CHALMERS

Mathematical Model for Countercurrent Feed Pellet Cooler

Master of Science Thesis

DAVID ANDERSSON
DANIEL JOHANSSON

Department of Signals and Systems
Division of Automatic Control, Automation and Mechatronics
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2008
Report No. EX001/2008

Preface

This report is a result of a master thesis within the Master Programme Systems, Control and Mechatronics, at the Department of Signals and Systems at Chalmers University of Technology. The project was initiated by Lantmännen.

We would like to give special thanks to:

Gustav Kämpe at Lantmännen for making this master thesis possible and for his support and supervision, Peter Baeling for sharing of his knowledge and experience around Lantmännen's process. Last but not least we would like to thank Jonas Sjöberg at Chalmers who have been of excellent help and support for us.

David Andersson and Daniel Johansson

Chalmers University of Technology, January 14, 2008

Abstract

In production of feed pellets it is necessary to have control of final moisture content and temperature, this to increase quality and minimize costs. This is a study of a steady state countercurrent flow feed pellet cooler. Focuses are at model development (from theoretical physics), analyse of bed, and what property of air that gives good result. The data is from a study in properties of feed pellets and air throughout a countercurrent cooler. Two models are presented. The first model describes properties of air and pellets inside the cooler using differential equations. The second model only considers properties of inlet and outlet flows, independently of the interaction between air and pellets inside the cooler. The results show that it is difficult to develop a model, based on theoretical physics for a countercurrent cooler. This because it is difficult to determine drying rate. A reliable model based on differential equations has therefore not been found. Further the results showed that air should be pre-dried, i.e. to a relative humidity that is in equilibrium with desired moisture content of the outlet pellets.

Contents

Authors' Contribution

- An analyse of temperature and moisture content for pellets and air throughout the bed. Variations in relative humidity of air is determined by mollier chart
- Evaluation of general drying model on a countercurrent flow cooler. Air has in this case a lower temperature than the medium that is under drying. Previous examples [1] have been the opposite
- Derive of an expression for outlet pellets in temperature and moisture content, which can be used if necessary parameters are measured and known

Nomenclature

a_v	characteristic interfacial area per unit volume, m^2/m^3
a_w	water activity
c	specific heat, kJ/kgK
E	energy, kJ
Δh_v	latent heat of vaporization, kJ/kg
L	length, m
l	characteristic pellet length, m
M	molar mass, kg/mol
m	mass, kg
$\dot{m}$	mass flow, kg/s
P	total atmospheric pressure, Pa
p	vapour pressure, Pa
q	heat flux, kW/m^2
r	characteristic pellet radius, m
S	cross-sectional area normal to flow direction, m^2
t	temperature, $^\circ C$
W	dry mass flow, kg/s
w_D	rate of drying, kg/m^2s
w_{DI}	initial rate of drying, kg/m^2s
X	moisture content solid per dry basis, kg/kg
Y	moisture content gas per dry basis, kg/kg
α	heat transfer coefficient, kW/m^2K
β	coefficient, kW/K
ε	porosity
ρ	density, kg/m^3
τ	time, s

Subscripts

b	bulk
g	gas
in	inlet
out	outlet
p	pellet
s	dry solid
v	vapour
w	water

Chapter 1

Introduction

A short introduction is given in this chapter, including project background, objective and delimitations.

1.1 Background

Lantmännen is one of the main actors in food, energy and agricultural industry in Sweden. Business area feed division of Lantmännen provides 70% of the livestock in Sweden with feed. Livestock feed is manufactured in ten factories from Umeå in north to Åhus in south.

In the manufacturing process of livestock feed pellets, steam is added to the feed mixture to purify from bacteria such as salmonella and to give the mixture correct consistence to be able to compress to pellets. In this stage of the process the pellets receive an approximate temperature of $80°C$ and a water content of 15% wet basis (kg water/kg total). To achieve desired quality of the final product, the pellets temperature must be reduced to approximately $5°C$ above ambient temperature and their moisture content to 12%[1].

The quality and value of pellets are dependent on the cooling and drying process. Over drying results in lower firmness of the pellets, increased energy consumption and decreased value, because the price is based on weight. Insufficient drying or cooling could result in condensation of water inside storage facility, which increase the risk of growth of mould and fungus.

[1]Value depends on which type of feed that is produced

1.2 Objective

The objective is to determine a way to control the cooling and drying process, so a desired temperature and moisture content of the pellets are reached. In this case a desired temperature of pellets should be $5°C$ above ambient temperature and moisture content of $12 \pm 0.5\%$.
Following questions will be discussed:

- What is the prerequisite to receive desired moisture content?
- How do temperature and moisture content vary throughout the process?
- How should the process be modelled?
- Can the objectives be achieved with current system?

1.3 Delimitations and Assumptions

Delimitations and assumptions are necessary to focus and simplify. These are the following:

- The process is assumed to be at steady state i.e. variables are constant during time, no dynamics are considered
- Exchange in heat only occur between air and pellets i.e. heat loss is neglected
- Air throughout the cooler is homogeneous i.e. all vapour have been adsorbed
- Air that is drawn throughout the cooler is assumed to origin from inlet i.e. no air is entering the cooler from leaks
- Top of the bed is seen as plan i.e. no difference in bed height
- Flows are equal troughout the bed in both cross sectional area and flow direction
- Pellets are constant in size and compound throughout the bed i.e. porosity is constant
- The process data from a previous study [2] are assumed to be reliable
- Inlet pellets do not dry nor cool when they fall from the matrix to the top of the bed

Chapter 2

Process Description

A description of the production chain from ingredients to final product is described in this chapter.

2.1 The Pelleting Process

To achieve the intended nutritional composition of a feed, different raw materials (example: grain, soy, molasses) are measured and mixed according to a recipe. The mixture enters a conditioner where it interacts with the steam, the temperature as well as the moisture content increase. Moisture received from the conditioner gives the compound a sufficient consistency to be able to extrude to pellets. The mash enters the pelleting machine where it gets extruded through a matrix (see figure **??**). Because of friction during this process additional heat is added to the pellets, also moisture content is decreased [3]. The hot and moist pellets fall down and form a deep bed in the cooler.

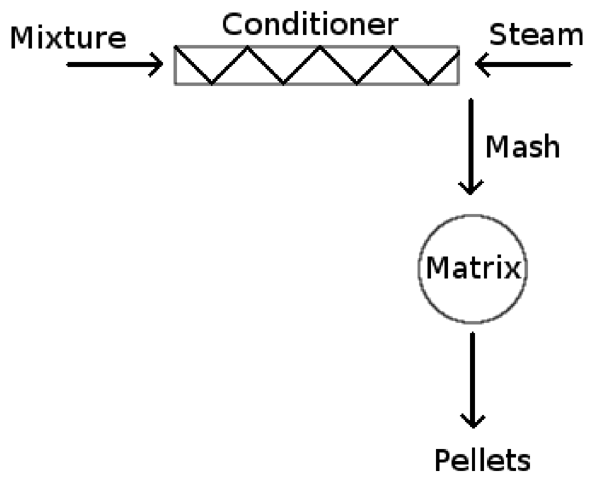


Figure 2.1: *Inlet mixture interacts with steam in the conditioner, and the mash enters the pelleting matrix. The extruded pellets then fall down into the cooler.*

2.2 The Cooling and Drying Process

Cooling and drying of feed pellets at the factories of Lantmännen are made by countercurrent coolers. The advantage with this type of cooler compared to other is its low energy consumption, less maintenance, small dimensions and it also gives good control of moisture content [4]. To remove the moisture and at the same time cool the pellets, a fan is used to draw air through the bed. Inlet pellet flow to the cooler is continuous and is dependent on the pellet size and the recipe. Height of the bed is determined by a level sensor on the wall of the cooler. When the sensor gets trigged by pellets, outlet of pellets starts, and the height decreases. After a certain time the outlet closes and bed height starts to raise [5].

Countercurrent coolers at the factories of Lantmännen have either single (figure 2.2) or double deck[1] (figure 2.3). The advantage with the dual is its ability to continue the production of pellets when change in type pellets. Hatches divide into two different compartments. A new type of pellets is stored until the rest of previous type of pellets is fully dried and cooled. By doing this, production stops are decreased and the avoidance of mixing different types. Two additional level sensors are available, they are used in the control of the rate of fan. Most of the time the bed height is at its highest

[1]Single decked observed at factory in Lidköping and double at factory in Falkenberg

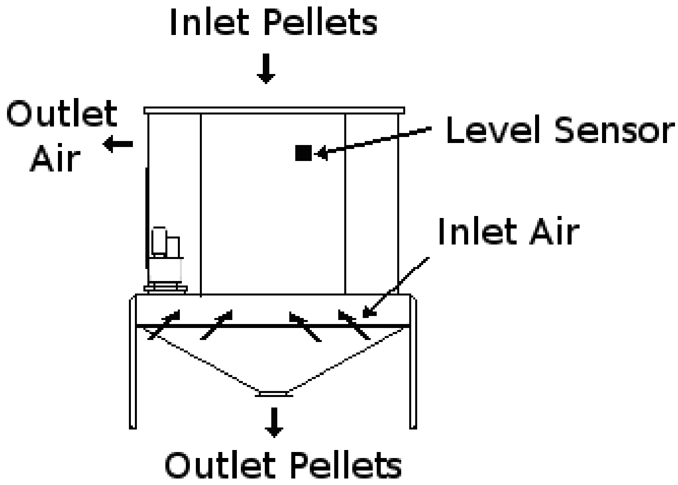


Figure 2.2: *Single decked countercurrent cooler at Lantmännen's factory in Lidköping, with marked flows and bed level sensor.*

level. The frequency that control the fan rate is only changed when the cooler is emptied or (re-)filled [3]. Control of the cooling process is independent of what type of pellets produced.

