BULK FLOW PROPERTIES OF WHEAT

by

QI BIAN

B.A., Henan University of Technology, 2011

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Grain Science and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2014

Approved by:

Major Professor
Kingsly Ambrose

Copyright

Abstract

Consistent and reliable flow of bulk wheat from hoppers and silos is very significant in wheat handling and processing. Bulk wheat flow challenges such as inconsistent flow, arching, etc., are common during handling. The irregular size and non-uniformity of physical properties, the presence of impurities affects the flow of wheat. Chaff and insects infested kernels are the two most common impurities present in bulk wheat. In this research, the effect of these two impurities on bulk wheat physical and flow properties were studied.

Physical and flow indicators, such as bulk, tapped, particle densities, angle of repose, Hausner ratio, Carr index, and porosity measures the flowability of uncompacted bulk solids. Meanwhile, flow properties measured by shear testing principle based on Jenike's method simulated bulk wheat under pressure in bins/hoppers. The dynamic properties tested quantify the energy required to flow, compressibility and permeability at dynamic handling situations. Due to the presence of impurities and moisture content differences, bulk density and angle of repose of wheat varied from 801.54kg/m^3 to 718.36kg/m^3, and 23.6° to 38.4°, respectively. Angle of internal friction and wall friction angle that reflect interaction between particles and particle with bins/hopper walls, ranged from 23.95° to 43.13° and 15.46° to 20.33°, respectively.

In addition to instrumental flow properties, the flow profile, discharge rate, and particle velocity during hopper flow of bulk wheat was studied using Particle Image Velocimetry method. Mass flow and funnel flow hopper dimensions were used for flow profile analysis. The discharge rate decreased from 1.67 to 1.12 kg/s for mass flow and 1.42 to 0.86 kg/s for funnel flow when the chaff in bulk wheat increased from 0% to 7.5% (weight basis). Analysis of the active flow zone indicated that bulk wheat without chaff had a uniform flow compared to wheat with chaff in the bulk. The findings from this study will be useful for design of hopper bottom bins and handling equipment based on the wheat quality and percent moisture content.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to thank everyone who has helped me over the course of this thesis study, especially my major professor, Dr. Kingsly Ambrose. His guidance and patience helped me improve step by step. Meanwhile, I would also like to thank my two committee members, Dr. Bhadriraju Subramanyam, and Dr. Hulya Dogan for their suggestions and guidance on the way of my M.S. study progress.

I would like to thank John Yin from Freeman Technology Co. for his help on solving my confusions and problems on the FT- 4 powder rheometer. I would like to thank Binghui Liu, who helped me plotting the blueprint of the hopper model design. I would like to thank Travise Schmeal's help on building on the hopper model and his suggestions on the hopper design. Meanwhile, I appreciate the help from Shawn Thiele, Hal Ross Mill and Blossom Sehgal for helping prepare my experiments samples with insects. I would like to thank Frances Churchill, Yonghui Li and Dr. Susan Sun'lab for their help on the sample conditioning and particle size measurement. Meanwhile, thank to the help from our group members Abhay Patwa and Kaliramesh Siliveru.

Moreover, I would like to thank Ms. Terri Mangiaracino, Ms. Beverly McGee, Ms. Liz Savage and all the staff in Department of Grain Science and Industry.

At last, I appreciate the support from my parents and my girlfriend, Xiwen Chen, so much. And thank all of my friends who have helped me during the past two years.

Dedication

To my dear parents

I dedicate this thesis to my parents, Ke Bian and Jiwei Hou, for their love and encouragements to my life.

Chapter 1 - Introduction

This thesis presents a study on the effect of moisture content and impurities proportion on the bulk flow characteristics of wheat. The physical properties such as densities, flow indicators, and flow properties such as flow energy, stability, compressibility, permeability, and shear characteristics was studied. Particle image velocimetry (PIV) analysis to study the discharge profile of bulk wheat in laboratory scale hopper was also included. Understanding these characteristics help support the bulk wheat processing facilities in design of hoppers and to predict the bulk wheat flow and discharge from silos/hoppers.

This chapter gives an overview on the flow characteristics of bulk wheat, which is the primary focus of this study. In Section 1.1 wheat characteristics and the factors that influence flow were enumerated. The hypothesis and goals, and the objectives of this study are given in Section 1.2 and 1.3, respectively. Section 1.4 provides an overview of the remainder of this thesis.

1.1 Bulk Wheat Flow Characterization

With an increasing quantity and variety of bulk grains being handled, processed, and produced in grain based food and feed industry, there is growing need for information on material characteristics that is significant for design of handling and storage equipment. Knowledge of bulk properties of particulate materials is essential for the design of industrial equipment, efficient and reliable material processing as well as for estimation of quality of raw material (Molenda and Stasiak, 2002). Furthermore, physical properties of bulk solids are important for quality assessment of the final product as well as during subsequent storage, handling, and transport. In addition, flow properties of bulk solids influence handling and processing operations, such as flow from silos and hoppers, transportation, mixing, compaction and packaging (Knowlton et al., 1994).

Most of the bulk solid characteristics are not inherent properties or does not depend on their individual particle physical characteristics. In general, the particulate properties are influenced by environmental factors, such as moisture content, relative humidity, temperature; and processing history, such as consolidation and vibration. In the U.S., wheat is one of the major cereal grains processed as food and feed. Wheat is usually stored in metal bins or concrete silos with capacities ranging from few tons to more than million bushels of grain. Uniform flow of wheat is expected from the bins/silos, during discharge, or when handled using mechanical conveyors. Many researchers have studied the bulk physical (Glenn et al., 1991; Al-Mahasneh and Rababah, 2007) and flow properties of wheat (Versavel and Britton, 1986; Molenda et al., 1998, 2004, 2005). Most of these studies concluded that wheat is a free flowing bulk material.

Bulk wheat, before cleaning and during storage, often contains impurities such as chaff, broken kernels, insect damaged kernels, dust, frass, etc. These impurities, due to their difference in size and density affect the flow characteristics of wheat due to spoilage, interlocking, cohesion, and compaction. Changes in physical properties lead to arching, crust formation, and caking of grains. Grain bin entrapment, due to poor flow of grains, is a major grain based hazards when working with flowing grain. However, not much research has been done on the effect of impurities on the physical and flow properties. In this thesis, based on the foreign material level in bulk wheat and within the moisture content of wheat that is commonly stored or handled, the physical and flow properties were investigated.

1.2 Research Hypotheses

The bulk physical properties provide a macroscopic view at uncompacted or unconsolidated condition. The flow properties simulate handling conditions to understand the properties under consolidation or during the flow. The working hypothesis of this study is that moisture content and impurities proportion influence the physical and flow properties of bulk wheat. In this study, instrumental evaluation and flow profile analysis were employed to investigate the bulk wheat characteristics and they are discussed in detail in subsequent sections.

1.3 Research Objectives

The overall goal of this project is to understand the flow characteristics of bulk wheat with impurities (chaff and lesser grain borers infested kernels). Particle image velocimetry (PIV) technique was also used to understand the profile of wheat kernels during discharge from hoppers. The objectives of the research are:

1. To measure the physical and flow properties of bulk wheat with different proportion of chaff at three moisture content level.
2. To measure the physical and flow properties of wheat with different proportion of lesser grain borer infested kernels at different moisture content levels.
3. To study the flow profile of wheat through mass and funnel flow hoppers using particle image velocimetry technique.

1.4 Thesis Outline

The rest of this thesis is divided into four chapters. Chapter 2 contains the literature review on bulk solids flow. Physical and flow properties affected by the presence of impurities and insects damaged kernels is discussed in Chapter 3 and Chapter 4, respectively. Chapter 5 contains the flow profile analysis in mass and funnel flow hoppers. In Chapter 6, the findings from this study has been summarized and provides suggestions for future work based on the understanding developed from this study.

1.5 Chapter References

Al-Mahasneh, M.A. and Rababah, T. M. 2007. Effect of moisture content on some physical properties of green wheat. Journal of Food Engineering 79, 1467-1473.

Grain Inspection Handbook. 2013. Book II, Chapter 13 - Wheat. Federal Grain Inspection Service, U.S. Department of Agriculture.

Glenn, G.M., Younce, F. L. and Pitts, M. J. 1991. Fundamental physical properties characterizing the hardness of wheat endosperm. Journal of Cereal Science 13, 179-194.

Knowlton, T.M., Carson, J.W., Klinzing, G.E. and Wen-Ching, Y. 1994. The importance of storage, transfer and collection. Chemical Engineering Progress 90, 44–54.

Molenda, M., Horabik, J. and Rossi, J. 1998. Stress and deformation of wheat in direct shear test. International Agrophysics 12, 115-118.

Molenda, M., Horabik, J., Thompson, S. A. and Rossi, J. 2004. Effects of grain properties on loads in model silo. International Agrophysics 18, 329-332.

Molenda, M. and Horabik, J. 2005. Mechanical Properties of Granular Agromaterials and Food Powders for Industrial Practice Part1: Characterization of Mechanical Properties of Particulate Solids for Storage and Handling. Lublin, Poland: Institute of Agrophysics Polish Academy of Sciences.

Molenda, M. and Stasiak, M. 2002. Determination of elastic constants of cereal grain in uniaxial compression. International Agrophysics 16, 61–65.

Versavel, P. A. and Britton, M. G. 1986. Interaction of bulk wheat with bin wall configuration in model bins. Transaction of the ASAE 29(2), 533–536.

Chapter 2 - Literature Review

In this chapter, the factors that influence the physical and flow properties are presented. In section 2.1, the importance of bulk properties of wheat is discussed. Flow characteristics and common flow issues are discussed in section 2.2. The physical and flow properties of bulk solids are presented in sections 2.3 and 2.4, respectively. Hopper flow patterns and discharge flow rate prediction methods are discussed in section 2.5. In section 2.6, particle image velocimetry technique is reviewed in relation to hopper discharge analysis. The aim of this chapter is to describe the details in quantifying flow characteristics of bulk granular material.

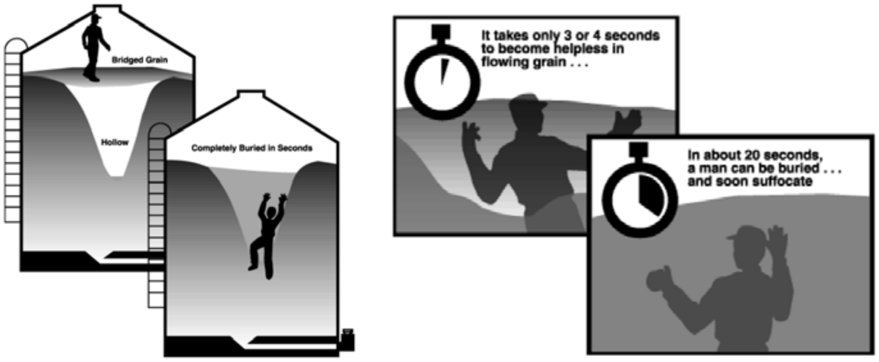
2.1 Bulk Properties of Wheat

Flowing grain is a term that is used to describe the movement (downward) of grain during handling especially from a storage bin or hopper. During unloading, velocity increases as grain flows from the bin wall at the top of the grain mass into a small, vertical column at the center of the bin. Flowing grain behaves like fluids while discharging. Information on the flow rate of grain through various sizes and shapes of orifices is needed to properly size the opening for flow control during the transfer of grain. The flow rate of grain through an opening is independent of the depth of grain above the opening if the mode of flow remains the same (Ketchum, 1919; Fowler and Glastonbury, 1959). Stahl (1950) indicated that flow of grain through a horizontal opening was proportional to the cube of the diameter, or the product of length and width of the opening.

In the agriculture industry, grain engulfment is a bigger challenge resulting in fatalities. As mentioned above, flowing grain behaves like fluid with high rate of flow at the bin center. Grain entrapments usually happen when the grain bridges or arches in the silo. A grain bridge is a layer of condensed, crusted, spoiled grain, which can conceal voids beneath the bridge (Yutaka, 1994). From Fig 2.1 it could be observed that, if a worker walks on the crusted surface, the additional weight will cause the crust to break and collapse, and the worker will be partially or completely submerged immediately (in 20 seconds). In Jenike’s theory, an important assumption is that an arch would form if the unconfined yield stress of material is greater than the major principal stress caused by the self-weight in the arch. Published literature (Kudrolli and

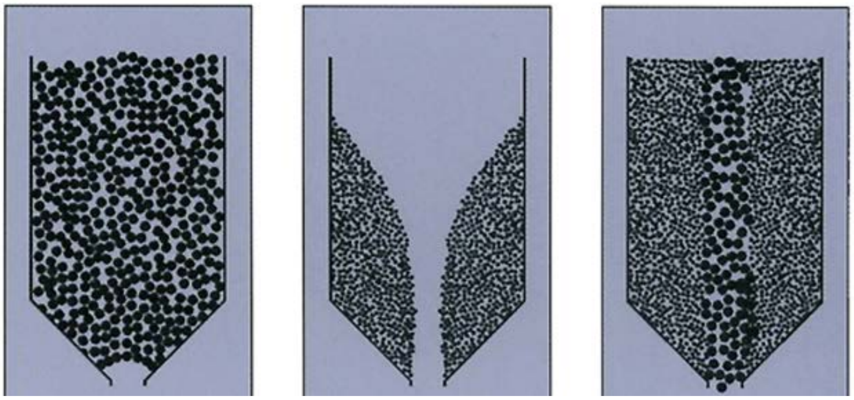
Samadani, 2001; Zuriguel et al., 2003; Zuriguel et al., 2005) indicates that a series of processes and phenomena affects the dynamics of grain flow during emptying of the silo. The effects could be divided into: arching, ratholing, irregular flow, jamming, caking, and segregation (Fig 2.2). Though the particle size, density and shape characteristics influence the flow characteristics, because of their biological origin, the properties of cereal grains are also highly influenced by their composition and environmental factors. Hence, understanding the characteristics of stored materials and storage condition can help predict the flowability of bulk cereal grains.

Fig 2. 1 Grain entrapment



(Source: North Dakota State University Agriculture and University Extension)

Fig 2. 2 Challenges in grain flow



a. Arching b. ratholing c. Segregation

Due to the presence of impurities in wheat during storage and handling, the handling process will be more complex than a mono-sized bulk material system. Larger differences in particle size, irregular shape and particle size distribution can affect the flow and flow properties during handling. However, limited research has been done on characterizing the flow properties of wheat in the presence of impurities.

2.2 Flow Characteristics and Common Flow Issues

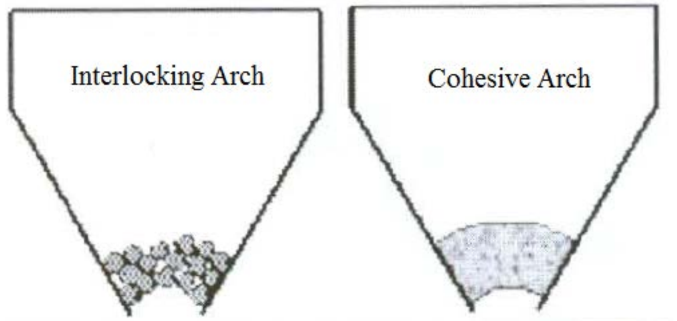
Most of the raw materials that are currently being used in the grain based food and feed industries are in particulate form. The materials include various ingredient and end products. Two of the most common problems encountered in solids processing plants occur during the transporting and handling (Merrow, 1988). In particular, problems arise from the difficulty encountered in withdrawing material from a storage hopper without interruption and at the required rate. These complications are caused by failure to incorporate accurate flowability measurements into the design. The end result, if the solids are not characterized before handling, is frequent stoppage of the process. This results in loss in production time and time of additional staff to restore the process flow. Many studies have described the impact of hopper design, material characteristics, and operating conditions on hopper flow (Marinelli and Carson 1992; Johanson, 2002). These studies included experimental, theoretical, and modeling approaches with both ideal and real materials. It is generally understood that the particle internal friction, the particle–wall friction, and the hopper geometry (hopper angle, outlet size, and shape) contributes to the flow mode in a hopper.

Bulk solids property characterization is essential in providing theoretical and data support to facilities design and help troubleshoot the problem areas. Therefore, understanding the bulk characteristics and flowability of solids helps predict flow and handling behavior during processing. The flowability of a powder, which is defined as the capacity of a powder or a granular solid to flow under a specified set of conditions, is a complex characteristic of a material. It is highly dependent on the state of the powder and the application it is being used for. Because the flowability is multidimensional, its quantification is also a complex task. Prescott and Barnum (2000) stated that since flowability is not an inherent property of a material, but instead results from a combination of physical properties and environmental and processing factors, it cannot be described by any one value or any single index.

The flow properties of bulk solids might change significantly during various stages of processing, thus affecting the quality of the final product. However, the mechanisms of these changes are poorly understood (Muzzio et al., 2002). Bulk solids system is complex because it contains components not only in one state, but most of the time it's a combination of solid, liquid and gaseous state. Hence, testing the flow properties of solids and defining by a one-dimensional parameter value would be a tough task.

The most common flow problems are no-flow and inconsistent flow. No-flow could be caused by arching and caking. Arching occurs when an obstruction in the shape of a bridge form above the hopper outlet. This could be due to interlocking or cohesive arch (Fig 2.2), from the irregular shape of particles or particle cohesion (Eric, 2004). The inconsistent flow is the result of an obstruction alternating between an arch and flowing (Eric, 2004). The arch could be collapsed by its own weight or by external force. The sudden flow of bulk solid causes ununiform pressure distribution on the bin/silo walls, increasing the risk of bin/silo collapse. Segregation is also a common issue during hopper discharge of solids, due to the particle size distribution. Arteaga and Tüzün (1990) and Tüzün and Arteaga (1992) examined the segregation of binary and ternary materials discharging from mass-flow and funnel-flow hoppers. The results showed that most segregation occurred either during an initial transient or a final transient motion of the solids. In this thesis work, the effect of chaff and insect damaged kernels (impurities present in bulk wheat) on the bulk flow properties of wheat will be analyzed.

Fig 2. 3 Interlocking and cohesive arch during flow of solids (source: Eric, 2004)



2.3 Physical Properties

Physical characteristics that determine the flowability of bulk solids include particle surface properties, particle shape, densities, and the particle size and size distribution. Particles with irregular fibrous shapes and plate-shaped particles can interlock mechanically. Furthermore, some irregularities on the surface of particles can cause physical interlocking of the particles, restricting flow. Mechanical interlocking occurs in bulk solids containing particles of irregular or fibrous shapes, and with the aid of vibration or pressure, these particles can form a stable structure (Peleg, 1978). Fibrous, bulky, and flaky particles can interlock or fold about each other, resulting in ‘‘form-closed’’ bonds (Pietsch, 1997) contributing to interlocking in addition to frictional strength developed under constant normal stress of the system. Also, the formation of stable mechanical structures, such as arches above the aperture of silos and containers, is possible, but it depends on the three-dimensional shape and size of particles (Jenike, 1964).

2.3.1 Particle size

Considerable research has been carried out to study the effect of particle size and size distribution on the flowability of powders. In general, lower particle size reduces flowability of solids (Thomson, 1997). Smaller particles provide a greater surface area for surface cohesive forces to interact as well as friction to resist flow (Fitzpatrick et al., 2004a). An increase of surface-to-surface ratio becomes greater as the particles become smaller, increasing surface interactions (Peleg and Hollenbach, 1984; Griffith, 1991). The forces opposing flow are friction, attraction between particles (cohesion), attraction between the particles and system walls, and mechanical resistance or interlocking (Peleg, 1978).

2.3.2 Densities and relative flow indicators

Bulk, tapped and true density are the commonly measured density values to assess the bulk characteristics of powders. Bulk density accounts for the volume occupied by the inter-granular spaces, inner pores, and external pores of the solids. Bulk density gives an overall degree of packing in a specific volume. Tapped density is the density after vibration or tapping. Due to vibration, the structure of bulk solids collapses or densify significantly with smaller particles filling the inter-granular spaces. Tapped density gives the measure of the ability of powder to be compacted without applying consolidation pressure. Bulk and tapped density are used to calculate compressibility index (CI) and Hausner ratio (HR). As defined by Carr (1965) and Hausner (1967), CI and HR are the flowability indicators that measures the propensity of a powder to be compressed, reflecting the relative degree of interparticulate interactions. Based on the CI and HR values, the powders could be classified from having ‘excellent’ to cohesive’ (Table 2.1).

Table 2. 1 Hausner ratio and compressibility index (source: Eben, 2008)

Flow indicator	Excellent	Good	Fair	Passable	Poor	Very poor	Cohesive
Hausner’s ratio	1.00-1.11	1.12-1.18	1.19-1.25	1.26-1.34	1.35-1.45	1.46-1.59	>1.60
Compressibility index (%)	≤10	11-15	16-20	21-25	26-31	32-37	>38

True density is the density of the solid part of solids without voids in particles and intergranular spaces. By measuring true density, the porosity of bulk samples could be calculated. Porosity measures the potential permeability and aeration through the bulk solids. Porosity also helps in assessing the flow of gas through bulk grains during aeration, drying, heating, and cooling operations. Bulk wheat with low porosity will have greater resistance to water vapor escape during the drying process, which may lead to higher power to drive the aeration fans (Bhise et al., 2014).

2.3.3 Angle of repose

Angle of repose is not an intrinsic characteristic of bulk solids, but depends on the environmental conditions at which the pile has been stored or formed and the measurement accuracy. There is no universal or standard testing method for angle of repose, hence, different values of the angle can be obtained for the same materials. Some studies have indicated that angle of repose may be less accurate for predicting flowability of cohesive and compacted materials (Bell, 1993; Ileleji and Zhou, 2008). Consequently, a collection of a large number of data points is recommended for characterizing a single sample (Bell, 1993). Angle of repose can only reflect the flowability of bulk solids in an unconsolidated state. Moreover, the angle of repose is not an accurate test to apply in the design of silos, when bulk solids are under high stress, because the angle of repose does not represent how the strength varies with its state of compaction (Ileleji and Zhou, 2008).

2.3.4 Moisture Content

During handling and storage, bulk solids might uptake moisture from the air, if the relative humidity of ambient air was higher than the equilibrium relative humidity of stored materials (Fitzpatrick et al., 2004b). Moisture uptake increases the cohesion between the particles. These forces depend on the presence of liquid (usually water) at the outer surface layer of the particles. Liquid layers on the surface of particles promote cohesion by creating a meniscus between the particles. The more viscous the liquid, the stronger is the cohesive forces. Flowability can be affected by the amount of free and associated water inside each particle (Pablo and Gustavo, 2009). The ability to associate water within a powder bulk mass depends on the structural distribution of these components within each particle. Furthermore, surface properties such as friction, ductility, and interlocking capacity on the surface may depend on the powder’s composition and structural distribution (Pablo and Gustavo, 2009). Chang et al. (1984) conducted experiments with corn of various moisture contents and found that the flow rate was proportional to the orifice depending on the moisture content.

However, the properties mentioned above are usually considered the flow indicators because they are single measure and are therefore unable to fully reflect the potentially complex behavior that powders can exhibit during processing and storage. Limitations are in their sensitivity and ability to capture diverse flow aspects , especially with respect to characterizing samples during conveying, flow through hoppers, and at under consolidation.

