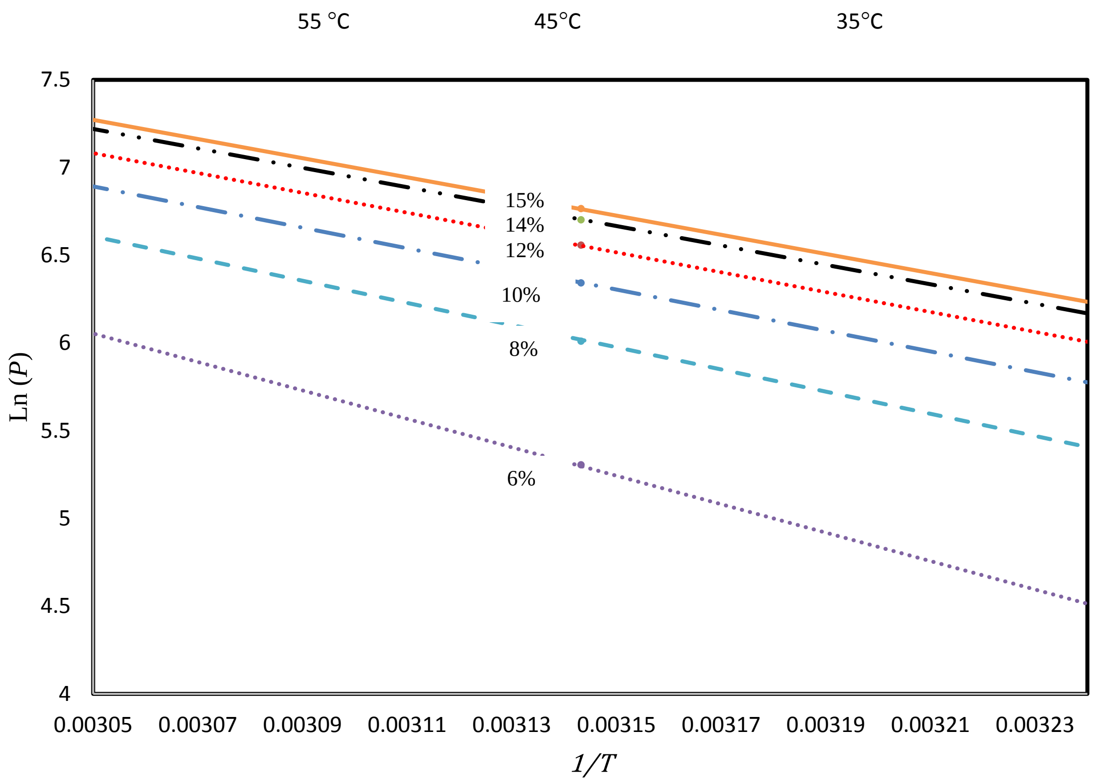

Figure 5-2. The slope of the natural log of *P* versus the reciprocal of *T* times the universal gas constant gives the latent heat of vaporisation of paunch.

Taking the slope of the lines (ln(*P*) over $\frac{1}{T}$) in Figure 5.2, multiplied by the universal gas constant and divided by the molecular weight of water, provided the latent heat of vaporisation. The equations for the lines in Figure 5.2 used for determining the latent heat of vaporisation are in table 5.4.

Table 5-4. The equation for the lines in Figure 5.2

MC %	Equation
6	Ln(P) = -8106.1(1/T)+30.778
8	Ln(P) = -6320(1/T)+25.884
10	Ln(P) = -5877.8(1/T)+24.82
12	Ln(P) =-5659(1/T)+24.342
14	Ln(P) = -5532.4(1/T)+24.094
15	Ln(P) = -5458.9(1/T)+23.922

The latent heat for paunch varied from 3741 to 2519 kJ/kg for 6 to 15% MC with the average latent heat of vaporisation for paunch found to be 2842 kJ/kg (Table 5.5).

Table 5-5. The latent heat of vaporisation for paunch at moisture content ranging from 6 to 15%.

MC (%)	L (kJ/kg)
6	3741
8	2917
10	2713
12	2612
14	2553
15	2519
Average	2842

5.6 Latent heat of vaporisation - discussion

Latent heat of vaporisation is important in drying as it tells how much heat is needed to remove water from a product and is also important for drying equations. Currently there are no published values for the latent heat of vaporisation of paunch.

The latent heat of paunch was calculated from the equilibrium RH values found on the EMC isotherms. The latent heat of vaporisation varied from 3 741 to 2 519 kJ/kg for 6 to 15% MC with the average latent heat of vaporisation for paunch found to be 2 842 kJ/kg (based on the average of the slopes found for each MC, Figure 5.2). The latent heat of vaporisation of water is 2 260 kJ/kg which is less than the latent heat of paunch. This was expected as the latent heat of vaporisation for agricultural products can be much higher than that for vaporising a kilogram of free water (Rodriguez-Arias, Hall, & Bakker-Arkema 1959). Paunch also followed the same trend as a study done on bananas where the latent heat of vaporisation decreased as the moisture content increased (Pereira da Silva et al. 2012).

Chapter 6 : Energy content

6.0 Energy content introduction

Oxygen bomb calorimetry is used to determine the gross heat of combustion (calorific value) of a product and measures temperature changes at constant volume. The oxygen bomb should be calibrated with a standard benzoic acid sample for each set of tests and the energy equivalent of the calorimeter calculated. The sample is then placed inside the calorimeter and the change in temperature and mass of the sample is recorded. The energy equivalent of the calorimeter, change in temperature, and mass of the sample is then used to calculate the gross heat of combustion (calorific value) in J/g.

The energy equivalent of the calorimeter is:

$$W = \frac{mH_c}{\Delta T}; \tag{6.1}$$

where W is energy equivalent of calorimeter, m is mass, H_c is heat of combustion of Benzoic acid, and ΔT is the change in temperature.

The gross calorific value is then calculated by:

$$H_g = \frac{\Delta T W}{m}; \tag{6.2}$$

where H_g is the gross heat of combustion, ΔT is the change in temperature, W is the energy equivalent of the calorimeter, and m is the mass.

Heating value, energy value and calorific value all refer to the energy content per unit mass of substance measured in Joules per kilogram. The gross calorific value (or higher heating value (HHV)) accommodates the situation where the water formed during combustion is condensed and therefore the latent heat of vaporisation is included in the total heat produced. The net calorific value (or lower heating value (LHV)) does not include the latent heat of vaporisation (see section 5.4) which is subtracted from the gross calorific value. The lower heating value is used for thermal analyses when it is assumed that the water from combustion remains as steam and does not condense. The lower heating value is useful for determining the available energy for biomass with differing moisture content. The lower heating value can be determined using the equation:

$$LHV = HHV(1 - MC) - 2.447MC; \qquad (6.3)$$

where LHV is the lower heating value (J/g), HHV is the higher heating value (J/g), MC is the moisture content wet basis (as a decimal) (Boundy et. al 2011).

6.1 Energy content procedure

Paunch was collected, separated into predominantly grass or grain type paunches, and dried for use in an oxygen bomb calorimeter. An XRY — 1A Oxygen Bomb Calorimeter (China) (Figure 6.1) was used and calibrated using Benzoic acid one gram pellets (Parr instrument Co., USA). Paunch sample particle size was reduced if large grain particles were present. This was done to reduce incomplete combustion of the samples in the bomb. All samples used for calculations were completely combusted with no sample residue left in bomb. Energy content was determined for 10 grain and 12 grass samples. Statistical software was chosen to analyse the energy content values; an analysis of variance (ANOVA) was then used to determine if there was a significant difference between samples.

Figure 6-1. An XRY-1A Oxygen Bomb Calorimeter (Nanbei 2014).

6.2 Energy content - results

Paunch was separated into grass or grain type paunches. Paunch was classified as grain if there was obvious grain present in the sample (refer to section 3.2). An oxygen bomb calorimeter was used to determine the gross calorific value. To account for variability in the paunch content statistical software was used to calculate the mean and standard deviation of the samples and to determine if there was a significant difference between the paunch types. The average gross calorific value for grass type paunch was found to be 17 MJ/kg with a standard deviation of 0.97, and for grain type paunches 20 MJ/kg with a standard deviation of 1.6 (Table 6.1).

Table 6-1. The average energy content for grass type paunch was 17 MJ/kg and 20 MJ/kg for grain type.

Type	Mean (MJ/kg)	N	Std. Deviation
Grain	20.34	10	1.60
Grass	16.9	12	0.97

A box plot (Figure 6.2) and an analysis of variance (ANOVA) (Table 6.2) were then used to determine if there was a significant difference between the energy contents. The analysis showed paunch calorific values varied from 17–20 MJ/kg depending on the type of paunch with a significance level of 0.000005 between grass and grain types, indicating there is a significant difference between the energy content of grass and grain type paunch.

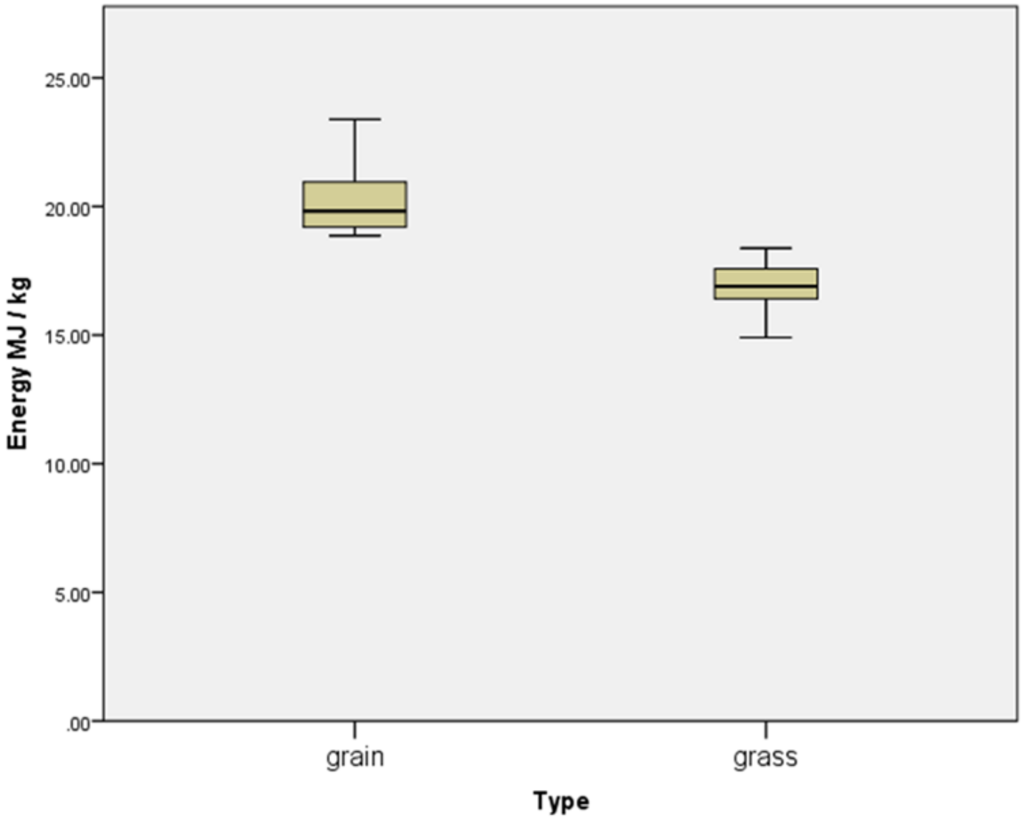

Figure 6-2. Box plot displaying the distribution of the energy content of grass and grain type paunch.

Table 6-2. A one-way ANOVA was used to determine if there was a significant difference between grass and grain type energy content.

ANOVA Energy MJ/kg	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	64.804	1	64.804	38.657	0.000005
Within Groups	33.528	20	1.676		
Total	98.331	21			

Lower heating values were calculated for both grass and grain type paunches. Table 6.3 shows that the LHV for grass type paunch (HHV 17 MJ/kg) ranged between -2.5 to 15.1 MJ/kg and for grain type paunch (HHV 20 MJ/kg) between -2.5 to 17.8 MJ/kg (from lower to higher). Figure 6.3 demonstrates the relationship between moisture content and energy content. As the moisture content increases the net energy content decreases.

Table 6-3. LHV for grass (HHV 17.03 MJ/kg) and grain (HHV 20.2 MJ/kg) type paunch.

MC (%)	LHV grass (MJ/kg)	LHV grain (MJ/kg)
10	15.1	17.8
20	13.1	15.5
30	11.2	13.3
40	9.2	11.02
50	7.3	8.8
60	5.3	6.5
70	3.4	4.3
80	1.4	2.04
90	-0.5	-0.2
100	-2.5	-2.5

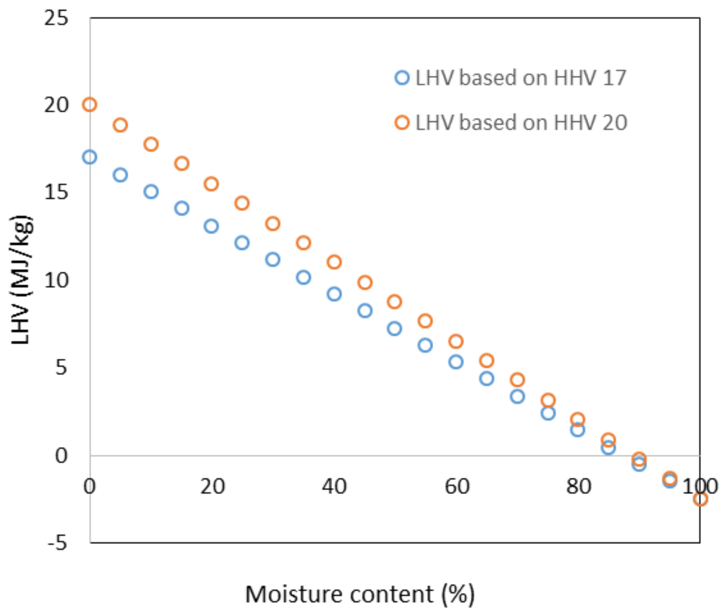

Figure 6-3. Relationship between moisture content and lower heating value of paunch. As the moisture content increases the calorific value decreases.

6.3 Energy content discussion

The standard for the energy content of paunch has been 16.7 MJ/kg (Ricci 1977). This value is comparable to the obtained grass type paunch value of 17.3 MJ/kg. However, there was a significant difference found in the calorific value for grain type paunches of 20.2 MJ/kg. It was anticipated that paunch would have similar energy contents between grass and grain types due to the large roughage component of both the grass and grain types. However, the box plot (Figure 6.2) and ANOVA (Table 6.2) demonstrated a clear difference between the spread of energy contents for each type resulting in a significant difference level of 0.000005 between types (Appendix F contains an energy paper in preparation).

Compared to other gross calorific values of commonly used fossil and biomass fuels, paunch shows a comparable energy content (Table 6.4). For mixed type paunches, the energy content will be between 17.3–20.2 MJ/kg. This energy range is also comparable to the energy content of 17–21 MJ/kg for all plant species as stated by McKendry (2002)   These values demonstrate paunch as a potentially useful waste to energy stream.

Table 6-4. Gross calorific values of paunch and other commonly used energy sources.

COMPARISON GROSS CALORIFIC VALUES		
Type	**HHV (MJ/kg)**	**Reference**
Paunch (grass - grain)	17.3 – 20.2	Current study
Black coal QLD	28.69	Coal analysis Dec 2015 (Spence, M 2016, pers. comm., 9 May)
Bituminous coal	34.89	Higgins & Elonka 1976
Wood	16-21	Stout 1983, eds. Rosilla-calle et.al 2007, Higgins & Elonka 1976
Corn cob	18.6	Stout 1983
Lignite coal	16.28-18.6	Higgins & Elonka 1976
Sawdust	18.14	Demirbas 2003
Wheat straw	17.51	Demirbas 2003
Cotton gin	15.5	Demirbas 2003
Rice husk	13.524	Demirbas 2003

Lower heating values were calculated for grass, 15.1 to −2.5 MJ/kg, and grain, 17.8 to −2.5 MJ/kg, type paunches for moisture content ranging between 10–100%. The LHV shows there is almost no recoverable energy at 85% MC with negative values for MC over 85%. The energy content is decreased with moisture and the LHV demonstrates that with drying, paunch will go from a waste product with no recoverable energy to a beneficial biomass.

Chapter 7 : Bulk density & Energy density

7.0 Bulk density introduction

Bulk density is a measure of material mass per unit volume (EHAP 1999) and is calculated by:

$$\rho_b = \frac{m}{V_t}; \tag{7.1}$$

where ρ_b is the dry bulk density (g/cm^3), m is the mass (g), and V_t is the total volume (cm^3). The dry bulk density is the dry mass of the sample (not including container weight) divided by the total volume. The wet bulk density or total bulk density is found by calculating the ratio of total mass (including liquid) to total volume. These should be calculated for both tapped and untapped samples. Tapped means that the sample is more tightly packed than an untapped sample. For example, the bottom of a stockpile compared to the top.

7.1 Bulk density procedure

Paunch was pre-dried for the dry bulk density determination. Paunch was placed inside a known volume and pre-weighed cylinder, and the total mass was weighed on four decimal place precision scales. The cylinder was then tapped and fill with more paunch to the same volume, reweighed, and tapped again until settled. The volume mass was taken from the total mass and then divided by the volume to determine density. The same procedure was followed for the 75% MC paunch, and for the untapped data (minus being tapped). A linear regression was used to determine predictive equations for tapped and untapped paunch bulk density.

7.2 Bulk density results

Bulk density was experimentally determined for both wet (75% MC) and dry tapped and untapped paunch. The bulk density for varying MC was then extrapolated for both tapped and untapped data using the assumption that the added mass of water would produce a linear change (Brusewitz 1975, Wratten et al. 1969 as cited in Noomhorm & Verma 1986).

The measured bulk density for untapped paunch ranged from 106 kg/m^3 (dry) — 440 kg/m^3 (wet 75%) and for tapped 152 kg/m^3 (dry) — 663 kg/m^3 (wet 75%) (Table 7.1). Statistical software was used to determine the mean and standard deviation between the bulk density samples.

Table 7-1. Bulk density values for tapped and untapped paunch.

Type	Mean (kg/m^3)	N	Std. Deviation
Wet (75%MC) untapped	439.91	8	61.7
Wet (75%MC) tapped	663.3	7	51.1
Dry untapped	105.8	6	7.4
Dry tapped	152.04	6	11.6

A linear regression was performed and the equation for untapped paunch bulk density was calculated as:

$$BD = 3.9791 \times MC + 105.76; \quad (7.2)$$

where BD is the bulk density in kg/m^3, and MC is the moisture content in percent, this returned an R^2 value of 0.962. The equation for tapped paunch bulk density was calculated as:

$$BD = 7.1028 \times MC + 152.04; \quad (7.3)$$

where BD is the bulk density in kg/m^3, and MC is the moisture content in %, this returned an R^2 value of 0.9902. Based on the newly derived equations, the bulk density for untapped paunch ranges from 106 kg/m^3 (dry) — 504 kg/m^3 (100%) and for tapped 152 kg/m^3 (dry) — 862 kg/m^3 (100%) (Table 7.2).

Table 7-2. Bulk density values for paunch based on the newly derived bulk density equations.

MC (%)	Untapped (kg/m^3)	Tapped (kg/m^3)
100	503.7	862.3
90	463.9	791.3
80	424.1	720.3
70	384.3	649.2
60	344.5	578.2
50	304.7	507.2
40	264.9	436.2
30	225.1	365.1
20	185.3	294.1
10	145.6	223.1
0	105.8	152.1

7.3 Bulk density discussion

The bulk density of paunch available in the literature has mostly been calculated for the compost potential of the paunch waste. Values determined by Fleming and MacAlpine (2004) ranged from fresh (at the start of their study) tapped 795 kg/m^3 to 780 kg/m^3 after 116 days. Bridle (2011) measured 266 kg/m^3 for a dewatered grass and 273 kg/m^3 for a dewatered grain type paunch. In another study McCabe et al. (2016) measured bulk density for 2–16 week old paunch (but did not record the initial value). Their values ranged from 176 ± 4.9 kg/m^3 (at 12 weeks) to 780 ± 15.6 kg/m^3 (at 2 weeks) with a final bulk density of 407–490 ± 25.9 kg/m^3 for untapped and tapped at 16 weeks.

In the current study, bulk density was experimentally determined for wet 75% MC tapped (663.3 kg/m^3) and untapped (439.91 kg/m^3) paunch and for dry tapped (152.04 kg/m^3) and untapped (105.8 kg/m^3) paunch, for both grass and grain. The bulk density for 100% MC was then extrapolated for both tapped and untapped data using the assumption that the added mass of water would produce a linear change (Brusewitz 1975). Brusewitz (1975) did a study on the density of various grains and fit the data with first and second degree polynomials and determined that the improvement of a second degree polynomial was small and therefore presented his data with a linear fit. Wratten et al. (1969 as cited in Noomhorm & Verma 1986) also used a linear model for the bulk density of long grain rice in relation to its MC. The newly determined bulk density equation for paunch appears to be a good fit to the data with R^2 values above 0.9. The experimentally determined bulk density in the current study appears to fall reasonably within the range of past work, apart from the Bridle (2011) study which appears closer to the current study's dry bulk density as opposed to the stated dewatered (≈ 70% MC) in the Bridle (2011) study.

Boundy et al. (2011) state 'the bulk density (and hence energy density) of most biomass feedstocks is generally low, even after densification – between about 10 and 40% of the bulk density of most fossil fuels'. The bulk density of coal ranges from 700–850 kg/m^3 for low rank (lignite, sub-bituminous) to high rank (bituminous, anthracite) coal respectively (Boundy et al. 2011). Paunch appears to lie in the expected range of bulk density compared to other biomass feedstocks (Boundy et al. 2011). Bulk density and LHV were then used to calculate energy density values for paunch.

7.4 Energy density introduction

Energy density is the amount of energy per unit volume and is a measure used to calculate a return on energy for varying MC using the bulk density (at a specific MC) times the energy content (LHV or HHV for bone dry) (Quaak Knoef, & Strassen 1999).

7.5 Energy density results

The energy density values for paunch (Table 7.3 and Figure 7.1) varied from 4865 to −2110 MJ/m^3. The highest energy density (4084 MJ/m^3) found for grass type paunch belonged to 35% MC and for grain type paunch the highest energy density (4865 MJ/m^3) also occurred at 35% MC.

Table 7-3. Energy density calculated from LHV energy content and extrapolated bulk density.

MC (% w.b)	Bulk density tapped (kg/m^3)	LHV based on HHV 17 (MJ/kg)	LHV based on HHV 20 (MJ/kg)	Energy density (MJ/m^3) based on HHV 17	Energy density (MJ/m^3) based on HHV 20
5	188	16.0	18.9	3006	3541
10	223	15.1	17.8	3358	3961
15	259	14.1	16.6	3642	4301
20	294	13.1	15.5	3856	4562
25	330	12.1	14.4	4001	4743
30	365	11.2	13.3	4077	4844
35	401	10.2	12.1	**4084**	**4865**
40	436	9.2	11.0	4022	4807
45	472	8.2	9.9	3891	4669
50	507	7.3	8.8	3690	4451
55	543	6.3	7.7	3421	4154
60	578	5.3	6.5	3083	3777
65	614	4.4	5.4	2675	3320
70	649	3.4	4.3	2199	2783
75	685	2.4	3.2	1654	2167
80	720	1.4	2.0	1039	1471
85	756	0.5	0.9	355	695
90	791	-0.5	-0.2	-397	-160
95	827	-1.5	-1.3	-1219	-1095
100	862	-2.4	-2.4	-2110	-2110

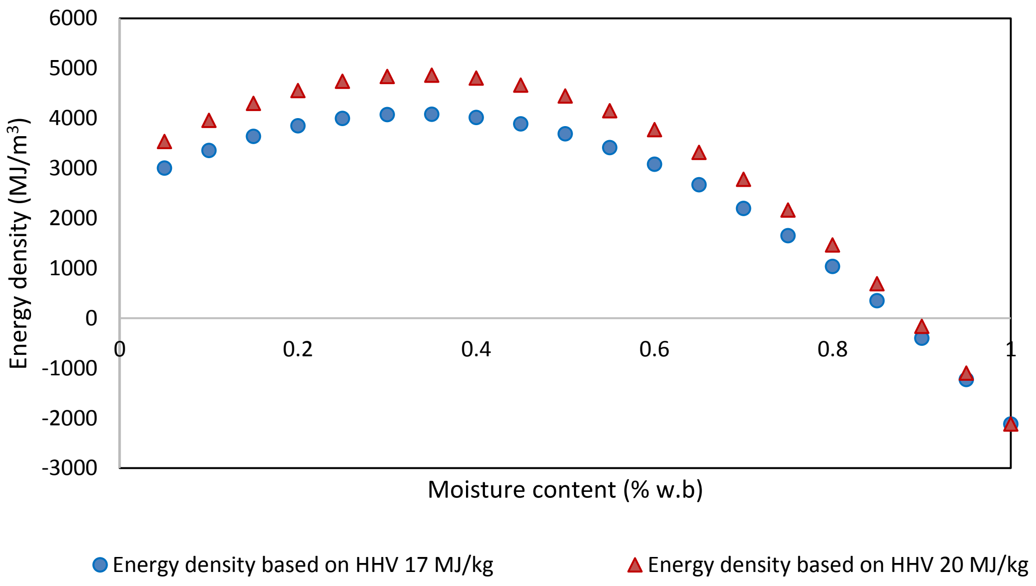

Figure 7-1. Graphical representation of energy density versus moisture content.

