



Evaluating grain silo aeration of maize using CFD simulation and scaling

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ABSTRACT

Concrete grain silos are used in South Africa to store maize to ensure year-round availability. Aeration is used to manage grain temperature that affects storage safety and quality. At a large South African grain management company, aeration management is primarily guided by experience-based practice, and limited quantitative information is available to predict the effect of aeration on bulk temperature and moisture content, or the time required for these effects to become observable. Full-scale modelling and controlled validation are additionally constrained by the size of the silo, continuous plant operation, and limited instrumentation. This study, therefore, develops and validates a small-scale modelling and experimental framework to quantify aeration outcomes and support more consistent operational decision-making.

A transient three-dimensional CFD model of an aerated maize bulk has been developed, modelling the packed bed as a porous medium with coupled heat and moisture transfer. In addition, a numerical calculation model has been implemented to estimate dwell temperature and moisture content for specified inlet air temperature and relative humidity conditions. A scaling approach has been formulated using the temperature-front concept, relating front propagation to air velocity, grain temperature, and bulk geometry. The CFD model has been validated against measurements from a purpose-built small-scale silo testbench. The simulation reproduced the measured temperature and front speed trends, with moderate overprediction of initial cooling; this behaviour is attributed to the literature-based drying constant correlation used in the model.

The validated model has been used to quantify temperature front speed ratios (front speed normalised by air velocity) over a range of initial grain temperatures and aeration scenarios, highlighting that cooling effectiveness is highest at aeration onset and decreases with continued operation. For initial grain temperatures ranging between 20 and 35 [°C], the temperature front speed ratios ranged between 4.86 and 15.27 [mm/s]/[m/s]. A secondary comparison has been performed using available full-scale silo data; however, due to non-ideal comparability of operating conditions and uncertainty in full-scale airflow and initial bulk state, the scaling relationship could not be definitively validated from the available dataset. Finally, practical guidelines have been proposed to support silo managers in predicting aeration outcomes and time-to-effect under defined inlet conditions.

Keywords: aeration, CFD, packed bed, scaling, temperature, moisture

DEDICATION

Firstly, I would like to dedicate this work to my Lord Jesus, without whom none of this would have been possible, for His love, grace, wisdom, and joy every single day.

To my husband, Joshua, for his love, patience, insights, and unending support.

DECLARATION

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LIST OF ABBREVIATIONS

ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
CFD	Computational fluid dynamics
DEM	Discrete element method
EMC	Equilibrium moisture content
EES	Engineering Equation Solver
FDM	Finite difference method
FEM	Finite element method
FVM	Finite volume method
GMC	Grain Management Company
GUI	Graphical user interface
RTC	Real time clock
SCADA	Supervisory Control and Data Acquisition
SEP	Standard error of prediction
UDF	User-Defined Function
UDS	User-Defined Scalar
3D	Three-dimensional

NOMENCLATURE

Symbol	Name	Units
A	Chung-Pfost isotherm constant	[°C]
B	Chung-Pfost isotherm constant	[-]
C	Chung-Pfost isotherm constant, or discharge coefficient	[°C], [-]
C_2	Inertial resistance term	[m ⁻¹]
c	Specific heat	[kJ/kg°C]
d	Diameter	[m]
D	Diameter	[m]
D_{eff}	Effective diffusion coefficient of moisture	[m ² /s]
E	Enthalpy	[J/kg]
EMC	Equilibrium moisture content	[%]
F	Coefficient or factor	[-]
g	Gravitational constant	[m ² /s]
H	Height	[m]
h	Heat (of vaporisation or sorption)	[J/kg]
i	Counter	[-]
K	Drying constant equation constant	[-]
k	Thermal conductivity	[W/m°C]
L	Length	[m]
MC	Moisture content	[kg/kg]
$\frac{\partial MC}{\partial t}$	The rate of grain moisture adsorption or desorption	[s ⁻¹]
N	Drying constant equation constant	[-]
n	Number of data points	[-]
P	Pressure	[Pa]
Re	Reynolds number	[-]
RH	Relative humidity	[%]
S_e	Energy source term	[W/m ³]
S_m	Moisture source term	[kg/m ³ s]
T	Temperature	[°C], [K]
t	Time	[s]
v	Velocity	[m/s]
x	Variable	

Greek

$1/\alpha$	Viscous resistance term	$[\text{m}^{-2}]$
β	Diameter ratio	$[-]$
ε	Porosity, or expansion factor	$[\%], [-]$
κ	Drying constant	$[\text{s}^{-1}], [\text{h}^{-1}]$
μ	Viscosity	$[\text{Pa} \cdot \text{s}]$
ρ	Density	$[\text{kg}/\text{m}^3]$
ω	Specific humidity	$[\text{kg}/\text{kg}]$

Subscripts

A	Anisotropic flow resistance, or Zone A
a	Air
atm	Atmospheric
B	Zone B
C	Celsius or zone C
D	Pipe with diameter D
d	Dry basis
est	Estimate
$flow$	Current flow time
g	Grain (maize)
h	Horizontal component
I	Inertial loss component
K	Kelvin
o	Orifice
obs	Observed
p	Particle, or constant pressure (specific heat)
s	Sorption
sim	Simulated
sat	Saturated
t	True (as opposed to bulk density)
ts	Time step
V	Viscous loss component
v	Vertical component, vapour, vaporisation, or constant volume (specific heat)
w	Wet basis

CHAPTER 1 INTRODUCTION

1.1 Background

1.1.1 Aeration in grain storage

Agriculture is a multibillion-rand industry in South Africa, with the production of field crops, including grain, contributing to 29% of the total gross value of agricultural production in South Africa in the 2022/2023 production year (Directorate: Statistics and Economic Analysis, 2023). Considering just one of the field crops, maize, an estimated amount of 15.6 million tonnes was produced in the 2022/2023 production year (Reidy, 2023), and according to U.S. Department of Agriculture (2024) maize is the most produced crop in South Africa.

The harvest period for maize in South Africa is from May to August (U.S. Department of Agriculture, 2024), depending on when in the planting season different farmers planted their crops. Thus, the surplus of maize produced should be stored to ensure that there is maize available to the market to be consumed year-round. The safe storage of maize is of high importance, as maize is reported to be one of the most consumed staple foods in South Africa (Swart, 2022). A commonly used storage solution that can preserve the maize is a concrete grain silo.

One of the major grain storage companies in South Africa, from here on referred to as Grain Management Company (GMC), makes use of a process called aeration to help ensure the safe storage of grain. Navarro et al. (2002) defines aeration as the process in which air is forced through a bulk of grain when the ambient air conditions are favourable. Furthermore, a grain bulk contained in a silo is described as an ecosystem with low levels of biological activity. Navarro and Noyes (2002) mention that the biological activity of the grain bulk can remain in a dormant condition if the moisture content of the grain is low enough to allow for safe storage. If the moisture content of the grain bulk exceeds the safe storage limit, the growth of microflora can occur, and if the temperature is too high, it creates favourable conditions for the growth of insects.

For fungi and mite, an intergranular relative humidity of less than 70%, which corresponds to approximately 13%¹ moisture content for cereal grains in general, is required to ensure their growth does not occur (Armitage and George, 1986; Navarro et al., 2002). These figures are, however, a simplification, as the intergranular relative humidity and moisture content relationships for different grains vary, and the relationship is temperature dependent. Therefore, grain-specific regulations are followed to inform safe

¹ Wet mass basis, and so throughout.

moisture contents for long-term storage. A grain and microclimate temperature range of 17 to 22 [°C] allows for safe storage in terms of insect management (Burgess and Burrell, 1964, cited in Navarro et al., 2002). Navarro et al. (2002) explains that for this temperature range, the insect life cycle takes 3 months or more to complete, and the population growth is insignificant; thus, insect damage at this temperature range is negligible.

An additional motivation for GMC to aerate their grain is due to the regulations concerning grain moisture content. For maize, the regulations on the grading of maize to be sold in South Africa stipulate that its moisture content must not exceed 14% (Department of Agriculture (South Africa), 2009). Thus, if GMC receives grain of a higher moisture content from their clients, the grain needs to be dried using a dryer and/or aerated in the silo tube to be able to be sold later. Furthermore, the price of the grain bought from farmers and then sold to mills and other parties is based on the 14% moisture content regulation. Thus, if the moisture content of the grain is less than 14%, the total mass of grain that can be sold is unnecessarily reduced.² Therefore, it is beneficial for GMC to store maize not much lower than 14%; otherwise, they indirectly lose money if aeration decreases the moisture content too far below the regulatory value.

1.1.2 Aeration time prediction

When aerating a bulk of grain, three zones are formed, which are separated by two fronts (Sutherland et al., 1971; Thorpe, 2002a), as depicted in Figure 1.1. The grain bulk is initially at a specific temperature and moisture content, referred to as zone C. After aerating for an extended period, the grain bulk reaches equilibrium with the incoming air; thus, the grain temperature is equal to the incoming air temperature, and the moisture content is equal to the equilibrium moisture content (EMC). The EMC is the moisture content of the grain when it is in equilibrium with air having a certain temperature and relative humidity. This state is known as zone A. Between zones A and C lies zone B, which is known as the dwell state. The boundary between zones C and B is defined as the temperature front, and the boundary between zones B and A is the moisture front. The temperature front propagates at a velocity approximately 1000 times slower than the incoming air velocity, and the moisture front propagates about 100 times slower than the temperature front (Thorpe, 2002a).³

² For example, if one initially has 100 [kg] of maize at 14% moisture content, if the moisture content is reduced to 10% after aeration, the total mass is reduced by 4 [kg]. Therefore, one is left with only 96 kg of maize to be sold at the same price per kilogram.

³ For example, if an aeration flow rate of 9 [m³/s] is used, the silo's diameter is 18 [m], and it is filled with 20 [m] of grain, it would take approximately 157 hours for the temperature front to move through, while the moisture front will take more than 654 days to move through.

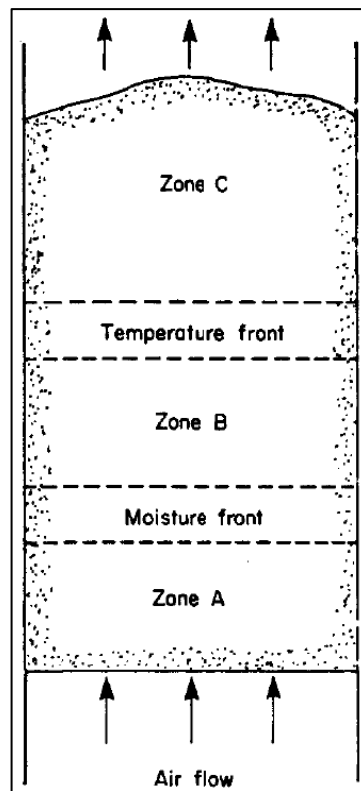


Figure 1.1: Zones and fronts formed in a grain bulk during aeration (Sutherland et al., 1983)

Since the moisture front moves slower than the temperature front, at some point during aeration, the majority of the grain bulk will be at the dwell state. Thus, it is a good aeration design principle to ensure that the dwell state conditions are favourable for grain storage (Thorpe, 2002a). On the other hand, if aeration is continued until both the temperature front and moisture front have moved through the grain bulk, the bulk will be in equilibrium with the ambient air. Thus, the ambient conditions should be favourable to ensure the outcome of aeration is favourable for grain storage. For example, when the ambient air is cooler than the temperature inside the silo, and the relative humidity inside and outside the silo is similar, aeration can be used to cool the grain. Depending on the exact values of the relative humidity, there will be a small change in moisture content. The influence of temperature and relative humidity on the EMC of the grain is further discussed in Chapter 2.2.

The speeds of the temperature and moisture fronts are dependent on the velocity of the air moving through the grain. Furthermore, it has been observed that the front speeds are also largely dependent on the grain temperature and moisture content, the air wet-bulb temperature, and the grain bulk geometry (Hunter, 1986a; Sorenson et al., 1967; Sutherland et al., 1983, 1971). Several researchers have calculated the front speeds as a function of the air velocity (Sorenson et al., 1967; Sutherland et al., 1971), this is expanded upon in Chapter 2.3.4. Thus, it is possible to predict the time it will take for the grain bulk to either reach the dwell state or equilibrium with the incoming air, depending on what the goal of aeration is. After the

desired temperature and intergranular relative humidity, or grain moisture content, are reached, the conditions in the silo can be maintained for months, due to the low thermal conductivity of grain (Navarro et al., 2002). This is why the aeration process is effective for bulk grain storage.

1.1.3 Aeration at Grain Management Company

This study focusses on one of GMC's silo tubes⁴, silo tube A1. The silo tube has a volumetric capacity of 9000 cubic meters; thus, the silo can store up to about 7000 tonnes of maize. This silo's aeration unit is equipped with a 45 [kW] fan, and the fan is specified to supply a volumetric flow rate of 9 [m³/s]. The actual flow rate that it supplies during aeration is not currently being measured. The 9 [m³/s] corresponds to a flow rate of 4.6 [m³/h/tonne]. From literature, one study reported that a minimum of 10 [m³/h/tonne] is required to achieve satisfactory aeration during the warmest years in the U.K. (Armitage et al., 1991, cited in Navarro et al., 2002:6). Another study focussing on 11 southern states in the U.S. recommended an air flow rate of 6 [m³/h/tonne] (Arthur et al., 1998). Thus, the flow rate used by GMC is slightly low, yet still comparable to the flow rates described in literature.

Silo tube A1 is equipped with a temperature measurement string, in the centre of the silo, and relative humidity and temperature sensors, one at the aeration fan inlet and one at the top of the silo, which continuously log data on the Supervisory Control and Data Acquisition (SCADA) system. The temperature measurements are used by GMC as the primary tool to monitor the condition of the grain being stored. Furthermore, the grain moisture content is measured upon arrival at the silos, and after it is removed from the silos to be sold. The grain is sometimes also moved from one silo tube to another, and during this process, moisture content measurements are also taken.

At GMC, aeration is currently done according to the guidelines provided by the grain quality department. These guidelines stipulate how aeration should be done:

- a) After a silo tube is filled, aeration is done for 72 hours whenever the ambient conditions are favourable.^{5,6}

⁴ In industry, a silo tube refers to a singular cylindrical silo unit, whereas silo is usually used to refer to the silo plant. For this study, both silo and silo tube will be used to refer to a singular cylindrical silo unit.

⁵ This is not necessarily a continuous process, as the ambient conditions are not always favourable. Furthermore, aeration is also turned off during the day if the power demand from other silo plant operations is too high, and during the peak electricity tariff window.

⁶ Aeration case a) is specifically used since they have found that this time period is sufficient to ensure all pockets are worked out. These pockets refer to pockets of grain that form due to the air channelling, as is observed in a gas-solid fluidisation system (Kunii and Levenspiel, 1991).

- b) After the initial 72 hours, aeration is done whenever the ambient conditions are favourable, as deemed necessary.
- c) When the moisture content of maize is close to 14%, aeration is managed manually, under the guidance of the grain quality department.

For cases a) and b), the aeration system is set to automatic, thus the fans will automatically start to aerate when the ambient conditions are favourable. These favourable ambient conditions refer to the temperature, relative humidity, and EMC⁷ of the air at the fan inlet, and the values are specified by the grain quality department at GMC.⁸ Even though the grain quality department provides silo managers with these guidelines for aeration management, the execution of the aeration guidelines is largely dependent on the silo managers' own interpretation and experience.

The physical outcomes GMC has for aeration are, firstly, to cool the grain. The grain can arrive at the silo with temperatures as high as 35 [°C], specifically in the summer. Secondly, aeration is used to obtain a uniform temperature in the grain bulk, since the silo tube will consist of layers of grain with different temperatures and moisture contents.⁹ The silo managers have observed that when the temperature delta between layers is too large, condensation can occur, which can lead to accelerated spoilage.

Even though the aeration guidelines inform when aeration should be done, the guidelines provide no information on what the outcome of the aeration will be or how long it will take to achieve the outcome. The only outcome of aeration that the silo managers expect to see during aeration is the temperature change on the temperature measurement strings as the incoming air moves from the bottom to the top.

1.1.4 Method of investigation

Aerating a grain bulk causes the temperature and moisture content to change with time, thus leading to a three-dimensional (3D) distribution of temperature and moisture content. By visualising this 3D distribution, it is possible to better understand the flow of air through the grain in a silo, as well as identify areas where air flow is insufficient. Insufficient air flow includes any areas in the silo that have less air flow than other areas, or areas that have no air flow, i.e., dead zones. Insufficient air flow is mainly due to the

⁷ The EMC is calculated from the temperature and relative humidity measurements.

⁸ Typical values are 25°C, 65% relative humidity, and 17% EMC. Aeration will thus start when the temperature, relative humidity, and EMC are below these values.

⁹ Each silo tube is filled with grain from many different farmers; thus, each batch forms a new layer in the silo tube, which has its own temperature and moisture content. A silo tube is only filled with one type of grain at a time.

design of the silo and aeration channels. A 3D visualisation can also be used to determine how fast the fronts move through the grain bulk.

A 3D distribution of aeration requires the calculation of variables, including temperature, moisture content, and pressure drops, for multiple points within the silo for the entire time period of aeration. Thus, calculating these values analytically is not feasible. A numerical method, computational fluid dynamics (CFD), is used to solve for various flow field values at discrete points in space and time (Gerhart et al., 2021). Thus, the transient 3D distribution of temperature and humidity due to aeration can be obtained using CFD. This simulation model can be used to determine the aeration time needed to reach a desired end state, such as favourable dwell conditions, as well as investigate the air flow patterns in the silo. The results can give GMC valuable information on what the outcome of aeration is for certain initial conditions, to possibly inform better aeration practices.

Such a simulation needs to be validated using experimental data. Even though GMC's silos already log several measurements, it is not ideal for the experimental model. Firstly, the physical size of the silo would require a very computationally expensive simulation model, making it impractical to solve. Secondly, since normal silo plant operations cannot be halted, the experimental conditions would be out of the researcher's control. Lastly, the lack of flow rate sensors currently installed in the silo means crucial flow rate measurements cannot be obtained without expensive and possibly damaging additions of the required sensors to the silo.

Thus, a much smaller, scaled experimental model can instead be used for validation, complete with all the necessary sensors. The simulation model must then be set up to correspond to the small-scale silo, and the small-scale silo can be built to be geometrically similar to the full-scale silo. This, however, means that the simulation results might not be directly applicable to GMC's full-scale silos. Thus, to validate whether the results can be scaled to the full-scale silo, the data that GMC has available can be used for this secondary validation step. The applicability of the small-scale results for use in the full-scale silo is promising due to the use of similar geometry and the front speed ratios which produce normalised results and not explicit small-scale specific results.

Due to validation performed on a geometrically similar scaled silo, the study includes an explicit similarity analysis to justify how results are transferred to the full-scale silo. The scaling approach identifies which parameters must be accounted for.

1.1.5 Conclusion

Aeration is used to obtain favourable conditions in a grain bulk, to ensure grain can be stored safely for extended periods of time. The two main objectives for using aeration can be summarised as follows: firstly,

to cool the grain, and secondly, to partially dry the grain. Cooling is seen as the primary purpose of aeration because:

- GMC primarily monitors the grain temperature during storage to ensure the grain is both cool and uniform.
- A large reduction in moisture content is not desirable, since a loss in mass leads to a reduction in selling price.
- The temperature front moves much faster through the grain bulk than the moisture front.

1.2 Problem statement

GMC's aeration guidelines are largely experience-based and lack data-backed information on the effect of aeration on the grain bulk. In particular, the guidelines do not specify what effect certain ambient conditions will have on the temperature and moisture content of the grain bulk, or how long it will take to observe the effect of aeration. A full-scale investigation on the effects of aeration is impractical due to the silo's size and ongoing plant operations. As a result, this study must rely on a small-scale silo for the investigation however the validity of scaling small-scale results to the full-scale silo is not currently established.

1.3 Research aim

The aim is to develop a transient CFD simulation that gives a 3D distribution of the temperature and moisture content within a silo due to the grain being aerated, to make use of this simulation to determine what temperature effect certain aeration scenarios have on the grain bulk, including determination of dwell conditions, and to determine how long it takes to see these effects, by means of the temperature front speed ratios. Furthermore, the aim is to establish the validity of scaling the results from a small-scale model to the full-scale silo, to the end of allowing for better informed aeration practices.

1.4 Research objectives

The primary research objectives are as follows:

- Set up a transient CFD model for the aeration of maize in a silo, to simulate the aeration process.
- Design and build a small-scale silo testbench.
- Develop a method that can be used to easily calculate the dwell conditions.
- Develop a scaling methodology.
- Validate the simulation model.
- Determine the relationship between the temperature front speeds and the air velocity, for different grain temperatures and air conditions.
- Perform the full-scale silo scaling validation.

- Develop a guide on how the silo managers can make use of the results obtained in this study to evaluate what effect certain aeration initial conditions will have on the grain bulk.
- Determine if any air flow dead zones exist where no cooling occurs in the silo.

1.5 Research scope & constraints

1.5.1 Scope

The scope of this study is as follows:

- Only the aeration of the grain maize is investigated.
- Simulations are only performed for a homogeneous grain bulk. Foreign matter that is present in the grain at the silos, and the effect it has on flow and heat transfer, is not considered.
- The temperature increase due to the aeration fan is not investigated. Thus, when referring to inlet, it means the inlet into the silo, downstream of the fan, unless otherwise specified.
- The interaction of multiple temperature fronts with each other is not considered in this study.
- Only cooling temperature front speeds are investigated.

1.5.2 Constraints

The constraints of this study are as follows:

- Simulating a full-scale silo is not feasible in terms of the computer resources needed, and the corresponding experimental validation data is very limited. Therefore, a scale model approach is used for simulation and experimentation, and the normalised results are compared to that of the full-scale silo.
- The amount and nature of measurements taken during experimentation are limited by the data logging equipment available.
- Experimental conditions are dependent on the grain available and the environmental conditions at the time of experimentation.

1.6 Research methodology

The research methodology that is followed in this study is as follows:

1. Research is done about relevant topics.
2. A transient CFD simulation model is set up to simulate the aeration of grain in a silo. The model is set up based on the small-scale silo.

3. A numerical calculation model is developed to calculate the grain bulk dwell conditions from the initial bulk state and aeration inlet conditions.
4. A small-scale silo testbench is designed and built, including the necessary sensors.
5. The simulation model is verified by doing a mesh independence study and analysing whether the time step used in the problem is adequate (Gerhart et al., 2021).
6. A scaling validation methodology is developed.
7. Experimentation is done on the small-scale silo testbench.
8. With the verified model, the simulation is solved for the experimental conditions.
9. The simulation model is then validated using the experimental data obtained.
10. After the simulation model is validated, various scenarios are simulated.
11. Temperature fronts speed ratios are determined from the simulation scenario results.
12. Full-scale silo data is obtained and is compared to the simulation results using the scaling methodology developed.

1.7 Chapter outline

The dissertation chapter outline is discussed below.

- **Chapter 2: Literature review**

The literature review investigates various sources that focus on the topics of grain aeration, previous research and experimental work done, heat transfer of grain, and other relevant topics.

- **Chapter 3: Theoretical implementation**

Important theoretical aspects used when developing the CFD simulation are reviewed in this chapter. The most important theory from Ansys Fluent and additional theory used in developing the User-Defined Function (UDF) are discussed.

- **Chapter 4: Simulation setup and verification**

In this chapter, the aeration simulation model is set up, and the model verification is done. The simulation model is set up to correspond to the experimental testbench, which is discussed in Chapter 5.

- **Chapter 5: Experimental validation**

In this chapter, details regarding the experimental testbench are discussed. The experimental method that is used to obtain validation data is discussed. Additionally, the scaling validation methodology is given.

- **Chapter 6: Results**

In this chapter, the experimental validation is done. Thereafter, the processed results of several scenario simulations are presented. Lastly, secondary validation for the full-scale silo is done.

- **Chapter 7: Conclusion and recommendations**

In this chapter, the research conclusions are discussed, specifically whether the research problem is answered, and whether the aim and objectives are met. Recommendations for further research are also made from the outcome of the study results.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This literature review examines several topics related to aeration theory, aeration modelling, and aeration research. Firstly, the concept of the equilibrium moisture content is discussed. Thereafter, the zones and fronts formed during aeration, as well as the dwell conditions, are investigated. The concept of evaporative cooling during aeration is then discussed. Several studies that focussed on modelling the fronts formed during aeration are examined. In these studies, the fronts were modelled using either experimental or analytical theoretical methods. Based on the research on front speeds, an approach to estimate the aeration time required is discussed.

Numerical methods have also been widely used to model aeration. Aeration research done by several different researchers using different numerical methods is first summarised. Thereafter, two specific approaches that make use of 3D CFD simulations are discussed. These two approaches using CFD that have been used to model the aeration of grain include a combined DEM (discrete element method) and CFD approach, and a porous model approach. These two approaches, and studies that focussed on each approach, are discussed.

The different approaches concerning modelling equilibrium in a grain bulk undergoing aeration are reviewed. Lastly, since scaling is of interest, studies that researched scaling porous models are investigated.

2.2 Equilibrium moisture content

The equilibrium moisture content is a term widely used in grain management and aeration, since it is used to relate air conditions to grain moisture content. The EMC is defined as the grain moisture content for which the water vapour pressure of the grain and air is equal, thus the air cannot absorb any more moisture (Thorpe, 2002a). In other words, the EMC is the theoretical moisture content of the grain when the air and grain are in equilibrium. The EMC of the grain for a certain air temperature and relative humidity can be calculated using an isostere equation, also known as a sorption isotherm. The modified Chung-Pfost isotherm equation (2.1) can be used to calculate the relative humidity as a function of temperature and moisture content:

$$RH = e^{\left(\frac{-A}{T_c + C}\right) e^{-B \cdot MC_d}} \quad (2.1)$$

where RH is the relative humidity, T_c is the temperature in [°C], MC_d is the moisture content of the grain (dry basis), and A , B , and C are grain-specific constants. For maize, the constants A , B , and C have the following values (Pfost et al., 1976, cited in Thorpe, 2002:137):

$$A = 312.31 [^{\circ}\text{C}]$$

$$B = 16.958 [-]$$

$$C = 30.205 [^{\circ}\text{C}]$$

2.3 Aeration zones and fronts

Aeration is the forced movement of air through a grain bulk when ambient conditions are favourable, to the end of improving grain storage conditions (Navarro et al., 2002). As discussed in Chapter 1.1.2, when a grain bulk is aerated, three zones are formed, which are separated by two fronts (Sutherland et al., 1971; Thorpe, 2002a):

- Zone A: The grain is in equilibrium with the incoming air.
- Zone B: The dwell state.
- Zone C: The initial grain conditions.
- Temperature front: A front characterised by a significant change in temperature that separates zones B and C. A slight change in moisture content is accompanied by the change in temperature.
- Moisture front: A front characterised by a significant change in moisture content that separates zones A and B. A slight change in temperature is accompanied by the change in moisture content.

In the following section, the dwell state conditions are discussed. Thereafter, the influence of the inlet air conditions on the outcome of aeration is discussed. Finally, the two fronts are discussed, including characteristics of the fronts, as well as the determination of their speeds.

2.3.1 Estimating the dwell state conditions

The dwell state conditions can be predicted using the following design steps (Hunter, 1988; Thorpe, 2002a):

1. Assume the moisture content in zone B is equal to that of zone C.
2. The first approximation of zone B's temperature is calculated as the dry-bulb temperature for a wet-bulb temperature equal to that of zone A and a relative humidity equal to the equilibrium relative humidity for the moisture content in zone C at the estimated dry-bulb temperature. This estimation can be done using a Psychrometric chart or by means of an iterative calculation.
3. The moisture content of zone B is estimated using the rule for cereal grains that states for every 28 $[^{\circ}\text{C}]$ of cooling, the moisture content decreases by 1%. For this temperature delta, the temperature difference between zone C's temperature and the temperature calculated in step 2 is used.
4. Recalculate zone B's temperature using the same process as in step 2, but using the moisture content calculated in step 3.

With all three grain zones now defined, the concept of evaporative cooling during grain aeration is discussed next.

2.3.2 Evaporative cooling

The inlet air conditions greatly influence the outcome of aeration. When aerating a grain bulk, it is possible to obtain a zone B grain bulk temperature that is less than the inlet air temperature, even when the initial grain bulk temperature is equal to or higher than the inlet air temperature. This is due to the concept of adiabatic cooling, which is more commonly known as evaporative cooling in aeration management. Sorenson et al. (1967) observed this phenomenon in an experiment where they cooled a grain bulk initially at 90 [°F] with inlet air held at a constant temperature of 85 [°F], and the relative humidity of the air less than that of the grain. Figure 2.1 shows how, after 40 hours of aeration, the grain bulk was cooled to approximately 80 [°F] with the 85 [°F] air. Thus, the process of evaporative cooling can be used to cool grain even when the ambient conditions are not in favour of cooling.

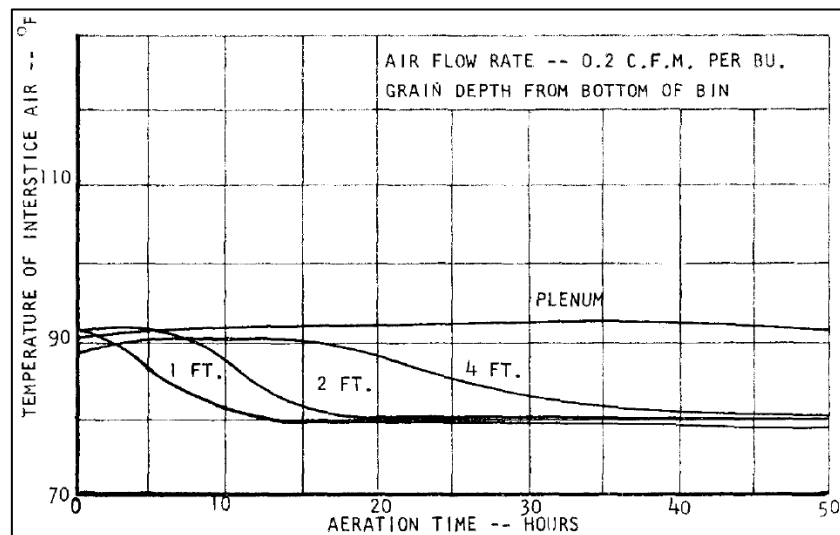


Figure 2.1: Cooling a grain bulk to a temperature lower than the inlet air and initial grain temperature (Sorenson et al., 1967)

In the next section, more information on the fronts and how they move through the grain bulk is reviewed.

2.3.3 Propagation of fronts

During aeration, two fronts are formed: the faster-moving temperature front and the slower-moving moisture front. The temperature and moisture fronts move through the bulk of grain in the same direction as the air flow (Navarro et al., 2002; Sutherland et al., 1971). The fastest-moving wave of the front is known as the leading edge, and the slowest-moving wave is the trailing edge.

Depending on the air inlet and initial grain conditions, the temperature front can either be a heating or cooling front, and the moisture front can either be a drying or wetting front. A cooling temperature front is when the air temperature is lower than the grain temperature, and the opposite is true for a heating temperature front. For the scenario in which the air temperature is higher than the grain temperature, but evaporative cooling occurs, the front is still a heating front, since the final grain temperature, after reaching equilibrium with the incoming air, will be higher than the initial grain temperature. Regarding the propagation of the fronts through the grain bulk, several researchers (Sorenson et al., 1967; Sutherland et al., 1983, 1971) have observed that cooling and wetting fronts widen, while heating and drying fronts remain square. When the leading edge of the front moves faster than the trailing edge, the front widens (Sutherland et al., 1983). Sutherland et al. (1971) predicted using their equilibrium characteristic theory model that for a heating and drying front, the leading edge moves slower than the trailing edge, which is not possible, and thus concluded that the front formed is a zero-width or square front. Figure 2.2 below illustrates the difference in how widening and square fronts propagate through a bulk of grain past equally spaced temperature sensors. The square heating front can be seen at the top of Figure 2.2, it is evident that the rate of temperature change remains constant. In contrast, the slope of the widening cooling front at the bottom of Figure 2.2 decreases as the front propagates through the grain.

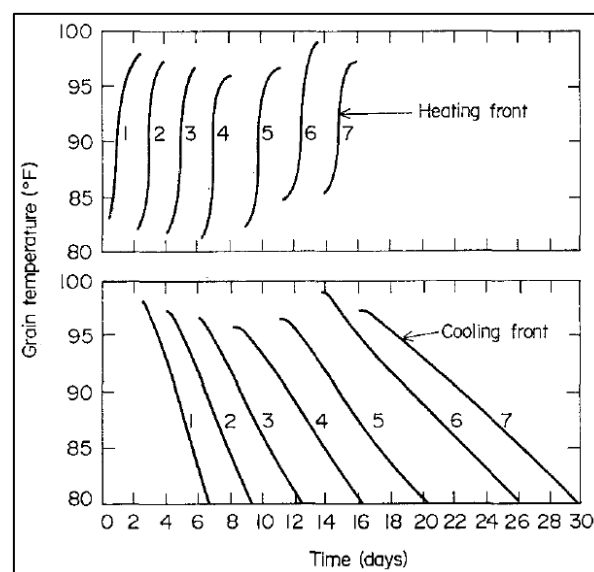


Figure 2.2: Temperature change due to square heating (top) and widening cooling (bottom) fronts propagating through a bulk of grain (Sutherland et al., 1971)

Figure 2.3 below depicts the theoretical temperature distributions through beds of grain due to a widening front (left) and a square front (right) from the work of Sutherland et al. (1971). For the widening front, there is a gradual change in temperature through the bulk of grain between the initially warmer grain in zone C and the cooled grain in zone B. The square front, on the other hand, changes quite abruptly from the initial cool grain in zone C to the warmer grain in zone B.

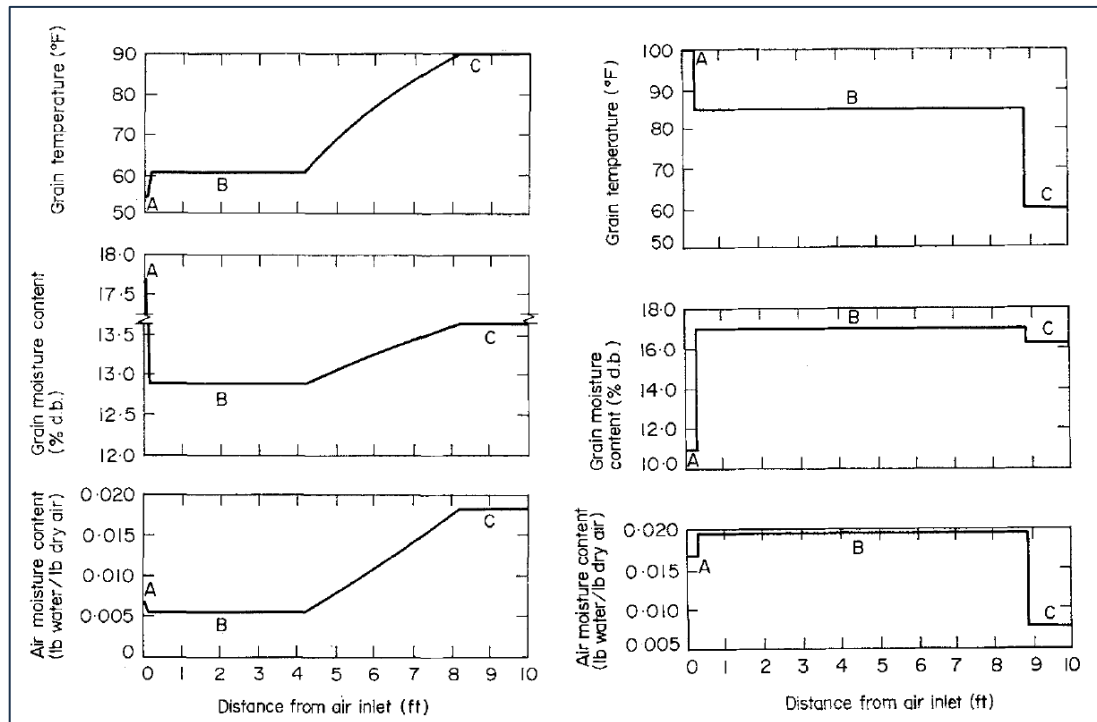


Figure 2.3: Temperature distributions in beds of grain due to a widening front (left) and a square front (right) (Sutherland et al., 1971)

Research done to estimate the speeds of the temperature and moisture fronts is investigated in the following section.

2.3.4 Speeds of fronts

The speeds at which the temperature and moisture fronts propagate through a bulk of grain have been studied by several researchers. In this section, previous research on front speeds is examined, and the factors that influence the front speeds are considered.