2.4 Flow Properties

Flow properties characterize the behavior of solids during hopper flow, conveying through feeders, and other handling equipment. Flow assurance is also crucial for the design of bins or hoppers especially to maximize the use of discharge units to their design capacity in order to prevent costly downstream handling problems (de Jong et al., 1999). Generally, flowability properties tests can be divided into three classes: uncompacted conditions (e.g. angle of repose), tapped or vibrated (Hausner ratio and compressibility index), and consolidated (shear tests). While the first two simple methods are of problematic accuracy, the industry standard has become the Jenike shear-tester, as a reliable tool in the industrial silo design (Schulze, 1996a, b). The Jenike shear-tester is a widely-accepted method for predicting the flow of bulk solids in a compacted state, but it is common opinion that this requires a high level of training and skill, is time and products-consuming and is sensitive to the way how materials are conditioned before testing (Schwedes, 2003; Krantz et al., 2009). The accuracy of the results depends upon the material being tested and the technician performing the procedures, and often has reproducibility problems (Ganesan et al., 2008).

More recently, the measurement of dynamic flow properties have been commonly used by the industry. Dynamic flow properties help assessing the flow characteristics at consolidated, compacted and aerated conditions. Dumarey et al. (2011), Alisa et al. (2011) and Leturia et al. (2014) have shown the use of measuring dynamic flow properties of powders for accurate flow characterization. The FT4 powder rheometer (Freeman Technologies, UK) is one of the commonly used instruments for measuring dynamic flow properties. The FT4 powder rheometer (Fig 2.4) is designed to characterize powders under various conditions in ways that resemble large-scale production environments.

The initial state of the powder prior to testing is particularly important. An advantage of FT4 is that the instrument conditions the samples so that the measurement is reproducible and repeatable (Freeman, 2007). Traditional test methods (Berry and Bradley, 2005; Carr and Walker, 1968; Schulze, 1996; Peschl, 1989) often lack an initial conditioning stage to remove the powder's history and operator variability. The methods used in FT4 include rheological, torsional shear, compressibility and permeability tests (Fig 2.5) which can be performed using a small amount of bulk samples.

Fig 2. 4 FT-4 powder rheometer

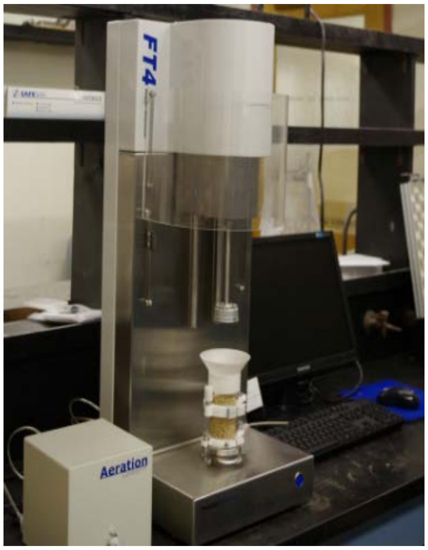
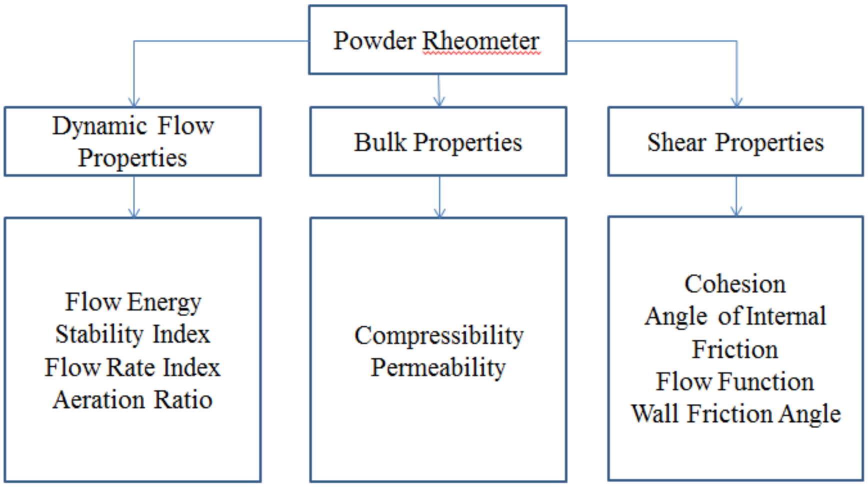


Fig 2. 5 Powder rheometer test categories



2.4.1 Dynamic flow properties

Mohammad and Behdad (2006), Freeman (2007), Freeman and Cooke (2009), Guillaume and Nicolas (2010), and Leturia et al. (2014) have mentioned the application of FT-4 powder rheometer for measuring dynamic flow properties. Through dynamic tests, the instrument evaluates energy required to make the material flow, and the relative indices such as stability index, flow rate index, and aeration ratio. In the dynamic flow properties test, flow energy was tested with/without aeration, to evaluate the effect of air flow during the flowing of material. Haifeng et al (2011) reported the discharge of coal in an aerated hopper to promote the flowability of cohesive powders. Aeration assisting the flow near hopper outlet has been stated by Papazoglou and Pyle (1970) and Donsi and Ferrari (1991). Moreover, Ouwerkerk et al. (1992) found that aeration in hopper through a porous cone section would create an opposite pressure gradient, and thereby increase the discharge rate.

2.4.2 Compression and permeability

Grain during storage experiences packing and compaction due to the vertical pressure exerted by the grain mass. Packing results in a change in bulk density of the grain mass, which in turn results in a change in porosity since little particle deformation is expected at the low pressures typically experienced during grain storage (Thompson and Ross, 1983). Quite often the testing of bulk solids is done for silo design purposes, hence, not only the dynamic properties need to be tested, but also the static properties under compaction need to be measured. Annular shear cells and uniaxial testers are instruments that can easily be automated and give reproducible results, although their sensitivity may vary according to the tested powder (Jorg, 2003). Indirect evaluation of flow properties has also been attempted by measuring compressibility of bulk solids using uniaxial compression testers (Ehlermann and Schubert, 1987).

Permeability is a property of porous materials that quantifies the relative ease with which a transporting substance can pass through the material. For example, the air permeability of grain stored in a grain bin will help engineers to determine how much air pressure will be needed to make air flow through the grain at a required flow rate in designing a grain drying process (Ludger and Arthur, 2007). Determining the permeability of grain as a function of bulk density is important for predicting natural convention current in stored grain. Permeability classification is given in Table 2.2

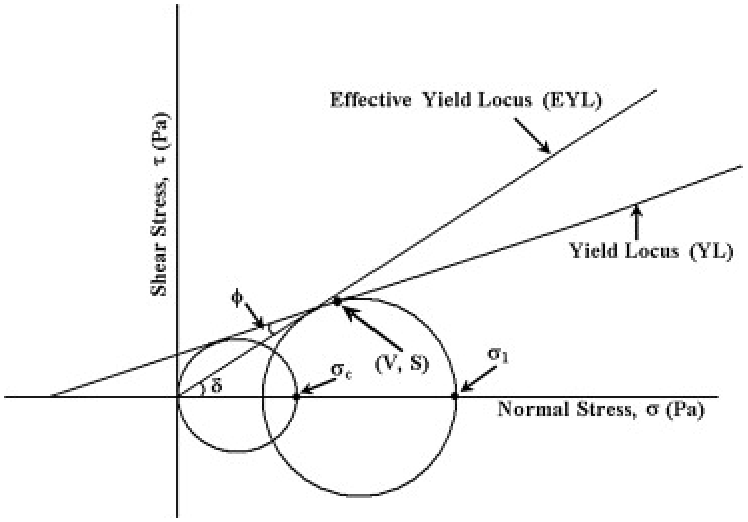
Table 2. 2 Bulk solid permeability classification (source: Huang et al., 2012)

Permeability	Pervious	Semi-Pervious	Impervious
κ (cm^2)	$10^{-3} – 10^{-6}$	10^{-7}-10^{-10}	10^{-11}-10^{-15}

2.4.3 Shear and wall friction

To analyze the flow of solids from bins and silos, and to develop a model of flow and no-flow conditions, Jenike used the principles of plastic failure (Fig 2.6) with the Mohr-Coulomb failure criteria (Thomson, 1997). Ideally, in free flowing powders, the resistance to flow is due to the result of friction; but in cohesive powders, the inter-particle forces are enhanced by compaction, which results in mechanical strength in the bulk (Peleg, 1983). Shear testing procedure for the design of bins, have been commonly used for research purposes and in industrial practice for characterizing granular materials (Ashton et al., 1965; Schrämli, 1967; York, 1975; Kamath et al., 1993; Duffy and Puri, 1994, 1999; Schwedes, 1996).

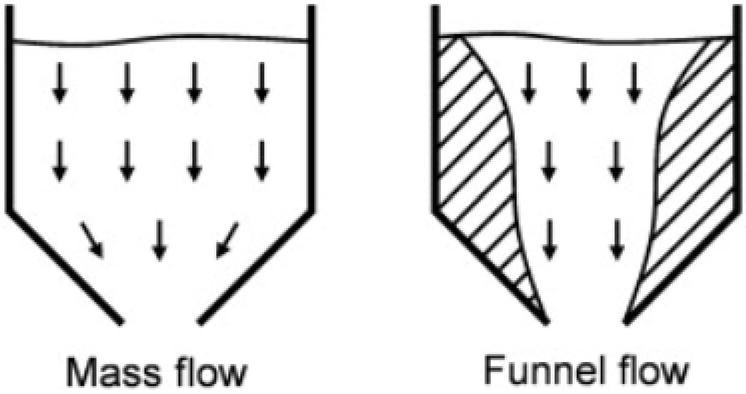
Fig 2. 6 Typical Mohr circle failure plot based on Jenike's theory (source: Ganesan et al., 2008)



2.5 Hopper Flow

In most industries where hoppers are used, it is of interest to know how the solid materials flow from the hopper as it empties under gravitational force. The shear test could provide data to determine the hopper opening and half hopper angle. Flow from hopper can be divided into two modes — the "mass-flow" and "funnel-flow" (Jenike, 1961, 1964), as indicated in Fig 2.7. In mass-flow, the whole particulate material moves simultaneously during discharge while in funnel-flow, the material at the center of the hopper exits first, followed by the material closest to the walls of the hopper. In extreme cases, a ratholing is formed during funnel-flow and the hopper may not empty completely under the force of gravity alone. Funnel-flow can also induce segregation of a powder into non-uniform fractions during discharge, as reported by Johanson (1978), Prescott and Hossfeld (1994), Kirkwood et al. (1999), Pittenger et al. (2000) and Tang and Puri (2004).

Fig 2. 7 Mass flow and funnel flow from hoppers (source: William et al., 2009)



Wood (1981) stated that powder discharge is closely connected with both the hopper structure and the powder properties. By using the approaches described by Jenike (1961, 1964), the mode of flow for a given system could be predicted for a known material and hopper. Jenike used continuum models which were validated against experimental data to develop a series of "hopper design charts" that are being widely used. The design charts, as shown in Fig 2.8, are specific to a certain hopper geometry (conical, wedge-shaped, etc.) and powder internal friction. Once the appropriate chart is selected, the user could locate the intersection point of the hopper wall angle on the x-axis and the wall friction angle on the y-axis to determine whether the powder will discharge in mass- or funnel-flow mode. Based on Jenike's classification and with reference to the Eurocode 1 and DIN 1055, the two critical points to classify the flow pattern is 40° and 60° for mass flow and funnel flow, respectively, as shown in Fig 2.9.

Fig 2. 8 Hopper design chart for a conical hopper based on Jenike's theory (source: Jenike, 1961, 1964)

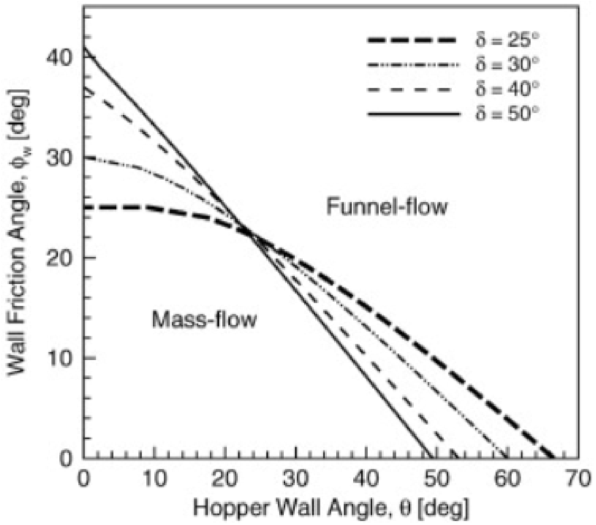
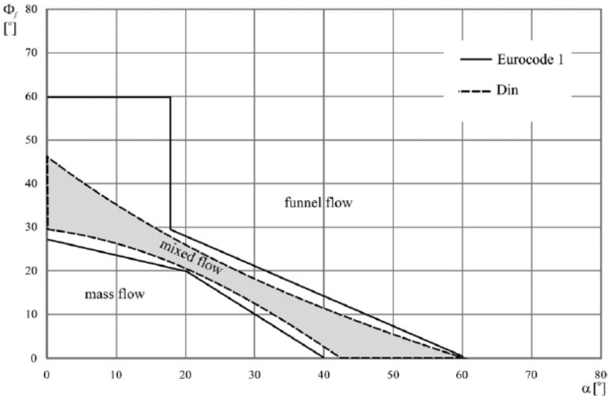


Fig 2. 9 Flow pattern classification based on Eurocode 1 and DIN 1055 (source: Eric, 2004)



The general accepted thumb rule is that interlocking arches can be overcome by ensuring that the outlet diameter is six to eight times of that of largest particle size for a hopper with circular opening outlet, or the width is three to four times the largest particle size for a hopper with slotted opening. (Slotted outlets must be at least three times as long as they are wide for such conditions to apply) (Eric, 2004).

2.5.1 Discharge rate

Knowledge of the discharge rate is of importance for the design of reliable and controllable transport systems. But, prediction of rate is often difficult due to the complexity associated with granular flow, such as inhomogeneous solid distribution, irregular velocity profile and diverse particle size and shape (Seville et al., 1997). Beverloo (1961) and Johanson (1965) evaluated the flow rate form silos for different particulate materials and developed standard equations that are widely being used to estimate the hopper discharge rate.

The Johanson equation is given as:

$$\dot{m} = \rho^{o} A \sqrt{\frac{Bg}{2(1+m)Tan(\theta)}} \tag{2.1}$$

where θ is the half angle of the hopper, *m* is the discharge rate (kg/sec), ρ^o is the bulk density (kg/m^3), and g is the gravity acceleration (9.8 m/s^2)

The Beverloo equation is given as:

$$\dot{m} = 0.58\rho^{o} g^{0.5}(D - kd_{p})^{2.5} \tag{2.2}$$

where, d_p is the particle diameter (m)， *k* is the constant, typically $1.3 < k < 2.9$ with $k = 1.4$ if discharge rate data are not available. The term kd_p accounts for the wall effect where the particles do not fully flow at the perimeter of the outlet, and *D* is the outlet diameter (m).

Recently, discrete element method (DEM) simulations have been conducted by Cleaver and Nedderman (1993), Langston and Tüzün (1994), and Langston et al. (1997), to predict discharge rate. The DEM simulations had good agreement with the experimental discharge rate and the Beverloo equation values. In general, the Beverloo equation gives a good prediction for spherical particles. However, in DEM simulations, the predictability decreases with shape deviation from spheres (Liu et al., 2014).

2.6 Particle Image Velocimetry

Particle image velocimetry (PIV) is a powerful optical surface velocity measuring tool to visualize two-dimensional flow or deformations (Tejchman, 2006). It could evaluate velocity magnitude contours, velocity vector fields, velocity distributions, etc based on analyzing the particles displacement in two sequencing frames. The review work by Adrian (1991) is a reference baseline for early development of the PIV technique and its applications. The improvement of the PIV technique made by Willert and Gharib (1991) provided a dramatic reduction in image processing time, but at a cost of spatial resolution. Willert and Gharib (1991) and Westerweel et al. (1991) demonstrated that measurement accuracy is not adversely affected by a switch to digital processing. Digital Particle Image Velocimetry (DPIV), as it has come to be commonly known, has thus found application in a number of situations in which the processing of large numbers of PIV images is beneficial or necessary for the accuracy of the analysis results.

PIV uses particle displacement over a specified small finite separation time to provide a velocity field for particle flow. PIV, therefore, requires that the materials must contain an adequate number of small particles for sufficient representation of velocities. The quality or accuracy of any flow visualizations using particle motion in the bulk flow primarily depends on the fidelity with which individual particles track the surrounding fluid. The first experimental concern for PIV is the mechanical coupling between the fluid and the particles. The particle density, or the number of particles per unit volume, should be sufficiently low to preserve the original flow dynamics (Crowe et al., 1998; Merzkirch, 1987).

Experimental investigations of flow patterns in converging hoppers have been presented in numerous publications, e.g. Pariseau (1969), Blair-Fish and Bransby (1973), Lee et al. (1974), Nguyen et al. (1979), Tüzün and Nedderman (1982), Langston et al. (1996, 1997), and Ooi et al. (1998). Pitman (1986) investigated stress and velocity fields in two- and three-dimensional hoppers. To investigate granular flows in laboratory models, special techniques such as X-ray, ultrasonic measurement, transparent walls has been used. Kvapil (1959) used two different colors of investigating materials to detect the zones of flow and the stagnant zones. Drescher et al. (1978) presented experiments in a plane parallel/converging bunker using a stereo-photographic technique. Dosekun (1980) measured the granular material flow in a wedge-shaped hopper with transparent walls. Also, other non-invasive measurement techniques used were spy-holes, radio transmitters, and positron emission (Ooi et al., 1998). More details on different techniques used in investigations of granular flow in small models can be found in Ooi et al. (1998) and Lueptow et al. (2000). Irena et al. (2006) used amaranth seed as material to explore the velocity vector fields, flow profiles, and geometrical characteristics of the granular material flowing in the Plexiglas wedged hopper model.

Flow patterns are important to understand the flow efficiency and to understand the hopper design requirements. Hence, in this research, PIV technique was used to study the flow profile of wheat during mass and funnel flow.

This review indicates that to understand challenges in handling bulk wheat, it requires a fundamental understanding on the bulk properties. An in-depth understanding of the flow characteristics of bulk wheat during handling is needed in order to design appropriate and efficient hoppers or storage bins. Therefore, the primary focus of this thesis is to pursue a fundamental investigation on bulk characteristics of bulk wheat.

2.7 Chapter References

Alisa V., Benjamin, J. G. and Fernando, J. M. 2011. Shear and flow behavior of pharmaceutical blends — Method comparison study, Powder Technology 208, 628–636

Adrian, R.J. 1991 Particle-imaging techniques for experimental fluid mechanics. Annual Review of Fluid Mechanics 23, 261-304.

Ashton, M.D., Farely, R. and Valentin, F.H.H. 1965. Some investigations into the strength and flow properties of powders. Rheologica Acta 4 (3), 206–218.

Bell, T.A. 1993. Measurement of powder flowability. In Powders, Characterization and Quality Control, ed. A Lawley, S Armour. Proc. Int. Conf. Exhib. Powder Metall. Part. Mater. 169.

Berry, R. J. and Bradley, M.S.A. 2005. Investigation of the effect of test procedure factors on the failure loci and derived failure functions obtained from annular shear cells, Conf. Particulate Systems Analysis, Stratford-upon-Avon, UK.

Beverloo W. A., Leniger H. A. and Van de Velde J. 1961.The flow of granular material through orifices. Chemical Engineering Science 15, 260-296.

Beverloo, W.A. Leniger, H.A. Velde. and J. van de. 1961. The flow of granular solids through orifices. Chemical Engineering Science, 15, 260–269.

Bhise, S. R., Kaur, A. and Manikantan, M. R. 2014, Moisture Dependent Physical Properties of Wheat Grain (PBW 621). International Journal of Engineering Practical Research, 3 (2), 40-45.

Blair-Fish, P.M. and Bransby, P.L. 1973. Flow patterns and wall stresses in a mass-flow bunker. Journal of Engineering for Industry 95, 17–26.

Carr, J.F. and Walker, D.M. 1968. An annular shear cell for granular materials, Powder Technology 1, 369–373.

Carr, R.L. 1965. Evaluating flow properties of solids. Chemical Engineering 72, 163–167.

Chang, C. S., Converse, H. H. and Lai, F. S. 1984. Flow rate of corn through orifices as affected by moisture content. Transactions of the ASAE 27(5), 1586-1589.

Cleaver, J.A.S. and Nedderman, R.M. 1993 Measurement of velocity profiles in conical hoppers. Chemical Engineering Science 48, 3703–3712.

Crowe, C. T., Sommerfeld, M. and Tsuji, Y. 1998. Multiphase flows with droplets and particles, CRC Press, Boca Raton, Florida, USA, Merzkirch, W. 1987. Flow visualization, Academic Press, Orlando.

de Jong, J. A. H., Hoffman, A. C. and Finkers, H. J. 1999. Properly determine powder flowability to maximize plant output. Chemical Engineering Progress 95(4), 25–34.

Donsi, G. Ferrari, G. 1991. Improvement of bulk flow properties of powders. Powder Technology 65, 469–476.

Donsi, G., Ferrari, G., Poletto, M. and Russo, P. 2004. Gas pressure measurements inside an aerated hopper. Chemical Engineering Research and Design 82 (A1) 72–84

Dosekun, R. 1980. The flow of granular materials. Ph.D. Thesis. University of Cambridge.

Drescher, A., Cousens, T.W. and Bransby, P.L. 1978. Kinematics of the mass flow of granular material through a plane hopper. Geotechnique 28, 27.

Duffy, S. P. and Puri, V. M. 1994. Effect of moisture content on flow properties of powders. ASAE Paper No. 944033.

Duffy, S.P. and Puri, V.M. 1999. Measurement and comparison of flowability parameters of coated cottonseeds, shelled maize and soybeans at three moisture contents. Transactions of the ASAE, 42 (5), 1423–1427.

Dumarey, M., Wikström, H., Fransson, M., Sparén, A., Tajarobi, P., Josefson, M. and Trygg, J. 2011. Combining experimental design and orthogonal projections to latent structures to study the influence of microcrystalline cellulose properties on roll compaction. International Journal of Pharmaceutics 416,110-119.

Eben, H. 2008. Development of a composite index for pharmaceutical powders, Unpublished Ph. D dissertation, North-west University, Potchefstroom, South Africa.

Ehlermann, D. and Schubert, H. 1987. Compressibility characteristics of food powders: Characterizing the flowability of food powders by compression tests. In M. R. Jowitt, F. Escher, M. Kent, B. McKenna, & R. Roques (Eds.), Physical properties of foods2, 445–454. New York: Elsevier Applied Science.

Eric, P. 2004. Practical solutions for solving bulk solids flow problems. Cement Industry Technical Conference. IEEE-IAS/PCA, 139 – 147

Fitzpatrick, J.J., Iqbal, T., Delaney, C., Twomey, T. and Keogh, M.K. 2004b. Effect of powder properties and storage conditions on the flowability of milk powders with different fat contents. Journal of Food Engineering 64(4), 435–44.