7.6 Energy density discussion

The bulk density and LHV was used to calculate the energy density of paunch. The energy density identifies the optimum moisture content to energy return. An unexpected peak at 35% MC for grass type paunch (4084 MJ/m^3) and for grain type paunch (4865 MJ/m^3) showed that the greatest return on energy is at these moisture contents. Although the dry paunch has a higher calorific value than wet paunch, the lower bulk density means that the total energy gained per cubic metre is less than optimum. The increase in energy density at 35% MC is most likely due to the addition of moisture acting as a lubricant and compacting force on the paunch. Bone dry paunch is "fluffy" with more void (air) spaces, increasing the MC allows the paunch particles to slide past each other and compacts the paunch thus decreasing the void space. This increases the bulk density due to more paunch fitting in the same volume until the optimum compression is reached.

Simplistically, increasing the bulk density increases energy density. Therefore, densification such as pelletising increases the energy density. Pelletising was not examined but increasing the energy density by pelletising lower MC paunch could be expected to be of benefit for uses such as reducing the feed rate, and efficiency loss in a boiler, if used as a coal substitute. However, the increased return on energy may be lost due to the energy required to dry and pelletise the paunch compared to the energy gained.

7.5.1 Case study

The energy density can also be used to identify viable energy application scenarios for use such as co-combustion or coal replacement in a boiler. A coal HHV of 28.69 MJ/kg was obtained from an abattoir in south east Queensland. The coal has an initial MC of 3.3% so the LHV is 27.66 MJ/kg. The same medium sized abattoir uses approximately 2 200 Tonne of coal per year and produces 60–90 m^3 of paunch per week with a MC of approximately 75% (w.b) (Spence 2012).

In an article by Bridle (2011a) it was suggested that paunch could be disposed of in a boiler with a MC of 70%. Using the energy density of wet tapped paunch at 70% MC and 90 m^3 of paunch produced per week, operating 52 weeks per year for comparison, the possible energy production for grass type paunch is 10.29×10^6 MJ per year and for grain type is 13.53×10^6 MJ per year (Table 7.4). This would possibly produce approximately one fifth of the required total energy for the site. However, boiler efficiency drop has not been included in this calculation. Water content impacts boiler output and is boiler specific. Boiler efficiency loss is approximately 0.1% for each 1% increase in MC (Hatt 1997).

Table 7-4. Potential energy production per year.

Type	MC (%)	Energy density or LHV	Amount of potential energy per year MJ
Coal	3.3	28.69 MJ/kg	60 852 000
Paunch - grass	70	2199 MJ/m3	10 291 320
Paunch - grain	70	2783 MJ/m3	13 525 380
Paunch - grass	35	4084 MJ/m3	19 113 120
Paunch - grain	35	4865 MJ/m3	22 768 200
Paunch - grass	dry	2585 MJ/m3	12 096 302
Paunch - grain	dry	3041 MJ/m3	14 230 944

These values show that while dry paunch has a significantly higher energy content than the wet (> 70% MC) the lower bulk density of the dry means that the energy density of the dry is comparable to the wet energy density. This demonstrates the possible benefit of pelletising dry paunch to increase the energy density before use in the boiler. This would also allow easier feeding into the boiler and storage of the pre-dried paunch.

Another consideration for disposal of paunch in the boiler is using the higher MC of paunch to raise the MC of the coal. The moisture content of coal is generally increased to 9% before use in the boiler (which would also affect the LHV). The mixing ratio of two products for a set overall moisture content can be solved for the mass of the second product:

$$m_2 = \frac{(m_1 \times G) - (m_1 \times MC_1)}{MC_2 - G}; \qquad (7.4)$$

where m_1 and m_2 are the mass kg, G is the goal moisture content, MC_1 and MC_2 are the products' moisture content percentage. Note that the moisture goal must be between the moisture contents' of the two materials being mixed (Trautmann & Richard 1996).

If the moisture content of paunch is 70% and there is one cubic metre at 649 kg/m^3 then the mixing ratio of coal to paunch is:

$$m_2 = \frac{(649\times 9)-(649\times 70)}{3.3-9}; \qquad (7.5)$$

where mass, m_2, of coal per cubic meter to be mixed with paunch is 6 945 kg to 649 kg/m^3 of paunch or a **11:1** mix for above moisture contents. This demonstrates that although there may be one fifth of the total coal energy demand replaceable by paunch, the increase in coal used to create a consistent boiler with an efficient MC would not be viable. The ratio of 11:1 coal to paunch with 70% MC would not be a feasible paunch disposal method for abattoirs to use.

Chapter 8 : Simplified heat balance equation

8.0 Modelling introduction

Modelling can predict behaviour. Predictive drying models are the precursor to equipment design; there are no predictive drying models for paunch in the literature. Two drying models were chosen, a generic simplified heat balance equation and the more robust Hukill equation.

The simplified heat equation provided a gross error check and starting point for the Hukill equation. The heat balance and Hukill share some parameters, however; the simplified heat balance has less parameters and uses area and volume in its calculations whereas the Hukill equation has more parameters and uses depth based on thin layer constants specific to a product. The Hukill equation was chosen due to its success in modelling grain and providing information regarding moisture content at any depth and time within a dryer. The future benefit of successful paunch depth models will allow specific dryer parameters such as airflow and temperature to be modelled and drying times predicted.

8.1 Simplified heat balance equation

Using the latent heat of vaporisation and bulk density of paunch the simplified heat balance equation from Brooker, Bakker-Arkema and Hall (1992) can be used to calculate approximate drying times for a specific dryer or gross approximations for generic dryers. The simplified heat balance equation is:

$$\frac{Q_A}{v} c_a (T_a - T_{wb}) t = L(m_d)(MC_i - EMC); \qquad (8.1)$$

where Q_A is the volumetric flow rate (flow speed times cross sectional area) (m^3/s), v is specific volume of air (m^3/kg), c_a is the specific heat of air (kJ/kg°C) $T_a - T_{wb}$ is the temperature drop (°C) where T_a is the ambient temperature and T_{wb} is the matching wet bulb temperature, t is time (s), L is the latent heat of vaporisation (kJ/kg), m_d is dry matter content (kg), MC_i is the initial MC in decimal dry basis, EMC is the equilibrium moisture content in decimal dry basis (Brooker, Bakker-Arkema & Hall 1992). Specific heat of air is 1.005 (kJ/kg°C) for the temperature range in this study.

Dry matter is calculated using the bulk density of the material and can be calculated:

$$m_d = BD(1.00 - MC)V; \qquad (8.2)$$

where BD is bulk density (kg/m^3), MC is the MC in decimal, V is volume of material (m^3) (Brooker, Bakker-Arkema & Hall 1992).

If a product is dried at depth, then a drying front will pass through the product producing drying zones (Figure 8.1). As the drying air, T_a, enters the product the first layer will dry with a drying zone moving upwards towards the damp zone. The exit air will initially pick up moisture, T_{wb}, (increase in RH) until the entire bed has dried to EMC matching the temperature and humidity of the entry air.

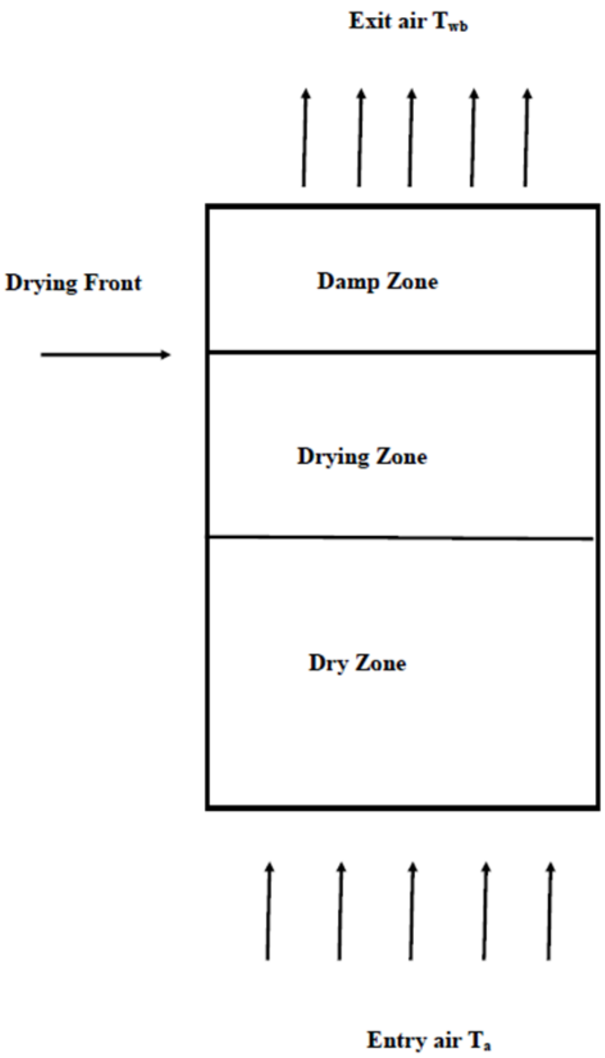

Figure 8-1. Drying zones produced by the drying front.

The specific volume of air and temperature drop are determined from a psychrometric chart but need ambient/ heated air conditions to be selected before use. The temperature drop is the difference between the entry/ plenum (heated or ambient temperature) air, T_a, and the exit air, T_{wb}. The exit air is the wet bulb (wb) temperature for the plenum conditions (heated or ambient) found on a psychrometric chart.

8.1.0 Psychrometry

The psychrometric chart graphically represents the thermodynamic properties of moist air. Moist air is a mix of dry air and water vapour where the amount of water vapour is dependent on the temperature and pressure (ASHRAE 2009). A psychrometric chart (Figure 8.2) includes information such as the humidity ratio, wet bulb temperature, dry bulb temperature, RH, enthalpy of the air, and the specific volume of air.

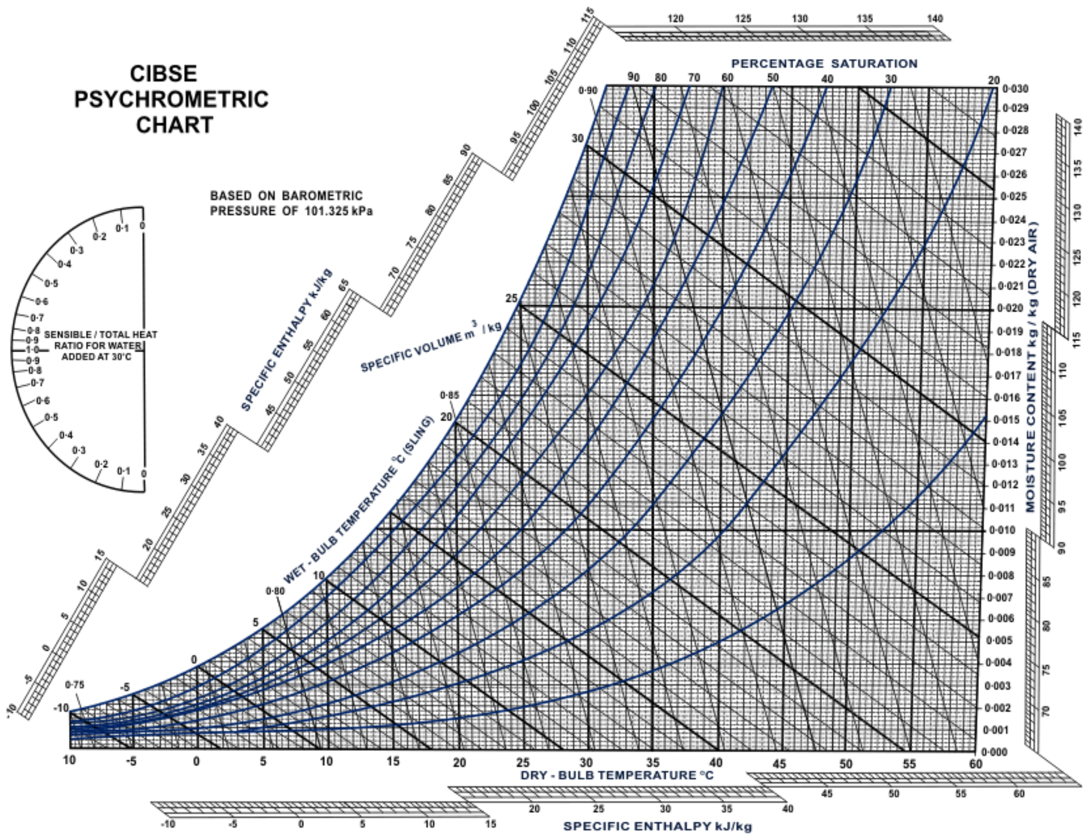

Figure 8-2. Psychrometric chart in SI units and degrees Celsius (Thermopedia n.d).

The humidity ratio also known as the absolute humidity or specific humidity is the mass of water vapour in moist air per unit mass of dry air:

$$H_A = \frac{m_w}{m_d}; \tag{8.3}$$

where H_A is the humidity ratio (absolute humidity) (kg/kg), m_w is the mass of water vapour (kg), m_d is the mass of dry air (kg).

This value is found on the right hand vertical axis on the psychrometric chart (appears as moisture content kg/kg dry air in Figure 8.2). The value for drying should range from 0.005 to 0.2 kg water /kg dry air (Brooker, Bakker-Arkema & Hall 1992).

Wet bulb temperature is the temperature of a thermometer with its bulb covered by a wet wick. The wet bulb is the temperature of the air if it were cooled to saturation by the evaporating water on the wick and is a lower than the dry bulb temperature. The dry bulb temperature is the ambient air conditions found using a non-modified thermometer (BOM n.d). The wet bulb temperature is the curved left hand side vertical axis in Figure 8.2 and dry bulb temperature is the horizontal axis.

RH is the ratio of the water vapour pressure in the air to the saturated water vapour pressure in the air at the same temperature and pressure and is expressed as a decimal or percentage (BOM 2011). It is called the percentage saturation in Figure 8.2 and is found on the top horizontal axis.

Enthalpy on the psychrometric chart is the heat content of moist air per unit mass of dry air and ranges from 23 kJ/kg to 314 kJ/kg for drying purposes (Brooker, Bakker-Arkema & Hall 1992). It is found below the dry bulb temperature on the bottom horizontal axis in Figure 8.2.

The specific volume of air is the value for the plenum (air chamber) conditions and is the reciprocal of density. Density can be calculated by:

$$\rho_{dry\ air} = \frac{p}{RT}; \tag{8.4}$$

where $\rho_{dry\ air}$ is the density of dry air (kg/m^3), p is air pressure (Pa), R is the specific gas constant for dry air (J/kgK), and T is temperature (K). The atmospheric pressure at sea level is 1013.25 hPa and the specific gas constant for dry air is 287.05 (kgK). Therefore, the specific volume is:

$$v = \frac{1}{\rho}; \tag{8.5}$$

where v is the specific volume of dry air (m^3/kg), ρ is the density of dry air (kg/m^3). Some psychometric charts will have the specific volume of air in place of enthalpy of air located on the same axis as the wet bulb temperature. However, in Figure 8.2 the specific volume of air is located on the diagonal left hand axis.

8.1.1 Air flow rate

Air is used in drying to carry the heat used for evaporation into a system and then carry the evaporated moisture out. The air flow speed through a product is dictated by the available static pressure from the fan and friction due to the airflow being forced between individual particles of the product. To generate an airflow, there must be enough pressure (generally created by fans but also by natural convection) to overcome the resistance and force air through the product (Hellevang 2013). The airflow resistance of a crop is a function of particle size and shape, bed depth, and desired airflow rate. Pressure drop is the term used to describe a product's resistance to airflow whereas static pressure is the pressure a fan must develop to overcome the pressure drop. Flow speeds vary from natural convection approximately 0.01 m/s, to laminar flow < 2 m/s, and turbulent > 3 m/s with turbulent being the most effective in a drying system (Brenndorfer et al. 1987).

8.2 Simplified heat balance equation results

A simplified heat balance equation can be used to estimate drying times for paunch in a deep bed dryer. It is useful as a first step in evaluating a possible dryer, as it only requires the bulk density, latent heat and EMC values for paunch.

The simplified heat balance was used to perform a preliminary analysis on the determined paunch characteristics and to determine the approximate range of values for airflow to use in the Hukill equation. An example of the heat balance equation includes: if there is 223 kg/m^3 of dry matter paunch in a dryer with an area of 40m^2 (at depth 0.025m) with a flow speed of 0.18 m/s at 35 °C then it would take 307 minutes to dry the paunch to EMC. This rate is comparable to (although a little slower) than the measured thin layer rate of approximately 200 min.

Using the heat balance equation to demonstrate the effect of increasing air flow speed is also a useful calculation. Choosing set conditions and only changing the flow speed allows drying times to be calculated. In Figure 8.3 the area of the dryer was chosen as 40 m^2 with a drying temperature of 35 °C. The graph shows the relationship between drying time and air flow speed. Increasing the flow speed decreases drying time, however the gain in increasing the air flow speed (in this scenario, flow speed over approximately 1.5 m/s for a decrease of only a few hours) is offset due to increased operational costs such as increasing fan size. Therefore, 1.5 m/s was the upper limit placed on the value for airflow used in the Hukill equation.

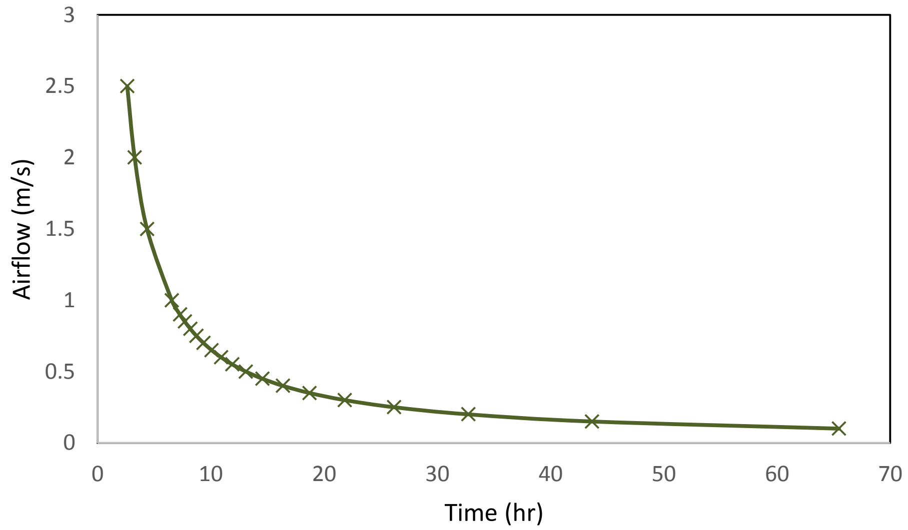

Figure 8-8-3. Airflow (m/s) versus time (hours). An increase in airflow from approximately 1 m/s does not greatly improve drying rates.

8.3 Simplified heat balance discussion

The simplified heat balance is useful for preliminary calculations for specific dryer parameters. It is not as robust as models that include more terms specific to the product being dried such as models based on thin layer rates. It is limited to one operating temperature and assumes that the sensible heat lost by the air to the product is equal to the latent heat of the product and that the product does not change temperature due to the operating air conditions at the start of the drying (Brooker, Bakker-Arkema & Hall

1992). However, the simplified heat balance equation showed that the values obtained for the latent heat, bulk density, and the EMC of paunch appear to be within the correct range, with the equation predicting 307 minutes to dry paunch as opposed to the 200 minutes found experimentally.

The simplified heat balance is also useful for easily changing parameters and testing drying theory. Changing air flow speed clearly demonstrates the drying theory that over certain velocities an increase in flow speed will not significantly decrease the drying times. Flow speed is important in terms of economic consideration, natural convection is the cheapest method (although least efficient) with turbulent the most expensive but also most efficient. The cost associated with forced airflow is in the initial cost of the fan and the associated cost in running and maintaining it. Some of the cost in running the fan can be mitigated by using either wind or solar power to provide the motive force to run the fan (Brenndorfer et al. 1987). However, it is beneficial to be able to use the set conditions for a dryer and change the airflow to determine the optimum return on airflow to drying time.

Chapter 9 : Hukill Equation

9.0 Deep bed drying equations

While thin layer drying rates are an important characteristic it is unlikely that a thin layer dryer will be used to dry paunch. This is due to the large amount of paunch produced on site. For example, spreading paunch at a depth of 1 mm would require an area of 9000 m × 10 m to account for the 90 m^3 of paunch produced at a medium sized abattoir per week. Therefore, drying at depth is a practical requirement and thus needs to be determined.

An important consideration when designing a dryer is the time taken to dry a product. In the case of the RMP industry, there is a daily production of paunch which will need to be dried in a timely manner so as to avoid a back log of paunch needing to be stored. Paunch freshness is also an issue for drying; as stated by Griffith and Brusewitz (1980) there is 'on the average a lower drying constant at intermediate ages and an increased drying constant for old paunch contents. The drying constant decreases during the 12 to 20 day period. As the paunch ages further, the variation in drying constant increases'. Drying time is therefore a key decision parameter to optimise handling and operating costs.

Logarithmic deep bed drying equations can be used to identify optimal paunch drying parameters to satisfy practical operational management. Logarithmic drying equations are a simplified method that use select parameters (including thin layer derived MR half-lives) to represent any deep-bed drying system (Brooker, Bakker-Arkema & Hall 1992).

9.1 Hukill deep bed drying equation introduction

The Hukill logarithmic equation can be used to determine the MC of a product at any time and depth inside a dryer (Brooker, Bakker-Arkema & Hall 1992). The limitations of using the Hukill equation include being unable to vary inlet temperature, or for very high temperature drying (Brooker, Bakker-Arkema & Hall 1992). However, for the purposes of this study the two limitations are not applicable. The Hukill equation was therefore chosen as it can be used to give estimations of drying times and a test of the parameters found in this study.

The Hukill (1954 in Brooker, Bakker-Arkema & Hall 1992) deep bed drying equation is:

$$MR = \frac{2^D}{2^D + 2^Y - 1}; \tag{9.1}$$

where MR is the moisture ratio, D is dimensionless bed depth factor, and Y is the dimensionless time unit.

9.1.0 Bed depth

The deep bed drying equation is graphically represented by the standard deep bed drying curves in Figure 9.1. These curves represent the dimensionless bed depth factors 0 to 16 for the MR versus dimensionless time units. These curves can be solved to give MC at any time or depth in a fixed bed drying system (Brooker, Bakker-Arkema & Hall 1992).

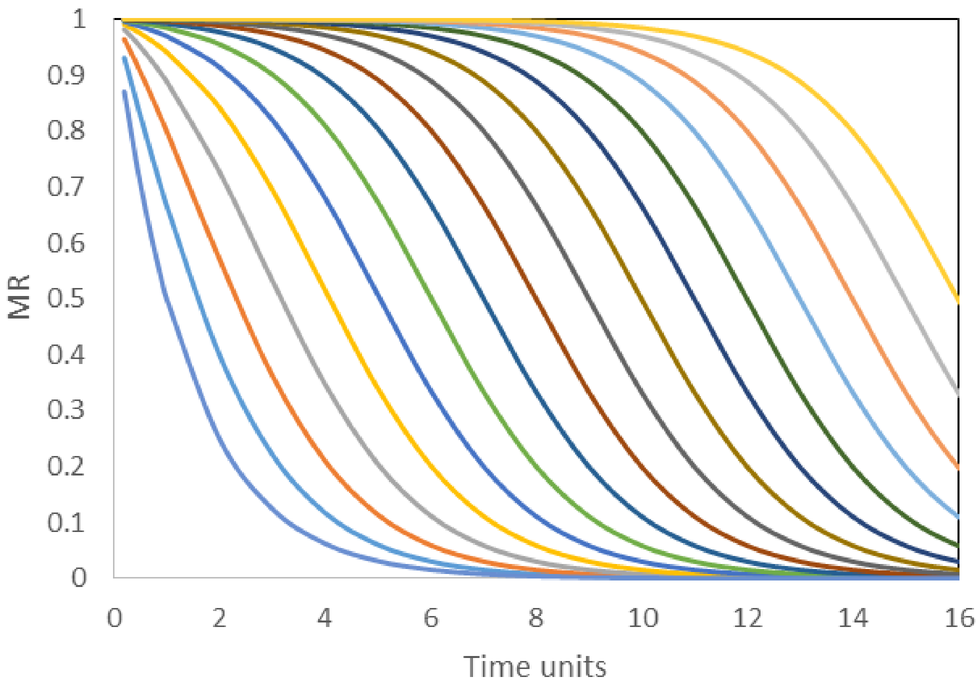

Figure 9-1. The standard deep bed drying curves from the Hukill equation.

9.1.1 Solving the Hukill equation

The dimensionless bed depth unit is:

$$D = \frac{x\rho_p L(MC_i - MC_e)}{\frac{Q}{v} c_a t_{MR(0.5)}(T_a - T_{wb})}; \tag{9.2}$$

where D is the dimensionless bed depth factor, x is the paunch depth (m), ρ_p is the density of paunch (kg/m^3), L is the latent heat of vaporisation of paunch (J/kg), MC_i is the initial MC (decimal), MC_e is the EMC (decimal), Q is the flow speed (m/s), v is specific volume of air (m^3/kg), c_a is the specific heat of air (kJ/kg°C), $t_{MR(0.5)}$ is the half response time (when the MR equals 0.5) of the thin layer MR at T_a, T_a is the inlet (or ambient) temperature (°C), T_{wb} is the wet bulb temperature (outlet temperature) (°C) of the air corresponding to Ta.

The dimensionless time unit is:

$$Y = \frac{t}{t_{MR(0.5)}}; \tag{9.3}$$

where Y is the dimensionless time unit, t is drying time, $t_{MR(0.5)}$ is the half response time of the thin layer MR at T_a.