Sorenson et al. (1967) experimentally determined cooling temperature front times to the aim of developing design methods for conditioned-air grain storage bins. They experimentally determined the time it takes for the leading and trailing edges of a cooling temperature front to move through their experimental grain bin for several different air flow rates, using sorghum grain. The data was used to fit two exponential functions that give the time it takes for the leading and trailing edges to exit the grain bulk as a function of flow rate. The equation for the leading edge is valid for all air and grain conditions. However, the equation for the trailing edge is only valid for the case where the air EMC is equal to the initial moisture content of the grain, and the air temperature is maintained at a constant dry-bulb temperature equal to the desired final grain temperature; thus, it is not applicable for evaporative cooling.

From Sorenson et al. (1967) experimental results, the trailing edge takes in the order of 10 times longer than the leading edge to exit the grain bulk. Furthermore, as the air flow rate increased from 0.05 to 5 [cfm/bushel]¹⁰ the time it takes for the trailing edge of the cooling front to exit the grain bin decreased from approximately 200 to 10 hours.

Regarding the factors influencing the front speeds, Sorenson et al. (1967) mention that the time it takes to cool a grain bulk is dependent on the air flow rate, as can be seen from their experimental results. Furthermore, the air and grain conditions also influence the cooling time, due to evaporative cooling; however, this was not investigated.

Sutherland et al. (1971) developed an analytical model to predict zone B conditions, front velocities, and front profiles for a wheat grain bulk. Regarding the front profiles, Sutherland et al. (1971) obtained theoretical results for a cooling front for which Sutherland et al. (1970, cited in Sutherland et al., 1971:380-383) obtained experimental results, pictured in Figure 2.4 below. Sutherland et al. (1971) observed that the shapes of the experimental and theoretical fronts were similar, but the experimental front was somewhat wider. Sutherland et al. (1971) concluded that the difference between the experimental and theoretical fronts was probably due to the effects of finite heat and moisture transfer coefficients, since in their analytical model, they assumed infinite heat and mass transfer coefficients.

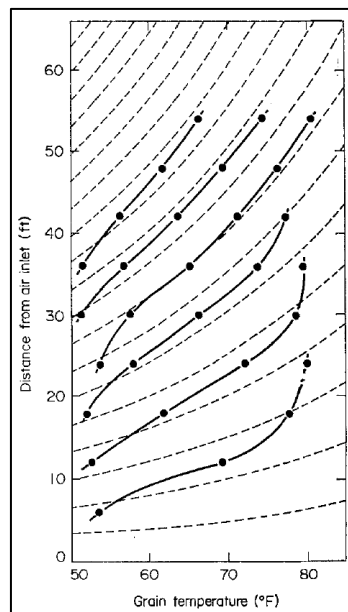


Figure 2.4: Theoretical (dashed lines) and experimental (solid lines) cooling front shape comparison
(Sutherland et al., 1971)

¹⁰ The metric equivalent of 1 [cfm/bushel] is approximately 66.9 [m³/h/tonne] for sorghum.

Regarding the front velocities, Sutherland et al. (1971) compared the theoretical leading and trailing edge times to the experimental results of Sorenson et al. (1967). The theoretical values were 51 and 116 hours, for the leading and trailing edges, respectively, and the experimental values were 40 and 140 hours, which shows reasonable agreement. Sutherland et al. (1971) attributed the difference, firstly, to the assumption of infinite transfer coefficients in their model. Secondly, the analytical model indicates that the front times are directly proportional to a decrease in flow rate, whereas Sorenson et al. (1967) found the decreases to be to the power of 0.94 and 0.65 of the flow rate. Thirdly, Sorenson et al. (1967) did not account for the effect that the grain and air conditions have on the speeds of the fronts.

Sutherland et al. (1983) made use of the theoretical model of Sutherland et al. (1971) to calculate the cooling and wetting (widening) front velocities for a range of conditions. Figure 2.5 depicts the speed of the temperature (cooling) front for different moisture contents (left) and the speed of the moisture (wetting) front for different temperatures (right) normalised by the air face velocity. The air face velocity is the average air velocity in the direction of bulk air movement. These are referred to as the front speed ratios. From these results, Sutherland et al. (1983) concluded that the moisture content of the grain has little influence on the speed of the temperature front, while it significantly influences the speed of the moisture front. For both the temperature and moisture fronts, the grain temperature significantly influences the front speeds. Regarding the square front velocities, Sutherland et al. (1983) explains that an approximate speed can be calculated from the average of the speeds of the leading and trailing edges of the corresponding widening front; however, the error of the result increases when the difference between the conditions before and after the front increases.

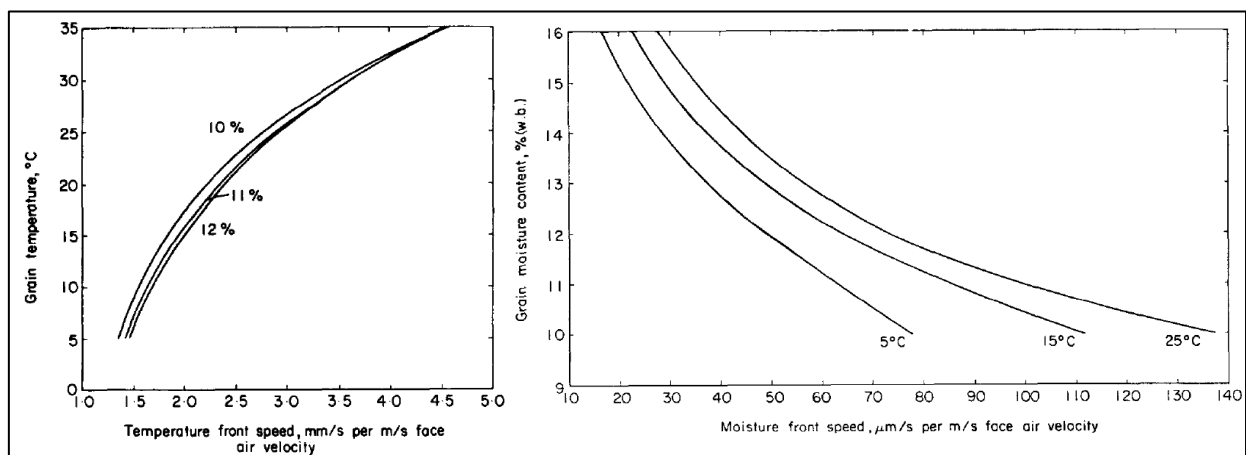


Figure 2.5: Temperature front speed ratio (left) and moisture front speed ratio (right) for different grain moisture contents (Sutherland et al., 1983)

The analytical model of Sutherland et al. (1971) was set up for the simple scenario of air moving uniformly through a cylindrical grain bulk. However, the geometry and air inlet position have an influence on the front speeds, as is demonstrated by Hunter (1986a). Hunter (1986a) derived formulas to calculate the

traverse times for several inlet air duct and bulk geometries. Traverse time refers to the time it takes for a gas to move through a grain bulk to a certain position, and the time it takes for temperature or moisture fronts to move through a grain bulk is directly proportional to the traverse time. Traverse time formulas were obtained for a rectangular bulk with a central duct for both upwards and downwards flow (two-dimensional), a cylindrical bulk with a conical base with the air duct at the cone apex (three-dimensional), radial flow in both two and three dimensions, and crossflow in a cylindrical bulk.

Hunter (1986a) used the experimental results of Hohner and Brooker (1964), which was obtained using wheat grain, to validate their theoretical results for the scenario of a cylindrical bulk with crossflow. Visual comparison of the results, Figure 2.6, showed that there is good agreement between the theoretical and experimental results. Hunter (1986a) explains that the differences in results are likely due to some inaccuracy in the experimental equipment, and the square law term in Ergun's equation used in the theoretical prediction, which can cause the front lines near the boundary to lag.

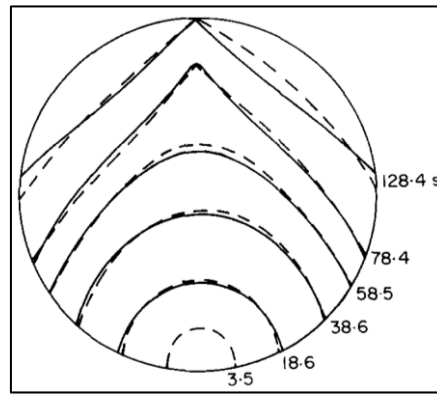


Figure 2.6: Theoretical (solid line) and experimental (dashed line) comparison of traverse times of a cylindrical bulk with crossflow (Hunter, 1986a)

To illustrate the impact different ducts and geometries have on the time it takes for a gas to traverse through a grain bulk, Hunter (1986a) compared the traverse time for two scenarios. Firstly, for a 10 [m] by 25 [m] rectangular bulk, 5 [m] deep, with a central duct and upwards flow of $0.0125 \text{ [m}^3/\text{s]}$, the traverse time to reach a point on the upper surface, 10 [cm] from the wall, is calculated to be 31 hours. For the same flow rate and same total mass of wheat, for a 10 [m] diameter cylindrical bulk with a conical base, with the height above the cone apex 19.25 [m], and the air duct at the cone apex, the traverse time is calculated to be 14 hours. Thus, it is evident that the air duct and bulk geometry significantly influence the traverse time, consequently also the front speeds.

2.4 Predicting the required aeration time

Thorpe (2002a) used the temperature and moisture front speed ratio figures of Sutherland et al. (1983) (Figure 2.5) to explain how the time it takes a temperature or moisture front to traverse through a bulk of grain can be calculated. The time it takes for the front to traverse through the grain bulk is simply equal to the height of the grain bulk divided by the front speed, and the front speed is calculated using the ratio from the figure and the air face velocity. Thorpe (2002a) states that when calculating the speed of the leading edge of the temperature front, the grain temperature is used to obtain the correct ratio from the figure, and for the trailing edge, the dwell temperature is used. For the moisture front, to obtain the ratio for the leading edge, the dwell moisture content is used, and for the trailing edge, the EMC is used.¹¹

This methodology can be used to predict the actual aeration time required to obtain a certain outcome using the theoretical front speeds.

2.5 Numerical methods for aeration modelling

Four types of numerical methods have been used to model the heat and mass transfer that occur in a grain bulk while being aerated, i.e., finite difference method (FDM), finite element method (FEM), finite volume method (FVM), and discrete element method (DEM) (Panigrahi et al., 2020b). FDM, FEM, and FVM are three discretisation techniques that can be used to obtain a numerical solution of the governing differential equations in a CFD simulation (Gerhart et al., 2021). CFD is used to simulate fluid flow problems, while DEM is used to simulate particle movement and interactions.

Several researchers have modelled the aeration of grain using numerical methods. Table 2.1 below summarizes the work done in 6 studies. The purpose of Table 2.1 is to summarize key assumptions and provide context of the typical validation accuracies common in the literature. Firstly, the numerical method employed is specified. Only studies that made a 3D model are included; thus, all the studies are FVM, since FDM and FEM are generally not used for 3D models. Secondly, the focus of the study, airflow, heat and/or moisture transfer, is given. Thirdly, key assumptions are stated. Lastly, the validation results are briefly summarised.

¹¹ Thorpe (2002a) did not discuss the ratio for the trailing edge of the moisture front; however, this follows from the previous three ratios.

Table 2.1: Summary of numerical methods used to model aeration

Method	Focus	Assumptions	Validations results	Source
FVM	Airflow	- Grain shrinkage due to drying was neglected. - Steady state momentum transfer. - Linear porosity variation from the centre to the wall.	Air velocities error % for a peaked grain mass: - Constant porosity: 2.9-87.5% (centre) and 0.0-123.4% (periphery) - Variable porosity: 2.9-50.0% (centre) and 129.4-196.4% (periphery)	Lawrence and Maier (2011)
FVM	Heat and moisture transfer	- The aeration air reached the equilibrium relative humidity in the grain bulk. - Constant temperatures on the boundary (wall) surfaces. - Constant grain properties during aeration.	Temperature error % ranged from 2.9% to 6.3% (0.3 [°C] and 0.7 [°C]).	Liu et al. (2016)
FVM	Airflow	- Uniform spatial arrangement of grain in an element. - Constant airflow from the fan. - Steady state flow. - The porosity varies radially from the core to the periphery. - Uniform porosity with depth. - The grain eave has a constant angle of repose of 21°.	The standard error of prediction for static pressure at four different positions ranged from 1 [Pa] to 93 [Pa].	Panigrahi et al. (2020a)
FVM and DEM	Heat transfer and airflow	The contact force between the particles changes nonlinearly with the amount of contact overlap.	The average errors for the pressure drop were less than 10%. The maximum error at the surface for the temperature was less than 4 [°C].	Liu et al. (2023a)
FVM and DEM	Heat transfer and airflow	Air is an incompressible fluid.	The average error of the pressure drop for the laboratory scale model was: 8% for the FVM and DEM model 21% for the homogenous porous model (FVM) 10% for the anisotropic porous model (FVM) The relative error % for the pilot scale model and anisotropic porous simulation ranged from 6.3% to 13.8% for the static pressure, and	Liu et al. (2023b)

Method	Focus	Assumptions	Validations results	Source
			the temperature error was less than 1 [°C].	
FVM	Heat and moisture transfer, and airflow	• The grain and inter-granular air in each element are in local thermal equilibrium. • Negligible grain shrinkage or expansion during aeration. • No-slip wall condition. • Incompressible flow	The maximum temperature error was less than 2 [°C] and the moisture content error was less than 1%.	Panigrahi et al. (2023)

A few of the studies in Table 2.1 are now examined in detail. This is done by focussing on two specific aeration modelling approaches that were used by the studies in Table 2.1. Firstly, the approach of modelling aeration using CFD and DEM is examined. Thereafter, modelling aeration using a porous model CFD simulation is looked at.

2.5.1 Combined DEM and CFD aeration approach

Combined DEM and CFD models have been widely used in grain storage and preservation modelling. Many of these studies focussed on fluidised bed drying, rather than fixed bed aeration, since DEM is more commonly used to model the movement and interaction of particles (Zhu et al., 2008). These models are then typically called a coupled CFD-DEM model, since the models are solved semi-consecutively and share information while solving (Ansys Inc., 2025a). CFD and DEM can also be used separately; thus, using DEM to obtain the complex packed pore structure of a grain bulk and then using CFD to solve for the flow and heat transfer that occur while air is forced through the porous structure during aeration.

Liu et al. (2023a) investigated the flow and heat transfer of non-spherical grains, including maize, during aeration using a DEM and CFD model and an experimental testbench. For the experimental testbench, they made use of a small test chamber of 100 [mm] in diameter and filled with 60 [mm] of grain, with the air inlet at the bottom of the test chamber. For the simulation model, the grain particles were created using multiple spheres to approximate the non-spherical grain shapes, and DEM was then used to create randomly packed beds of grain, for each of the three grain types. For the CFD simulation, only a quarter of the packed bed was used to reduce computational cost. The flow and heat transfer were solved using the CFD software Ansys Fluent 2020 R2.

Liu et al. (2023a) solved their simulation model for the experimental conditions. The moisture content of the grains at the start of the experiments ranged from 12.8% to 13.3%, and the grain temperature was 19.5 [°C]. A centrifugal heating fan was used to obtain an inlet air of 55 [°C], and the velocity ranged between 0.05 and 0.8 [m/s].

The results Liu et al. (2023a) focussed on was the distributions of the pressure, velocity, and temperature for the three different grain types. Regarding the pressure distribution, the simulation results were in good agreement with the experimental results, with the average errors less than 10%. For the velocity range, the pressure drops across the fixed beds ranged from 1.24 [Pa] to 164.27 [Pa], with the pressure drops of the soybean being the lowest of the three grains. Liu et al. (2023a) explains that this is because of the increased sphericity and smoother texture of the soybeans, compared to the other grain types. For the temperature results, Liu et al. (2023a) compared the surface temperatures obtained with the simulation model with those of the experiments, for 45 minutes of aeration, refer to Figure 2.7 below, and the results were in good agreement. After 45 minutes, all three grain types have reached the incoming air temperature. Liu et al. (2023a) observed that the maize reached the incoming air temperature first and attributed it to the larger porosity of the maize fixed bed.

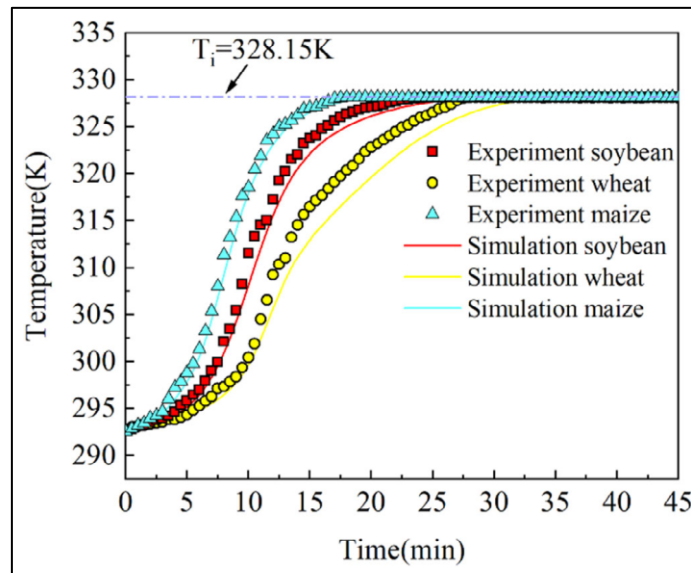


Figure 2.7: Experimental and simulation results comparison of surface temperatures for three grain types for 45 minutes of aeration (Liu et al., 2023a)

Even though Liu et al. (2023a) measured the moisture content of the grain at the start of the experiment, they did not consider the humidity of the air or how the grain's moisture content was influenced due to the aeration.

2.5.2 Porous model aeration approach

The aeration in a silo can be modelled using CFD by modelling the grain bulk as a porous medium. Several researchers have found that the air flow resistances of a grain bulk are anisotropic. Panigrahi et al. (2020a) reported the findings from several researchers that the horizontal resistance as a proportion of the vertical resistance ranged between 30% and 70% for six different grain types. Thus, research has been done to more accurately model the anisotropic nature of a grain bulk using the porous model approach. Furthermore,

work has also been done to be able to accurately model the moisture transfer between the porous grain bulk and the interstitial air, since commercial CFD software packages do not readily account for this (Thorpe, 2008).

Liu et al. (2023b) investigated the flow and heat transfer in a grain aeration system using an anisotropic porous CFD simulation model. In this study, Liu et al. (2023b) built on their previous work (Liu et al., 2023a), with the aim of obtaining a porous CFD aeration model that accurately models the flow and heat transfer, and which can be used in large-scale storage systems, since their previous approach is computationally too expensive for large applications. Liu et al. (2023b) developed two porous models. In the first, the porosity is constant throughout the bulk, and this model is called the homogeneous continuum model (HCM). In the second, the porosity varies radially, and this model is called the anisotropic continuum model (ACM). These two models are compared to the CFD-DEM model (called the particle-resolved CFD model (PRCFD)) and to experimental results.

Liu et al. (2023b) first compared the pressure drop for the three models to the experimental results for an inlet velocity ranging from 0.05 to 0.8 [m/s], refer to Figure 2.8. As can be seen in Figure 2.8, the HCM underestimated the pressure drop, more significantly so at the higher velocities, while the ACM slightly overestimated the pressure drop, specifically at the middle to higher velocities. The PRCFD was closest to the experimental results over the range of velocities. The average errors of the HCM, ACM, and PRCFD models were 21%, 10%, and 8%, respectively. Liu et al. (2023b) explains that the PRCFD was the most accurate due to it taking into account several factors, such as the particle shape, wall effects, internal friction, and the sudden expansion and contraction of the flow channel during fluid flow. The ACM proved to be more accurate than the HCM, due to the inclusion of the porosity variation in the ACM.

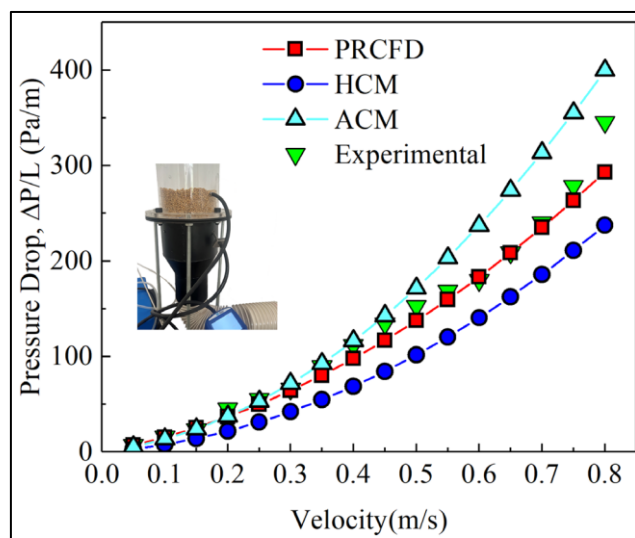


Figure 2.8: Experimental and simulation (PRCFD, HCM, and ACM) pressure drop comparison

(Liu et al., 2023b)

In terms of computational time, Liu et al. (2023b) reported that the PRCFD, HCM, and ACM solved the simulation in 1752, 12, and 23 hours, respectively. The computational volume used for these simulations was a quarter cylinder of 100 [mm] in diameter and 100 [mm] high and filled with 50 [mm] of grain.

Liu et al. (2023b) also performed experiments and ACM simulations for a pilot-scale grain bin of 1.5 [m] in diameter and 3 [m] in height with a cone top and filled with 2.4 [m] of grain. Experimental and simulation static pressure values were obtained for an aeration flow rate of 10 [m³/h/tonne]. The relative error between the experimental and simulation results ranged from 6.3% to 13.8% between the 9 measurement points. Liu et al. (2023b) explains that the discrepancy may be due to the interference of the aeration duct's opening and welding processes, which they did not account for in the ACM.

Liu et al. (2023b) did not obtain any experimental temperature results, even though they did compare temperature distributions of the three simulation models. Furthermore, Liu et al. (2023b) did not take air or grain moisture into account in their study.

Panigrahi et al. (2020a) modelled the aeration of an on-farm silo containing barley using the porous model approach in Ansys Fluent 2019 R1, and specifically focussed on implementing the physical velocity formulation, as opposed to the superficial velocity formulation, to obtain more realistic velocities. In Ansys Fluent, the superficial velocity formulation does not account for porosity when calculating the convection and diffusion terms of the transport equations, as opposed to the physical velocity formulation, which does account for porosity (Ansys Inc., 2025b). In addition to using the physical velocity formulation, Panigrahi et al. (2020a) also implemented multiplication factors used in the conservation of momentum equation to more accurately calculate the pressure drops and implemented variable porosity in the radial direction.

Panigrahi et al. (2020a) accounted for the varying pressure drops in the horizontal and vertical directions by multiplying the viscous and inertial resistance terms, present in the conservation of momentum equation, with an additional factor. The multiplication factors for the vertical viscous and inertial resistances were first obtained using a trial-and-error method, which also involved experimental measurements, based upon the factors proposed by Lawrence and Maier (2011) for maize. The horizontal and vertical resistance factors are related by a percentage proportion. Panigrahi et al. (2020a) thus varied the resistance proportion between 40% and 95%, and comparing the simulation results obtained from this to experimental static pressure measurements, they found the proportion that resulted in the least error for their scenario.

Panigrahi et al. (2023) expanded on the work of Panigrahi et al. (2020a) and implemented heat and moisture transfer for the on-farm silo. To model the moisture transfer between the grain and intergranular air, Panigrahi et al. (2023) created a custom transport equation in Ansys Fluent, which is done using the User-Defined Scalar (UDS) function, and the moisture source term was based on the formulation of Thorpe (2008). A User-Defined Function (UDF) is then used to calculate the moisture source term and to send the value to Fluent's solver to solve all the transport equations. To model the effect that the moisture transfer

has on the heat transfer between the intergranular air and the grain, a transient energy source term, also based on the formulation of Thorpe (2008), was also implemented into the UDF.

Panigrahi et al. (2023) optimised the time step size and solution discretisation schemes of the simulation model in terms of accuracy and computation time. The optimised solution method was used to solve for the on-farm silo experimental conditions. The experiment entailed aerating a silo that is 12.8 [m] in diameter and 10.06 [m] in height, filled with 970 tonnes of barley, for 24 hours at ambient conditions. The silo had a V-shaped aeration inlet on the flat bottom surface of the silo. The silo was equipped with four measurement cables, three of which measured temperature, and the last measured both temperature and relative humidity, and made use of proprietary EMC curves to calculate the grain moisture content. Figure 2.9 below shows the experimental results obtained for the 24-hour aeration experiment, compared to the simulation results. From Figure 2.9 below, it is evident that the simulation model accurately predicted the grain temperature and moisture content values and trends, with the greatest temperature difference being less than 2 [°C] and the moisture content less than 1%.

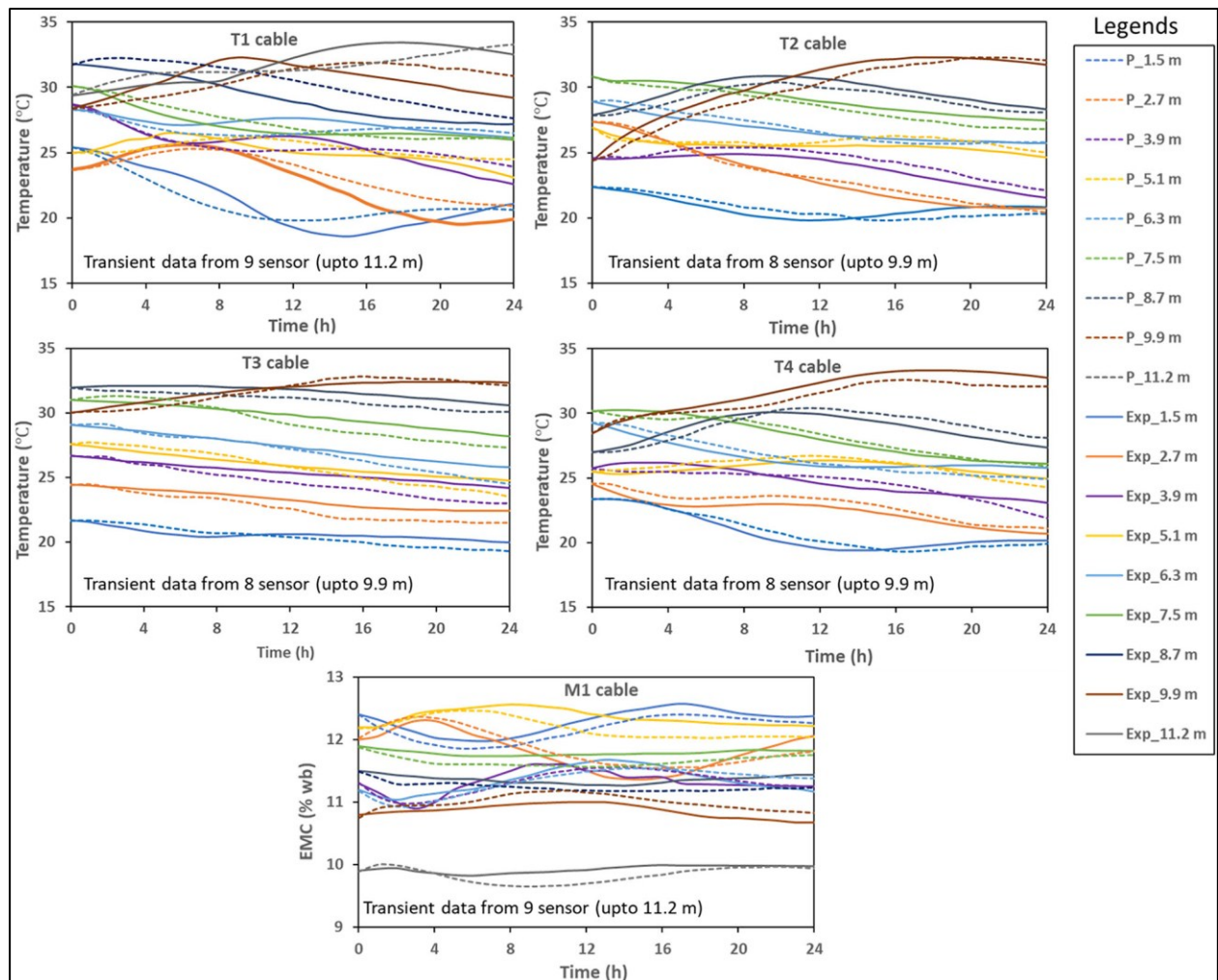


Figure 2.9: Experimental and simulation temperature and EMC results comparison for 24 hours of aeration (Panigrahi et al., 2023)

2.6 Grain heat and moisture transfer models

The aeration of grain can be modelled using either an equilibrium or a non-equilibrium model. In equilibrium models, it is assumed that the grain and intergranular aeration air are in thermal and moisture equilibrium during a discrete period throughout the grain bulk (Panigrahi et al., 2020b; Sutherland et al., 1971). The study done by Sutherland et al. (1971) is an example of an equilibrium aeration model. Regarding non-equilibrium models, there are a few different key assumptions that are used by several researchers for different models. Different non-equilibrium models assume that the grain and intergranular air are in thermal equilibrium (Panigrahi et al., 2023), that the partial pressure difference of the water vapour drives the moisture transfer in the grain bulk (Kanujoso et al., 1995), or the model is based on partial differential equations of the conservation of mass, momentum, and heat transfer for a porous medium (Kanujoso et al., 1995). Additionally, non-equilibrium models more accurately model the transfer of moisture by incorporating thin-layer wetting and drying equations (Panigrahi et al., 2020b).

2.7 Scaling of porous models

Small-scale models have been widely used to study the behaviour of real-world problems, where modelling the real-world problem would be impractical due to practical and financial constraints.

Kumar et al. (2024) developed scaling laws to study the fluid flow and heat transfer of cuboid and cylindrical packed beds filled with monosized particles. First, dimensionless similarity parameters were derived for the cuboid packed bed and thereafter modified to the cylindrical geometry. For the flow through the packed bed, the superficial velocity formulation was used. Geometrically, the scaling laws were defined such that if the packed bed's length is divided in half, the particle's diameter should also be halved. The derived scaling laws showed consistent results for pressure drop and temperature for different heat generation and mass flow rates for a cuboid packed bed. The scaling laws were further shown to be applicable for cylindrical packed beds as well.

2.8 Conclusion

In this literature review, the concept of equilibrium moisture content has been reviewed, and an equation to relate it to air temperature and relative humidity has been given. Thereafter, the fronts and zones formed when aerating a grain bulk have been discussed. A method that can be used to estimate the dwell conditions of a grain bulk has been provided. Subsequently, the concept of evaporative cooling, and how it can be used to obtain a cooler dwell temperature than the aeration air temperature, has been discussed.

The propagation of fronts, cooling and heating, and drying and wetting, has been discussed in depth. Thereafter, the work done by several researchers to characterise the speeds of fronts has been discussed. Furthermore, the factors on which the front speeds are dependent have been identified, which include the

air velocity, bulk geometry, and the grain temperature and moisture content. Following the front speed research, a method to predict the aeration time required has been described.

Numerical methods used to model the aeration of a grain bulk have been investigated. The work done by several researchers has been reviewed. The porous model approach has been used by several researchers, with specific focus on implementing accurate anisotropic flow through the porous region, and heat and moisture transfer between the grain and intergranular air. The results obtained from these studies have demonstrated promising results.

Regarding modelling equilibrium in an aerated grain bulk, several methods of modelling non-equilibrium have been used by researchers, since these methods more accurately predict the moisture transfer.

The scaling of porous simulation models has been investigated. Kumar et al. (2024) developed scaling laws for both a cuboid and cylindrical porous region experiencing fluid flow and heat transfer. However, for the scaling laws, both the bulk and particle were scaled. Thus, the results do not apply to a scenario where the particles are not scaled down along with the bulk.

From the literature it is evident that aeration propagation, time predictions, and modelling has been investigated widely. However, for the majority of the studies the grain store had a uniform aeration inlet at the bottom. Hunter (1986a) did investigate the traverse times for grain bulks with several different inlet air configurations, however none of these resemble silo A1 that is being investigated in this study. Thus, the unique inlet air configuration of silo tube A1, the propagation of the aeration air through the silo as a result of the inlet position, and the resulting front speeds are identified as gaps in the literature.

In the following chapter, the theory used to develop a simulation model to simulate the aeration of grain is given, and the implementation is discussed.

CHAPTER 3 THEORETICAL IMPLEMENTATION

3.1 Introduction

In this chapter, all the theory used to ultimately solve the problem stated in the Introduction is reviewed.

Firstly, all the theory used to develop the transient CFD simulation model, which is used to model aeration in the small-scale silo, is reviewed. The CFD software package Ansys Fluent 2025 R1 is used for the simulation model.

Secondly, a numerical model is created to predict the dwell state for certain initial grain and inlet air conditions. The numerical equation-solving program Engineering Equation Solver (EES) is used to create this model.

Thirdly, equations used for experimental results processing are given. Lastly, any additional equations that are required are provided.

3.2 CFD simulation model

This section describes the development of the transient CFD aeration simulation model, with heat and moisture transfer and anisotropic flow through the porous structure. From Section 2.5 in the Literature review FVM was predominantly used to model aeration. In these studies, the grain bulk was modelled using a porous medium, and extensive research was done to accurately model the air flow, and heat and moisture transfer through the porous bulk. Additionally, using FVM, as opposed to using DEM and FVM, has the advantage of being less computationally expensive, while providing results of similar accuracy.

The work done by Thorpe (2008), Panigrahi et al. (2020a), and Panigrahi et al. (2023) is used to help develop the transient CFD aeration simulation model. First, the model geometry is presented and discussed. Next, all the key assumptions used in developing the model are explained. Thereafter, the governing conservation equations used in Ansys Fluent are discussed, as well as how they are adapted to accurately model the heat and moisture transfer, and anisotropic flow due to aeration. The air and maize property equations are given. Lastly, the implementation of the model is described.

3.2.1 Model geometry

The small-scale model that is used for the simulation and experimentation is based on the full-scale silo A1 of GMC.¹² The geometry of the full-scale silo, in comparison with the small-scale silo that is manufactured for experimentation, is discussed in this section, focussing specifically on factors that are relevant to the simulation. More details on the small-scale silo model are given in Section 5.2.2.

Silo tube A1 is 18 [m] in diameter and 43 [m] in height. The silo has a tapered floor, and there is a single air inlet in the wall of the silo near the highest point of the tapered floor. To aid in distributing the incoming air around the silo, there is an aeration duct over the inlet that stretches around the circumference of the silo. The tapered floor has square-shaped holes in the floor that are used when draining the grain from the silo.

For the experimental small-scale silo model, a 1000-litre Slimline JoJo tank is used for the body of the silo. This tank is chosen, since its dimensions of 0.84 [m] in diameter and 2.06 [m] in height, results in a 2.45 height-to-diameter ratio, in comparison to the silo tube A1 that has a ratio of 2.39. Due to manufacturing limitations, the floor of the small-scale silo model is made without the square-shaped holes, and consists of two surfaces angled at 17° , the same as silo tube A1's floor. Additionally, the top surface of the aeration duct is manufactured to be flat, whereas for silo tube A1, it is at an angle. A CAD model picturing the floor and aeration duct of the small-scale silo model is given in Figure 3.1.

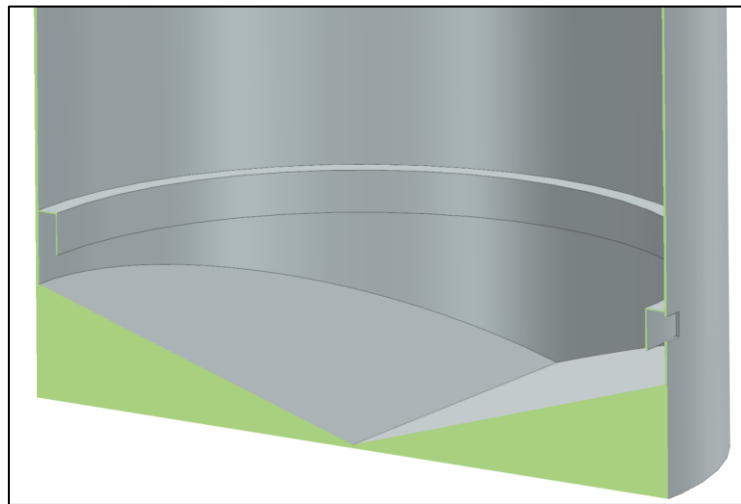


Figure 3.1: Small-scale silo model floor and aeration duct

¹² Even though this study focusses on one specific silo bin, the geometry of the rest of GMC's silos are reasonably similar.

For the CFD simulation, only the volume of interest that experiences flow is simulated. Thus, only the grain bulk volume and air duct volume are included in the simulation. Furthermore, the top surface of the grain bulk is assumed to have an angle of repose of 23° (Wilcke and Wyatt, 2002). The mean height of the grain bulk, from the bottom point, is assumed to be 1 [m]. Additionally, it is assumed that the grain does not flow into the aeration duct but rather fills up the area so that the grain surface is horizontal and touches the bottom edge of the aeration duct.