Fitzpatrick, J. J., Barringer, S. A. and Iqbal, T. 2004a. Flow property measurement of food powders and sensitivity of Jenike's hopper design methodology to the measured values. Journal of Food Engineering 61(3):399–405

Fowler, R. T. and Glastonbury, R. 1959. The flow of granular solids through orifices. Chemical Engineering Science10, 150-156.

Freeman, R. 2007. Measuring the flow properties of consolidated, conditioned and aerated powders — a comparative study using a powder rheometer and a rotational shear cell, Powder Technology 174, 25–33.

Freeman, R. 2007. Measuring the flow properties of consolidated, conditioned and aerated powders−A comparative study using a powder rheometer and a rotational shear cell, Powder Technology 174 (1–2),25–33.

Freeman, R., Cooke, J.R. and Schneider, L.C. R. 2009. Measuring shear properties and normal stresses generated within a rotational shear cell for consolidated and nonconsolidated powders, Powder Technology 190 (1–2), 65–69.

Ganesan, V., Rosentrater, K.A. and Muthukumarappan, K. 2008. Flowability and handling characteristics of bulk solids and powders – a review with implications for DDGS. Biosystems Engineering 101(4), 425–435.

Griffith, E.J. 1991. Cake Formation in Particulate Systems. New York: VCH conditions on the flowability of milk powders with different fat contents. Journal of Food Engineering 64(4), 435–44.

Guillaume, L. and Nicolas, A. 2010. Stress distribution in lubricated vs unlubricated pharmaceutical powder columns and their container walls during translational and torsional shear testing. Powder Technology 203, 534–547.

Lu, H., Guo, X., Gong, X., Cong, X. and Dong, W. 2011. Study on the fluidization and discharge characteristics of cohesive coals from an aerated hopper. Powder Technology. 207(1–3), 199–207

Hausner, H.H. 1967. Friction conditions in a mass of metal powder. International Journal of Powder Metallurgy 3, 7–13.

Hilton, J.E. and Cleary. P.W. 2011. Granular flow during hopper discharge. Physical Review E84, 011307.

Huang, W.G., Wang, Z.T., Xin, L., Duan, T.H. and Kang, G. J. 2012. Feasibility study on underground coal gasification of No. 15 seam in Fenghuangshan Mine. Journal of the South African Institute of Mining and Metallurgy 112 (10), 897-903.

Ileleji, K.E. and Zhou, B. 2008. The angle of repose of bulk corn stover particles, Powder Technology 187, 110–118.

Jenike, A.W. 1965. Storage and flow of solids. Bull. 123, Eng. Expt. Sta., Utah State University.

Johanson, J.R. 1965. Method of calculating rate of discharge from hoppers and bins SME of AIME, Transactions 232, 69–80.

Johanson. J.R. 1978. Particle segregation… and what to do about it. Chemical Engineering, 183–188.

Johanson., J.R. 2002.Troubleshooting bins, hoppers and feeders. Chemical engineering progress 98 (4), 24–36.

Jorg, S. 2003. Review on testers for measuring flow properties of bulk solids. Granular Matter 5, 1–43.

Kamath, S., Puri, V.M., Manbeck, H.B. and Hogg, R. 1993. Flow properties of powders using four testers – measurement, comparison and assessment. Powder Technology 76, 277–289

Ketchum, M. S. 1919. Design of walls, bins, and grain elevators. McGraw-HU, NY.

Kirkwood, C., Roberts, A.W. and Craig. D.A. 1999. The anti-segregation and blending characteristics of a mass-flow hopper and rotary valve. Powder Handling and Processing 11 (1), 71–74.

Krantz, M., Zhang, H. and Zhu, J. 2009. Characterization of powder flow: static and dynamic testing. Powder Technology 194, 239–245.

Kvapil, R. 1959. Theorie der Schuttgutbewegung. VEB Verlag Technik, Berlin.

Langston, P.A., Nikitidis, M.S., Tuzun, U., Heyes, D.M. and Spyrou, N.M. 1997. Microstructural simulation and imaging of granular flows in two- and three-dimensional hoppers. Powder Technology 94, 59–72.

Langston, P.A., Nikitidis, M.S., Tüzün, U., Heyes, D.M. and Spyrou., N.M. 1997. Microstructural simulation and imaging of granular flows in two- and three-dimensional hoppers. Powder Technology 94, 59–72.

Langston, P.A., Tuzun, U. and Heyes, D.M. 1996. Distinct element simulation of interstitial air effects in axially symmetric granular flows in hoppers. Chemical Engineering Science 51, 873–891.

Langston, P.A. and Tüzün. U. 1994. Continuous potential discrete particle simulations of stress and velocity fields in hoppers: transition from fluid to granular flow. Chemical Engineering Science 49, 1259–1275.

Lee, J., Cowin, S.C. and Templeton, J.S. 1974. An experimental study of the kinematics of flow through hoppers. Transactions of the Society of Rheology 18, 247–269.

Leturia, M., Benali, M., Lagarde, S., Ronga, I. and Saleh, K. 2014. Characterization of flow properties of cohesive powders: A comparative study of traditional and new testing methods. Powder Technology 253, 406–423.

Liu, S.D., Zhou, Z.Y., Zou, R.P., Pinsonb, D. and Yu, A.B. 2014. Flow characteristics and discharge rate of ellipsoidal particles in a flat bottom hopper. Powder Technology 253, 70–79.

Ludger, O. F. and Arthur, A.T. 2007. Food physics: physical properties –measurement and applications, Heidelberg, Germany: Springer Press, (Chapter 6).

Lueptow, R.M., Akonur, A. and Shinbrot, T. 2000. PIV for granular flows. Experiments in Fluids 28, 183–186.

Marinelli, J. and Carson. J.W. 1992. Solve solids flow problems in bins, hoppers, and feeders. Chemical engineering progress 88, 22–28.

Merrow, E.W. 1988. Estimating startup times for solids-processing plants. Chemical Engineering Progress 89(10), 89.

Mohammad, Z. and Behdad, M. 2006. Terry F. W., Flow properties of biomass and coal blends. Fuel Processing Technology 87, 281 – 288.

Muzzio, F.J., Shinbrot, T. and Glasser, B.J. 2002. Powder technology in the pharmaceutical industry: the need to catch up fast, Powder Technology 124, 1–7.

Ooi, J.Y., Chen, J.F. and Rotter, J.M. 1998. Measurement of solids flow patterns in a gypsum silo. Powder Technology 99, 272–284.

Ouwerkerk, C.E.D. and Molenaar, H.J. 1992. Aerated bunker discharge of fine dilating powders. Powder Technology l72, 241–253.

Pablo, J. and Gustavo, V. B. 2009. Food Powders Flowability Characterization: Theory, Methods, and Applications. Annual Review of Food Science and Technology 1, 211-239.

Papazoglou, C.S. and Pyle, D.L. 1970. Air-assisted flow from a bed of particles. Powder Technology 4, 9–18

Pariseau, W.G. 1969. Discontinuous velocity fields in gravity flows of granular materials through slots. Powder Technology 3, 218–226.

Peleg, M. and Hollenbach, A. 1984. Flow conditioners and anticaking agents. Food Technology 38(3), 93–102.

Peleg, M. 1978. Flowability of food powders and methods for its evaluation—a review. Journal of Food Process Engineering, 1, 303–328.

Peleg, M. 1983. Physical characteristics of food powders, E. Bagley (Eds.), Physical Properties of Foods, AVI, New York, 293–323.

Peschl, I.A.S.Z. 1989. Measurement and evaluation of mechanical properties of powders, Powder Handling and Processing, 1, 135–141.

Pietsch, W. B. 1997. Size enlargement by agglomeration. In M. E. Fayed & L. Otten (Eds.), Handbook of powder science and technology, 202–252. New York: Chapman and Hall.

Parafiniuk, P., Molenda, M. and Horabik, J. 2013. Discharge of rapeseeds from a model silo: Physical testing and discrete element method simulations. Computers and Electronics in Agriculture 97, 40–46.

Pitman, E.B. 1986. Stress and velocity fields in two- and three-dimensional hoppers. Powder Technology 47, 219–231.

Pittenger, B.H., Purutyan, H. and Barnum, R.A. 2000. Reducing/eliminating segregation problems in powdered metal processing. Part II: methods of controlling segregation. P/M Science & Technology Briefs, 2 (2) 10–13.

Prescott, J.K. and Barnum, R.A. 2000. On powder flowability, Pharmaceutical Technology 24(10), 60–84.

Prescott, J.K. and Hossfeld., R.J. 1994.Maintaining product uniformity and uninterrupted flow to direct-compression tableting presses. Pharmaceutical Technology. 98–114.

Ristow., G.H. 1997. Outflow rate and wall stress for two-dimensional hoppers. Physica A, 235, 319–326.

Rosentrater, K. R. and Williams, G. D.2004. Design Considerations for the Construction and Operation of Grain Elevator Facilities. Part II: Process Engineering. ASAE Paper No.044146. St. Joseph, MI.: ASAE.

Samadani, A. and Kudrolli, A. 2001. Angle of repose and segregation in cohesive granular matter. Physical Review E 64, 051301 2001

Schrämli, W. 1967. On the measurement of the flow properties of cement. Powder Technology 1, 221–227.

Schulze, D. 1996a. Flowability and time consolidation measurements using a ring shear tester, Powder Handling & Processing 8, 221–226.

Schulze, D. 1996b. Measuring powder flowability: a comparison of test methods Part I. Powder and Bulk Engineering 10, 45–61.

Schulze, D. 1996c. Measuring powder flowability: a comparison of test methods Part II. Powder and Bulk Engineering 10, 17–28.

Schwedes, J. 2003. Review on testers for measuring flow properties of bulk solids. Granular Matter 5, 1–43.

Seville, J.P.K., Tüzün, U. and Clift. R. 1997. Processing of Particulate Solids, Chapman and Hall/Kluwer, London, UK.

Stahl, B. M. 1950. Grain bin requirements. USDA Circular No. 835

Tang, P. and Puri, V.M. 2004. Methods for minimizing segregation: a review. Particulate Science and Technology 22, 321–337

Tejchman, J. 2006. Effect of fluctuation of current void ratio on the shear zone formation in granular bodies within micro-polar hypoplasticity. Computers and Geotechnics 33 (1), 29–46.

Thompson, S. A. and Ross, I. J. 1983. Compressibility and frictional coefficients of wheat. Transactions of ASAE 26(4), 1171-1176, 1180.

Thomson, F.M. 1997. Storage and flow of particulate solids. In Handbook of Powder Science and Technology, ed. ME Fayed, L Otten, 389–486. New York: Chapman & Hall

Train, D. 1958. Some aspects of the property of angle of repose of powders. Journal of Pharmacy and Pharmacology 10, 127–135.

Tüzün, U., Houlsby, G.T., Nedderman, R.M. and Savage, S.B. 1982. The flow of granular materials-II; velocity distributions in slow flow. Chemical Engineering Science 37, 1691–1709.

Tüzün, U. and Nedderman, R.M. 1982. An investigation of the flow boundary during steady-state discharge from a funnel-flow bunker. Powder Technology 31 (1), 27–43

Westerweel, J., Flör, J.B. and Nieuwstadt. F.T.M. 1991. Measurement of dynamics of coherent flow structures using particle image velocimetry. Appl. Laser Tech. Fluid Mech. eds. Adrian, R.J. et al., Springer, Berlin, 476-499.

William, R. K., Jennifer, S. C., Carl, R. W. and Bruno, C. H. 2009. Predicting the flow mode from hoppers using the discrete element method. Powder Technology 195(1), 1–10

Willert, C.E. and Gharib, M. 1991. Digital particle image velocimetry. Experiments in Fluids 10, 181-193.

Wood, J.G.M., 1981. The development of standards for the design and use of silos. Powder Bulk Solids Technology 5 1–6.

York, P. 1975. The use of glidants to improve the flowability of fine lactose powder. Powder Technology 11, 197–198.

Yutaka, K. 1994. Quantitative analysis of closure stress-crack separation curve in grain bridge toughening of polycrystalline ceramics. Materials Science and Engineering: A176 (1–2), 379–383.

Zhu, H.P. and Yu, A.B. 2004. Steady-state granular flow in a three-dimensional cylindrical hopper with flat bottom: microscopic analysis. Journal of Physics D: Applied Physics 37, 1497–1508.

Zuriguel I., Pugnaloni, L. A., Garcimartn, A. and Maza, D. 2003. Jamming during the discharge of grains from a silo described as a percolating transition. Physical Review E (RC) 68, 30301.

Zuriguel, I., Garcimartn, A., Maza, D., Pugnaloni, L.A. and Pastor, J.M. 2005, Jamming during the discharge of granular matter from a silo. Physical Review E 71, 051303.

Chapter 3 - Effect of Chaff on Flow Properties of Wheat

3.1 Introduction

Wheat is one of the most consumed cereal grains in the world. In the grain processing industry, wheat grains are largely used as raw materials for a number of food applications, and more particularly for the production of wheat flours (Carman, 1996; Landillon et al., 2008). Storage and handling of bulk wheat is an important aspect of the process and grain handling industries. Bulk wheat is subjected to a series of static and dynamic loads during handling, transport, processing, and storage (Bargale et al., 1995). During these operations, the physical and flow properties intrinsically affect the bulk behavior such as flow from hoppers and silos (Peleg, 1978; Knowlton et al., 1994). Bulk wheat is considered free flowing and the change in compressed bulk density is minimal compared to other solids or powders such as wheat flour (Schulze, 2008).

Wheat is graded into different grades based on the percent dockage in the bulk. Dockage is described as the “weed seeds, weed stems, chaff, straw, or grain other than wheat (Womach, 2005). Depending on the grade, the dockage could make up to 2% of bulk wheat (FGIS, 2013). Though the wheat kernels are irregular in shape, however they are easy-flowing solids. But, the impurities such as chaff are highly irregular in shape and have a high tendency to interlock that affects bulk flow (Peleg, 1978).

Bulk density, true density, porosity, and angle of repose are some of the useful flow indicators, under gravity. In addition, angle of repose that relates to the interparticulate friction or resistance to movement between particles (Train, 1958), provides a rough estimate of the cohesive behavior of bulk solids (Zhou et al., 2008). Bulk and tapped densities, and derived indices such as Compressibility Index (CI) and Hausner’s Ratio (HR) as defined by Carr, 1965 and Hausner, 1967, measures the ability of a granular material to be compressed, reflecting the relative degree of interparticulate interactions. However, flow indicators mentioned above provide some insight into the behavior of bulk solid, but these are single measures and therefore does not reflect the potentially complex behavior that any granular material exhibit. Limitations are in their sensitivity and ability to capture diverse aspects of flow behavior, especially with respect to characterizing samples during flow.

The flowability of bulk solids, which is defined as the capacity of a granular solid to flow under a specified set of conditions, is a complex characteristic of a material; it is highly dependent on the state of the materials and the application it is being used for. Since the flowability is multidimensional, its quantification is a complex task (Vasilenko et al., 2011). The design and modification of equipment, in particular storage silos and hoppers, for wheat with impurities will require a fundamental understanding of physical properties and their effects on flow behavior. In this chapter, the effect of the different levels of chaff and moisture content on the flow characteristics of wheat is discussed.

3.2 Materials and Methods

3.2.1 Samples

Hard red winter (W) wheat kernels were obtained from Farm Coop, Manhattan, Kan., USA. Wheat chaff was gathered from Hal Ross flour mill, Kansas State University, Manhattan, Kan., USA. Moisture content of the wheat was measured using the American Society of Agricultural and Biological Engineers (ASABE) Standard S352.2 of drying 10 g of unground samples in air oven at 130° for 19 h (ASABE, 2006). The moisture content of chaff was measured using the ASABE Standard S358.3 of drying 25 g samples cut to small pieces and dried at 103 °C for 24 h (ASABE, 2012). Initial moisture content of wheat and chaff were 11.7 and 10.4% wet basis (w.b.), respectively. Experiments were conducted within the moisture range of 10-14% (w. b.). Moisture content of chaff was also maintained at the same moisture content as wheat. Wheat kernels and chaff were rewetted to about 15% (w. b.) moisture content by adding calculated amount of distilled water. After rewetting, the samples were stored at 4 ℃ for 72 h for equilibration. Drying to desired moisture level (10, 12, 14% w. b.) was carried out in ambient conditions by spreading kernels and chaff in thin layers without any additional heat or airflow. Due to the difference in drying, the wheat and chaff the final moisture content was not uniform. The moisture content of wheat and chaff used (Fig 3.1) in this study are given below in Table 3.1. The abbreviation MC1, MC2, MC3 denotes moisture content of wheat and chaff at about 10, 12 and 14% (w.b.), respectively.

Fig 3. 1 Wheat and chaff samples

Table 3. 1 Moisture content of samples, % w. b.

Moisture content	Wheat	Chaff
MC1	9.89	10.40
MC2	11.67	11.83
MC3	13.35	14.01

The overall size of wheat kernel was measured using a single kernel characterization system (SKCS 4100, Perten Instruments, Inc., and Springfield, IL, USA). Chaff dimensions were measured using a Vernier caliper (General Tools, New York City, NY, USA.). Wheat and chaff (C) were mixed at specific proportion (W: C at 100:0%, 97.5:2.5%, 95:5%, 92.5:7.5% and 0:100%) by weight basis. The proportion of mix was selected based on the U.S. grade of wheat with different broken and foreign material level (FGIS, 2013). As per the Federal Grain Inspection Handbook, foreign material consists of broken wheat, chaff, insect damaged kernels, live insects, and frass. In this study only chaff was mixed with bulk wheat to simulate different U.S. grades.

3.2.2 Physical properties and flow indicators

3.2.2.1 Bulk density

The bulk density of wheat, chaff and the wheat-chaff mix was measured by using a Winchester cup setup (Seedburo equipment Company, Chicago, IL, USA.). A one pint (4.7318×10^{-4} m^3) cup was set under a funnel and the samples poured through the funnel to maintain a natural flow into the cup. Excess sample was scraped off using a wooden scrapper in a zig-zag motion and the cup was weighed using a balance (sensitivity: 0.001g; Mettler-

Toledo, Heightstown, NJ, USA). The bulk density (ρ_B) was then calculated from the weight and volume of the samples.

3.2.2.2 Tapped density

Tapped density, that measures the compaction during handling, was measured using an autotap instrument (AT 6-1-110-60, Quantachrome Instruments, FL, USA) according to ASTM Standard B527-6 (ASTM, 1985). The samples were filled in a volumetric cylinder (250 ml) and the cylinder was tapped for 750 times. The number of taps was optimized for change in volume during tapping in a preliminary experiment (data not shown). After tapping, the change in volume of sample was measured and the tapped density (ρ_T) was then calculated from the volume of sample after tapping and the weight.

3.2.2.3 Compressibility index and Hausner ratio

Compressibility Index (CI) and Hausner Ratio (HR) indicate the cohesiveness and compaction mechanism that occurs during handling of particulate materials due to vibration or tapping. CI and HR were calculated from the bulk and tapped density using the following equations (Kingsly et al., 2010):

$$\mathrm{CI} = 100 \times \left(\frac{(\rho_\mathrm{T} - \rho_B)}{\rho_T} \right) \tag{3.1}$$

$$\mathrm{HR} = \frac{\rho_\mathrm{T}}{\rho_B} \tag{3.2}$$

where ρ_B is the bulk density (kg/m^3) and ρT is the tapped density (kg/m^3).

3.2.2.4 True density

True density of the samples was measured using a gas pycnometer (AccuPyc II 1340, Micromeritics, Norcross, GA, USA). Helium gas was used to fill the chamber containing samples to determine the particle volume and the true density was calculated from the weight and the solid particle volume.

3.2.2.5 Porosity

Porosity was calculated using the relationship between bulk and true densities according to Mohsenin (1986) as follows,

$$\varepsilon = (1 - \frac{\rho_B}{\rho_{Ture}}) \times 100 \tag{3.3}$$

where ρ_B is the bulk density (kg/m^3), and ρ_{Ture} is the true density (kg/m^3).

3.2.2.6 Angle of repose

A fixed diameter (0.09 m) plate was set under a funnel which was held at a height (0.1 m) above the plate and the samples were poured to maintain a natural flow on the plate. After pouring the samples, the height of the cone was measured and the angle of repose was calculated using the following relationship (Ozguven and Kubilay, 2004):

$$\theta = \arctan\left(\frac{2H}{D}\right) \tag{3.4}$$

where H and D are the height and average diameter of the pile, respectively.

3.2.3 Flow properties

The FT4 Powder Rheometer (FT4, Freeman Technologies, Gloucestershire, UK) was used to evaluate the flow properties in terms of energy required to make the solid flow. Detailed descriptions of this equipment and its use in flow characterization can be found in Lindberg et al., 2004; Freeman, 2007; and Leturia et al., 2014. The FT4 powder rheometer system consists of a vertical glass sample container (120 mm height; 50 mm internal diameter) and a rotating blade (48 mm diameter; 10 mm height), which navigates through the sample up and down, and either in clockwise or anti-clockwise direction. FT4 calculates the flow properties by continuously measuring the forces causing deformation and flow of the powder imposed by moving blade (Leturia et al., 2014). The flow properties, described in the following sections, were evaluated during the displacement of powders in a controlled manner. The FT4 standard dynamic test cycle includes preconditioning, conditioning cycle, and test cycle. Preconditioning cycle mixes the sample to make the bed uniform before energy measurement. However, as the dimension and densities of wheat kernels and chaff had significant difference, during preconditioning, chaff moved to the top of the cylindrical vessel. To avoid measurement error due to this segregation, preconditioning cycle was not used in the dynamic flow property measurement in this study.