Dry matter can be calculated per depth factor using a similar heat balance equation with the thin layer term added:

$$DM = \frac{Q_A c_a (T_a - T_{wb}) t_{MR(0.5)}}{vL(MC_i - MC_e)}; \tag{9.4}$$

where DM is the amount of dry matter per depth factor (kg/depth factor), Q_A is the volumetric air flow rate (flow speed times cross sectional area) (m^3/s), c_a is the specific heat of air (kJ/kg°C), T_a is the inlet (or ambient/ heated) temperature (°C), T_{wb} is the wet bulb temperature (outlet temperature) (°C) of the air corresponding to Ta, v is the specific volume of dry air (m^3/kg), L is the latent heat of vaporisation of paunch (J/kg), MC_i is the initial MC (decimal d.b), MC_e is the EMC (decimal d.b), $t_{MR(0.5)}$ is the half response time (when the MR equals 0.5) of the thin layer MR at T_a.

9.2 Depth equation results

It is common practice to develop deep bed drying models as a series of thin layers (e.g. Lopez, Pique & Romero 1998, Srivastava & John 2002). The Hukill deep bed drying equation (1954 as cited in Barre, Baughman & Hamdy 1971) is a logarithmic model based on the thin layer moisture ratio equation. An example of a graphical representation for the Hukill deep bed drying curves using the thin layer half-life of the moisture ratio, $t_{(MR0.5)}$, belonging to 40% RH with 0 to 16 dimensionless depth units is shown in Figure 9.2. This graph indicates the dimensionless time units with the matching time in hours below, along with the MR and matching MC in percent wet basis (w.b) on the vertical axis. The moisture content at any time and depth (on the deep bed drying curves) can be found by finding the dimensionless depth unit, D, [Eqn. 9.2] and the dimensionless time unit, Y, [Eqn. 9.3] and substituting these values into the Hukill equation [Eqn. 9.1] and then solving for the moisture ratio, MR.

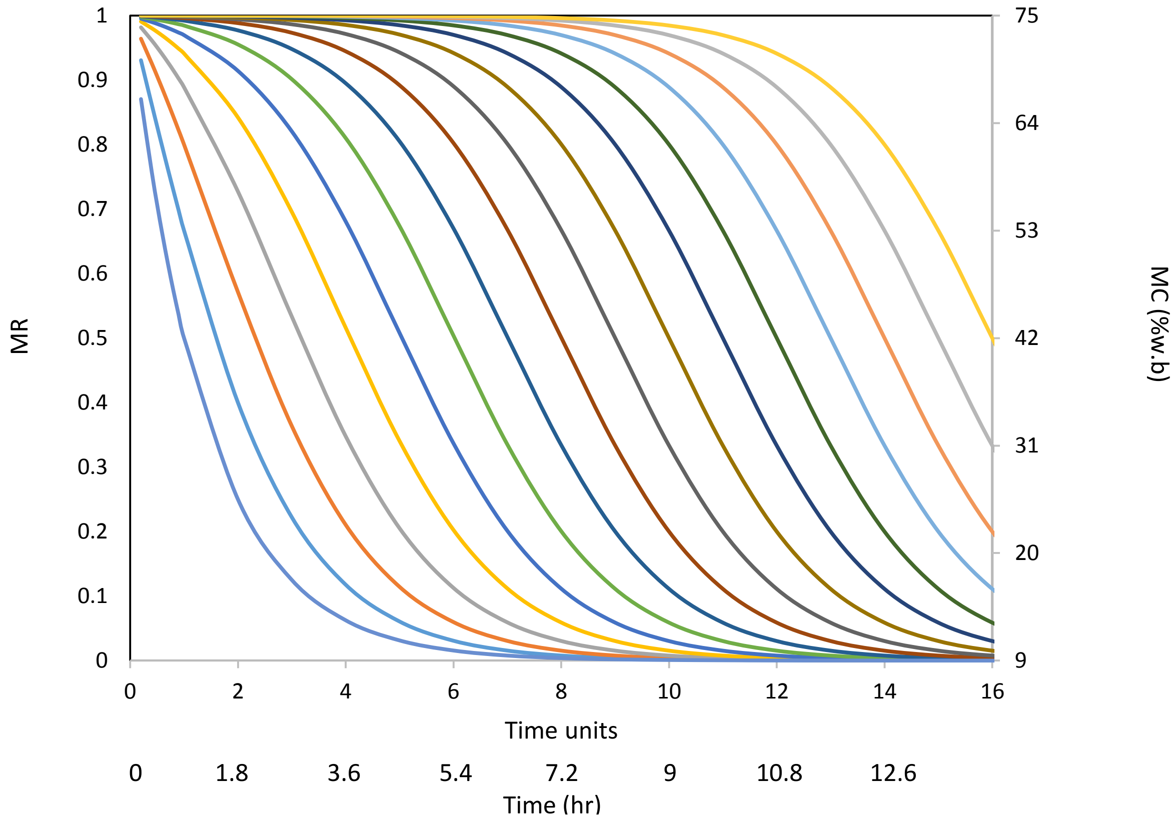

Figure 9-2. Example drying curves for the Hukill equation using the thin layer half-life, $t_{MR(0.5)}$, for 40% RH with 0–16 depth units. Each time unit is 0.9 hours with an initial MC of 75% (w.b).

The fixed terms used in the bed depth equation (Table 9.1), are bulk density for bone dry paunch, latent heat of vaporisation for paunch, the specific heat of air, and the specific volume of air. The latent heat of vaporisation would change in a deep bed drying situation due to changing moisture content and temperature within the drying zones. Nevertheless, it is standard practise to use the mean value for latent heat and keep it constant in the dimensionless bed depth equation [Eqn. 9.2] (Brooker, Bakker-Arkema & Hall 1992).

Table 9-1. Fixed term values for the dimensionless bed depth equation, *D*.

Fixed terms	Value	Units
ρ bulk density	152.04	kg/m^3
L latent heat	2842.4	J/kg
c specific heat	1.004	kJ/kg°C
v specific volume	0.865	m^3/kg

The parameters that are variable for different conditions, (Table 9.2), are paunch depth, initial and equilibrium MC, airflow rate, half response time of the thin layer MR, and ambient and wet bulb temperature. The EMC, half response time, and wet bulb temperature are all reliant on the ambient/ heated operating air temperature. For a given set of conditions (once the operating conditions have been selected) only the depth and airflow rate can be varied within the dimensionless bed depth equation. However, comparisons between different parameters such as temperature can be performed.

Table 9-2. Variable terms for the dimensionless bed depth equation, *D*.

Variable term	Value range/ limit	Unit
x paunch depth	No set limit	m
MC_i	≈75 < 85% MC	decimal
MC_e	≈7.1 < 13.5% MC	decimal
Q airflow rate	Based on velocities > 0.01 < 1.5 m/s	m^3/s
$t_{MR(0.5)}$	3240 < 8280	s
Ta ambient/entry air	35–55	°C
Twb wet bulb	24.5–55	°C

9.2.0 Time for $MR_{(0.5)}$

Using the drying constant, *k*, and time exponent, *n*, determined from the Page equation [Eqn. 4.1] in the thin layer drying experiments, the MR half-lives were calculated for the MR equations belonging to the 40, 60, and 80% RH equations and a combined temperature equation. The MR half-life is the time taken for the MR to reduce to 50% of the initial moisture value. Figure 9.3 is a graphical representation of the four equations that were developed from the thin layer experiments. The values for time when the MR reached the half-life, $MR_{(0.5)}$, are shown in Table 9.3, the half-lives ranged from 0.9–2.3 hr^{-1}.

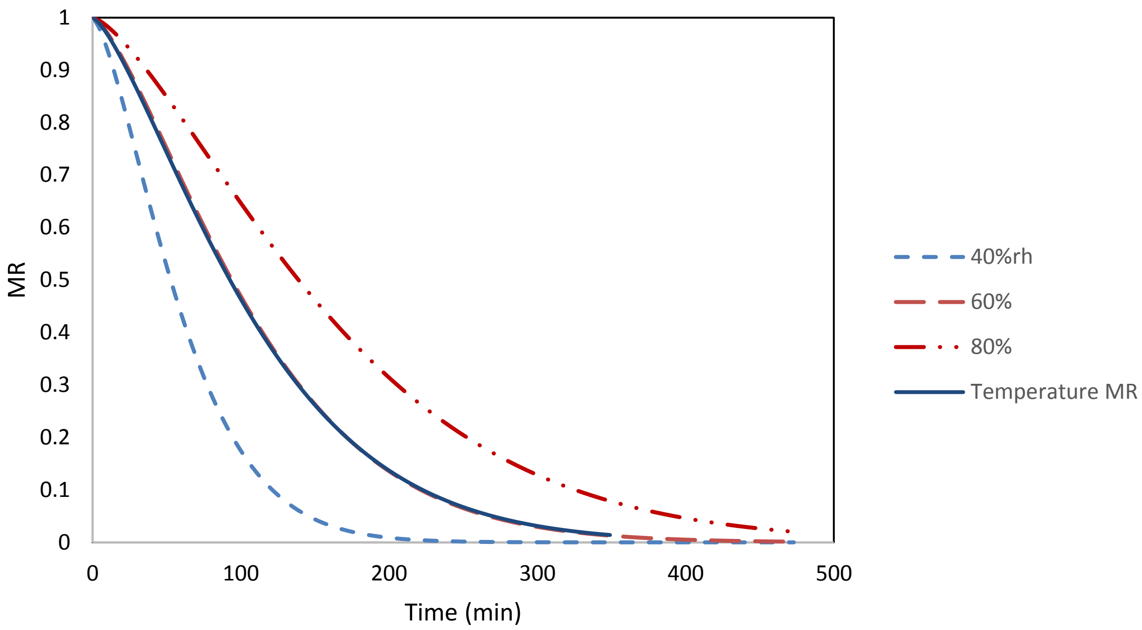

Figure 9-3. MR versus time (min) for MR (40, 60, 80% RH) and MR (35, 45, 55°C).

Table 9-3. The moisture ratio half-life, $MR_{(0.5)}$, values for temperature and RH.

Temp °C	**Time (hr^{-1})**
35, 45, 55	≈1.55
%RH	
40	0.9
60	1.6
80	2.3

9.2.1 Depth equation solutions

A solution for MC and time to dry at depth can be seen in Figure 9.4. The solutions use the RH MR half-life from the thin layer equations for 40, 60, and 80% RH at varying depths and temperature.

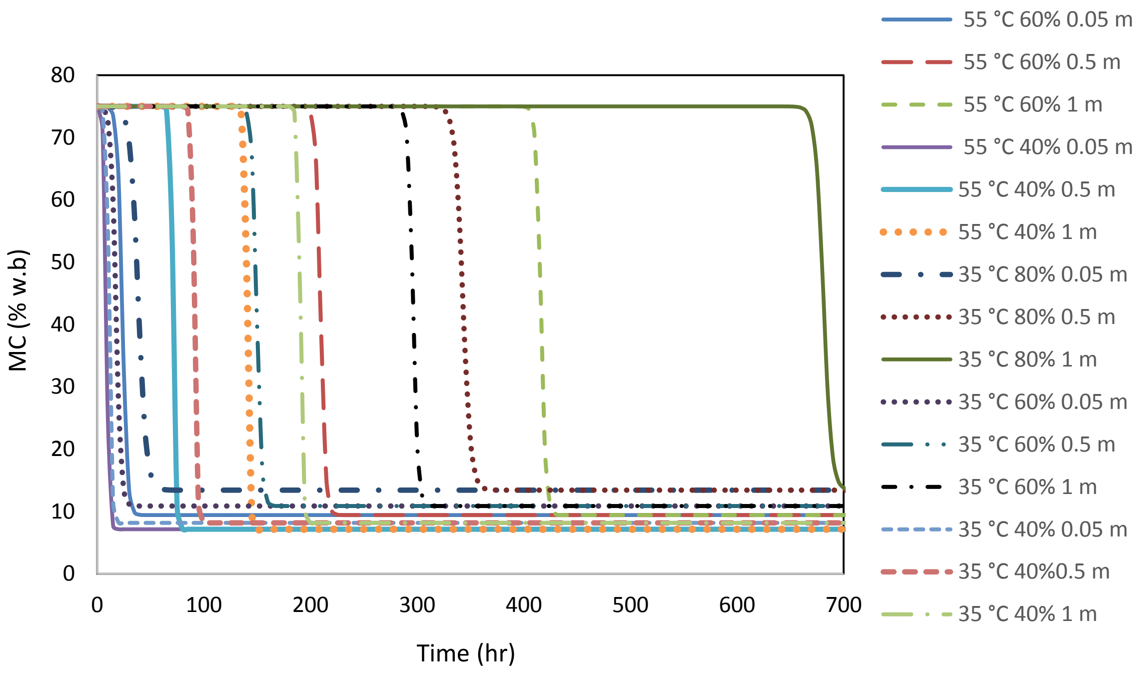

Figure 9-4. Time for different operating temperatures and depth using the MR half-life values for RH.

The model was then run using the 40% RH MR half-life at 1 x 10^{-11} m depth (close to zero) to allow comparison to the measured data (thin layer 35 °C 40% RH samples a and b). As the depth approaches zero in the dimensionless bed depth equation, D, the Hukill model becomes independent of the dimensionless bed depth parameters while still being affected by the time unit. This simplifies the model to become an approximation of the thin layer, thus potentially validating the Hukill model which is built upon the theory that drying at depth is a series of thin layers.

Comparison of the Hukill model to the measured paunch samples a and b (Figure 9.5) showed a good correlation, with sample a having an R^2=0.99 to the Hukill model and sample b having an R^2=0.95 to the Hukill model. The half-life point for the model and samples were a good fit, however, the final data ranges showed some deviation.

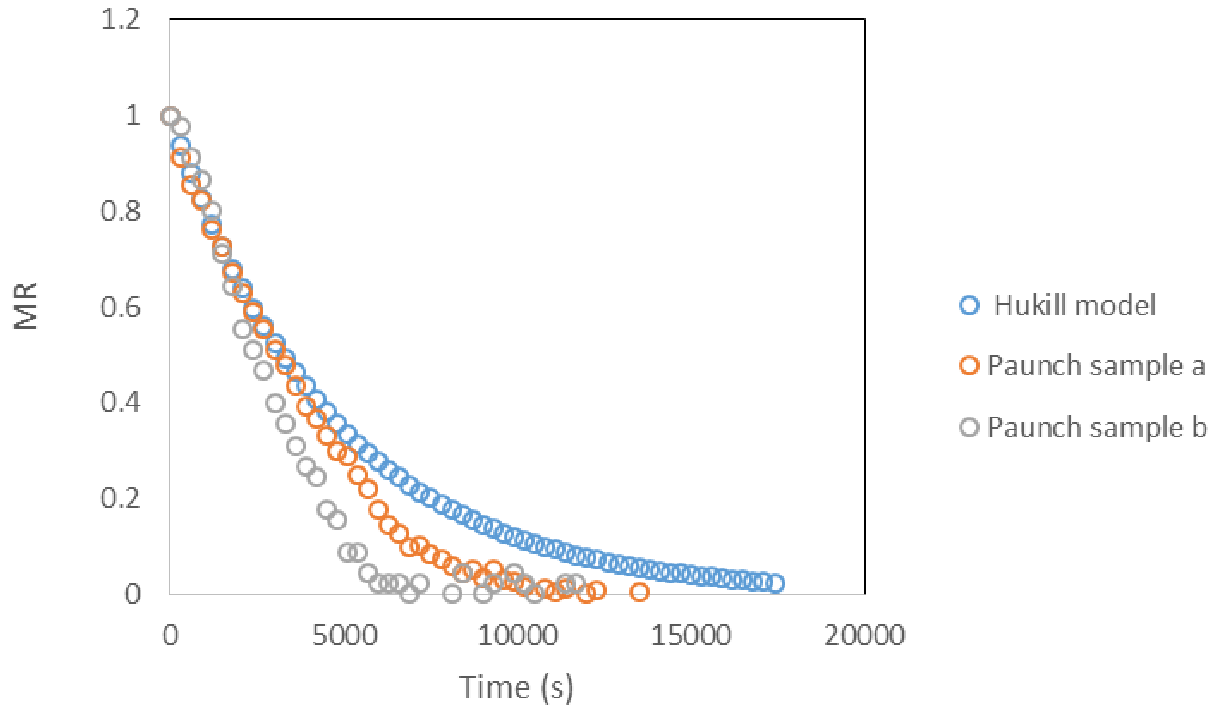

Figure 9-5. Comparison of Hukill model for 1 x 10^{-11} m depth to paunch thin layer 35 °C, 40% RH samples a and b.

Statistical software was used to determine the optimum value for the dimensionless depth unit, *D*, that would give the best fit to the paunch sample MR data. The value found was *D* = -0.714 with R^2 = 0.928, this is shown in Figure 9.6. The Hukill model shows a better fit to the data with sample a having an R^2 = 0.99 and sample b having an R^2 = 0.98 to the Hukill model. However, a negative dimensionless depth unit is not a real solution as either the wet bulb temperature would have to be greater than the ambient temperature, the EMC would have to be greater than the initial MC, or one of the set values would need to be negative (which is not a real situation). It is therefore, possible that the parameter affecting the fit is the dimensionless time unit, *Y*.

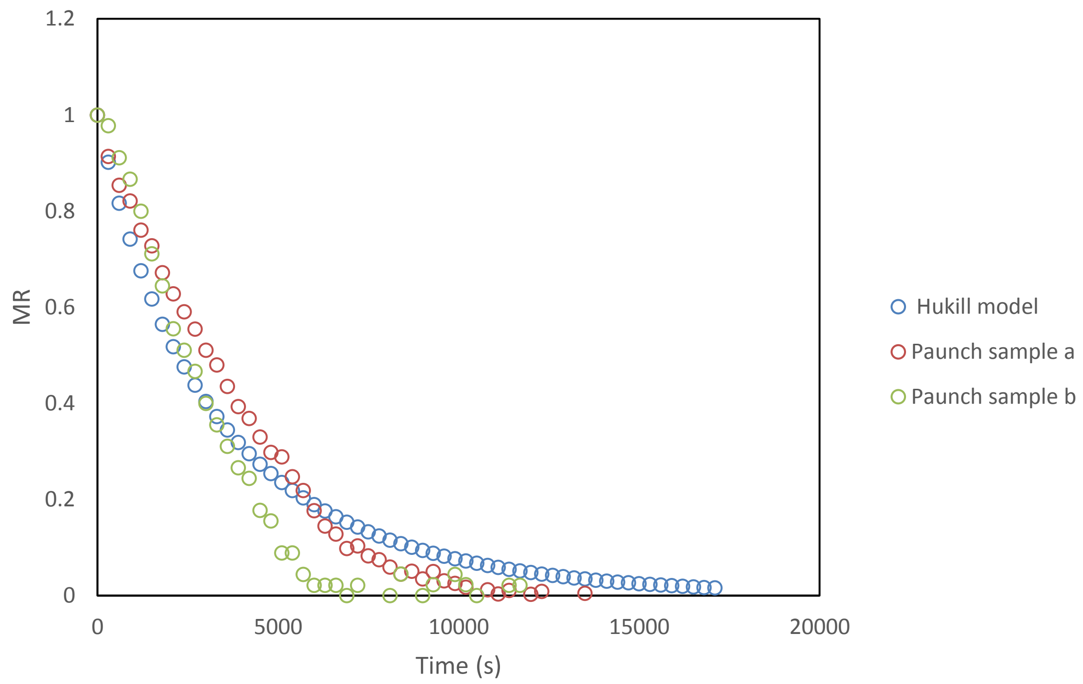

Figure 9-6. A non-linear regression was used to find the optimum D value for the set conditions, this gave *D* = -0.714 in the Hukill equation producing an R^2 of 0.928.

9.2.3 Second and time based Hukill equation

A check was performed on the acquired thin layer drying constants by using the 2nd and time based Hukill equation (Bihercz 2006):

$$MR = \frac{2^{kt^n}}{2^{kt^n} + 2^{kt^B} - 1}; \tag{9.5}$$

where k, n, and B are constants and t is time in (min). Putting the thin layer determined values of k = 0.0023 and n = 1.44, determined from the Page equation into the Hukill equation and then performing a non-linear regression for B gives B = 1.65 (Table 9.4). These values show a good correlation (R^2 = 0.988 for sample a, R^2 = 0.986 for sample b) to the model, leading to the conclusion that the thin layer values are an appropriate representation of the experimentally acquired thin layer data (Figure 9. 7). The values determined for this equation restrict its application as they do not allow for changing depth however, the coefficient B demonstrates that the dimensionless time unit, Y, appears to be a contributing factor to the poor fit to the experimental data.

Table 9-4. Constants for use in the 2nd and time based Hukill equation.

Constant	Value
k	0.0023
n	1.44
B	1.65

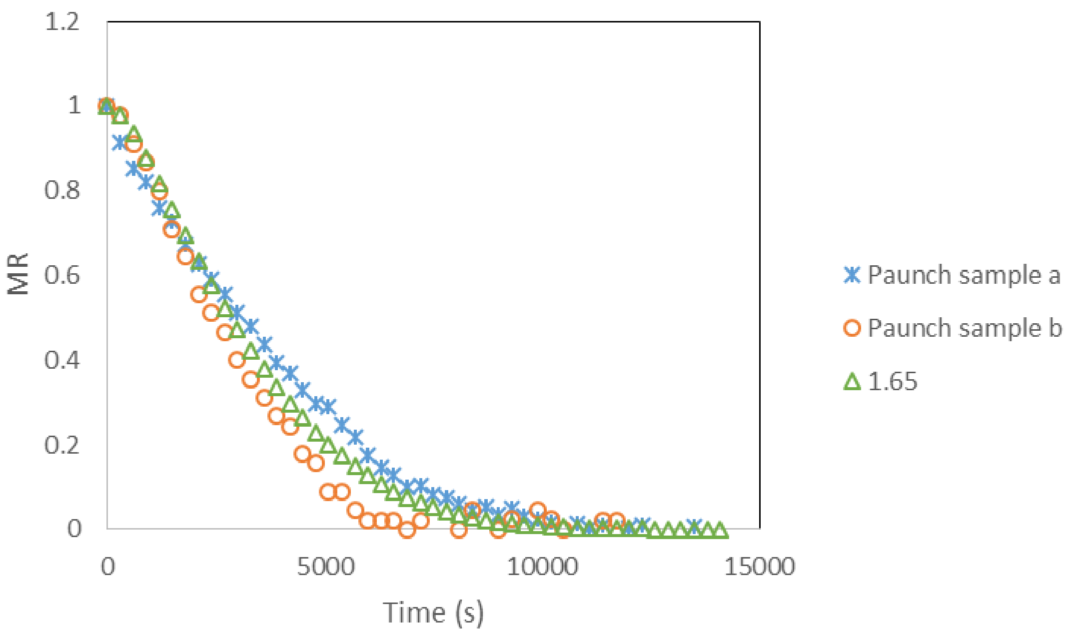

Figure 9-7. A plot of the experimentally determined thin layer constants applied to the constants in the 2nd and time based Hukill equation with the experimentally determined thin layer paunch samples.

9.2.4 New coefficients for the Hukill equation

In order to find an appropriate fit to the experimental data, coefficients for the Hukill equation were required. Coefficients in the Hukill equation were tested using statistical analysis software to perform a non-linear regression. The equation:

$$MR = \frac{2^D}{2^D + 2^{\frac{Y}{A}+B} - C}; \tag{9.6}$$

where *D* is the dimensionless depth unit, *A*, *B*, and *C* are constants, and *Y* is the dimensionless time unit was solved for *A*, *B* and *C* at depth 0 was found to produce the highest R^2 value. A non-linear regression was used to find the constants $A = 0.379$, $B = -1.904$ and $C = 0.252$ at depth, $x \approx 0$ m, giving an R^2 value of 0.98. Figure 9.8 demonstrates a better fit for the data to the depth model using the constants.

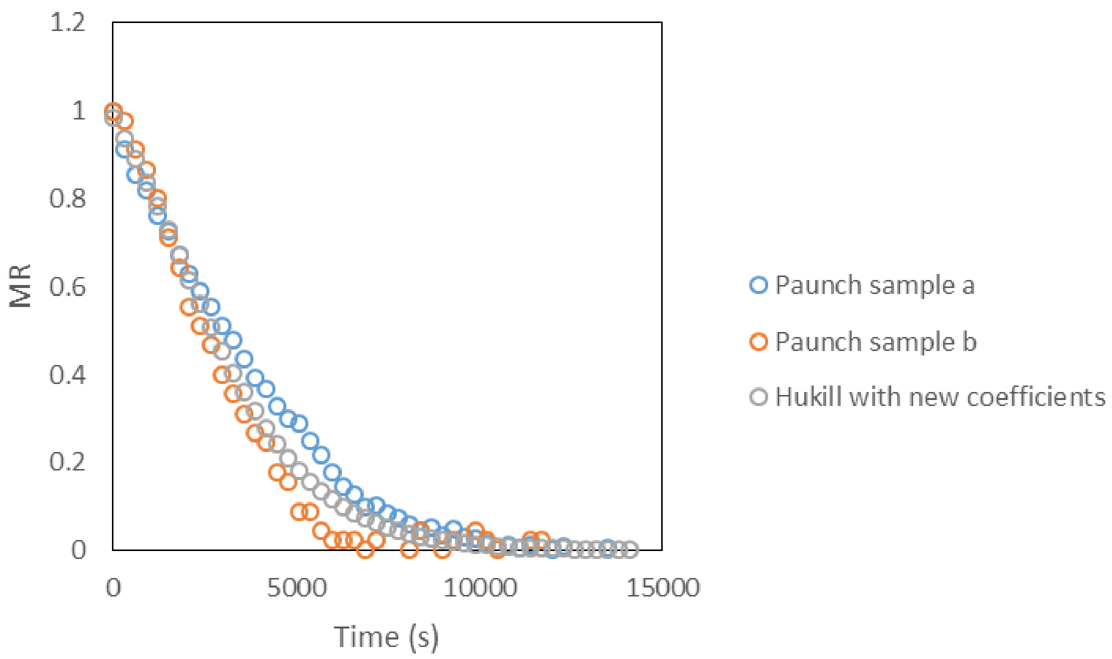

Figure 9-8. The Hukill equation with coefficients added to the time constant, R^2 values are 0.997 for the thin layer and 0.998 for the 2.5 cm sample.