3.2.2 Model assumptions

The following assumptions are used in the development of the model:

- The grain bulk porosity is constant throughout. From the results of Lawrence and Maier (2011) it is evident that including variable porosity in the simulation does not necessarily increase the accuracy of the velocity results. Therefore, the simpler of the two approaches are used.
- The grain density is constant (Azmir et al., 2018).
- The flow is transient.
- The air flow is incompressible (Panigrahi et al., 2023, 2020a).
- The physical velocity formulation is used (Panigrahi et al., 2023, 2020a).
- The grain and intergranular air are in local thermal equilibrium (Panigrahi et al., 2023; Thorpe, 2008)
- The air has enough capacity to absorb the moisture from the grain; that is, it will not become saturated. From Equation (2.1), for a temperature range of 0 to 40 [°C], the highest equilibrium relative humidity for 14% moisture content maize is 75%, thus for the target moisture content the air will not become saturated.
- The flow of the air in the cavity above the grain bulk in the silo has no significant influence on the flow in the rest of the silo, and thus it does not form part of the simulation model. The pressure drop of the air in the open cavity is negligible compared to the pressure drop through the porous bulk.
- The top surface of the grain bulk has a constant angle of repose of 23° (Wilcke and Wyatt, 2002).

3.2.3 Conservation of mass

The conservation of mass equation used by Ansys Fluent for a porous medium and the physical velocity formulation is given in Equation (3.1) below:

$$\frac{\partial(\epsilon\rho_a)}{\partial t} + \nabla \cdot (\epsilon\rho_a\vec{v}) = 0 \quad (3.1)$$

where $\frac{\partial(\varepsilon\rho_a)}{\partial t}$ is the time rate of change of mass over the control volume, and $\nabla \cdot (\varepsilon\rho_a \vec{v})$ is the net rate of mass flow through the control surface (Ansys Inc., 2025c; Gerhart et al., 2021). The porosity, ε , is included in the equation since the physical velocity formulation is used to model the flow through the porous media.

3.2.4 Conservation of momentum

The conservation of momentum equation used by Ansys Fluent for a porous medium and the physical velocity formulation is given in Equation (3.2) below:

$$\frac{\partial(\varepsilon\rho_a \vec{v})}{\partial t} + \nabla \cdot (\varepsilon\rho_a \vec{v} \vec{v}) = -\varepsilon \nabla P + \nabla \cdot (\varepsilon \mu \nabla \vec{v}) - \left(\frac{\mu}{\alpha_i} \vec{v} + \frac{C_{2,i} \rho_a}{2} |\vec{v}| \vec{v} \right) \quad (3.2)$$

where $\frac{\partial(\varepsilon\rho_a \vec{v})}{\partial t}$ is the time rate of change of linear momentum of the contents of the control volume, $\nabla \cdot (\varepsilon\rho_a \vec{v} \vec{v})$ is the net rate of flow of linear momentum through the control surface, $\varepsilon \nabla P$ is the pressure gradient in the porous element, $\nabla \cdot (\varepsilon \mu \nabla \vec{v})$ is the diffusive momentum transfer due to the viscous effect, and $-\left(\frac{\mu}{\alpha_i} \vec{v} + \frac{C_{2,i} \rho_a}{2} |\vec{v}| \vec{v} \right)$ is the momentum source term (Ansys Inc., 2025b, 2025c; Gerhart et al., 2021; Panigrahi et al., 2020a). In the momentum source term, $\frac{1}{\alpha}$ is the viscous resistance term in $[\text{m}^{-2}]$, and C_2 is the inertial resistance term in $[\text{m}^{-1}]$, and $i = h, v$ for the horizontal and vertical components, respectively. The viscous and inertial resistance terms are entered in the Ansys Fluent graphical user interface (GUI). The viscous and inertial resistance terms can be calculated using Ergun's equation (Ergun, 1952) for flow through a packed bed, Equation (3.3):

$$\frac{|\Delta P|}{L} = \frac{150\mu(1-\varepsilon)^2}{d_p^2 \varepsilon^3} v + \frac{1.75\rho(1-\varepsilon)}{d_p \varepsilon^3} v^2 \quad (3.3)$$

where d_p is the geometric mean diameter of the grain particles. Thus, the viscous resistance component can be calculated using Equation (3.4):

$$\frac{1}{\alpha_i} = F_{V,i} \frac{150(1-\varepsilon)^2}{d_p^2 \varepsilon^3} \quad (3.4)$$

and the inertial resistance component can be calculated using Equation (3.5):

$$C_{2,i} = F_{I,i} \frac{3.5(1-\varepsilon)}{d_p \varepsilon^3} \quad (3.5)$$

where F_V and F_I are the viscous and inertial loss coefficients (Panigrahi et al., 2020a). These coefficients are used to adjust the pressure drops, since Lawrence and Maier (2011) found that Ergun's equation

overestimated the air velocity. Lawrence and Maier (2011) determined suitable loss coefficients for maize: $F_V = 3.0$ and $F_I = 1.7$. Furthermore, to model the anisotropic flow of air through the grain, Panigrahi et al. (2020a) incorporated an anisotropic air flow resistance proportion. Thus, the horizontal and vertical resistances are related by a factor F_A , Equation (3.6):

$$F_A = \begin{cases} \frac{F_{V,h}}{F_{V,v}}, & \text{for the viscous loss coefficients} \\ \frac{F_{I,h}}{F_{I,v}}, & \text{for the inertial loss coefficients} \end{cases} \quad (3.6)$$

Kay et al. (1989) determined that a factor $F_A = 58\%$ is suitable for maize.

3.2.5 Conservation of energy

The conservation of energy equation used by Ansys Fluent for a porous medium and the physical velocity formulation is given in Equation (3.7) below:

$$\frac{\partial(\varepsilon\rho_a E_a + (1-\varepsilon)\rho_g E_g)}{\partial t} + \nabla \cdot (\varepsilon\rho_a \vec{v} E_a) = \nabla \cdot (k_{eff} \nabla T) + S_e \quad (3.7)$$

where $\frac{\partial(\varepsilon\rho_a E_a + (1-\varepsilon)\rho_g E_g)}{\partial t}$ is the time rate of increase of the total stored energy of the system, $\nabla \cdot (\varepsilon\rho_a \vec{v} E_a)$ is the energy transfer due to convection, $\nabla \cdot (k_{eff} \nabla T)$ is the energy transfer due to conduction, and S_e is the energy source term (Ansys Inc., 2025b, 2025c; Gerhart et al., 2021; Panigrahi et al., 2023). The energy source term is implemented using a UDF. In Equation (3.7), ρ_g refers to the bulk density of the grain. E_a and E_g are the enthalpies of the interstitial air and grain, respectively, and are calculated using Equation (3.8):

$$E = c_p T \quad (3.8)$$

where T is the local temperature and c_p is the specific heat, constant pressure. The effective thermal conductivity, k_{eff} , of the porous medium is calculated using Equation (3.9):

$$k_{eff} = \varepsilon k_a + (1-\varepsilon)k_g \quad (3.9)$$

The energy source term, S_e , can be calculated using Equation (3.10):

$$S_e = h_s(1-\varepsilon)\rho_t \frac{\partial MC}{\partial t} \quad (3.10)$$

where h_s is the differential heat of sorption liberated or extracted during the moisture adsorption or desorption process, ρ_t is the true density of the grain, and $\frac{\partial MC}{\partial t}$ is the rate of grain moisture adsorption or desorption (Panigrahi et al., 2023). The rate of grain moisture adsorption or desorption can be calculated using Equation (3.11):

$$\frac{\partial MC}{\partial t} = -\kappa(MC - EMC) \quad (3.11)$$

where κ is the ubiquitous drying constant (Lewis, 1921; Thorpe, 2008). The moisture content variables in Equation (3.11) are fraction dry basis, and so throughout the rest of Sections 3.2.5 and 3.2.6. Page (1949) derived an equation for the thin layer drying of maize and used it to express the ubiquitous drying constant in the following form, Equation (3.12):

$$\kappa = KNt_{flow}^{N-1} \quad (3.12)$$

where K and N are grain-specific drying constants, and t_{flow} refers to the current flow time. Misra and Brooker (1978, cited in Jayas et al., 1991) determined grain drying constants K and N , which are given in Equations (3.13) and (3.14), respectively:

$$K = 0.0549 + 0.00504T \quad (3.13)$$

$$N = 0.54 + 0.0032RH \quad (3.14)$$

For the values determined from Equations (3.13) and (3.14), the time used in Equation (3.12) should be in [h], thus the unit of κ is $[h^{-1}]$.

EMC in Equation (3.11) can be calculated using the inversion of Equation (2.1):

$$EMC = -\frac{1}{B} \ln \left(\frac{-(T + C)}{A} \ln RH \right) \quad (3.15)$$

The relative humidity, RH , of the intergranular air can be calculated using Equation (3.16):

$$RH = \frac{P_v}{P_{sat}} \quad (3.16)$$

where P_v is the vapour pressure of water, and P_{sat} is the vapour pressure of water in saturated moist air. The saturation vapour pressure of water can be calculated using the following empirical correlation, Equation (3.17):

$$P_{sat} = \frac{6 \times 10^{25}}{T_K^5} e^{\left(\frac{-6800}{T_K}\right)} \quad (3.17)$$

where T_K is the temperature in [K] (Hunter, 1986b). The vapour pressure of water can be calculated using Equation (3.18):

$$P_v = \frac{\omega P_{atm}}{0.622 + \omega} \quad (3.18)$$

where ω is the specific humidity of the intergranular air, and P_{atm} is the atmospheric pressure (Thorpe, 2002b).

Back to Equation (3.10), the differential heat of sorption, h_s , is required. An equation to calculate the differential heat of sorption is derived from the Clausius-Clapeyron equation and the ideal gas law (Panigrahi et al., 2023). The heat of sorption is expressed as a ratio of the latent heat of vaporisation, h_v , as can be seen in Equation (3.19):

$$\frac{h_s}{h_v} = \left(\frac{dT}{dP_{sat}} \frac{dRH}{dT} \frac{P_{sat}}{RH} \right) + 1 \quad (3.19)$$

such that it consists of the product of the derivative of the sorption isotherm of grain (Equation (2.1)) and inverse of the derivative of the saturated vapour pressure of water (Equation (3.17)). The derivative of the sorption isotherm is:

$$\frac{dRH}{dT} = \frac{A \cdot RH}{(T_C + C)^2} e^{-B \cdot EMC} \quad (3.20)$$

Inverting the derivative of Equation (3.17) yields:

$$\frac{dT}{dP_{sat}} = \frac{\frac{T_K}{P_{sat}}}{\frac{6800}{T_K} - 5} \quad (3.21)$$

An equation for the latent heat of vaporisation is obtained by calculating the line of best fit between 0.01 and 65 [°C] from the thermodynamic table in Borgnakke and Sonntag (2017):

$$h_v = -2.3827T_c + 2501.7 \quad (3.22)$$

where h_v is in [kJ/kg].

3.2.6 Conservation of moisture (custom transport equation)

To model the moisture transfer between the grain and intergranular air, a custom transport equation is created in Fluent. This is done using the User-Defined Scalar (UDS) function in Fluent, with the specific humidity, ω , being the scalar quantity. Thus, the resulting conservation of moisture equation used by Ansys Fluent is given in Equation (3.23):

$$\frac{\partial(\varepsilon\rho_a\omega)}{\partial t} + \nabla \cdot (\varepsilon\rho_a\vec{v}\omega) = \nabla \cdot (\varepsilon\rho_a D_{eff}\nabla\omega) + S_m \quad (3.23)$$

where D_{eff} is the effective diffusion coefficient of moisture in $[m^2/s]$, and S_m is the moisture source term due to moisture absorption and desorption from the grains in $[kg/m^3s]$ (Panigrahi et al., 2023). The moisture source term is implemented using a UDF. The moisture source term can be calculated using Equation (3.24) from Thorpe (2008):

$$S_m = -(1 - \varepsilon)\rho_t \frac{\partial MC}{\partial t} \quad (3.24)$$

3.2.7 Air and grain properties

The properties of air are dependent on temperature and relative humidity. Tsilingiris (2008) derived equations for the properties of humid air as a function of temperature for a temperature range of 0 to 100 $^{\circ}C$. These property equations are valid for all relative humidities (0 to 100%), and Tsilingiris (2008) showed that the equations are in reasonable agreement with other literature and experimental data. The equations for density, specific heat, thermal conductivity, and viscosity of air are given in Equations (3.25) to (3.28), respectively, below:

$$\rho_a = 1.293394 - 0.005538444T_C + 3.860202 \times 10^{-5}T_C^2 - 5.253606 \times 10^{-7}T_C^3 \quad (3.25)$$

$$c_{p,a} = 1004.571 + 2.050637T_C - 0.1631537T_C^2 + 0.0062123T_C^3 - 8.830479 \times 10^{-5}T_C^4 + 5.071307 \times 10^{-7}T_C^5 \quad (3.26)$$

$$k_a = 0.0240074 + 7.27841 \times 10^{-5}T_C - 1.788037 \times 10^{-7}T_C^2 - 1.351704 \times 10^{-9}T_C^3 - 3.322413 \times 10^{-11}T_C^4 \quad (3.27)$$

$$\mu_a = 1.715748 \times 10^{-5} + 4.722402 \times 10^{-8}T_C - 3.663027 \times 10^{-10}T_C^2 + 1.873237 \times 10^{-12}T_C^3 - 8.050219 \times 10^{-14}T_C^4 \quad (3.28)$$

Doymaz and Pala (2003) derived coefficients from experimental data for the effective diffusion coefficient equation of maize that is represented by a simple Arrhenius type equation. The resulting equation to calculate the effective diffusion coefficient of moisture is given in Equation (3.29):

$$D_{eff} = 1.67 \times 10^{-5} e^{\left(\frac{-29.56 \times 10^3}{8.3144598 T_K}\right)} \quad (3.29)$$

To model the solid part of a porous medium, the thermal conductivity, specific heat, and density of the material is required. Verma and Prasad (2000) experimentally determined the specific heat and thermal conductivity of maize (Kisan cultivar) as a function of both temperature and moisture content. From their results, Verma and Prasad (2000) fitted regression equations for each of the properties. The correlations of the data to the regression equations are all above 96%, indicating a good fit. The specific heat of maize, $c_{p,g}$, can be calculated using Equation (3.30) (Verma and Prasad, 2000):

$$c_{p,g} = 1.3066 + 1.2045 MC_d + 0.0198 T_C \quad (3.30)$$

Furthermore, the thermal conductivity of maize, k_g , can be calculated using Equation (3.31) (Verma and Prasad, 2000):

$$k_g = 0.028 + 0.1321 MC_d + 3.4981 \times 10^{-3} T_C - 0.128 MC_d^2 - 2.24 \times 10^{-5} T_C^2 \quad (3.31)$$

The bulk density of a porous medium is related to particle density as follows:

$$\rho_g = \rho_t (1 - \varepsilon) \quad (3.32)$$

where the true density of maize is: $\rho_t = 1270 \text{ [kg/m}^3\text{]}$ (Azmir et al., 2018).

3.2.8 Grain heat and moisture transfer UDF implementation

The energy source and moisture source terms are implemented in the Fluent simulation model using a UDF. The UDF code is written in C and consists of multiple DEFINE macros provided by Ansys Fluent, which are used to implement the grain heat and moisture transfer. The UDF consists of four main sections: the initialisation macro, the adjust macro, and two source term macros. The UDF is compiled in Fluent using Visual Studio and then loaded. After loading the UDF, the functions need to be hooked to the relevant components in the Fluent GUI. This is further discussed in Section 4.3.

The four main sections of the UDF are now discussed in detail. Furthermore, additional functions used in the UDF are also discussed. The full UDF code can be found in Appendix A.1.

3.2.8.1 Initialization

The initialisation macro, `DEFINE_INIT`, is used to initialise the moisture content of the grain and calculate all other relevant initial values. In the `DEFINE_INIT` macro, the initial temperatures and moisture contents are provided using an array. The domain is then broken up into zones, that is, a zone for the air duct, where there is no grain, and a zone for the porous grain bulk. The temperatures are then assigned to the temperature flow variable, `C_T`, and the moisture content is assigned to a custom memory variable, `C_UDMI`. For the air-filled zone, the moisture content is set to 0 (Thorpe, 2008). The temperature is given in [K], since UDFs in Fluent use and return values in SI units, and for temperature Kelvin is used. Where applicable, the temperature is converted to [°C] in the UDF for the equations that use [°C]. The moisture content is given as a fraction wet basis, since in industry the moisture content is measured as a percentage wet basis. The moisture content is then converted to dry basis, since dry basis moisture content is required for the majority of the equations. The moisture content is converted from wet to dry basis using Equation (3.33) below (Thorpe, 2002a):

$$MC_d = \frac{MC_w}{1 - MC_w} \quad (3.33)$$

From the temperature and moisture content, the relative humidity of the intergranular air is calculated using Equation (2.1). Next, the saturation vapour pressure is calculated using Equation (3.17). Using the intergranular relative humidity and the saturation vapour pressure, the vapour pressure is calculated by rearranging Equation (3.16). Lastly, the specific humidity of the intergranular air is calculated using Equation (3.18). The specific humidity is stored in a custom scalar memory variable, `C_UDSI`, since specific humidity is the scalar quantity for the custom transport equation, which calculates the moisture transfer.

3.2.8.2 Adjust

The adjust macro, `DEFINE_ADJUST`, is used to calculate the new property values, specifically moisture content, for each time step, which are then used to calculate the source terms. The property values must be updated every time step, not every iteration (Thorpe, 2008). Thus, a global variable is used to track and update what the current time step of the simulation is.

At the start of the `DEFINE_ADJUST` macro, using the updated temperature and specific humidity values retrieved from Fluent, the saturation vapour pressure, vapour pressure, intergranular relative humidity, and EMC are calculated using Equations (3.17), (3.18), (3.16), and (3.15), respectively. Next, the drying constant equation constants K and N are calculated using Equations (3.13) and (3.14), respectively. The rate of grain adsorption or desorption, $\frac{\partial MC}{\partial t}$, is then calculated by substituting the drying constant κ (Equation

(3.12)) into Equation (3.11). The updated moisture content is then calculated using the following equation, Equation (3.34):

$$MC_{ts} = MC_{ts-1} + \frac{\partial MC}{\partial t} \Delta t_{ts} \quad (3.34)$$

where MC_{ts} is the moisture content calculated for the current time step, MC_{ts-1} is the moisture content of the previous time step, and Δt_{ts} is the time step size in [s]. Finally, Equations (3.20), (3.21), (3.22), and (3.19) are used to calculate the heat of sorption. The rate of grain adsorption or desorption and the heat of sorption are saved to C_UDMI's so that these parameters can be used in the source term calculations.

3.2.8.3 Energy and moisture sources

The energy and moisture source terms are calculated in two DEFINE_SOURCE macros. Using the parameters calculated in the DEFINE_ADJUST macro, the energy and moisture source terms are calculated using Equations (3.10) and (3.24), respectively.

3.2.8.4 Additional functions

Additional functions that are used in the UDF are, firstly, those used to calculate the temperature and moisture dependent properties. The macros DEFINE_PROPERTY, DEFINE_SPECIFIC_HEAT, and DEFINE_DIFFUSIVITY are used to calculate all the relevant air and grain properties. Fluent only allows temperature-dependent functions to be used in the calculation of the specific heat (Ansys Inc., 2025d); thus, a constant moisture content is used to calculate the specific heat of maize. For the diffusivity, Ansys expects diffusivity in the units [kg/m · s]; thus, it has to be multiplied with the air density.

Additionally, a DEFINE_EXECUTE_ON_LOADING macro is used to give each of the custom memory variables a name that will then display in the Fluent GUI and assist in the identification of which variable is which.

3.3 Dwell state calculation model

A numerical model to calculate the dwell state of a grain bulk is created using EES. This model is based on the dwell state conditions design steps described in Chapter 2.3.1. The implementation of the model is now discussed. The inputs required by the model are discussed, followed by an explanation of the iterative calculation process. Lastly, the outputs produced by the model are discussed. The EES dwell state calculation model code can be found in Appendix A.2.

3.3.1 Model inputs

The model inputs that need to be specified are the initial grain bulk conditions and the air input conditions. For the grain conditions, the temperature and moisture content (wet basis) are required. These are the zone C conditions. From these values, the dry basis moisture content and intergranular relative humidity are calculated using Equations (3.33) and (2.1), respectively. The intergranular specific humidity is calculated using one of EES's internal thermophysical property functions, with the temperature and intergranular relative humidity being the inputs for this calculation.

For the air input conditions, the temperature and either the relative humidity, specific humidity, or wet bulb temperature are required. The remaining two properties whose values are not given are then calculated using EES's internal thermophysical property functions. Furthermore, the EMC of the intergranular air of zone A is calculated from the temperature and relative humidity using Equation (3.15).

3.3.2 Iterative calculations

The zone B conditions are calculated using an iterative function. A function is written in EES that takes the moisture content of the grain and the wet-bulb temperature of the air as inputs. In this function, the temperature is incremented by 0.1 [°C] starting from 0 [°C]. For each temperature value, the relative humidity for the grain moisture content supplied is calculated, and then the wet-bulb temperature for the calculated relative humidity is calculated. This is repeated until the calculated wet-bulb temperature differs less than 0.1 [°C] from the incoming air wet-bulb temperature. The corresponding dry-bulb temperature is the first approximation of the zone B temperature.

Using the first approximation of zone B's temperature, the zone B moisture content is calculated using the rule for cereal grains, given by Equation (3.35) below:

$$MC_B = MC_C - \frac{T_C - T_{B,est}}{28 \cdot 100} \quad (3.35)$$

where $T_{B,est}$ is the first approximation of zone B's temperature, and the moisture contents are in wet basis. Using zone B's moisture content and the incoming air wet-bulb temperature, the zone B temperature is calculated using the same iterative function used to calculate the first approximation of zone B's temperature.

3.3.3 Model outputs

The primary results of the model are the zone B temperature and moisture content. The results are displayed on a psychrometric chart; an example is given in Figure 3.2 below.

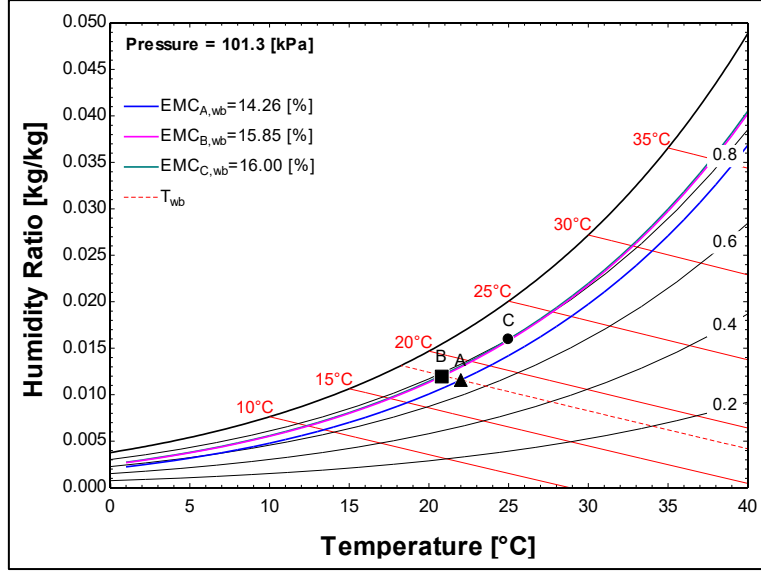


Figure 3.2: Psychrometric chart example

3.4 Experimental equations

The experimental velocity is determined from experimental differential pressure measurements measured using a monometer and an orifice plate. Refer to Section 5.2.3.3 for further elaboration on the experimental measurement equipment, and the design of the orifice plate and manometer. The equations used to calculate the velocity from the differential pressure measurement across an orifice plate are from the standards ISO 6157-1:2003(E) and ISO 5167-2:2003(E) (International Organization for Standardization, 2003a, 2003b).

The mass flow rate, $\dot{m}$, can be calculated using Equation (3.36):

$$\dot{m} = \frac{C}{\sqrt{1 - \beta^4}} \varepsilon \frac{\pi}{4} d_o^2 \sqrt{2 \Delta P \rho_1} \quad (3.36)$$

where C is the discharge coefficient, β is the diameter ratio, ε is the expansion factor, d_o is the orifice diameter, ΔP is the pressure differential across the orifice plate, and ρ_1 is the density of air upstream of the orifice plate. The diameter ratio, β , can be calculated using Equation (3.37):

$$\beta = \frac{d_o}{D} \quad (3.37)$$

where D is the diameter of the pipe. The discharge coefficient can be calculated using Equation (3.38):

$$\begin{aligned}
C = & 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521 \left(\frac{10^6 \beta}{Re_D} \right)^{0.7} \\
& + (0.0188 + 0.0063A)\beta^{3.5} \left(\frac{10^6}{Re_D} \right)^{0.3} \\
& + (0.043 + 0.080e^{-10L_1} - 0.123e^{-7L_1})(1 - 0.11A) \frac{\beta^4}{1 - \beta^4} \\
& - 0.031(M'_2 - 0.8M_2'^{1.1})\beta^{1.3} + 0.011(0.75 - \beta) \left(2.8 - \frac{D}{25.4} \right)
\end{aligned} \tag{3.38}$$

where Re_D is the Reynolds number of the flow in the pipe. The parameters A , L_1 , and M'_2 can be calculated using the following equations:

$$A = \left(\frac{19000\beta}{Re_D} \right)^{0.8} \tag{3.39}$$

$$L_1 = \frac{l_1}{D} \tag{3.40}$$

$$M'_2 = \frac{2 \left(\frac{l'_2}{D} \right)}{1 - \beta} \tag{3.41}$$

where l_1 is the distance between the upstream pressure tapping and the upstream face of the orifice plate, and l'_2 is the distance between the downstream pressure tapping from the downstream face of the orifice plate.

The Reynolds number in the pipe can be calculated using Equation (3.42):

$$Re = \frac{\rho D v}{\mu} \tag{3.42}$$

The expansion factor, ε , can be calculated using Equation (3.43):

$$\varepsilon = 1 - (0.351 + 0.256\beta^4 + 0.93\beta^8) \left[1 - \left(\frac{P_2}{P_1} \right)^{c_v/c_p} \right] \tag{3.43}$$

where P_2 is the downstream pressure, and P_1 is the upstream pressure.

The differential pressure can be calculated from the differential pressure height using Equation (3.44):

$$\Delta P = \rho g \Delta H \tag{3.44}$$

where g is the gravitational constant and ΔH is the differential pressure height measurement.

The uncertainty of the mass flow rate can be calculated using Equation (3.45):

$$\frac{\delta \dot{m}}{\dot{m}} = \sqrt{\left(\frac{\delta C}{C}\right)^2 + \left(\frac{\delta \varepsilon}{\varepsilon}\right)^2 + \left(\frac{2\beta^4}{1-\beta^4}\right)^2 \left(\frac{\delta D}{D}\right)^2 + \left(\frac{2}{1-\beta^4}\right)^2 \left(\frac{\delta d_o}{d_o}\right)^2 + \frac{1}{4} \left(\frac{\delta \Delta P}{\Delta P}\right)^2 + \frac{1}{4} \left(\frac{\delta \rho_1}{\rho_1}\right)^2} \quad (3.45)$$

The relative uncertainty of the discharge coefficient for $0.2 \leq \beta < 0.6$ and $D < 71.12$ [mm] can be calculated using Equation (3.46):

$$\frac{\delta C}{C} = \frac{1}{100} \left(0.5 + 0.9(0.75 - \beta) \left(2.8 - \frac{D}{25.4} \right) \right) \quad (3.46)$$

The relative uncertainty of the expansion factor can be calculated using Equation (3.47):

$$\frac{\delta \varepsilon}{\varepsilon} = \frac{1}{100} \left(3.5 \frac{\Delta P}{\frac{c_p}{c_v} P_1} \right) \quad (3.47)$$

3.5 Additional equations

To determine if the flow in the silo air duct and main silo volume is turbulent or laminar, the Reynolds number is required. The Reynolds number in a packed bed can be calculated using Equation (3.48) (Ergun, 1952):

$$Re = \frac{d_p \rho v_{superficial}}{\mu(1 - \varepsilon)} \quad (3.48)$$

where $v_{superficial}$ is the superficial velocity. Equation (3.49) can be used to relate the superficial velocity to the physical velocity:

$$v_{superficial} = \varepsilon v_{physical} \quad (3.49)$$

The standard error of prediction can be calculated using Equation (3.50) below (Montgomery and Runger, 2018):

$$SEP = \sqrt{\frac{\sum_{i=1}^n (x_{obs,i} - x_{sim,i})^2}{n}} \quad (3.50)$$

where x_{obs} is the measured value and x_{sim} is the predicted value, and n is the number of data points.

3.6 Conclusion

In this chapter, all the relevant theory used in developing the transient CFD simulation of aeration in a silo has been given. The model geometry and the model assumptions have been discussed. The conservation equations have been given, and the implementation of the heat and moisture transfer during aeration by means of a UDF has been elaborated on. Furthermore, the development of a dwell state calculation model in EES has been discussed.

In the following chapter, the simulation setup in Ansys Fluent is reviewed. Thereafter, verification of the simulation model is done.

CHAPTER 4 SIMULATION SETUP AND VERIFICATION

4.1 Introduction

This chapter focusses on the development, implementation, and verification of the aeration simulation model. All relevant parameters of the simulation model are provided in this chapter. Firstly, the small-scale silo model geometry and mesh details are provided. Next, the model setup and UDF implementation are discussed. Lastly, model verification is performed, which consists of a mesh independence study and time step size investigation. Additionally, the EES dwell state calculation model is verified against the simulation model.

4.2 Simulation model geometry

The small-scale silo model used in the simulation is based on the geometry and dimensions of the experimental model, and it is a 1:20 scale model of the full-scale silo tube A1. The small-scale model is symmetrical along the vertical plane through the air inlet, thus only half of the model is simulated. Furthermore, only the volumes that experience flow are simulated; this includes the grain bulk and the air duct volumes. Figure 4.1 pictures the simulated volumes, the grain volume is grey, and the air duct volume is green.



Figure 4.1: Small-scale silo simulated volumes

Figure 4.2 below pictures the small-scale silo model used in the simulation, the air inlet is highlighted in blue, the air outlet is red, and the symmetry plane is yellow.

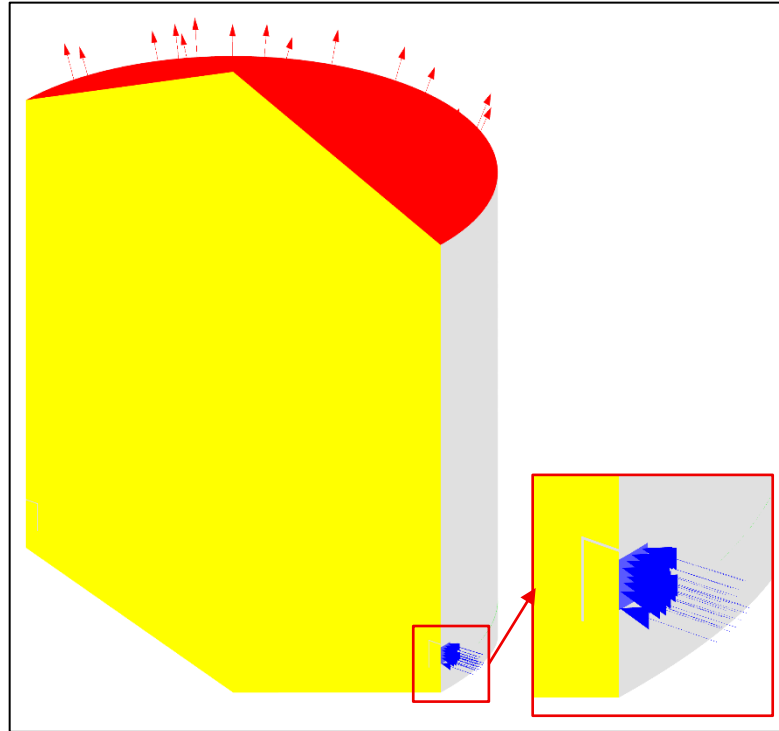


Figure 4.2: Small-scale silo simulation model

The model is meshed using Ansys Mechanical. The mesh around the air duct volume needs to be fine, firstly because of the intricate features and secondly because the most complex flow occurs near the air inlet into the duct. Thus, mesh refinements are applied to this region. To preserve mesh quality at the air inlet without causing an excessive element count, which would result in a higher computation cost, a hexahedral mesh was used for the duct volume. The final mesh is pictured in Figure 4.3 below. The front view, with a detail view of the duct, is pictured on the left of Figure 4.3, and a section view of the duct is pictured on the right.

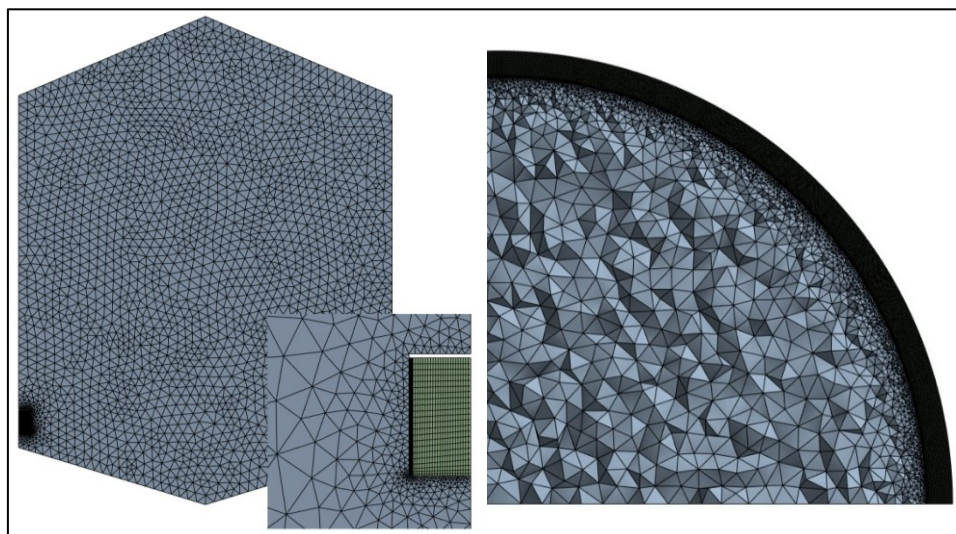
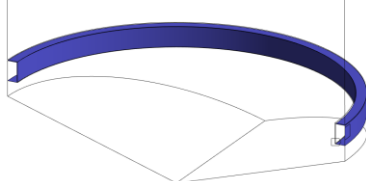
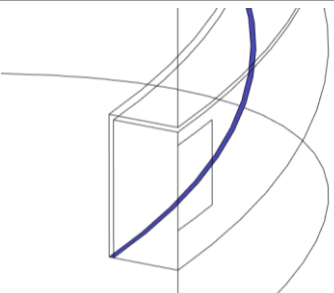
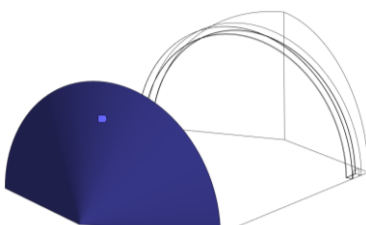
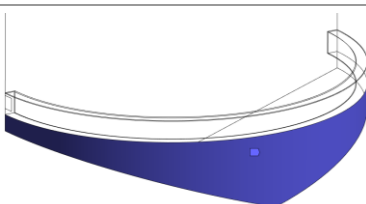
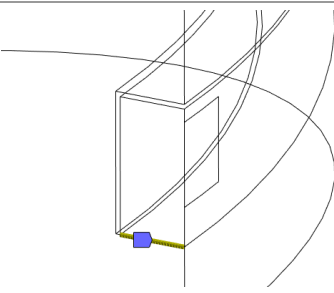


Figure 4.3: Mesh front view (left) and duct-section view (right)

The final mesh details are summarised in Table 4.1 below.

Table 4.1: Fluent model mesh details

Parameter	Details	
Mesh type	Tetrahedral and hexahedral	
Element size	0.02 [m]	
Maximum size	0.02 [m]	
Number of elements	2290648	
Orthogonal quality	0.202 (Minimum) - Good	
Skewness	0.798 (Maximum) - Good	
Face sizing	Air duct faces Element size 0.00225 [m]	
Face sizing	Duct wall gap Capture proximity: yes	
Face sizing	Grain top surface Capture curvature: off	
Face sizing	Grain lower side face Element size 0.01 [m]	
Edge sizing	Air-grain interface edge Element size 0.001 [m]	

4.3 Fluent simulation model setup

The simulation model setup details are summarised in Table 4.2. Table 4.2 describes the model setup in terms of the workflow in Fluent, including hooking the UDF, and in the order in which the actions are performed during the model setup.