3.2.3.1 Basic flowability energy (BFE) and stability index (SI)

The energy required to establish a specific flow pattern for a precise volume of particulate materials is called the basic flowability energy. SI evaluates the effect of flow on the bulk physical changes on powders and solids. Some physical changes such as segregation (of chaff and wheat kernels) and agglomeration due to interlocking during flow of bulk wheat will help in developing better understanding on the wheat and chaff mix. BFE and SI were used to evaluate the flow properties of the granular material under free surface conditions. The flow energy is calculated from the anticlockwise motion of blade (23.5 mm diameter), through the samples, when it traverses through the vessel top to the bottom. The instrument conducts eleven test cycles to calculate BFE. The first seven test cycles were performed at a blade tip speed of 100 mm/s to examine the effect of segregation on the bulk wheat during flow. For subsequent tests (test 8 to 11), the blade tip speed was gradually reduced from 100 mm/s to 70, 40 and 10 mm/s to evaluate the sensitivity of the particles to different flow rates. From the 11 test cycle results, the flow parameters were calculated (Leturia et al., 2014). BFE corresponds to the stabilized flow energy (test 7) that represents the energy needed to displace a conditioned particulate sample during downward movement of the blade:

$$\mathrm{BFE} = \mathrm{Flow\ \ energy\ \ at\ \ test\ \ 7} \tag{3.5}$$

SI is the factor evaluating flow energy changes during repeated testing and assesses how easily the particles are affected by being made to flow:

$$\mathrm{SI} = \frac{\mathrm{Flow\ \ energy\ \ at\ \ test\ \ 7}}{\mathrm{Flow\ \ energy\ \ at\ \ test\ \ 1}} \tag{3.6}$$

3.2.3.2 Aeration ratio (AR)

Bulk wheat with chaff is very porous and has intergranular spaces filled with air. The presence/absence of air or the porosity affects the bulk flow properties. Depending on their physical characteristics, easily aeratable solids have better flow properties because low applied energy is sufficient to initiate flow. For AR measurement, the samples were placed in a 160 ml vessel (50 mm inner diameter) glass vessel with a porous base that was connected to an air flow controller. The flow of samples was simulated by moving the blade in an axial helical path through the test sample at a blade tip speed of 100 mm/s. In the second test cycle, the blade was moved along a downward helical path, (-10° at the sample blade tip speed) but in the opposite direction, to impose compaction, thereby forcing the sample to flow around the blade. Progressively, from test 1 to 6, the air flow rate was increased from 0 mm/s to 10 mm/s at 2 mm/s increment. At each condition, the flow energy was recorded by the instrument and using the relationship below, the aeration ratio was calculated:

$$\mathrm{AR} = \frac{\text{Flow energy (at air velocity 0 mm/s)}}{\text{Flow energy (at air velocity 10 mm/s)}} \tag{3.7}$$

3.2.3.3 Compressibility

The compressibility reflects the particle density change during compaction, which is., the decrease in volume of the packed bed of particles under normal stress (Turki and Fatah, 2008; 2010). Wheat and chaff samples were placed in a 50 ml cylindrical vessel and using a vented piston normal stress from 0.5 to 15 kPa (0.5, 1, 2, 4, 6, 8, 10, 12, and 15 kPa) was applied to consolidate the samples. Each normal stress was maintained for about 25 s to reach equilibrium at the target stress. The force applied on the sample and the compressibility as a percentage change in volume was recorded.

3.2.3.4 Permeability

Permeability is part of the proportionality constant in Darcy's law which relates discharge (flow rate) and fluid physical properties (e.g. viscosity), to a pressure gradient applied to the porous media. Permeability testing by FT4 measures the pressure drop across the powder bed while the applied normal pressure was varied and the air velocity through the aeration base was maintained constant at 2 mm/s (Leturia et al., 2014). During testing, the sample was compressed using a piston with stainless steel mesh end that allowed air to pass through during compression. The air flow velocity was kept constant at 2 mm/s and the resistance to air flow was measured as air pressure drop.

$$\mathrm{k} = \frac{V\mu \mathrm{L}}{\triangle \mathrm{P}} \tag{3.8}$$

where k is the permeability (cm^2); v is the air velocity (cm/s); $\triangle P$ is the pre powder bed (Pa); μ is the air viscosity (Pa·s); and L is the length of powder bed (cm).

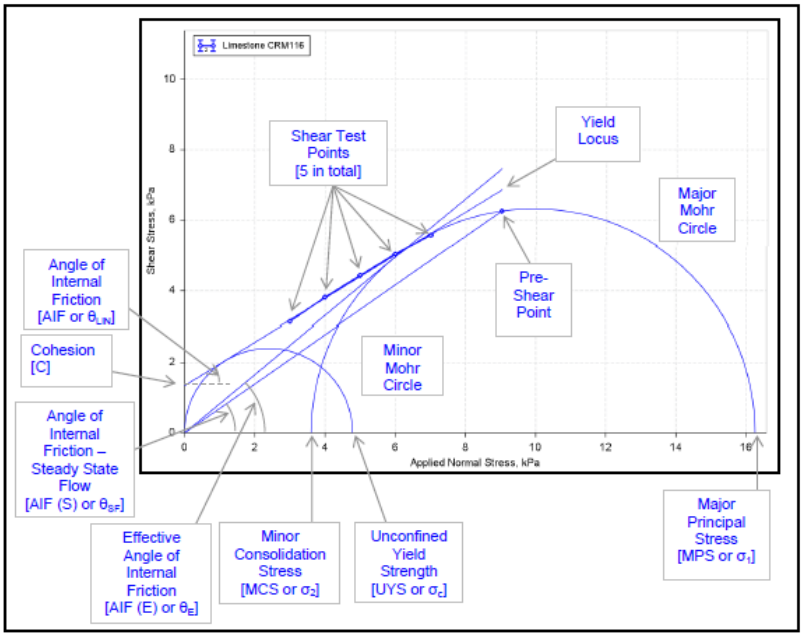
3.2.3.5 Shear tests

The relationship between normal stress and shear stress are plotted to obtain experimental yield locus that represents the failure during shearing of the bulk solids (Fig. 3.2). In free flowing powders, the yield locus follows a straight line that passes through the origin (Peleg, 1978) and its slope defines the angle of internal friction, as calculated by equation 3.9. For cohesive powders, however, the experimental yield locus is generally non-linear at different consolidation stresses (Thomson, 1997; de Jong et al., 1999). The shear test determines the following material characteristics as related to flow: the flow function (FF), the effective angle of internal friction (δ), and the angle of wall friction (ϕ_w). The flow function is derived from the relationship between unconfined yield strength (UYS), σ_c, of the powder against major principal stress (MPS), σ_1, acting on the solids. FF represents the strength of the consolidated sample that must be surpassed to initiate flow. The smaller value at which the larger Mohr circle intersects the x-axis is the minor consolidation stress (MCS) σ_2.

$$\phi = \tan^{-1}\left(\frac{\tau_{s/w}}{\sigma_{s/w}}\right) \tag{3.9}$$

where $\tau_{s/w}$ indicates the shear stress in shear test/wall friction test, $\sigma_{s/w}$ indicates the normal stress in shear test/wall friction test.

Fig 3. 2 Mohr circle analysis of shear test results



3.2.4. Statistical analysis

The flow property measurements were performed in triplicates and the mean and standard error (SE) values are reported in this thesis. Statistical analyses were conducted using SAS (SAS Institute Inc., Cary, NC, USA). The effect of moisture content, chaff proportion and their interactions on physical and flow properties were evaluated by subjecting the data to two-way analysis of variance (ANOVA) at α= 0.05, using PROC GLM. Ryan or Ryan-Einot-Gabriel-Welsch Q (REGWQ) multiple comparison tests was used to calculate the differences ($P \leq 0.05$) due to moisture content and impurity percent.

3.3 Results and Discussion

3.3.1 Bulk physical properties

The average size of wheat kernels were 2.78±0.35 mm, 2.82±0.34 mm, and 2.78±0.32mm at moisture contents 9.89, 11.67 and 13.35 % w.b., respectively. Size of chaff was not uniform and the chaff length ranged from 15.90±2.18 to 26.08±3.31 mm with an average diameter of 4.71±1.38 mm.

Moisture content and chaff proportion had significant influence on the bulk, tapped and true densities of bulk wheat (Table 3.2, 3.3 and 3.4). The bulk density of wheat, chaff and the wheat-chaff mixture decreased significantly with the increase in moisture content. The decrease in bulk and true density, with increase in moisture content, could be attributed to the relatively larger increase in kernel volume compared to the increase in kernel mass. The negative relationship of bulk density with moisture content was also observed for wheat (Karimi et al., 2009), gram (Dutta et al., 1988), and soybeans (Deshpande et al., 1993). As expected, with the increase in chaff proportion, the bulk density of wheat decreased as the density of chaff is significantly lower than the wheat kernels (Table 3.2).

Tapped density exhibited similar trend as that of bulk density. During handling or transportation, the structure of cohesive bulk solids collapse significantly due to vibration, while the weak or free-flowing particulate material has less scope for further consolidation (Eben, 2008). When there is reduced friction between the particles, the particles rearrange and thus tapping results in improved packing conditions. The effect of chaff proportions and the moisture content on bulk, tapped and true densities are significantly different.

Table 3. 2 Bulk density of wheat with chaff

Sample	Bulk density, kg/m^3		
	MC 1	MC 2	MC 3
W 100%	805.50±0.33a	801.54±0.51b	785.91±0.12c
W 97.5%-C 2.5%	783.68±0.49d	776.62±0.37e	767.71±0.40f
W 95%-C 5%	758.36±0.42g	747.68±0.38h	734.52±0.21i
W 92.5%-C 7.5%	738.24±0.39j	729.40±0.33k	718.36±0.25l
C 100%	322.79±0.50m	308.47±0.49n	293.35±0.71o

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

Table 3. 3 Tapped density of bulk wheat with chaff

Sample	Tapped density, kg/m^3		
	MC 1	MC 2	MC 3
W 100%	831.52±1.22a	825.33±0.57b	811.51±0.19c
W 97.5%-C 2.5%	811.90±0.61c	800.73±0.85d	793.15±1.09e
W 95%-C 5%	781.00±1.06f	781.00±1.06g	766.82±2.80h
W 92.5%-C 7.5%	762.75±2.95i	762.75±2.95j	746.31±0.60k
C 100%	359.78±1.51l	359.78±1.51m	323.11±2.20n

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

Table 3. 4 True density of bulk wheat with chaff

Sample	True density, kg/m^3		
	MC 1	MC 2	MC 3
W 100%	1404.63±3.58Aa	1386.71±1.63Ab	1379.67±3.65Ac
W 97.5%-C 2.5%	1395.58±3.04Ba	1371.01±0.58Bb	1371.12±1.09Bc
W 95%-C 5%	1393.69±3.40Ba	1380.57±1.39Bb	1370.11±0.73Bc
W 92.5%-C 7.5%	1391.79±1.26Ba	1379.42±0.91Bb	1367.13±2.59Bc
C 100%	1364.57±2.93Ca	1354.36±4.50Cb	1341.10±3.80Cc

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference (P < 0.05) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference (P < 0.05) due to moisture content.*

Because the interparticulate interactions that influence the bulking properties of a solid are also the interactions that interfere with solid material flow, a comparison of the bulk and tapped densities gives a measure of the relative importance of these interactions. HR and CI of wheat, chaff and their mixture are given in Table 3.5 and 3.6. Based on Carr's indices of CI and HR, flowability of wheat could be classified as 'excellent' with minimum effect from the presence of chaff (Carr, 1965). Chaff had the highest CI and HR for their irregularity in shape, weak structure and varying size distribution. CI and HR could be effective indicators for the effect of chaff proportions and moisture content on bulk wheat flow.

Porosity is the fraction of a porous medium that is void space (John, 2010). The porosity of samples increased as the moisture content and chaff proportion significantly (Table 3.7) Chaff was highly porous and presence of chaff in wheat influenced the porosity of bulk wheat significantly. Moisture content also had significant effect on the porosity of wheat-chaff mixture.

Angle of repose of bulk wheat with chaff (Table 3.8) showed positive correlation with moisture content, and the value increased with the chaff proportion in bulk wheat samples. Similar results have been reported for wheat (Tabatabaeefar, 2003; Karimi et al., 2009) and pigeon pea (Shepherd and Bhardwaj, 1986). The smaller sized chaff occupied the intergranular space of the wheat kernels and resulted in an increase in angle of repose from higher interlocking between the chaff particles. Higher angle of repose could indicate poor flow of bulk material. Other than affecting flow through hopper bottoms, higher angle of repose could also reduce the overall bin capacity.

Table 3. 5 Hausner ratio of bulk wheat with chaff

Sample	Hausner's ratio		
	MC 1	MC 2	MC 3
W 100%	$1.03\pm0.15\times10^{-2}$Ba	$1.03\pm0.07\times10^{-2}$Ca	$1.03\pm0.02\times10^{-2}$Ba
W 97.5%-C 2.5%	$1.04\pm0.08\times10^{-2}$Ba	$1.03\pm0.11\times10^{-2}$BCa	$1.03\pm0.14\times10^{-2}$Ba
W 95%-C 5%	$1.03\pm0.14\times10^{-2}$Ba	$1.04\pm0.27\times10^{-2}$Ba	$1.04\pm0.38\times10^{-2}$Ba
W 92.5%-C 7.5%	$1.03\pm0.40\times10^{-2}$Ba	$1.03\pm0.09\times10^{-2}$BCa	$1.04\pm0.09\times10^{-2}$Ba
C 100%	$1.11\pm0.47\times10^{-2}$Aa	$1.12\pm0.25\times10^{-2}$Aa	$1.10\pm0.75\times10^{-2}$Aa

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.*

Table 3. 6 Compressibility index of bulk wheat with chaff

Sample	Compressibility index		
	MC 1	MC 2	MC 3
W 100%	3.05±0.14Ba	2.81±0.07Ca	3.07±0.02Ba
W 97.5%-C 2.5%	3.41±0.07Ba	3.01±0.1Ca	3.14±0.13Ba
W 95%-C 5%	2.83±0.13Ba	3.75±0.25Ba	4.14±0.35Ba
W 92.5%-C 7.5%	3.14±0.37Ba	3.13±0.37BCa	3.68±0.08Ba
C 100%	10.22±0.38Aa	10.78±0.19Aa	9.14±0.62Aa

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.*

Table 3. 7 Porosity of bulk wheat with chaff

Sample	Porosity, %		
	MC 1	MC 2	MC 3
W 100%	42.65±0.15a	42.20±0.07b	43.04±0.15c
W 97.5%-C 2.5%	43.85±0.12d	43.76±0.02d	44.01±0.04e
W 95%-C 5%	45.59±0.13f	45.84±0.05g	46.39±0.03h
W 92.5%-C 7.5%	46.96±0.05i	47.12±0.03j	47.46±0.10k
C 100%	76.34±0.05l	77.22±0.08m	78.13±0.06n

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference ($P < 0.005$).*

Table 3. 8 Angle of repose of bulk wheat with chaff

Sample	Angle of repose, deg		
	MC1	MC2	MC3
W 100%	23.61±0.62Da	24.31±0.61Db	25.36±0.60Dc
W 97.5%-C 2.5%	25.01±1.05Ca	25.71±0.60Cb	26.39±0.59Cc
W 95%-C 5%	25.71±0.60BCa	26.39±0.59BCb	26.73±0.59BCc
W 92.5%-C 7.5%	26.39±0.59Ba	26.73±0.59Bb	27.41±0.58Bc
C 100%	36.53±0.47Aa	37.87±0.79Ab	38.40±0.45Ac

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis)*
*** The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.*

3.3.2 Dynamic flow behavior

BFE corresponds to the stabilized flow energy that represents the energy needed to displace a conditioned bulk particulate sample during testing. BFE of bulk wheat had a positive relationship with moisture, meanwhile as the chaff proportion increased BFE decreased (Table 3.9). With lesser chaff content, the bulk wheat had low compressibility and high transmission of particle-to-particle forces that makes the bulk material flow easily. But for chaff, the transmission zone is localized due to higher porosity that resulted in low flow energy.

SI values for stable solids range from 0.9 – 1.1. Solids with good stability value indicate that they do not segregate or disintegrate during flow. The measured stability values for bulk wheat are in the range of 0.9- 1.1 (Table 3.10). Based on statistical analysis, the effect of chaff proportion and moisture content are significantly different with $P < 0.001$. Within the range of moisture content and the chaff proportions evaluated, bulk wheat does not change their properties during flow. Bulk solids are sometimes considered to be relatively stable entities like the individual solid particles that make up their mass. This is not the case since the rheological properties of the mass are greatly influenced by the presence or absence of air. Solids consolidate on compaction and yet following aeration will usually flow readily, even in some cases fluidizing occurs across the bed. Because the effect of air is so significant, an important industrial need is to be able to characterize the bulk solids in relation to air content (Freeman, 2003). Understanding how air affects flow properties is a prerequisite of efficient handling and processing of powders. Aeration ratio (AR) of bulk wheat is given in Table 3.11. Aeration ratio values close to 1 indicates that the materials are not sensitive to air flow in specific conditions (air flow rate from 0mm/s to 10mm/). For bulk wheat, including chaff, the AR values are close to 1.

Table 3. 9 Basic flow energy of bulk wheat with chaff

Sample	Basic flow energy		
	MC 1	MC 2	MC 3
W 100%	805.5±0.33Aa	801.54±0.51Ab	785.91±0.12Ac
W 97.5%-C 2.5%	783.68±0.49Ba	776.62±0.37Bb	767.71±0.40Bc
W 95%-C 5%	758.36±0.42BCa	747.68±0.38BCb	734.52±0.21BCc
W 92.5%-C 7.5%	738.24±0.39Ca	729.40±0.33Cb	718.36±0.25Cc
C 100%	322.79±0.50Da	308.47±0.49Db	293.35±0.71Dc

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference (P < 0.05) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference (P < 0.05) due to moisture content.*

Table 3. 10 Stability index of bulk wheat with chaff

Sample	Stability index		
	MC 1	MC 2	MC 3
W 100%	1.00±0.03Aa	1.01±0.02Aa	0.98±0.02Aa
W 97.5%-C 2.5%	0.99±0.01Aa	0.99±0.04Aa	0.98±0.02Aa
W 95%-C 5%	0.98±0.06Aa	0.99±0.03Aa	0.96±0.04Aa
W 92.5%-C 7.5%	0.97±0.06Aa	0.95±0.03Aa	0.96±0.05Aa
C 100%	0.99±0.13Aa	1.01±0.18Aa	1.05±0.11Aa

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference (P < 0.05) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference (P < 0.05) due to moisture content.*

Table 3. 11 Aeration ratio of bulk wheat with chaff

Sample	Aeration ratio		
	MC 1	MC 2	MC 3
W 100%	1.04±0.03Aa	1.0±0.04Aa	1.12±0.05Ab
W 97.5%-C 2.5%	1.11±0.09Aa	1.06±0.10Aa	1.17±0.09Ab
W 95%-C 5%	1.18±0.14Aa	1.13±0.11Aa	1.19±0.13Ab
W 92.5%-C 7.5%	1.12±0.01Aa	1.20±0.16Aa	1.19±0.06Ab
C 100%	0.97±0.07Aa	1.12±0.13Aa	1.17±0.08Ab

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.*

3.3.3. Bulk flow properties

Compressive property are important in many problems associated with the design of machines and the analysis of the behavior of the product during operations such as drying, cleaning and milling. Meanwhile, compressibility of particles is relative to many process environments such as storage in silos or behavior during roller compaction (Akaaimo and Raji, 2006). Compressibility of wheat samples increased with the increase of moisture content (Table 3.12). In bulk solids with poor flow characteristics, relatively large voids are formed due to the action of adhesive forces. This is not the case with free flowing particulate materials. Thus, it is expected that poorly flowing bulk solids are more compressible.

Permeability is a property of porous materials that quantifies the relative ease with which a fluid can pass through the bulk material. Grain during storage experiences packing and compaction due to the vertical pressure exerted by the grain mass. Packing results in a change in bulk density of the grain mass, which in turn results in a change in porosity. Determining the permeability of grain as a function of bulk density is important for predicting natural convention current in stored grain. The wheat-chaff mix didn’t indicate any specific trend of permeability in relation to chaff content (Table 3.13). Negative relationship was observed between the permeability and moisture content. The permeability was measured at consolidated conditions, so the chaff had lower permeability than wheat. Under consolidation, due to particle rearrangement and reduction in interparticulate void space, the chaff exhibited lower permeability. Presence of chaff in bulk wheat could impact the air flow during drying and aeration.

Table 3. 12 Compressibility of bulk wheat with chaff at 15kPa pressure

Sample	Compressibility, %		
	MC 1	MC 2	MC 3
W 100%	4.84±0.59Aa	4.86±0.11Aa	5.58±0.17Ab
W 97.5%-C 2.5%	4.98±0.73ABa	7.32±0.28ABa	7.58±0.45ABb
W 95%-C 5%	5.33±0.60Ba	7.49±0.09Ba	7.76±0.21Bb
W 92.5%-C 7.5%	5.52±0.06Ba	7.59±0.69Ba	7.99±1.40Bb
C 100%	18.31±3.68Ca	22.55±2.31Ca	23.20±2.85Cb

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference (P < 0.05) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference (P < 0.05) due to moisture content.*

Table 3. 13 Permeability of bulk wheat with chaff at 15kPa pressure

Sample	Permeability		
	MC 1	MC 2	MC 3
W 100%	$1.46\times10^{-7}\pm4.86\times10^{-10}$a	$1.81\times10^{-7}\pm1.58\times10^{-9}$b	$1.28\times10^{-7}\pm2.63\times10^{-9}$c
W 97.5%-C 2.5%	$1.60\times10^{-7}\pm1.29\times10^{-9}$d	$1.53\times10^{-7}\pm2.84\times10^{-9}$ad	$1.34\times10^{-7}\pm6.65\times10^{-10}$c
W 95%-C 5%	$1.62\times10^{-7}\pm2.74\times10^{-9}$d	$1.55\times10^{-7}\pm3.01\times10^{-9}$d	$1.33\times10^{-7}\pm9.03\times10^{-10}$c
W 92.5%-C 7.5%	$1.58\times10^{-7}\pm2.12\times10^{-9}$d	$1.58\times10^{-7}\pm1.24\times10^{-9}$d	$1.40\times10^{-7}\pm3.83\times10^{-9}$ac
C 100%	$1.25\times10^{-7}\pm1.48\times10^{-9}$ce	$1.33\times10^{-7}\pm3.16\times10^{-9}$dc	$1.20\times10^{-7}\pm3.79\times10^{-9}$ce

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

3.3.4 Shear properties

Shear properties indicate how easily a previously at rest, consolidated powder will begin to flow. From Table 3.14, there is no significant difference in the angle of internal friction of bulk wheat samples with different proportion of chaff. The larger the angle of internal friction and wall friction, it is harder for material to flow. The angle of internal friction of rye, barley, oats and corn has been studied by Molenda and Horabik (2005) and they reported that the value of angle of internal friction increased with moisture content. In comparison, the angle of internal friction of barley and corn is higher than wheat, but the value for rye and oats are lesser than wheat. The angle of internal friction values from this study agrees with the results reported by Molenda and Horabik (2005).

Knowledge of wall friction provides important information on whether the bulk solid will flow against the material with which it is in contact. It is the frictional resistance to bulk solids flow that exists between the bulk solids and hopper/silo wall material (Iqbal and Fitzpatrick, 2004). Similar to angle of internal friction, at MC 1 and MC 2 moisture contents, the wall friction results are not significantly different. The wall friction was higher at 14% (MC 3) moisture content (Table 3.15). The results indicate that increase in moisture content will lead to a higher wall friction influencing the bulk flow of wheat.

All the shear properties were significantly affected by chaff proportion (Tables 3.16 – 3.20). Cohesion values of wheat and wheat - chaff mixture was in the range from 0.1 – 1.8. For free flowing material like wheat, the cohesion value should be close to 0. The results obtained in this study reflected the findings reported by Molenda and Horabik (2005) of cohesion values ranging from 0.9 -2.8. However, the flow function values had larger standard deviation (Table 3.10) which might due to the configuration of the FT-4 rheometer. As stated in Jenike's methods (Jenike, 1960) the diameter of the shear tester base should be 30 times than the diameter of bulk solids. The flow function of chaff (Table 3.20) was much lower compared to the wheat grains. Jenike (1964) and Fitzpatrick and Iqbal (2004) stated that the lower the flow function the worse the flowablity of samples. Furthermore, samples with FF value higher than 10 indicates free flowing and based on the results from this study, wheat samples did not fall in that classification.