2.3 Control Variables

Variables that can be controlled in the cooling and drying process are:

- Rate of air flow, by changing speed of fan. Easy to change because fan is controlled by frequency
- Bed height, pellet residence time in cooler, by adjusting the position of the height sensor. It requires manual adjustment by operator

2.4 Disturbances

There are several disturbances that can influence the process. Temperature and moisture content of inlet pellets will always vary [2, 3]. The reasons are:

- The properties of the ingredients in the pellets vary depending from their origin [3]
- Influences on temperature and moisture during extruding in matrix [3]

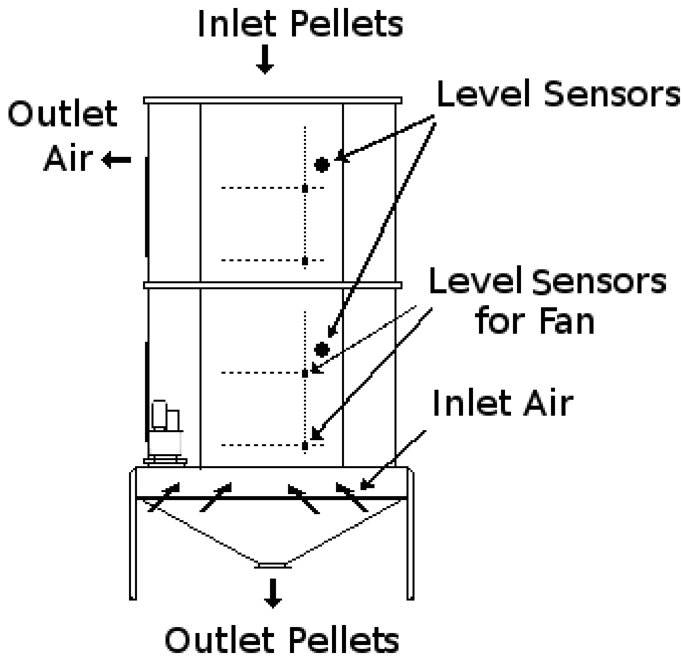


Figure 2.3: *Double decked countercurrent cooler at Lantmännen's factory in Falkenberg, with marked flows. Bed level sensors are placed in similar way as on single decked coolers. Two additional level sensors are at lower deck, they are used in control of fan rate.*

- It is not known how much of the steam that actually absorbs into the mixture in the conditioner [6]

Because of this the actual properties of the inlet pellets can never be known. The cooler is not totally sealed. Air leaks into the cooler and might influence depending on where the leaks are, temperature, moister content and airflow throughout the bed can be affected. The properties of inlet air will vary. The moisture content of inlet air is never considered, it depends on the moisture content in the ambient air. Temperature of inlet air is considered in some cases[2] when it is below $0°C$. The air is then preheated to $5°C$.

[2] In Lantmännen's factory in Umeå

Chapter 3

Frame of Reference

Theories in drying of organic materials, drying techniques, mass and energy balance and related work are presented in this chapter.

3.1 Dry and Wet Basis

There are two ways to describe water content in a material. The most common way in the industry is to define moisture content as the amount water per dry basis (kg water/kg dry basis). Another way is to describe it as the percentage amount of water per wet (total) basis (kg water/kg total). The most common way to describe water content simplifies calculations and assumptions, and is therefore used.

3.2 Drying of Organic Material

In drying of organic materials drying mainly depends on the difference in water activity between the substance and the gas (air) [2]. Water activity

$$a_w = \frac{p}{p_0} \tag{3.1}$$

is a value between 0 and 1, and is the ratio between the partial steam pressure, p, over material and steam pressure over pure water, p_0, at the same temperature [7], which also is the definition of relative humidity of air. When water activities reache equilibrium with relative humidity of air no further water transport will occur. This means that it is not possible to dry a substance to a less water activity than the relative humidity of the drying medium [6]. Depending on the water activity of the organic material different micro organisms can proliferate [8]

Microorganism Inhibited	a_w
Bacillus Pseudomonas Some yeasts	1.00 – 0.95
Escherichia coli Lactobacillus Salmonella Some molds	0.95 – 0.91
Many yeasts Micrococcus	0.91 – 0.87
Most molds Staphylococcus aureus	0.87 – 0.80
Most halophilic bacteria	0.80 – 0.75
Xerophilic molds	0.75 – 0.65
Osmophilic yeasts	0.65 – 0.60
No microbial proliferation	0.60 –

By controlling the water activity it is possible to increase quality and durability of the feed. To determine air properties one can use a mollier chart[1]. By knowing three of the following four parameters, the relative humidity, water ratio, Y, atmospheric pressure, P, and temperature, t, the third can be determined. By using Antoine equation [1]

$$p_0 = exp\left(A - \frac{B}{C+t}\right) \tag{3.2}$$

which describes an approximation of saturated vapour pressure and

$$Y = \frac{M_w p_0}{(M_g(P - p_0))} \tag{3.3}$$

an approximation of the mollier chart is derived [9]. A, B and C refer to constants specific for water

Constant	**Value**
A	16.376953
B	3878.8223
C	229.861

t refers to the current temperature in $°C$ and p_0 is vapour pressure of pure water at current temperature. M_w and M_g refer to the molar mass of water and air.

[1]Mollier chart for humid air is shown in appendix C

The drying process can be divided into three different drying periods, which are dependent of the drying goods (figure 3.1). Factors that affect are composition of the drying goods, porosity, size of particles, etc. During the first drying period, the rate of drying is constant and both inside and surface of the drying goods contain free water. The second drying period starts when dry spots start to appear on the surface of the drying goods, the drying rate then starts to decade. The third drying period begins when the surface is completely dry and continues until the drying goods is in equilibrium with relative humidity of the drying gas. The drying rate then come to a complete halt. The transitions between the drying rates are not as sharp as shown in figure 3.1.

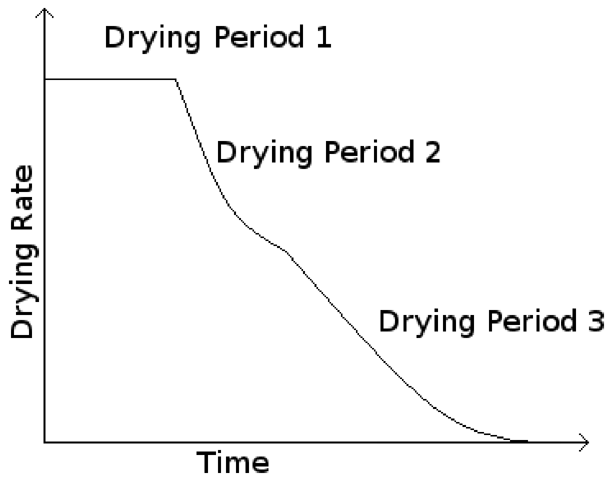


Figure 3.1: *Drying rate during a constant drying event [1]. This is an illustration of a possible drying event.*

3.3 Diffusion and Sorbtion Isotherm

The transport of water inside pellets is mainly by diffusion [2] (drying period two and three). To describe diffusion in solid masses during drying is a complex procedure. The rate of diffusion is highly dependent on temperature, often by moisture content, variety in size [10] and compound of included substances [1].

Sorption isotherm describes a substance hygroscopic (ability to attract, subtract water vapour) properties during an isothermic (constant temperature) event [1]. For most organic materials such as provisions and agricultural products, isotherms tend to have significant hysteresis (figure 3.2) dependent if water is transported away (desorption) or to (adsorption) the drying goods [2].

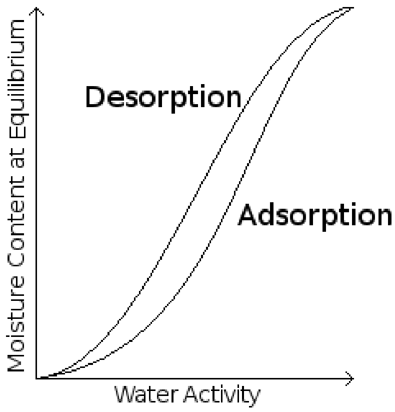


Figure 3.2: *The sorption isotherms hysteresis during adsorption and desorption for an organic material [1].*

3.4 Mass Balance

A general mass balance for moisture content is

$$(X_{in} - X_{out})W_p = (Y_{out} - Y_{in})W_g \tag{3.4}$$

where, X, is moisture content for the solid and, Y, for air. When calculations are made it is common to use dry flows, that means dry air, W_g, and dry solid, W_p, rates. The advantages are that it is not necessary to consider changes in volume and weight, which are necessary if calculations are made with the use of wet flows.

3.5 Constitutive Energy Equations

To describe a general energy balance it is necessary to consider more than for a general mass balance. Each medium has a specific heat, c, which is the amount of energy needed to heat one kg of the medium one $°C$. A change in temperature, Δt, will increase or decrease the energy that is accumulated in a mass, m, which can be described by

$$E = cm\Delta t \tag{3.5}$$

When water evaporates it is necessary to consider latent heat of vaporization, Δh_v, which is the energy needed to transform one kg water to vapor at a specific temperature. The amount of energy needed is then

$$E = \Delta h_v m \tag{3.6}$$

where m is the mass of evaporated water. How latent heat of vaporization depends on temperature is

$$\Delta h_v = \Delta h_{v0} + c_v t - c_w t \tag{3.7}$$

Δh_{v0} refers to latent heat of vaporization at 0 $°C$, which is 2501.3 kJ/kg [11]. Mass flow of evaporated water will also contribute to a decrease or increase of the specific heat capacity in the mediums. Therefore it is necessary to consider how the amount of water is changing, and for a solid substance that contains bound water. This can be described as the sum of the specific heat for the dry solid, c_s, and the specific heat of water, c_w, times moisture ratio, X

$$c = c_s + Xc_w \tag{3.8}$$

For a gas it is equal if specific heats are changed to vapour and gas. Mass of evaporated water will also contribute to a decrease or increase of energy equal to equation 3.5. The amount of energy is then dependent between temperature difference of the evaporated water and the medium that accumulates it. Difference of temperature between the mediums will also result in energy transport in form of heat flux

$$q = \alpha(t_g - t_p) \tag{3.9}$$

between them. Heat transfer coefficient, α, is dependent of the air flow, i.e. if it is laminar or turbulent [11].

3.6 Techniques in Agricultural Drying

Different types of dryers are used to dry small corned materials. A batch dryer is loaded with an amount of drying goods and holds it for a specific time. Then the entire content is exchanged with a new load of goods. A continuous cooler has continuous flow of drying goods. Three types are used, crossflow where the mediums cross each other, countercurrent where they go in opposite direction and concurrent where they go in the same direction [12]. Figure 3.3 shows the different types.

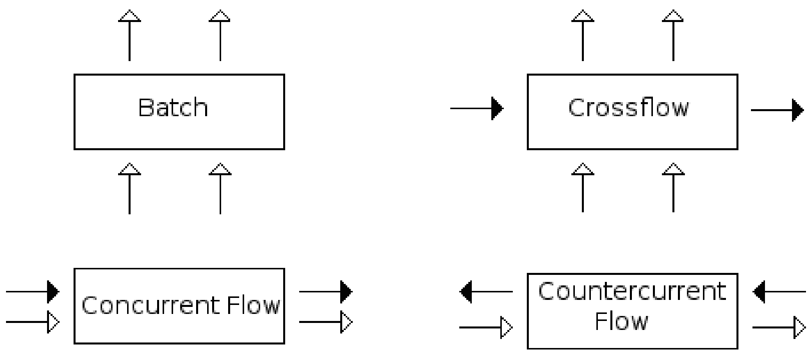


Figure 3.3: *White arrows refer to air flow and black arrows to drying goods flow. Batch driers consist of a bed where the entire bed get exchanged after a certain period of time.*

3.7 Related Work

According to N. Laws and J.L Parry [12] there are three ways to model deep bed dryers, logarithmic, heat and mass balance, and with partial differential equations. The classification is not strict, there are combinations of them. Logarithmic model

$$X = \frac{2^L}{2^L + 2^\tau - 1} \tag{3.10}$$

describes the moisture content, X, as a function of the bed depth, L, and the time, τ. The main advantage of the logarithmic approach is its simplicity, but it has its limitations since it can only be acceptable in slow processes with low temperature [12].