To determine if the flow should be modelled as laminar or turbulent, the flow rate must first be discussed. As was mentioned in Section 1.1.3, the volume flow rate in the full-scale silo is $9 \text{ [m}^3/\text{s]}$, and for an 18 [m] diameter silo, this equates to an average superficial velocity in the silo tube of 0.0353 [m/s] . The maize particles' diameter used in the simulation is based on real maize kernels; thus, regarding the packed bed Reynolds number (Equation (3.48)), for the small-scale model and full-scale silo to have the same Reynolds number, the velocity should also be the same. Using conservation of mass, the velocity at the inlet of the small-scale silo is then calculated to be 13.4 [m/s] . However, since the inlet and air duct geometry are quite small compared to the rest of the model, and the calculated inlet velocity is quite high, the simulation time step would have to be very small, resulting in increased computation time.

Since the normalised temperature front speed ratio is independent of velocity, the precise value of the velocity is not important; thus, a smaller velocity can be used. How the velocity and aeration time component, is related between the small-scale and full-scale silos are discussed in Section 5.4.1. Thus, a velocity of 9 [m/s] is chosen for the target experimental velocity, refer to Section 5.2.3.3 for the discussion of this velocity choice. However, many more verification and scenario simulations are performed than experimental simulations; therefore, a lower velocity is chosen for these simulations to further reduce computational cost and time. Therefore, a velocity of 4.5 [m/s] , which is half the experimental velocity, is chosen, since it is low enough to allow for more reasonable commutation times, while not being so small that much longer simulation time is required to capture the movement of the temperature front. The resulting average grain bulk velocities for the chosen experimental and simulation velocities are calculated to be 0.0176 [m/s] and 0.00879 [m/s] , compared to the full-scale silo bulk velocity of 0.0353 [m/s] . For these velocities, the Reynolds numbers in the grain bulk are calculated to be 9.33, 4.67, and 25.5, respectively. Thus, for all three velocities, the flow remains laminar in the grain bulk.

The flow regime in the air duct should also be determined. The velocity can be approximated by assuming that half of the volumetric flow rate flows into the left and the other half into the right of the air duct after the inlet, thus the velocity in the air duct is 2.99 [m/s] . Some of the flow will also exit the channel below the inlet; thus, this is a conservative estimate. The Reynolds number is calculated to be 10261; thus, the flow is turbulent. In reality, there will be an area of very high velocity near the inlet in the air duct, with a velocity higher than the one calculated above.

Regarding the solution methods, Panigrahi et al. (2023) investigated various solution methods in terms of solution accuracy and computation time. The SIMPLE pressure-velocity scheme resulted in a lower computation time than the COUPLED scheme, with similar accuracy. The Least Squares Cell-Based

gradient discretisation scheme solved slightly faster than the Green Gauss Node-Based scheme, while also resulting in similar accuracy results. The second-order pressure and momentum discretisation schemes are recommended, since the first-order schemes are not suitable due to discontinuous pressure gradients imposed by the porous medium (Panigrahi et al., 2023). The second-order energy and first-order scalar spatial discretisation, and the first-order transient formulation resulted in a low simulation time and reasonable accuracy, in comparison to several other combinations.

Table 4.2: Fluent model setup parameters

Fluent workflow item	Level 1 details	Level 2...n details
Launcher	Solver options	Double precision
Setup: General	Solver	Pressure-based
	Time	Transient
	Gravity	$-9.81 \text{ [m/s}^2\text{]}$
Setup: Models	Energy	
	Viscous	SST k-omega
User-defined: Memory	18 locations	
User-defined: Scalars	1 scalar	Applied to all zones. ¹³
User-defined: Functions	Compiled	Add source code file. The library is built (compiled) using Visual Studio and then loaded.
User-defined: Function hooks	Initialisation	Initialisation macro from the UDF library.
	Adjust	Adjust macro from the UDF library.
Setup: Materials	Fluid: Air	Link user-defined properties for air from the UDF library.
	Solid: Maize (custom)	Link user-defined properties for maize from the UDF library. Maize density is constant: $762 \text{ [kg/m}^3\text{]}$. ¹⁴
Setup: Cell zone conditions	Zone: Grain	Porous formulation: Physical velocity. Edit: Enable porous zone and source terms. Porous zone: - Direction-1 vector: (0,0,1) - Direction-2 vector: (0,1,0)

¹³ Trying to apply the scalar only to the grain zone resulted in fluent crashing during initialisation due to a segmentation fault. Thus, the scalar is defined for all zones, but in the cell zone conditions, it is only applied for the grain.

¹⁴ Calculated using Equation (3.32).

Fluent workflow item	Level 1 details	Level 2...n details
		- Viscous resistance: Calculate using Equation (3.4). - Inertial resistance: Calculate using Equation (3.5). - Maize particle diameter: 6.5 [mm] - Fluid porosity: 0.4 (Lawrence and Maier, 2011) - Thermal model: Equilibrium - Solid material name: Maize Source terms: - Energy: Energy source term macro from the UDF library. - Scalar: Moisture source term macro from the UDF library.
Setup: Boundary conditions	Air inlet: Velocity inlet	Momentum: Velocity magnitude of inlet air. Thermal: Temperature of inlet air. UDS: Specific humidity (specified value) of inlet air.
	Air outlet: Pressure outlet	Thermal: Temperature of outlet air. UDS: Specific humidity (specified value) of outlet air.
	Symmetry plane: Symmetry	
	All other surfaces: Walls	Thermal: Adiabatic
Solution: Methods	Pressure-velocity coupling	Scheme: SIMPLE
	Spatial discretization	Gradient: Least Squares Cell-Based Pressure: Second-order¹⁵ Momentum: Second-order upwind Turbulent kinetic energy: Second-order upwind Specific dissipation rate: Second-order upwind Energy: Second-order upwind Scalar: First-order upwind Transient formulation: First-order implicit
Solution: Monitors	Residuals	Continuity, x-velocity, y-velocity, z-velocity, uds: 0.0001 Energy: 1e-06

¹⁵ For the pressure discretization scheme, Ansys Inc. (2025b) states that a unique scheme is used when modelling a porous medium regardless of the scheme chosen in the solution methods.

Fluent workflow item	Level 1 details	Level 2...n details
		k, omega: 0.001
Solution: Initialisation	Standard initialisation	Temperature: Initial grain temperature. Specific humidity: Initial grain specific humidity.
Solution: Run calculation	Number of times steps	Set number of time steps for desired simulation time.
	Time step size	0.5 [s]
	Max iterations per time step	200

4.4 Fluent simulation model verification

In this section, the simulation model verification is done. Before implementing the UDF in the simulation, the simulation had been calculated with the applicable parameters in Table 4.2 to verify that the results are reasonable. Thereafter, the UDF implementation is done. A mesh independence study, time step size investigation, and combined mesh size and time step investigation is now done. For these studies, the temperature and specific humidity at two points, pictured in Figure 4.4 below, after 1 hour of simulation time are monitored. For these simulations, a velocity of 4.5 [m/s] is used, with the inlet air at 20 [°C] and 60% relative humidity, and the grain initially at 30 [°C] and 14% moisture content, wet basis.

Two different computers were used for the model verification simulations, denoted computer A and B. Thus, the computation times between computer A and B are not necessarily comparable. Computer A is equipped with an Intel® Xeon® Gold 6140 CPU and 128 GB DDR 4. Computer B is equipped with an Intel® Xeon® E5-1650 v3 CPU and 32 GB DDR 3.

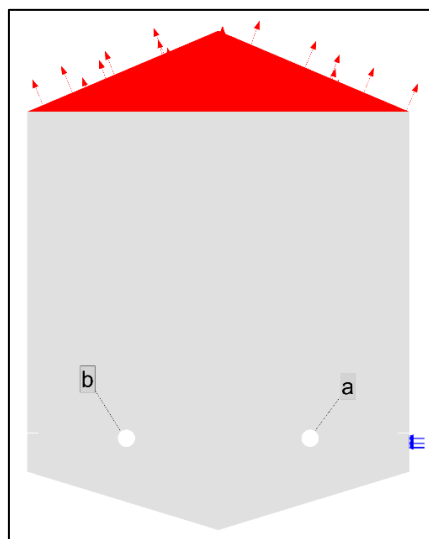


Figure 4.4: Verification monitoring points a and b

4.4.1 Mesh independence

The mesh independence study is done by varying the mesh element and maximum size and observing the effects on the computation time and results. The mesh sizes investigated are summarised in Table 4.3 below. Table 4.3 contains the element and maximum sizes used in the investigation, along with the corresponding number of elements. A constant time step of 0.1 [s] is used in the investigation.

Table 4.3: Mesh sizes investigated

Mesh # [-]	Element size [m]	Maximum size [m]	Number of elements [-]	Time step [s]
1	0.04	0.06	2071240	0.1
2	0.02	0.04	2147038	0.1
3	0.02	0.02	2290648	0.1
4	0.01	0.01	4085831	0.1

The temperature and computation time results obtained for each of the four mesh sizes investigated are visualised in Figure 4.5 below. From Figure 4.5 it is evident that the meshes with maximum sizes of 2, 4, and 6 [cm] resulted in very similar temperature results and computation times, with the mesh with a maximum size of 2 [cm] having the fastest computation time. The temperature results for the smallest mesh are also very similar to those of the other mesh sizes, but the computation time was nearly twice that of the second smallest mesh. Reducing mesh element size (and correspondingly increasing the element count) primarily affects two factors relating to computation time in a transient simulation. The first factor is the number of iterations per time step required to reach convergence, and the second factor is the computation time per iteration. If the number of elements increases the computation time per iteration increases, because there are more elements to solve. Furthermore, if the elements are too large, the number of iterations per time step increases, because it is more difficult to reach convergence. Thus, for both the 1 and 2 [cm] mesh sizes, the elements were small enough to ensure very few iterations per time step are required to reach convergence, but for the 1 [cm] mesh size the almost doubling in number of elements compared to the 2 [cm] mesh size resulted in the computation time being approximately double.

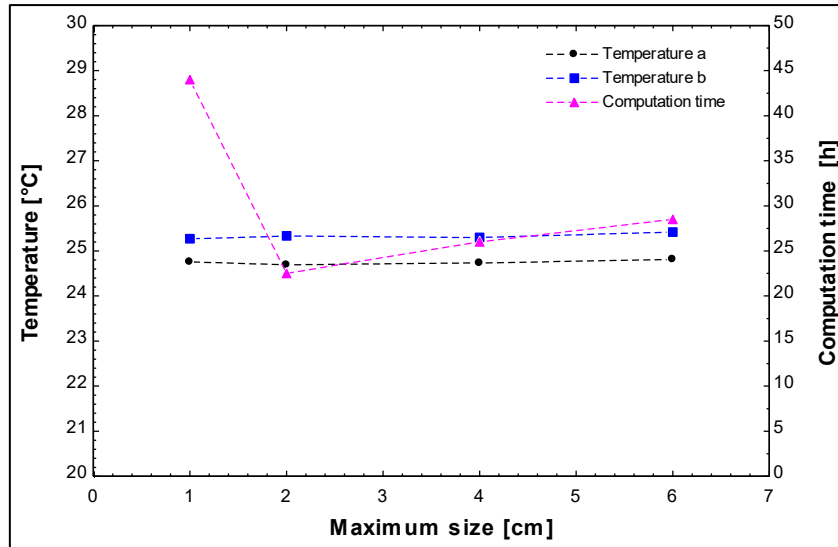


Figure 4.5: Mesh independence: Temperature and computation time vs. maximum size

The specific humidity and computation time results for each of the four mesh sizes investigated are visualised in Figure 4.6 below. From Figure 4.6 it is evident that the specific humidities for the three smallest mesh sizes are very similar, while the specific humidity for the largest mesh size is slightly higher. Thus, from Figure 4.5 and Figure 4.6, the mesh with a maximum size of 2 [cm] resulted in the fastest computation time, with the temperature and specific humidity results being very consistent with those of the smaller and larger mesh.

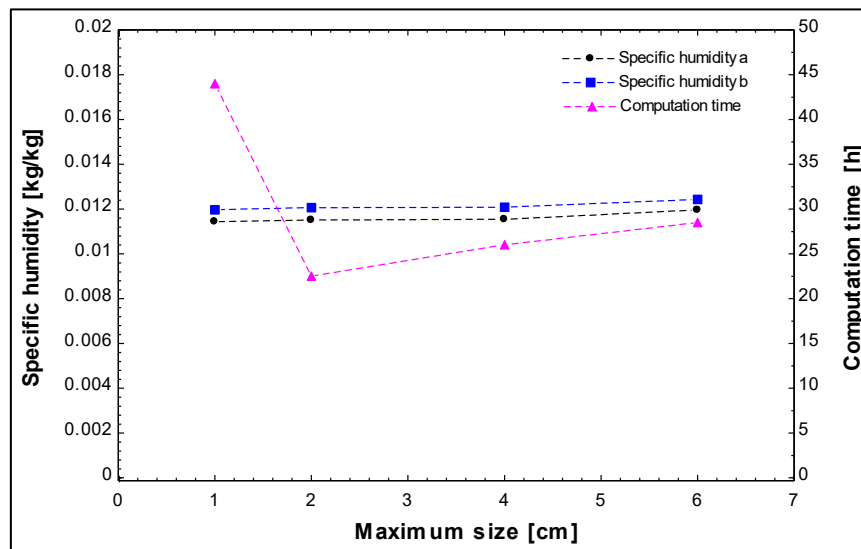


Figure 4.6: Mesh independence: Specific humidity and computation time vs. maximum size

The mesh independence study results are tabulated in Table 4.4 below.

Table 4.4: Mesh independence results after 1 hour simulation time

Mesh # [-]	Computation time (Computer A) [h]	Temperature a [°C]	Temperature b [°C]	Specific humidity a [kg/kg]	Specific humidity b [kg/kg]
1	28.5	24.81	25.42	0.01196	0.01243
2	26	24.73	25.30	0.01154	0.01208
3	22.5	24.69	25.34	0.01150	0.01206
4	44	24.75	25.27	0.01144	0.01196

4.4.2 Time step size investigation

The time step size investigation is done by varying the time step and observing the effects on the computation time and results. The time steps investigated are 0.05, 0.1, 0.25, 0.5, and 1 [s]. For these simulations, the mesh with an element size of 2 [cm] and a maximum size of 4 [cm] is used. The temperature and computation time results obtained for each of the time steps investigated are visualised in Figure 4.7 below. From Figure 4.7 it is evident that as the time step increased, the temperature values decreased slightly, and the computation time decreased as well. The smallest time step's computation time is 5 times longer than the second smallest time step, while the temperature results are very similar. The largest time step has the shortest computation time, but its temperature value differed the most from that of the smaller time steps. The second largest time step's computation time is slightly longer than that of the largest time step, and its temperature result is closer to that of the smaller time steps. Thus, the second largest time step, 0.5 [s], has a good balance between computation time and consistency of the temperature results.

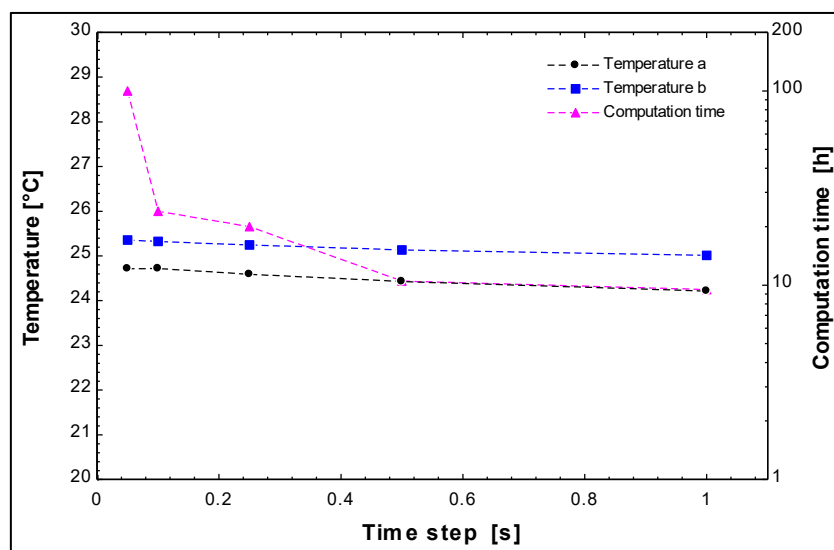


Figure 4.7: Time step size investigation: Temperature and computation time vs. time step

The specific humidity and computation time results for each of the time steps investigated are visualised in Figure 4.8 below. From Figure 4.8 it is evident that the specific humidity results are very consistent for the different time steps investigated.

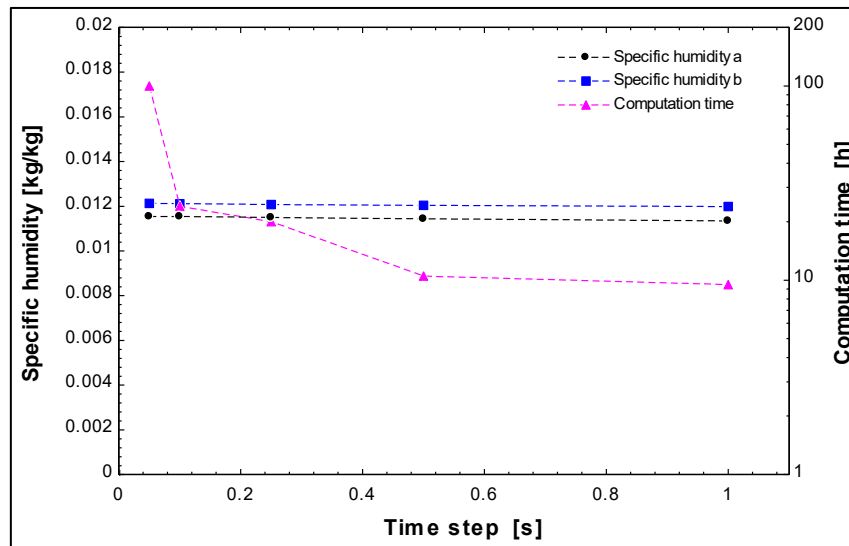


Figure 4.8: Time step size investigation: Specific humidity and computation time vs. time step

The time step size investigation results are tabulated in Table 4.5 below.

Table 4.5: Time step size investigation: Results after 1 hour simulation time

Time step size [s]	Computation time (Computer B) [h]	Temperature a [°C]	Temperature b [°C]	Specific humidity a [kg/kg]	Specific humidity b [kg/kg]
0.05	100	24.72	25.36	0.01154	0.01213
0.1	24	24.72	25.33	0.01154	0.01212
0.25	20	24.59	25.24	0.01149	0.01208
0.5	10.5	24.43	25.13	0.01143	0.01204
1	9.5	24.22	25.01	0.01134	0.01198

4.4.3 Mesh size and time step investigation

From the mesh independence study, the mesh with a maximum size of 2 [cm] was chosen, and the time step used in that simulation was 0.1 [s]. Additionally, from the time step size investigation, the 0.5 [s] time step was chosen, and the corresponding mesh had a maximum size of 4[cm]. Thus, an investigation is now conducted in which each time step is simulated with both mesh sizes to verify the choice of time step and mesh size. The temperature and computation time results obtained for each of the time steps and mesh sizes

investigated are visualised in Figure 4.9 below. From Figure 4.9, it is evident that the temperature results are very similar for the different time step and mesh size combinations. The 0.5 [s] time step computation times are much shorter than those of the 0.1 [s] time step. Additionally, the 2 [cm] mesh size had a slightly shorter computation time than the 4 [cm] mesh size. Thus, the 2 [cm] mesh size and the 0.5 [s] time step resulted in the shortest computation time, with the temperature results being consistent.

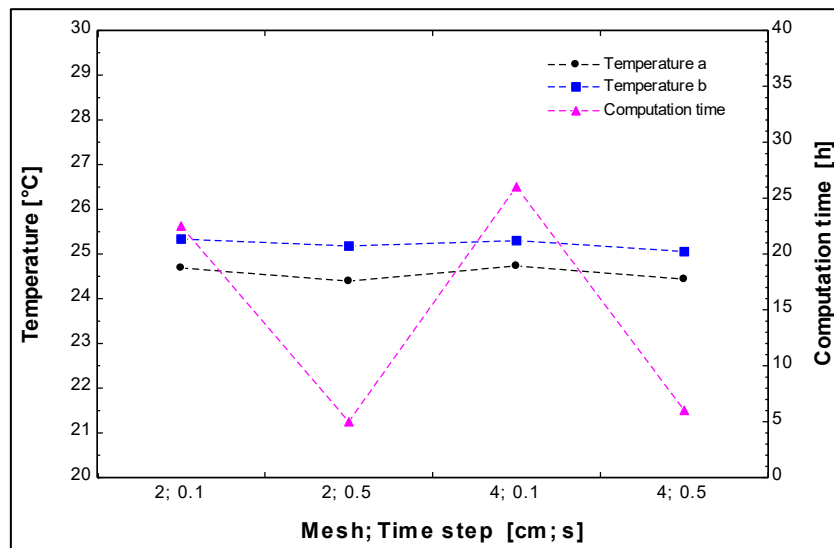


Figure 4.9: Mesh and time step investigation: Temperature and computation time

The mesh and time step size investigation results are tabulated in Table 4.6 below. From Table 4.6 it is evident that the specific humidity results are also very consistent for the different time steps and mesh sizes investigated.

Table 4.6: Mesh and time step size investigation: Inputs and results after 1 hour simulation time

Maximum size (Computer A) [m]	Time step size [s]	Computation time [h]	Temperature a [°C]	Temperature b [°C]	Specific humidity a [kg/kg]	Specific humidity b [kg/kg]
0.02	0.1	22.5	24.69	25.34	0.01150	0.01206
0.02	0.5	5	24.39	25.18	0.01139	0.01203
0.04	0.1	26	24.73	25.30	0.01154	0.01208
0.04	0.5	6	24.44	25.05	0.01143	0.01200

4.5 EES dwell state model verification

In this section, the verification of the EES dwell state calculation model against the simulation model is done. Two cases are used in the verification, Table 4.7 below contains the initial grain and the inlet air conditions for the two cases.

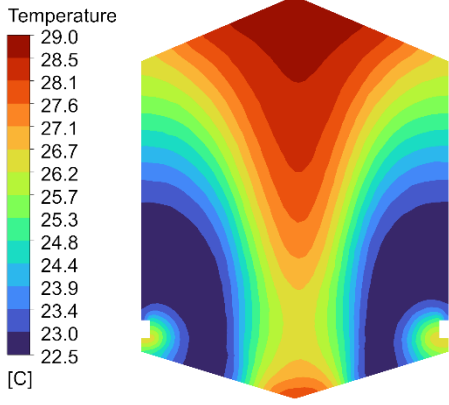
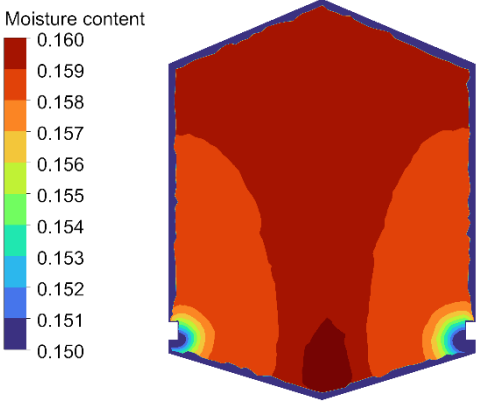
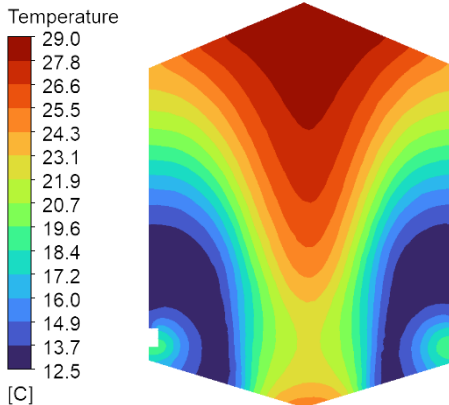
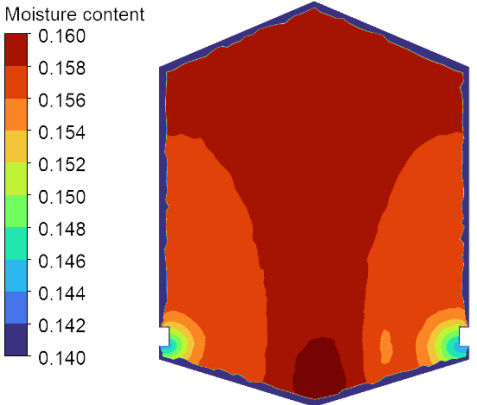
Table 4.7: EES dwell state model verification cases

Case #	Grain temperature [°C]	Grain moisture content [%]	Air temperature [°C]	Air relative humidity [%]
1	30	16	26.5	55.87
2	30	16	19.3	35.10

The dwell temperature and moisture content of the grain bulk for the two cases are calculated using EES and the Fluent simulation model. For the simulation model, the dwell conditions are determined after 3 hours of simulation time. The dwell region is visually identified, and the average value of the area is calculated. The dwell conditions results obtained from EES and the simulation model are summarised in Table 4.8 below. From Table 4.8 it is evident that for the first case the results are very consistent, with the dwell temperatures differing about 0.5 [°C] and the moisture content approximately 0.11%. For the second case the results differ a bit more than for the first; the dwell temperatures differ about 0.7 [°C] and the moisture content approximately 0.29%. In both cases, the EES dwell temperature was slightly higher than the simulation model, and the moisture content was slightly lower. For the temperatures, the difference is within the measurement equipment's accuracy of ± 1 [°C]. The moisture content differences are also within the measurement equipment's accuracy of 0.3% moisture content. Refer to Section 5.2.3 for a discussion on the measurement equipment used, and their accuracies.

In Table 4.8 in the dwell temperature column, the zones and fronts formed during aeration can be identified from the contour images. The temperature front in both images lies between the dark red and dark blue regions, these correspond to zone C and zone B, respectively. Furthermore, at the region near the inlet the onset of the moisture front can be seen. This corresponds to what is expected from literature.

Table 4.8: EES dwell state model verification results

Case #	Model	Dwell temperature [°C]	Moisture content [%]
1	EES	22.8	15.74
	Fluent	~ 22.75 	~15.85 
2	EES	13.8	15.41
	Fluent	~13.1 	~15.7 

4.6 Conclusion

In this chapter, the Fluent simulation model geometry and mesh parameters have been given, and the setup and implementation of the simulation have been discussed. The simulation model has been verified in terms of mesh size and time step size, and the final mesh size and time step have been chosen to be 2 [cm] maximum size and 0.5 [s], respectively. Additionally, the EES dwell state calculation model has been verified against the simulation model, and the results were within the measurement equipment accuracy. In the following chapter, the experimental validation methods for the simulation model and scaling approach are presented.

CHAPTER 5 EXPERIMENTAL VALIDATION METHODS

5.1 Introduction

In this chapter, the experimental validation methods are described. The experimental validation includes, firstly, validating the simulation model using a small-scale silo testbench, and secondly, validating the scaling of the simulation results to the full-scale silo.

Firstly, the particulars of the small-scale silo experimental testbench are discussed. Next, the experimental method used to obtain experimental validation data is described. Lastly, for the validation against the full-scale silo, a scaling methodology is developed.

5.2 Experimental testbench

In this section, the experimental testbench is discussed. Firstly, an overview of the experimentation and the experimental schematic diagram is given. Next, the dimensional specifications of the testbench, specifically relating to the full-scale silo, are discussed. The measurement equipment, including their calibration, is reviewed. Lastly, the final small-scale silo testbench model is presented.

5.2.1 Experimentation overview

The small-scale silo testbench is used to perform an aeration experiment and collect data, which is used to validate the simulation model. In the aeration experiment, air is forced through a bulk of maize for a set amount of time. The grain is initially at a certain temperature and moisture content. The experiment is performed in a closed room with the air conditioning set to a constant temperature, to ensure that the inlet aeration air's conditions vary minimally throughout the experiment. The air flow is supplied by a fan, and a T-junction and ball valve in the air supply pipe are used to achieve the desired flow rate. Figure 5.1 below pictures the experimental schematic diagram.

The initial grain temperature and moisture content are measured, and the grain temperature during aeration is measured at various points throughout the bulk using temperature measurement strings. The air temperature and relative humidity are measured before the inlet into the silo, and at an opening near the outlet. The differential pressure across an orifice plate in the air supply pipe is measured periodically during the experiment, and this measurement is used to calculate the air flow rate. The temperature in the pipe upstream of the orifice plate is also measured.

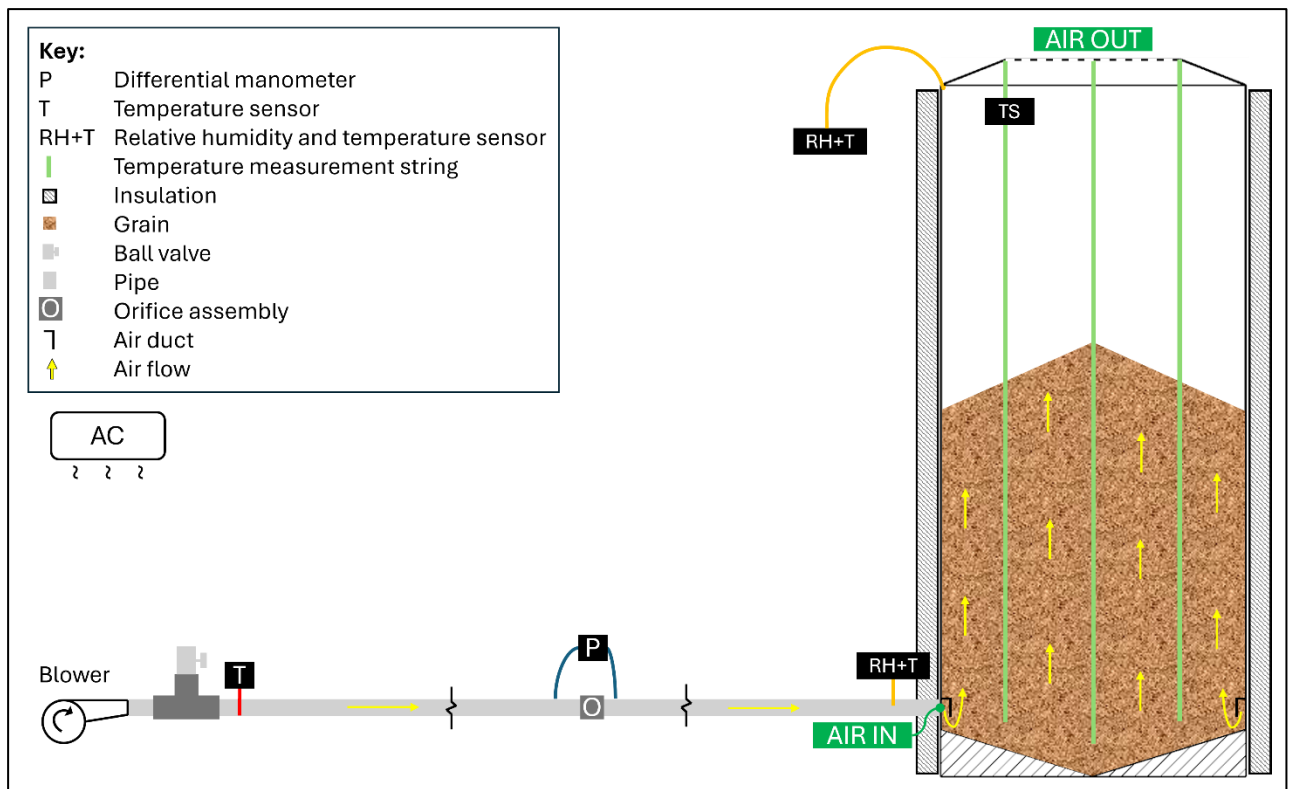


Figure 5.1: Experimental schematic diagram

5.2.2 Testbench dimensional specifications

The testbench is designed and constructed to be an accurate scale model of the full-scale silo tube A1. The most important components that need to be considered for the small-scale silo to be geometrically similar to the full-scale silo are:

- the silo body,
- the inclined floor,
- the air inlet,
- the air distribution duct, and
- the height of the air inlet.

Each of these components of the testbench are discussed below. Table 5.1 below summarises the final dimensions of each component compared to those of silo tube A1.

Table 5.1: GMC silo tube A1 and experimental small-scale silo dimensional comparison

Parameter	Unit	Silo tube A1	Small-scale silo
Silo tube height	[m]	43	2.06
Silo tube diameter	[m]	18	0.84
Air inlet width	[m]	0.99	0.0495
Air inlet height	[m]	0.58	0.029
Duct width	[m]	0.462	0.023
Duct height	[m]	0.931	0.047

Regarding the silo body, a 1000 litre Slimline JoJo tank was procured since its height-to-diameter ratio closely matches that of silo tube A1, that is, 2.45 for the tank compared to 2.39 for the silo tube. Additionally, this tank is small enough to ensure it is easy to handle, and the number of temperature sensors required is reasonable, while it is also large enough that the maize particles are still relatively small compared to the tank size, thus ensuring it is a realistic aeration scenario. The height and diameter of the tank and silo tube A1 are given in Table 5.1. From these dimensions, the tank is approximately a 1:21 scale model of silo tube A1. Since the rest of the components are scaled to fit in the tank, a 1:20 scale is used to simplify the scaling of the components.

As was mentioned in Section 3.2.1, the floor of silo tube A1 is inclined at a 17° angle and has square-shaped holes used to drain grain from the silo. The inclined floor of the small-scale silo is manufactured from plywood, and for ease of manufacturing, the square-shaped holes are not included; instead, the base is manufactured as two flat inclined surfaces. Additionally, the base is manufactured to be at the same angle as the floor in silo tube A1.

The air distribution duct of silo tube A1 has a tapered top and vertical sides. The air distribution duct for the small-scale silo is manufactured from sheet metal; thus, due to manufacturing constraints, it was not possible to replicate the tapered top of silo tube A1. For the small-scale duct height, the full-scale silo duct height, up to its highest point, is scaled down 20 times. Additionally, the duct width is also scaled down. The dimensions can be found in Table 5.1.

To aid in fastening the duct to the tank, the duct is manufactured to have an outer ring that can be bolted to the silo. Since the air distribution duct is over the air inlet, the air inlet hole is cut out of the air distribution duct's outer support ring. The air inlet's dimensions and the height of the inlet in relation to the air distribution duct are scaled down from the dimensions of silo tube A1.

Regarding the air inlet's height, a hole for a pipe connector is made in the side of the JoJo tank, such that the height from the bottommost point of the tapered floor is scaled down to the height of the air inlet in silo tube A1. The air supply piping is connected to the tank via this connection. The diameter of the pipe connector and the air supply piping is selected so that it is greater than the air inlet, so that it is not obstructed. Thus, PVC piping with an outer diameter of 50 [mm] is chosen.

5.2.3 Measurement equipment and calibration

Measurements that need to be taken during experimentation include grain temperature and moisture content, air temperature and relative humidity, and air flow rate. The sensor and/or equipment used for each of these is discussed below, including their calibration.

5.2.3.1 Grain temperature: Temperature strings

To measure the grain temperature, temperature measurement strings are manufactured from type T thermocouple wire, and measurements are taken by connecting the thermocouple wire to an Endress & Hauser RSG40 memograph. Type T thermocouples have an accuracy of ± 1 [°C] (RS Components, 2020). Three temperature measurement strings are manufactured with a total of 12 measurement points, 10 of which are covered by grain during experimentation. Figure 5.2 below shows the positions of the 12 measurement points with respect to the simulated volume. Temperature measurement string A is positioned in the centre of the small-scale silo and has four measurement points in the grain bulk. String C is in line with the air inlet, with the first point positioned slightly above the inlet. String B is approximately the same distance away from string A as string C, and at an angle of approximately 60°.