Figure 9.9 demonstrates the solutions to the model based on the Hukill equation using the new coefficients with varying depth from 0 to 0.2 m. Table 9.5 shows the set values used in the dimensionless depth equation used to solve the Hukill equation and calculate the curves in Figure 9.9.

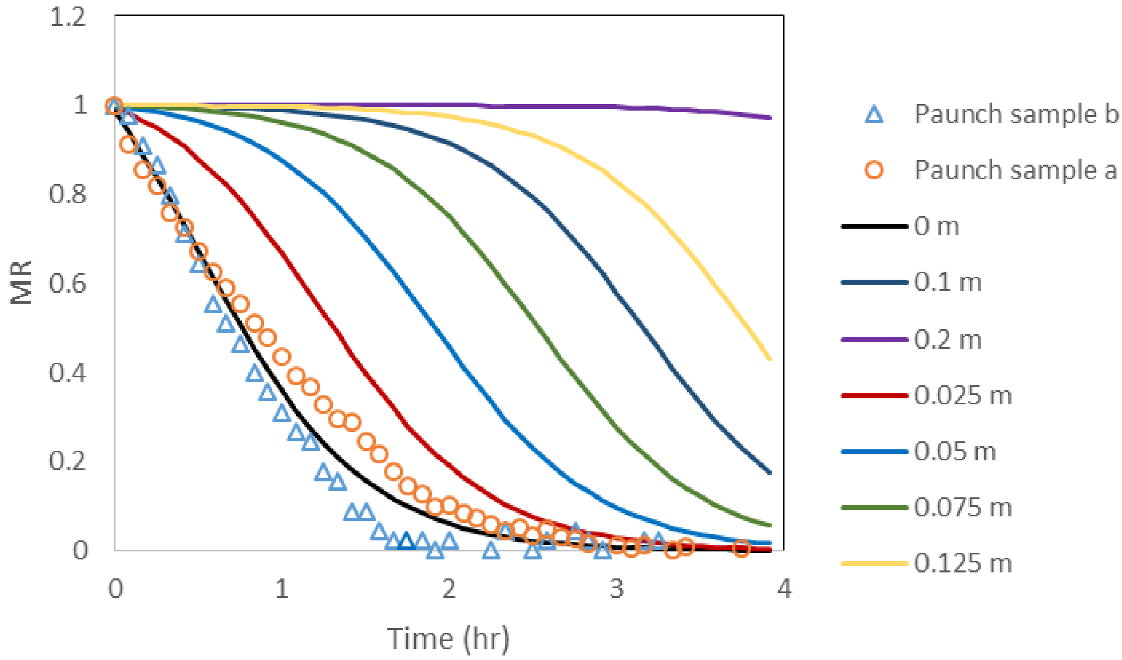

Figure 9-9. Solution to the Hukill equation for paunch at varying depth using new coefficients on the dimensionless time unit.

Table 9-5. Set values for the dimensionless depth unit equation used in solving the Hukill equation.

Parameters	Chosen set values	Units
x	$1 \times 10^{-11} – 0.2$	m
ρ	152.04	kg/m^3
L	2842.4	J/kg
MC_i (d.b)	2.57	decimal
MC_e (d.b)	0.087	decimal
T_i	35	°C
T_o	24.5	°C
Q	0.37	m^3/s
c	1.004	kJ/kg°C
$t_{(0.5)}$	3240	s
v	0.865	m^3/kg

9.3 Depth equation - discussion

The solutions to the Hukill depth equation can be used to test the sensitivity of changing parameters (excluding at depth equals zero) within the equation and to find MC at any time and depth within a dryer. Parameters specific to paunch for the Hukill equation to work are the bulk density, latent heat of vaporisation, MR half-life (of the thin layer, section 4.3), initial MC, and EMC. The initial solution found for the Hukill equation showed an expected increase in time with depth and increasing humidity. However, comparison to the acquired data for paunch at depth ≈ 0 m showed a poor correlation to the final data ranges. The MR half-life point for both the data and the model showed a good fit with the model appearing to be able to predict mid-range to high MR values. However, the Hukill equation was unable to predict the lower range MR to time values.

The next step was to test if the MR half-life from the thin layer equation was affecting the model. A check was performed on the thin layer drying rates, by putting Pages equation into the second and time based Hukill model (Bihercz 2006) (the exponential based modified Hukill equation (Barre, Baughman & Hamdy 1971, Bihercz 2006) was also attempted as a solution, however, the fit was extremely poor). The thin layer constants and a constant for the time unit (found by a non-linear regression) were put into the new model and graphed against the paunch data. The constants used in the equation showed a much better fit to the experimentally acquired data. The equation is not useful for modelling changing depth but showed that the thin layer constants matched the solutions to the MR equations from which the Hukill and Page equation were derived and to the experimental data. Applying the constant to the time unit used with the thin layer constants, lead to the conclusion that the time unit in the Hukill model must be the contributing factor to the poor fit seen compared to the paunch data.

Literature suggests success with the Hukill model for products such as grain where the MC is generally low. For example, Young and Dickens (1975) applied the Hukill model for grains with an initial MC of 21% to a final MC of 15% with good success. The model may be limited to lower initial MC's and it is possible that the initial boundary conditions that were used to solve the original moisture ratio DE to develop the Hukill equation had an exponential boundary condition set on it. It may be more likely in this case to be an exponential with a linear function of time. This may be why the Hukill equation solves lower initial MC well but does not seem able to fully predict paunch possibly due to the high initial MC. A non-linear regression was used to find coefficients for the time unit in the original version of the Hukill equation. The constant A slowed the time unit while still maintaining the half-life point. These new coefficients produced a consistent fit to the thin layer (depth equals zero), experimentally acquired paunch data. The new constants are:

- $A = 0.379$
- $B = -1.904$
- $C = 0.252$

The fit at $D \approx 0$ produced an R^2 of 0.98.

Brenndorfer et al. (1987) cautions that equations derived from experimental work that used air velocity from 1-10 m/s in their experimental design are not suitable for modelling data for velocities < 0.1 m/s. The airflow used in the Hukill equation was based on the airflow used in the thin layer experiment (airflow in the environment chamber times the chamber area). The predicted lines using the new constants and airflow rate in the Hukill equation appear to develop consistently with time as depth is increased.

Chapter 10 : Discussion

10.0 Introduction

The RMP industry in Australia is important for economic and employment reasons: 'Total beef and veal production was 2.2 million tonnes in 2008–09 with a farm gate value of $8 billion' and 'the beef industry employs more than 220, 000 people at the farm, processing and retail levels' (Primary Industries Standing Committee 2009).

However, increasing economic and environmental pressures are placing strain on industries. Industry specific waste to energy streams may help to alleviate rising energy costs and reduce their carbon footprint, helping to create a more sustainable industry. Paunch has shown promise as a biomass, however, its high initial MC has held back its implementation into industry. Drying a product requires a knowledge of the end use for which the product is intended and an understanding of certain inherent characteristics that inform how the product will dry. For paunch to be used for purposes such as co-combustion, pyrolysis or gasification then a final MC of $\leq$ 35% is required. Drying rates, energy content and EMC (and associated characteristics) are needed to allow optimum dryer design.

A systematic characterisation process has been developed to allow informative drying information to be calculated for paunch. A new custom designed thin layer dryer was used in laboratory testing to produce paunch constants that may be used to develop predictive models for paunch drying. Fundamental properties such as the EMC, thin layer drying constants, energy content, bulk density and latent heat of vaporisation were calculated. These specific properties of paunch will allow the use of further modelling predictions to be made regarding paunch drying at depth and selection of future dryer design.

10.1 Summary of developed equations

Paunch characteristics and predictive equations have been determined and new coefficients for the Hukill equation have been developed to allow future work to be done with regard to designing a paunch dryer. The new predictive equations are:

Thin layer drying, Page's equation for temperature in the range of 35–55 °C,

$$MR = e^{-0.0013t^{1.42}} \ . \tag{10.1}$$

Thin layer drying, Page's equation for humidity,

$$MR_{40\%} = e^{-0.0023t^{1.44}} \tag{10.2}$$

$$MR_{60\%} = e^{-0.0012t^{1.40}} \tag{10.3}$$

$$MR_{80\%} = e^{-0.00066t^{1.41}} \tag{10.4}$$

The Chung-Pfost equation (as rearranged in Hutchinson & Otten 1984) for EMC,

$$MC_e = (\ln 492.88 - \ln(T + 25.550) - \ln(-\ln(RH)\,)\,)\ \frac{1}{30.751}. \tag{10.5}$$

Predictive equation for untapped paunch bulk density,

$$BD = 3.9791 \times MC + 105.76 \tag{10.6}$$

Predictive equation for tapped paunch bulk density,

$$BD = 7.1028 \times MC + 152.04. \tag{10.7}$$

The Hukill deep bed drying equation with new co-efficients,

$$MR = \frac{2^D}{2^D + 2^{\frac{Y}{0.379} - 1.904} - 0.252}. \tag{10.8}$$

The average gross calorific value for grass type paunch was found to be 17 MJ/kg, with grain type paunches 20 MJ/kg. The energy density values for paunch varied from 4865 to -2110 MJ/m3. The average latent heat of vaporisation for paunch was found to be 2842.38 kJ/kg.

The calculated characteristics where possible have been compared to previously published results. The measured results appear within expected ranges and the predicted models show a reasonable fit to the data. The determined characteristics should help improve the field of knowledge in regards to paunch drying and allow future modelling of specific paunch dryers to be developed.

10.2 Future dryer design

To dry paunch a suitable dryer type needs to be identified. Basic dryer designs are generally based on the same principals whether they are run using fossil or renewable fuel sources. Most dryers are either direct or indirect in how they provide heat for drying. A direct dryer uses contact between the product and the drying air such as; hot air, steam, or ambient air to dry the product. Indirect dryers avoid contact with the product and drying air relying on the contact between the product and the heated chamber to cause the drying.

For paunch to become an economically viable biofuel choice for abattoirs it needs to be dried cheaply and quickly. It would be uneconomical to use a drying method that uses more energy than is recoverable and costs more than the competing fossil fuel (e.g. paunch as a coal replacement in a coal fired boiler). This means that at least the bulk of the drying should be done using a cheap renewable energy fuel source.

One of the simplest methods for reducing the drying costs is to use a “free” energy source such as the sun. There are two methods for utilizing the suns energy for drying: solar drying or sun drying. A solar dryer is an enclosed unit that uses solar thermal energy to dry substances as opposed to open air sun drying which as the name suggests is just spreading the substance to be dried out in the sun. There are a number of drawbacks to open air drying including the large surface area required to spread the product, lengthy sun exposure time, it is dependent on climatic conditions, possible infestation from insects, the product is exposed to the elements such as rain, and possible odour problems, etc. (e.g. Bennamoun & Belhamri 2003, Belessiotis & Delyannis 2010). Solar dryers, on the other hand, do not face these problems, are independent of weather conditions, have low labour costs, and are also capable of increasing temperature and air movement. Decreasing the relative humidity (RH) which not only increases the drying rate but also increases the throughput of the product (e.g. Brenndorfer et al. 1985, Belessiotis & Delyannis 2010). Solar dryers also offer advantages over fossil fuel run dryers in that they are generally cheaper to build and have lower maintenance costs (Weiss & Buchinger n.d).

Solar drying using an active or passive dryer with a suitable absorber appears to be a possible solution to cheaply drying paunch. The drying constants show a sensitivity to relative humidity and control of this will be important in the final dryer design. The modified Hukill equation should allow possible dryer designs to be modelled and drying times assessed. An ideal end use for paunch would be cheap solar drying followed by use in a coal fired or co-combustion boiler, with or without pelletising. This would utilise a waste product and turn it into an easily implemented energy stream.

Chapter 11 : Conclusion

11.0 Conclusion

Paunch waste appears to be a viable site-specific bioenergy stream for the RMP industry to adopt. However, little research in this area combined with the high initial moisture content of the paunch waste has hindered the implementation of this resource. Robust characterisation of paunch waste is needed to allow informed decisions to be made regarding suitable methods for integrating paunch as a waste to energy stream in RMP plants.

Optimum drying times, economic viability, and product handling are all reliant on appropriate dryer selection which is in turn reliant on the specific properties of the product. Therefore, before paunch can be implemented, a thorough characterisation needed to be performed to allow informed decisions to be made regarding paunch handling and dryer design.

The aim to physically characterise abattoir paunch waste and develop predictive equations to facilitate adoption of paunch as a useful biomass was successful. The physical properties of paunch for use as a biomass such as energy content, equilibrium moisture content, bulk density, and energy density have been determined, along with the latent heat of vaporisation, thin layer drying rates, and a predictive deep-layer drying model.

A new thin layer dryer was developed using an environment chamber with purpose built-load cells used to record changing weight. The investigations performed in this study showed that the drying constant, k, varied from 0.0002 to 0.0029 min^{-n} with an average n value of 1.42 ± 0.081 for 35–55 °C operating air at 40, 50, 60, and 80% RH. The EMC varied from 7.14–13.44% MC and constants for the Chung-Pfost equation were determined.

Due to the large variation on cattle finishing procedures new energy calculations were performed for grass and grain type paunches. Calorific values varied from 17–20 MJ/kg for grass and grain type paunches respectively. The previously determined value generically given for paunch of 16.7 MJ/kg (Ricci 1977) was reviewed and found to be consistent with grass type paunches however a new value of 20 MJ/kg was determined for grain type.

Based on the newly derived equations the bulk density for untapped paunch ranges from 106 kg/m^3 (dry) to 504 kg/m^3 (100%) and for tapped 152 kg/m^3 (dry) to 862 kg/m^3 (100%). The energy density values for paunch varied from 4 865 to -2 110 MJ/m^3. The highest energy density (4 084 MJ/m^3) for grass and (4 865 MJ/m^3) for grain type paunch belonged to 35% MC. The latent heat of vaporisation for paunch varied from 2 519 to 3 741 kJ/kg for 15 to 6% MC. The modified Hukill equation with coefficients is:

$$MR = \frac{2^D}{2^D + 2^{\frac{Y}{0.379}-1.904} - 0.252}. \tag{11.1}$$

Lack of knowledge into the inherent properties of paunch has caused a potential waste to energy stream to go unutilised. The characteristics of paunch determined in this study will allow future work to be carried out into the design of a paunch dryer by allowing needed characteristics and constants to be used in future drying models. The modified Hukill equation [Eqn. 11.1] will allow industry to use specific dryer parameters such as airflow and temperature, to determine the time it will take for paunch to dry at depth. The importance of humidity cannot be ignored and dryers with regulated humidity control will be required. The characteristics of paunch found in this study are not unique to Australian type paunch and will be applicable to the international RMP community.

11.1 Limitations of the study & future work

There were some limitations in regards to this study. The study was restricted to the temperature range of 35–55 °C (with 55 °C operating temperature unable to maintain 80% RH) for the thin layer data. Recommendations for future work are outlined below:

(i) Acquire thin layer drying constants to include higher operating ranges for temperature and lower relative humidity ranges.

(ii) Depth data acquisition — a pilot or lab scale deep-bed dryer should be built to test the constants developed for the modified Hukill equation.

(iii) Development of automatic paunch type detection software such as modified image recognition software, or modified remote sensing image processing software.

(iv) The original differential equations used for the development of the Hukill equation should be resolved using new boundary limits.

(v) A study on the casehardening of paunch and the use of relative humidity as a control would be beneficial, although breaking of the paunch crust is a possible solution to this problem.

(vi) A study on pelletizing paunch to increase the energy density and as a storage and handling method would also be beneficial to the RMP industry.

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Appendix A – Drying rate graphs

Page equation fit to the experimental data.

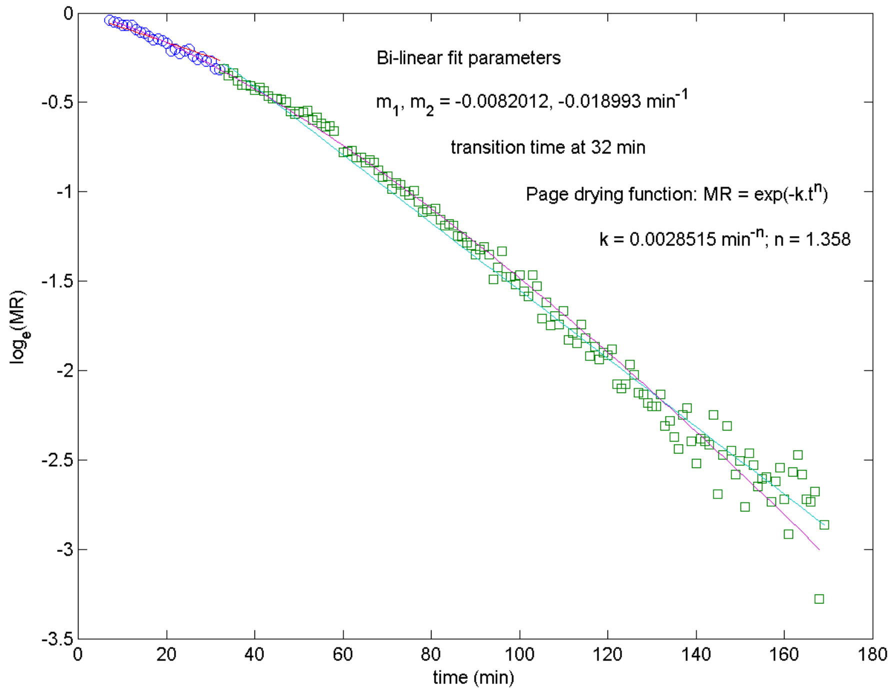

Figure A-1 - Thin layer grain 35 °C, 40% RH.

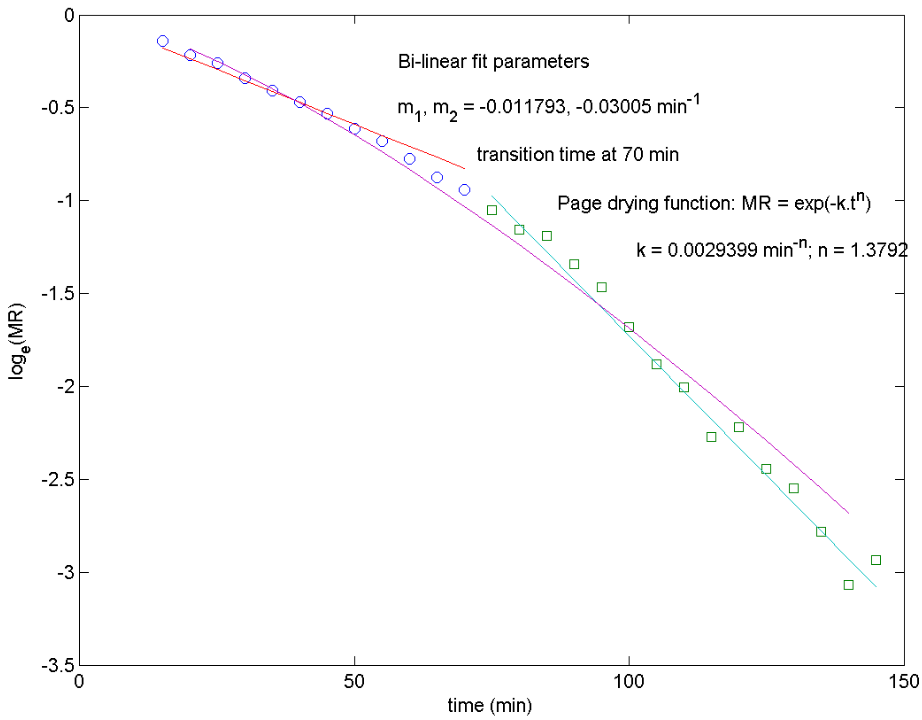

Figure A-2 - Thin layer grass 35 °C, 40% RH.

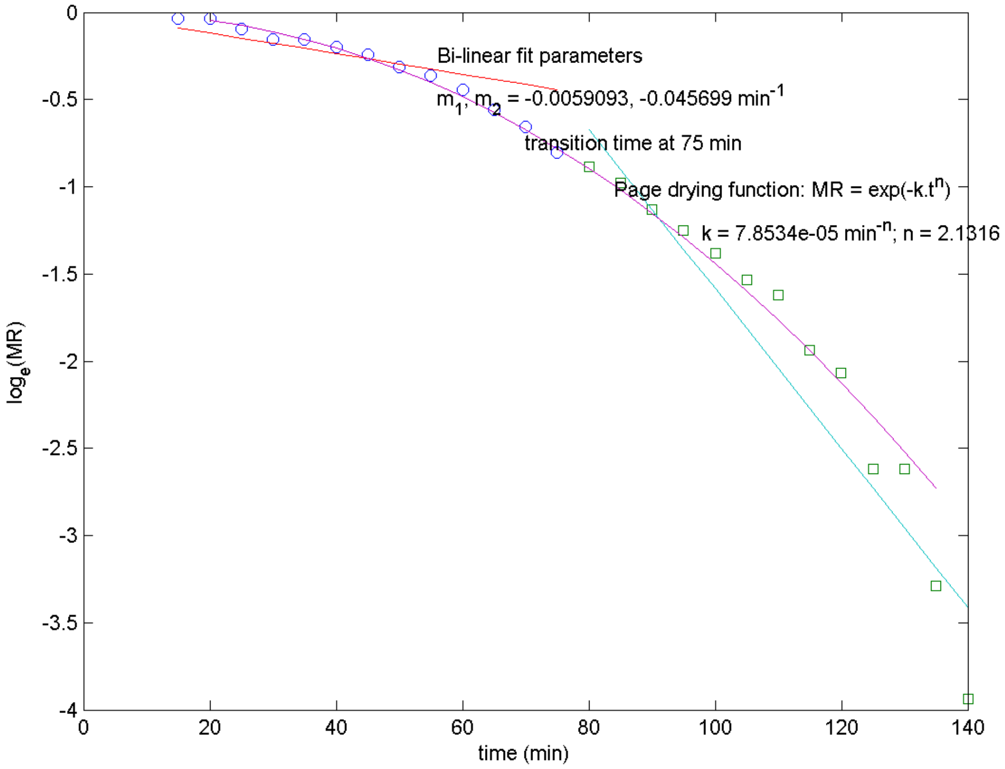

Figure A-3 - Thin layer grass 35 °C, 40% RH.

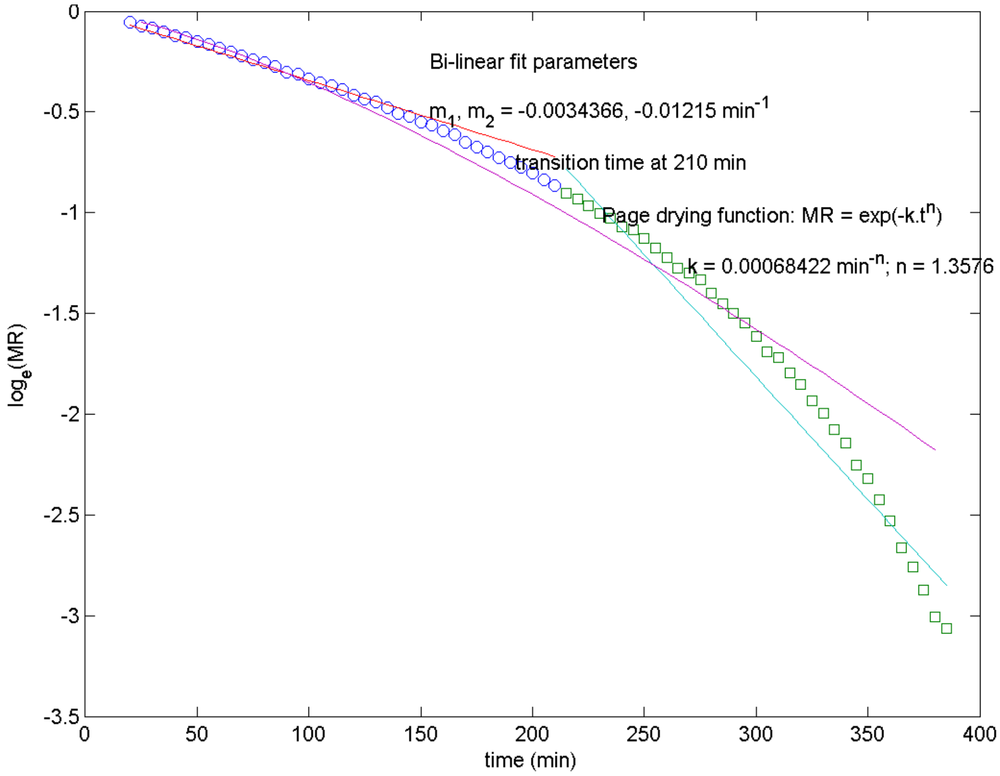

Figure A- 4 - Thin layer grass 35 °C, 50% RH.