Other approaches have been to build models by dividing the bed into thin slices (aggregated models), where properties are assumed constant during a given space of time. Air and pellet temperature, and moisture content are calculated using laws of heat and mass balance for each slice. Good results have been shown in previous studies with some types of crops, but assumptions made during derivation restrict the accuracy of the prediction [12].

T. Nybrant [13] arranges a general mathematical model of a cross flow grain drier by dividing the bed in slices (figure 3.4), which can be seen as a sequence of batches. In a cross flow dryer all sections are equally exposed to the air flow. The properties of each section is determined by the time it has been inside the dryer.

The influence between each section regarding temperature and moisture content is neglected, and variable x refer to moisture content in the current section or the outlet air temperature. Laws regarding heat and mass balance are used to arrange models based on partial differential equations.

Further, T. Nybrant describes models of a cross and concurrent flow dryers based on identifying the process by experiments in a laboratory. Step response (grain flow) on the dryers showed that they where non-linear. Sampling was made according to distance the grain had moved throughout the dryer and the signal input was a telegraphic signal which controlled grain outlet. Signal output was in first case (crossflow dryer) outlet air temperature and in second case (concurrent dryer) outlet grain temperature. This gave ARMAX models with different order. Sample interval was 5-10 minutes which made the procedure very time consuming.

J. Yrjölä [14] describes like T. Nybrant [13] a cross flow process, which is used to dry wood chips. To create the model, assumptions are made: melting of ice, heating of particles and evaporation of water are assumed to occur sequentially. During the state of heating and melting the dryer is seen

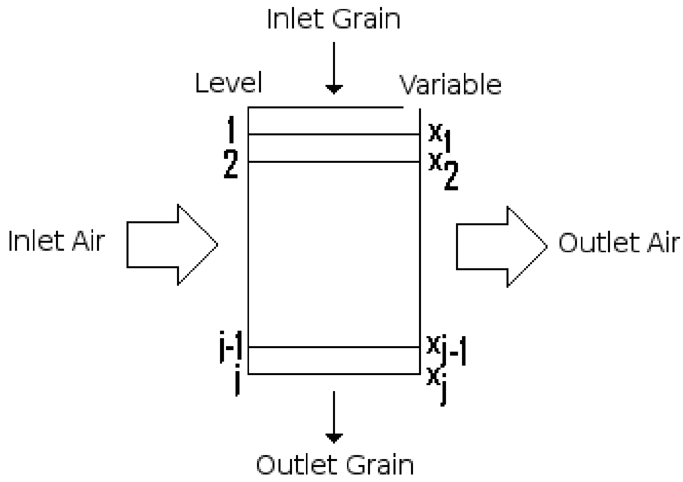


Figure 3.4: *T. Nybrant's general model of a cross flow grain dryer [13], in this case x refers to temperature or moisture ratio, j refer to number of slices.*

as a heat exchanger and during state of evaporation the outlet air is assumed to be saturated (with water vapour) and that the air properties change along a curve with constant enthalpy. The air is preheated before entering the dryer.

Modelling of the bed is made by dividing it into small cells (figure 3.5). Heat and mass transfer are set up for a spherical particle inside each cell, which then is combined with the mass and heat transfer for the entire bed. The output variable from one cell is the input to the next. When the flows are crossing each other, no iterative calculations are needed to determine the value of the variable to the next cell.

D.E Maier and F.W. Bakker-Arkema have been studying drying and cooling of feed pellets using a countercurrent cooler in laboratory environment [4]. This was done by using a prototype of a full scale cooler, which construction is very much alike the cooler used at Lantmännen's factories. The presented model was based on infinite volume element, on which mass and energy balance was constructed during a steady state. The equations were integrated with a deep bed view, in that way moisture and temperature of the pellets was calculated for each level in the bed.

To use their model, great knowledge regarding properties of the pellets are required. Values such as specific heats, diffusion coefficient and sorption isotherms are necessary to solve the equation system. Assumptions are made such as uniformity of the pellets regarding form, size and properties, no heat nor moisture exchange is made between the pellets, heat capacity in the walls

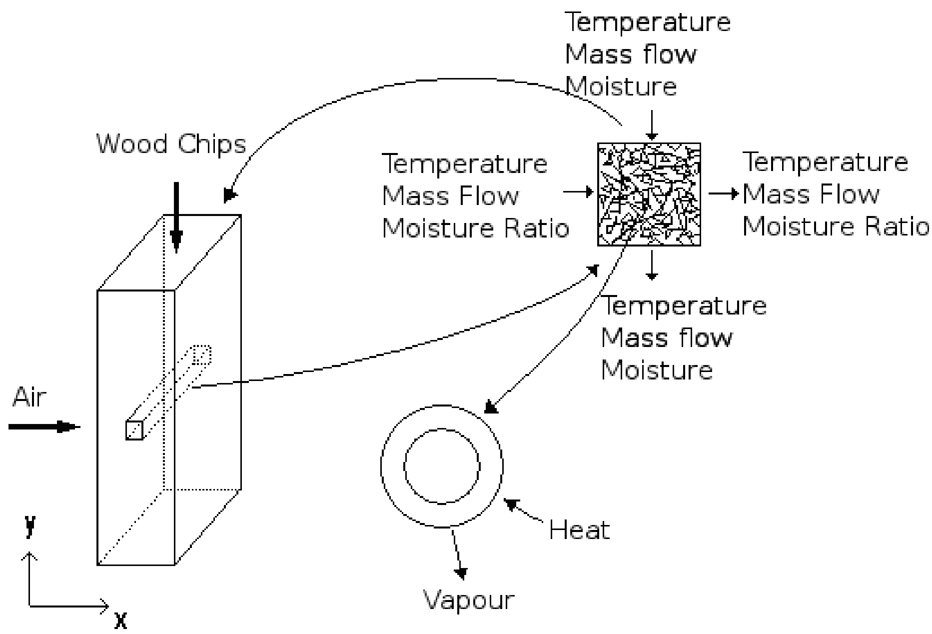


Figure 3.5: *The bed divided into cells, where properties of the cell is based on a spherical particle [14].*

of the cooler is neglected, there are only diffusion in radial direction of the pellets and drying only occur in the second and third drying period [2].

Verification of the model showed that it could predict the trends regarding temperature and moisture content, but there were a difference in both temperature (10-28%) and moisture content (3-60%) within the pellets. The reason for the difference between predicted and measured value, was according to [4], that the moisture equilibrium equation and the drying equation for single pellet was insufficient. Further results from the study showed that the parameters with the major effect on the result of the drying was the height of the bed and the ratio between air and pellet flow. Also there exists a bed height optimum for a given pellet/air ratio. Experiments showed that outlet air is never fully saturated, it can in theory adsorb more water [2].

The study made by Å. Björnwall [2], which in a great deal resemble the study made by D.E. Maier and F.W. Bakker-Arkema, showed that both temperature and moisture content of the pellets will level after a certain depth.

3.8 Related Work versus Lantmännen

The process at Lantmännen differs from once in section 3.7. J. Yrjölä [14] and T. Nybrant [13] both describe cross flow processes. To construct a model, by dividing the cooler into sections and make simplifications which do not affect the estimated value, are easier with a cross flow process than for a countercurrent flow process. The reason for this is that the state of air and pellets (moisture content and temperature) in each section can be seen as independent parts which do not interact with each other. Applying these types of simplifications at a countercurrent flow process, is not plausible because state of the air in each section is dependent on previous states (figure 3.6).

This is the reason why T. Nybrant does not construct a mathematical model in his study, just identifying an ARMAX model using frequency analysis on the concurrent flow dryer. Another difference in [13, 14] is that the inlet temperature of the air is higher (preheated) than the temperature of the goods under drying, which gives that the air is cooled instead of adsorbing heat.

Theories in energy and mass transfer described by T. Nybrant [13] and J. Yrjölä [14] are applicable to Lantmännen's conuntercurrent flow process. This, because same medium (air) is used. F.W. Bakker-Arkema and D.E. Mayer's publication [4] describes a process more or less equal to Lantmännen's cooler, the only difference is the size. Å. Björnwall carry out an identical ex-

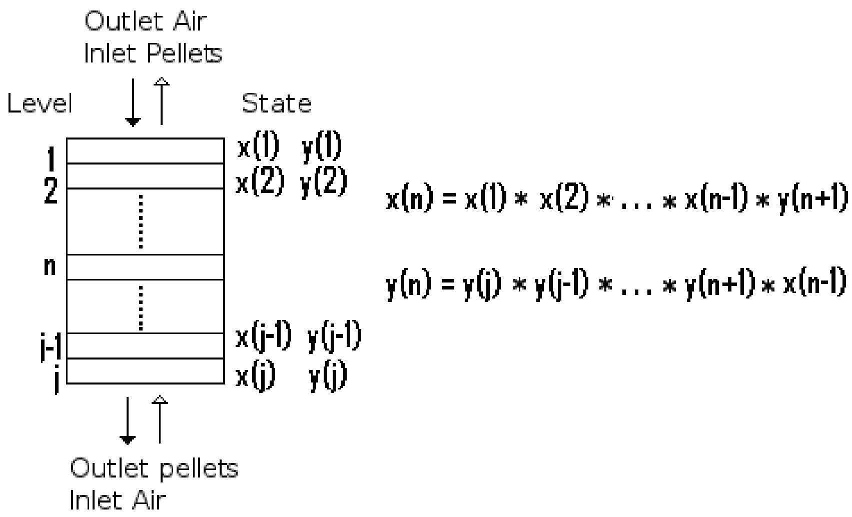


Figure 3.6: *x refers to state of the pellets and y state of the air, i.e. moisture content and temperature. White arrows refer to direction of air flow and black arrows to direction of pellet flow. Star refer to dependence between states.*

periment but on a full scale cooler. Therefore their works and conclusions are instantly applicable.

3.9 Control of Cooling and Drying Processes

Examples where air flow rate have been the main way to control drying of organic materials have not been found in literature. Rate of diffusion in drying goods is as described in section 3.3 not direct dependent on the rate of air flow. On the other hand air flow affect temperature of the goods under drying. If air flow is too high, cooling of the pellets will increase. The result of this is that diffusion rate and thereby also drying rate will decrease. If the rate of air flow is too low, cooling of pellets and difference in water activity between drying goods and air will decrease. This will also result in a decrease in the rate of drying.

By optimize the rate of air flow it is possible to receive an optimal rate of diffusion, but in the end it is the time pellets have been inside the dryer which is the main factor. According to [2, 4] it is possible to control temperature and moisture content of drying goods by combining the relation between air/pellet flow and bed height.

Chapter 4

Bed Properties

Following chapter describes air and pellet variations in temperature and moisture content in the cooler, and measurement data. Figures are made using Matlab®.