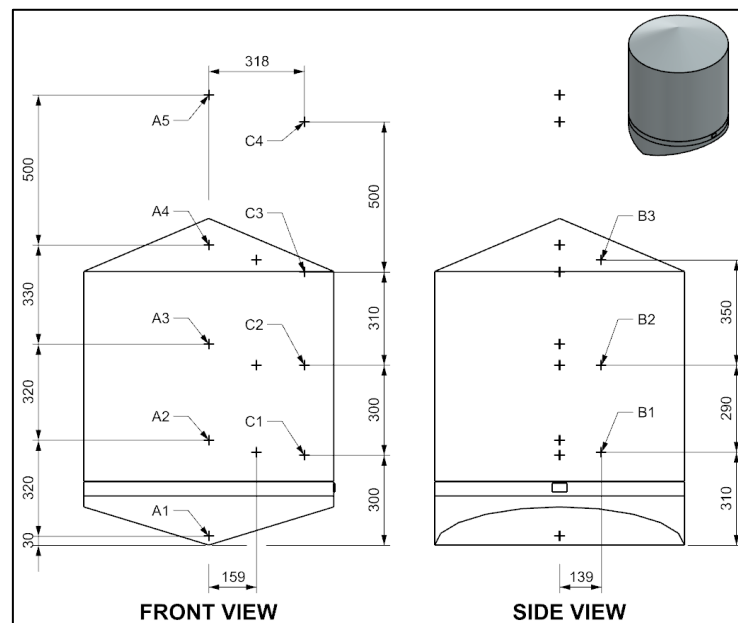


Figure 5.2: Temperature string measurement points

The memograph is calibrated for a temperature range of 15 to 45 [°C]. Temperature measurements are taken for an upper and lower value with the thermocouples and a calibrated thermometer. The true and measured values are entered into the memograph for each measurement string point. These values are tabulated in Table B.1 in Appendix B.1. Next, to confirm that the memograph is adequately calibrated, measurements are taken with the thermocouples and the calibrated thermometer for four temperatures within the calibrated range. These values are tabulated in Table B.2 in Appendix B.1. The largest difference measured is 0.5 [°C], with the majority of the measurements differing by 0.2 [°C] or less. Thus, the calibration of the memograph is verified.

5.2.3.2 Grain moisture content: Grain moisture meter

The grain moisture content is measured using GMC's Perten AM 5200-A grain analyser at the start and end of experimentation. Grain moisture meters have an accuracy of $\pm 0.3\%$ moisture content (U.S. Department of Agriculture, 2015). The calibration certificate of the Perten AM 5200-A grain analyser can be found in Figure B.1 in Appendix B.2.

5.2.3.3 Air flow rate: Orifice plate and manometer

The flow rate of the air during experimentation is obtained by measuring the differential pressure across an orifice plate in the air supply pipe, as can be seen in Figure 5.1. The orifice plate is designed according to the standards ISO 6157-1:2003(E) and ISO 5167-2:2003(E) (International Organization for Standardization, 2003a, 2003b). The design of the orifice plate is discussed in Appendix B.3. The air velocity is calculated from the differential pressure measurement using the equations discussed in Section 3.4. These equations are implemented in EES; the code can be found in Appendix A.3. The calculation of the flow rate measurement uncertainty is also discussed in Section 3.4.

The differential pressure across the orifice plate is measured using a U-tube manometer filled with a mixture of 98% isopropyl alcohol and blue alcohol-based food dye. The calculation of the working fluid's density can be found in Appendix B.4. The differential pressure height is measured using a 10 [cm] ruler. Isopropyl alcohol was chosen as the working fluid because it has a lower density than water, which means it will have a larger differential pressure height at a given air velocity. A large differential pressure height is desired to minimise measurement uncertainty. Additionally, it is also desirable for the velocity to be as small as possible, because, as was mentioned in Section 4.3, a larger velocity requires a smaller time step, and results in increased computation time. Thus, considering the minimum velocity that is possible with the blower and setup, a velocity of 9 [m/s] is chosen.

The velocity calculated from the differential pressure measurement is calibrated using a handheld T4201 Top Tronic anemometer. The calibration can be found in Appendix B.5.

5.2.3.4 Air temperature and relative humidity: Sensors and Arduino

The temperature and relative humidity at the inlet and outlet of the small-scale silo are measured using two HIH8121-021-001 Honeywell HumidIcon digital humidity/temperature sensors. These sensors have an accuracy of $\pm 2.0\%$ relative humidity and ± 0.5 [°C] (Honeywell, 2015).¹⁶ Furthermore, the temperature upstream of the orifice plate is measured using a DS18B20 temperature sensor, which has an accuracy of ± 0.5 [°C] (DFRobot, 2025). The temperature and relative humidity measurements were obtained using an Arduino UNO R3 and CoolTerm software, which was used to save the data. The Arduino code can be found in Appendix A.4 and more information on the physical setup of the Arduino can be found in Appendix B.6.

Regarding calibration, both the HIH8121-021-001 and the DS18B20 are factory calibrated.

5.2.4 Testbench setup and description

The final testbench setup can be seen in Figure 5.3 below. At the far left, the blower is connected to the air supply piping. The temperature sensor, which measures the upstream temperature, is positioned after the blower. The ball valve, which is positioned next to the temperature sensor, is used to achieve the desired flow rate. Approximately halfway along the air supply piping is the orifice plate, pressure tapings, and manometer. At the right end of the air supply piping, right before the air inlet into the tank, is the first temperature and relative humidity sensor. The sensors are connected to the Arduino, which is connected to a laptop on which the data is logged using the application CoolTerm. The right end of the air supply piping is connected to the JoJo tank. The second temperature and relative humidity sensor is positioned at the top of the tank, in an outlet hole in the side of the tank. The temperature measurement strings enter the tank at the top and are secured in place using guide wires. The temperature measurement strings are connected to the memograph, which is positioned next to the tank. Additional images of the individual components can be found in Appendix C.

¹⁶ The sensor's accuracy is specified for a supply voltage of 3.3 [V], thus this voltage value was supplied to the sensors.

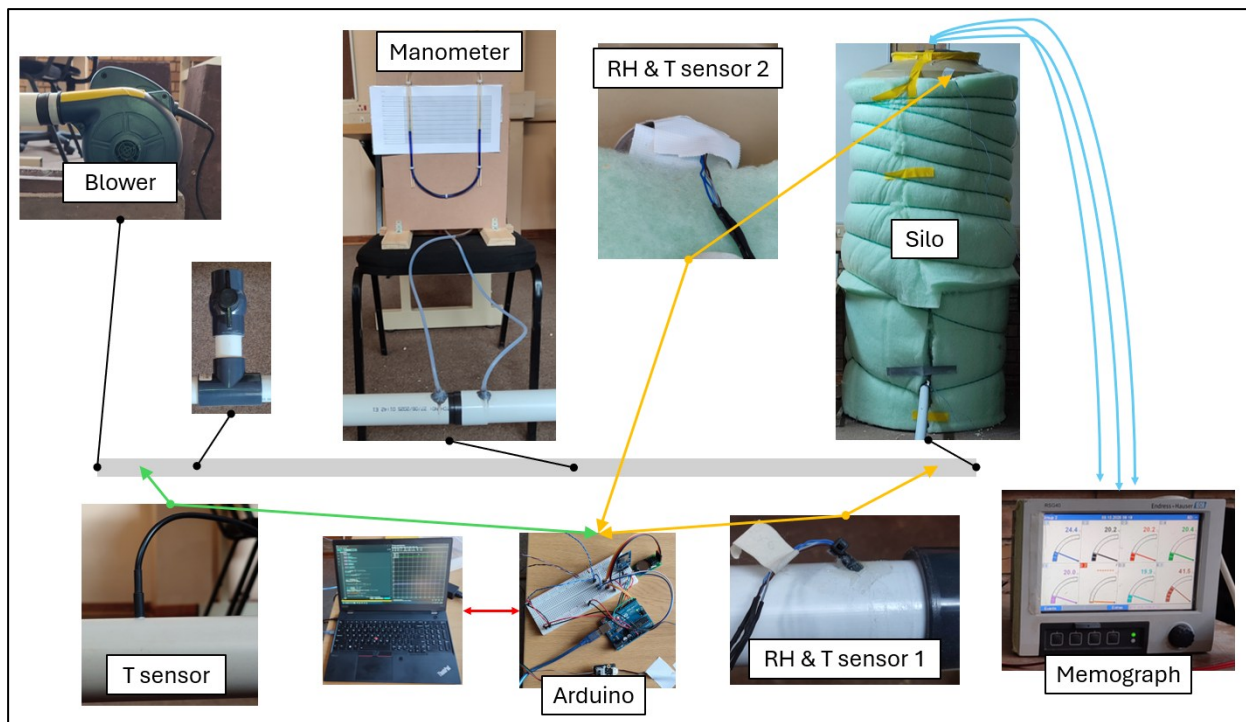


Figure 5.3: Experimental testbench setup diagram

As can be seen in Figure 5.3, the experimental testbench consists of the following components:

- 1000 litre Slimline JoJo tank (Figure C.1)
- Inclined wooden base (Figure C.2)
- Sheet metal air distribution duct (Figure C.3)
- Pipe connector
- The air supply piping
- Roofing insulation (secured with rope)
- Ryobi BL-600 electric mini blower (Figure C.4)
- Air conditioner

The air supply piping consists of the following components:

- 50 [mm] diameter ball valve
- 50 [mm] diameter PVC T-piece
- 50 [mm] diameter straight connector
- Orifice plate
- 5 [m] of 50 [mm] diameter PVC piping, 2.5 [m] downstream of the orifice, 2 [m] upstream of the orifice, 0.4 [m] connecting the blower to the T-piece, and 0.1 [m] connecting the T-piece and ball valve.

The measurement equipment installed/used on the testbench includes:

- Three thermocouple temperature measurement strings (Figure C.5)
- Memograph (Figure C.6)
- Manometer (Figure C.7)
- Two HIH8121-021-001 temperature and humidity sensors
- DS18B20 temperature sensor
- Arduino Uno R3 (including a DS1302 real time clock and accessories) (Figure C.8)

5.3 Experimental method

In this section, the experimental method is discussed. Firstly, the experimental parameters and measurements are discussed. Thereafter, the experimental procedure is given.

5.3.1 Experimental parameters, variables, and measurements

For the experiment, there are several parameters and variables. Parameters are the measurements that are used as input to the simulation. Variables are the measurements that are compared to the simulation results for validation.

The experimental parameters are as follows:

- Air inlet temperature
- Air outlet temperature
- Air inlet relative humidity
- Air outlet relative humidity
- Orifice plate upstream air temperature
- Upper silo air temperature
- Initial grain temperature
- Initial grain moisture content
- Air supply piping differential pressure
- Experimental duration

The experimental variables are as follows:

- Grain temperature
- Final grain moisture content

Table 5.2 below summarizes the measurements that are taken during experimentation, and the frequency at which each one is taken.

Table 5.2: Measurement frequency

	Measurement	Frequency
Air	Inlet temperature	~5 [s]
	Inlet relative humidity	~5 [s]
	Outlet temperature	~5 [s]
	Outlet relative humidity	~5 [s]
	Orifice plate upstream temperature	~5 [s]
	Upper silo temperature	Minutely averaged
	Air supply piping differential pressure	Hourly
Grain	Temperature	Minutely averaged
	Initial moisture content	~48 hours before experimentation ¹⁷
	Final moisture content	~48 hours after experimentation ¹⁸

5.3.2 Experimental procedure

The experimental procedure is as follows:

1. Take five samples of the grain.
2. Measure the moisture content of the five grain samples.
3. Fill the silo with the grain up to the desired height.
4. Set the air conditioning to the desired temperature.¹⁹
5. Start recording on all the continuous measurement equipment (the memograph and the Arduino via CoolTerm).
6. Switch on the blower.

¹⁷ The moisture content of several samples was measured before filling the small-scale silo with the grain. Additionally, after filling the silo, the start of the experiment was delayed due to more favourable ambient conditions predicted for two days later.

¹⁸ The samples taken at the end of the experiment could only be tested two days later, since the experiment was conducted on a weekend. The tank's top was kept closed for this period to prevent the grain's final conditions from changing.

¹⁹ The air conditioning is started shortly before starting the blower, so that the air entering at the top opening of the tank does not cool the grain.

7. Take the first differential pressure measurement and continue to do so hourly throughout the duration of the experiment. Adjust the ball valve as needed to maintain steady flow, then retake the differential pressure measurement.
8. After the desired experiment duration has been reached, switch off the blower.
9. Take grain samples from the side and from the top of the grain pile.
10. Measure the moisture content of the grain samples.

5.4 Scaling method

In this section, the scaling method is discussed. Firstly, the methodology is conceptualised by reviewing what needs to be scaled. Some of the literature reviewed in Chapter 2 is used in conceptualising the methodology. Thereafter, the temperature front speed graph is discussed. Lastly, the scaling validation methodology is given.

5.4.1 Scaling requirements and methodology conceptualisation

In this section, the scaling requirements are reviewed, and the methodology that is used to scale the small-scale model results to a full-scale silo for validation is conceptualised. Firstly, from the research investigated in Section 2.7 regarding the scaling of porous models, only one applicable study was found. However, in this study, the individual particles were scaled along with the entire porous bulk. This method is not feasible, since the maize particles cannot be downscaled for the experimental validation. Thus, a different method is needed. To find a method that can be used to scale the small-scale model, one must first determine what results need to be compared between the small and full-scale silo for validation. To validate that the small-scale model accurately models the full-scale silo, the predicted grain conditions after a certain amount of time need to be consistent. Thus, the final grain conditions, for certain inlet aeration conditions, and a time component are required.

Firstly, the final grain conditions required are the temperature and moisture content of the grain. These are independent of silo size and are only dependent on the initial grain and inlet air conditions. The final grain conditions are dependent on the total heat and moisture transfer. Thus, if the initial and final conditions, and the total heat and moisture transfer for two different volumes are the same, it follows that the heat and moisture transfer times for the two volumes will differ. The effect of aeration, the temperature and moisture content change with time, that is, the fronts, can be observed, and the fronts also indicate where zones A, B, and C are. As was discussed in Chapter 2.3.4 of the literature review, the speeds of the fronts can be estimated and are mainly dependent on the air and grain conditions, air velocity, and the bulk geometry. The bulk geometry of the small-scale silo is modelled to be an accurate scale model of the full-scale silo.

Thus, the last aspect to consider is the air velocity. Sutherland et al. (1983) determined the speed of the fronts as a ratio of the inlet air velocity, for different temperatures and moisture contents, and presented the results graphically (Figure 2.5). Thorpe (2002a) then demonstrated how these results can be used to predict how long it takes for a front to pass through a grain bulk. Thus, using the small-scale model, graphs similar to those of Sutherland et al. (1983) can be created, and these can then be used to evaluate how long it takes to see the effects of aeration for the full-scale silo. Since the primary focus of aeration is to cool the grain, it is only necessary to create a graph for the cooling temperature front.

5.4.2 The temperature front speed graph

The purpose of the temperature front graph is to calculate how long it takes for the temperature front to move through a bulk of grain. Similarly, it can be used to calculate how far the temperature front has advanced for a certain amount of aeration time. Due to the positioning of the aeration inlet being at the side of the silo, the aeration does not progress uniformly from the bottom to the top. However, GMC only has a temperature measurement string in the centre of their silos; consequently, the only way for them to track the aeration as it progresses is by using this temperature measurement string. Therefore, the temperature front speed graph is set up to track the front speed along the centre axis of the small-scale silo.

Since the air does not propagate uniformly through the silo, a single temperature front speed ratio for the entire bulk height will not allow for the accurate calculation of the temperature front speed or position at discrete points along the bulk height. Thus, the temperature front speed ratio is calculated for several points along the centre axis of the small-scale silo. Figure 5.4 below depicts the points that are used to calculate the temperature front speed ratio. The height of the lowest point is chosen so that it is a distance above the inlet, since it is expected and observed from the verification simulations that the flow below the inlet flows towards the bottom of the silo.

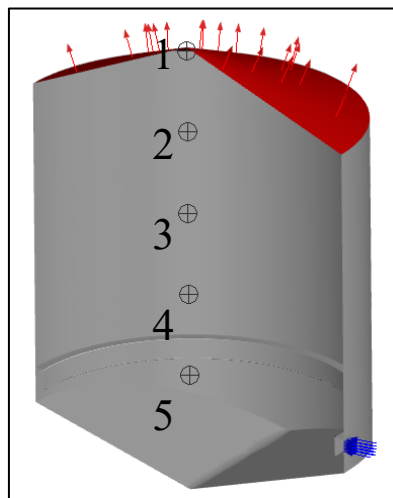


Figure 5.4: Temperature front tracking points

The temperature front speed graph is created from data of different grain bulk and aeration inlet conditions obtained using the CFD simulation model. The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) climatic design conditions (American Society of Heating, Refrigeration and Air-Conditioning Engineers, 2021) are used to obtain wet bulb and dry bulb temperatures for the air inlet conditions. For the grain conditions, a range of temperatures and a single moisture content are chosen as the initial conditions. It is assumed that the temperature front speed is minimally influenced by the grain moisture content, as was observed by Sutherland et al. (1983). The simulation is then solved for each of the conditions. A simulation time of 12 hours is used for each simulation. From the initial simulations, it was observed that this period is sufficient to track the propagation of the temperature front through the small-scale model for the chosen velocity.

Using the obtained data, the following steps are used to set up the graph:

1. For each simulation, a range of temperatures that form part of the temperature front is visually identified.
2. For each of the points in Figure 5.4, the time it takes to reach each of the temperatures identified in Step 1 is found.
3. The time it takes for the temperature front to move from the lowest point (5) to each of the four higher points (2, 3, 4, and 5) is calculated by subtracting the time of point 5 from the time of the other point. This is done for each of the temperatures identified in Step 1.
4. The temperature front speed between point 5 and each of the four other points, and for each of the temperatures identified in Step 1, is calculated by dividing the height difference between the two points by the time delta calculated in Step 3.
5. The physical velocity of the air is calculated from the air inlet velocity using the conservation of mass.
6. The temperature front speed ratio between point 5 and each of the four other points, and for each of the temperatures identified in Step 1, is calculated by dividing the temperature front speed calculated in Step 4 by the physical velocity calculated in Step 5.
7. For each of the time values for point 5 identified in Step 2, the temperature of each of the other four points at these times is found. This process is repeated for each of the temperatures identified in Step 1.
8. The average grain temperature for each of the temperature front speed ratios calculated in Step 6, is calculated by taking the average of the temperature at the point 5 (the temperature identified in Step 1) and the temperature at the other point (1, 2, 3, or 4) (the temperature found in Step 7) and the temperature of all other points between these two points.
9. The graph is created by plotting the temperature front speed ratio on the y-axis and the average grain temperature on the x-axis. For each of the point deltas, a separate graph is created.

5.4.3 Scaling validation methodology

The scaling of the simulation results to the full-scale silo by means of the temperature front speed ratio graph is validated using full-scale silo data. Due to the nature of the data obtained from GMC for validation, which directly follows from the specific silo's aeration management for the period for which data is obtained, the only feasible method to perform validation of the scaling is to calculate a temperature front speed ratio and compare it to the simulation temperature front speed ratios. Thus, the scaling methodology is as follows:

1. From GMC's silo data, identify a period of aeration.
2. For this aeration period, calculate a temperature front speed ratio according to the steps discussed in Section 5.4.2.
3. Compare the results.

5.5 Conclusion

In this chapter, the validation methods have been discussed. The experimental testbench has been discussed, including the dimensional specifications, measurement equipment and their calibration, and the components that make up the testbench. The experimental parameters and measurements have been reviewed. Additionally, the experimental procedure has been given. The scaling requirements have been reviewed, and based on them, the scaling methodology has been conceptualised. The creation of the temperature front speed ratio graph has been discussed. Lastly, the scaling validation methodology has been given.

In the following chapter, the experimental validation, simulation scenarios, and scaling validation results are given and discussed.

CHAPTER 6 RESULTS

In this chapter, the validation and simulation scenario results are presented. Firstly, the experimental validation is done. Next, the processed simulation scenario results are given. Thereafter, the scaling validation is done. Lastly, the practical applications of the results are discussed.

6.1 Experimental validation

In this section, the experimental validation is done. Firstly, the experimental conditions are given. Thereafter, the experimental and simulation results are given and compared.

6.1.1 Experimental conditions

In this section, the experimental conditions are given. Two 10-hour-long experiments with different initial grain conditions were conducted. However, the experimental conditions of the first experiment did not yield very useful results. For the initial grain and inlet air conditions, the dwell conditions were predicted to be very close to the zone C (initial grain) conditions. Additionally, from the experimental data, it was observed that most of the temperature measurement points experienced very little change over the course of the experiment, and the points closest to the inlet showed an increase in temperature.

The second experiment's conditions yielded favourable results; thus, only this experiment is used for the validation. Additional experiments were not conducted due to several constraints. Firstly, the process of filling and draining the silo damages the temperature measurement strings, secondly, the experimental validation simulations are computationally very expensive, and thirdly, limited grain was available.

The initial grain conditions for the experiment are tabulated in Table 6.1 below. For the temperatures, the average of the measurement points in the same layer is used as input for the simulation. The temperatures at each of the measurement points can be found in Table D.1 in Appendix D.1. For the moisture content, the average of several samples was calculated by the silo manager providing the grain.

Table 6.1: Experiment initial grain conditions

Parameter	Value	Unit
Temperature layer 1 (A1)	19.7	[°C]
Temperature layer 2 (A2, B1, C1)	21.2	[°C]
Temperature layer 3 (A3, B2, C2)	21.6	[°C]
Temperature layer 4 (A4, B3, C3)	20.9	[°C]
Average moisture content	14.5	[%]

The air conditioning in the room was set to 17 [°C] during experimentation. However, the room air temperature cycled throughout the experiment because the room air conditioning switched off when the air near the air conditioner reached the desired temperature and only switched back on when the temperature exceeded a certain threshold temperature. Thus, a polynomial fit of the measured inlet temperature is obtained to provide steadier data as input to the simulation to improve convergence. The measured inlet temperature and the polynomial fit of the data are pictured in Figure 6.1 below. The average inlet air temperature was 20.9 [°C]. The average temperature of the air after the blower was 25.5 [°C], thus the blower heated the air by 8.5 [°C], and the air then cooled down almost 5 [°C] along the length of the air supply pipe.

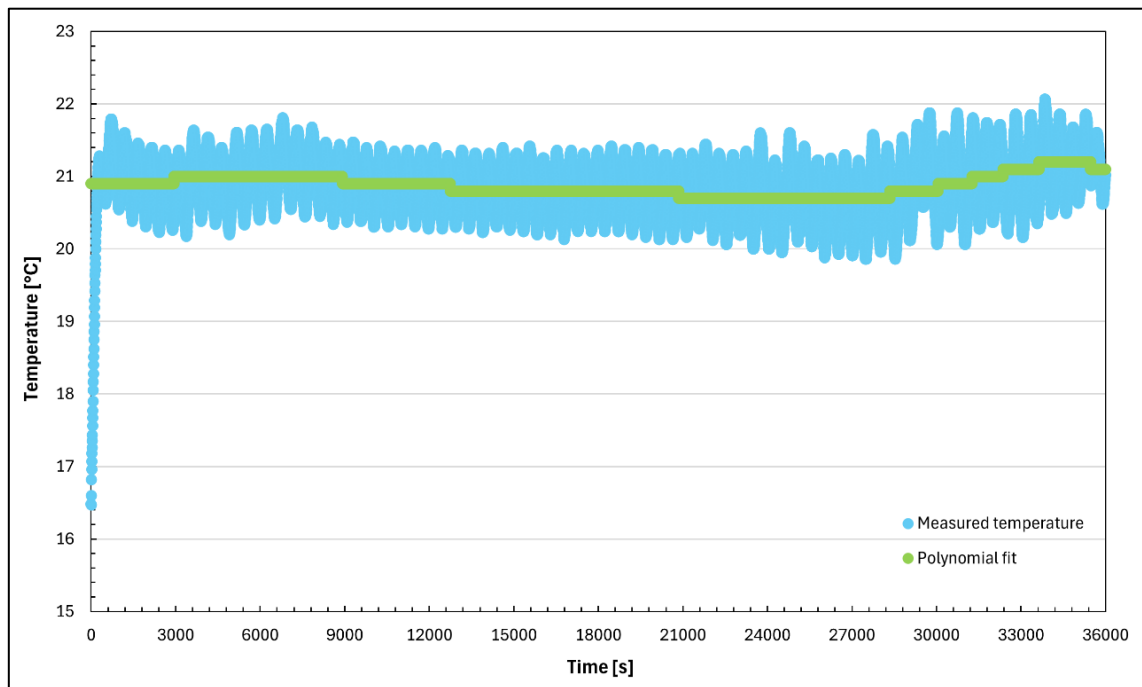


Figure 6.1: Experimental air inlet temperature

Due to the air temperature in the room cycling during the experiment, the relative humidity also cycled. Additionally, since environmental conditions changed throughout the day and the room was not perfectly sealed from the outside, the relative humidity experienced additional fluctuations. Thus, a polynomial fit of the relative humidity measurements at the inlet is also obtained to provide steadier data as input to the simulation. The measured inlet relative humidity and the polynomial fit of the data are pictured in Figure 6.2 below. The average inlet relative humidity was 31%.

The average air velocity for the duration of the experiment is calculated from the differential pressure measurements. The average air velocity was 8.5 [m/s]. The differential pressure measurements and the calculated velocities can be found in Table D.2 in Appendix D.1.

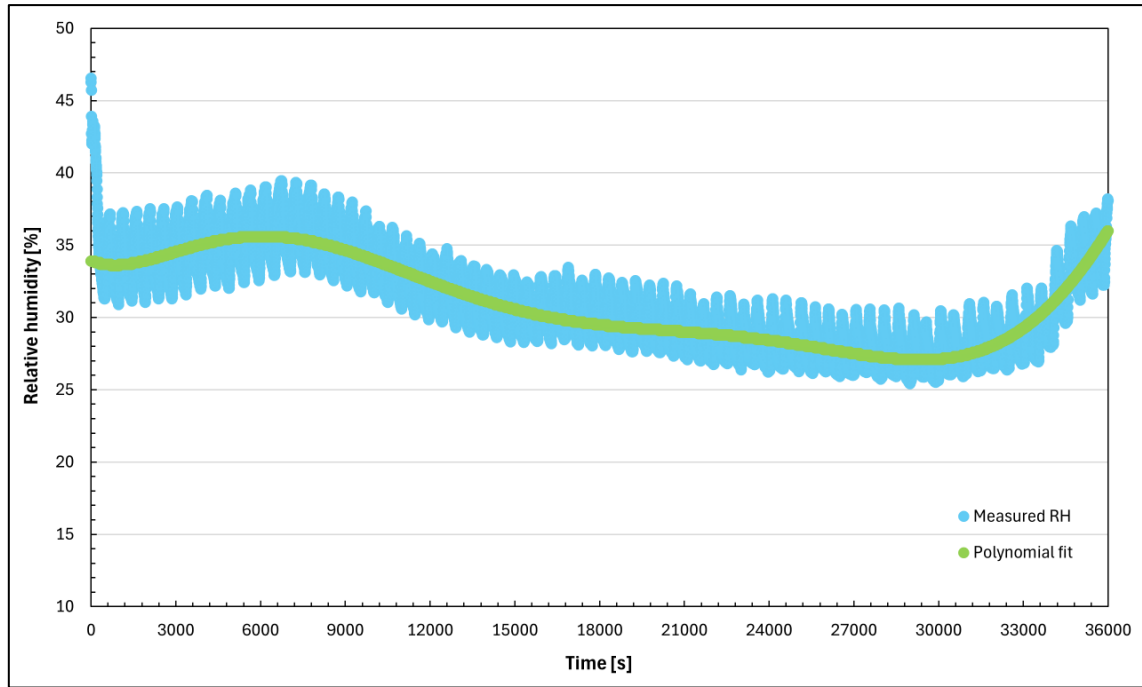


Figure 6.2: Experimental air inlet relative humidity

6.1.2 Experimental and simulation validation results

The simulation was solved for the experimental conditions given in the previous section. In this section, the experimental and simulation results are compared. The temperature for the different measurement point layers, the moisture content at two points, the dwell conditions, and the temperature front speed ratio are compared. The standard error of prediction (SEP) of the results is calculated. Lastly, reasons for deviations are discussed.

6.1.2.1 Temperature comparison

The average experimental and simulation temperatures of the points in each of the top three layers are compared in Figure 6.3 to Figure 6.5 below. Additionally, the average temperature for a cluster around each measurement point for discrete times throughout the aeration period is also compared to verify that using only the point values is valid. The temperature results for the bottom layer are not included because, after unloading the grain from the tank, measurement point A1 began reading negative values, which is incorrect. Thus, the reliability of A1's results is in question. But, since the starting temperature at A1 is in line with the other points' temperatures, it was still used as input for the simulation.

In Figure 6.3 below the temperature results for the average of measurement points A2, B1, and C1 are compared. The cluster temperature values all fall on the average point values line, thus confirming the validity of using these to compare with the experimental results. From Figure 6.3 it is evident that at the start of aeration, for the first 50 minutes, the cooling of the grain is overpredicted by the simulation

However, for the rest of the aeration period, the temperature trends of the simulation and experiment are similar and only offset by the initial overprediction. At the start of aeration, the temperature difference between the experiment and simulation increases, and after 50 minutes, the difference increases minimally. In Section 6.1.2.5, the temperature results are compared after compensating for the initial overprediction. The standard error of prediction between the simulation and experimental results is 2.4 [°C].

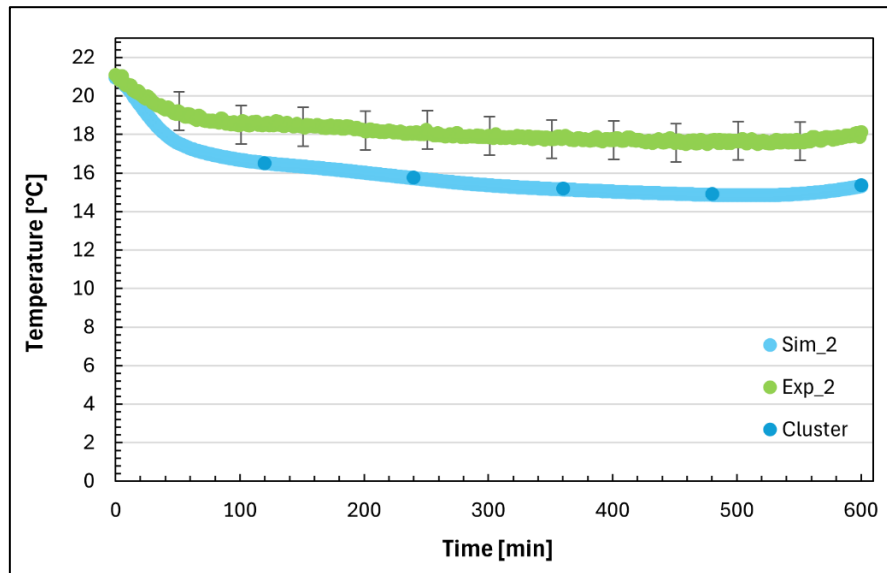


Figure 6.3: Experimental and simulation results comparison: Layer 2 (A2, B1, C1) temperatures

In Figure 6.4 below the temperature results for the average of measurement points A3, B2, and C2 are compared. Once again, the cluster temperature values and the point temperature values correspond with one another. From Figure 6.4 a very similar trend to that observed in Figure 6.3 is seen. At the start of aeration, the cooling is overpredicted, and for the rest of the aeration period, the trends very closely follow each other, again with an offset caused by the initial overprediction. The standard error of prediction between the simulation and experimental results is 2.3 [°C].

In Figure 6.5 below the temperature results for the average of measurement points A4, B3, and C3 are compared. For this layer, the cluster temperature values and the point temperature values once again correspond with one another. From Figure 6.5 it is evident that at the start of the aeration, both the simulation and experimental temperatures did not change a lot, for approximately the first hour the temperatures remained at approximately 21 [°C]. Thereafter, the simulation temperature, once again, dropped more significantly than the experimental temperature, for a period between 100 and 200 minutes, whereafter the temperature difference changed minimally. After thus period, the simulation and experimental trends closely follow each other. The standard error of prediction between the simulation and experimental results is 2.7 [°C].

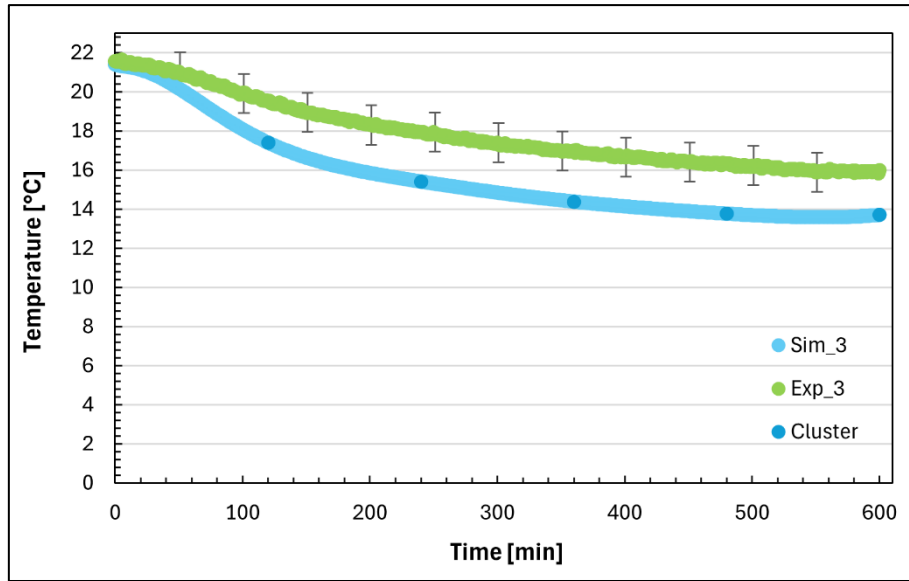


Figure 6.4: Experimental and simulation results comparison: Layer 3 (A3, B2, C2) temperatures

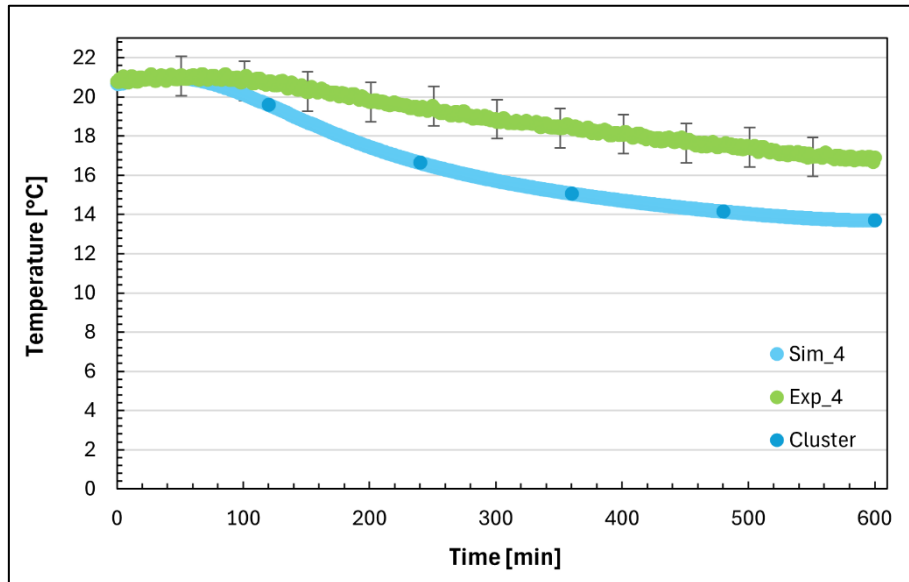


Figure 6.5: Experimental and simulation results comparison: Layer 4 (A4, B3, C3) temperatures

When comparing the temperatures of the three layers, it is evident that the lowest layer (layer 2) experienced the cooling effect the fastest. Its temperature started declining almost immediately, since it is just above the inlet. The second highest layer took about half an hour to an hour for its temperature to start declining more rapidly. The highest layer's temperature only started declining more rapidly after an hour of aeration had passed. These trends are expected, since the temperature front moves from the bottom to the top.

6.1.2.2 Moisture content comparison

The experimental and simulation moisture contents at the end of aeration are compared in Table 6.2 below. Grain samples at two locations, the top of the bulk and from an opening in the side of the silo, were taken to measure the moisture content at the end of the experiment. For the sample at the side, it is not possible to know exactly how the grain flowed out of the silo, and thus what the original location of the sample kernels was, but an approximate location of where the grain most likely was in the silo was used to obtain the simulation value. Comparing the moisture content at the top, the simulation predicted the moisture content to be 0.3% higher than what was measured, and for the moisture content at the side, the simulation predicted the moisture content to be approximately 0.1% lower than what was measured. Since the experiment was only started 48 hours after measuring the moisture content at the start, and the moisture content at the end could also only be measured approximately 48 hours after the experiment was finished, it is possible that there occurred moisture transfer between the grain and air during that time. This would explain why the moisture content between the experiment and simulation at the top differs more than at the side, since the side is not directly in contact with the air. Nevertheless, the errors are still within the moisture meter's measurement accuracy.