Table 3. 14 Angle of internal friction angle of bulk wheat with chaff at 15kPa

Sample	Angle of Internal friction		
	MC 1	MC 2	MC 3
W 100%	23.95±0.95Aa	26.58±0.49Aa	28.64±2.46Ab
W 97.5%-C 2.5%	25.31±0.44Aa	26.67±1.62Aa	30.441.44Ab
W 95%-C 5%	27.92±0.29Aa	29.60±0.29Aa	28.10±2.17Ab
W 92.5%-C 7.5%	29.44±0.26Aa	30.33±0.53Aa	27.92±0.74Ab
C 100%	33.81±3.16Ba	34.45±2.60Ba	43.13±7.17Bb

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.*

Table 3. 15 Wall friction angle of bulk wheat with chaff at 15kPa

Sample	Wall Friction Angle		
	MC 1	MC 2	MC 3
W 100%	17.39±0.29Aa	18.24±0.50Aa	20.33±0.50Ab
W 97.5%-C 2.5%	16.99±0.82ABa	17.78±0.55ABa	19.40±1.77ABb
W 95%-C 5%	16.94±0.29Ba	17.07±0.17Ba	19.04±1.88Bb
W 92.5%-C 7.5%	16.32±0.26Ba	16.52±0.62Ba	18.37±0.45Bb
C 100%	15.46±0.60Ca	15.43±0.37Ca	16.37±0.28Cb

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.*

Table 3. 16 Effect of chaff on cohesion of bulk wheat with chaff

Sample	Cohesion		
	MC 1	MC 2	MC 3
W 100%	0.74±0.33Aa	0.63±0.11Aa	0.68±0.49Aa
W 97.5%-C 2.5%	0.75±0.08Aa	0.63±0.26Aa	0.34±0.19Aa
W 95%-C 5%	0.40±0.04Aa	0.28±0.22Aa	0.69±0.22Aa
W 92.5%-C 7.5%	0.17±0.10Aa	0.20±0.06Aa	0.68±0.31Aa
C 100%	1.39±0.68Ba	1.79±0.51Ba	1.14±0.46Ba

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.*

Table 3. 17 Effect of chaff on unconfined yield stress (UYS) of bulk wheat with chaff

Sample	UYS, kPa		
	MC 1	MC 2	MC 3
W 100%	2.07±1.25Aa	2.03±0.34Aa	2.24±1.52Aa
W 97.5%-C 2.5%	2.36±0.26Aa	2.04±0.78Aa	1.17±0.64Aa
W 95%-C 5%	1.17±0.14Aa	0.98±0.75Aa	2.28±0.63Aa
W 92.5%-C 7.5%	0.59±0.32Aa	0.69±0.19Aa	2.24±1.00Aa
C 100%	5.13±2.22Ba	6.75±1.58Ba	5.30±1.94Ba

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.*

Table 3. 18 Effect of chaff on major principle stress (MPS) of bulk wheat with chaff

Sample	MPS, kPa		
	MC 1	MC 2	MC 3
W 100%	18.07±2.27a	24.54±0.17b	23.71±0.34bc
W 97.5%-C 2.5%	25.27±0.48b	24.88±1.38bc	23.60±0.50b
W 95%-C 5%	24.29±0.15b	23.65±0.71bc	24.66±1.18b
W 92.5%-C 7.5%	23.01±0.26bc	23.10±0.95bc	23.94±1.38bc
C 100%	26.18±1.42b	29.67±1.34d	33.38±2.90d

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

Table 3. 19 Effect of chaff on major consolidation stress (MCS) of bulk wheat with chaff

Sample	MCS, kPa		
	MC 1	MC 2	MC 3
W 100%	9.70±1.76Aa	8.59±0.14Aa	7.53±0.13Ab
W 97.5%-C 2.5%	9.06±0.16Aa	8.70±0.66Aa	7.34±0.36Ab
W 95%-C 5%	8.37±0.11Aa	7.68±0.18Aa	8.07±0.91Ab
W 92.5%-C 7.5%	7.78±0.21Aa	7.51±0.24Aa	7.87±0.42Ab
C 100%	5.95±0.41Ba	6.34±0.47Ba	4.80±1.23Bb

**where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference (P < 0.05) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference (P < 0.05) due to moisture content.*

Table 3. 20 Effect of chaff on flow function (FF) of bulk wheat samples

Sample	FF		
	MC 1	MC 2	MC 3
W 100%	10.23±3.78Aa	12.31±2.02Aa	14.56±9.41Aa
W 97.5%-C 2.5%	10.25±0.75ABa	13.53±5.45ABa	25.45±15.39ABa
W 95%-C 5%	18.29±2.37ABa	36.18±26.06ABa	11.22±2.35ABa
W 92.5%-C 7.5%	149.4.±155.89Ba	35.89±20.42Ba	12.58±6.46Ba
C 100%	5.86±2.64Aa	4.58±1.21Aa	6.27±1.93Aa

** where W indicates wheat kernel, C indicates chaff and MC is the moisture content (% wet basis);*
*** The same uppercase letter in the same column indicates no significant difference (P < 0.05) due to chaff proportion, the same lowercase letter in the same row indicates no significant difference (P < 0.05) due to moisture content.*

3.4 Conclusions

The effect of proportion of chaff and moisture content on the bulk physical and flow properties of wheat was studied. Results indicate that the moisture content and chaff proportion influence both the physical and flow properties of wheat. Flow indicators, such as bulk density, tapped density, and angle of repose, showed that the flowability of bulk wheat decrease as moisture content and chaff proportion increase. Under compaction, changes in density altered the bulk porosity of samples. Meanwhile, more void in the sample due to the presence of chaff made it easier to be compacted at the same pressure level. The energy required to initiate the flow of bulk wheat is higher than chaff due to higher bulk density. The presence of chaff and from their interlocking behavior, the flow of wheat with chaff will be challenging than clean wheat.

3.5 Chapter References

Akaaimo, D.I. and Raji, A.O. 2006. Some physical and engineering properties of prosopis Africana seed. Biosystems Engineering 95, 197-205.

American Society of Agricultural and Biological Engineers (ASABE). 2006. ASAE S352.2 moisture measurement grain and seeds. In ASAE standards 2006. St. Joseph, MI 49085-9659, USA: American Society of Agricultural and Biological Engineers.

American Society of Agricultural and Biological Engineers (ASABE). 2012. ANSI/ASAE S358.3 MAY2012 moisture measurement - forages. In ASAE standards 20012. St. Joseph, MI 49085-9659, USA: American Society of Agricultural and Biological Engineers.

American Society for Testing and Materials (ASTM). 2006. ASTM B527 – 06 standard test method for determination of tap density of metallic powders and compounds, In ASTM standards 2006. West Conshohocken, PA 19428-2959, USA: American Society for Testing and Materials Standard.

Bargale, P.C., Irudayaraj, J. and Marquis, B. 1995. Studies on rheological behavior of canola and wheat. Journal of Agricultural Engineering 61, 267-274.

Carman, K. 1996. Some physical properties of lentil seeds. Journal of Agricultural Engineering Research 63, 87-92.

Carr, R.L. 1965. Evaluating flow properties of solids. Chemical Engineering 72, 163–167.

Casada, M. E. and Young, J.H. 1994. Model for heat and moisture transfer in arbitrarily shaped two dimensional porous media. Transactions of the ASAE 37, 1927-1938.

De Jong, J. A. H., Hoffman, A. C., and Finkers, H. J., 1999. Properly determine powder flowability to maximize plant output. Chemical Engineering Progress 95, 25–34.

Deshpande, S. D., Bal, S. T. and Ojha, P. 1993. Physical properties of soybean. Journal of Agricultural Engineering Research 56, 89–98.

Dutta, K., Nemav, K. and Bhardwaj, R. K. 1988. Physical properties of gram. Journal of Agricultural Engineering Research 39, 259-268.

Eben, H. 2008. Development of a composite index for pharmaceutical powders, Unpublished Ph. D dissertation, North-west University, Potchefstroom, South Africa.

Freeman, R. 2007. Measuring the flow properties of consolidated, conditioned and aerated powders — a comparative study using a powder rheometer and a rotational shear cell. Powder Technology 174, 25-33.

Freeman, R. 2003. The importance of air content on the rheology of powders – an empirical study using the FT4 powder rheometer, Particulate Systems Analysis Conference 2003, Harrogate, UK- August 2003.

Grain Inspection Handbook. 2013. Book II, Chapter 13 - Wheat. Federal Grain Inspection Service, U.S. Department of Agriculture.

Hausner, H.H. 1967. Friction conditions in a mass of metal powder. International Journal of Powder Metallurgy 3, 7–13.

John, R. F. 2010. Chapter 4: Porosity and Permeability. Integrated Reservoir Asset Management: Principles and Best Practices, Gulf Professional Publishing; 1 edition.

Karimi, M., Kheiralipour, K., Tabalabaeelar, A., Khoubakhl, G.M., Naderi, M. and Heidarbeigi, K. 2009. The effect of moisture content on physical properties of wheat. Pakistan Journal of Nutrition 1, 90-95.

Khankari, K. K., Patankar, S.V. and Morey, R. V. 1995. A mathematical model for natural convection moisture migration in storage grain. Transection of ASAE 38, 1777-1778.

Kingsly, A. R. P., Ileleji, K. E., Clementson, C. L., Garcia, A., Maier, D. E., Stroshine, R. L. and Radcliff, S. 2010. The effect of process variables during drying on the physical and chemical characteristics of corn dried distillers grains with soluble DDGS – Plant scale experiments. Bioresource Technology 101, 193-199.

Knowlton, T.M., Carson, J.W., Klinzing, G.E. and Yang, W.C. 1994. The importance of storage, transfer and collection. Chemical Engineering Progress 90, 44–54.

Landillon, V., Cassan, D., Morel, M.H. and Cuq, B. 2008, Flowability, cohesive, and granulation properties of wheat powders. Journal of Food Engineering 86, 178–193.

Leturia, M., Benali, M., Lagarde, S., Ronga, I. and Saleh, K. 2014. Characterization of flow properties of cohesive powders: A comparative study of traditional and new testing methods. Powder Technology 253, 406–423.

Ludger, O. F. and Arthur, A.T. 2007. Permeability, Food physics: physical properties – measurement and applications, Heidelberg, Germany: Springer Press, 233-255.

Mohsenin, N.N. 1986. Physical Properties of Plant and Animal Materials, seconded. Gordon and Breach Science Publishers, New York.

Molenda, M. and Horabik, J. 2005. Mechanical Properties of Granular Agromaterials and Food Powders for Industrial Practice Part1: Characterization of Mechanical Properties of Particulate Solids for Storage and Handling. Lublin.

Montross, M. D., Maier, D. E. and Haghighi, K. 2002. Development of a new finite element stored grain ecosystem model. Transaction of ASAE 45, 1455-1464.

Ozguven, F. and Kubilay, V. 2004. Some physical, mechanical and aerodynamic properties of pine Pinus pinea nuts. Journal of Food Engineering 68, 191-196.

Peleg, M. 1978. Flowability of food powders and methods for its evaluation—a review. Journal of Food Process Engineering 1, 303–328.

Schulze, D. 2008. Powders and Bulk Solids: Behavior, Characterization, Storage, and Flow. Springer.

Shepherd, H. and Bhardwaj, R. K. 1986. Moisture dependent physical properties of pigeon pea. Journal of Agricultural Engineering Research 35, 227-234.

Singh, A. K., Leonardi, E. G. and Thorpe, R. 1993. A solution procedure for the equations govern three-dimensional free convection in bulk stored grains. Transactions of ASAE 36, 1159-1173.

Tabatabaeelar, A. 2003. Moisture-dependent physical properties of wheat. International Agrophysics 17, 207-211.

Thompson, S. A. and Ross, I. J. 1983. Compressibility and frictional coefficients of wheat. Transactions of ASAE 26, 1171-1176, 1180.

Thomson, F. M. 1997. Storage and flow of particulate solids. In M. E. Fayed and L. Otten (Eds.), Handbook of powder science and technology (2nd ed., 389–486). New York: Chapman and Hall.

Train, D. 1958. Some aspects of the property of angle of repose of powders. Journal of Pharmacy and Pharmacology 10, 127–135.

Turki, D. and Fatah, N. 2008. Behavior and fluidization of the cohesive powders: agglomerates sizes approach. Brazilian Journal of Chemical Engineering 25, 697–711.

Vasilenko, A., Glasser, B. J. and Muzzio, F. J. 2011. Shear and flow behavior of pharmaceutical blends -method comparison study. Powder Technology 208, 628–636.

Womach, J. 2005. Agriculture: A Glossary of Terms, Programs, and Laws, 2005 ed..Washington, DC: The Library of Congress.

Zhou, B., Ileleji, K.E. and Ejeta, G. 2008. Physical properties relationship of bulk corn stove particles. Transactions of the ASABE 51, 581-59

Chapter 4 - Effect of Insects Infested Kernels on Flow Properties of Wheat

4.1 Introduction

Wheat quality standards presented by GIPSA (Grain Inspection, Packers and Stockyards Administration) regulate the wheat grades with details on the contaminants that lower the wheat grade. As defined by GIPSA, damaged kernels are pieces of wheat kernels those are ground-damaged, weather-damaged, diseased, frost-damaged, germ-damaged, heat-damaged, insect-bored, mold-damaged, sprout-damaged, or otherwise materially damaged. Insect-damaged kernels are kernels bored or tunneled by insects (GIPSA, 2013). While a wheat kernel may visually appear to be sound or uninfested, insects may be present inside some kernels. The insects may eventually emerge and cause further damage to kernels by fragmenting the kernels into flour. The presence of live or dead insects in wheat kernels lowers the overall wheat quality (Maghirang et al., 2003)

The lesser grain borer (LGB), *Rhyzopertha dominica (F.),* is a primary pest in stored grain. The insect is injurious to cereals; breeds in wheat, corn, rice and in other substrates containing starch (Subramanyam et al., 2007). The optimum temperature for LGB infestation is 28 ℃ (Howe, 1950) and at grain moisture contents between 12 and 14% (wet basis, w.b.) at 26 to 34 ℃ (Birch, 1945). It is well known that 12 to 14% (w.b.) is the optimum wheat storage moisture content. The grade of wheat is discounted based on the number of insect damaged kernels (IDK) in the lot during grading. A wheat consignment containing more than 32 insect damaged kernels per 100 g is designated as sample grade (FGIS, 1997).

Adult feeding activities of LGB produce large amounts of frass, most of which consists of ovoid granules of apparently undigested endosperm mixed with a finer floury part (Breese, 1960). The frass contain feces, fragments of immature insects, and other by-products, which could affect the end-use quality of the infested grain (Sanchez-Marinez et al., 1997; Seitz and Ram, 2004; Park et al., 2008). The larvae and adult *R. dominica* feed on both the germ and endosperm and are capable of reducing wheat kernels to the pericarp (Chanbang et al., 2008).

With the presence of impurities, the handling and processing of bulk wheat will be affected by the differences in particle size and by the filling of void spaces with frass or dust generated by the insect activity. According to Peleg (1978), particles with irregular or fibrous shapes can mechanically interlock the particles during bulk flow. Understanding the physical and flow properties are important for their effect on particles' behavior in handling and processing operations, such as flow from hoppers and silos, transportation, mixing, compression, and packaging (Knowlton et al., 1994). Failure to understand these characteristics could result in unreliable and inconsistent discharge leading to loss of production time.

Insect damage could decrease the quality of wheat and most importantly could affect the flowability. Arching of bulk wheat, due to improper flow through hoppers or from bins happens during wheat storage. Other than affecting the capacity, arching is also a serious safety issue and a concern in grain handling facilities across U.S. So understanding the properties of the wheat containing IDK could help predict the bulk wheat flow and to prevent accidents originating from arching in bins. Though the flow behavior of bulk wheat is well studied, but the effect of insect damage and the influence of dust on the bulk flow of wheat has not been characterized. In this chapter, the effect of moisture content and insect damaged kernels proportion on the physical and flow properties of bulk wheat is discussed.

4.2 Materials and Methods

4.2.1 Sample preparation

Hard red winter wheat kernels were obtained from Farm Coop, Manhattan, Kan., USA. Moisture content of the wheat was measured using the American Society of Agricultural and Biological Engineers (ASABE) Standard S352.2 of drying 10 g wheat samples in air oven at 130° for 19h (ASABE, 2006). Initial moisture content the wheat was 11.7% w. b. Physical and flow experiments were conducted at the general storage moisture contents of approximately12 and 14% (w. b.). Wheat kernels were conditioned to about 15% (w. b.) by adding calculated amount of distilled water. After conditioning, the samples were stored at 4 ℃ for 72 h for moisture equilibration. Drying to desired moisture level (12 and 14% wet basis) was carried out in ambient conditions by spreading kernels in thin layer without any additional heat or airflow, decreasing the moisture content to target levels (Ileleji et al., 2003).

Moisture conditioned wheat samples were used for preparing insects infested kernels. Insect damaged kernels were prepared by adding 200 Lesser Grain Borer (LGB) insects to 400 g sound wheat per jar. The wheat sample with insects was cultured in an incubator at 65±5% relative humidity at 32±1℃ for 42 days (Boina et al., 2012). About 7 kg of wheat samples were cultured for measuring the bulk physical and flow properties. The infested wheat samples contained sound kernels, LGB damaged kernels, dead LGB, and grain dust produced from the infestation. The final moisture content of wheat and insects infested kernels are given in Table 4.1. In the cultured samples, the insects damaged kernel to sound kernel ratio was 18±3:100 and 25±5:100 at MC 1 and MC 2, respectively. The average dust generated by insect infestation was 1.43 and 2.31 % (by weight) at MC 1 and MC 2, respectively. The particle size of wheat kernel was measured using a single kernel characterization system (SKCS 4100, Perten Instruments, Inc., Springfield, IL, USA). The particle size of grain dust was measured using a LECOTRAC LTS-150 Particle Size Analyzer (LECO Corporation, Tampa, FL). LGB infested kernels are as shown in Fig 4.1.

Fig 4. 1 LGB infested kernels

Table 4. 1 Moisture content of wheat and insects infested kernels, % wet basis

Moisture content	Wheat	Insects infested kernels
MC1	11.67±0.30	11.83±0.10
MC2	13.35±0.10	14.01±0.2

** MC1, MC2 denotes the conditioned moisture content of wheat and insects infested kernels at approximately 12 and 14% (w.b.), respectively.*

Wheat (W) and infested wheat kernels (I) were mixed at specific proportion (W: I at 100:0%, 97.5:2.5%, 95:5%, 92.5:7.5% and 0:100%) on weight basis. The proportion of mix was selected based on the U.S. grade of wheat with different broken and foreign material level (FGIS, 2013). To avoid segregation of dust and damaged wheat kernels, before adding with sound wheat kernels, the cultured samples were mixed thoroughly and a Boerner divider (Seedburo Equipment Co., IL, US) was used to draw representative samples for each replicate measurement of physical and flow properties.

4.2.2 Physical properties and flow indicators

The procedures described in chapter 3 were used for the measurement of bulk density (3.2.2.1), tapped density (3.2.2.2), CI, HR (3.2.2.3), true density (3.2.2.4), porosity (3.2.2.5), and angle of repose (3.2.2.6).

4.2.3 Flow properties

The FT4 Powder Rheometer (FT4, Freeman Technologies, Gloucestershire, UK) was used to evaluate the flow properties of wheat, insects infested wheat kernels, and the mix samples. Detailed descriptions of this equipment and its use in flow characterization can be found in Lindberg et al. (2004), Freeman, (2007) and Leturia et al. (2014).

The same experimental procedures detailed in chapter 3 for the measurement of basic flowability energy and stability index (3.2.3.1), aeration ratio (3.2.3.2), compressibility (3.2.3.3), permeability (3.2.3.4), and shear tests (3.2.3.5) was used.

4.2.4 Statistical analysis

All the tests were performed in triplicate and the mean values and standard deviations (mean ± standard deviation) are reported in this paper. Statistical analyses were conducted using SAS (SAS Institute Inc., Cary, NC, USA). The effect of moisture content, insects infested kernels proportion and their interactions on physical and flow properties were evaluated by subjecting the data to two-way analysis of variance (ANOVA) at $\alpha = 0.05$, using PROC GLM. Ryan or Ryan-Einot-Gabriel-Welsch Q (REGWQ) multiple comparison tests were used to separate the differences ($P \leqslant 0.05$) between the effect of moisture content and impurities.

4.3 Results and Discussion

The average size of wheat kernels and the grain dust generated by insects was about 3mm and 48 µm, respectively. This variation and difference in particle size within the bulk wheat could make the flow of wheat with insects damaged kernel a complex operation. Bulk solids, comprised of larger particle size have better flow than the bulk solids containing smaller particles (Hou and Sun, 2008). The smaller sized dust could occupy the external void spaces in between wheat kernels and thus increasing the bulk cohesion. Due to this, the energy required to make the bulk wheat flow will be higher. However, the prediction of bulk flowability on the basis of a particle size distribution is difficult and can sometimes be misleading. So, an accurate and quantified characterization of bulk properties is essential to understand the flow (Schulze, 2007).

4.3.1 Bulk physical properties

The average bulk density of dust generated from the insect infestation was 528.4 and 514.1 kg/m^3 at MC 1 and MC 2, respectively. These values were much lower than the density of sound wheat kernels (Table 4.2) that contributed to the decrease of bulk density with the increase in the insect damaged kernel proportion. Moisture content had also significant effect on the bulk density. Similar negative relationship of bulk density with moisture content was also observed for wheat (Karimi et al., 2009), gram (Dutta et al., 1988), sunflower seeds (Gupta and Das, 1997), and soybeans (Deshpande et al., 1993). Moisture content had similar effect on the tapped density of bulk wheat samples. At lower proportion of insect damaged kernels, the change in tapped density was not significant (Table 4.3). The tapped density of insect damaged kernels was higher than the other samples. The dust, insect damaged kernels, and sound kernels vary in average size and density. So, during tapped density measurement, the particles rearranged and compacted within the container volume due to vibration. So, handling bulk wheat with high insect infestation will be challenging. The compaction and rearrangement of particles could lead to arching and bridging of particles leading to poor flow. However, due to the presence of smaller sized grain dust particles, the true density increased slightly with the proportion of insects infested kernels added to the bulk wheat. Addition of insects infested kernels did not had any significant effect on the true density (Table 4.4). The true density of dust was 1483.2 and 1487.8 kg/m^3 at MC 1 and MC 2, respectively. The dust particles filled the intergranular space of the wheat kernels that resulted in an increased true density. As the same effect of chaff proportions and the moisture content mentioned in the last chapter, the effect of LGB infested kernel proportions and moisture content on bulk, tapped and true density of bulk wheat are significantly different.