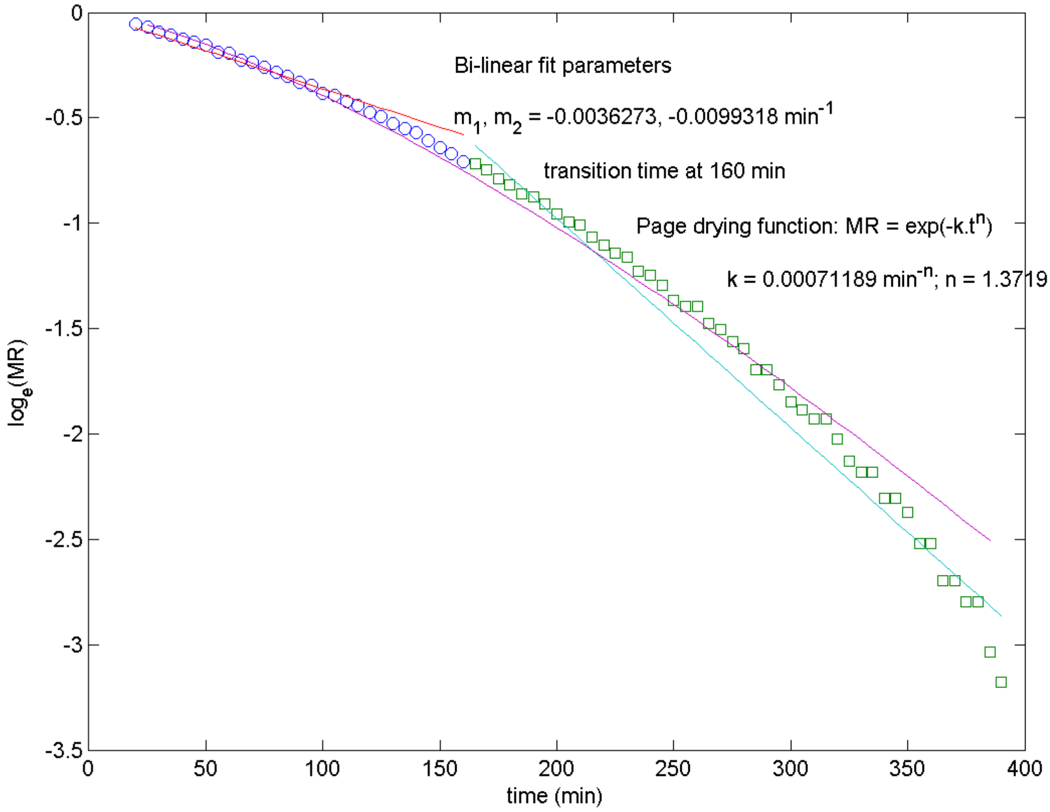

Figure A-5 - Thin layer grain 35 °C, 60% RH.

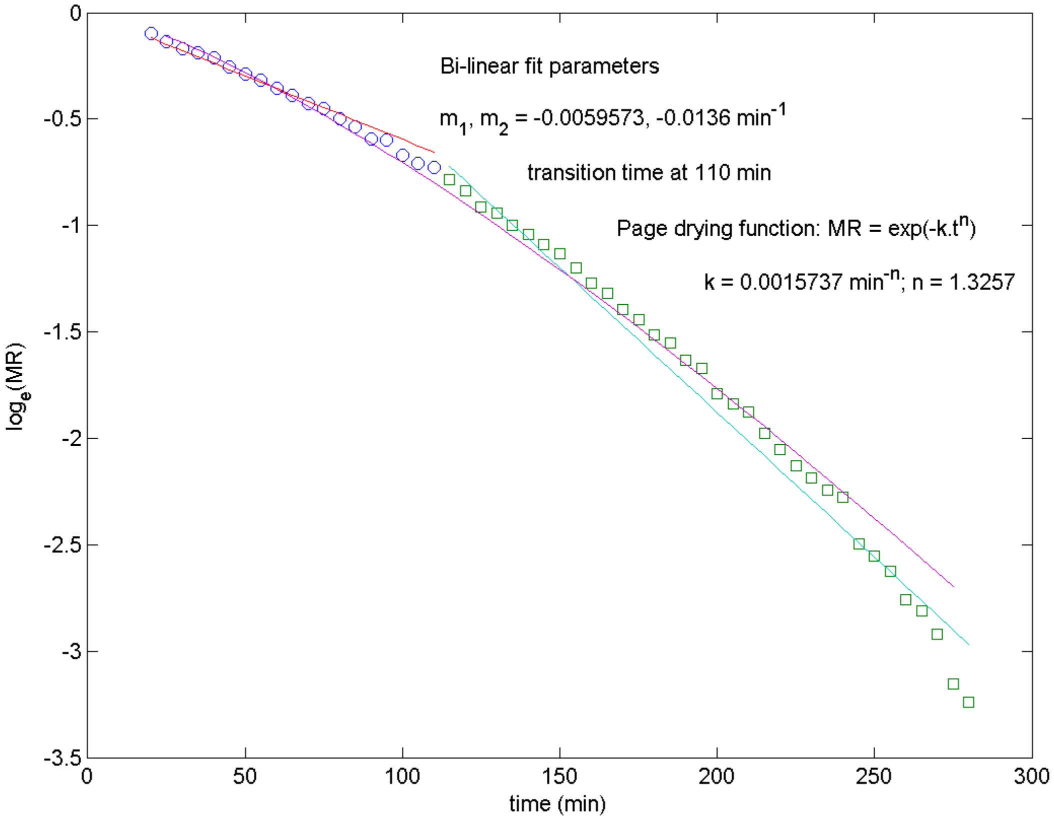

Figure A-6 - Thin layer grain 35 °C, 60% RH.

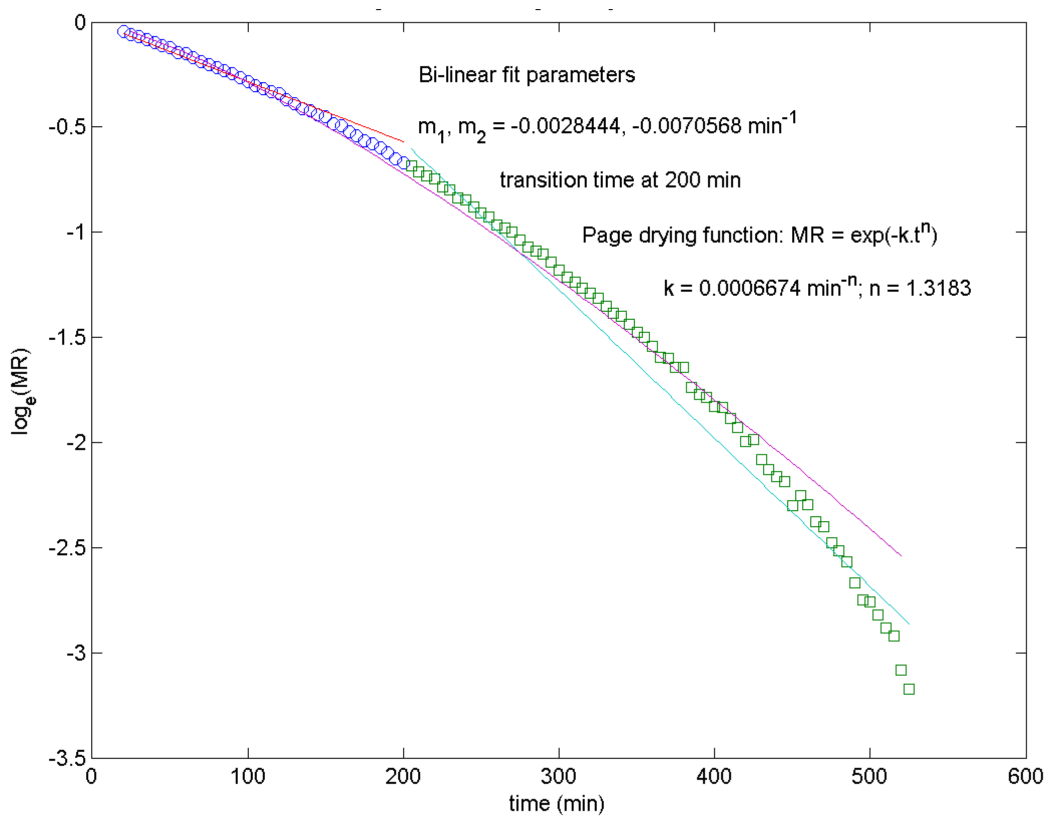

Figure A-7 - Thin layer grain 35 °C, 80% RH.

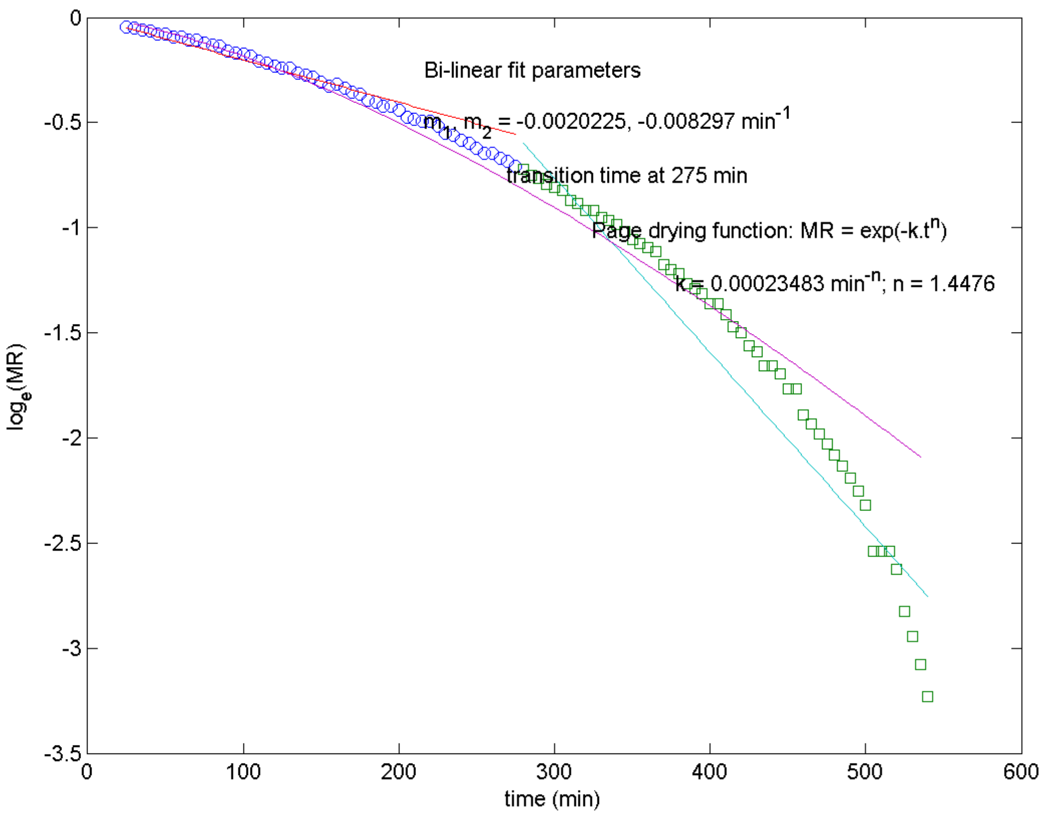

Figure A-8 - Thin layer grass 35 °C, 80% RH.

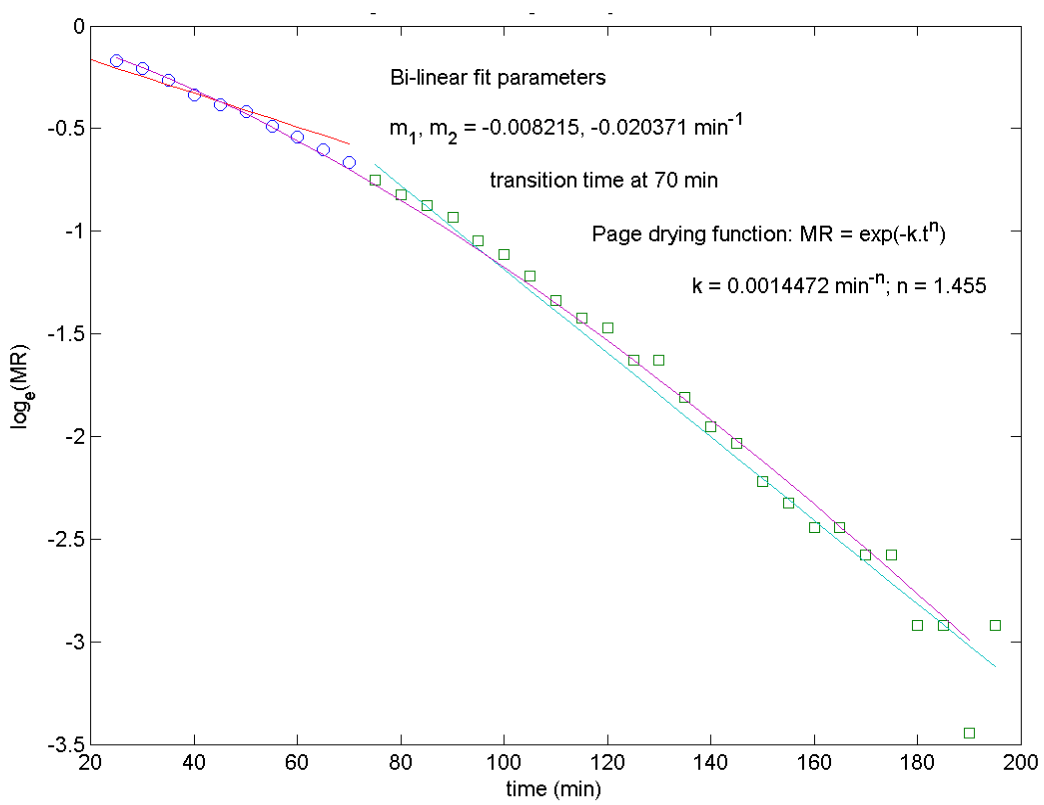

Figure A-9 - Thin layer grass 45 °C, 40% RH.

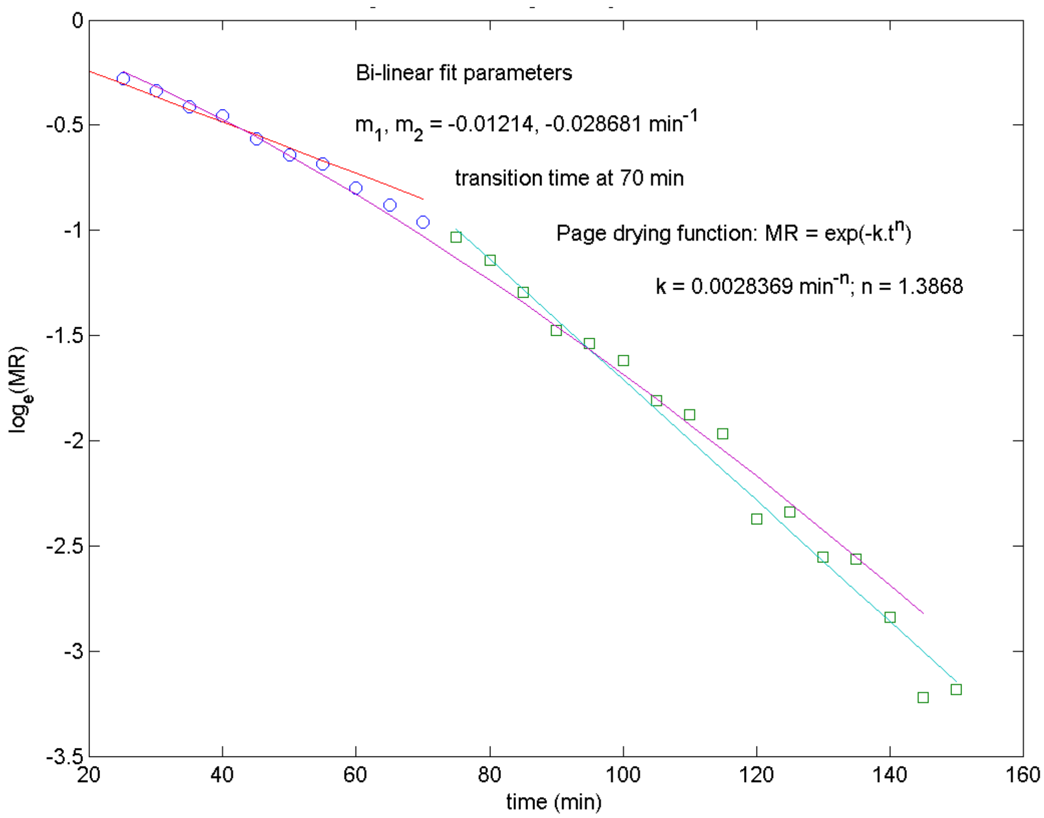

Figure A-10 - Thin layer grass 45 °C, 40% RH.

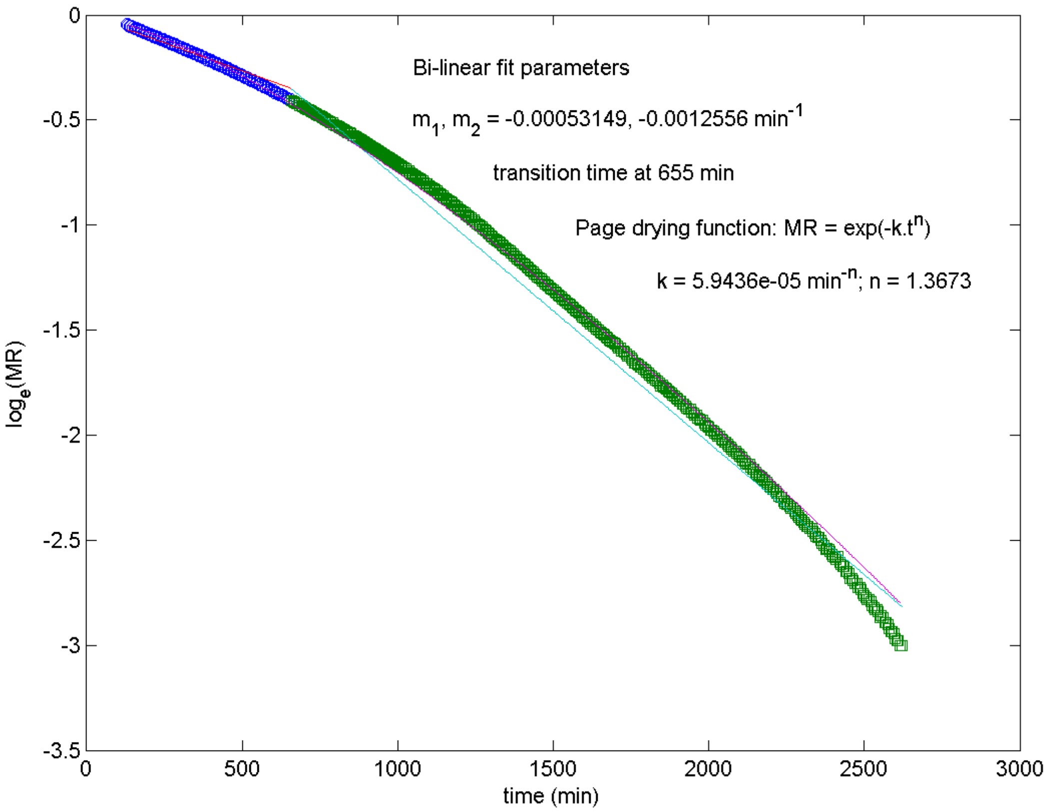

Figure A-11 - 2.5cm layer grass 45 °C, 50% RH.

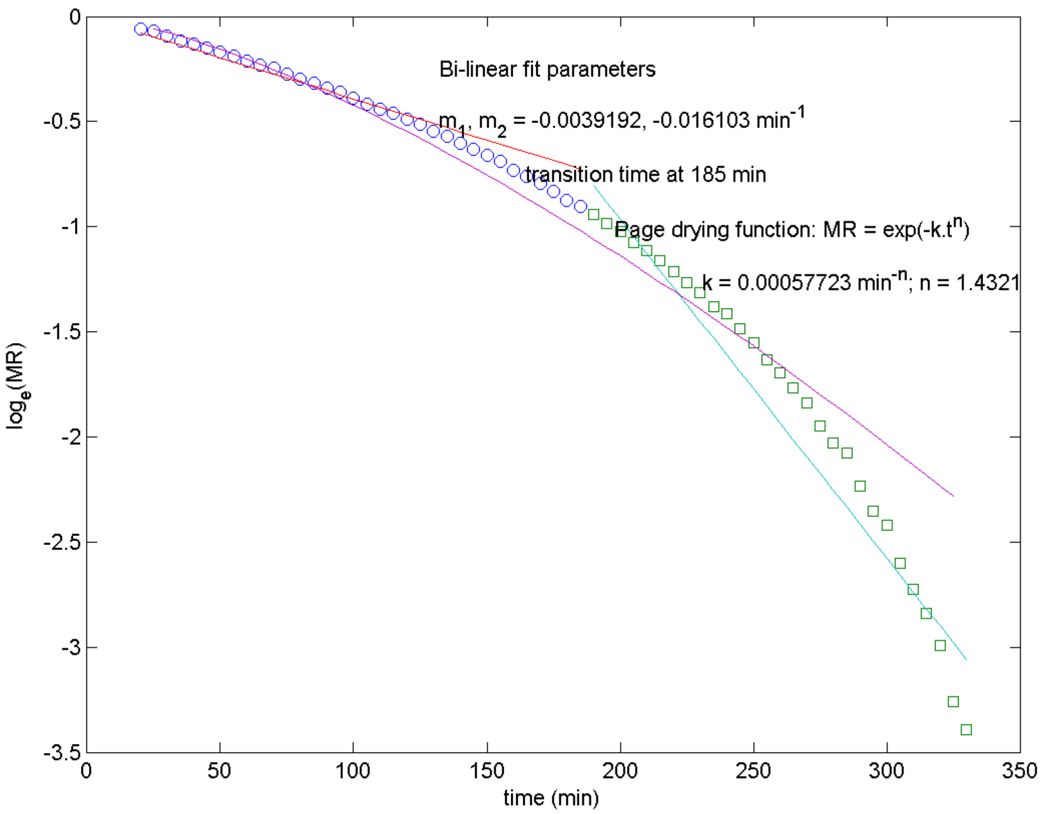

Figure A-12 - Thin layer grass 45 °C, 50% RH.

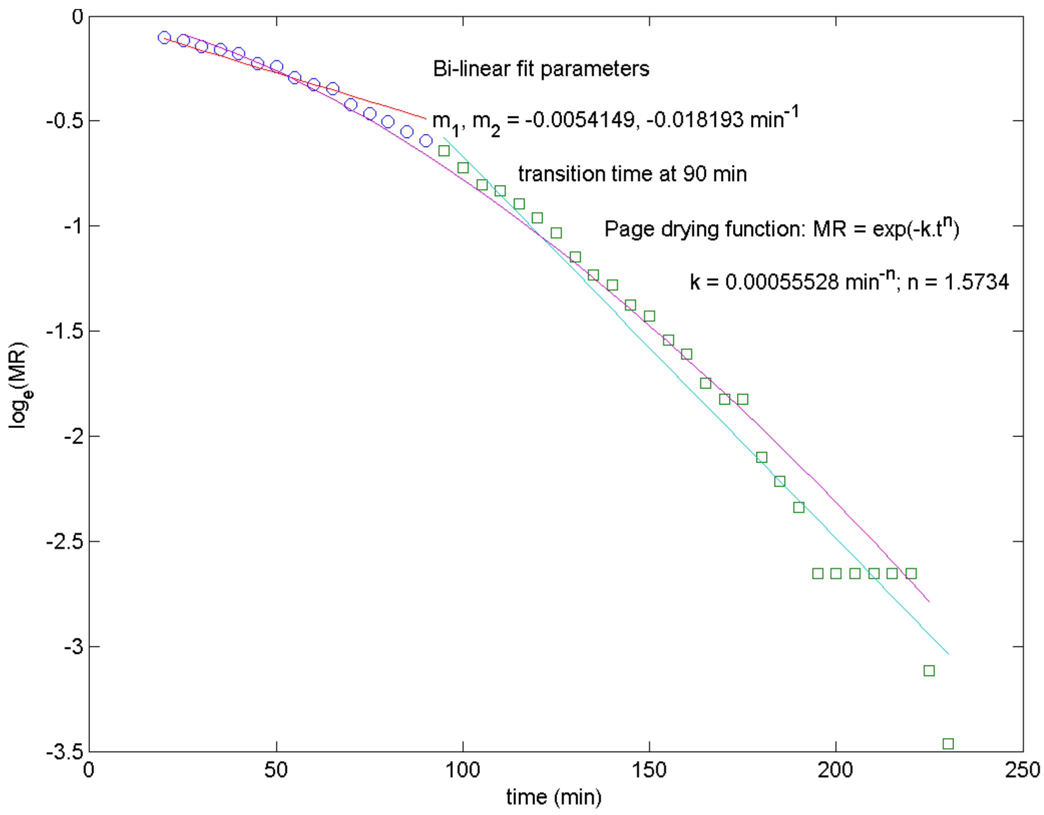

Figure A-13 - Thin layer grass 45 °C, 60% RH.