Table 6.2: Experiment and simulation moisture content comparison

Position	Experiment	Simulation
Top	14.1%	14.4%
Side	14.2%	~14.1%

6.1.2.3 Dwell conditions comparison

The dwell conditions predicted by the experiment and the EES calculation model, compared to the experimental results, are presented in Table 6.3 below. The dwell temperature predicted by the simulation is 1.7 [°C] lower than the experimental value, and the dwell temperature predicted by EES is 0.7 [°C] lower than the experimental value. For the moisture content, the simulation predicted it to be 0.2% higher, and EES predicted it to be 0.1% higher than the experimental value.

Table 6.3: Dwell conditions comparison: Experiment, simulation, and EES calculation model

Parameter	Experiment	Simulation	EES calculation model
Dwell temperature [°C]	15.4	13.7	14.7
Dwell moisture content	14.2%	14.4%	14.3%

6.1.2.4 Temperature front speed ratio comparison

From the experimental and simulation results, the temperature front speed ratio between points A2 and A3 is calculated. In Figure 6.6 below the experimental and simulation temperature front speed ratios at three temperatures are compared. From Figure 6.6 it is evident that the experimental and simulation results follow the same trend, with the simulation's temperature front speed ratios being higher than those of the experiment. This follows from the temperature results compared in Figure 6.3, Figure 6.4, and Figure 6.5. Since the cooling was overpredicted in the simulation, the calculated temperature front speed is expected to be faster than for the slower cooling effect observed in the experiment. The standard error of prediction between the simulation and experimental results is 2.1 [mm/s]/[m/s].

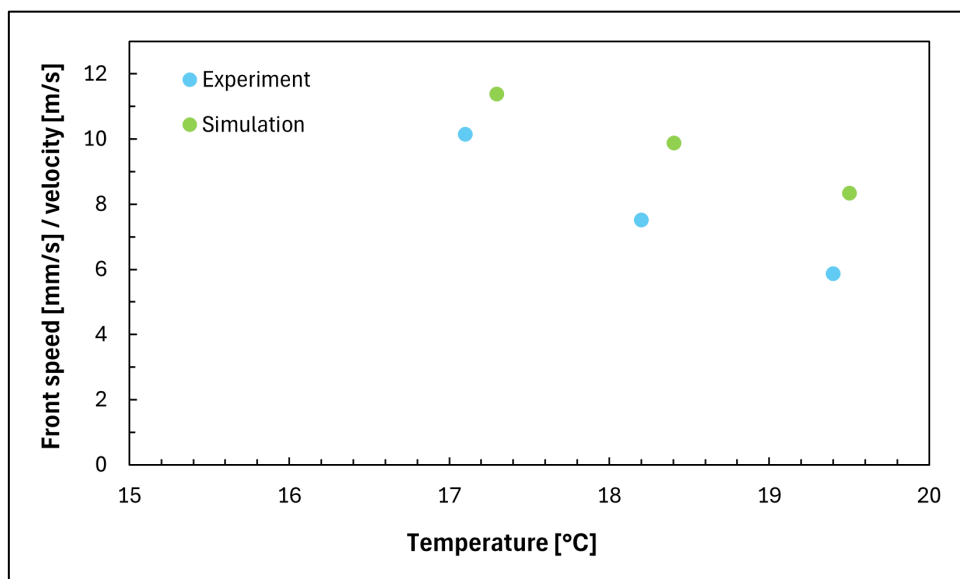


Figure 6.6: Experimental and simulation results comparison: Temperature front speed ratio

The overall temperature front speed ratio trend differs from what is expected from literature (Figure 2.5 by Sutherland et al. (1983)). As was mentioned in Section 2.3.4, Figure 2.5 gives the temperature front speed ratios for a cooling temperature front. Because the average initial grain temperature, 20.9 [°C], and the average inlet air temperature, 20.9 [°C], from the experiment are equal, the aeration can neither be described as cooling nor heating. The cooling that did occur during the aeration is due to evaporative cooling. Thus, the trends differ because the aeration schemes between the literature and experiment differ. The purpose of this comparison with literature is not for additional validation, but rather to address the different trends observed between the validation temperature front speed ratio graphs and that of the simulation scenarios.

The experimental and simulation temperature front speed ratios and temperatures can be found in Table D.3 in Appendix D.1.

6.1.2.5 Reasons for deviations

The reasons for the deviations observed between the experimental and simulation results of temperature, moisture content, and temperature front speed ratio are likely due to:

- Measurement equipment accuracy
- Quality of the grain
- Simulation assumptions
- Thin layer drying constant equation

Firstly, the accuracy of the measurement equipment can influence the accuracy of the simulation results, since the values measured in the experiment are used as input for the simulation. Specifically, since the simulation makes use of various experimental measurements to calculate the solution, the errors can compound to have a significant effect. The temperature measurement strings, temperature and relative humidity sensors, temperature sensor, and moisture meter have accuracies of ± 1 [°C], ± 0.5 [°C] and $\pm 2\%$, ± 0.5 [°C], and $\pm 0.3\%$. The uncertainty of the air mass flow rate measurement is 16.81%.

Secondly, the grain quality has an influence on the simulation results. The grain used for experimentation contained many contaminants. The properties and equations used in the simulation were all determined for clean grain; thus, if the grain has contaminants, the accuracy of the results can be affected.

Thirdly, some simulation assumptions, constants, and equations can influence the accuracy of the results. The assumption of constant porosity throughout the grain bulk may not be suitable, specifically when the grain also contains contaminants and dust. The viscous and inertial resistance values used may not be suitable for the specific bulk of maize used in the experiment. A different isotherm equation, or different constants for the current equation, might more accurately relate the EMC to the air temperature and relative humidity.

Lastly, the thin layer drying constant used in the simulation is most likely the reason for the simulation overpredicting the drying at the start of the aeration. To further demonstrate the effect of the drying constant equation, several drying constant equations for maize and other grains, which can be found in Appendix D.2, for a one-minute period, are compared in Figure 6.7 below. The drying constant axis is logarithmic, and the time axis is linear. Firstly, from Figure 6.7 it is evident that the drying constants for maize are orders of magnitude greater than those of the two other grain types compared. Additionally, the drying constants for maize start quite high, and as aeration continues, they drop orders of magnitude until they start to plateau. For the simulation model, one of the more conservative drying constants for maize was used, the one labelled as 1. Thus, it is evident that even the more conservative drying constant overpredicts the drying at the start of aeration.

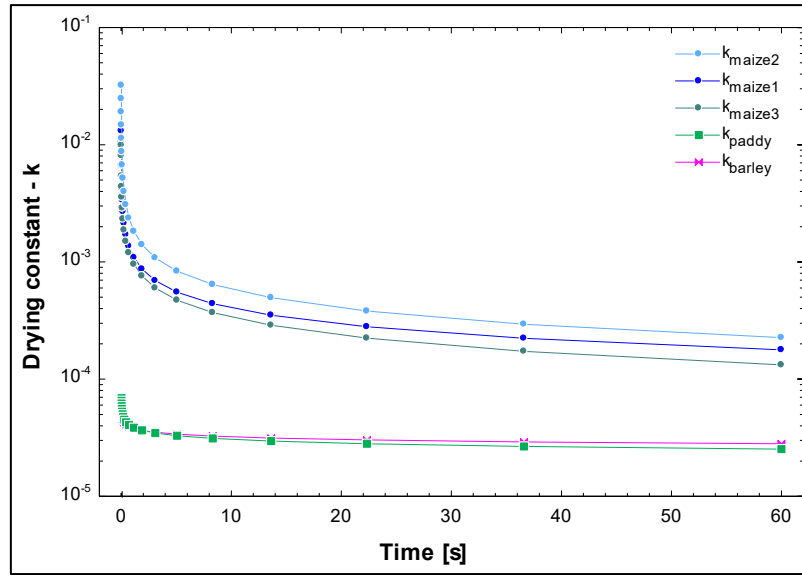


Figure 6.7: Drying constant equations comparison (1 minute)

To illustrate the change of the drying constant over a greater period of time, the drying constants for 10 hours of drying are plotted in Figure 6.8 below. In Figure 6.8 both axes are logarithmic. From Figure 6.8 it is evident that the drying constants of maize only start to approach those of barley and paddy after approximately an hour.

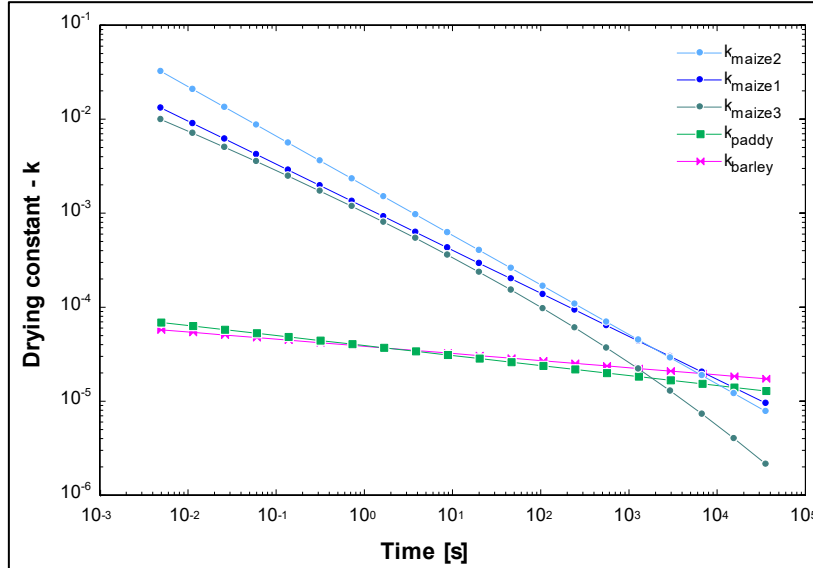


Figure 6.8: Drying constant equations comparison (10 hours)

The claim of the drying constant overpredicting the initial drying/cooling is now investigated. To compensate for the overprediction that occurs at the start of aeration, the simulation temperature results are adjusted by adding the absolute average deviation between the simulation and experimental temperatures. In Figure 6.9 below the experimental and adjusted simulation temperature results for layer 2 are compared.

As can be seen from Figure 6.9 after adjusting the simulation temperatures, the simulation and experimental results after the initial sharp decline in temperature are very similar. This illustrates that the overprediction of the cooling at the start of aeration is likely the main issue, and using a drying constant that more accurately predicts the evaporative cooling effect will increase the accuracy of the simulation.

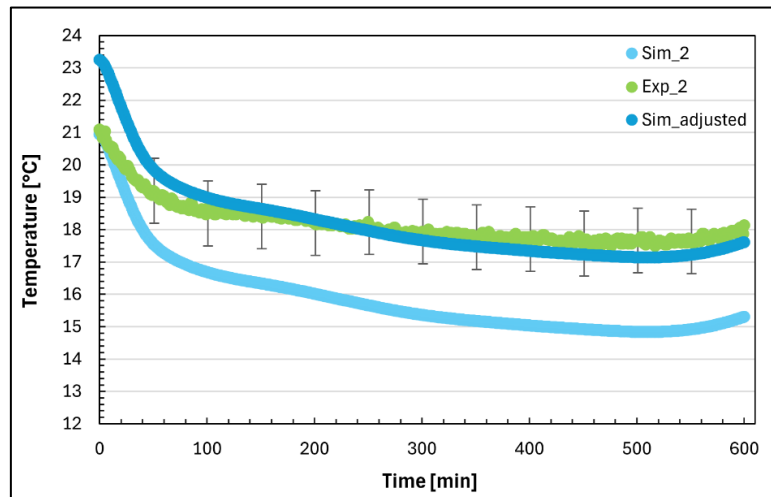


Figure 6.9: Adjusted simulation and experimental results comparison: Layer 2 temperatures

In Figure 6.10 below the experimental and adjusted simulation temperature results for layer 3 are compared. In Figure 6.10 the same is observed as was observed in Figure 6.9, for the adjusted simulation temperatures, the simulation and experimental results after the initial sharp decline in temperature are very similar.

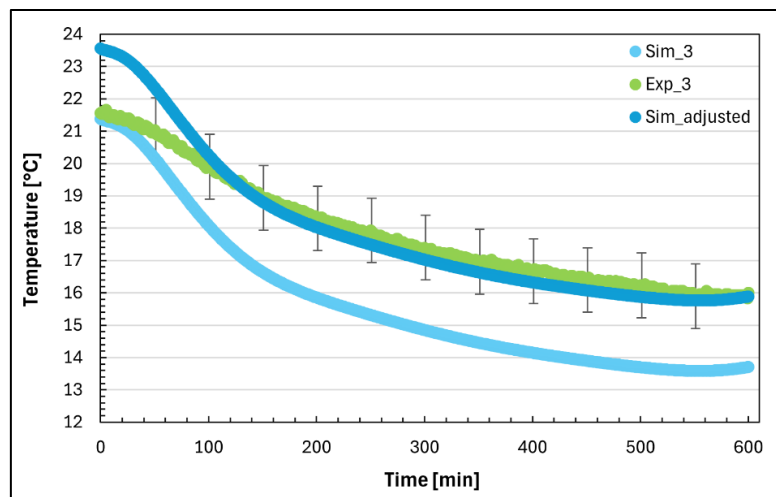


Figure 6.10: Adjusted simulation and experimental results comparison: Layer 3 temperatures

In Figure 6.11 below the experimental and adjusted simulation temperature results for layer 4 are compared. The initial decline in temperature for this layer is less sharp than that of the other layers because it is much higher up in the grain bulk; thus, it takes longer to cool this region, and it is more gradual. But, with the

adjusted simulation temperatures, the simulation and experimental results for the latter part of the aeration, after the initial gradual decline, are very similar.

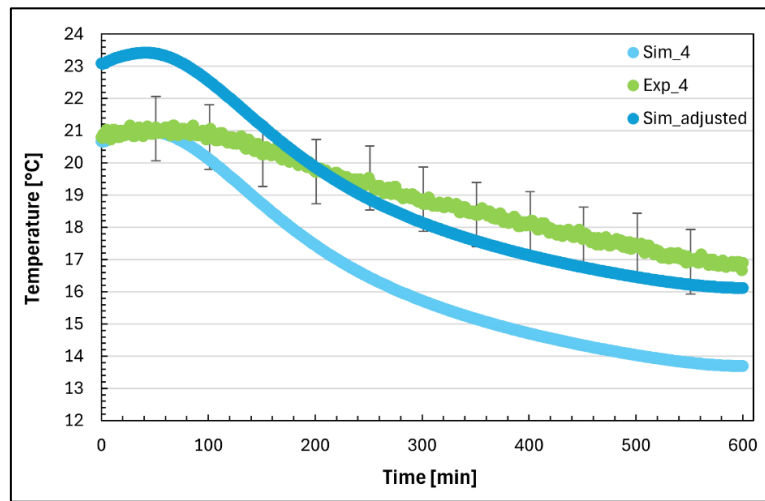


Figure 6.11: Adjusted simulation and experimental results comparison: Layer 4 temperatures

6.1.2.6 Validation conclusion

In conclusion, even though the predicted temperatures are lower than the experimental values, and the temperature front speed ratio is higher, it is still acceptable in the context of the measurement uncertainty. Thus, the simulation is valid to be used to obtain scenario results to construct the temperature front speed ratio graphs. Additionally, the dwell conditions predicted by the EES calculation model closely matched the experimental results; thus, this can be used in conjunction with the temperature front speed graph to predict the effects of aeration on temperature and moisture content.

6.2 Simulation scenarios

In this section, the simulation scenario results are presented. Firstly, the simulation scenarios are discussed. Next, the temperature front speed ratio graphs are presented. Thereafter, the contours of a few of the scenarios are presented to illustrate the propagation of the temperature front through the small-scale silo.

6.2.1 Simulation inputs

For the simulation scenarios, a range of grain temperatures and air conditions from the ASHRAE climatic design conditions are used as input for the simulation. The simulation inputs are summarised in Table 6.4 below. As can be seen in Table 6.4, the grain temperatures used as input are 35, 30, 25, and 20 [°C], and a constant moisture content of 16% is used. This temperature range is chosen because the higher temperatures represent the scenario in which the grain is freshly harvested and loaded into the silo while it is still hot. The lower temperatures represent grain in the silo that has already been aerated; thus, it is cooler, or grain

that was harvested when it was cooler and then loaded into the silo. A constant moisture content is used, since the literature showed that the temperature front speed is minimally dependent on the initial moisture content of the grain. The moisture content is chosen as 16%, which is higher than the desired regulatory value of 14%, because it is expected that the grain will likely be harvested and brought to the silo at a higher moisture content, and the aeration cooling process will cause some drying of the grain to occur.

For the air, the climatic design conditions for the months of December, July, and August are used. December is used because it is a very wet month, July is a very dry month, and August is the month in which GMC receives most of their maize during the harvest season. In Table 6.4 the dry bulb and wet bulb temperatures from the ASHRAE tables are given, and the relative humidity and specific humidity are calculated from the temperatures. The specific humidity of the grain interstitial air, which is calculated from the temperature and moisture content, is also given, as this is used as an input for the initialisation of the simulation.

For the December grain conditions, 25 and 20 [°C] grain simulations were performed to visualise and compare a heating temperature front with a cooling temperature front, which is the focus of this study. The rest of the scenarios in Table 6.4 are all cooling aeration scenarios.

Table 6.4: Simulation inputs

Month	Grain			Air				
	Temperature [°C]	Moisture content [%]	Specific humidity [kg/kg]	Dry bulb [°C]	Wet bulb [°C]	Relative humidity [%]	Specific humidity [kg/kg]	Velocity [m/s]
December	35	16	0.02996	26.5	20.1	55.87	0.01211	4.5
December	30	16	0.02198	26.5	20.1	55.87	0.01211	4.5
December	25	16	0.01595	26.5	20.1	55.87	0.01211	4.5
December	20	16	0.01143	26.5	20.1	55.87	0.01211	4.5
July	35	16	0.02996	19.3	11.1	35.10	0.004862	4.5
July	30	16	0.02198	19.3	11.1	35.10	0.004862	4.5
July	25	16	0.01595	19.3	11.1	35.10	0.004862	4.5
July	20	16	0.01143	19.3	11.1	35.10	0.004862	4.5
August	35	16	0.02996	22.4	12.9	32.01	0.005371	4.5
August	30	16	0.02198	22.4	12.9	32.01	0.005371	4.5
August	25 ²⁰	16	0.01595	22.4	12.9	32.01	0.005371	4.5

²⁰ For the August air conditions, 25 [°C] is the lowest grain temperature used, since 20 [°C] will result in the grain bulk undergoing heating, and not cooling.

6.2.2 Scenario results

The simulation scenario results are presented in this section. The temperature front speed ratios for each of the scenarios in Table 6.4 are processed as explained in Section 5.4.2. The temperature front speed graphs are given in Figure 6.12 to Figure 6.15. Each graph gives the temperature front speed ratio between the lowest point in Figure 5.4 in Section 5.4.2 and each one of the higher points.

Figure 6.12 below gives the temperature front speed graph between points 1 and 5. From Figure 6.12 it is evident that each of the four grain temperatures used in the scenarios very distinctly formed its own curve. Thus, it can be concluded that at the start of aeration, the ability to remove moisture from the grain is higher, and as aeration continues, this ability decreases. For each of the initial grain temperature curves, the curve approaches the initial grain temperature asymptotically. This means that when cooling the grain very slightly from its initial temperature, the cooling occurs very fast. But, as the target temperature to which the grain is being cooled decreases, the cooling time increases exponentially, and the front speed nears zero.

The resulting temperature front speed graph differs from what is expected from literature (Figure 2.5 by Sutherland et al. (1983)). The reason for this difference is because the temperature front speed of Sutherland et al. (1983) was calculated using an equilibrium model, which less accurately predicts the transfer of moisture. The non-equilibrium model used in the simulation more accurately predicts the transfer of moisture. Specifically, including the drying constant equation in the model means that the moisture on the surface of the kernels, which is initially present and dries easily, is captured. After the surface moisture is driven off, the ability to dry the grain becomes increasingly difficult because the moisture within the grain kernels must first diffuse back to the surface.

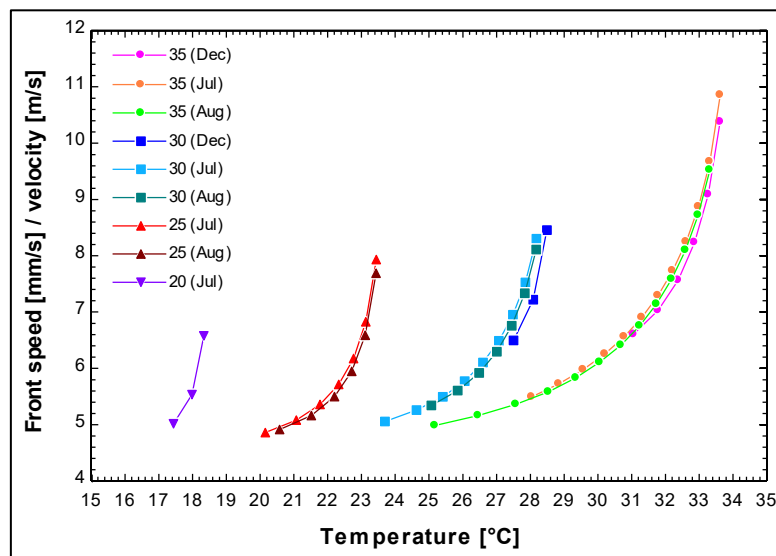


Figure 6.12: Temperature front speed ratio: 1 – 5

Figure 6.13 below gives the temperature front speed graph between points 2 and 5. The same trends and observations seen in Figure 6.12 is also evident in Figure 6.13. Comparing Figure 6.13 with Figure 6.12, it is evident that the temperature front speeds are higher for the two points that are closer together and, on average, lower than the two points that are a little further apart and higher. This makes sense because if the distance decreases, the time to see the same temperature change should decrease.

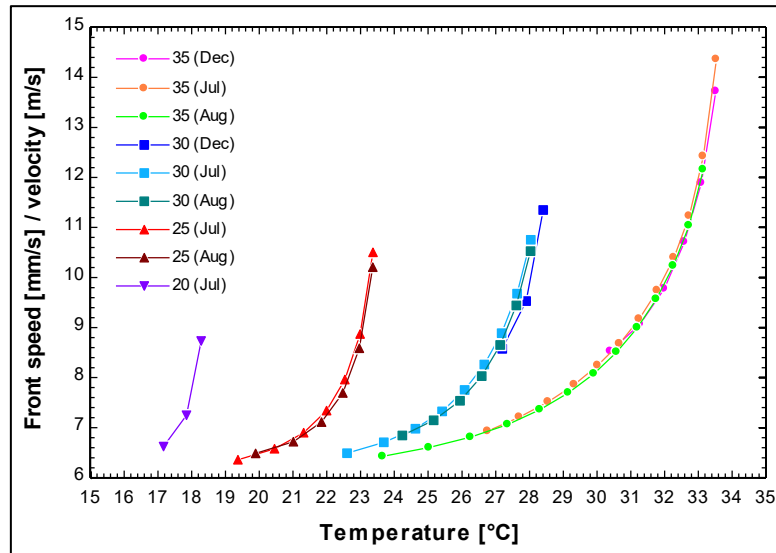


Figure 6.13: Temperature front speed ratio: 2 – 5

Figure 6.14 below gives the temperature front speed graph between points 3 and 5. Once again, the same trends that are observed in Figure 6.12 is also evident in Figure 6.14. Furthermore, the temperature front speed ratios in Figure 6.14 is higher than that in Figure 6.13 and Figure 6.12. This is because points 3 and 5 are closer together and on average lower than the two other point pairs.

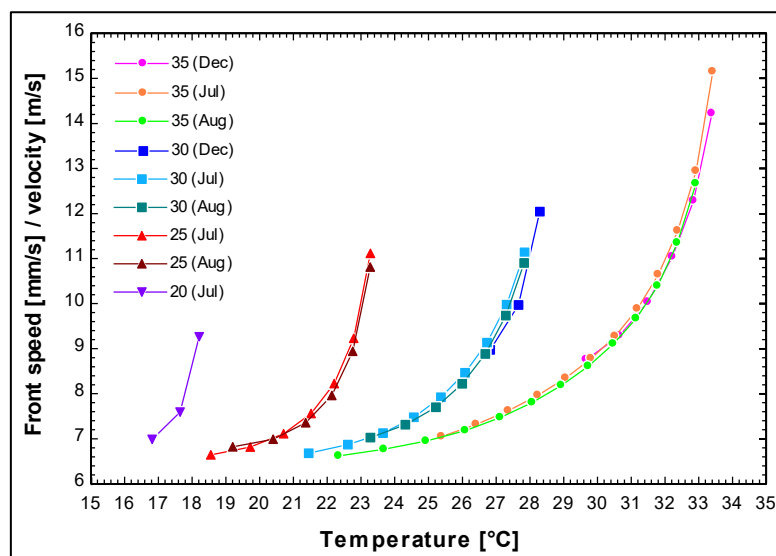


Figure 6.14: Temperature front speed ratio: 3 – 5

Figure 6.15 below gives the temperature front speed graph between points 4 and 5. Once again, the same trends that are observed in Figure 6.12 is also evident in Figure 6.15. The temperature front speed ratios in Figure 6.15 is only slightly higher than that of Figure 6.14. The reason for this is due to the manner in which the air propagates through the grain bulk. Since the air does not propagate uniformly from the bottom to the top, for the points nearer to the inlet, the difference in the temperature front speed is minimal.

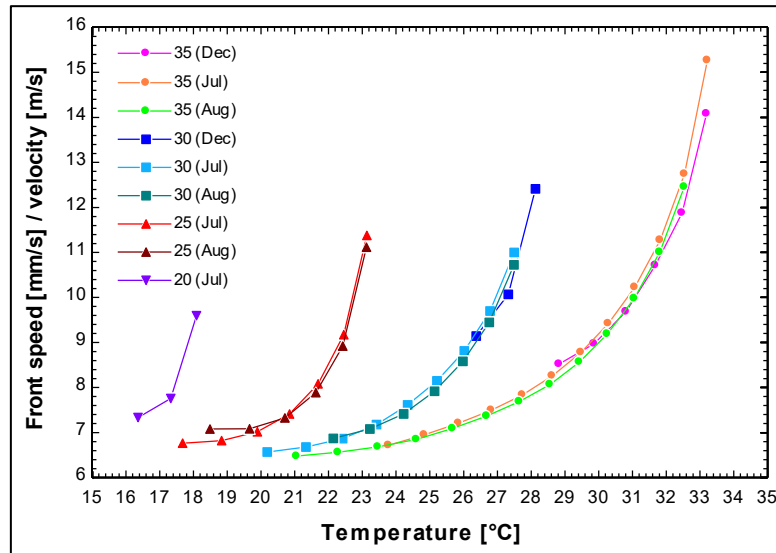


Figure 6.15: Temperature front speed ratio: 4 – 5

The propagation of the air through the silo during aeration is visualised in Figure 6.16 below. The results in Figure 6.16 are for the scenario where the grain is initially at 35 [°C] and the air conditions are for December. It is evident from Figure 6.16 that the cooling temperature front reaches the core of the silo last. After 6 hours of aeration, the sides of the bulk have already cooled to the dwell temperature of approximately 22 [°C], but at the core, the temperatures range from a little warmer than the dwell temperature at the bottom, to 32 [°C] at the top of the bulk. Thus, it can be concluded that tracking the temperature front speed along the centre axis is not representative of the conditions in the majority of the bulk. The centre axis is used for the calculation of the temperature front speed because GMC has only one temperature measurement string in the centre of the silo. This temperature string is their only source of information about what is happening inside the silo during aeration. Thus, with the measurement technology currently implemented, the current method is the only way to predict the outcome of aeration, which can be observed during aeration. However, the method is still very useful because, in general, the goal of aeration is to cool the entire bulk. Therefore, to do this, the centre will necessarily have to be cooled as well, even though it takes longer.

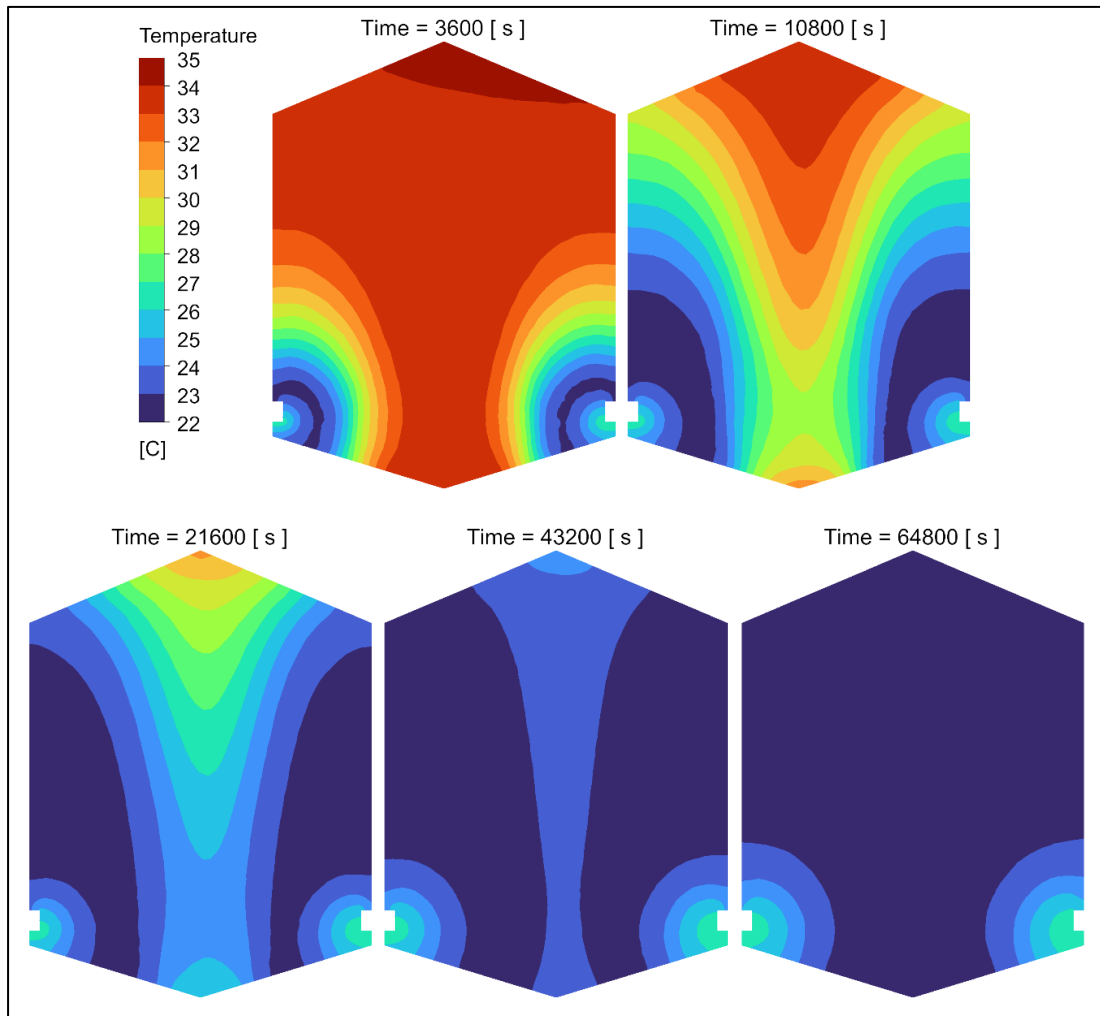


Figure 6.16: Cooling temperature front propagation

The results of two of the time steps of the simulation scenario discussed above are also presented as a 3D visualisation in Figure 6.17 below. From Figure 6.17 it is evident that there are no areas where the air flow does not reach, i.e., no dead zones. There are, however, areas where aeration cooling is slightly delayed. From Figure 6.17 it can be seen that after 3 hours of aeration, the bottommost centre area has only been cooled minimally. However, after a further 3 hours of aeration, this area has been cooled such that it is only approximately 3 [°C] warmer the dwell zone temperature. As mentioned previously, the cooling of the core of the bulk is also slightly delayed, but with continuous aeration, a uniform temperature can be achieved.

The temperature waves that can be observed near the air inlet in Figure 6.16, specifically from 10800 seconds onwards, is the temperature change that accompanies the moisture front. The propagation of the moisture front, for the same conditions as were used in Figure 6.16, is pictured in Figure 6.18 below. From Figure 6.18 it is evident that the moisture front moves very slowly. After 22 hours, the moisture front has only propagated a very short distance through the grain bulk. This is consistent with the literature, which also found that moisture fronts move significantly slower than temperature fronts.

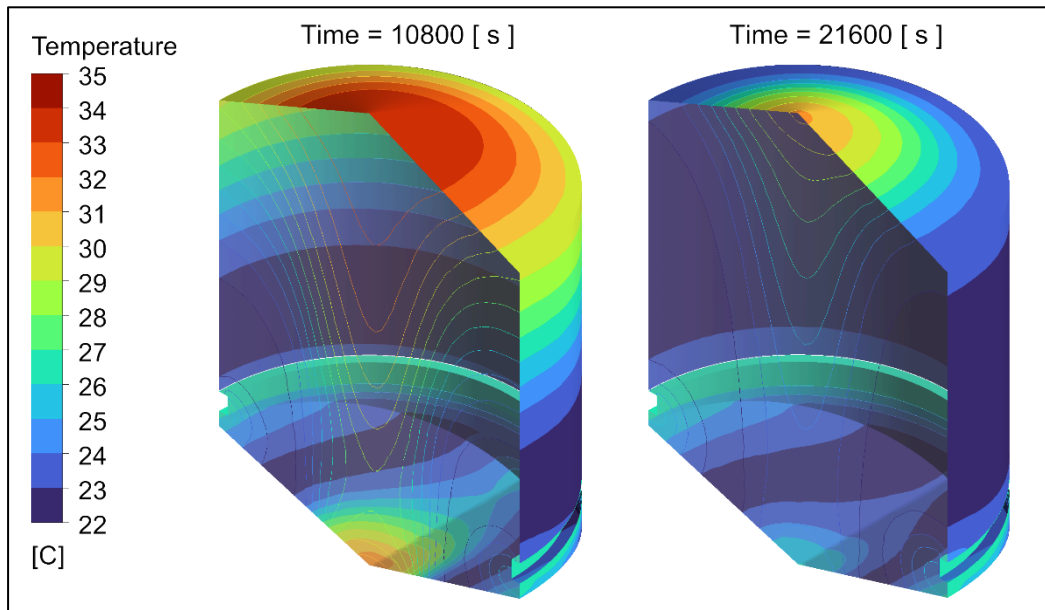


Figure 6.17: 3D cooling temperature front propagation

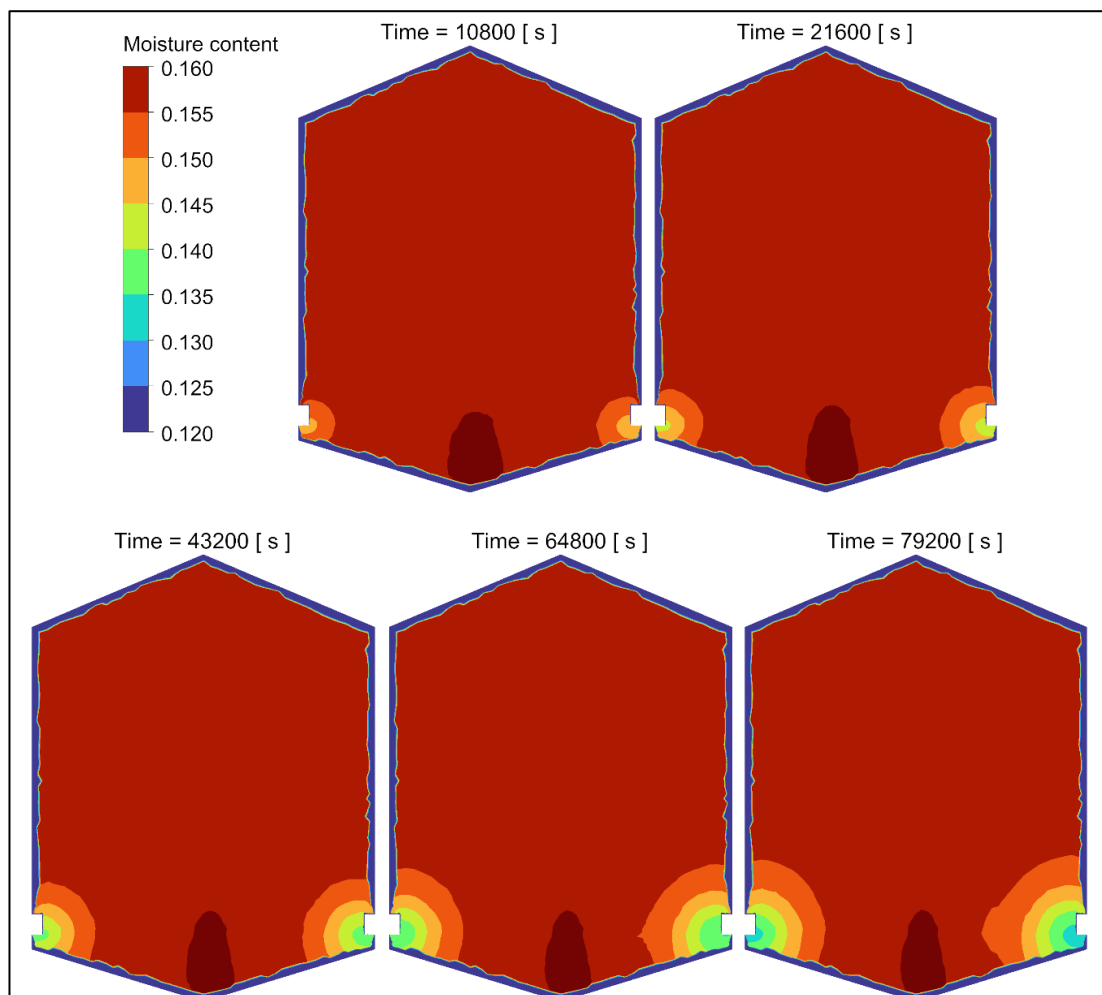


Figure 6.18: Moisture front propagation

Lastly, for the simulation scenario results section, the propagation of a heating temperature front is examined. The movement of a heating temperature front, with the grain initially at 20 [°C] and the inlet air conditions of December, is visualised in Figure 6.19 below. From Figure 6.19 it is evident that at the start of aeration, a cooling temperature wave moves through the entire bulk, cooling the bulk approximately 2 [°C]. This is due to evaporative cooling, as the air moves through the grain, the surface moisture evaporates, and the grain cools down. After this initial cooling, the grain bulk's temperature starts to increase by means of heating waves. It is observed that each heating wave propagates through the bulk on its own. This is in contrast to the cooling front, where all the waves of the front propagate together, each at its own pace.