Table 4. 2 Bulk density of wheat mixed with insect damaged kernels

Sample	Bulk density, kg/m^3	
	MC 1	MC 2
W 100%	801.54±0.51a	785.91±0.12b
W 97.5%-I 2.5%	799.55±0.10c	785.59±0.97d
W 95%-I 5%	798.48±0.34e	784.36±0.95f
W 92.5%-I 7.5%	796.52±0.61g	780.86±1.06h
I 100%	777.64±0.28i	769.60±1.93j

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

Table 4. 3 Tapped density of wheat mixed with insect damaged kernels

Sample	Tapped density, kg/m^3	
	MC 1	MC 2
W 100%	825.33±0.57a	811.51±0.19b
W 97.5%-I 2.5%	824.40±0.52ac	810.77±1.28b
W 95%-I 5%	823.21±1.07ac	809.78±2.89bd
W 92.5%-I 7.5%	822.26±0.81ac	807.64±1.98d
I 100%	832.44±0.67e	831.31±1.34e

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

Table 4. 4 True density of wheat mixed with insect damaged kernels

Sample	True density, kg/m^3	
	MC 1	MC 2
W 100%	1386.71±1.63a	1379.67±3.65b
W 97.5%-I 2.5%	1391.35±1.11ac	1380.06±0.51b
W 95%-I 5%	1391.68±0.49c	1380.38±0.24b
W 92.5%-I 7.5%	1392.31±0.32c	1380.70±0.58b
I 100%	1412.17±1.25d	1401.13±2.76e

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

The derived flow indicators of Hausner's ratio (HR) and compressibility index (CI) of wheat samples are given in Table 4.5 and 4.6, respectively. The difference in HR and CI values for wheat with insect damaged kernels was not statistically significant. But, the increase in HR and CI values indicate that the increase in insect damaged kernel proportion in bulk wheat could make the flow challenging. The two-way ANOVA results indicate that the moisture content did not affect HR significantly, but did affect the CI of bulk wheat samples.

Table 4. 5 Hausner's ratio of wheat mixed with insect damaged kernels

Sample	Hausner's ratio	
	MC 1	MC 2
W 100%	1.03±0.0007a	1.03±0.0002a
W 97.5%-I 2.5%	1.03±0.0007a	1.03±0.0016a
W 95%-I 5%	1.03±0.0013a	1.03±0.0037a
W 92.5%-I 7.5%	1.03±0.0010a	1.03±0.0025a
I 100%	1.07±0.0009b	1.08±0.0017c

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

Table 4. 6 Compressibility index of wheat mixed with insect damaged kernels

Sample	Compressibility index	
	MC 1	MC 2
W 100%	2.88±0.07a	3.15±0.02ab
W 97.5%-I 2.5%	3.01±0.06a	3.11±0.15ab
W 95%-I 5%	3.00±0.13a	3.14±0.35ab
W 92.5%-I 7.5%	3.13±0.10ab	3.32±0.24b
I 100%	6.58±0.08c	7.42±0.15d

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

The porosity of samples increased with the moisture content and insects infested (Table 4.7) proportion significantly. This could be due to the presence of holes drilled by LGB inside the wheat kernels. Though insect infestation produces dust that could fill the intergranular space of wheat kernels, but the void space created by drilling is higher than the amount of dust produced. Higher porosity could lead to increased compaction of the bulk during storage.

Angle of repose of bulk wheat, except for the insect damaged samples, ranged from 24.31 to 27.37° (Table 4.8). At lower proportion of insect damaged kernels, the difference in angle of repose was not statistically significant. The insect damaged samples had higher angle of repose due to the presence of dust that occupied the intergranular space and increase the angle of repose value. In addition, grain dust increases the contact area between particles. Carr (1965) suggested that angle of repose below 30° indicate good flowability, 30°-45° some cohesiveness, 45°-55° true cohesiveness, and >55° sluggish or very high cohesiveness with very limited flowability. Wheat samples with different proportion of insect damaged kernels could be categorized under solids with "good flowability" because the angle of repose was less than 30º.

But, angle of repose is a qualitative and relative data that at best may help in finding differences between samples and angle of repose are not applicable in design of handling and storage systems (Zhou et al., 2008). The angle of repose is a measure in uncompacted condition and differs from the conditions during storage or handling. As expected, with the increase in moisture content, angle of repose increased due to higher cohesion between particles. The effect of LGB infested kernel proportions and moisture content played significantly.

Table 4. 7 Porosity of wheat mixed with insect damaged kernels

Sample	Porosity, %	
	MC 1	MC 2
W 100%	42.20±0.07a	43.04±0.15b
W 97.5%-I 2.5%	42.53±0.04c	43.10±0.07b
W 95%-I 5%	42.62±0.04c	43.15±0.09b
W 92.5%-I 7.5%	42.78±0.05d	43.50±0.07e
I 100%	44.94±0.04f	45.09±0.04g

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

Table 4. 8 Angle of repose of wheat mixed with insect damaged kernels

Sample	Angle of repose, º	
	MC1	MC2
W 100%	24.31±0.61a	25.36±0.60ab
W 97.5%-I 2.5%	24.84±0.53a	26.42±1.14b
W 95%-I 5%	25.50±0.84ab	26.60±0.16b
W 92.5%-I 7.5%	26.79±1.37b	27.37±0.63b
I 100%	36.02±1.20c	40.30±0.30d

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

4.3.2 Dynamic flow behavior

The BFE results indicate that the energy required to make the bulk wheat flow, irrespective of the proportion of insects damaged kernels, was significantly different (Table 4.9). In addition, moisture content had significant effect on BFE due to higher interparticle friction though moisture content affects the BFE, the data (Table 4.9) shows that bulk wheat, irrespective of impurity proportion, does not resist flow. Stability index (SI) values of bulk wheat ranged between 0.9-1.1 that classifies the bulk wheat as 'stable' indicating no physical change occurs during handling of wheat with insect damaged kernels (Table 4.10).

With the difference in particle size between dust and wheat kernels, there could be potential segregation with dust settling at the bottom of conveying equipment and storage vessels. Aeration ratio of bulk wheat samples was almost uniform with values close to 1, indicating samples are not sensitive to the air flow in the measured 0 -10 mm/s range (Table 4.11). There was no significant difference due to the presence of insect damaged kernels and moisture content.

Table 4. 9 Basic flow energy of wheat mixed with insect damaged kernels

Sample	Basic Flow Energy	
	MC 1	MC 2
W 100%	131.40±2.48a	158.49±3.10b
W 97.5%-I 2.5%	127.36±2.60a	149.29±4.06c
W 95%-I 5%	132.70±3.36a	148.81±4.23c
W 92.5%-I 7.5%	130.44±4.43a	155.03±2.42bc
I 100%	140.74±2.97d	149.03±3.15c

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference ($P < 0.005$).*

Table 4. 10 Stability index of wheat mixed with insect damaged kernels

Sample	Stability index (SI)	
	MC 1	MC 2
W 100%	1.01±0.02a	0.98±0.02b
W 97.5%-I 2.5%	0.99±0.01b	1.01±0.03a
W 95%-I 5%	1.05±0.01a	1.01±0.02a
W 92.5%-I 7.5%	1.02±0.04a	1.00±0.05a
I 100%	0.97±0.04a	1.01±0.05a

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

Table 4. 11 Aeration ratio of wheat mixed with insect damaged kernels

Sample	Aeration ratio	
	MC 1	MC 2
W 100%	1.01±0.04a	1.12±0.05b
W 97.5%-I 2.5%	1.03±0.04ab	1.07±0.06ab
W 95%-I 5%	1.09±0.01b	1.06±0.04ab
W 92.5%-I 7.5%	1.04±0.00a	1.09±0.04b
I 100%	1.05±0.05a	0.99±0.03a

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

4.3.3 Bulk flow properties

Proportion of insect damaged kernels in bulk wheat did not affect the bulk compressibility of wheat samples (Table 4.12). Presence of insect damaged kernels and moisture content increased the compressibility of wheat kernels. In addition, the compressibility of insect damaged kernels was significantly different than bulk wheat samples with proportion of IDK. Rearrangement of finer dust particles and the breaking of wheat kernels with insect drilled holes might have resulted in a higher compressibility for insect damaged kernels. The compressibility result shows that if there is insect activity in a section of grain stored in a bin, the compressibility of that section of grain could increase the cohesive strength of the bulk grain. Localized increase in strength could lead to arching and caking of grains within grain bins.

Permeability is a measure of the storage and flow capacity, respectively, in a porous medium (John, 2010). The permeability of air through the grain in bin will help grain handling/process facility managers to determine the air pressure required to make the air flow through the grain at a required flow rate during aeration and in-bin drying operations (Ludger and Arthur, 2007). The permeability, measured under consolidation, for bulk wheat samples are given in Table 4.13. In this study, any specific trend due to the presence of insect damaged kernels or the effect of moisture content was not noticed. The variation in particle size could have resulted in this high standard deviation. Grain packing during storage results in a change in bulk density of the grain mass, but little particle deformation is expected at the low pressures typically experienced during grain storage (Thompson and Ross, 1983).

Table 4. 12 Compressibility of wheat mixed with insect damaged kernels

Sample	Compressibility, %	
	MC 1	MC 2
W 100%	4.86±0.11a	5.58±0.17b
W 97.5%-I 2.5%	4.92±0.39a	5.59±0.12b
W 95%-I 5%	5.18±0.19a	5.64±0.05b
W 92.5%-I 7.5%	5.12±0.20a	5.64±0.21b
I 100%	5.44±0.10ab	6.07±0.21c

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference ($P < 0.005$).*

Table 4. 13 Permeability of wheat mixed with insect damaged kernels

Sample	Permeability, cm^2	
	MC 1	MC 2
W 100%	1.42×10-7±3.36×10^{-9}a	1.28×10-7±2.63×10^{-9}b
W 97.5%-I 2.5%	1.57×10-7±5.19×10^{-9}c	1.26×10-7±1.44×10^{-9}b
W 95%-I 5%	1.38×10-7±3.59×10^{-9}a	1.41×10-7±3.34×10^{-9}ad
W 92.5%-I 7.5%	1.36×10-7±5.19×10^{-10}a	1.37×10-7±2.63×10^{-9}a
I 100%	1.46×10-7±7.31×10^{-9}ad	1.39×10-7±3.31×10^{-9}e

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference ($P < 0.005$).*

4.3.4 Shear properties

During storage and processing, solids would be subjected to consolidation stresses, causing changes in density and mechanical inter-particulate forces. Shear properties measures the flowability of powder under consolidation. At a specific normal stress, higher shear stress corresponds to higher angle of internal friction and wall friction angle indicating a higher shear stress is needed to make cohesive materials to flow. From Table 4.14 and 4.15, the decrease in trend can be observed for angle of internal friction and wall friction angle at different insects damaged kernel proportion. But the values are not statistically different. With increase in inter-particulate cohesion, arches might form in a grain bin. But with changes in angle of internal friction due to application of load, for e.g. a person stepping on the cohesive grain arch, the cohesively bonded grain would break leading to sudden change in flow. Grain entrapment accidents happens as grain arch breaks due to changes from static to dynamic conditions resulting from the lowered friction between the grain kernels. From Tables 4.16 - 4.20 indicate that the shear properties are not significantly different and were not affected by moisture content and with the proportion of insects infested kernels.

The possible reason would be the minor changes in physical properties due to the presence of insect damaged kernels that influenced the bulk properties of wheat. Flow function is a significant measure to evaluate the flowability of bulk solids. As stated by Jenike (1964), higher flow function value indicates better flowability. However, from the results in Table 4.20, moisture content and proportion of LGB infested kernels did not significantly differ. Due to differences in particle size and density, the standard deviation between replication was very high. This might be from the reproducibility limits of shear test (Alisa et al., 2011).

Table 4. 14 Angle of internal friction at 15kPa of wheat mixed with insect damaged kernels

Sample	Angle of Internal friction, °	
	MC 1	MC 2
W 100%	26.96±0.21ab	28.64±2.46a
W 97.5%-I 2.5%	26.06±0.12ab	26.07±0.80ab
W 95%-I 5%	24.63±0.28b	24.37±3.91ab
W 92.5%-I 7.5%	23.82±0.27b	23.35±1.76b
I 100%	23.37±0.23b	25.00±2.90ab

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference ($P < 0.005$).*

Table 4. 15 Wall friction angle at 15kPa of wheat mixed with insect damaged kernels

Sample	Wall Friction Angle, °	
	MC 1	MC 2
W 100%	18.24±0.31Aa	20.33±0.63Ab
W 97.5%-I 2.5%	18.55±0.60Aa	18.89±1.42Ab
W 95%-I 5%	17.86±0.51Aa	18.76±0.13Ab
W 92.5%-I 7.5%	17.54±1.11Aa	18.04±0.05Ab
I 100%	15.64±0.83Ba	16.53±0.62Bb

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
***Capital letter indicates the analysis between impurity proportions in columns, lowercase represents the analysis between moisture contents in rows.*

Table 4. 16 Cohesion of wheat mixed with insect damaged kernels

Sample	Cohesion	
	MC 1	MC 2
W 100%	0.63±0.11a	0.68±0.49a
W 97.5%-I 2.5%	0.19±0.05a	0.29±0.09a
W 95%-I 5%	0.61±0.31a	0.71±0.51a
W 92.5%-I 7.5%	0.32±0.07a	0.64±0.13a
I 100%	0.50±0.17a	0.22±0.31a

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

Table 4. 17 Unconfined yield stress (UYS) of wheat mixed with insect damaged kernels

Sample	UYS, kPa	
	MC 1	MC 2
W 100%	2.03±0.34ab	2.24±1.52c
W 97.5%-I 2.5%	0.59±0.16b	0.94±0.29b
W 95%-I 5%	0.74±0.92b	2.17±1.46b
W 92.5%-I 7.5%	0.97±0.19b	1.94±0.34b
I 100%	1.51±0.48b	0.49±0.27b

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
*** Different letters indicates significant difference (P < 0.005).*

Table 4. 18 Major principle stress (MPS) of wheat mixed with insect damaged kernels

Sample	MPS, kPa	
	MC 1	MC 2
W 100%	24.56±0.17Aa	23.71±0.34Aa
W 97.5%-I 2.5%	21.76±0.67Ba	21.81±0.43Ba
W 95%-I 5%	22.20±1.78Ba	22.22±0.79Ba
W 92.5%-I 7.5%	21.99±0.46Ba	23.12±0.01Ba
I 100%	22.62±0.72Ba	20.83±0.45Ba

**where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% w. b.);*
***Capital letter indicates the analysis between impurity proportions in columns, lowercase represents the analysis between moisture contents in rows.*

Table 4. 19 Major consolidation stress (MCS) of wheat mixed with insect damaged kernels

Sample	MCS, kPa	
	MC 1	MC 2
W 100%	8.59±0.14Aa	7.53±0.13Ab
W 97.5%-I 2.5%	8.38±0.44ABa	8.13±0.30ABb
W 95%-I 5%	9.19±0.96ABa	8.14±0.76ABb
W 92.5%-I 7.5%	8.92±0.18Ba	9.01±0.55Bb
I 100%	9.12±0.37ABa	7.96±0.50ABb

** where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% wet basis);*
***Capital letter indicates the analysis between impurity proportions in columns, lowercase represents the analysis between moisture contents in rows.*

Table 4. 20 Flow function (FF) of wheat samples mixed with insects damaged kernels

Sample	FF	
	MC 1	MC 2
W 100%	12.31±2.02^{Aa}	14.56±9.41^{Aa}
W 97.5%-I 2.5%	38.68±10.28^{Aa}	24.62±7.21^{Aa}
W 95%-I 5%	86.91±83.76^{Aa}	13.37±8.79^{Aa}
W 92.5%-I 7.5%	23.23±4.41^{Aa}	12.98±2.69^{Aa}
I 100%	15.89±4.45^{Aa}	48.59±24.95^{Aa}

**where W indicates wheat kernel, I indicates IDK and MC is the moisture content (% w. b.);*
***Capital letter indicates the analysis between impurity proportions in columns, lowercase represents the analysis between moisture contents in rows.*

4.4 Conclusions

Physical and flow properties of hard red winter wheat, insects infested wheat kernels and their mixture was investigated as a function of moisture content. Knowledge on these characteristics is necessary for design of handling equipment and to understand the behavior of grain during storage and handling. Increase in moisture content significantly influenced the physical and flow properties. The bulk and tapped density decreased with increase in percent insects damaged kernels in bulk wheat. The rearrangement of smaller sized frass and less denser insect damaged kernels influenced the density of bulk wheat. Basic flow energy and compressibility increased with the increase proportion of insect damaged kernels. Moisture content and the proportion of insects damaged kernels, within the tested range, did not have any significant effect on the shear properties of bulk wheat. Presence of insect damaged kernels and the dust from insect activity could increase the compressibility and lead to arching and caking of grains affecting their flowability.

4.5 Chapter References

Alisa, V., Benjamin, J. G. and Fernando, J. M. 2011. Shear and flow behavior of pharmaceutical blends — Method comparison study. Powder Technology 208, 628–636.

American Society of Agricultural and Biological Engineers (ASABE). 2006. ASAE S352.2 Moisture measurement grain and seeds. In ASAE standards 2006. St. Joseph, MI 49085-9659, USA: American Society of Agricultural and Biological Engineers.

American Society for Testing and Materials (ASTM). 2006. ASTM B527 – 06 Standard test method for determination of tap density of metallic powders and compounds, In ASTM standards 2006. West Conshohocken, PA 19428-2959, USA: American Society for Testing and Materials Standard.

Birch, L.C. 1945. The mortality of the immature stages of Calandra oryzae L. small strain and Rhizopertha dominica Fab. in wheat of different moisture contents. Australian Journal of Experimental Biology and Medical Science 23, 141-145.

Boina, D. R., Subramanyam, B. and Mutambuki, K. 2012. Delayed mortality responses of Rhyzopertha dominica (F.) adults subjected to short exposures on spinosad-treated wheat. Journal of Stored Products Research 48, 149-152.

Breese, M.H. 1960. The infestibility of stored paddy by Sitophilus sasakii Tak. and Rhyzopertha dominica F.. Bulletin of Entomological Research 51, 599-630.

Carr, R.L. 1965. Evaluating flow properties of solids. Chemical Engineering 72, 163–167.

Chanbang, Y., Arthur, F., Wilde, G., Throne, J. and Subramanyam, B. 2008. Susceptibility of eggs and adult fecundity of the lesser grain borer, Rhyzopertha dominica, exposed to methoprene. Journal of Insect Science 8, 48.

Deshpande, S. D., Bal, S. T. and Ojha, P. 1993. Physical properties of soybean. Journal of Agricultural Engineering Research 56, 89–98.

Duttas, K., Nemav, K. and Bhardwaj, R. K. 1988. Physical properties of gram. Journal of Agricultural Engineering Research 39, 259-268.

Freeman, R. 2007. Measuring the flow properties of consolidated, conditioned and aerated powders — a comparative study using a powder rheometer and a rotational shear cell. Powder Technology 174, 25-33.

Grain Inspection Handbook. 2013. Book II, Chapter 13. Federal Grain Inspection Service, U.S. Department of Agriculture.

Gupta, R. K. and Das, S. K. 1997. Physical properties of sunflower seeds. Journal of Agricultural Engineering Research 66, 1-8.

Hou, H. and Sun, C. C. 2008. Quantifying effects of particulate properties on powder flow properties using a ring shear tester. Journal of Pharmaceutical Sciences 97, 4030-4039.

Howe, R.W. 1950. The development of Rhyzopertha dominica F. Coleoptera: Bostrichidae under constant temperature. Entomologist’s Monthly Magazine 86, 1-5.

Ileleji, K. E., Wilcke, W. and Morey, R. V. 2003. Relative storability of high-oil and Bt corn hybrids compared to conventional hybrids. Transactions of the ASABE 46, 407-414.

John, R. F. 2010. Chapter 4: Porosity and Permeability, Integrated Reservoir Asset Management, Gulf Professional Publishing; 1st edition.

Karimi, M., Kheiralipour, K., Tabalabaeelar, A., Khoubakhl, G.M., Naderi, M. and Heidarbeigi, K. 2009. The effect of moisture content on physical properties of wheat. Pakistan Journal of Nutrition 1, 90-95.

Kingsly, A. R. P., Ileleji, K. E., Clementson, C. L., Garcia, A., Maier, D. E., Stroshine, R. L. and Radcliff, S. 2010. The effect of process variables during drying on the physical and chemical characteristics of corn dried distillers grains with solubles DDGS – Plant scale experiments. Bioresource Technology 101, 193-199.

Knowlton, T.M., Carson, J.W., Klinzing, G.E. and Yang, W.C. 1994. The importance of storage, transfer and collection. Chemical Engineering Progress 90, 44–54.

Leturia, M., Benali, M., Lagarde, S., Ronga, I. and Saleh, K. 2014. Characterization of flow properties of cohesive powders: A comparative study of traditional and new testing methods. Powder Technology 253, 406–423.

Lindberg, N, O., Palsson, M., Pihl, A, C., Freeman, R., Freeman, T., Zetzener, H. and Enstad, G. 2004. Flowability measurements of pharmaceutical powder mixtures with poor flow using five different techniques. Drug Development and Industrial Pharmacy 30, 785-791.

Ludger, O. F. and Arthur, A.T. 2007. Food physics: physical properties –measurement and applications, Heidelberg, Germany: Springer Press, Chapter 6.

Maghirang, E.B., Dowell, F.E., Baker, J.E. and Throne, J.E. 2003, Automated detection of single wheat kernels containing live or dead insects using near-infrared reflectance spectroscopy, Transactions of the ASAE 46, 1277–1282.

Mohsenin, N.N. 1986. Physical Properties of Plant and Animal Materials, seconded. Gordon and Breach Science Publishers, New York.

Molenda, M. and Horabik, J. 2005. Mechanical Properties of Granular Agromaterials and Food Powders for Industrial Practice Part1: Characterization of Mechanical Properties of Particulate Solids for Storage and Handling. Lublin.

Ozguven, F. and Kubilay, V. 2004. Some physical, mechanical and aerodynamic properties of pine Pinus pinea nuts. Journal of Food Engineering 68, 191-196.

Park, S.-H., Arthur, F.H., Bean, S.R. and Schober, T.J. 2008. Impact of differing population levels of Rhyzopertha dominica F. on milling and physicochemical properties of sorghum kernel and flour. Journal of Stored Products Research 44, 322-327.

Peleg, M. 1978. Flowability of food powders and methods for its evaluation—a review. Journal of Food Process Engineering 1, 303–328.

Sanchez-Marinez, R.I., Cortez-Rocha, M.O., Ortega-Dorame, F., Morales-Valdes, M. and Silveira, M.I. 1997. End-use quality of flour from Rhyzopertha dominica infested wheat. Cereal Chemistry 74, 481-483.

Schulze, D. 2007. Powders and Bulk Solids: Behavior, Characterization, Storage and Flow, Springer Berlin, Heidelberg, New York.

Subramanyam, B., Toews, M. D., Ileleji, K. E., Maier, D. E., Thompson. D. and Pitts, T. J. 2007. Evaluation of spinosad as a grain protectant on three Kansas farms. Crop Protection 26, 1021-1030.

Thompson, S. A. and Ross, I. J. 1983. Compressibility and frictional coefficients of wheat. Transactions of ASAE 26, 1171-1176, 1180.

Thomson, F. M. 1997. Storage and flow of particulate solids. In M. E. Fayed and L. Otten (Eds.), Handbook of powder science and technology (2nd ed., 389–486). New York: Chapman and Hall.