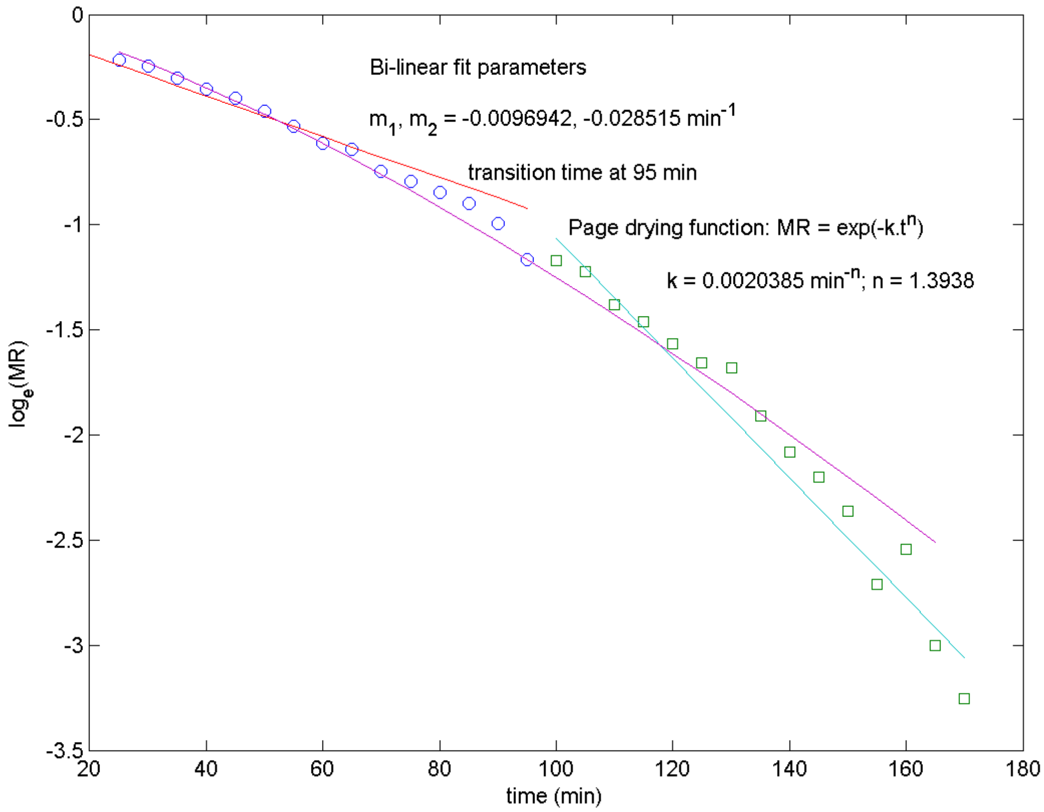

Figure A-14 - Thin layer grass 45 °C, 60% RH.

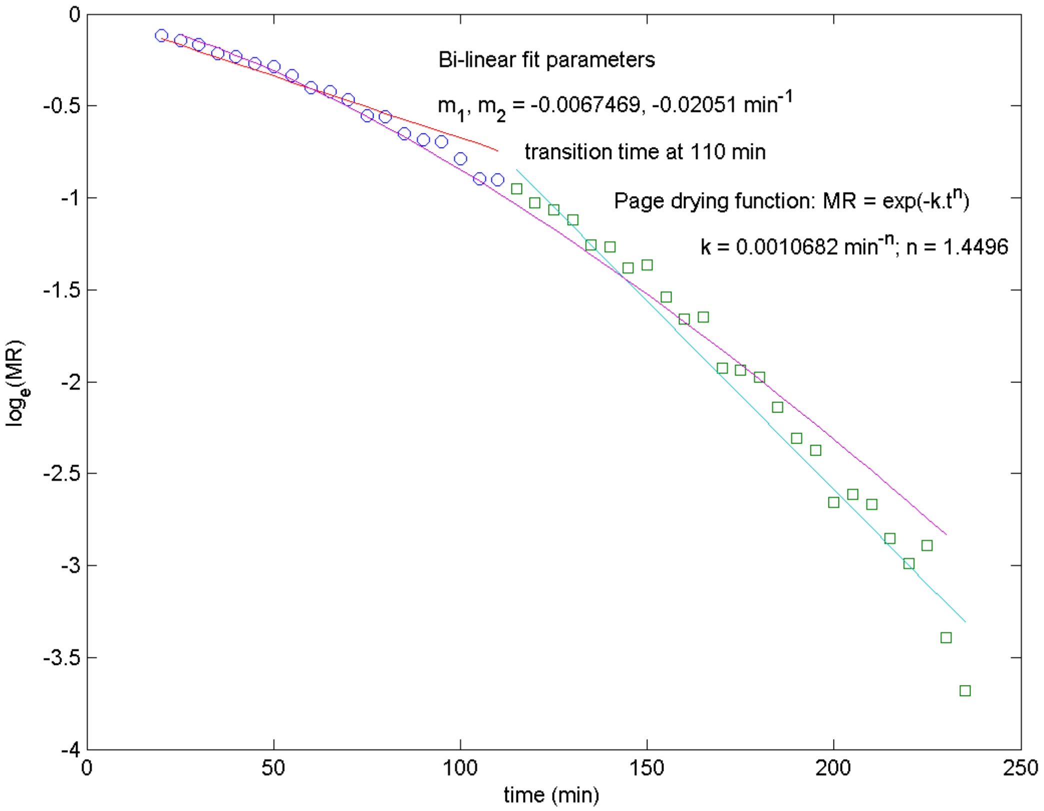

Figure A-15 - Thin layer grass 45 °C, 80% RH.

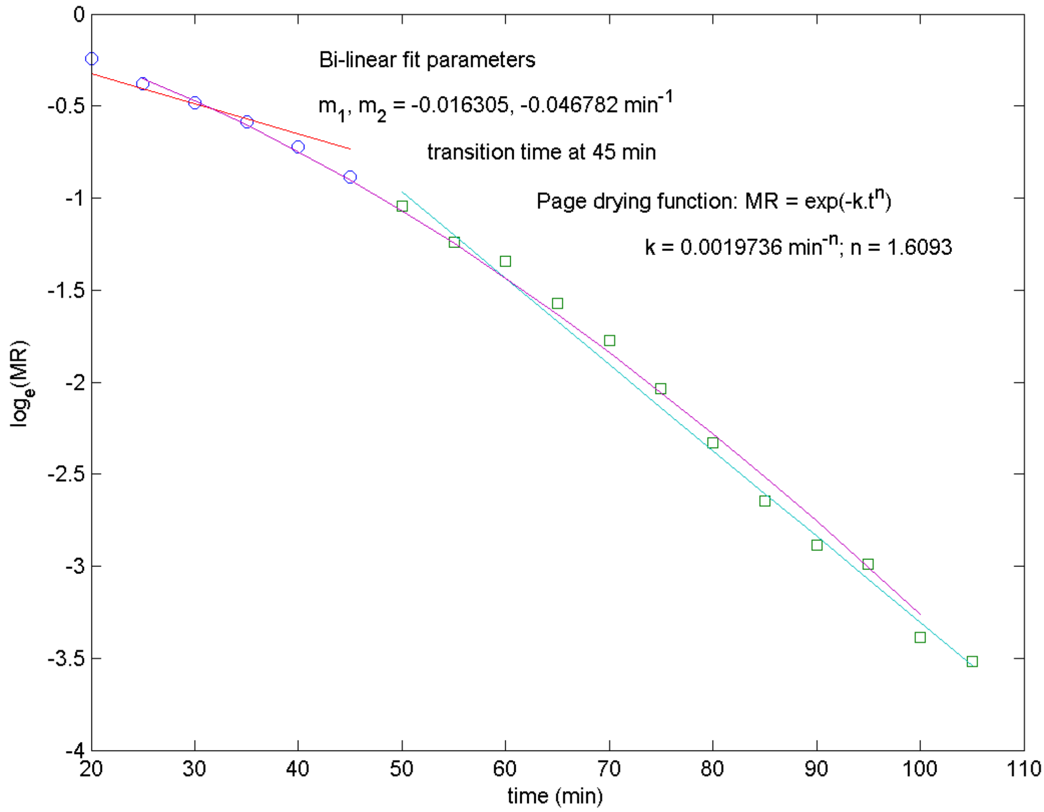

Figure A-16 - Thin layer grass 55 °C, 40% RH.

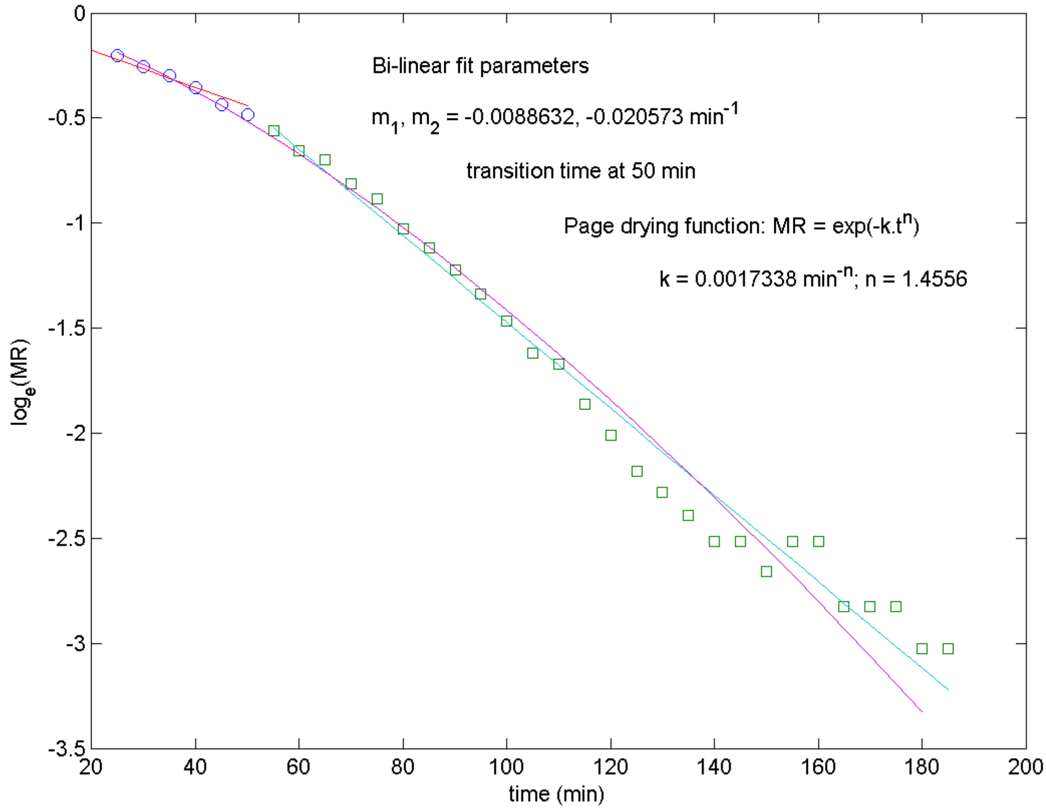

Figure A-17 - Thin layer grass 55 °C, 40% RH.

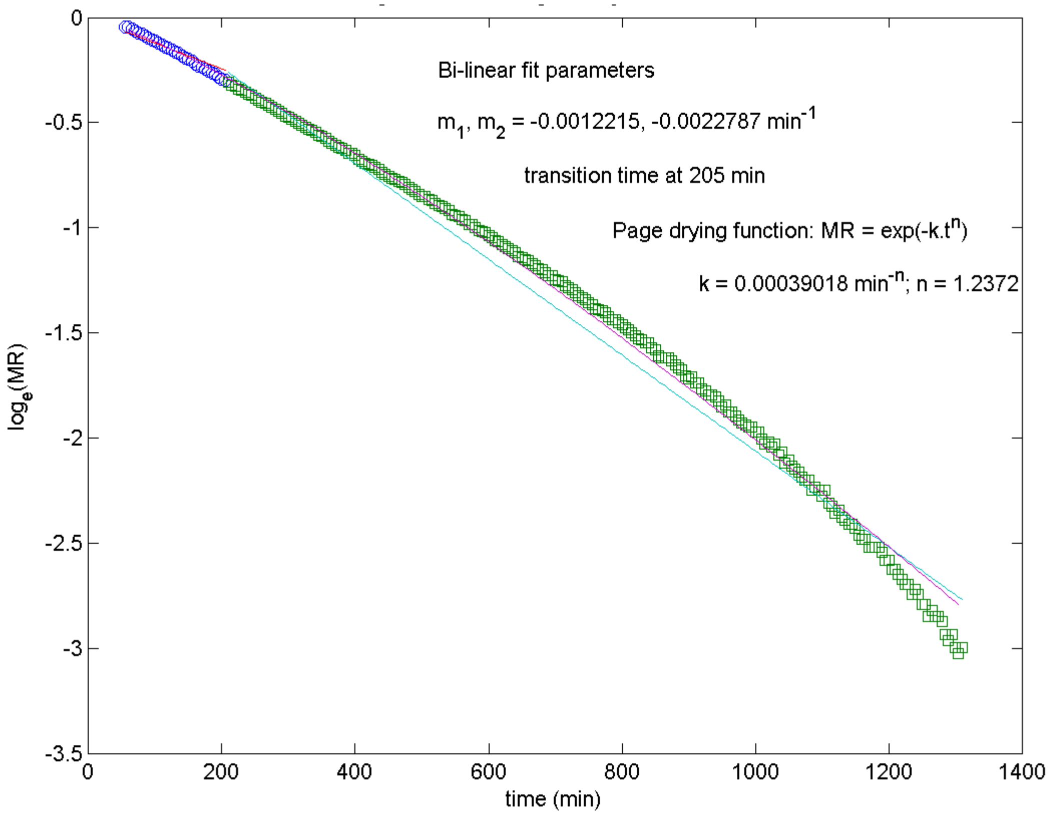

Figure A-18 - 2.5cm layer grain 55 °C, 50% RH.

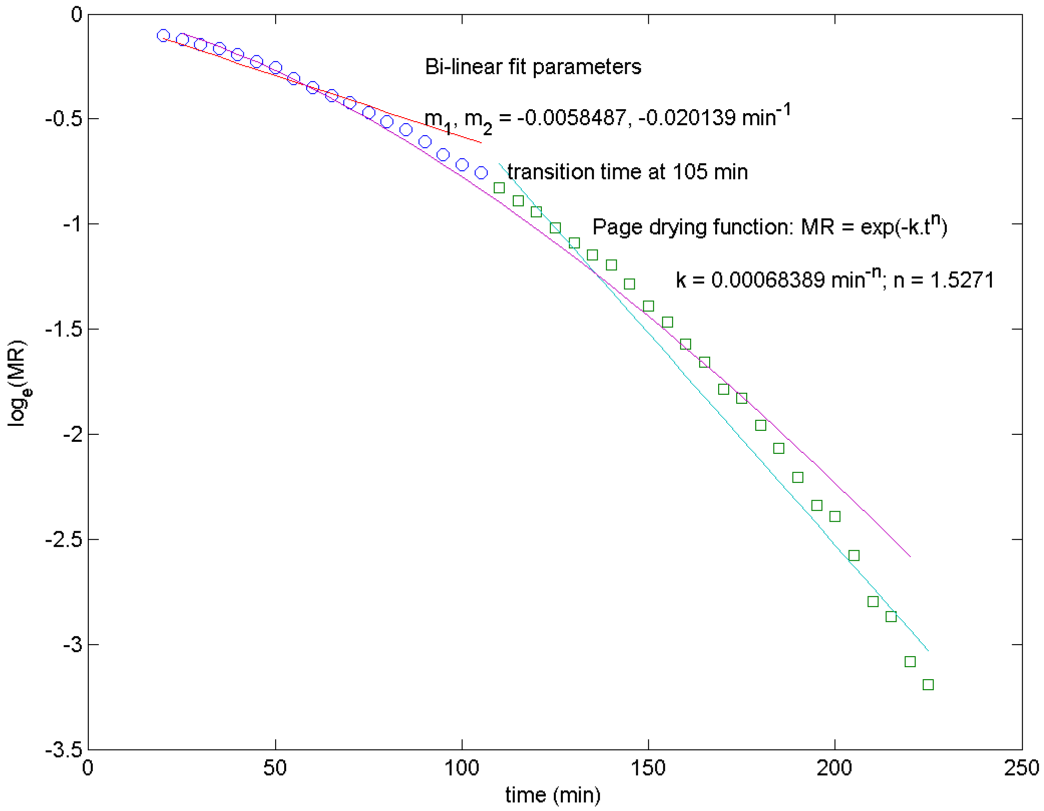

Figure A-19 - Thin layer grain 55 °C, 50% RH.

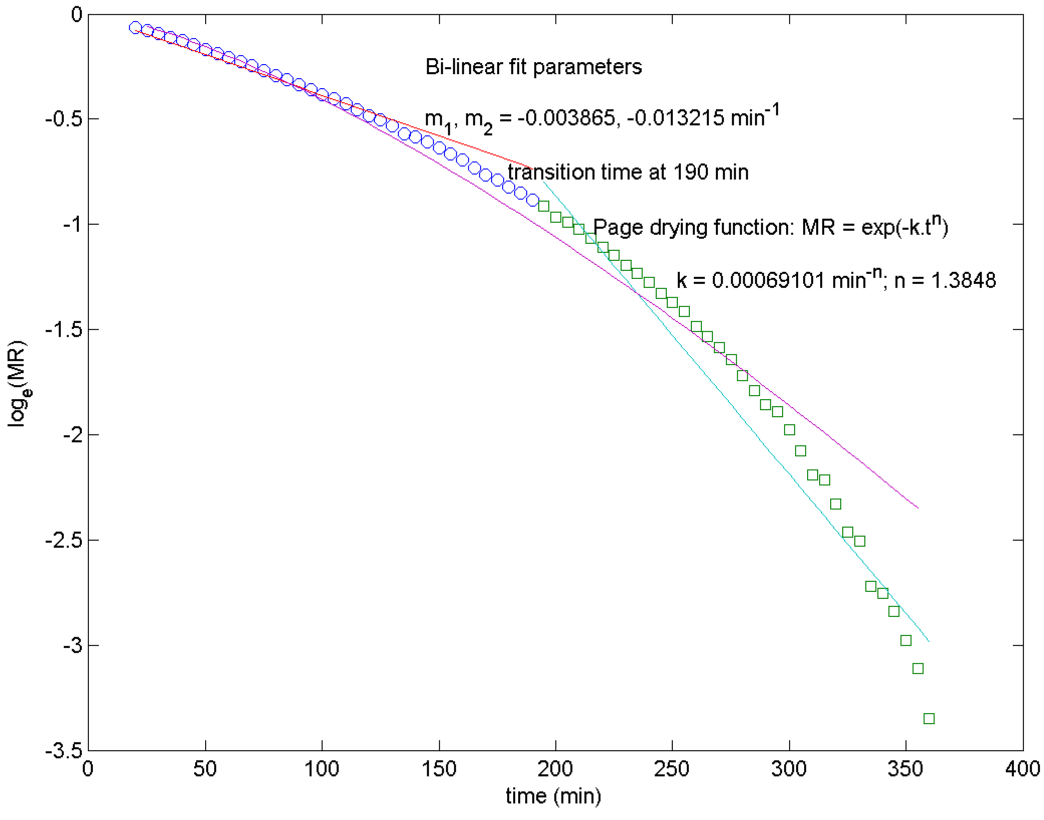

Figure A-20 - Thin layer grass 55 °C, 60% RH.

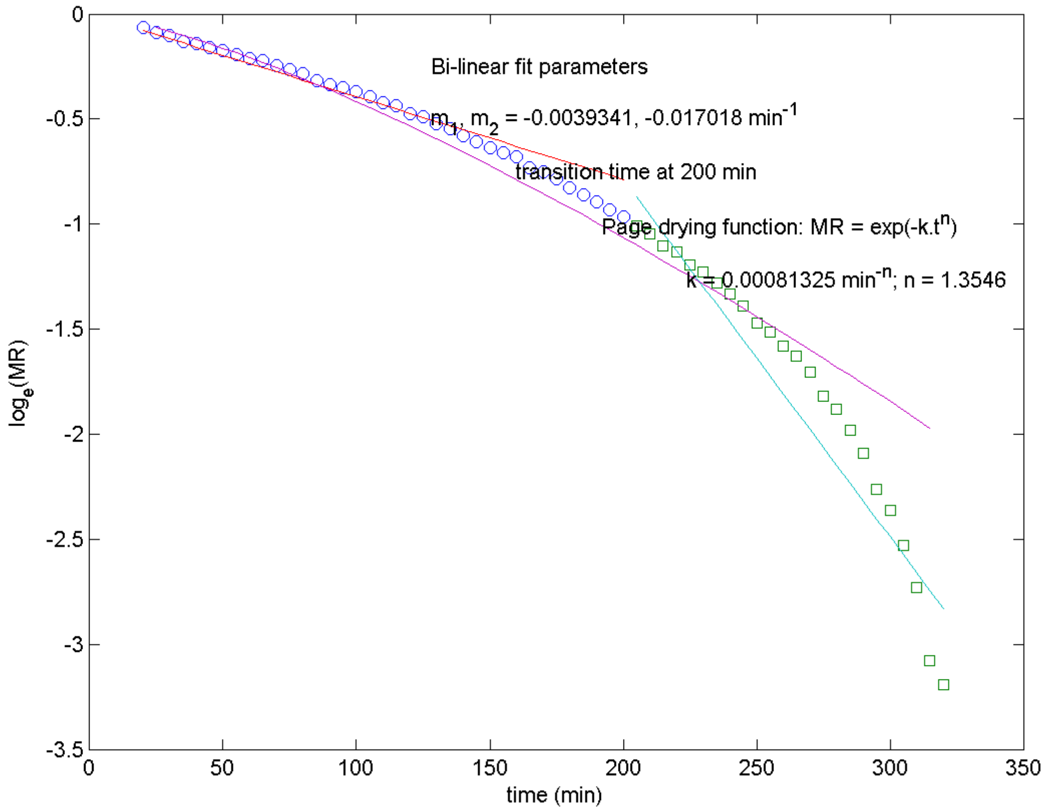

Figure A-21 - Thin layer grass 55 °C, 60% RH.

Appendix B – Wet and dry basis MC conversion table

Table B.1 shows matching moisture content in wet and dry basis.

Table B-1 - Wet and dry basis MC Conversion table.

$MC_{w.b}$ (%)	$MC_{d.b}$ (%)
5	5
10	11
15	18
20	25
25	33
30	43
35	54
40	67
45	82
50	100
55	122
60	150
65	186
70	233
75	300
80	400
85	567
90	900
95	1900
99	9900

Appendix C – Lower heating values

Table C.1 demonstrates the lower heating values for moisture contents ranging from 5 to 100% wet basis.

Table C-1 - Lower heating values from 5 to 100% moisture content.

MC % in decimal	LHV based on HHV 17.03 MJ/kg	LHV based on HHV 20.2 MJ/kg
0.05	16.06	19.07
0.1	15.08	17.94
0.15	14.11	16.80
0.2	13.13	15.67
0.25	12.16	14.54
0.3	11.19	13.41
0.35	10.21	12.27
0.4	9.24	11.14
0.45	8.27	10.01
0.5	7.29	8.88
0.55	6.32	7.74
0.6	5.34	6.61
0.65	4.37	5.48
0.7	3.40	4.35
0.75	2.42	3.21
0.8	1.45	2.08
0.85	0.47	0.95
0.9	-0.50	-0.18
0.95	-1.47	-1.31
1	-2.45	-2.45

Appendix D – AMPC report

This report was written by J. Spence on behalf of NCEA as part of her PhD thesis. The idea and proposal were written by J. Spence. The data in this report was acquired and analysed by J. Spence and at least 95% written by J. Spence.

Development of Methodologies for Characterising Paunch Waste (PW) to Inform Dewatering/Drying Technologies

The Australian Meat Processor Corporation acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

1.0 Executive Summary

Paunch waste has potential to become a site specific waste to energy stream for the red meat processing industry. Numerous possible end uses have been identified for paunch waste such as pyrolysis, incineration, or co-combustion (e.g. Ricci 1977, eds Witherow & Scaief 1976). However, the high initial moisture content of paunch has inhibited the implementation of resuse in the red meat processing industry. Very little research has been done to understand the characteristics of paunch to enable informed decisions on suitable treatment methods.

A review on the current understanding of paunch characteristics relating to drying identified a lack of knowledge on the inherent properties of paunch such as drying rates and equilibrium moisture content. This lack of knowledge has held back the implementation of paunch reuse strategies.

To inform this lack of knowledge a detailed methodology has been developed to inform paunch drying characteristics. Drying rates based on temperatures of 35, 45, and 55°C and relative humidities of 40, 60, and 80% were determined along with matching equilibrium moisture contents. The drying rates were primarily affected by paunch type, paunch variability, and relative humidity with temperature having a lesser effect than expected. Equilibrium moisture content ranged from approximately 7 to 13 % for relative humidities ranging from 40 to 80% in the temperature range of 35 to 55°C. Dryer designs should therefore accommodate relative humidity as a high temperature dryer will not perform well if the humidity is not controlled.

Calorific values for grass and grain type paunches were calculated and determined to be between 17.3–20.2 MJ/kg. This showed paunch has the potential to replace nearly half of the annual coal usage for a medium sized abattoir.

Further work should continue into paunch characteristics and into the possibility of using paunch as a rewetting agent for coal. Solar dryer designs should be investigated with a focus on humidity control inside the dryer.

2.0 Introduction

Paunch is the partially digested feed from the first stomach of ruminant animals such as, sheep, pigs, and cows and may be a viable fuel source for use in co-combustion units, as a coal substitute, or pyrolysis (e.g eds Witherow & Scaief 1976, Bridle 2011). Early energy measurements done with a Parr Oxygen Bomb Calorimeter showed that paunch has an average energy content of 16.7 MJ/kg (Ricci 1977). This energy content is comparable to other biomass crops such as switch grass which has an energy content of 18.4 MJ/kg (McLaughlin et al. 1999).

The main problem regarding paunch for use as a biomass is its moisture content. The high moisture content (around 80 -85% when dewatered of surface water (Ricci 1977, eds Witherow & Scaief 1976)) of undried paunch makes it a non-viable biomass, instead the paunch needs to be dried to below 70% moisture content to become useful. Bridle (2011) stated that paunch with a 70% (wet basis) moisture content, while burnable, has little or no recoverable energy and therefore burning paunch at this moisture content would only be beneficial as a waste disposal method.