4.1 Measurement Data

Data[1] from a study [2] on an equal countercurrent flow cooler are used for explanations and simulations. Samples were collected at inlet, outlet and at different bed depths and coordinates in cross sectional area normal to flow direction. The cooler was at steady state, which in the study meant that it had been going for approximately 30 minutes. Three of the measurement series are similar and therefore a mean value (arithmetic) of these are used. With similar means that flows, bed height, properties of air and pellets are almost equal. Mean values are a way to decrease error in measurements and are therefore used in following sections and chapters. Temperature and moisture content inside the bed are measured at two positions for specific levels, centre and wall. With the assumption in section 1.3 that flows are equal throughout the bed a mean value of centre and wall is used.

4.2 Moisture

How moisture content of pellets vary according to bed depth can be seen in figure 4.1. The dotted blue line is an assumption that pellets do not dry between inlet and top of the bed, the dashed vertical black line points out average bed height. Moisture content at the outlet is assumed to be equal

[1] For data see appendix B

to pellet at bottom in cooler. It is easy to see that a lot of moisture are removed from pellets in the beginning, which means that they have been in the cooler for up to around 1/3 of their total process time. According to the assumption above (moisture content at outlet) it can be seen that pellets are absorbing moisture at the end, at the last part of their total process time. In the middle part, almost no moisture have been desorbed.

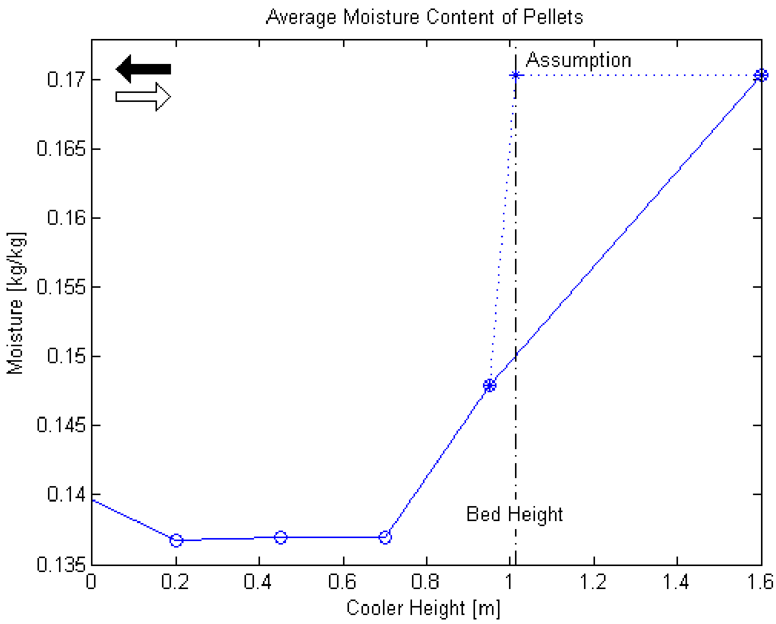


Figure 4.1: *Circles refer to average (mean from three measurements) moisture content of pellets for specific heights in cooler, dashed black line refers to bed height and dotted blue line refers to assumption that moisture content for pellets at top of bed and inlet is equal. White arrow refer to air flow direction and black refers to pellets.*

It is reasonable to assume that all moisture at a specific height that have been desorbed from the pellets have been absorbed by the air at same level (according to equation 3.4 in section 3.4). Considering dry flows (air and pellets), and change in pellets moisture between each level, it is possible to calculate how moisture content in air changes according to height, which is shown in figure 4.2. Calculated outlet moisture content for air differ from measured (mean) outlet, approximately 12%.

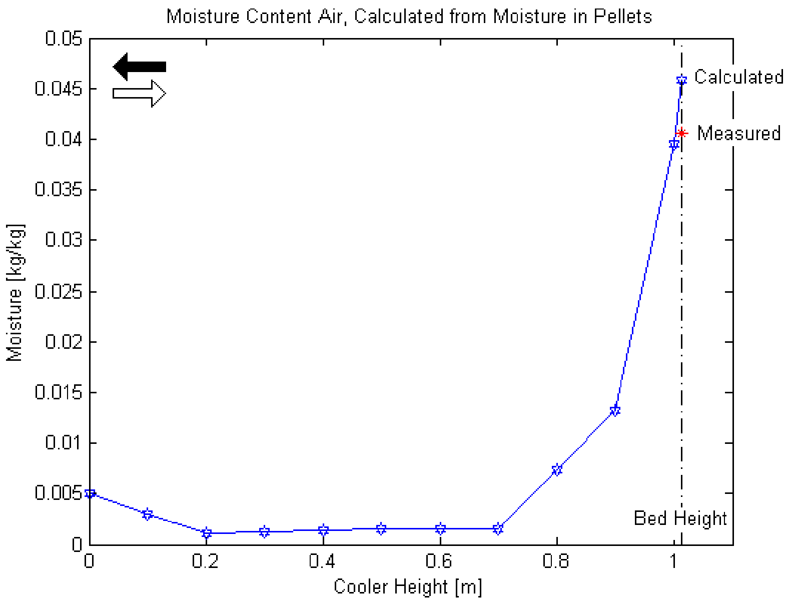


Figure 4.2: *Moisture content of air calculated from change in moisture content of pellets. Dashed black line refers to bed height. Red star refers to mean value (three measurements) measured of outlet air moisture content. Calculated outlet value is higher than measured. Calculations are made from bottom of cooler. Stars refer to height where moisture content is read in figure 4.1. White arrow refers to air flow direction and black refers to pellets.*

4.3 Temperature

Average air temperature have as described in section 4.1 been calculated from measurements. The result is shown in figure 4.3. Dotted blue line is an assumption that air temperature only changes inside the bed, air temperature above is by that equal to the temperature in top of the bed. Air temperature at inlet is assumed to be equal to air temperature at bottom in cooler. Temperature is increasing throughout the bed and increasing rate is highest at the top of the bed.

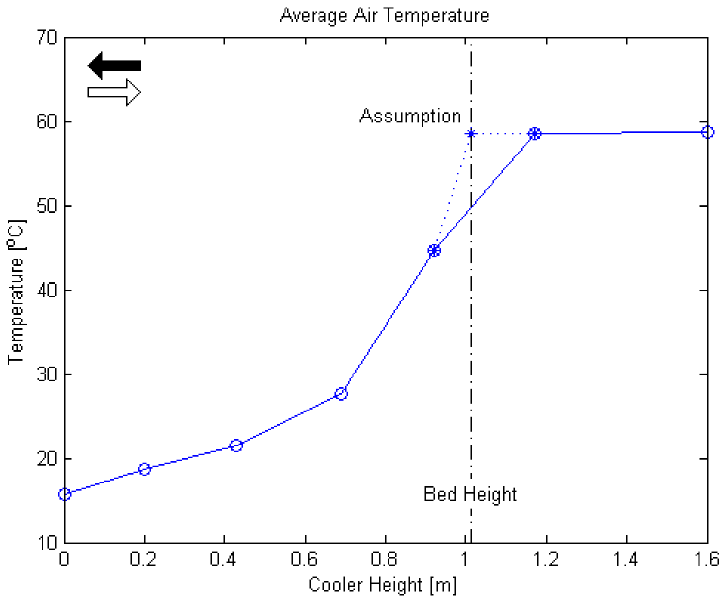


Figure 4.3: *Circles refer to average (mean from three measurements) temperature of air for specific levels in cooler, dashed black line refers to bed height and dotted blue line refers to assumption that temperature at top of bed is equal to outlet. White arrow refers to air flow direction and black refers to pellets.*

Through energy equations in section 3.5 and with boundary values for pellet temperature[2], it is possible to describe and calculate pellet temperature. This is done by

$$\Delta t_p c_p W_p = \beta(t_p - t_g) + \dot{m}_w \Delta h_v \tag{4.1}$$

where

$$\beta = \alpha a_v \tag{4.2}$$

[2]For data see appendix B

For definition of characteristic pellet area, a_v, see equation 5.8 in section 5.1. The equation is general and it is necessary to calculate a new solution for a new step range, which depends on how many parts the bed is divided into. This gives a new β for that step range and by solving the equation β will be empirical determined, specific heat of 1.6 kJ/kg for pellet is used [6]. Δt_p refers to temperature difference of pellets through each step and $\dot{m}_w$ to mass flow evaporated water. A possible description of pellet temperature, with a step range of 0.1 m is shown in figure 4.4. Equation system was solved using Mathematica®. Temperature for pellets is like for air, increasing through out the bed and increasing rate is highest at the top of the bed.

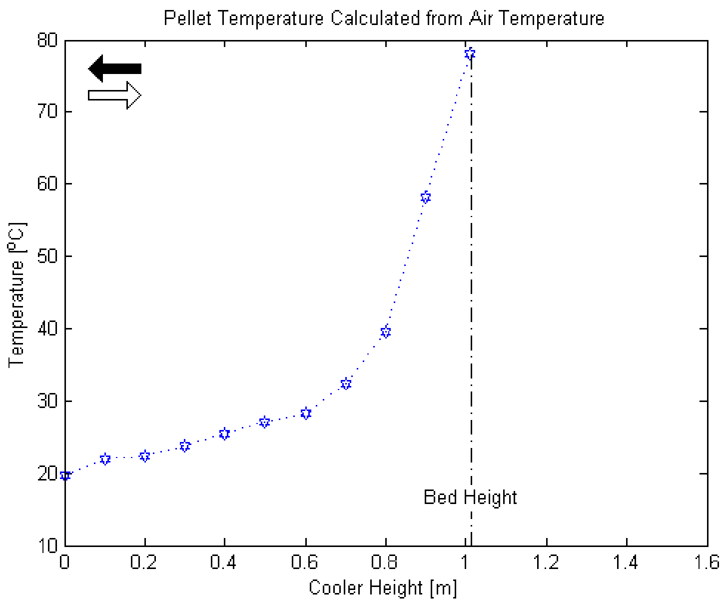


Figure 4.4: *Stars refer to temperature of pellets calculated from temperature change in air (equation 4.1). Dashed black line refers to bed height. White arrow refers to air flow direction and black refers to pellets.*

4.4 Bed Sections

By air properties in section 4.2 and 4.3 it is possible to draw a mollier chart of the air on its way through the bed. How relative humidity (water activity, a_w, times 100) varies in the bed is described in figure 4.5[3]. With this chart and figures in section 4.2 and 4.3 it can be seen that there are three different

[3]For more legible and clear mollier chart see appendix C

parts in the bed. In the top part of the bed, around 1/3 of total bed height, almost all drying occur (blue line (3) in figure 4.5) and there is also a large change in temperature. According to section 3.2, water activity for pellets must be much greater than for air in this area. Temperature change of pellets is large because water evaporates and also for air because transported water by itself contains accumulated energy (temperature differences between pellet and air). This contributes to higher increase in enthalpy for air, than if there were only heat flux, q. This part of the cooler can then be seen as both drying and cooling part.