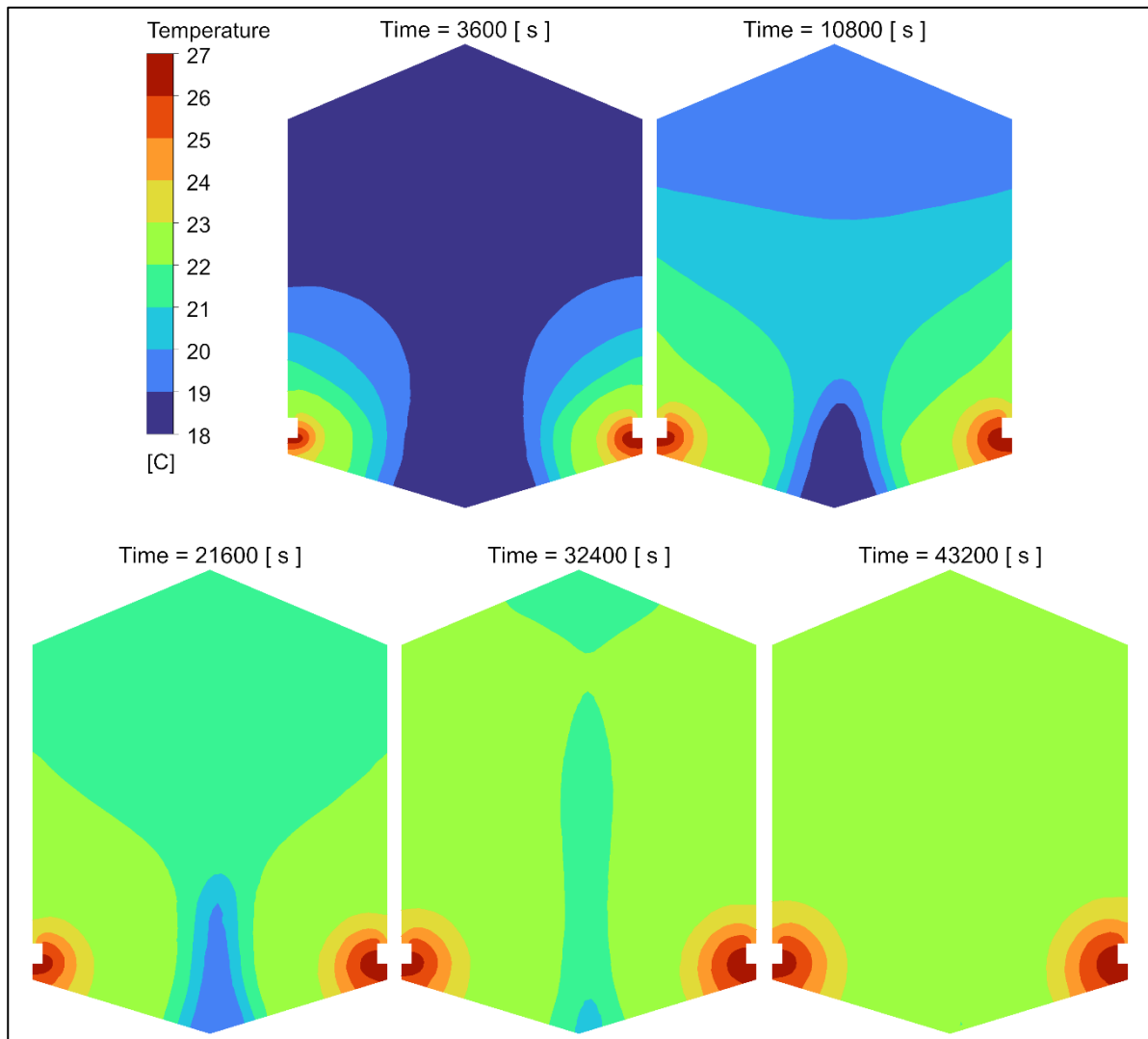


Figure 6.19: Heating temperature front propagation

6.3 Scaling validation results

Aeration data for the full-scale silo is provided by GMC for a period of 5 months, from when the silo first started to be filled with grain at the beginning of the harvest season. During this period, the grain level

changed regularly as the silo was being filled. An aeration period of 15 hours is identified from the data. This aeration period is chosen, since it follows a period of non-aeration of 20 hours, which is the longest non-aeration period after the grain level stopped changing. A long period of non-aeration preceding the aeration is desirable to ensure the moisture has had time to diffuse to the surface of the grain kernels. The temperature string data for the month of August can be found in Figure D.1 in Appendix D.3. The 15-hour aeration period used for the validation started the afternoon of the 17th and concluded the morning of the 18th. For this period, the average air temperature was 19 [°C], for the first 2 hours the average temperature was 27 [°C], and for the rest of the period it was 16.5 [°C]. The average air relative humidity was 63%.

At the start of the identified aeration period, the average grain temperature was 17 [°C]. The grain was not originally 17 [°C] when loaded into the silo, the temperature has changed due to heating and cooling aeration since it was loaded into the silo 2 months prior to this period. But, since this is the temperature of the grain at the start of the identified aeration period, this temperature is used. Using the methodology described in Section 5.4.3²¹, the temperature front speed ratio is calculated to be 1.51 [mm/s]/[m/s] for a grain temperature of 16.9 [°C]²². This temperature front speed ratio is calculated for the points in the full-scale silo that correspond to points 4 – 5 used in the simulation scenario results.

The full-scale temperature front speed ratio data point is now compared to Figure 6.15. Firstly, the closest curve to which the data point can be compared is the 20 [°C] initial grain temperature curve, thus this curve is used. When comparing the full-scale silo data point to the 20 [°C] curve, at 16.9 [°C] the temperature front speed ratio is approximately 7.5 [mm/s]/[m/s], compared to the full-scale silo value of 1.51 [mm/s]/[m/s]. The full-scale silo value is five times smaller than the simulation value. The reasons for deviations are discussed next.

The first reason for the deviation between the full-scale silo data and the simulation is the air velocity. The velocity used for the temperature front speed ratio calculation is based on the 9 [m³/s] air flow rate for the 45 [kW] fan. However, from the data, the fan power draw varies between 45 and 35 [kW], and the fan

²¹ Due to the non-uniform grain temperatures, analysing the time taken for temperature points to reach the same temperature would not be representative of the movement of the temperature front. Therefore, the time taken for the temperature points to display the same delta is used. Using this analysis method for the scenario results is the same as analysing the change to the same temperature, as the temperatures there all start at the same point. The temperature at which the temperature front speed ratio point is assessed is taken as the average temperature of all the points analysed.

²² The 16.9 [°C] is the x-axis temperature value for the temperature front speed ratio, while the 17 [°C] is the initial grain temperature, which refers to the temperature curve.

curve is not available to determine the actual flow rate. Therefore, for a lower power draw, the actual flow rate will be lower than the 9 [m³/s], which would result in a larger ratio.

The second reason for the deviation is attributed to the grain that was aerated almost constantly for 2 months prior to the aeration period investigated. This results in the evaporative cooling potential being significantly reduced, in turn reducing the temperature front speed. This phenomenon, in which the temperature front speed is much lower after aerating for a while than just after starting to aerate, is also observed in the simulation scenario temperature front speed graphs.

Thirdly, the grain bulk consists of layers of varying temperature that have not reached a uniform temperature, even after months of aeration. The prior aeration was also not always conducted at temperatures conducive to cooling, resulting in the grain being heated up or showing no change during aeration.

The fourth reason is regarding the moisture content. The moisture content of the grain is unknown. Even though it is assumed that moisture content has a minimal influence on the temperature front speed, as was seen by Sutherland et al. (1983), it is not known to what extent this assumption holds, nor how much the real moisture content differs from that used in the simulations. Additionally, the different grain layers most likely had varying moisture contents, and the effect of this on the results is unknown.

Lastly, the ambient air temperature did not remain constant throughout the aeration period, but rather varied up to 17 [°C]. Periods of heating followed by periods of cooling during a single aeration session counteract one another. This results in the total aeration time not contributing towards cooling the grain. Additionally, the total time during which the air is cooler than the grain does not contribute towards cooling the grain below its initial temperature, because a portion of this time is used to undo the heating that had previously occurred. Thus, the aeration time that was spent undoing the heating could result in an inflated temperature front propagation time. Furthermore, since the temperature front speed is calculated as the distance between the measurement points divided by the time taken for a temperature change to propagate between the two points, a larger propagation time would decrease the temperature front speed and consequently also the temperature front speed ratio. Therefore, if the heating did not occur during the aeration period, the calculated ratio could have been larger.

In conclusion, due to the limitations identified, the full-scale silo and simulation comparison is treated as a preliminary consistency check rather than a definitive scaling validation. The comparison shows that, with the available operational silo data and the assumptions used, the full-scale silo temperature front speed ratio lies below the nominal simulation trend. The full-scale silo result is largely influenced by the uncertainties in air flow, boundary condition variations, and initial grain state. To achieve a more conclusive assessment of the scaling validity, additional full-scale silo measurements are required, particularly of air flow (or

pressure drop) and bulk moisture content. Furthermore, carefully selected aeration events, that more closely replicate the controlled conditions of the simulation study would be necessary to strengthen the validation.

6.4 Practical application of results

In this section, the practical applications of the results are discussed. One of the objectives of this study is to develop guidelines on how the results can be used to better inform GMC's aeration management. The results that are specifically applicable to developing these guidelines are the temperature front speed graphs and the EES dwell conditions calculation model. The dwell conditions calculation model is used to predict the dwell state conditions that will be reached when aerating a bulk, initially at a certain temperature and moisture content, with air of a certain temperature and relative humidity. The temperature front speed graph is then used to predict how long it will take for the bulk to reach the dwell conditions²³, or a different desired temperature. When predicting the time until the front reaches another desired temperature, the bulk will not be uniformly at this temperature.

The following guidelines can be used to inform aeration management:

1. Calculate the dwell conditions from the initial grain temperature and moisture content, and the inlet air temperature and relative humidity.
2. Choose the applicable graph from which to calculate the temperature front speed ratio based on the height of the bulk.²⁴
3. Identify the grain temperature curve on the chosen graph that is closest to the initial grain temperature. If necessary, the required grain temperature curve can be interpolated from the two closest curves.
4. Using the curve, read off the ratio that corresponds to the desired grain temperature.
5. Using the ratio and the physical velocity of the air in the bulk, calculate the temperature front speed.
6. Using the calculated temperature front speed and the known height of the bulk, calculate the time required to reach the desired temperature.

²³ When stating that the bulk will reach the dwell conditions, it means that the majority of the bulk is at the dwell conditions. The moisture front will already have started propagating at the area near the inlet. The only way for the bulk to be completely uniform, is to aerate it until it reaches equilibrium with the air.

²⁴ If the bulk is more than approximately half full, the 1 – 5 graph can be used, although the resulting time will be somewhat optimistic.

These guidelines can also be used to calculate the grain temperature after aerating for a certain amount of time by simply reversing the steps. An example of how these guidelines can be used to inform the aeration management is now given.

Let the initial temperature and moisture content of a grain bulk filling half of silo A1 be 25 [°C] and 16%, respectively. The inlet ambient air has a temperature of 22 [°C] and a relative humidity of 70% and has a flow rate of 9 [m³/s]. Using the EES calculation model, the dwell temperature and moisture content are calculated to be 20.8 [°C] and 15.85%, respectively. Since the silo is half filled, Figure 6.12 is used to obtain the temperature front speed. From Figure 6.12, using the 25 [°C] grain temperature curve, the front speed ratio corresponding to a temperature of 20.8 [°C], is found to be approximately 5 [mm/s]/[m/s]. The physical velocity inside the silo is calculated to be 0.0884 [m/s]. Thus, the temperature front speed is calculated to be 0.442 [mm/s]. If half of the silo height is 21.5 [m], the time it takes for the trailing edge of the temperature front to reach the top of the grain bulk is calculated to be 13.5 hours.

6.5 Conclusion

In this chapter, the experimental results have been presented, and after comparing the validation simulation results with the experimental results, the simulation model has been validated. The EES calculation model has also been validated using the experimental results. From the experimental and simulation results, it has been observed that the simulation overpredicted the cooling at the start of the simulation, and it has been concluded that the drying constant used in the simulation is responsible for this overprediction.

Simulation results for various scenarios have been obtained and used to create the temperature front speed ratio graphs. From these results, it has been observed that at the start of aeration, there is a higher ability to cool the grain; thus, each initial grain bulk temperature formed its own temperature front speed curve. Additionally, it has been observed that the temperature front reaches the core of the silo last. Thus, the centre axis is not the ideal location for tracking the temperature front, but since GMC only has a temperature measurement string in the centre of the silo, this is the only way in which the temperature front can be observed.

Full-scale silo data has been obtained from GMC. From the data, an aeration period has been identified, and a temperature front speed ratio has been calculated. Compared with the simulation scenario results, the full-scale silo data resulted in a lower temperature front speed ratio. The reasons for the deviation have been discussed, and one of the main reasons has been attributed to the months of constant aeration that the silo underwent. Thus, the scaling has shown promising results but has not been definitively validated.

Lastly, guidelines on how the results can be used to better inform GMC's aeration management have been discussed.

CHAPTER 7 CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

Concrete silos are used in the grain management industry in South Africa to preserve grain after harvest for year-round consumption. This is especially true for maize, which is one of South Africa's largest staple foods. GMC is one of South Africa's largest grain management companies, and they make use of aeration to preserve the quality of their grain. The goal of aeration at GMC is to cool the grain down.

The grain quality department at GMC provides silo managers with guidelines for aeration management. These guidelines, however, do not provide information on the effect of aeration after a certain amount of time. Additionally, the interpretation of the guideline is largely dependent on the silo managers' own experience. Furthermore, the only live information that GMC has on what happens inside the silo during aeration is a single temperature measurement string in the middle of the silo.

In the mid to late 1900's several researchers investigated what happens to a grain bulk that is being aerated using analytical models. During aeration, three zones are formed: the initial grain conditions zone, the dwell state zone, and the zone where the grain has reached equilibrium with the incoming air. These zones are separated by two fronts, the temperature front and the moisture front. Research has been done on both estimating the dwell state conditions and the speed of the temperature front. Additionally, it has been found that the speed of the temperature front is primarily dependent on the initial grain temperature, the bulk geometry, and the air velocity.

More recently, 3D CFD simulations have been widely used to model the aeration of maize in a silo. For these simulations, the grain bulk is modelled as a porous medium. Several researchers have studied how these simulations can be adapted to more accurately model the aeration process. Specifically, research has been done to model the heat and moisture transfer during aeration and the anisotropic nature of the grain bulk.

The aim of this study was to develop a transient 3D simulation of the aeration of maize in a silo, to determine what the effects of aeration are, and how long it takes to observe these effects. However, due to computational and experimental validation limitations, it would not have been feasible to simulate the aeration in a full-size silo. Therefore, a small-scale model has been used for the simulation and experimental validation. For the results to be applicable to GMC's silos, a method of scaling the results has been developed. This has been done by determining the temperature front speed as a ratio of the velocity of the aeration air. The validity of the scaling methodology has been assessed using full-scale silo data.

The experimental validation results have shown that the simulation model moderately overpredicted the cooling and the temperature front speed during aeration, specifically at the start of aeration. This has been shown to be caused by the drying constant used in the simulation model, which had been obtained from literature.

The simulation scenarios' results have shown that at the start of aeration, there is a higher ability to cool the grain. Thus, each initial grain temperature results in its own curve on the temperature front speed ratio graph. Furthermore, it has been observed that the temperature front reaches the core of the silo last. Thus, tracking the temperature front speed along the centre axis is not ideal, but since it is the only location inside the silo for which GMC has live data, this is the only way in which the temperature front can be observed. Furthermore, it has been observed from a 3D visualisation of the results that no air flow dead zones exist inside the silo.

The full-scale silo scaling validation results have shown that the full-scale temperature front speed ratio is lower than that predicted by the simulation. However, the conditions under which the full-scale silo aeration data has been obtained is expected to result in lower values. The constant aeration that the silo underwent prior to the aeration period investigated significantly reduced the cooling potential, leading to a smaller temperature front speed ratio. Thus, the scaling has shown promising results but has not been definitively validated.

Finally, guidelines have been given on how the temperature front speed ratio results along with the EES dwell conditions calculation model could be used to better inform GMC's aeration management.

Therefore, the objectives of this study, to set up a simulation model, verify it, and validate it using experimental data, scale the results to be applicable for a full-scale silo, and develop a guide on how these results can be practically used, have been completed.

7.2 Problem statement revisited

From Section 1.2 the problem statement can be summarised into two points, 1) the aeration guidelines lack data on the effect of aeration on the grain bulk, and 2) the validity of scaling small-scale silo results to the full-scale silo is unknown. Firstly, the problem regarding a lack of data has been addressed with the scenario results obtained in this study. Furthermore, guidelines have been proposed for how this data and the EES dwell conditions calculation model can be used to determine what effect certain ambient conditions will have on the temperature and moisture content of the grain bulk, and how long it will take to observe the effect. Secondly, the validity of scaling the small-scale results to the full-scale silo could not be definitively confirmed, although it did show promising results. One of the main reasons identified for the deviation

between the small-scale and full-scale results has been attributed to the months of constant aeration that the silo underwent, which resulted in the evaporative cooling potential to be significantly reduced.

7.3 Recommendations

The following recommendations are made for future research:

- Evaluate different drying constants for maize to assess if any other drying constants available in literature are better able to accurately predict the cooling that occurs during aeration.
- With the temperature measurement limitation of GMC in mind, investigate how the conditions further away from the centre can be related to the conditions in the centre of the silo, so that the current temperature front speed ratios can be more effectively used to get an idea of what the state of the majority of the grain bulk is.
- Investigate the effect of implementing variable porosity into the simulation model.
- Investigate the feasibility of simulating a full-scale silo using advanced computer hardware.
- Investigate the trends of both cooling and heating temperature fronts, since the majority of the research was done in the 1900s. Thus, make use of 3D simulations to better understand the differences between cooling and heating temperature fronts.

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APPENDIX A CODES

A.1 UDF code

```
#include "udf.h"
#include "metric.h"
#include "mem.h"
#include "sg_udms.h"

/*      Heat and moisture transfer in porous grain bulk */

/*-----*/
/* Define constants */

#define A 312.31          /* Chung-Pfost, eq works with %db MC and tempratures in C*/
#define B 16.958
#define C 30.205

#define rho_m 1270       /* Maize density (dry basis) */

#define P_atm 101325

#define h_to_v 0.58
#define f_v 3.0          /* Viscous resistance component */
#define f_i 1.7          /* Inertial resistance component */
#define d_m 0.0065       /* Maize diameter*/

int last_ts = -1;        /* Global variable */

/*-----*/
/* Name UDM and UDS */

DEFINE_EXECUTE_ON_LOADING(udm_names,libname)
{
    #if PARALLEL

        Set_User_Memory_Name(0, "porosity");
        Set_User_Memory_Name(1, "moisture_content");
        Set_User_Memory_Name(2, "relative_humidity");
        Set_User_Memory_Name(3, "equilibrium_moisture_content");
        Set_User_Memory_Name(4, "K");
        Set_User_Memory_Name(5, "N");
        Set_User_Memory_Name(6, "dMC_dT");
        Set_User_Memory_Name(7, "hs");
        Set_User_Memory_Name(8, "E_con");
        Set_User_Memory_Name(9, "Source_T");
        Set_User_Memory_Name(10, "Source_M");
        Set_User_Memory_Name(11, "air_density");
        Set_User_Memory_Name(12, "air_conductivity");
        Set_User_Memory_Name(13, "air_viscosity");
        Set_User_Memory_Name(14, "D_Eff");
        Set_User_Memory_Name(15, "maize_bulk_density");
```

```

Set_User_Memory_Name(16, "maize_conductivity");
Set_User_Memory_Name(17, "MC_wb");

Set_User_Scalar_Name(0, "specific_humidity");

#endif
}

/*-----*/
/* Set the initial moisture content, MC, and the specific humidity, omega, of intergranular air */

DEFINE_INIT(moisture_i,d)
{
    #if PARALLEL

    cell_t c;
    Thread *t;

    real MC, T_K, T_C, ERH, P_sat, P_e, omega_e;

    real x[ND_ND];

    char zone;

    real T[5] = {298.15,295.55};
    real MC_wb[5] = {0.16,0};    /* WET BASIS */

    /* Loop through all the cell threads in the domain */

    thread_loop_c(t,d)
    {
        begin_c_loop(c,t)
        {
            C_CENTROID(x,c,t);

            if ( (sqrt(pow(x[0],2) + pow(x[1],2)) >= 0.393) && (x[2] <= 0.211) && (x[2] >=
0.16368396349) )
            {
                zone = 1;
            }
            else if (x[2] <= 1.2)
            {
                zone = 0;
            }
            /* Grain */

            C_T(c,t) = T[zone];    /*

Initialize temperature */

            T_K = C_T(c,t);
            /* Fluent uses K as SI unit */
            T_C = T_K - 273.15;

```

```

        C_UDMI(c,t,17) = MC_wb[zone];
        MC = MC_wb[zone] / (1 - MC_wb[zone]);          /* Convert from WB to
DB, to be used in calculations */
        C_UDMI(c,t,1) = MC;

        ERH = exp( -A/(T_C + C) * exp(-B * MC) );    /* ERH of intergranular air, it is
assumed that the grain and air is in local equilibrium at the start*/

        /* Ensure air does not become supersaturated */
        if (ERH > 0.99)
        {ERH = 0.99;}
        else if (ERH < 0.1)
        {ERH = 0.1;}

        P_sat = 6.0e25 / pow(T_K,5) * exp(-6800 / T_K);

        P_e = ERH * P_sat;

        omega_e = 0.622 * P_e / (P_atm - P_e);

        if(omega_e < 0.001)
        {omega_e = 0.001;}

        C_UDSI(c,t,0) = omega_e;

    }
    end_c_loop(c,t);
}
#endif
}

/*-----*/
/* Adjust values */

DEFINE_ADJUST(update_domain,d)
{
    #if PARALLEL

        real physical_dt, flow_time, T_K, T_C, MC, omega, porosity, P_sat, P_e, ERH, EMC,
drying_constant_K, drying_constant_N, dMC_dT, MC_new, vol, dT_dPsat, dERH_dT, hs_hv, hv, hs,
E_con;

        real x[ND_ND];

        cell_t c;
        Thread *t;

        int curr_ts;
        curr_ts = N_TIME;

        if (last_ts != curr_ts)
        {
            last_ts = curr_ts;

```

```

Message("ADJUST: iteration = %d \n", curr_ts);
physical_dt = CURRENT_TIMESTEP;
flow_time = CURRENT_TIME;

thread_loop_c(t,d)
{
    begin_c_loop(c,t)
    {

        T_K = C_T(c,t);
        T_C = T_K - 273.15;

        MC = C_UDMI(c,t,1);
        omega = C_UDSI(c,t,0);
        C_UDMI(c,t,0) = 0.4;          /*Porosity*/
        porosity = C_UDMI(c,t,0);

        P_sat = 6.0e25 / pow(T_K,5) * exp(-6800 / T_K);

        if(omega < 0.001)
        {omega = 0.001;}

        P_e = omega * P_atm / (0.622 + omega);

        ERH = P_e / P_sat;
        if (ERH > 0.99)
        {ERH = 0.99;}
        else if(ERH < 0.1)
        {ERH = 0.1;}

        C_UDMI(c,t,2) = ERH;

        EMC = -1/B * log( -(T_C + C)/A * log(ERH) ); /* DRY BASIS */

        C_UDMI(c,t,3) = EMC;

        drying_constant_K = 0.0549 + 0.00504*T_C;
        /* Misra & Brooker, 1978 */
        drying_constant_N = 0.54 + 0.0032*ERH;      /* DRY BASIS */
        C_UDMI(c,t,4) = drying_constant_K;
        C_UDMI(c,t,5) = drying_constant_N;

        dMC_dT = -(0.0002777777777) * drying_constant_K *
        drying_constant_N * pow((flow_time/3600),(drying_constant_N - 1)) * (MC - EMC); /*
        Divide by 3600, beacuse drying constant unit is per hour, but time in Fluent is in seconds.*/

        C_UDMI(c,t,6) = dMC_dT;

        MC_new = MC + dMC_dT * physical_dt;
        MC = MC_new;
        C_UDMI(c,t,1) = MC;
        C_UDMI(c,t,17) = MC / (1 + MC);
        /* Calculate new wb MC*/

```

```

        vol = C_VOLUME(c,t);

        dT_dPsat = (T_K / P_sat) / (6800 / T_K - 5);
        dERH_dT = A * ERH / pow((T_C + C),2) * exp(-B * EMC);

        hs_hv = 1 + P_sat / ERH * dT_dPsat * dERH_dT;
        hv = (-2.3827 * T_C + 2501.7) * 1000; /* Line
of best fit 0.01 to 65 C */

        hs = hs_hv * hv;
        C_UDMI(c,t,7) = hs;

        E_con = -vol * hs * (1 - porosity) * rho_m * dMC_dT; /* Multiply with
vol, so than E_con unit is W */
        C_UDMI(c,t,8) = E_con;

    }
    end_c_loop(c,t);
}

}
#endif
}

/*-----*/
/* Define energy source */

DEFINE_SOURCE(energy_source,c,t,dS,eqn)
{
    #if PARALLEL

        real porosity, dMC_dT, hs, Source_T;

        porosity = C_UDMI(c,t,0);
        dMC_dT = C_UDMI(c,t,6);
        hs = C_UDMI(c,t,7);

        Source_T = hs * (1 - porosity) * rho_m * dMC_dT;
        C_UDMI(c,t,9) = Source_T;

        dS[eqn] = 0.0;

        return Source_T;

    #endif
}

/*-----*/
/* Define moisture source */

DEFINE_SOURCE(moisture_source,c,t,dS,eqn)
{
    #if PARALLEL

        real dMC_dT, porosity, Source_M;

```

```

porosity = C_UDMI(c,t,0);
dMC_dT = C_UDMI(c,t,6);

Source_M = -(1 - porosity) * rho_m * dMC_dT;
C_UDMI(c,t,10) = Source_M;

dS[eqn] = 0.0;

return Source_M;

#endif
}

/*-----*/
/* Define properties */

DEFINE_PROPERTY(air_density,c,t)
{
    #if PARALLEL

    real rho_a, T_K, T_C;

    T_K = C_T(c,t);
    T_C = T_K - 273.15;

    rho_a = 1.293394 - 0.005538444*T_C + 3.860202e-05*pow(T_C,2) - 5.253606e-07*pow(T_C,3);
    C_UDMI(c,t,11) = rho_a;

    return rho_a;

    #endif
}

DEFINE_SPECIFIC_HEAT(air_cp,T,Tref,h,yi)
{
    #if PARALLEL

    Thread *t;
    cell_t c;
    real cp_a;

    if(T < 274.15)
    {T = 275.15;}

    cp_a = 1004.571 + 2.050637*(T-273.15) - 0.1631537*pow((T-273.15),2) + 0.0062123*pow((T-273.15),3) - 8.830479e-05*pow((T-273.15),4) + 5.071307e-07*pow((T-273.15),5);

    *h = cp_a * (T - Tref);

    return cp_a;

    #endif
}

```

```

}

DEFINE_PROPERTY(air_conductivity,c,t)
{
    #if PARALLEL

    real k_a, T_K, T_C;

    T_K = C_T(c,t);
    T_C = T_K - 273.15;

    k_a = 0.0240074 + 7.27841e-05*T_C - 1.788037e-07*pow(T_C,2) - 1.351704e-09*pow(T_C,3) -
3.322413e-11*pow(T_C,4);
    C_UDMI(c,t,12) = k_a;

    return k_a;

    #endif
}

DEFINE_PROPERTY(air_viscosity,c,t)
{
    #if PARALLEL

    real mu_a, T_K, T_C;

    T_K = C_T(c,t);
    T_C = T_K - 273.15;

    mu_a = 1.715748e-05 + 4.722402e-08*T_C - 3.663027e-10*pow(T_C,2) + 1.873237e-
12*pow(T_C,3) - 8.050219e-14*pow(T_C,4);
    C_UDMI(c,t,13) = mu_a;

    return mu_a;

    #endif
}

DEFINE_DIFFUSIVITY(uds_diffusivity,c,t,i)
{
    #if PARALLEL

    real E_a = 29.56e3;
    real D_0 = 1.67e-05;
    real R = 8.3144598;
    real T_K = C_T(c,t);
    real D_eff;
    real rho_a = C_UDMI(c,t,11);

    D_eff = rho_a * D_0 * exp(-E_a / (R * T_K));
    C_UDMI(c,t,14) = D_eff;

    return D_eff;
    #endif
}

```

```

        #endif
    }

DEFINE_PROPERTY(bulk_density,c,t)
{
    #if PARALLEL

        real porosity, rho_m_bulk;

        porosity = C_UDMI(c,t,0);
        rho_m_bulk = rho_m * (1 - porosity);
        C_UDMI(c,t,15) = rho_m_bulk;

        return rho_m_bulk;

    #endif
}

DEFINE_SPECIFIC_HEAT(maize_cp,T,Tref,h,yi)
{
    #if PARALLEL

        Thread *t;
        cell_t c;
        real cp_m;

        if(T < 274.15)
        {T = 275.15;}

        cp_m = ( 1.3066 + 1.2045*0.1905 + 0.0198*(T - 273.15) ) * 1000;          /* DRY BASIS */

        *h = cp_m * (T - Tref);

        return cp_m;

    #endif
}

DEFINE_PROPERTY(maize_conductivity,c,t)
{
    #if PARALLEL

        real k_m, T_K, T_C;
        real MC = C_UDMI(c,t,1);

        T_K = C_T(c,t);
        T_C = T_K - 273.15;

        k_m = 0.028 + 0.1321*MC + 3.4981e-03*T_C - 0.128*pow(MC,2) - 2.24e-05*pow(T_C,2);
        /* DRY BASIS */
        C_UDMI(c,t,16) = k_m;

        return k_m;

    #endif
}

```

```

    #endif
}

```

A.2 EES dwell state calculation model code

Procedure point_b(EMC3, T_wet, A, k_B, C: T, omega)

```

    i := 0
    wb = 0
    P_atm = 101.325 [kPa]

```

Repeat

```

    i := i + 0.1
    T := i
    RH := exp( -A/(T + C) * exp(-k_B * EMC3) )
    wb := wetbulb(AirH2O, T = T, r = RH, P = P_atm)

```

Until (T_wet - wb < 0.1)

```

    omega := humrat(AirH2O, T = T, r = RH, P = P_atm)

```

End

{Constants}

//Maize

```

A = 312.31 [C]
B = 16.958 [-]
C = 30.205 [C]

```

{Calculation for any T and RH}

```

P_atm = 101.325 [kPa]

```

```

T_air[1] = {26.5} {19.3} 22 [C]
RH_air[1] = 0.7 [-]
//omega_air[1] = 0.007 [-]
T_wet[1] = {20.1} 11.1 {12.9} [C]
//RH_air[1] = relhum(AirH2O, T = T_air[1], B = T_wet[1], P = P_atm)
omega_air[1] = humrat(AirH2O, T = T_air[1], r = RH_air[1], P = P_atm)
EMC_[1] = -1/B * ln( -(T_air[1] + C)/A * ln(RH_air[1]) )
T_wet_[1] = wetbulb(AirH2O, T = T_air[1], r = RH_air[1], P = P_atm)
EMC_A_wb = EMC_[1] / (1 + EMC_[1]) * 100

```

```

T_maize[1] = 25 [C]
MC_wb[1] = 0.16 {0.125} [-]
MC_[1] = MC_wb[1] / (1 - MC_wb[1])
RH_maize[1] = exp( -A/(T_maize[1] + C) * exp(-B * MC_[1]) )
omega_maize[1] = humrat(AirH2O, T = T_maize[1], r = RH_maize[1], P = P_atm)
EMC_C_wb = MC_wb[1]*100

```

"EMC Lines"

```

//A
EMC1 = EMC_[1]
Duplicate i=1,40

    T1_[i] = i
    RH1_[i] = exp( -A/(T1_[i] + C) * exp(-B * EMC1) )
    omega1_[i] = humrat(AirH2O, T = T1_[i], r = RH1_[i], P = P_atm)

End

//C
EMC2 = MC_[1]
Duplicate i=1,40

    T2_[i] = i
    RH2_[i] = exp( -A/(T2_[i] + C) * exp(-B * EMC2) )
    omega2_[i] = humrat(AirH2O, T = T2_[i], r = RH2_[i], P = P_atm)

End

"Air wet bulb line"
Duplicate i=0,100

    RH_wb[i] = i/100
    T_db[i] = temperature(AirH2O, B = T_wet_[1], r = RH_wb[i], P = P_atm)
    omega_wb[i] = humrat(AirH2O, T = T_db[i], r = RH_wb[i], P = P_atm)

End

//Estimated temperature

Call point_b(EMC2, T_wet_[1], A, B, C: T_est, )

"T_est = 25 [C]"

MC_dwell_wb[1] = MC_wb[1] - ( (T_maize[1] - T_est)/28 [C] )/100           //Estimated MC
EMC_B_wb = MC_dwell_wb[1]*100

//B
EMC3 = MC_dwell_wb[1] / (1 - MC_dwell_wb[1])
Duplicate i=1,40

    T3_[i] = i
    RH3_[i] = exp( -A/(T3_[i] + C) * exp(-B * EMC3) )
    omega3_[i] = humrat(AirH2O, T = T3_[i], r = RH3_[i], P = P_atm)

End

"omega_B[1] = humrat(AirH2O, T = T, B = T_wet_[1], P = P_atm)"
Call point_b(EMC3, T_wet_[1], A, B, C: T_B[1], omega_B[1])

$RunMacroAfter
UpdatePlot