Drying rates, equilibrium moisture contents and calorific values need to be known before a suitable method can be determined for drying paunch. A fundamental understanding of these characteristics will allow for the design and modelling of the most suitable dewatering/drying technology.

In previous work there has been a tendency to select a particular drying system and then investigate whether it can dry paunch rather than understand paunch characteristics and then design an optimum drying system. With such variation in design it is important to select the correct dryer for a specific product. Drying times, economic viability, and product handling are all reliant on appropriate dryer selection which is in turn reliant on the specific properties of the product.

During the 1970s and early 80s a number of studies were published regarding the handling/treatment methods and possible benefits of paunch, although research on this topic had decreased until recently (figure 1). As there are a limited number of papers relating to paunch drying the below literature review contains comprehensive highlights of the main findings associated with each paper.

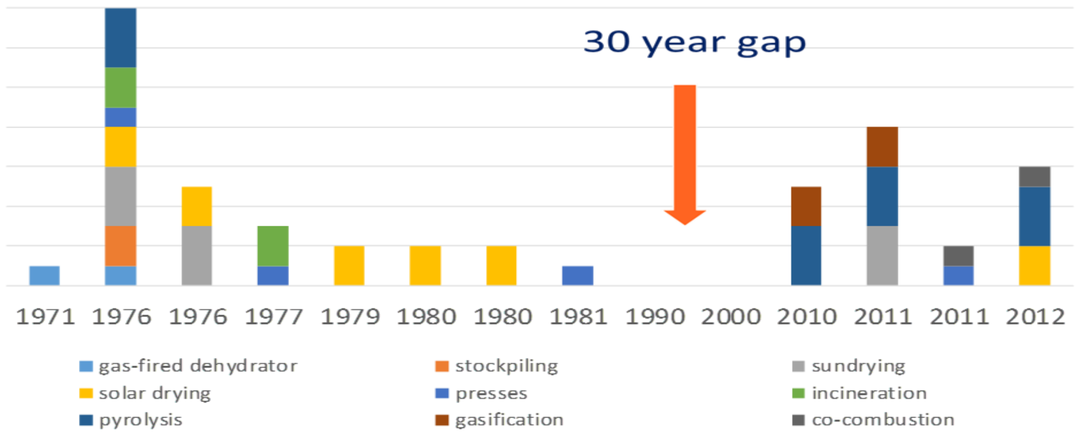

Figure *1*- Research performed into paunch as a biomass. The stacked columns are representative of the information contained in each paper (not representative of multiple papers).

2.1 Literature Review

As early as 1971, Baumann (1971) made recommendations to the beef processing industry that all abattoirs should install dehydrators for both blood and paunch for beneficial end uses such as a feed additive and reducing wastewater pollution. In an attempt to reduce environmental damage and financial burdens at abattoirs eds Witherow and Scaief (1976) identified numerous methods for handling paunch. Of particular interest are: lagooning or stockpiling, rotary dryers, presses, solar & air drying (Yin and Farmer as cited in eds Witherow & Scaief 1976), incineration, and pyrolysis.

Yin and Farmer (as cited in eds Witherow & Scaief 1976) claimed to have successfully used sun/air drying to dry paunch to 16 to 20 % moisture content in a week. They turned a 10 cm layer of paunch daily to stop a crust forming along the top. However, sun drying or open air drying (exposing a product to the sun) is not a feasible treatment method due to the many inherent disadvantages. Sun drying can be time consuming with a lengthy sun exposure time, it is dependent on climatic conditions and the product is exposed to the elements such as rain, possible infestation from insects, possible odour problems, and requires a large surface area for spreading the product (Belessiotis & Delyannis 2010). These disadvantages can be seen in some of the problems encountered by Yin and Farmer in their study such as rain rewetting the paunch, fly, and odour problems. These problems were dealt with through the building of a solar still with mechanical agitation as opposed to hand stirring of the paunch (eds Witherow & Scaief 1976).

Ricci (1977) set about to design and demonstrate a fluidized bed incineration system to handle the paunch waste stream produced by (beef) abattoirs. At the time of printing Ricci (1977) implied that this design would proceed and results in the implementation be presented in a subsequent report. Data are not readily available to indicate whether this study was successful or to allow investigation into whether it would be economically viable in today's market.

A study by Farmer, Brusewitz and Moustafa (1979) identified that solar dried paunch has the potential to become a fuel source for abattoirs. They modified a simple solar still design to test their hypotheses on drying paunch. The results from the Farmer, Brusewitz and Moustafa (1979) study such as:

'An open mesh tray bottom significantly increases the drying rate. Breaking of the crust on the second or third day increases the condensate production rate. Continued stirring on subsequent days is not necessary (Farmer, Brusewitz & Moustafa 1979, p 224)'. Should be applicable to all types of solar dryers, and not just modified solar still designs.

Of particular interest is Griffith and Brusewitz (1980) study using a tunnel dryer to determine a paunch drying constant as a function of air relative humidity, material depth, and time after slaughter in order to optimize paunch moisture reduction. To obtain a drying constant Griffith and Brusewitz (1980) used a set temperature of 35°C with varying relative humidity at 20%, 50%, and 80%. Their study found that paunch composition (i.e. grass or grain fed) had the greatest effect on drying rates compared to humidity, age, or depth. These authors found that the drying time for a high concentrate ration feed was five times higher than that for a high forage diet. There was also an age - humidity relationship for medium to high humidity and fastest drying occurred at low humidity and shallow depth. Griffith and Brusewitz's (1980) data suggests that there is no effect on the drying rate for depths of 2cm to 10cm. However, they only used solid wall drying pans which therefore restricted the flow of moisture transfer to the upward direction. Older paunch can also reduce the drying constant along with high humidity. It was found that all drying constants were high for humidities up to 20%. While the work demonstrates some interesting relationships for drying paunch there does appear to be some (possibly typographical) errors in their reported numerical drying constants.

Farmer, Farouk, and Brusewitz (1980) using direct solar energy and solar-regenerated desiccant for low-insolation days found that they could reduce paunch moisture from 80% to 30% in 5 days. The dryer was designed to operate independently as a modified solar still on high insolation days or in conjunction with the desiccant during low insolation days. This study was noteworthy due to the size of the dryer (pilot-plant size as opposed to laboratory studies) and an innovative concentrating solar air collector.

Brusewitz, Moustafa and Farmer (1981) claim that pneumatic dewatering of paunch to remove loosely held moisture could be done with less energy and in a fraction of the time compared to evaporation techniques. Their study showed that dewatering soon after slaughter removed the most amount of liquid and that storage at low temperatures (10°C) resulted in 10 to 50% less water being removed. Most abattoirs currently use some form of dewatering of paunch, as seen in the current best practices, to separate the liquid and solid waste stream.

Bridle (2010) undertook a desktop study to review waste pyrolysis using paunch and DAF sludge (DAF sludge is fat and protein, meat slivers and fat, which gets into the wash water). The study identified that there are potential economic and environmental benefits using abattoir waste for pyrolysis or gasification. However, the report showed that the paunch and DAF sludge would need to be dried to 20% moisture content (80% total solids) or below prior to being used. As moisture contents higher than 20% would require too much energy from the pyrolyser thus producing a poor quality syngas, rendering it uneconomical.

After the previous desktop study Bridle (2011) undertook to design a program to sun dry, characterise, and use paunch and DAF sludge in two systems; Pacific Pyrolysis, and BiGchar gasification. The study predicts that pyrolysis and gasification are the most attractive for the meat industry with possible gains of GHG credits up to 1 tonne CO2-e and net energy credits up to 3.2 GJ per tonne of feedstock. However, he claims that thermally dried paunch and DAF sludge is not economically viable for co-combustion in boilers, whereas dewatered paunch is viable for co-combustion due to some environmental benefits and as a disposal method. The economic factor that made co-combustion unattractive was the high cost associated with drying the paunch. However, this was based on the cost and maintenance of a fossil-fuel run dryer not a solar dryer.

The dewatered paunch approach as a waste disposal system was economically attractive due to paunch only needing a total solid of 30% to burn self-sustainingly. This is around the total solid count from dewatering systems such as a screw press. However, this method was only suggested for use as a waste disposal method with little or no energy recovered. The process to dry the paunch for the two system tests and for use in the desktop study was done by spreading 2 to 3 m^2 of paunch over an area of 25 m^2 at a depth of 10 to 15 cm and sun dried over a period of two weeks. The area was increased to 50 m^2 after the first week and the paunch was hand stirred twice a day. As with Yin and Farmer (as cited in (Witherow & Scaief 1976)) sun drying is not a viable drying method. Interestingly though Yin and Farmer (as cited in Witherow & Scaief 1976) stirred their paunch once a day and dried paunch in half the time as Bridle (2011) at a similar depth. This could possibly be explained by the disadvantages of sun drying such as climatic conditions affecting the drying rate.

Bridle (2011) then undertook an assessment of dewatered paunch for use in a co-combustion boiler. The results of this study show great promise for paunch waste to be used in co-combustion with a net economic benefit of $1.58 million over 20 years for use in existing boilers and a net economic benefit of $2.85 million over 20 years for a new boiler able to co-fire biomass. Paunch could provide 30% of boiler fuel requirements with potential for GHG credits. There were minor environmental impacts and no impact on boiler combustion performance (at 5% paunch rate with total solids of 30%). The environmental impact of increased stack emissions remained within regulatory guidelines.

These studies show that paunch has the potential to become a beneficial waste product if the initial moisture content can be reduced. Recoverable energy from paunch (although variable) is possible. As there has been very little research into paunch it would be beneficial to characterise paunch as Griffith and Brusewitz (1980) set out to do with their drying rates and to apply this knowledge to selecting a drying method. Industries such as the grain industry understand their products characteristics and select drying equipment appropriately and successfully. It seems appropriate that if paunch is to be utilized as a beneficial waste to energy stream that a similar understanding of its characteristics are needed before a suitable method for paunch handling can be designed.

2.2 The project objectives and approach

The aim of this project is to develop a methodology to determine the drying properties and characteristics of paunch. Characterisation of the material will enable optimum paunch drying times and conditions to be achieved which will assist in determining whether dried paunch is a viable biofuel.

2.3 Any limitations to the research.

This project has limited itself to three temperature ranges (based on time) with three relative humidities for thin layer drying rates and equilibrium moisture contents. This will limit optimum drying condition recommendations. Further limitations were found to be a problem with the operation of the 500g load cell at the higher temperature/humidity range (55 °C 60 – 80% RH) and with the environment chamber at 55 °C 80% RH operating range.

Other information outside the scope of this project includes the suitability of the dryer such as: economic feasibility, ability of the dryer to cope with the daily on-site production of fresh paunch, and the suitability of the end product for uses such as co-combustion.

2.0 Project Objectives - Paunch management and handling

Specific objective of this work include:

(i) A current review of paunch literature and identification of gaps in literature.

(ii) Develop a methodology to determine the drying properties and characteristics of paunch;

A standard method for paunch characteristics needs to be developed to allow study into the behavior of paunch and other abattoir waste streams. This will allow future studies to build upon the knowledge gained and create a consistent approach to characterise abattoir waste, determine suitable product handling/treatment techniques, and allow evaluation of future implemented treatment methods.

(iii) Determine the optimum paunch drying conditions.

Experimentally determined drying rates and equilibrium moisture contents are needed to allow suitable drying technology to be selected and evaluated.

(iv) Recommendations on the optimum drying conditions for paunch waste based on the inherent properties of paunch and future research suggestions.

4.0 Methodology

4.1 Characterisation of Paunch Waste Methodology

The methodology presented in sections 4.2, 4.3 and 4.4 provides an outline of the methodology developed for characterising paunch in terms of drying rates, equilibrium moisture content and calorific value (energy content). The drying rates will identify what conditions are optimum for fastest drying to enable dryer design selection. Equilibrium moisture content will inform the limit of drying and calorific value will inform the expected energy output from paunch.

4.2 Sample Collection and Preparation

As there is no standard for sampling or testing paunch the methodology for obtaining paunch samples was based on the Australian standard guide to sampling of particulate materials (1997). This standard ensures that all particles in the paunch stream have an equal chance of being selected and used in the final analysis. It also includes ways to eliminate bias by using good handling techniques such as eliminating sample contamination and not changing the samples moisture content during collection.

During sampling operator safety is important. Do not place any body part within equipment (e.g. contra shear screens, screw presses), make sure full access to the complete paunch stream is available, collect paunch sample as close as possible to the discharge point without visually segregating the sample. Collect the sample using a bucket or ladle type container. Pass it perpendicular across the full width of the paunch stream at as uniform a rate as possible with alternate directions used for each sample. Then place the sample in an airtight container with the date and sample number written on the container. Where possible obtain data on the finishing procedure used on the cattle during the week prior to slaughter (e.g. grass or grain fed cattle).

The best practice for the preparation of the paunch samples was based on the Australian standard guide part 2: preparation of samples (1997) with the aim being to keep the properties of the test samples the same as the original sample. All surfaces that the paunch comes into contact with should be abrasion-resistant to avoid contamination, corrosion-resistant trays should be used for drying, and no reduction of the sample should be carried out on samples that are to be used for particle size and/or bulk density determination. To reduce sample division errors the paunch sample should be manually mixed before any sample division takes place. Dust contamination is controlled in the sample collection by placing the paunch sample in an air tight container and in sample preparation by performing all handling, tests and analysis in a dust free laboratory. All equipment should be cleaned between tests to eliminate sample cross-contamination. Samples divided for chemical analysis must have a mass greater than 50 grams. These guidelines ensure that test results will be representative of the original sample.

Once the sample has been collected and prepared for testing at least two samples should be placed in a moisture balance for initial moisture content determination. Samples should also be classified as either predominantly grass or grain type paunches. This can be determined visually based on the particle size and shape of the paunch. Figure 2 shows a predominantly grass and a predominantly grain type paunch. Grass paunches display thin rectangular particles (and consist of roughage type feed such as grass or hay) while predominantly grain type paunches display thin rectangular particles (as per the grass type paunch) mixed with a variety of possible shapes such as round or elliptical particles. The grain type paunch will also feel and look grittier than the grass type paunch due to the grain content.

Figure *2*- An example of grass (left) and grain (right) type paunches

4.3 Drying Rates and Equilibrium Moisture Content

A thin layer dryer provides valuable drying information that can be used for product characterization, product quality management and evaluation, product drying computer simulation (using the products specific drying constant), selection and performance testing of drying equipment, and for obtaining a products optimum drying temperature and humidity (ASAE Standards 1999).

Thin layer dryers expose a product to constant air flow (generally about 1m/s with a minimum flow of 0.3 m/s), temperature, and relative humidity. The definition of a thin layer being a 'layer of material exposed fully to an airstream during drying. The depth (thickness) of the layer should be uniform and should not exceed three layers of particles' (ASAE Standards 1999). During drying the product weight is measured nearly continuously with a required accuracy of 0.2% of the sample mass. Temperature sensors need an accuracy of ± 1°C, relative humidity needs an accuracy of ± 3%, and air velocity needs an accuracy of ± 5% (ASAE Standards 1999). Having consistent and reliable control over drying conditions is necessary for the accurate quantification of drying parameters. A thin layer dryer is one such way to determine these fundamental parameters.

In a novel approach to create a thin layer dryer an environment chamber was used to produce consistent air conditions with a load cell wired into a custom built data logger used to record changing weight over time. Figure 3 shows the load cell incorporated into a tray holder which is wired into the data logger. Samples were placed inside the environment chamber and left until equilibrium moisture content was achieved. The data obtained was then converted into moisture content for use in the drying equations.

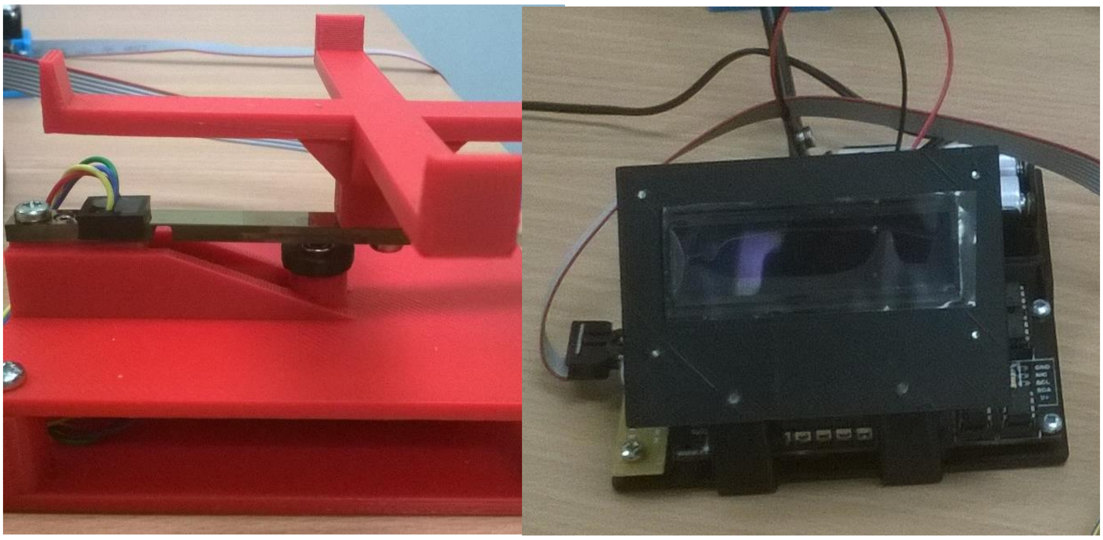

Figure *3* - Load cell incorporated into a tray holder (left) which is wired into the data logger (right)

Drying rate data for drying equations need to be obtained on an apparatus such as a thin layer dryer however equilibrium moisture contents are also needed for determining the moisture ratio and for complete product characterisation. Equilibrium moisture content is easily obtained at the end of a drying run as equilibrium is the final stage of drying. Equilibrium moisture content tells us the minimum moisture content that a substance can be dried to under set drying conditions. Equilibrium is met when the rate of evaporation equals the rate of condensing of a substance. Equilibrium moisture content is important in terms of drying in that once it has been reached; no further drying is possible at those conditions. Equilibrium is found during the drying run once there is no longer any change in weight of the sample. Figure 4 demonstrates the change in weight over time for 35°C temperature with 40% relative humidity. The graph shows the load cell maintained accuracy and shows an expected plateau around 15g where equilibrium was met.

The equilibrium moisture content of paunch waste will benefit future studies by providing storage information, drying limits, and values to be used in drying equations such as calculating the moisture ratio. Moisture ratios are calculated:

$$MR = \frac{(MC - MC_{e)}}{(MC_i - MC_{e)}};$$

Where MR is the moisture ratio, MC is the final moisture content, MC_i is the initial moisture content, and MC_e is the equilibrium moisture content. This calculation allows comparison between differing initial moisture contents.

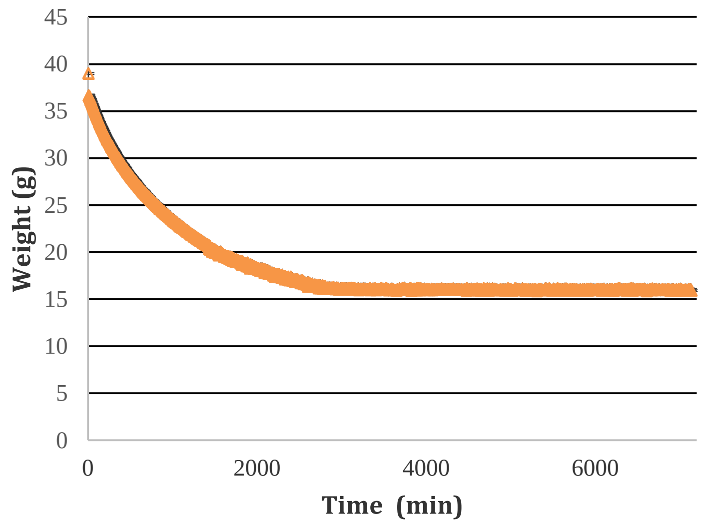

Figure *4*- Weight (g) versus time (mins) for 35°C temperature and 40% relative humidity

Average drying rates used for comparison are based on Farmer, Farouk and Brusewitz's (1980) equation for an average daily drying rate which is given by:
$MC = MC_i - ADR \times T$;
Where MC is the final moisture content, MC_i is the initial moisture content, ADR is the average daily drying rate, T is time.

4.4 Energy Content

Oxygen bomb calorimetry is a relatively cheap yet reliable method to determine the gross heat of combustion (calorific value) of a product. A bomb calorimeter measures heat changes at constant volume.

The oxygen bomb should be calibrated with a standard benzoic acid sample for each set of tests and the energy equivalent of the calorimeter calculated. The change in temperature is recorded as is the mass of the sample. These are used to calculate the gross heat of combustion (calorific value) of the sample.

The energy equivalent of the calorimeter is:

$$W = \frac{m * H_c}{\Delta T};$$

Where W is energy equivalent of calorimeter, m is mass, Hc is heat of combustion of Benzoic acid, ΔT is the change in temperature.

The gross calorific value of the sample is then calculated by:

$$H_g = \frac{\Delta T * W}{m};$$

Where Hg is the gross heat of combustion, ΔT is the change in temperature, W is the energy equivalent of the calorimeter, m is the mass.

5.0 Project Outcomes

Thin layer drying rates, equilibrium moisture content and calorific values were calculated for paunch waste acquired from two abattoirs in south east Queensland.

5.1 Drying Rates – Thin Layer

Thin layer drying was used to determine average drying rates of paunch as thin layer drying is the 'best case' drying time achievable for a product. Thin layer drying allows determination of how a product will react under certain drying conditions. The paunch was classified as either predominantly grass or grain and each test was run in duplicate using two load cells (average time for one test roughly one week). The average drying rate for 35, 45, 55°C air with humidities 40, 60, and 80% can be seen in figures 5, 6, 7. These show an expected trend in the decline of drying rates as the humidity is increased.

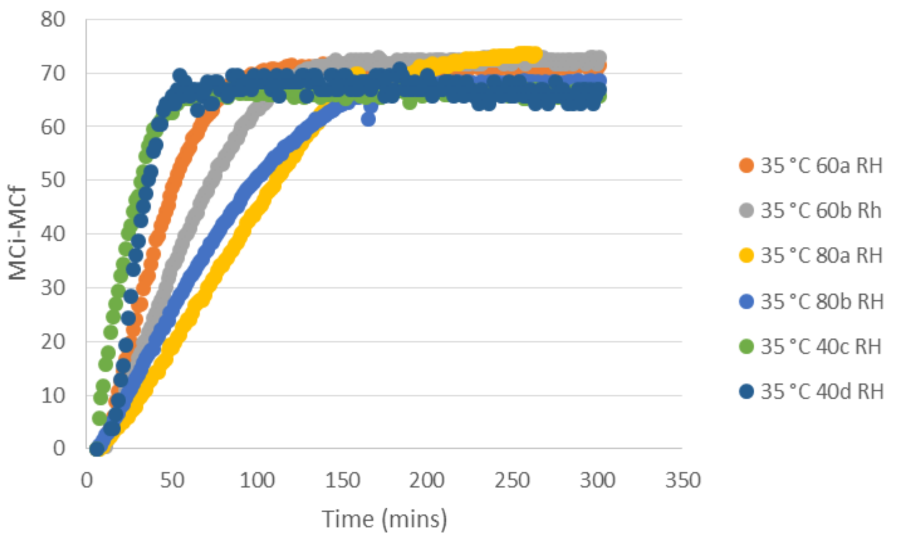

Figure 5- 35°C air temperature with 40, 60, 80% relative humidity.

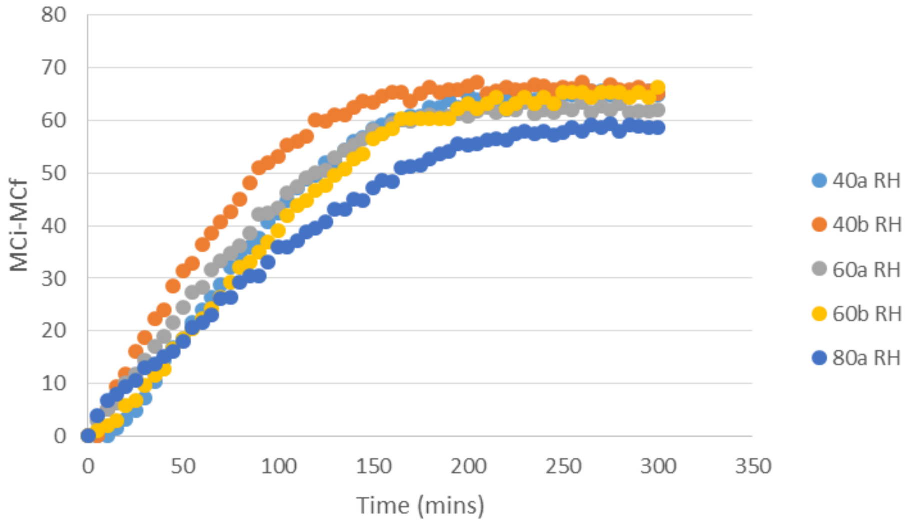

Figure *6* - 45°C air temperature with 40, 60, 80% relative humidity.