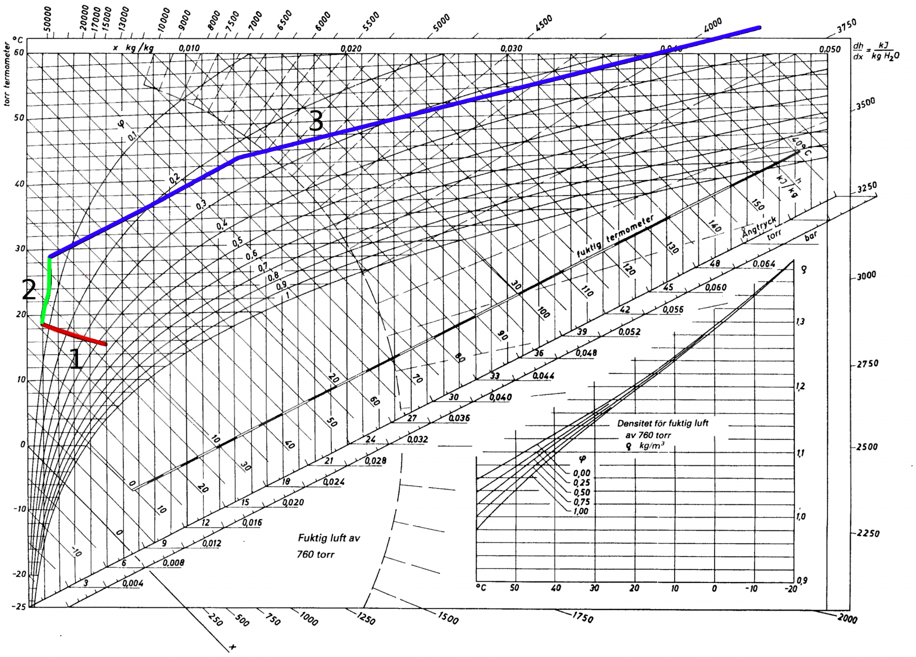


Figure 4.5: *Mollier chart [15] shows how temperature, moisture content and relative humidity of air changes through out the bed. Blue line (3) refers to the top part of bed, green (2) to the middle part and red line (1) refers to bottom part of the bed. The change in air pressure is negligible.*

In middle part of the bed (green line (2) in figure 4.5), around 1/2 of total bed height, drying has almost stopped. Water activity for pellet and air are therefore almost equal and because of this, temperature changes are mostly heat flux. In this part of the cooler only cooling of pellets occur. At bottom part of the bed (red line (1) in figure 4.5), around 1/5 of total bed height, pellets absorb water from the air[4] and water activity is here less for pel-

[4]Why this happens is explained in section 3.2 and 3.3

lets than for air. Pellet temperature is decreasing both of heat flux and of temperature difference between itself and water absorbed from air.

4.5 Inlet Air

Because Lantmännen uses ambient air that is not dried nor heated[5] before it enters the cooler. Humid inlet air will result in a higher temperature difference between outlet pellets and inlet air, than if the inlet air is dry. This is because specific heat for pellets depend on their moisture content, which in turn is controlled by humidity in the inlet air (see section 3.2). If inlet air is too cold it might cool the pellets too fast, which then can result in that not enough moisture is removed (see section 3.3).

[5] Except for the factory in Umeå

Chapter 5

Modelling

The models that are presented in this chapter are at a steady state condition and are based on theoretical physics, which in this case means that the variables are constant during time. No dynamics are considered i.e. no transients.

5.1 Mass and Energy Balance Based Model

If the following model is to be used it is necessary know flows of pellets, W_p, air, W_g, dimension of the cooler and the pellets, bulk density, ρ_b, heat capacities, c, drying rate, w_D, and properties of inlet pellets, outlet air. Equations describe how moisture contents, X, Y, and temperatures, t_p, t_g, variate depending on bed depth, L. This general description of a drying process is based on mass and energy balance according to A. Mujumdar [1] and are the following:

$$\frac{dX}{dL} = -\frac{S}{W_p} w_D a_v \tag{5.1}$$

$$\frac{dt_p}{dL} = \frac{S}{W_p} \frac{a_v}{c_p + c_w X} [q + w_D((c_w - c_V)t_p - \Delta h_{v0})] \tag{5.2}$$

$$\frac{dY}{dL} = -\frac{S}{W_g} w_D a_v \tag{5.3}$$

$$\frac{dt_g}{dL} = \frac{S}{W_g} \frac{a_v}{c_g + c_v Y} [q + w_D c_v (t_g - t_p)] \tag{5.4}$$

In the equations, S refer to cross sectional area normal to flow direction. The heat transfer, q, and the drying rate, w_D, can be calculated with equation

3.9 in section 3.5 and

$$w_D = w_{DI}\Phi \tag{5.5}$$

When drying rate is mainly dependent on the rate of diffusion in the material (drying period two and three) it is hard to find a physical relation between how water transports between the surface of the goods and the drying gas. It is thereby necessary to approximate this. In agricultural science

$$\Phi = e^{-k\tau} \tag{5.6}$$

is often used for this approximation. The rate of air flow, moisture content and temperature is embedded into this equation [1]. The time, τ, the pellets have been inside the cooler is calculated by

$$\tau = \frac{\rho_b S}{W_p} L \tag{5.7}$$

It is derivated from pellet flow, volume ($S \times L$), and bulk density, ρ_b. The characteristic interfacial area per unit volume, a_v, of a pellet is calculated by using

$$a_v = (1 - \varepsilon)\frac{2(r + l)}{rl} \tag{5.8}$$

and by the porosity

$$\varepsilon = 1 - \left(\frac{\rho_b}{\rho_p}\right) \tag{5.9}$$

To determine the porosity it is also necessary to know the pellets density, ρ_p. A problem with the above mentioned equations is that they demand extensive reliable data. To approximate and neglect can be a way to avoid this[1].

The specific heat capacity and the latent heat of vaporization are assumed to be constant in the temperature region. Also the denominator in equation 5.4, $c_g + c_v Y$ can be simplified and rewritten to c_g, when $c_v Y \ll c_g$. In equation 5.2 the denominator $c_p + c_w X$ can be set to a constant, when the variation in X is small (approximate size of 10^{-2}). One problem is to determine the specific heat capacity of the pellets c_p, which probably variate with the type of feed produced. Because same configuration is used on the cooler, independent of feed [3], this variation is neglected. The value of c_p is assumed to be $1.6 - 1.7\ kJ/kg$ [6]. The term $(c_w - c_v)t_p - \Delta h_{v0}$ can be set to a mean Δh_v, because variation in the latent heat of vaporization is small. To calculate a value for the heat transfer coefficient, α, Reynold's

[1] Data from a previous study [2] are used which can be found in appendix B

number combined with Prandtl's number can be used. This value is highly dependent on how air turbulence variate in the bed, which makes it hard to calculate a reliable value. To understand what size α should be, a part where the cooler only works as a heat exchanger is studied[2]. By using equation 3.9 then gives that α should have a size around 10^{-3} kW/m^2K. In similar way an approximate size of the initial drying rate w_{DI} can be determined, the only difference is that the parts where drying occur are considered. The size of w_{DI} should be around 10^{-4} kg/m^2s. The resulting simplified temperature equations are:

$$\frac{dt_p}{dL} = \frac{S}{W_p}\frac{a_v}{C}[q - w_D \Delta h_v] \tag{5.10}$$

$$C = c_p + c_w X \tag{5.11}$$

$$\frac{dt_g}{dL} = \frac{S}{W_g}\frac{a_v}{c_g}[q + w_D c_V (t_g - t_p)] \tag{5.12}$$

Approximations described above are verified further in section 6.1.

5.2 Input – Output Model for the Whole Cooler

The pellet bed can be described as a "box" which affects the flows (air, pellets) through it. By disregard the things that happen inside the box and only concern the flows in and out of the box, gives another way to describe the process. It is necessary to measure moisture content, temperature for the outlet and inlet air, and also for the inlet pellets. The specific heats, c_p, c_g, the latent heat of vaporization, Δh_v, and the flows (pellets and air) are also necessary to determine. The following equations can then be used to determine temperature and moisture content of outlet pellets:

$$X_{out} = X_{in} - [Y_{out} - Y_{in}]\frac{W_g}{W_p} \tag{5.13}$$

$$t_{pout} = t_{pin} - [(t_{gout} - t_{gin})c_g + \Delta h_v (Y_{out} - Y_{in})]\frac{W_g}{c_p W_p} \tag{5.14}$$

They are derived from the equations in sections 3.5 and 3.4. Conditions for the relations are that temperature transition is only between air and pellets, and that the air adsorb all evaporated water. Model described above is verified in section 6.2.

[2] A part where no drying occur, i.e. no moisture transfer between pellets and air

Chapter 6

Simulations & Results

In this chapter simulations and results of the models described in chapter 5 are presented. Figures are made using Matlab®.

6.1 Mass and Energy Balance Based Model

One way to verify and show the model description in section 5.1 is to generate figures based on the equations, showing how temperatures and moisture vary inside the bed. Variation in the drying rate as function of length, L, can be determined by substitution of the time, τ, in equation 5.6 with the pellets residence time, equation 5.7. The equations (5.1, 5.3) for moisture in the pellets and air can then be integrated with aspect to length, which then gives:

$$X = A_x(e^{-BL} - 1) + X_0 \tag{6.1}$$

$$Y = A_y(e^{-BL} - 1) + Y_0 \tag{6.2}$$

where

$$B = \frac{\rho_b S}{W_p} k \tag{6.3}$$

$$A_x = \frac{a_v}{\rho_b} \frac{w_{DI}}{k} \tag{6.4}$$

$$A_y = \frac{a_v}{\rho_b} \frac{W_p}{W_g} \frac{w_{DI}}{k} \tag{6.5}$$

Drying is assumed to occur during period two and three in the cooler, and therefore equation 5.6 is used in two different parts of the bed, with different values of constant k. A and B are fusions of constants and parameters according to section 5.1.

Constants that need to be determined and approximated are the initial drying rate, w_{DI}, the drying constants, k_1, k_2, and at what bed depth the transition between drying periods two and three occur. The constants are equal for pellets and air. The data[1] that is used are as described in section 4.1. To optimize accuracy of the approximation, minimization of the LMS (Least Mean Square) between calculated (by equation 6.1) and measured values for moisture content in pellets, at different bed levels is used. Genetic Algorithm [16] is used to estimate constants, and the fitness value is the inverse of the LMS. Figures 6.1 and 6.2 describe moisture contents for pellets and air for the best combination of calculated (approximated) constants, which are a initial drying rate (w_{DI}) of $2.1786 \times 10^{-4}\ kg/m^2s$, dry constants ($k_1, k_2$) of 9.8×10^{-3}, 9.3×10^{-3} and transition to third drying period at a depth of $0.1566\ m$.