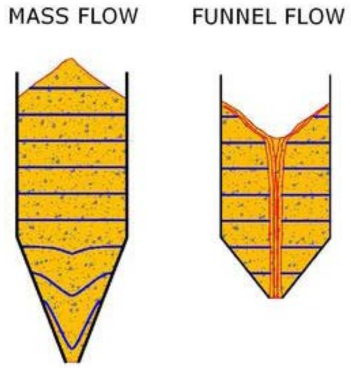
Zhou, B., Ileleji, K.E. and Ejeta, G. 2008. Physical properties relationship of bulk corn stove particles. Transactions of the ASABE 51, 581-590.

Chapter 5 - Particle Image Velocimetry of Bulk Wheat Discharge Flow

5.1 Introduction

Hoppers are the common handling equipment used by the grain based food and feed industry. The capacity of hoppers range from a few milliliters to many thousands of liters, and they vary in both their shape, basically conical or wedge-shaped, and size (Ketterhagen, et. al., 2009). Meanwhile, hoppers are also classified by the solids flow pattern as affected by their angle. Under gravity discharge conditions the flow behavior could be divided into two patterns (Fig 5.1): “Mass Flow” and “Funnel Flow” (Jenike, 1961, 1964).

Fig 5. 1 Illustration of mass flow and funnel flow



(Source: http://eng.tel-tek.no/Powder-Technology/Silo-design-and-powder-mechanics/Research-activities/Mass-flow-or-funnel-flow)

During mass flow all the particles move together during discharge. Once discharge starts, no particle or agglomerate remains in its original position. The particles in motion avoid formation of dead zone within the bin. The solids that enter the bin first, leave the bin first (first-in, first-out), which tends to keep a steady residence time in the bin in a continuous process. The bin can therefore be designed using a mass flow hopper bin to prevent arch formation that causes discharge stoppages (Amoros, 2000).

Funnel flow involves the formation of a flow channel aligned with the bin wall, surrounded by a region in which the material initially stands still. In funnel flow, the particles do not move together, which may make the flow at the outlet change progressively in the course of handling. Even when the bin has been almost completely emptied, material is still left inside. The accumulated material in the bin's dead zone not only lowers the bin effective capacity but can even become unserviceable if its properties change with time (by drying, oxidizing, etc.)(Amoros, 2000).

Jenike (1964), in conjunction with the measured data, applied two-dimensional stress analysis in developing a mathematical methodology for determining the minimum hopper angle and hopper opening size for mass flow from conical and wedge shaped hoppers. The measured flow properties used in his methodology are the flow function, the effective angle of internal friction and the angle of wall friction. These data are used for determining the dimensions of the hopper angle and opening size. Details of calculations can be found in Schulze (2008). During hopper flow, discharge rate and particle velocity are two important parameters. Beverloo et al. (1961) proposed the most widely accepted equation to predict the flow rate of grains through an orifice and its dependence on bulk density, outlet size and the particle size.

Particle Image Velocimetry (PIV) technique is a well-established experimental method in fluid mechanics for quantitative measurement of one or two-dimensional flow structure. PIV technique involves the measurement of instantaneous velocity and its correlation to related properties of fluids. The motion of the particles is then used to calculate speed and the direction of flow of a solid/liquid. A common application of PIV is to investigate the aerodynamics of aircraft and cars to optimize the fuel combustion. This indirect method of measurement was first used by Lueptow et al. (2000) to study granular flow. The authors recommended application of PIV to study quasi-two dimensional flows in transparent containers though images captured using a high-speed camera. PIV enables measurement of the instantaneous in-plane velocity vector fields within a planar section of the flow field. This method allows for the calculation of spatial gradients, dissipation of turbulent energy, and spatial correlations.

The typical PIV evaluation procedure is based on the analysis of two successive images of the flow, particle displacement direction and distance can be traced (Quenot et al., 1998). During video recording, it does not need any intrusive markers to be installed in granules since the grains themselves serve as tracers. As it was shown by Steingart and Evans (2005), and Sielamowicz et al. (2005, 2006), an application of PIV technique to granular flows in two-dimensional hoppers appears to be very promising to study the bulk flow characteristics. Despite its limitation that only flow close to the transparent wall can be observed, PIV technique offers unique possibility to obtain full field transient velocity fields.

In this thesis work, bulk wheat discharge was recorded at different hopper angle and chaff proportion. Flow profile, particle velocity, velocity vector fields, and discharge rate of HRW wheat during hopper was assessed.

5.2 Materials and Methods

5.2.1 Samples

Hard red winter wheat was obtained from Heartland Mills, Marienthal, Kan., USA and chaff was collected from Hal Ross mill, Department of Grain Science and Industry, Kansas State University. The moisture content of wheat and chaff was 11.12±0.06% and 11.34±0.21%, respectively. Wheat and chaff were mixed at specific proportion (W: C at 100:0%, 97.5:2.5%, 95:5%, 92.5:7.5% and 0:100%) by weight basis. Two different heights of sample was tested, 35 cm and 55 cm. At 55 cm height, only one proportion of chaff was used (W:C at 97.5:2.5%). The amount of sample in hopper during each test is given in Tables 5.1 and 5.2. The proportion of mix was selected based on the U.S. grade of wheat with different broken and foreign material level (Grain Inspection Handbook, 2013). The size of wheat kernel was measured using a single kernel characterization system (SKCS 4100, Perten Instruments, Inc., Springfield, IL, USA).

Table 5. 1 Amount of samples used in hopper flow test (with wheat height fixed as 35 cm)

Sample	Amount of sample in hopper, kg	
	A-40º	A-60º
W 100%	28.0±0.4	36.5±0.3
W 97.5%-C 2.5%	27.3±0.2	35.1±0.2
W 95%-C 5%	26.9±0.2	34.2±0.2
W 92.5%-C 7.5%	26.1±0.3	33.6±0.1

** where W indicates wheat kernel, C indicates chaff, and A is the hopper angle.*

Table 5. 2 Amount of samples used in hopper flow test (with wheat height fixed as 55 cm)

Sample	Amount of sample in hopper, kg	
	A-40º	A-60º
W 100%	40.1±0.4	50.3±1.4
W 97.5%-C 2.5%	39.1±0.2	49.4±1.0

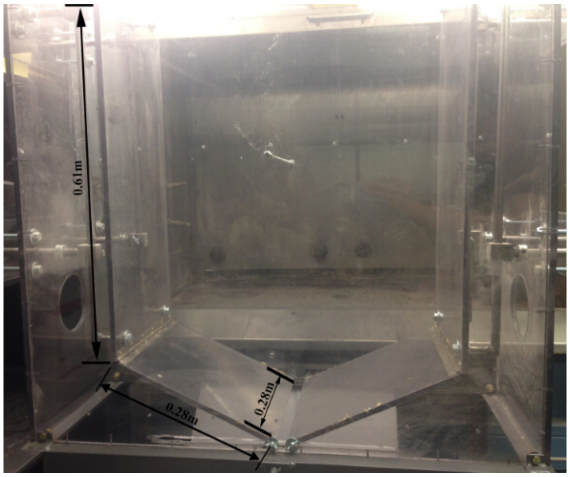
** where W indicates wheat kernel, C indicates chaff, and A is the hopper angle.*

5.2.2 Hopper flow analysis

5.2.2.1 Hopper model

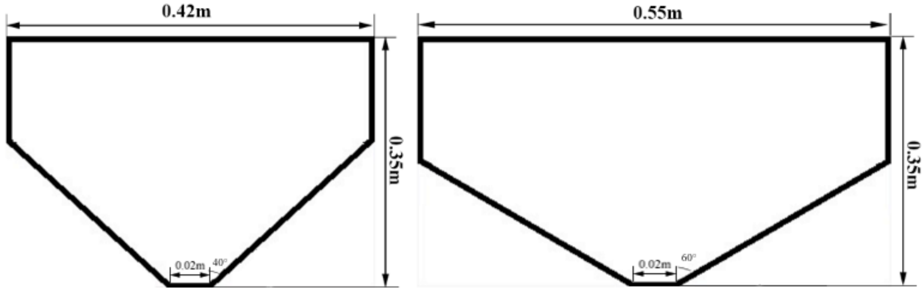
A plexiglass wedge-shaped hopper was fabricated (Fig 5.2) for testing wheat flow. The hopper was fabricated in such a way that the width, hopper angle and hopper opening are adjustable.

Fig 5. 2 Hopper model



For wedge-shaped hopper, the length of outlet should be at least 3 times the width of outlet (Eric, 2004). Interlocking arches can be overcome by ensuring that the outlet diameter is six to eight times the largest particle size in a circular opening, or the width is three to four times the largest particle size in a slotted opening. (Slotted outlets must be at least three times as long as they are wide for such conditions to apply) (Eric, 2004). By considering above mentioned standards, for this test, the hopper dimensions were fixed as given in Fig 5.3.

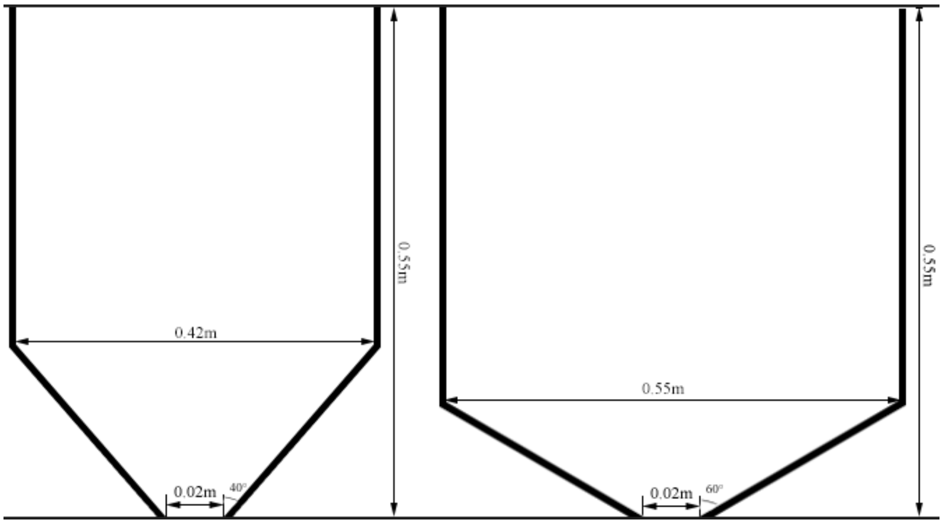
Fig 5. 3 Hopper dimensions of mass flow and funnel flow with 35 cm sample height



a) Mass flow

b) Funnel flow

Fig 5. 4 Hopper dimensions of mass flow and funnel flow with 55 cm sample height



a) Mass flow

b) Funnel flow

5.2.2.2 PIV experimental setup and analysis

Bulk wheat hopper discharge process was recorded using a high speed camera Casio EX-F1 (Casio computer co., ltd, Japan). For PIV measurement and analysis, the procedure used by Sielamowicz et al. (2005) was used. The rate of image capture was fixed at 30 frames per second and at 512 pixels ×384 pixels resolution. This recording speed and resolution was optimized based on the hopper size and camera specications. After recording, video frames at every 50 millisecond interval was selected for PIV analysis. The images were then imported into the PIVlab module (Thielicke and Stamhuis, 2014) of MATLAB (MATLAB 2010b, The MathWorks, Inc., Natick, MA, USA.). Using PIVlab, the particle flow vector, particle velocity and colored velocity magnitude zone were measured.

5.2.3 Statistical analysis

All the tests were performed in triplicate and the mean values and standard deviations (mean ± standard deviation) are reported in this thesis. Statistical analyses were conducted using SAS (SAS Institute Inc., Cary, NC, USA). The effect of chaff and hopper angle on hopper discharge rate was evaluated by subjecting the data to two-way analysis of variance (ANOVA) at $\alpha = 0.05$, using PROC GLM. Ryan or Ryan-Einot-Gabriel-Welsch Q (REGWQ) multiple comparison tests were used to separate the differences ($P \leq 0.05$) between the effect of moisture content and impurities.

5.3 Results and Discussions

5.3.1 Hopper discharge time and rate

Different levels of chaff and the hopper angle had significant effect on the discharge time and discharge rate (Table 5.3 and 5.4). Presence of chaff in wheat affects the density, size and size distribution of the materials present in the bulk. If the particles present in the bulk are uniform with minimum variation in physical properties, the discharge rate will be consistent. The chaff particles are non-uniform in size, has interlocking tendency and has higher inter-particle friction. Due to these effects, the discharge time progressively increased while the rate decreased with the increase in the amount of chaff. The results indicate that wheat, before cleaning, will have inconsistent hopper discharge. Furthermore, for effective handling of bulk wheat, mass flow hoppers could be used because of their better discharge time and rate (Table 5.3 and 5.4).

Table 5. 3 Discharge time and discharge rate of samples at 35 cm height

Sample	Discharge time, s		Discharge rate, kg/s	
	A40	A60	A40	A60
W 100%	16.75 ± 0.40^{Aa}	25.76 ± 0.29^{Ab}	1.67 ± 0.06^{Aa}	1.42 ± 0.02^{Ab}
W 97.5%-C 2.5%	18.90 ± 0.49^{Ba}	30.06 ± 2.13^{Bb}	1.44 ± 0.03^{Ba}	1.17 ± 0.08^{Bb}
W 95%-C 5%	20.54 ± 1.49^{Ca}	31.88 ± 0.40^{Cb}	1.32 ± 0.10^{Ca}	1.09 ± 0.02^{Cb}
W 92.5%-C 7.5%	23.43 ± 0.72^{Da}	38.90 ± 0.52^{Db}	1.12 ± 0.02^{Da}	0.86 ± 0.01^{Db}

** where W indicates wheat kernel, C indicates chaff and A is the hopper angle;*
*** Two-way ANOVA: discharge time: HA: $P < 0.001$, C: $P < 0.001$, HA*C: $P < 0.001$; discharge rate: A: $P < 0.001$, C: $P < 0.001$, A*C: $P = 0.8853$;*

Table 5. 4 Discharge time and discharge rate of samples at 55 cm height

Sample	Discharge time, s		Discharge rate, kg/s	
	A40	A60	A40	A60
W 100%	21.31±0.85	44.32±1.41	1.88±0.06	1.13±0.02
W 97.5%-C 2.5%	27.05±0.51	51.50±1.52	1.45±0.02	0.96±0.01

** where W indicates wheat kernel, C indicates chaff and A is the hopper angle*

5.3.2 PIV analysis

The velocity vector field and velocity magnitudes of bulk wheat flow through mass and funnel flow are presented in Fig 5.5 and 5.6, respectively. Different color indicates the velocity of grains and the arrows indicate the velocity vectors. With the increase of chaff proportion the discharge velocity decreased and this trend could be observed based on the color difference in Fig 5.5 and 5.6. For the 60º angle hopper, at 30 cm height (from the bottom of the hopper), dead zones were observed with no-flow when the outlet was opened. With the increase in chaff, the particles in motion decreased. At height 20 cm and 10 cm (from the bottom), there is no dead zone in the hopper, and the flow profiles were symmetrical. With the increase in chaff, the time taken by the top layer of wheat to reach a height of 20 cm and 10 cm (from the bottom) increased.

Fig 5. 5 Flow velocity vector field and velocity magnitude contours analysis results at 40° hopper angle at initial sample height of 35 cm

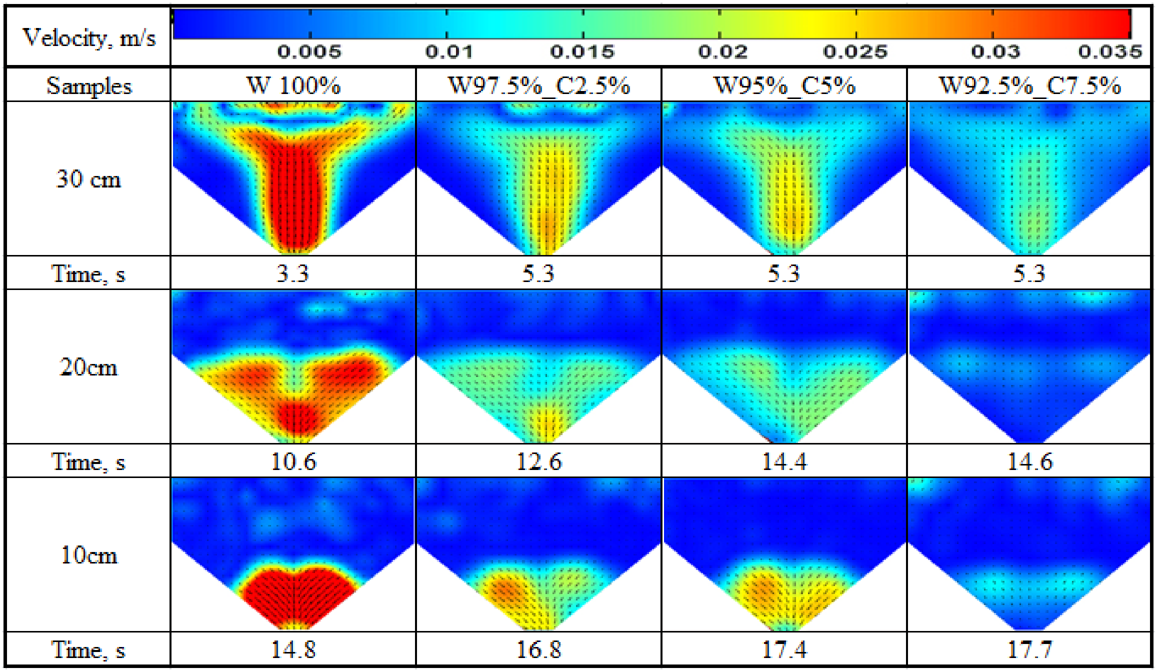
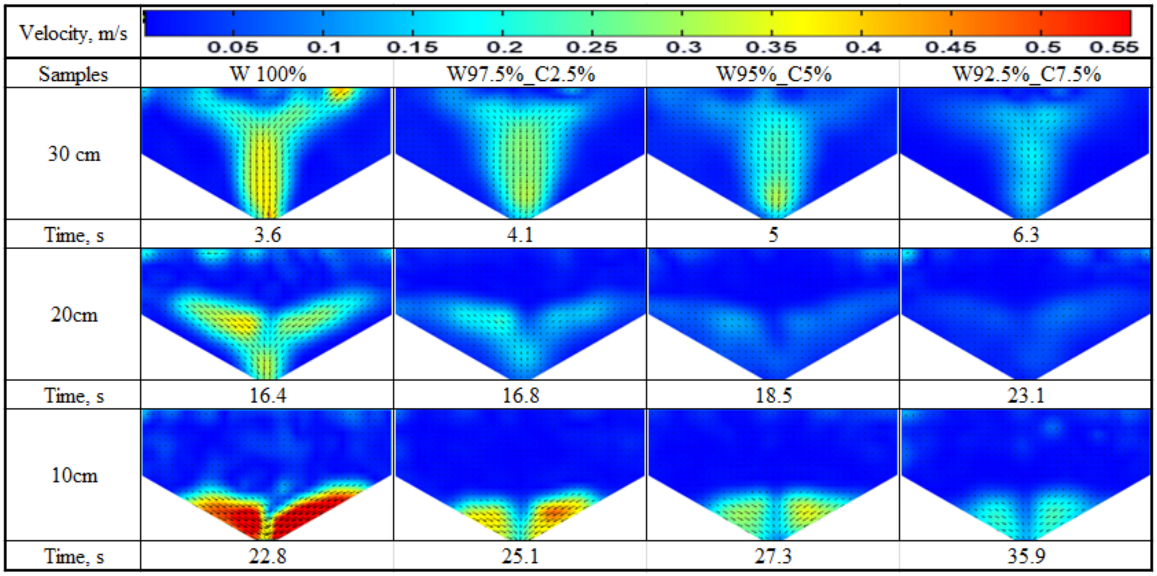
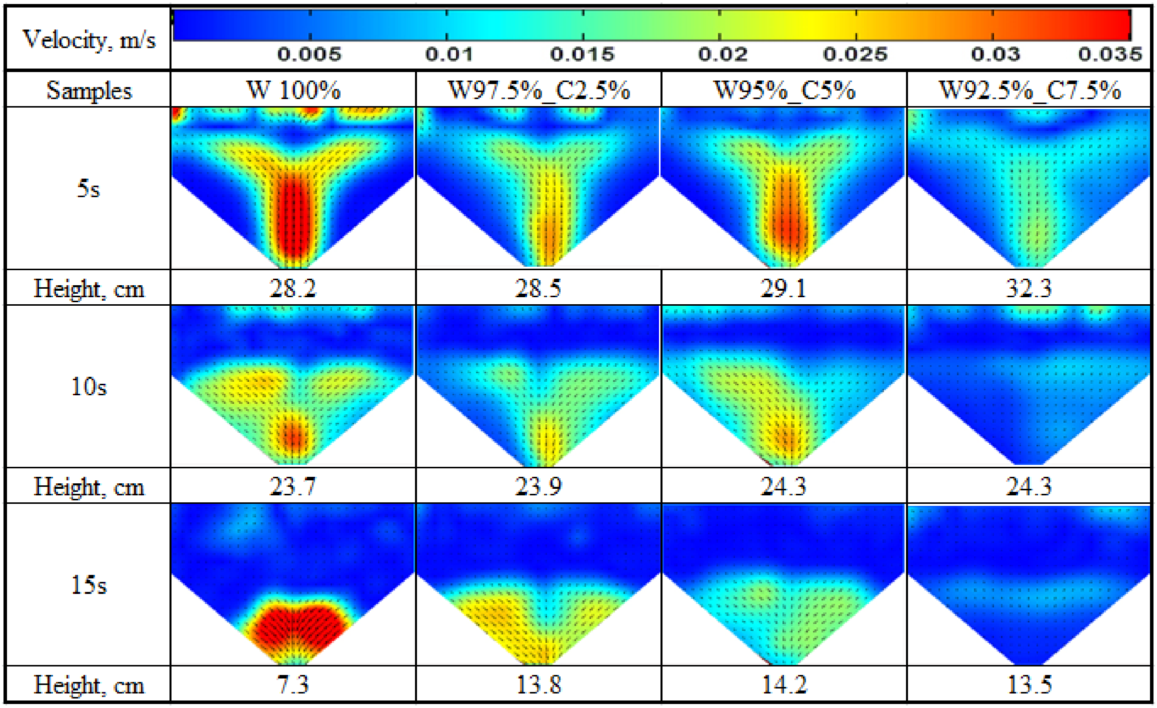


Fig 5. 6 Flow velocity vector field and velocity magnitude contours analysis results at 60° hopper angle at initial sample height of 35 cm



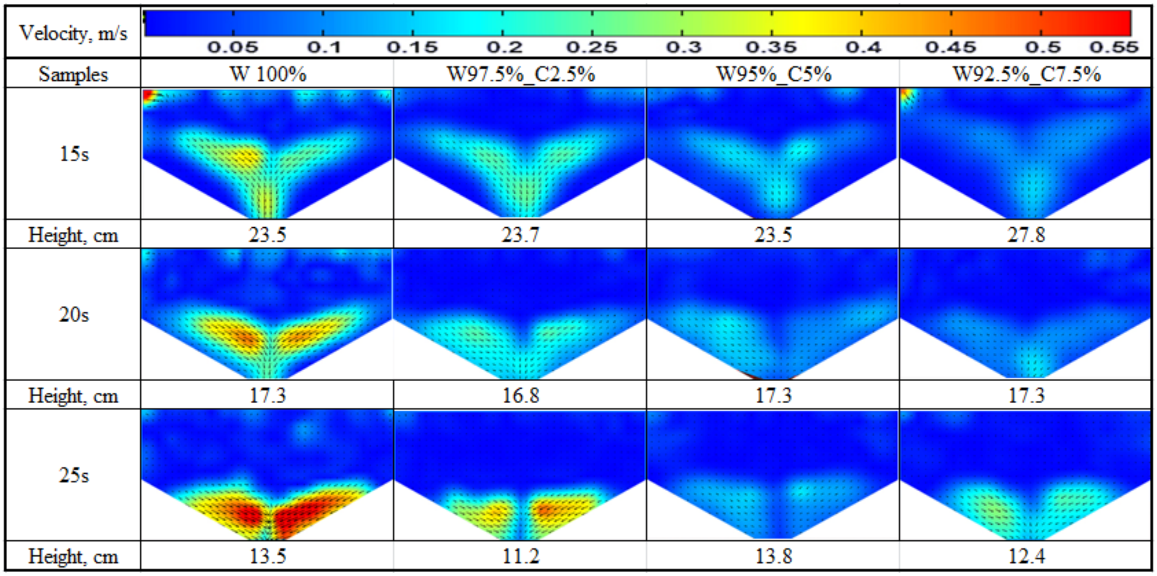
Compared to a mass flow hopper, more dead zone locations were observed in a funnel flow hopper with 60° hopper angle (Fig 5.6). Similar to the mass flow hopper results, increase in the proportion of chaff increased discharge time that corresponded to the results reported in Table 5.3. However, in the funnel flow especially towards the end of discharge, particles moved at a very low velocity. This indicates that, for bulk wheat with chaff, complete emptying of bins might not be possible using funnel flow hoppers with material stagnant on the sides of the hopper. With time and consolidation, existence of dead zone affects the quality of wheat and the handling efficiency. In Fig 5.7 and 5.8, the flow fields are compared at specific time points to observe the differences in flow. In general, the flow was irregular for bulk wheat with higher chaff proportion.