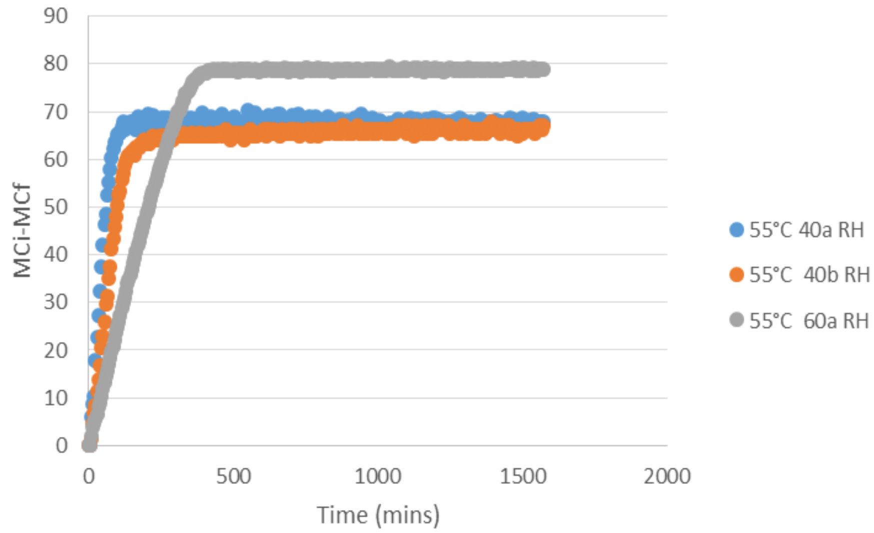

Figure *7*- 55°C air temperature with 40, 60% relative humidity.

Figure 8 graphically represents all three temperature ranges at varying humidities. This graph shows some unexpected possible groupings of equal humidity at varying temperature. The equal humidity lines were therefore graphed for varying temperature (figures 8, 9 10).

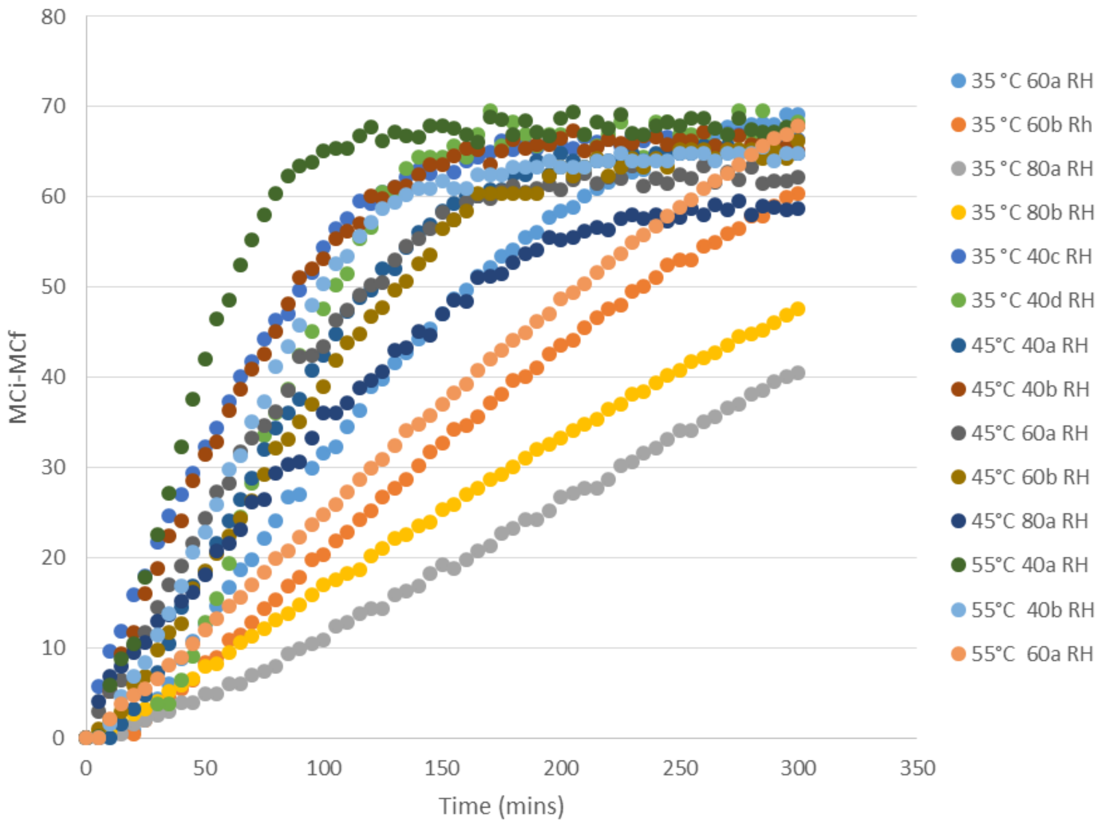

Figure 8- Graphical representation of all three temperatures (35, 45, 55°C) at varying humidity.

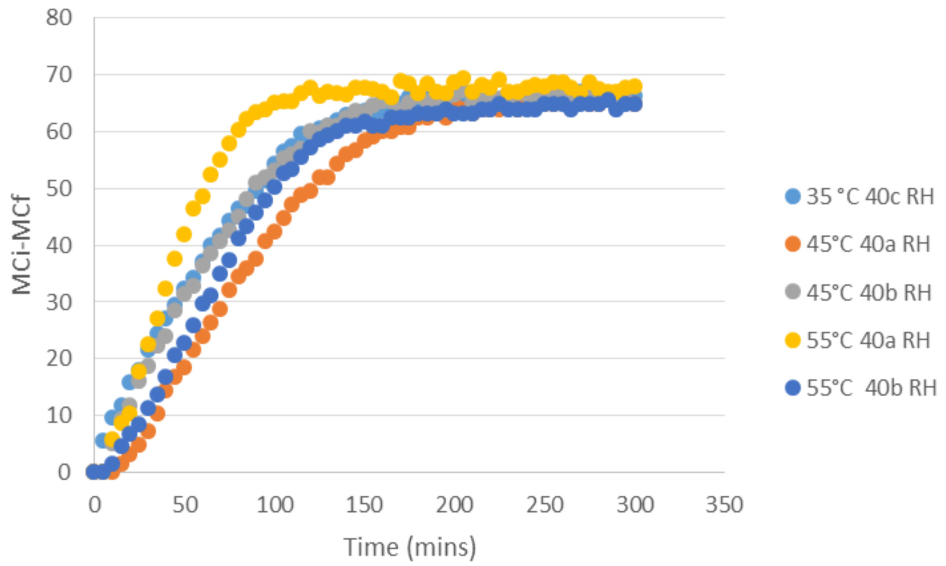

Figure *9* - 40 % relative humidity with 35, 45, 55°C temperature.

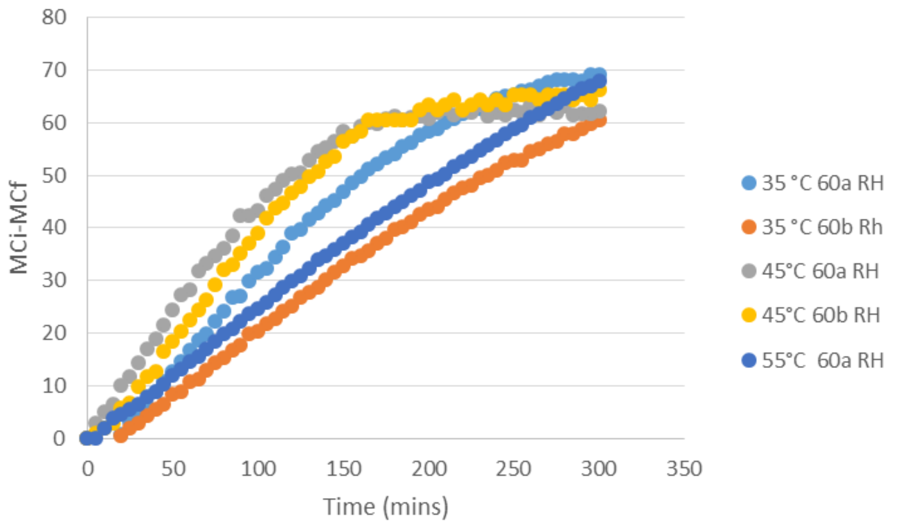

Figure *10* - 60% relative humidity with 35, 45, 55°C temperature.

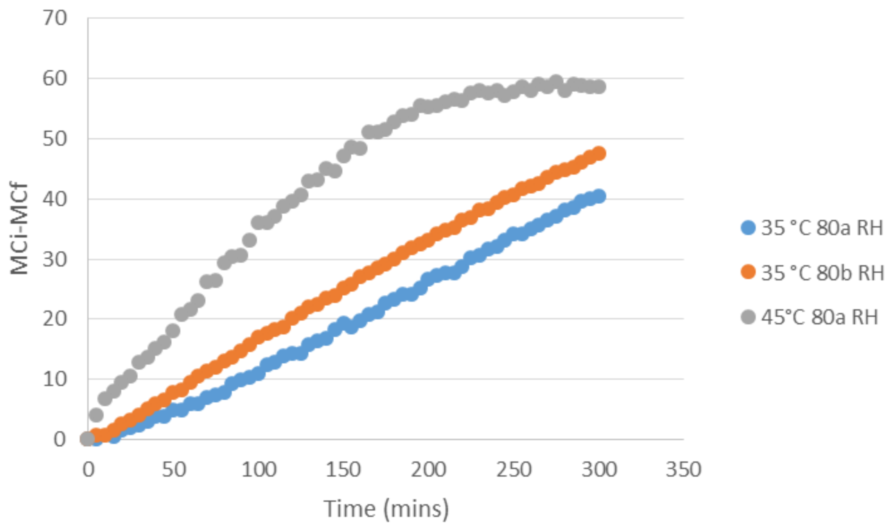

Figure *11* - 80% relative humidity with 35, 45°C temperature.

The average drying rates for 35, 45, and 55°C air temperature with relative humidities of 40, 60, and 80 % were determined and are summarized in table 1. Table 1 shows a consistent decline in drying rates as the humidity is increased for each temperature. The type classification of paunch in the table was further clarified to include grain/grass. These were more of a mixed type paunch as opposed to the predominantly grass or grain type paunches.

Table 2: Average drying rates for 35, 45, 55°C air temperature with 40, 60, 80% relative humidity (grain/grass was a more mixed type paunch compared to the predominantly grass or grain type paunches)

Temperature °C	Relative Humidity %	Average Drying Rates % per minute (w.b)	R squared	type
35	40	0.45	0.9	grass
35	60	0.25	0.99	grain
35	80	0.15	0.99	grain/grass
45	40	0.44	0.95	grass
45	60	0.41	0.99	grass
45	80	0.34	0.98	grain/grass
55	40	0.78	0.98	grass
		0.48	0.97	grain/grass
55	60	0.25	0.99	grain

5.2 Equilibrium moisture content

Equilibrium moisture content was calculated at the end of each drying run once no further change in weight occurred. Grass and grain samples were averaged together as there was only a slight variation between grass and grain equilibrium moisture content as seen in the standard deviation between samples.

Table 3: Averaged equilibrium moisture content values (% wet basis)

Averaged Equilibrium Moisture Content (% w.b)						
	Relative humidity					
Temperature °C	**40%**	**Std dev**	**60%**	**Std dev**	**80%**	**Std dev**
35	7.998	0.19	10.84	0.08	13.44	0.45
45	7.935	0.02	9.595	0.36	13.12	0.52
55	7.135	0.12	9.434	0.30		

5.3 Energy Content

Paunch was collected from two abattoirs in south- east Queensland and separated into predominantly grass or grain type paunches. These were dried and particle size reduced if large grain particles were present. This was done to reduce incomplete combustion of the samples in the bomb. All samples used for calculations were completely combusted with no sample residue left in bomb. An XRY – 1A Oxygen Bomb Calorimeter was used and calibrated using Benzoic acid one gram pellets (Parr instrument Co., USA). To account for variation in the paunch the standard deviation of the energy content values were taken for both grass and grain type paunches. The average gross calorific value for grass type paunches is 17.3 MJ/kg with a standard deviation of 0.483, grain type paunches is 20.2 MJ/kg with a standard deviation of 0.678. The standard deviation between the types is 1.917 which shows a significant difference between grass and grain type paunch energy content.

6.0 Discussion

6.1 Drying Rates – Thin Layer

Drying rates were determined for 35, 45, and 55°C air temperature at 40, 60, and 80% relative humidity. In accordance with drying theory the drying rates show an expected drop in rate as humidity increased.

Paunch type appeared to have a significant impact on drying time. The difference in slopes of the same temperature and humidity lines could be explained by the difference between grass or grain type paunches and variation in and between samples. This was demonstrated in the significant difference in the slopes belonging to the 55°C 40% drying rate which were 0.78 % per minute for grass and 0.48 % per minute for grain/grass. This would appear to be consistent with the findings of Griffith and Brusewitz (1980) that the drying time for grain type paunches can be up to five times longer than grass type paunches. This is likely due to the second stage (internal moisture migration) of drying where the moisture in the grain particles in the paunch have a longer path length to travel to the surface of the grain to allow evaporation than the grass particles.

Variation in both grass and grain type paunch drying rates is expected due the large variability in the samples. The 55°C 60% RH line demonstrated variation between samples as it appears to differ from the other graphed data lines. However, this ‘difference’ was due to an unusually high initial moisture content and a much more yellow/green liquid in the sample than other acquired samples. This variation in paunch composition is expected due to the large variation in cattle finishing procedures and the types of feed used. Variation is also due to the different treatment methods implemented at abattoirs for separating the liquid from the solid paunch waste such as screw presses and contra shear screens. These dewatering methods impact the initial moisture content of the sample which thus affects the drying time.

However, some unexpected results were also observed. There appears to be a larger than expected effect on drying due to relative humidity. While there was an overall trend in faster drying rates for lower humidity there appeared to be less distinction between temperatures. The fastest drying rate belonged to the 55°C 40% climatic conditions with the 35° 80% conditions having the slowest drying rate. Although the difference between temperatures does not appear to significantly reduce the drying time as opposed to the effect of humidity, paunch type, and dewatering method.

There is no control on the type or variation of paunch that will be need to be dried at an abattoir. However, a few factors must be considered to optimize dryer design. In terms of drying paunch with a suitable dryer, such as a solar dryer, less importance should be placed on the absorber (temperature achievable) as on the dryers’ ability to control relative humidity. The drying rates show that theoretically a dryer that could reach 55 degrees in summer and only 35 degrees in months (or on days) with less solar insolation should perform relatively similarly as long as humidity is controlled (such as condensation inside the dryer). The thin layer drying rates compared to the drying times achieved by other methods (one week to sun dry, 5 days in a modified solar still (eds Witherow & Scaief 1976, Bridle 2011, Farmer, Farouk, & Brusewitz 1980)) demonstrates the importance of the chamber design. The more surface area of the paunch exposed to the drying air will significantly reduce drying time. Solar stills can suffer from condensation problems as can most solar dryer designs. Solar dryer design selection should focus on designs that have incorporated solutions to this problem such as condensation collectors.

6.2 Equilibrium moisture content

Equilibrium moisture content tells us the minimum moisture content that a substance can be dried to under set drying conditions. This means that once equilibrium with the surrounding air has been met not further drying is possible. For example, 13.44% MC is the lowest possible MC for 35°C and 40% RH drying conditions (as shown in Table 2).

Table 2 shows that a reduction in humidity had a greater effect on reducing the equilibrium moisture content than increasing the temperature. Equilibrium appears to range between 7 to 13 % MC for humidities 40 to 80% in the temperature range of 35 to 55°C.

Dried paunch storage will be affected by equilibrium moisture content as a product will always try to reach equilibrium in any environment. Therefore, if the paunch is stored in a high humidity environment the moisture content will increase. In addition knowing the limit to drying at certain conditions will benefit future equipment drying designs and end uses.

6.1.3 Energy Content

The standard for the energy content of paunch has been 16.7 MJ/kg (Ricci 1977). This value is comparable to the obtained grass type paunch value of 17.3 MJ/kg. However, there was a significant difference found in the calorific value for grain type paunches of 20.2 MJ/kg. Compared to other gross calorific values of commonly used fuels paunch shows a viable energy content with only bituminous coal having a higher heating value (HHV) than grain type paunches as shown in Table 3.For mixed type paunches the energy content will be between 17.3 – 20.2 MJ/kg. These values demonstrate paunch as a potentially useful waste to energy stream.

Table 4: Gross calorific values of paunch and other commonly used energy sources

COMPARISON GROSS CALORIFIC VALUES		
Type	**HHV (MJ/kg)**	**Reference**
Black coal QLD	28.69	Coal analysis Dec 2015 (Spence, M 2016, pers. comm., 9 May)
Bituminous coal	34.89	Higgins & Elonka 1976
Wood	16-21	Stout 1983, eds. Rosilla-calle et.al 2007, Higgins & Elonka 1976
Corn cob	18.6	Stout 1983
Lignite coal	16.28-18.6	Higgins & Elonka 1976
Sawdust	18.14	Demirbas 2003
Wheat straw	17.51	Demirbas 2003
Paunch (grass - grain)	**17.3 – 20.2**	Spence 2016
Cotton gin	15.5	Demirbas 2003
Rice husk	13.524	Demirbas 2003

In reality the gross calorific value (or higher heating value) is not achievable. Moisture content of a sample needs to be taken into account due to the energy required to remove the moisture before combustion. The equilibrium moisture content values show that under certain conditions bone dry paunch is not possible. Therefore, the lower heating value (LHV) is measured by subtracting the latent heat of vaporisation of water from the HHV:

$$LHV = \text{HHV}(1-\text{M}) - 2.447\text{M};$$

where LHV is the lower heating value MJ/kg, HHV is the higher heating value MJ/kg, M is the wet basis moisture content in decimal, 2.447 is the latent heat of vaporisation of water MJ/kg (Sokhansanj 2011).

For example: equilibrium moisture content for 35°C air temperature at 40% relative humidity is 7.998%. Using the energy content of grain type paunches of 20.2 MJ/kg the LHV is 18.39 MJ/kg.

Assuming a medium sized abattoir produces 100 m3 of paunch per week at 75% initial moisture content then 33 m3 of paunch is produced per week at 7.998% EMC, this equates to 1 716 m3 per year (assuming 52 week operating period).

The coal value obtained from an abattoir in south east Queensland has a HHV of 28.69 MJ/kg at 3.3% MC with a LHV of 27.66 MJ/kg. The same medium sized abattoir uses approx. 2200 Tonne of coal per year.

Possible paunch energy = 1 716 000 kg/year x 18.39 MJ/kg (LHV) = 31 557 240 MJ per year

Possible coal energy = 2200 000 kg/year x 27.66 MJ/kg (LHV) = 60 852 000 MJ per year

This shows paunch has the potential to provide approximately 50% of the energy needed from coal use. However, a more detailed scenario needs to be calculated as the moisture content of coal is generally increased before use in the boiler (this would affect the LHV). It may be possible to use the higher moisture content of paunch as the rewetting agent in this case and new calculations made in regards to the actual achievable energy.

The mixing ratio of two products for a set overall moisture content can be solved for the mass of the second product:

$$m_2 = \frac{(m_1 \times G) - (m_1 \times MC_1)}{MC_2 - G};$$

where m is the mass kg, G is the goal moisture content %, MC is the products moisture content %. Note that the moisture goal must be between the moisture contents of the two materials being mixed (Trautmann & Richard 1996).

If the goal moisture content (G) is 9% for use in the boiler, mass of paunch (m_1) per week is 38 440 kg per week at a moisture content of 13.44%, coal moisture content (MC_2) is 3.3%.

$$m_2 = \frac{(38440 \times 9) - (38440 \times 13.44)}{3.3 - 9};$$

Mass of coal per week to be mixed with paunch = 29 943 kg to 38 440 kg of paunch or a **1:1.3** mix for above moisture contents.

The above energy and mix ratio calculations show that paunch has the potential to be a significant waste to energy stream for the red meat industry to implement.

7.0 Conclusions/ Recommendations

Drying rates were determined for 35, 45, and 55 °C air temperature at 40, 60, and 80% relative humidity. The drying rates showed an expected drop in rate as humidity increased with paunch type, variability, and humidity appearing to have a significant impact on drying time. As there is no control over the type or variation of paunch to be dried the main focus of a dryer design should be on its ability to control relative humidity (eg possibly an active solar dryer using fans to reduce condensation and increased humidity inside the dryer) as opposed to a focus on temperature. Although it appears that a high temperature, low humidity dryer will be the most efficient design there doesn’t appear to be a significant gain in increasing the drying temperature without humidity control.

Equilibrium moisture contents were determined with humidity having a greater effect on the moisture content than temperature. Equilibrium moisture content ranged from approx. 7 to 13 % MC for humidities 40 to 80% in the temperature range of 35 to 55°C. Equilibrium moisture content is the minimum moisture content achievable at certain climatic conditions.

Energy content was determined to be between 17.3 – 20.2 MJ/kg HHV for grass and grain type paunches. This energy content could significantly reduce the coal usage on sites with a coal fired boiler.

7.1 Future directions

Further characteristics of paunch should be found and the field of knowledge increased into the behavior of paunch. A number of interesting paunch behaviors were identified in this report and further comparison of drying rates (for grass and grain type paunches), rates for different depths, and more equilibrium moisture contents would create a robust understanding of this material. Also a more detailed scenario needs to be calculated for using paunch as a rewetting agent for coal to check if the LHV values are affected and then testing results in a boiler.

Solar dryer types need to be evaluated to determine the most effective design. A focus should possibly be on active dryers as opposed to passive dryers and tunnel type dryers over solar still designs. This is due to the ability to control increased humidity inside the dryer due to forced air over the sample as per an active dryer and better control over condensation inside a tunnel dryer as opposed to a modified solar still. Future work into the size of the dryer needed to handle the amount of paunch produced per week and the chamber design to increase the surface area of the product to be exposed to the drying air are also needed.

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Appendix E – Conference paper

This paper was invited for review in a special edition of Renewable Energy Journal and has been accepted.

ABATTOIR PAUNCH WASTE AS A BIOMASS ENERGY SOURCE: INVESTIGATIONS INTO DRYING RATES

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ABSTRACT: Industry-specific waste streams are potential sources of energy. Paunch waste, the partially digested grass and grain present in the first stomach of ruminants, is currently a waste product with minimal value (in some cases incurring a cost) to the Australian red meat industry. Research indicates that paunch has the potential to be a suitable source of biomass, yet there has been no uptake of this biomass waste as an energy bioresource. The challenge lies with the high initial moisture content of the paunch waste, which is around 85% when surface water is removed. At 70% moisture content paunch can be disposed of in a boiler with no recoverable energy whereas at 20% moisture content the material could be used for pyrolysis with significant recoverable energy. An efficient drying process is needed for paunch waste to become a viable energy bioresource. The work reported in this article was conducted to determine the drying rates and equilibrium moisture contents of paunch to then enable optimum dryer selection and operating conditions to be established. The equilibrium moisture content of paunch varied from 7.14% to 13.12% for drying in air between 35 and 55 °C, and at 40-80% relative humidity. The drying constant, k, varied from 0.00023 – 0.0029 min^{-n} with an average n value of 1.42 for air temperatures in the range of 35-55 °C. The variation in drying rates demonstrates a significant sensitivity to both air temperature and humidity. This provides evidence that careful management of drying conditions is required to optimise the drying process of paunch.

KEYWORDS: biomass; drying rates; equilibrium moisture content; paunch; slaughterhouse; waste-to-energy

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14 - 17 November 2016 Great School of St. John the Evangelist, Venice, Italy

Appendix F – Energy paper

This paper is currently being prepared for submission to an appropriate journal.

Title: Energy content, bulk density, and the latent heat of vaporisation of Australian abattoir paunch waste

Article Type: Research article

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Abstract

Abattoir paunch is the undigested grass and grain from the first stomach of ruminant animals. It is a waste product with limited or no value to the red meat processing industry. However, paunch may be a potential waste-to-energy stream for the red meat industry to adopt. An energy content of 16.7 MJ/kg has been the generic standard for paunch for 40 years. The16.7 MJ/kg value does not take in to account the large variation that exists in paunch content due to the different finishing procedures used on cattle before slaughter. The different feeding regimes of cattle produce paunch that can be categorised as grain or grass type. Subsequently, the energy content of paunch could vary substantially. Therefore, the actual achievable energy needs to be determined before decisions can be made as to true product viability. This study investigated higher heating values, lower heating values, bulk density and energy density for grass and grain type paunches. The higher heating values (gross calorific value) were 16.9 and 20.3 MJ/kg for grass and grain type paunches respectively. Bulk density ranged from 106 to 587 kg/m^3 for dry to wet untapped paunch, and 152.04 to 884.64 kg/m^3 for dry to wet tapped paunch. Energy density based on lower heating value and bulk density showed that the optimum moisture content for return on energy is 35% for grass type and 40% for grain type paunches (not including densification). These values show that paunch has the potential to be a useful waste-to-energy stream for implementation into industry.

Keywords: solid waste, slaughterhouse, energy contents, bulk density, latent heat, paunch waste.

Appendix G - Thin layer drying rates paper

This paper has been accepted for publication in Renewable Energy Journal. The below abstract is from the first revised draft. Renewable Energy journal is a Q1 journal, on the 1st of June 2017 Renewable Energy had an impact factor of 3.404, a 5-year impact factor of 4.068 and a SNIP of 2.029.

Investigation into thin layer drying rates and equilibrium moisture content of abattoir paunch waste

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ABSTRACT: The work reported in this article was conducted to determine thin layer drying rates and equilibrium moisture contents of abattoir paunch waste. The equilibrium moisture content of paunch varied from 7.14% to 13.12% for drying in air between 35 and 55 °C, and at 40-80% relative humidity. A predictive equilibrium moisture content equation based on the Chung-Pfost model was developed with the constants A found to be 586.72, B (27.461), and C (28.913) with a standard error of ± 0.0035. These values were comparable to the published values for wheat and barley. The thin layer drying constant, *k,* varied from 0.00023 – 0.0029 min^{-n} with an average time exponent, *n*, value of 1.42 for air temperatures in the range of 35-55 °C. The variation in drying rates demonstrated a significant sensitivity to humidity.

KEYWORDS: biomass; drying rates; equilibrium moisture content; paunch; slaughterhouse; waste-to-energy