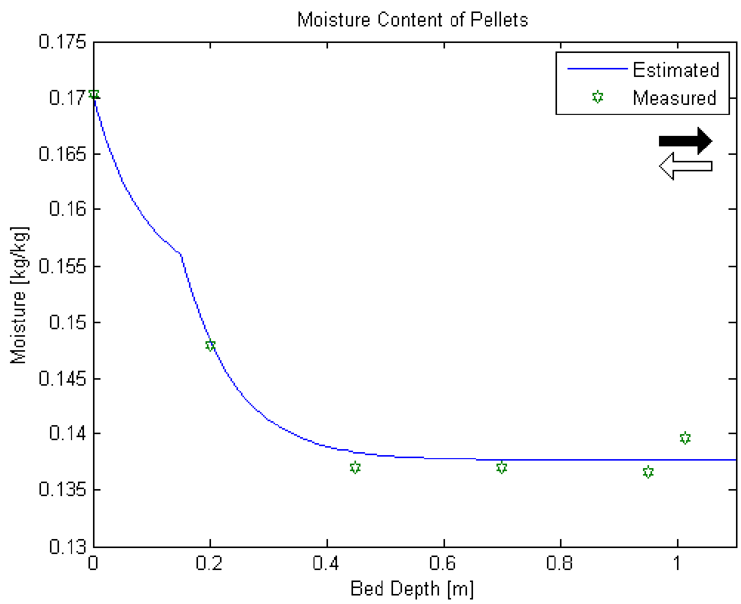


Figure 6.1: *Moisture content of pellets calculated with equation 6.1. Approximated constants are initial drying rate, w_{DI}, dry constants, k_1 k_2, and depth at transition to third drying period. Blue line refers to calculated function and stars refer to measured values. White arrow refers to air flow direction and black refers to pellets.*

Applying the constants to temperature equations, both before and after simplifications (equation 5.2, 5.4, 5.10 and 5.12 in section 5.1) and estimate of

[1]Values that are used for simulation can be found in appendix B

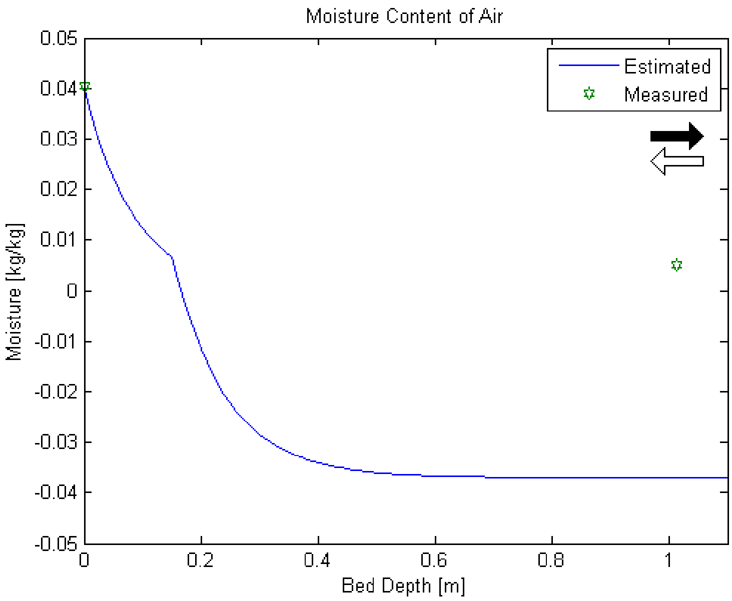


Figure 6.2: *Moisture content of air calculated with equation 6.2. Approximated constants for pellets are used. Blue line refers to calculated function and stars refer to measured values. White arrow refers to air flow direction and black refers to pellets. Moisture content in air reach values below zero, which in reality is not possible.*

the heat flux, α, it is possible to display how temperatures (air and pellet) depend on bed depth. With an $\alpha = 0.0019\ kW/m^2K$ and $\Delta h_{v0} = 2501.3\ kJ/kg$ these are described in figure 6.3. The dotted lines are the simplified temperature descriptions and the initial values are from top of the bed.

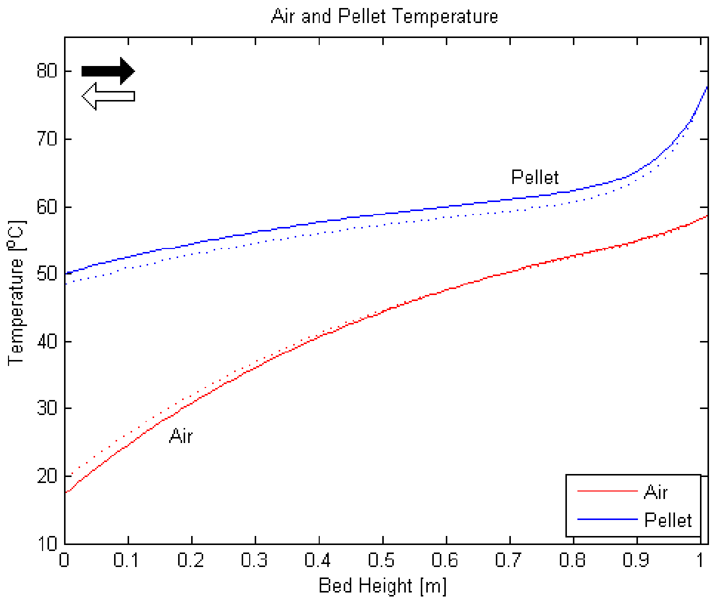


Figure 6.3: *Temperature variations throughout the bed. Pellets (blue), calculated with equations 5.2, 5.10 and air (red) with equations 5.4, 5.12. Dotted lines are the simplified temperature descriptions. Solid lines refer to descriptions of equations before simplifications. Initial values are from top of the bed. Approximated constants are heat transfer coefficient, α, initial drying rate, w_{DI}, dry constants, k_1 k_2, and depth at transition to third drying period. White arrow refers to air flow direction and black refers to pellets. Temperature difference between pellets and air is increasing with the depth of the bed, which in reality is not possible. This is discussed in chapter 7.*

6.2 Input – Output Model for the Whole Cooler

Moisture content for outlet pellets is as described in section 5.2 calculated with

$$X_{out} = X_{in} - [Y_{out} - Y_{in}]\frac{W_g}{W_p}$$

Inlet and outlet data[2] according to section 4.1 are used to verify the model. Calculations are done separately for the three measurements. Measured, calculated and error are

Moisture content	**Reference 1**	**Reference 2**	**Reference 3**
Measured values (kg/kg)	0.1400	0.1370	0.1420
Calculated values (kg/kg)	0.1421	0.1430	0.1459
Error (%)	1.5023	4.3824	2.7292

The errors refer to percentage difference between calculated and measured moisture content. Differences are $1 - 5\%$, which show that the equation and the measurements could be reliable. Temperature for outlet pellets is calculated with

$$t_{pout} = t_{pin} - [(t_{gout} - t_{gin})c_g + \Delta h_v(Y_{out} - Y_{in})]\frac{W_g}{c_p W_p}$$

Specific heats, $c_p = 1.6$ [6], $c_g = 1.02$ [1] and latent heat, $\Delta h_v = 2370$[3], are used for calculations and the results are

Temperature	**Reference 1**	**Reference 2**	**Reference 3**
Measured values $(°C)$	19.8000	19.2000	20.1000
Calculated values $(°C)$	17.4311	17.4311	18.3311
Error (%)	-11.9639	-9.2128	-8.8003

The errors refer to percentage difference between calculated and measured temperature. Differences are $8 - 12\%$, which could mean that the equation is not sufficient and/or an error in the specific heats, latent heat, measurements.

[2] Values that are used for simulation can be found in appendix B
[3] The arithmetic mean of latent heat at $30°C$ and $80°C$

Chapter 7

Discussion

If the pellets are fully dried before they reach bottom of the cooler (as in figure 4.1), it is possible to decrease the bed height. However this will increase temperature of outlet pellets and therefore it is necessary to increase air flow rate to compensate the increase in pellet temperature. If the air flow is increased it will affect both the drying rate and pellet temperature, which makes the relation between bed height and air flow complex. To theoretically determine this relation is probably not possible.

The approximated constants, w_{DI}, k_1, k_2 and bed depth for the transition between drying periods, are according to figure 6.1 plausible. If it is correct to divide drying rate into two periods and if drying equation is suitable is difficult to say. The drying equation 5.5 can only be used with the assumption that moisture only decrease from the pellets and not absorbed. According to the figures of moisture content, 4.2, 4.1 this is not the case. Therefore it could be necessary to have another description of drying rate at the bottom of the cooler.

Constants determined for pellets are used to describe moisture content in air. According to figure 6.2, moisture content is at the bottom below zero. This is in reality not possible and can be a result of errors in the measurements. It can be seen that there are something wrong in the values used for simulations. Adsorbed vapour in air is not equal to desorbed water from pellets.

Temperature difference between pellets and air is according to figure 6.3 increasing at the bottom of the cooler. If drying rate is set to zero, which it is in some parts of the cooler, it can be seen in equations 5.2, 5.4 that measured pellet or air flow might be incorrect. The temperature is then only depending on heat flux between pellets and air, decrease of temperature should then be higher for pellets than for air. If specific heats for the mediums are correct, a lower pellet flow or a higher air flow is necessary, which indicates of an error in the measurement of these flows. The simplification of the temperature equations (5.10 5.12) can probably be used if the original equations are correct. Figure 6.3 shows that it only results in a small difference.

Input – output model for the whole cooler gives more accurate result for outlet pellets in moisture content than for temperature. The reason for this is difficult to state. The temperature equation could be insufficient, more constants could decrease accuracy or there could be errors in the measurements.

Chapter 8

Conclusions

To achieve the desired moisture content, water activity and temperature of the pellets prerequisite two things:

- Relative humidity of inlet air should be in equilibrium to desired moisture content for outlet pellets
- Proper combination of residence time (bed height) for pellets and the air to pellet mass flow ratio

At current process it is not possible to control the relative humidity of inlet air. Therefore it is not possible to control the exact moisture content in the pellets, it can never be less than moisture content that is in equilibrium with relative humidity in ambient air.

Analyse of the bed showed that it can be divided into different parts (considering pellets). First a drying/cooling, then a cooling, finally an adsorbing/cooling part. Air is heated on its way throughout the cooler and the temperature of the air affects the pellets temperature and thereby the diffusion rate. This means that temperature of the air should not only be considered at the inlet, but also on its way throughout the cooler.

Mass and energy balance based model describes complexity in the process. The restricting factor is how to describe the drying rate. Which by derive from theoretical physics is extremely difficult. It depends on the difference in water activity between pellets and air, moisture content, dimension and compound of pellets, flows and temperatures. The countercurrent flow contributes to the complexity, because all previous states must be known and considered. The proposed approximation do not consider dynamics and is only applicable during the specific conditions. If the model should be used to determine how to control the process, dynamic in the drying rate must be known.