```

\$EndMacro

A.3 Orifice air flow rate calculation

```
D_pipe = 45 [mm]
d_orifice = {25} {34} 25.5 [mm]

beta = d_orifice / D_pipe
//beta = 0.75

E = 0.9 [mm] // E = e

d_t_o = 5 [mm]
t = 1.1 [mm]
d_t_i = d_t_o - 2*t

l_1 = D_pipe //include tolerance based on physical construction
l_2 = D_pipe/2 //include tolerance based on physical construction
l_2_prime = l_2 - E

A_pipe = pi/4 * D_pipe^2

A_orifice = (pi/4) * d_orifice^2

//Air properties

T_1 = {25 {20} [C]} (T_m2 + T_m3)/2
P = 86.11 [kPa]

rho = density(Air_ha, T = T_1, P = P)
mu = viscosity(Air_ha, T = T_1, P = P)
cp = cp(Air_ha, T = T_1, P = P)
cv = cv(Air_ha, T = T_1, P = P)

//Calculations

m_dot = C / sqrt(1 - beta^4) * epsilon * A_orifice*convert(mm^2,m^2) * sqrt(2 * deltaP * rho{1} )
m_dot = rho * V * A_pipe*convert(mm^2,m^2)

C = 0.5961 + 0.0261*beta^2 - 0.216*beta^8 + 0.000521*(10^6*beta / Re_D)^0.7 + (0.0188 +
0.0063*A)*beta^3.5*(10^6 / Re_D)^0.3 + (0.043 + 0.080*exp(-10*L1) - 0.123*exp(-7 * L1)) * (1 -
0.11*A) * beta^4/(1 - beta^4) - 0.031*(M_2_prime - 0.8*M_2_prime^1.1)*beta^1.3 + 0.011 * (0.75 -
beta) * (2.8 - D_pipe / 25.4 [mm])

Re_D = rho * V * D_pipe * convert(mm,m) / mu
A = (19000 * beta / Re_D)^0.8
L1 = 1 - {l_1 / D_pipe} {formula}
L2_prime = 0.47 {l_2_prime / D} {formula}
M_2_prime = 2 * L2_prime / (1 - beta)

//V = {7.5} {8.5} 18 [m/s]
//Re_D = 5000 //test
```

```
epsilon = 1 - (0.351 + 0.256*beta^4 + 0.93*beta^8) * (1 - (P_2 / P_1)^(1/kappa)) // for P_2 / P_1
>=0.75
```

```
P_1 = P_2 + deltaP*convert(Pa, kPa)
P_2 = 100 [kPa]//worst case scenario
rp = P_2/P_1
kappa = cp / cv
```

```
//deltaP = 774.99 [Pa] //Measured
```

```
rho_iso = 754.89 [kg/m^3]
g = 9.81 [m/s^2]
dH = {0.093 [m]} h2 - h1
deltaP = rho_iso * g * dH
```

```
v_inlet = m_dot / ( rho * (0.0495 [m] * 0.029 [m]) )
```

```
//Uncertainty
```

```
U_m_dot = sqrt( (U_C)^2 + (U_epsilon)^2 + (U_3)^2*(U_4)^2 + (U_5)^2*(U_6)^2 + 0.25*(U_7)^2 +
0.25*(U_8)^2 )
```

```
U_C = (0.5 + 0.9*(0.75 - beta)*(2.8 - D_pipe/25.4))/100
```

```
U_epsilon = (3.5 * deltaP / (kappa * P_1))/100
```

```
U_3 = 2 * beta^4 / (1 - beta^4)
```

```
U_4 = deltaD_pipe/ D_pipe
deltaD_pipe = 0.02 [mm]
```

```
U_5 = 2 / (1 - beta^4)
```

```
U_6 = deltad_orifice / d_orifice
deltad_orifice = 0.02 [mm]
```

```
U_7 = ddP / deltaP
ddP = rho_iso * g * ddH
ddH = 0.001 [m]
```

```
U_8 = 0 //assume incompressible air
```

A.4 Arduino code

```
#include <SPI.h>
```

```
#include <OneWire.h>
```

```
#include <DallasTemperature.h>
```

```
#include <Wire.h>
```

```

#include <ThreeWire.h>
#include <RtcDS1302.h>

#include <HIH8000_I2C.h>

// ----- Saving interval -----
unsigned long previousMillis = 0;

// ----- Temp sensor -----
const int ONE_WIRE_PIN = 2;
OneWire oneWire(ONE_WIRE_PIN);
DallasTemperature sensors(&oneWire);

// ----- RTC -----
const int RTC_CE_PIN = 3; // RST/CE
const int RTC_IO_PIN = 4; // DAT
const int RTC_SCLK_PIN = 5; // CLK
ThreeWire myWire(RTC_IO_PIN, RTC_SCLK_PIN, RTC_CE_PIN); // DAT, CLK, RST(CE)
RtcDS1302<ThreeWire> rtc(myWire);

#define SET_RTC_FROM_COMPILE_TIME /*true*/false

// ----- Temperature and RH sensor -----
HIH8000_I2C hihSensor1 = HIH8000_I2C(0x27);
HIH8000_I2C hihSensor2 = HIH8000_I2C(0x28);

void setup()
{
  Serial.begin(9600);
  Wire.begin();
  while (!Serial); // Wait for Serial Monitor

  // ----- Temp sensor -----
  sensors.begin();
  sensors.setResolution(12); // 12-bit ~750 ms conversion

  // ----- RTC -----
  rtc.Begin();
  rtc.SetIsWriteProtected(false);
  if (!rtc.GetIsRunning())
  {
    rtc.SetIsRunning(true);
  }

  // Optionally set RTC from compile time (first upload only)
  RtcDateTime compiled(__DATE__, __TIME__);
  #if SET_RTC_FROM_COMPILE_TIME
    rtc.SetDateTime(compiled);
  #else
    if (!rtc.IsDateTimeValid())
    {
      // if RTC lost power/time, set to compile time as a safe fallback
      rtc.SetDateTime(compiled);
    }
  }
}

```

```

#endif

// ----- Temp and RH sensor -----

hihSensor1.triggerMeasurement();
hihSensor2.triggerMeasurement();
delay(50);

Serial.println("Ready to start datalogging.");
Serial.println("Date,Time,T1 (C),RH1 (%),T2 (C),RH2 (%),T3 (C)");
}

void loop()
{
    unsigned long currentMillis = millis();

    if (currentMillis - previousMillis >= 5000)
    {
        previousMillis = currentMillis;

        // ----- Time and date from RTC -----
        RtcDateTime now = rtc.GetDateTime();

        char dateStr[11]; // YYYY-MM-DD
        char timeStr[9]; // HH:MM:SS
        snprintf(dateStr, sizeof(dateStr), "%04u-%02u-%02u", now.Year(), now.Month(), now.Day());
        snprintf(timeStr, sizeof(timeStr), "%02u:%02u:%02u", now.Hour(), now.Minute(), now.Second());

        // ----- Temp sensor -----
        sensors.requestTemperatures();
        float T3 = sensors.getTempCByIndex(0);
        /*lcd.setCursor(0, 0);
        lcd.print(T3);*/

        //-----Temp and RH sensor-----

        hihSensor1.fetchMeasurement();

        float T1 = hihSensor1.getTemperature();
        float RH1 = hihSensor1.getHumidity();

        hihSensor2.fetchMeasurement();

        float T2 = hihSensor2.getTemperature();
        float RH2 = hihSensor2.getHumidity();

        // ----- Writing data -----

        Serial.print(dateStr);
        Serial.print(",");

```

```
Serial.print(timeStr);
Serial.print(",");
Serial.print(T1);
Serial.print(",");
Serial.print(RH1);
Serial.print(",");
Serial.print(T2);
Serial.print(",");
Serial.print(RH2);
Serial.print(",");
Serial.println(T3);

hihSensor1.triggerMeasurement();
hihSensor2.triggerMeasurement();
delay(50);

}

}
```

APPENDIX B MEASUREMENT EQUIPMENT AND CALIBRATION

B.1 Memograph thermocouple calibration

Table B.1 below contains the true and measured temperature values used to calibrate the memograph for all the thermocouple temperature measurement string points.

Table B.1: Memograph thermocouple measured value adjustments

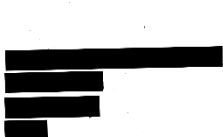
Thermocouple measurement point	Lower value		Upper value	
	True [°C]	Measured [°C]	True [°C]	Measured [°C]
A1	15.5	13.5	45.1	43.3
A2	15.5	13.0	45.1	42.9
A2	15.5	12.2	45.1	42.1
A4	15.5	12.6	45.1	42.5
A5	15.5	14.2	45.1	44.0
B1	15.5	13.2	45.1	43.0
B2	15.5	13.4	45.1	43.2
B3	15.5	13.4	45.1	43.3
C1	15.5	12.5	45.1	43.1
C2	15.5	12.2	45.1	42.9
C3	15.5	12.5	45.1	43.1
C4	15.5	12.5	45.1	43.4

Table B.2 below contains the accuracy verification temperature measurements for the memograph.

Table B.2: Memograph thermocouple calibration verification

Thermocouple measurement point	~15 [°C]		~25 [°C]		~35 [°C]		~45 [°C]	
	True [°C]	Measured [°C]	True [°C]	Measured [°C]	True [°C]	Measured [°C]	True [°C]	Measured [°C]
A1	15.5	15.5	25.4	25.5	35.3	35.3	45.1	45.1
A2	15.5	15.5	25.4	25.6	35.3	35.4	45.1	45.2
A2	15.5	15.5	25.4	25.6	35.3	35.4	45.1	45.1
A4	15.5	15.5	25.4	25.6	35.3	35.5	45.1	45.1
A5	15.5	15.4	25.4	25.5	35.3	35.5	45.1	45.2
B1	15.5	15.5	25.4	25.6	35.3	35.5	45.1	45.2
B2	15.5	15.5	25.4	25.7	35.3	35.5	45.1	45.2
B3	15.5	15.5	25.4	25.9	35.3	35.6	45.1	45.2
C1	15.5	15.5	25.4	25.5	35.3	35.6	45.1	45.1
C2	15.5	15.6	25.4	25.6	35.3	35.4	45.1	45.1
C3	15.5	15.6	25.4	25.7	35.3	35.5	45.1	45.0
C4	15.5	15.5	25.4	25.6	35.3	35.5	45.1	45.0

B.2 Moisture meter calibration certificate

		FOOD SAFETY AND GRAIN QUALITY LABORATORY		No.: [REDACTED] Tel: [REDACTED] Manager: [REDACTED]
INSTRUMENT: PERTEN AM5200		S/N: [REDACTED]	DATE: 11 April 2025	
TECHNICIAN: [REDACTED]		NAME: [REDACTED]		

SERVICE / CALIBRATION CERTIFICATE							
INI SLOPE: [REDACTED]		FIN SLOPE: [REDACTED]		INI BIAS: [REDACTED]		FIN BIAS: [REDACTED]	
SAMPLE ID	COMMODITY	PARAMETER	REFSAMPLE	INSTRUMENT READING	VARIATION	TOLERANCE	
M2502	MAIZE	MOISTURE	10.1	10.1	0.0	+/- 0.3	
M2503	MAIZE	MOISTURE	12.2	12.4	0.2	+/- 0.3	
M2504	MAIZE	MOISTURE	13.9	14.1	0.2	+/- 0.3	
M2501	MAIZE	MOISTURE	17.1	17.2	0.0	+/- 0.3	
M2502	MAIZE	HLM	81.1	81.0	-0.1	+/- 1.0	
M2503	MAIZE	HLM	77.4	77.7	0.3	+/- 1.0	
M2504	MAIZE	HLM	81.5	81.2	-0.3	+/- 1.0	
M2501	MAIZE	HLM	74.8	75.8	1.0	+/- 1.0	
SB2501	SOYA	MOISTURE	8.8	8.5	-0.2	+/- 0.3	
SB2502	SOYA	MOISTURE	9.7	9.6	-0.1	+/- 0.3	
SB2504	SOYA	MOISTURE	10.6	10.4	-0.2	+/- 0.3	
SB2503	SOYA	MOISTURE	11.4	11.3	-0.1	+/- 0.3	
SB2501	SOYA	HLM	74.3	73.6	-0.8	+/- 1.0	
SB2502	SOYA	HLM	75.6	75.0	-0.6	+/- 1.0	
SB2504	SOYA	HLM	72.7	71.9	-0.8	+/- 1.0	
SB2503	SOYA	HLM	74.7	73.7	-1.0	+/- 1.0	
SG2502	SORGHUM	MOISTURE	10.7	10.7	0.0	+/- 0.3	
SG2503	SORGHUM	MOISTURE	11.8	11.8	-0.1	+/- 0.3	
SG2501	SORGHUM	MOISTURE	12.8	13.1	0.3	+/- 0.3	
SG2502	SORGHUM	HLM	76.4	76.4	0.0	+/- 1.0	
SG2503	SORGHUM	HLM	73.3	73.5	0.1	+/- 1.0	
SG2501	SORGHUM	HLM	72.9	73.1	0.1	+/- 1.0	
FH2501	SUNFLOWER	MOISTURE	5.9	6.2	0.3	+/- 0.3	
FH2503	SUNFLOWER	MOISTURE	11.2	10.9	-0.3	+/- 0.3	
FH2502	SUNFLOWER	MOISTURE	13.2	13.0	-0.2	+/- 0.3	
FH2501	SUNFLOWER	HLM	42.8	42.9	0.1	+/- 1.0	
FH2503	SUNFLOWER	HLM	38.7	38.9	0.2	+/- 1.0	
FH2502	SUNFLOWER	HLM	37.3	38.1	0.8	+/- 1.0	

SAMPLE TRACESABILITY: SAGL	
REMARKS: All samples reads within specification as required.	
11 April 2026 NEXT SERVICE	 CUSTOMER  LAB REPRESENTATIVE

Figure B.1: Perten AM 5200-A calibration certificate

B.3 Orifice plate design

The orifice plate and its pressure tapings are designed according to the standards ISO 6157-1:2003(E) and ISO 5167-2:2003(E) (International Organization for Standardization, 2003a, 2003b). Figure B.2 below depicts a schematic of a standard orifice plate design, and Figure B.3 below depicts the pressure tapings schematic. All the design parameters in Figure B.2 and Figure B.3 are tabulated in Table B.3 below. Table B.3 contains all the parameters and values, and their design requirements or the justification for why a certain value is used. The orifice plate is laser cut out of 0.9 [mm] stainless steel sheet metal.

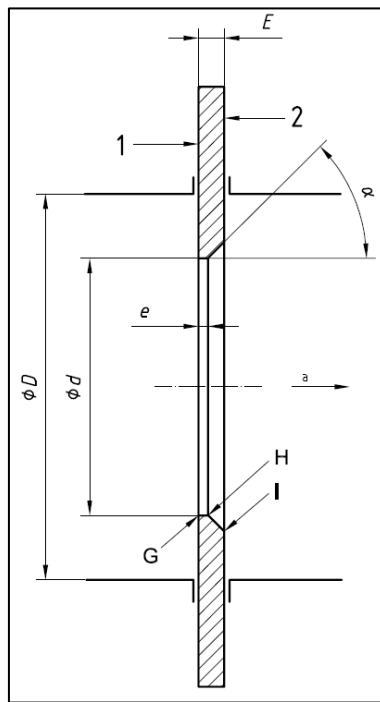


Figure B.2: Standard orifice plate schematic (International Organization for Standardization, 2003a)

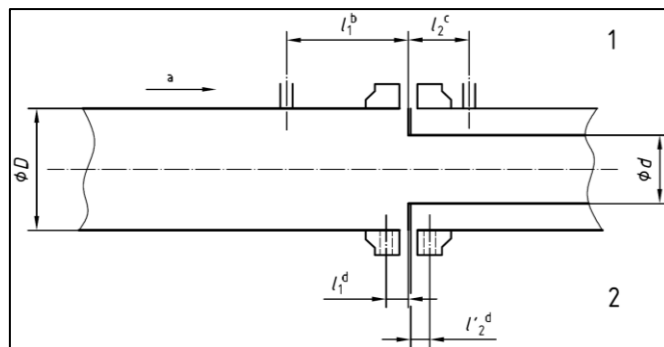


Figure B.3: Orifice plate D and $D/2$ pressure tapings (International Organization for Standardization, 2003a)

Table B.3: Orifice plate design specifications

Parameter	Requirement / Justification	Value	Unit
e	$0.005D \leq e \leq 0.02D$	0.9	[mm]
E	$e \leq E \leq 0.05D$	0.9	[mm]
α	$e = E$	0	[°]
D		45	[mm]
d	$d \geq 12.5$ [mm] and $0.1 \leq \beta \leq 0.75$	25.5	[mm]
β	$0.1 \leq \beta \leq 0.75$	0.567	
l_1	$0.9D \leq l_1 \leq 1.1D$	45	[mm]
l_2	$0.48D \leq l_2 \leq 0.52D$ for $\beta \leq 0.6$	22.5	[mm]
d_t	$d_t < 0.13D$ and $d_t < 13$ [mm]	2	[mm]
$L_{downstream}$	$\geq 29D$	2.5	[m]
$L_{upstream}$	$\geq 7D$	2	[m]

The orifice plate is pictured in Figure B.4 below.

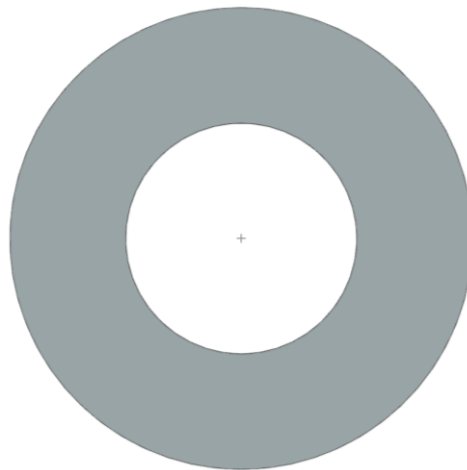


Figure B.4: Orifice plate

B.4 Manometer working fluid density calculation

The density of the manometer working fluid is calculated by first measuring out 90 [ml] of the fluid with a measurement beaker. Next, a different beaker is placed on a laboratory scale, and it is zeroed. The measured-out fluid is poured into the beaker on the laboratory scale. The mass of the fluid is measured as 67.94 [g]. Thus, the density of the working fluid is calculated to be 754.89 [kg/m³].

B.5 Velocity calibration

The velocity value calculated from the differential pressure measurement is calibrated using a handheld T4201 Top Tronic anemometer. The velocity in the air supply pipe is calculated for a range of differential pressure measurements. The air velocity is measured using the anemometer at an outlet in the side of the JoJo tank with the same diameter as the air supply pipe. The results are tabulated in Table B.4 below. The maximum deviation between the calculated and measured velocities is 5.3%, with the average deviation being 2.8%.

Table B.4: Velocity calibration data

Measurement #	Differential pressure height [m]	Calculated velocity [m/s]	Measured velocity [m/s]	Deviation [%]
1	0.097	7.929	7.9	0.4
2	0.059	6.210	5.9	5.3
3	0.08	7.212	7.1	1.6
4	0.032	4.599	4.5	2.2
5	0.009	2.476	2.6	4.8

B.6 Arduino setup

The sensor measurements are taken using an Arduino Uno R3. Firstly, a real time clock (RTC) module is used with the Arduino to set and keep the time during experimentation, so that the time at which each measurement is taken is logged. The RTC is connected to the Arduino according to its specifications. Next, the relative humidity and temperature sensors, the HIH8121-021-001s, are connected according to the application circuit given in their datasheet, along with a capacitor and two resistors. The DS18B20 temperature sensor is connected to the Arduino via a resistor adaptor. Figure B.5 below gives a schematic of the connections between the sensors, the RTC module, and the Arduino.

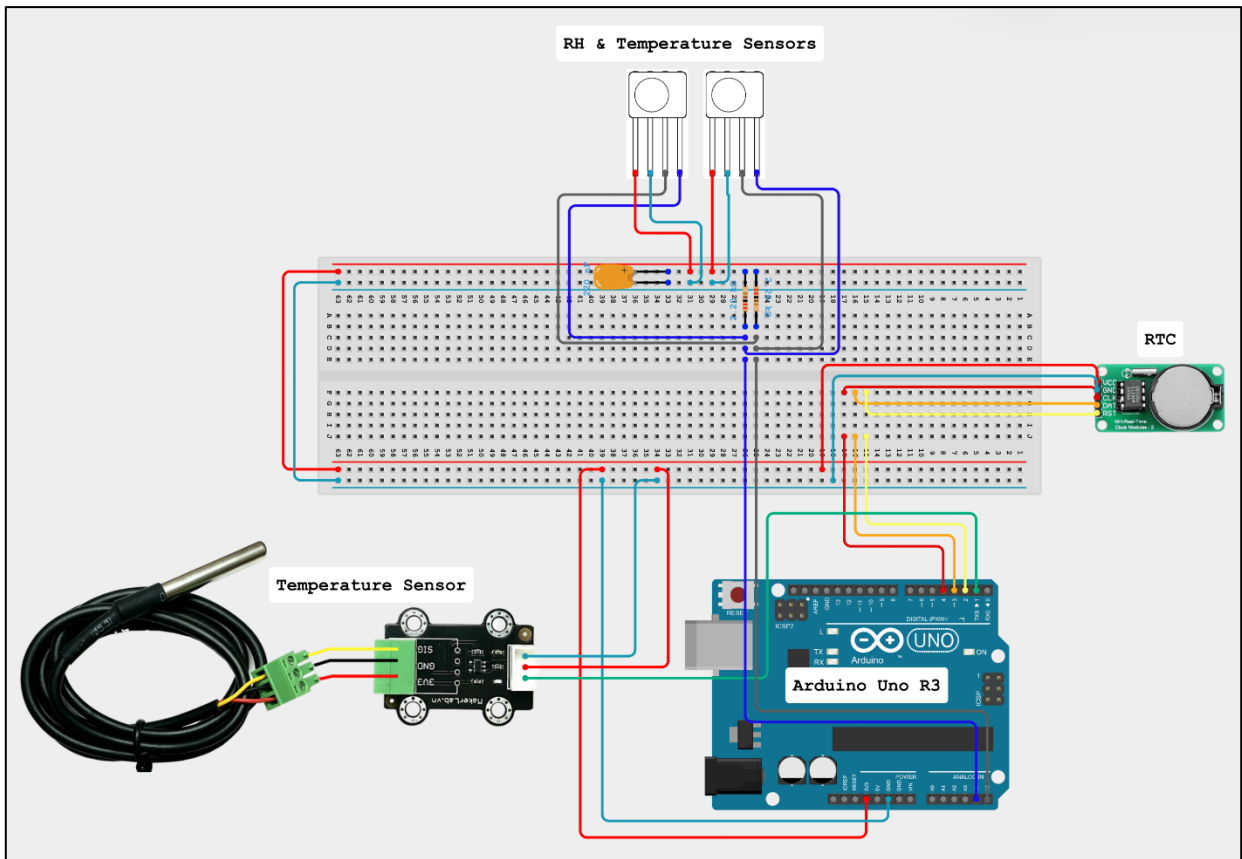


Figure B.5: Arduino Schematic Diagram

APPENDIX C TESTBENCH

C.1 Testbench components and construction

Figure C.1 pictures the Slimline JoJo tank wrapped in the roofing insulation.



Figure C.1: 1000 litre Slimline JoJo tank wrapped in roofing insulation

Figure C.2 pictures the wooden base. On the left of Figure C.2, the inclined wooden base that is not yet assembled is pictured. The base is manufactured from 18 [mm] plywood, and rests on 40×40 [mm] wood supports. On the right of Figure C.2, the assembled wooden base installed in the tank is pictured. The hooks, on which the temperature measurement strings' support wires are fastened to, can be seen installed on the wooden base on the right of Figure C.2.



Figure C.2: Inclined wooden base; not assembled (left), and assembled and installed (right)

An assembly drawing of half of the air distribution duct is given in Figure C.3.

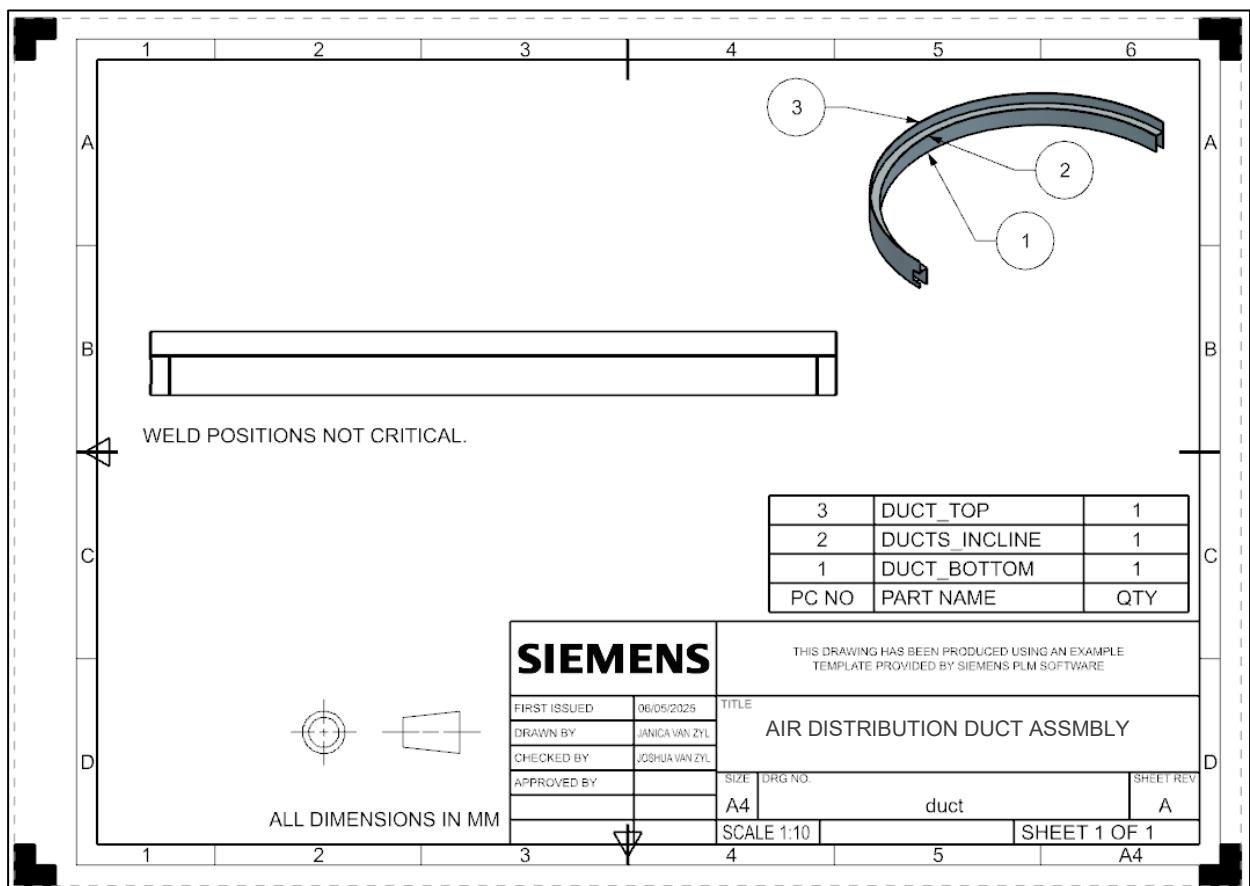


Figure C.3: Sheet metal air distribution duct assembly drawing

Figure C.4 pictures the Ryobi BL-600 electric mini blower used as the aeration fan during experimentation.



Figure C.4: Ryobi BL-600 electric mini blower

Figure C.5 shows the temperature measurement strings installed in the tank.

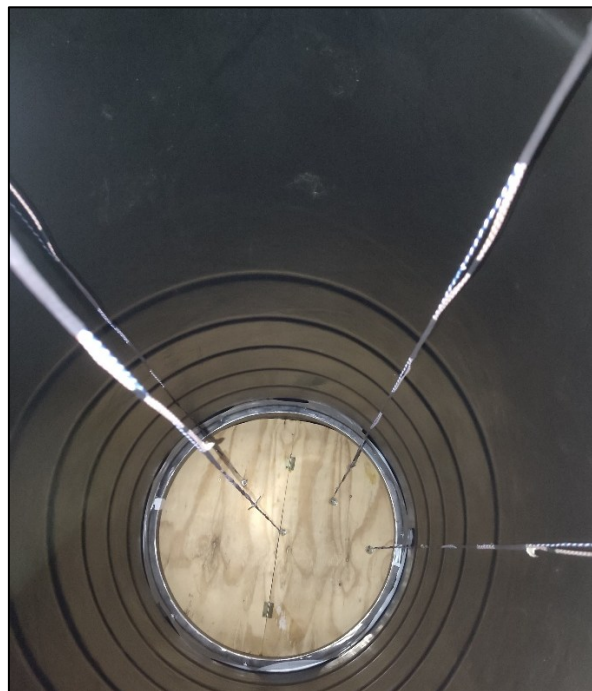


Figure C.5: Thermocouple temperature measurement strings

Figure C.6 pictures the Endress & Hauser memograph.



Figure C.6: Memograph

Figure C.7 pictures the manometer.



Figure C.7: Manometer

Figure C.8 shows the Arduino Uno R3 with all the sensors connected.²⁵

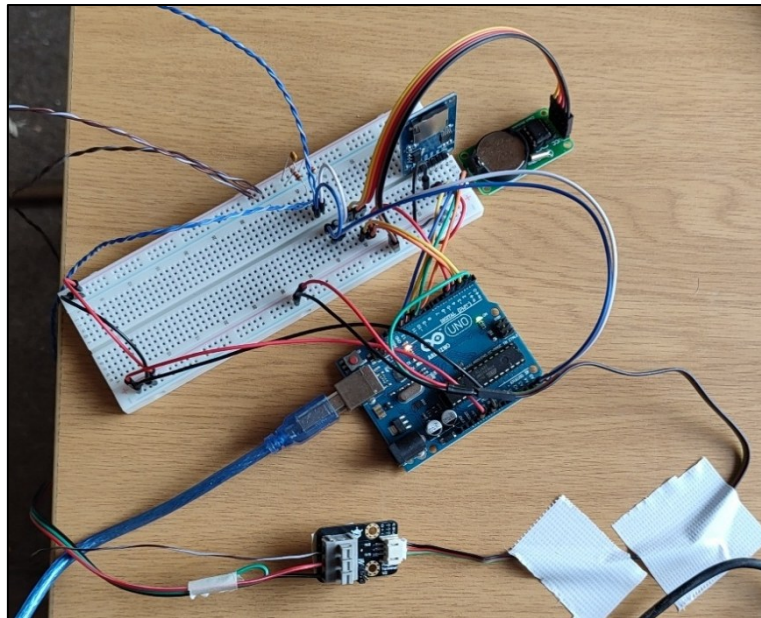


Figure C.8: Arduino UNO R3 setup

²⁵ A SD card reader is also connected to the Arduino in the picture, but it was not used during experimentation.

APPENDIX D RESULTS DATA

D.1 Experimental validation data

Table D.1 contains the initial grain temperatures at each of the temperature measurement string points at the start of the experiment.

Table D.1: Experiment initial grain temperatures

Measurement point	Temperature [°C]
A1	19.7
A2	21.9
A3	21.9
A4	20.9
B1	21.1
B2	21.8
B3	21.1
C1	20.7
C2	21.2
C3	20.8

Table D.2 contains the experimental differential pressure and temperature measurements, and the calculated inlet velocity.

Table D.2: Experimental differential pressure measurements and calculated velocities

Measurement #	Differential pressure [m]	Temperature 1 [°C]	Temperature 2 [°C]	Pipe velocity [m/s]	Pipe Reynolds number [-]	Inlet velocity [m/s]
1	0.097	19.4	25.1	7.891	19695	8.743
2	0.090	20.2	25.6	7.614	18930	8.436
3	0.091	20.9	25.6	7.661	19005	8.487
4	0.091	21.1	25.7	7.663	18993	8.490
5	0.090	20.8	25.7	7.619	18902	8.441
6	0.090	20.9	25.4	7.618	18910	8.440
7	0.090	20.7	25.6	7.618	18910	8.440
8	0.090	20.9	25.3	7.617	18914	8.439
9	0.090	20.7	25.2	7.615	18926	8.437
10	0.088	20.7	25.6	7.534	18702	8.347
11	0.093	21.0	25.4	7.742	19213	8.578
12	0.094	21.0	25.7	7.785	19302	8.625
13	0.094	21.0	25.6	7.784	19306	8.624

Table D.3 contains the experimental and simulation temperature front speed ratios and the corresponding temperatures.

Table D.3: Experimental and simulation temperature front speed ratio results

Data #	Experiment		Simulation	
	Temperature [°C]	Temperature front speed ratio [mm/s]/[m/s]	Temperature [°C]	Temperature front speed ratio [mm/s]/[m/s]
1	19.4	5.87	19.5	8.34
2	18.2	7.51	18.4	9.88
3	17.1	10.15	17.3	11.38

D.2 Additional drying constant equations

The drying constant equation constants for the first alternative drying constant equation for maize are given in Equation (D.1) below (Jayas et al., 1991):

$$K = e^{(-7.1735 + 1.2793 \ln(1.8T_c + 32) + 0.1378v)} \quad (D.1)$$

$$N = 0.0811 \ln(RH \times 100) + 0.78MC_d$$

The drying constant equation constants for the second alternative drying constant equation for maize are given in Equation (D.2) below (Jayas et al., 1991):

$$K = e^{-xt^y} \quad (D.2)$$

$$x = \sqrt{6.0142 + 0.0001RH^2} - 0.01(1.8T_c + 32)\sqrt{3.352 + 0.001RH}$$

$$y = 0.1245 - 0.0022RH + 2.3 \times 10^{-5}(1.8T_c + 32) - 5.8 \times 10^{-5}(1.8T_c + 32)$$

$$N = 0.664$$

The drying constant equation constants for the drying constant equation for barley are given in Equation (D.3) below (Basunia and Abe, 2003). The time in the drying constant equation should be given in [min].

$$K = 0.000105T_c + 0.00158RH - 0.00108 \quad (D.3)$$

$$N = 0.924$$

The drying constant equation constants for the drying constant equation for paddy are given in Equation (D.4) below (Jayas et al., 1991):

$$K = 0.02958 - 0.44565RH + 0.01215T_c \quad (D.4)$$

$$N = 0.13365 + 1.93653RH - 1.77431RH^2 + 0.009468T_c$$

D.3 Scaling validation data

Figure D.1 shows the temperature string data for the bottom 12 temperature points for the month of August. The 15-hour aeration period used for the validation started the afternoon of the 17th and concluded the morning of the 18th. As can be seen in Figure D.1, before this period, the bulk was not aerated for approximately a day. This is the first extended period of non-aeration since the first grain was loaded into the silo in June of the same year. The sections of data where the lines appear cleaner are periods of sparse data due to data logging issues on the SCADA. Such data cannot be used due to hours passing without any data.

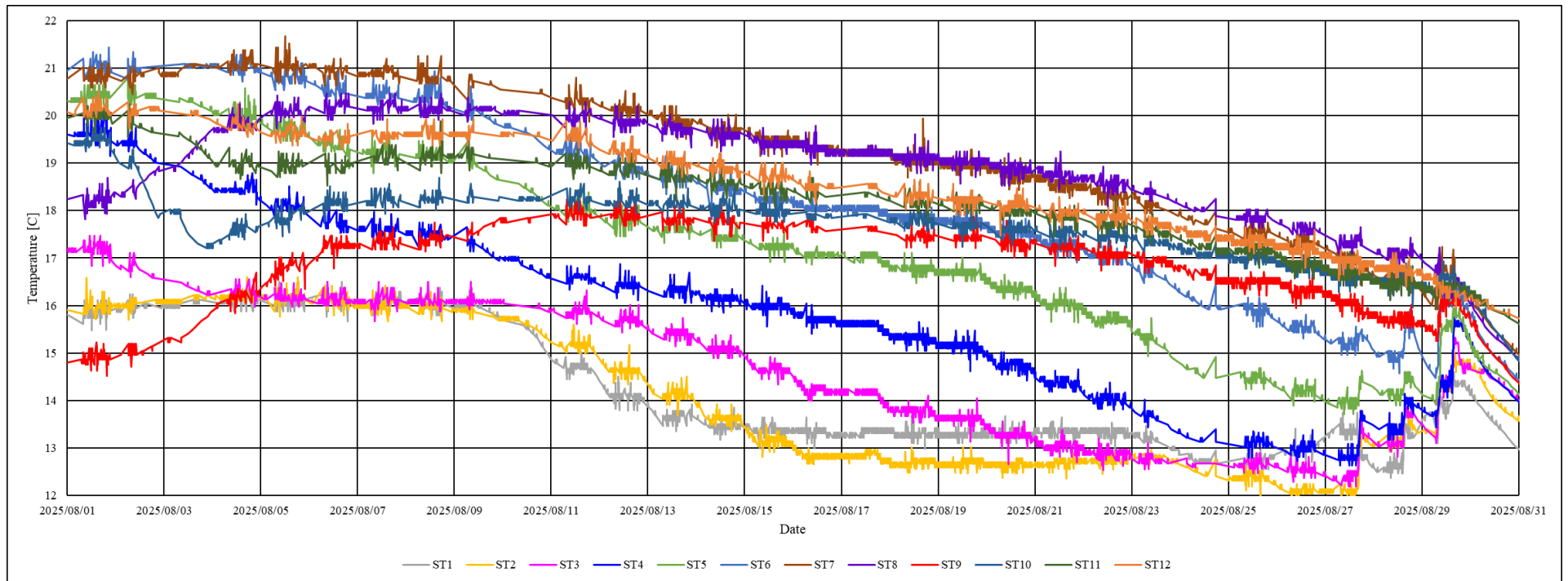


Figure D.1: Temperature string data for August