Fig 5. 7 Comparison of flow velocity vector field and velocity magnitude contours analysis results of 40° hopper angle at different time interval at initial sample height of 35 cm



Samples	W 100%	W97.5%_C2.5%	W95%_C5%	W92.5%_C7.5%
5s				
Height, cm	28.2	28.5	29.1	32.3
10s				
Height, cm	23.7	23.9	24.3	24.3
15s				
Height, cm	7.3	13.8	14.2	13.5

Fig 5. 8 Comparison of flow velocity vector field and velocity magnitude contours analysis results of 60° hopper angle at different time interval at initial sample height of 35 cm



Samples	W 100%	W97.5%_C2.5%	W95%_C5%	W92.5%_C7.5%
15s				
Height, cm	23.5	23.7	23.5	27.8
20s				
Height, cm	17.3	16.8	17.3	17.3
25s				
Height, cm	13.5	11.2	13.8	12.4

From Table 5.3 and 5.4, it could be observed that the flow rate decreased due to the pressure applied by the self-weight of wheat samples. Comparing the time interval listed in Fig 5.9 and 5.10, the flow mode is similar to the figures shown in Fig 5.5 and 5.6. In mass flow, wheat close to bin walls were initiated earlier than those in funnel flow mode. Meanwhile, the existence of chaff decreased the flow velocity. And for mass flow, it requires more time to discharge all the samples from bins.

Fig 5. 9 Comparison of flow velocity vector field and velocity magnitude contours analysis results of 40° hopper angle at different time interval at initial sample height of 55 cm

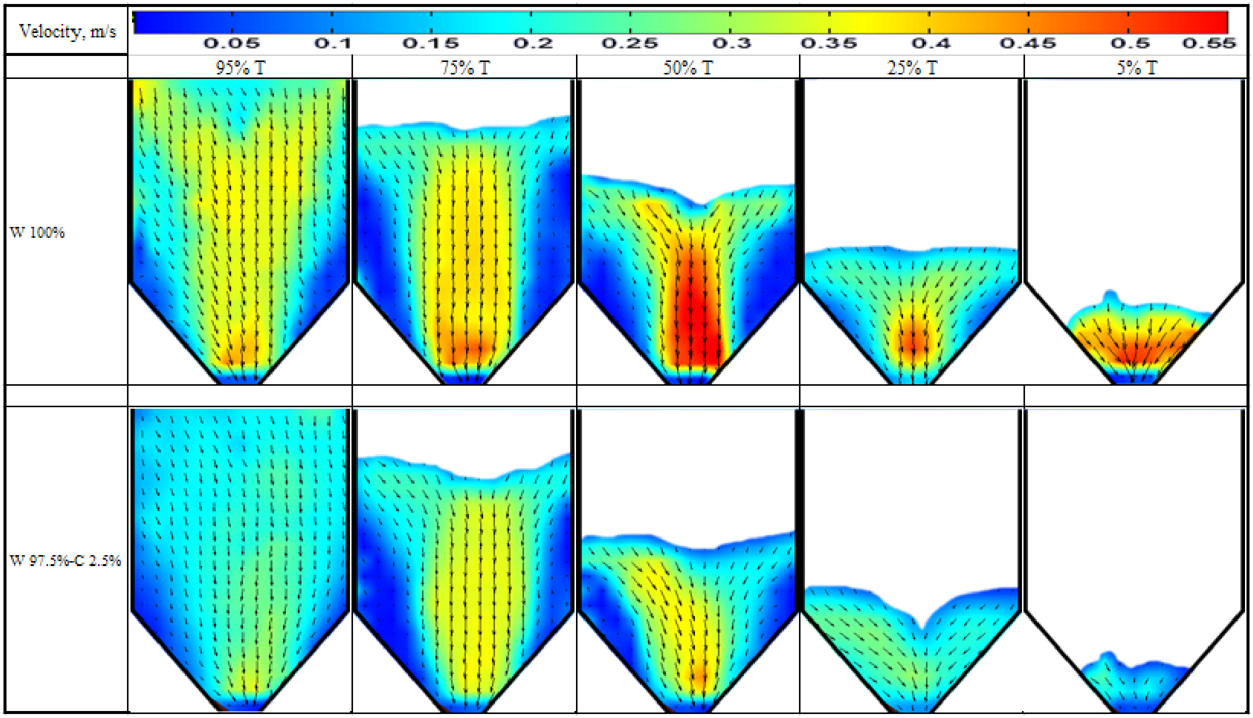


Fig 5. 10 Comparison of flow velocity vector field and velocity magnitude contours analysis results of 40° hopper angle at different time interval at initial sample height of 55 cm

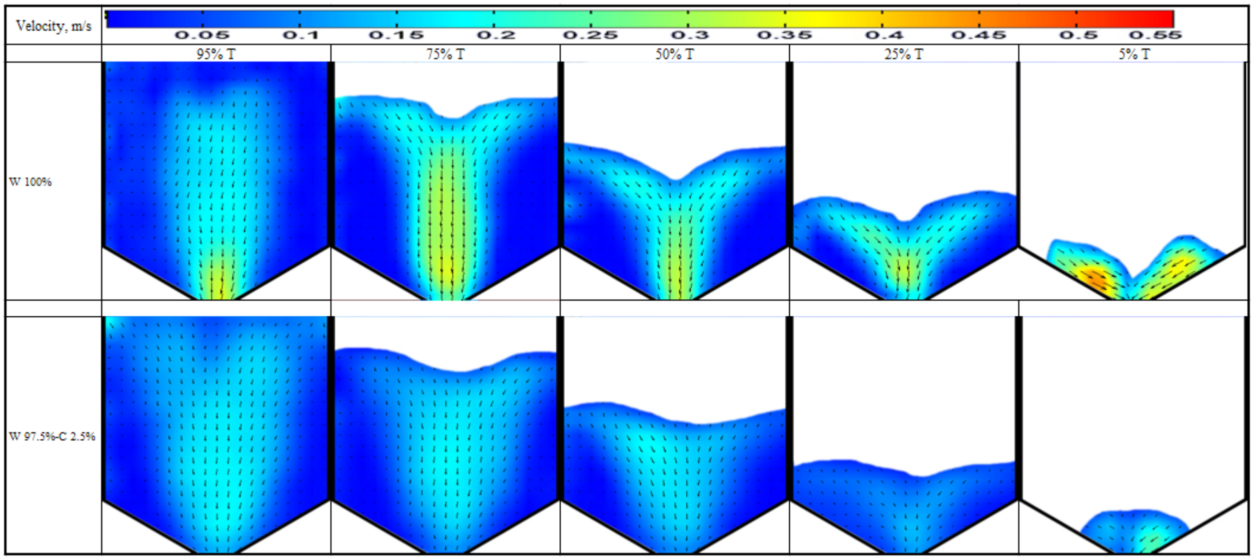
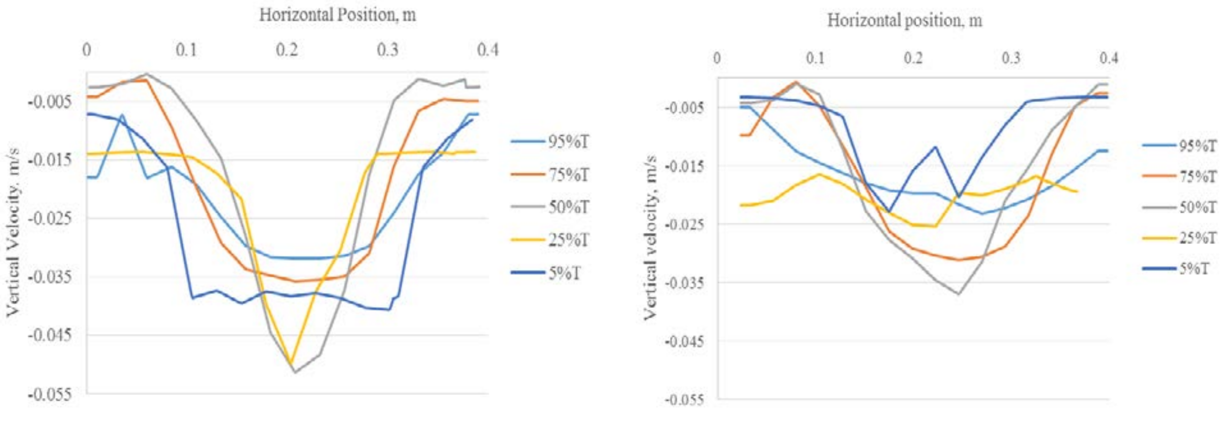


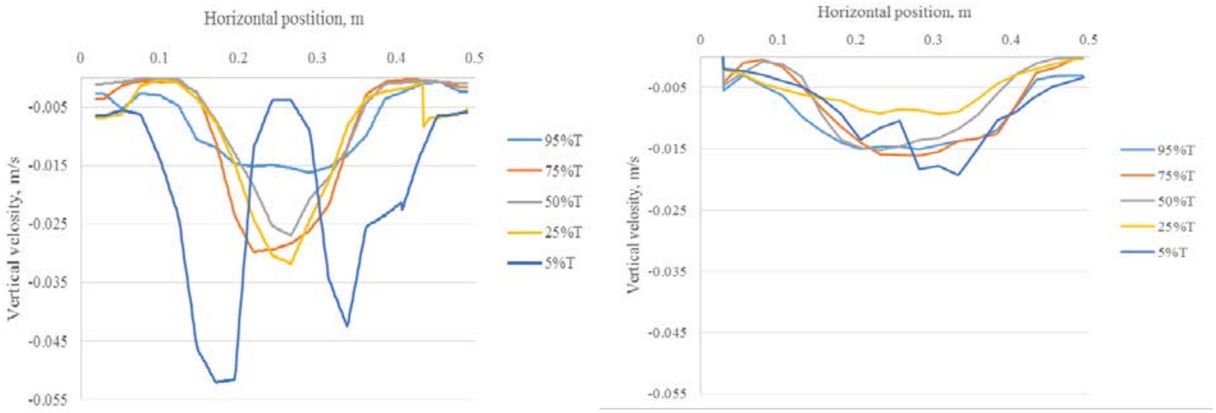
Fig 5. 11 Profile of vertical velocity of 40° hopper angle at different hopper geometries at initial sample height of 35 cm



W 100%

W97.5% - C 2.5%

Fig 5. 12 Profile of vertical velocity of 60° hopper angle at different hopper geometries at initial sample height of 55 cm



W 100%

W97.5% - C 2.5%

From Fig 5.11 and 5.12, it could be observed that towards the end of wheat dischage, there would be two peaks of velocity as the central section of flow ended first, followed by the wheat close to the bin wall.

5.4 Conclusions

The particle image velocimetry (PIV) method can be used as an effective optical technique to evaluate the flow pattern and quantify particle velocity of bulk wheat by processing successive digital images. Though strains inside the bulk materials cannot be traced by using this method, PIV gives the surface movement characteristics. This study indicated that chaff had significant influence on the discharge time and rate of bulk wheat hopper flow. Two stages were tested to research the effect of pressure change to wheat discharge flow. Compared to funnel flow hoppers, mass flow hoppers could be efficient for handling bulk wheat. PIV results indicated the presence of dead/no-flow zones during handling of wheat with chaff. In funnel flow hoppers, presence of chaff increased the tendency of bulk wheat to be stagnant near the hopper walls. The results indicated that clean wheat has better flow characteristics than bulk wheat with impurities. Arch formation and segregation potential will be high for wheat with chaff and impurities compared to bulk clean wheat.

5.5 Chapter References

Amoros, J.L., Mallol, G., Sanchez, E. and Garcia, J. 2000. Design of bins and hoppers for the storage of particulate materials; problems associated with the discharge operation. Brick and Tile Industry International 16, 168-177.

Beverloo, W. A., Leniger H. A. and Van de Velde J. 1961. The flow of granular material through orifices. Chemical Engineering Science 15, 260-296.

DIN (Deutsches Institut für Normung: German institute for standardization) 1055. 1987. Teil 6 Lasten in Silo zellen, Deutsche Norm.

Eric, P. 2004. Practical solutions for solving bulk solids flow problems. Cement Industry Technical Conference. IEEE-IAS/PCA, 139 – 147

EUROCODE 1. 2003. Basis of design and action on structures. Part 4. Action in silos and tanks. DD ENV, 1991–1994.

Jenike, A.W. 1964. Bulletin 123: Storage and flow of solids. Salt Lake City, UT.

Jenike, A.W. 1961. Bulletin 108: Gravity flow of bulk solids. Salt Lake City, UT.

Johanson, J.R. 1965. Method of calculating rate of discharge from hoppers and bins SME of AIME, Transactions 232, 69–80.

Lueptow, R.M., Akonur, A. and Shinbrot, T. 2000. PIV for granular flows. Experiments in Fluids 28, 183–186.

Mankoc, C., Janda, A., Arevalo, R., Pastor, J.M., Zuriguel, I. and Garcimartín, A. 2007. The flow rate of granular materials through an orifice. Granular Matter 9(6), 407-414.

MATLAB and Statistics Toolbox Release 2011b, The MathWorks, Inc., Natick, Massachusetts, United States.

Molenda, M. and Horabik, J. 2005. Mechanical Properties of Granular Agromaterials and Food Powders for Industrial Practice Part1: Characterization of Mechanical Properties of Particulate Solids for Storage and Handling. Lublin.

Quenot, G. M., Pakleza, J. and Kowalewski, T. A. 1998. Particle image velocimetry with optical flow. Experiments in Fluids 25, 177-189.

Schulze, D. 2008. Powders and Bulk Solids: Behavior, Characterization, Storage and Flow. Springer Berlin Heidelberg. New York, USA.

Sielamowicz, I. and Blonski, S. 2004. Particle image velocimetry analysis of granular material flows. XXI International Congress of Theoretical and Applied Mechanics 15-21, Warsaw, Poland.

Sielamowicz, I., Blonski, S. and Kowalewski, T.A. 2005. Optical technique DPIV in measurements of granular material flows, Part 1 of 3-plane hoppers. Chemical Engineering Science 60, 589–598.

Sielamowicz, I., Blonski, S. and Kowalewski, T.A. 2006. Digital particle image velocimetry DPIV technique in measurements of granular material flows, Part 2 of 3-converging hoppers, Chemical Engineering Science 61, 5307 – 5317.

Steingart, D.A. and Evans, J.W. 2005. Measurements of granular flows in two-dimensional hoppers by particle image velocimetry. Part I: experimental method and results. Chemical Engineering Science 60, 1043–1051.

Thielicke, W. and Stamhuis, E. J. 2014. PIVlab - Time-Resolved Digital Particle Image Velocimetry Tool for MATLAB version: 1.35. http://dx.doi.org/10.6084/m9.figshare.1092508

Ketterhagen, W. R., Curtis, J. S., Wassgren, C. R. and Hancock, B. C.2009. Predicting the flow mode from hoppers using the discrete element method, Powder Technology 195, 1–10.

Womach, J. 2005. Agriculture: A Glossary of Terms, Programs, and Laws, (2005 ed.) .Washington, DC: The Library of Congress.

Zuriguel I., Pugnaloni L. A., Garcimartín A. and Maza, D. 2003. Jamming during the discharge of grains from a silo described as a percolating transition. Physical Review E 68, 30301.

Chapter 6 – Summary of Conclusions

6.1. Restatement of Thesis Goals

To understand challenges in grain flow during handling requires better understanding of grain physical and flow characteristics, to guide design appropriate equipment and prevent accidents. Due to the complexity of the bulk solids handling system, in this Thesis, two main factors that affect the flowability of bulk wheat are studied. Physical properties that act as a quick pre-overview parameter could help estimate the flowability of material in uncompacted condition (e.g. bulk density, angle of repose) and tapped condition (e.g. Hausner's ratio and Compressibility index). However, in most of the processing operations bulk wheat is being processed or handled under consolidation. At these conditions, physical properties alone cannot provide solid theoretical support for design purposes. Hence, more reliable materials' data under specific compacted or flow condition are required for characterizing the flowability of bulk wheat.

The aims of this thesis was to study the flow characterization of bulk wheat and the specific objectives as stated in Chapter 1were,

1. To measure the physical and flow properties of bulk wheat with different proportion of chaff at three moisture content level.
2. To measure the physical and flow properties of wheat with different proportion of lesser grain borer infested kernel at three moisture content level.
3. To study the flow profile of wheat through mass and funnel flow hoppers using particle image velocimetry technique.

This thesis work explores to address three main objectives associated to characterize bulk wheat with two main impurities, chaff and insects infested kernels, and moisture content. Meanwhile, image analysis of the discharge flow of bulk wheat with chaff in laboratory-scale hopper was conducted for better understanding on the bulk wheat flow. In this part of the thesis, a project overview is described in Section 6.2. In Section 6.3, the major findings from the experiments are discussed. Potential future work based on the questions evolved while conducting this research are stated in Section 6.4.

6.2. Project Overview

The storage and handling challenges of bulk wheat, project hypothesis and goals were discussed in Chapter 1. The studies and results available in previous literatures were explaining the bulk solids characterization, flow in hopper, hopper structures and digital image analysis were reviewed in Chapter 2. The common flow issues such as no-flow and inconsistent flow during discharging and grain entrapment were briefly discussed. Physical properties such as densities, flow indicators, angle of repose and moisture content were discussed in detail. Different flowability evaluation methods were discussed for a comprehensive understanding of flow properties during handling.

Hopper structure is a significant link in processing affecting the efficiency and reliable. Basic hopper design theory and flow patterns were reviewed. The review provided theoretical support to fabricate a laboratory-scale hopper for visualizing the discharge flow by Particle Image Velocimentry (PIV) analysis. PIV analysis provided the flow profile of discharge, but the limitation of this method is also obvious, because of 2-D analysis the internal flow happen cannot be analyzed by PIV. In Chapter 2, possible evaluation methods for flowability of bulk solids were discusses.

In the Chapter 3 and 4, the effect of chaff and insects infested kernels on bulk wheat characterization at different moisture content are characterized. Physical and flow properties were comprehensively tested and reported. Chapter 5 focused on particle image analysis by using PIV technique. Particle flow vector, particle velocity and colored velocity magnitude zone were plotted using image analysis. In this part of work, chaff proportions in bulk wheat and flow pattern (mass flow and funnel flow) was varied to study the effect on discharge flow rate and time.

6.3. Discussion of Major Findings

Physical and flow properties of bulk wheat affected by impurities and moisture content have been evaluated. The PIV analysis quantified the particle velocity, velocity direction and velocity vector distribution.

Results indicate that the moisture content, chaff proportion and the presence of insects damaged kernels influence both the physical and flow properties of wheat. Knowledge on these characteristics is necessary for design of handling equipment and to understand the behavior of grain during storage and handling. Flow indicators, such as bulk density, tapped density, and angle of repose, showed that the flowability of bulk wheat decreases as moisture content, chaff and insects infested kernels proportion increase. Under compaction, changes in density altered the bulk porosity of samples. Meanwhile, more void in the sample due to the presence of chaff made it easier to be compacted at the same pressure level. The main difference due to the presence of chaff or insects infested kernels is the shape of particles that make-up the bulk wheat. The rearrangement of grain dust and less denser insect damaged kernels influenced the overall density characterisitics of materials. The energy required to initiate the flow is higher for wheat than those of samples with impurities at lower densities. Moisture content and the proportion of these two impurities, within the tested range, did not have any significant effect on the shear properties of bulk wheat. Presence of chaff and insect damaged kernels and the dust from insect activity could increase the compressibility and lead to arching and caking of grains affecting their flowability. The flow of wheat with impurities will be challenging than clean wheat. This observation was supported by the PIV analysis. PIV results indicated that presence of chaff increases the discharge time and reduces the discharge rate. Flow of wheat, with impurities, will be challenging in funnel flow hoppers.

6.4. Future Work

Fundamental and applied studies to understand the physical and flow characteristics of bulk wheat has been undertaken in this thesis study. Adjustable Plexiglas hopper model was developed to understand the bulk discharge behavior of bulk wheat during laboratory-scale handling. The application of these potential research areas may not be limited to bulk wheat but also could be applied for other bulk grain handling and storage systems.

6.4.1 Industrial scale testing of wheat flow

This study focused in labscale and pilot scale testing of flow of wheat grains. The bulk flow of wheat could be scaled up and tested at industrial scale hoppers and bins. Because, during storage, weather conditions influence the cohesion between the particles due to the presence of chaff and insect damaged kernels.

6.4.2 Discrete Element Method (DEM) Simulation

Recently, DEM modeling has been accepted as a method to provide detailed understanding for equipment design. William et al. (2009) and Balevičius et al (2011) has used DEM to predict the flow mode from hoppers. In the future, DEM can be used for characterizing bulk flow of wheat.

6.5 Chapter References

Balevičius, R., Kačianauskas, R., Mrózc, Z. and Sielamowiczd, I. 2011. Analysis and DEM simulation of granular material flow patterns in hopper models of different shapes. Advanced Powder Technology 22(2), 226–235.

William, R. K., Jennifer, S. C, Wassgren, C. W. and Bruno, C. H. 2009. Predicting the flow mode from hoppers using the discrete element method. Powder Technology 195(1), 1–10