Input – output model model for the whole cooler can be used to calculate the temperature and moisture content of the outlet pellets, during steady state. This can be useful to indicate if something is wrong with the cooler.

Chapter 9

Further Work

Recommendations for further work that can contribute to a better control of moisture content in pellets:

- Examine the possibility to control inlet air properties i.e. relative humidity and temperature

- Construct a chart of pellets, describing how water activity and moisture content vary, depending on temperature at specific pressures. This makes it possible to determine moisture content of pellets when they are at equilibrium with drying air

- Carry out experiments to further verify the input – output model. Variations can be in inlet air, bed height etc. Tables of these results (calculations) can be useful for the operator to tune in the cooler

Recommendation to capture process dynamic:

- Carry out experiments using frequency analyse with a laboratory model or a full scale factory. This will increase the knowledge in how parameters affect the result

Bibliography

[1] Mujumdar, A. S. (2007) *Handbook of Industrial Drying*. CRC Press Taylor & Francis Group.

[2] Björnwall, Å. (1994), Torkning av Foderpelleter.

[3] Tietz, F. and Edqvist, G. Factory manager, process operator, falkenbergfabriken, Aug (2007),0346-851 24.

[4] Maier, D. E. and Bakker-Arkema, F. W. (1992) The Counterflow Cooling of Feed Pellets. *J.agric. Engng Res.*.

[5] Kämpe, G. (2007) Supervisor Lantmännen, Personal communication.

[6] Baeling, P. (2007) Civilingenjör Lantmännen, Personal communication, 0708-574200.

[7] Nationalencyklopedin (2007) Vattenaktivitet, http://www.ne.se/jsp/search/article.jsp?i_art_id=339889.

[8] Fennema, R. O. (1996) *Food Chemistry 3rd ed.*. Marcel Dekker Inc.

[9] Padfield, T. (2007), Equations Describing the Physical Properties of Moist Air. http://www.natmus.dk/cons/tp/atmcalc/ATMOCLC1.HTM#rh.

[10] Jacobsen, E., Sørberg, K., and Nielsen, H. (1983) Køling af Industrielt Fremstilled Foderpiller. *Bioteknisk Institut*.

[11] Çengel, Y. A. and Turner, R. H. (2001) *Fundamentals of Thermal- Fluid Sciences*. McGraw- Hill.

[12] Laws, N. and Parry, J. L. (1982) Mathematical Modelling of Heat and Mass Transfer in Agricultural Grain Drying. *Proc. R. Soc. Lond.*.

[13] Nybrant, T. (1986) *Modelling and Control of Grain Driers*. Uppsala.

[14] Yrjölä, J. (2006) *Modelling and Experimental Study on Wood Chips Boiler System with Fuel Drying and with Different Heat Exchangers*. Ph.D. thesis, Helsinki University of Technology.

[15] Mörtstedt and Hellsten (1987) Mollier Chart Moist Air.

[16] Wahde, M. (2006) *An Introduction to Adaptive Algorithms and Intelligent Machines*.

Appendix A

In this appendix is moisture content for pellets and air calculated with the best combination of constants and equations 6.1, 6.2. Calculations are made separately for each series. Constants are according to section 6.1, and they are beginning drying rate (w_{DI}) of $2.1786 \times 10^{-4} kg/m^2 s$, dry constants $(k1, k2)$ of $9.8 \times 10^{-3}, 9.3 \times 10^{-3}$ and transition to third drying period at a depth of $0.1566m$ from top of bed.

Pellets

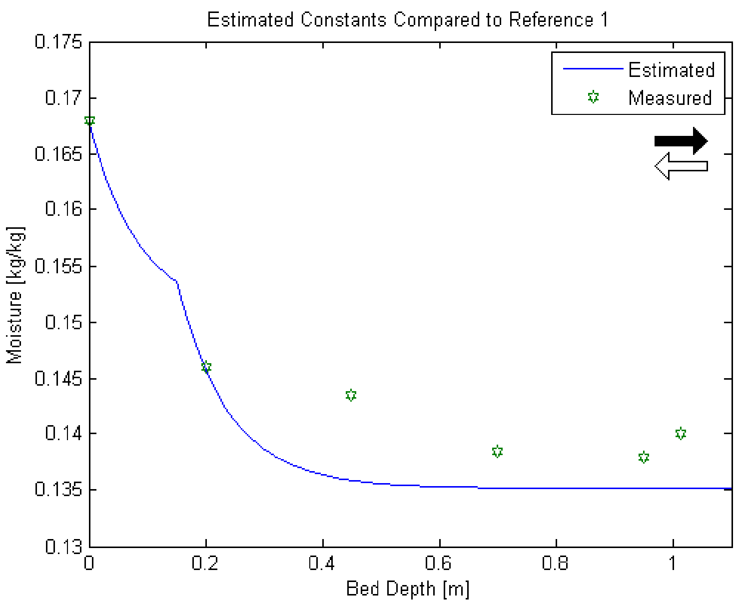


Figure A.1: Moisture content in pellets, reference 1. Blue line refers to calculated function and stars refer to measured values. White arrow refers to air flow direction and black refers to pellets

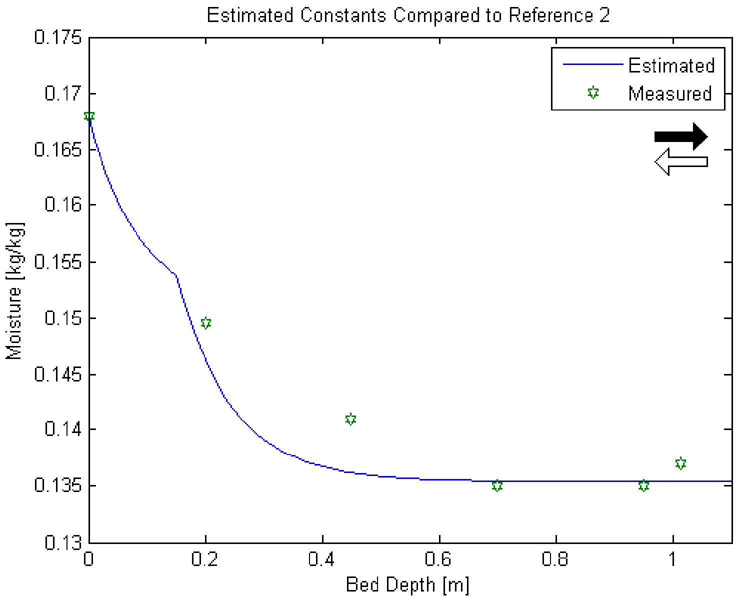


Figure A.2: Moisture content in pellets, reference 2. Blue line refers to calculated function and stars refer to measured values. White arrow refers to air flow direction and black refers to pellets

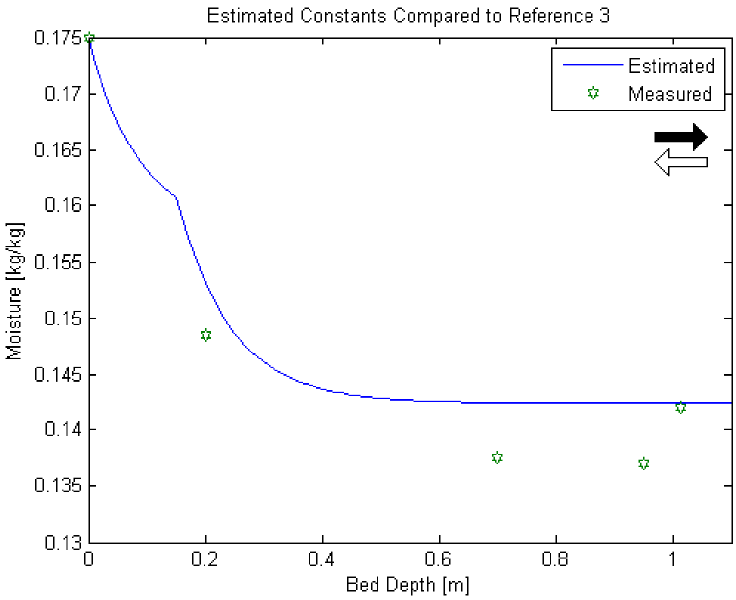


Figure A.3: Moisture content in pellets, reference 3. Blue line refers to calculated function and stars refer to measured values. White arrow refers to air flow direction and black refers to pellets

Air

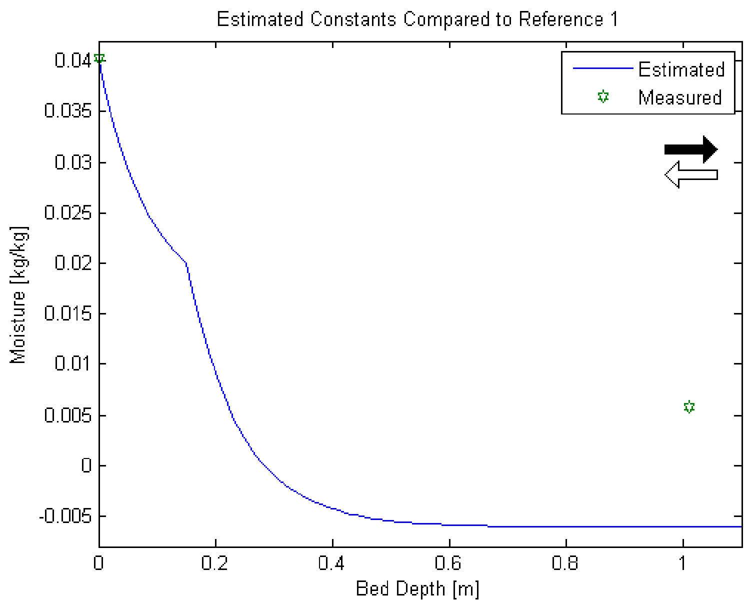


Figure A.4: Moisture content in air, reference 1. Blue line refers to calculated function and stars refer to measured values. White arrow refers to air flow direction and black refers to pellets

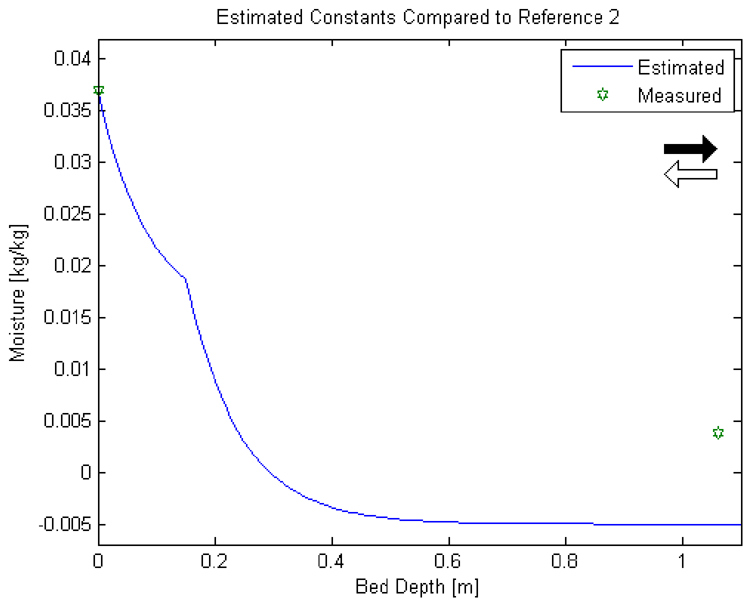


Figure A.5: Moisture content in air, reference 2. Blue line refers to calculated function and stars refer to measured values. White arrow refers to air flow direction and black refers to pellets

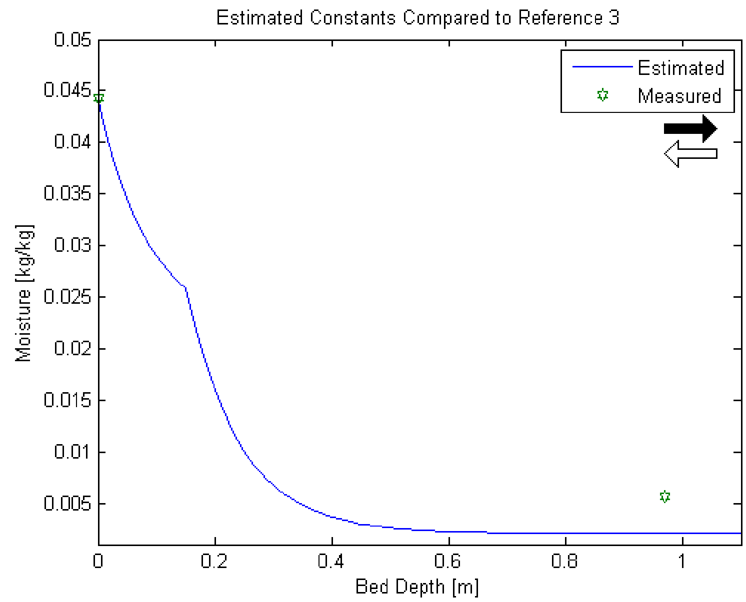


Figure A.6: Moisture content in air, reference 3. Blue line refers to calculated function and stars refer to measured values. White arrow refers to air flow direction and black refers to pellets

Appendix B

Data from previous study of a countercurrent flow cooler [2]. Three reference measurements from this study have been used. Miscellaneous data is also included.

Refecence 1 – "Försök 1"

Bed height = 1.06 m

Table B.1: *Inlet and outlet properties of pellets and air.*

	Inlet Air	Outlet Air	Inlet Pellets	Outlet Pellets
Temperature	17°C	58°C	77.8°C	19.8°C
Humidity ratio	5.8 g/kg	40.3 g/kg	0.168 kg/kg	0.140 kg/kg
Realtive Humidity	47.8 %	33.7 %	-	-

Table B.2: *Mass flow rates, air and pellets.*

	Air	Pellets
Dry flow	8.03 ton/h	11.1 ton/h
Water transport	277 kg/h	309 kg/h

Table B.3: *Air temperature at different heights and positions.*

Air Temperature		
Height	Wall	Center
0.20	17°C	19°C
0.43	17°C	23°C
0.69	23°C	30°C
0.92	45°C	38°C
1.17	63°C	53°C

Table B.4: *Moisture content of pellets at different heights and positions.*

Pellets Moisture Content		
Height	Wall	Center
0.20	0.139 kg/kg	0.137 kg/kg
0.45	0.140 kg/kg	0.137 kg/kg
0.70	0.144 kg/kg	0.143 kg/kg
0.95	0.148 kg/kg	0.144 kg/kg

Refecence 2 – "Försök 5"

Bed height = 1.01 m

Table B.5: *Inlet and outlet properties of pellets and air.*

	Inlet Air	Outlet Air	Inlet Pellets	Outlet Pellets
Temperature	12°C	58°C	77.8°C	19.2°C
Humidity ratio	3.8 g/kg	37.1 g/kg	0.168 kg/kg	0.137 kg/kg
Realtive Humidity	43.3 %	31.2 %	-	-

Table B.6: *Mass flow rates, air and pellets.*

	Air	Pellets
Dry flow	8.84 ton/h	11.6 ton/h
Water transport	294 kg/h	359 kg/h

Table B.7: *Air temperature at different heights and positions. "*" refers to fault in thermo element.*

Air Temperature		
Height	Wall	Center
0.20	18°C	20°C
0.43	21°C	*°C
0.69	24°C	31°C
0.92	48°C	40°C
1.17	63°C	55°C

Table B.8: *Moisture content of pellets at different heights and positions.*

Pellets Moisture Content		
Height	Wall	Center
0.20	0.136 kg/kg	0.134 kg/kg
0.45	0.136 kg/kg	0.134 kg/kg
0.70	0.141 kg/kg	0.141 kg/kg
0.95	0.152 kg/kg	0.147 kg/kg

Refecence 3 – ”Försök 6”

Bed height = 0.97 m

Table B.9: *Inlet and outlet properties of pellets and air.*

	Inlet Air	Outlet Air	Inlet Pellet	Outlet Pellet
Temperature	18°C	60°C	78.7°C	20.1°C
Humidity ratio	5.6 g/kg	44.4 g/kg	0.175 kg/kg	0.142 kg/kg
Realtive Humidity	43.0 %	33.8 %	-	-

Table B.10: *Mass flow rates, air and pellets.*

	Air	Pellets
Dry flow	8.79 ton/h	11.5 ton/h
Water transport	341 kg/h	379 kg/h

Table B.11: *Air temperature at different heights and positions.*

Air Temperature		
Height	Wall	Center
0.20	19°C	19°C
0.43	20°C	22°C
0.69	28°C	30°C
0.92	58°C	39°C
1.17	61°C	56°C

Table B.12: *Moisture content of pellets at different heights and positions.*

Pellets Moisture Content		
Height	Wall	Center
0.20	0.138 kg/kg	0.136 kg/kg
0.45	0.140 kg/kg	0.135 kg/kg
0.70	0.112 kg/kg	0.141 kg/kg
0.95	0.156 kg/kg	0.141 kg/kg

Miscellaneous Data

Miscellaneous data from [2]

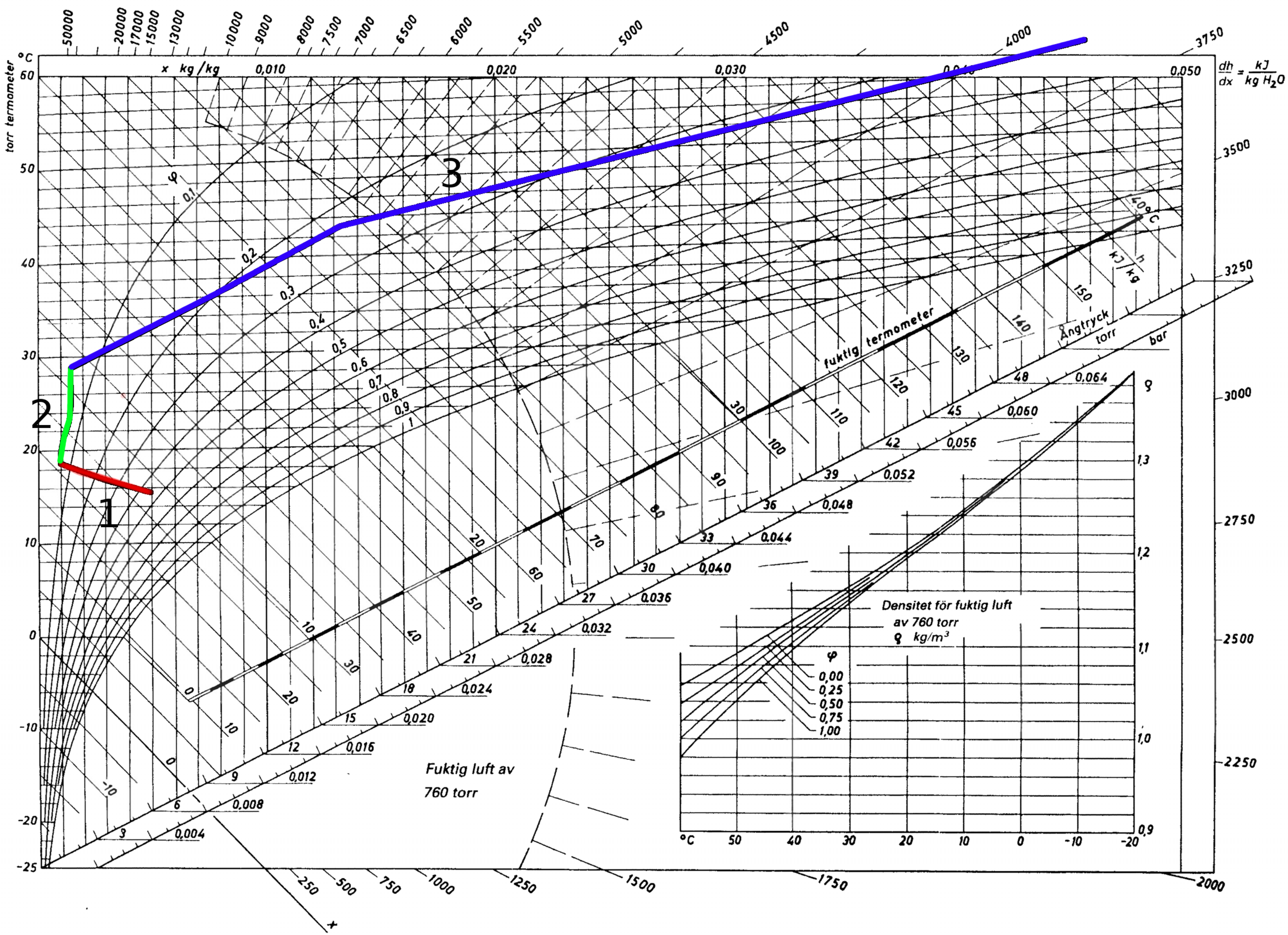
Cooler height = 1.60 m
Cooler width = 2.80 m
Cooler depth = 2.40 m

Average values:
Bulk density = 636 kg/m^3
Pellet density = 1189 kg/m^3
Pellet length = 14.7 mm

Appendix C

Mollier Chart

A more legible and clear figure of a mollier chart. Blue line (3) refers to top part of bed, green line (2) refers to middle and red line (1) refers to bottom part of bed.



x kg/kg
dh/dx = kJ/kg H2O
°C torr termometer
φ
h kJ/kg
40° C
Ångtryck torr bar
fuktig termometer
Densitet för fuktig luft av 760 torr ϱ kg/m3
φ 0,00 0,25 0,50 0,75 1,00
Fuktig luft av 760 torr
1
2
3