CHARACTERIZATION OF THE MIXING OF WHEAT STRAW SLURRIES THROUGH ELECTRICAL RESISTANCE TOMOGRAPHY (ERT)

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AUTHOR’S DECLARATION

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ABSTRACT

Characterization of the Mixing of Wheat Straw Slurries through Electrical Resistance Tomography (ERT)

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Wheat straw is a good source for the production of bioethanol. It can be converted into smaller fibers using mechanical treatment such as milling and grinding. These fibers can then be suspended in water and the slurry behaves as a non-Newtonian fluid possessing yield stress. In mixing operations, the presence of yield stress creates a region of active motion (called cavern) around the impeller, and stagnant zones in the rest of the tank. 2D and 3D electrical resistance tomography (ERT) images of wheat straw slurries were used in this study to measure the cavern diameter and height, respectively, created by mixing the slurries, and to estimate their yield stress from these dimensions. The average yield stresses of 5, 7, and 10 wt% slurries were 1.31 Pa, 4.2 Pa, and 14.8 Pa, respectively, when fiber size was ≤ 2 mm, and 3.4 Pa, 6.8 Pa, and 16.7 Pa, respectively, when fiber size was 8 mm ± 0.014 mm. The author believes that this study is the first novel application of ERT to estimate the yield stress of wheat straw slurries, as opposed to directly measuring it with a rheological instrument.
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To Saeed

For his love and support

and

To my daughter and son, Soha and Illia
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INTRODUCTION

Mixing of non-Newtonian fluids in stirred vessels is a common operation encountered in the chemical, biochemical, pharmaceutical, polymer, mineral, food, and wastewater treatment industries. A main group of non-Newtonian fluids exhibits the shear-thinning behaviour with yield stress (Skelland, 1967), such as pulp suspensions, certain polymers, biopolymer solutions, and wastewater sludge (Etchells et al., 1987). The shear-thinning fluids have low apparent viscosities at high shear rates and high apparent viscosities in low shear rates.

The design of the mixing systems for non-Newtonian fluids is more challenging than for Newtonian fluids due to the complex rheology of non-Newtonian fluids. Mixing of fibrous suspensions, which are non-Newtonian fluids with a yield stress, causes a well-mixed zone around the impeller called cavern with stagnant regions elsewhere (Wichterle and Wein, 1975). The stagnant regions within the mixing vessel result in ineffective heat and mass transfer (Amanullah et al., 1997). To improve the mixing efficiency of a reactor, it is always beneficial to eradicate such undesired stagnant zones in the mixing of non-Newtonian fluids with yield stress.

The size of the cavern has significant effect on the mixing quality. Numerous experimental techniques, such as laser Doppler anemometry (LDA), X-ray photography, hotwired anemometry (HWA), planner laser induction (Arratia et al., 2006), ultrasonic Doppler velocimetry (UDV), positron emission particle tracking (PEPT) and electrical
resistance tomography (ERT), and the numerical technique called computational fluid dynamics (CFD) have been applied to study the formation of cavern generated in the mixing of yield stress fluids.

In the literature, there seems to be no study on the cavern evaluation of wheat straw suspensions. The recent and rapid development of non-intrusive ERT seems to provide an efficient tool for the analysis and control of mixing processes especially in the case of non-Newtonian fluids (either opaque or transparent). Electrical resistance tomography (ERT), which is an emerging technology, can be the best alternative to measure the cavern size and to analyze fluid flow in 2D and 3D.

This study will try to employ ERT to study the mixing of wheat straw slurries, which are yield–pseudoplastic fluids, with the A200, A310, and A100 impellers in terms of cavern shape and size. In this study, for the first time, the yield stress of the wheat straw slurries was estimated by applying the cavern size obtained from ERT tomograms.
CHAPTER 1

LITERATURE REVIEW

1.1  Wheat Straw

Wheat straw is an agricultural residue made of stalks, stem, and dried leaves of the wheat plant. It contains about 58-78 wt % total sugars depending on the species (Himmel et al., 2007).

International wheat production statistics from years 2000 to 2010 show that wheat straw is the largest biomass feed stock in Europe (FAOSTAT Database, 2011). More than 21% of the world’s food depends on the wheat crop, so, in order to satisfy the great demand of human’s need, the production of wheat crop need to be increased.

Wheat straw is a complex mixture of three main components: cellulose, hemicellulose and lignin. Generally, wheat straw contains of 33-40 (wt%) of cellulose, 20-25 (wt%) of hemicellulose, and 15-20 (wt%) of lignin (Prasad et al., 2007). Cellulose is a linear monomer polymer chain comprised of D-glucose units attached to each other via β-1→4-glycosidic bonds. Hemicellulose consists of long chain of xylose molecules, etc. Lignin is an amorphous polymer consisting of phenylpropane units, and it has three aromatic alcohols (monolignols) precursors of p-coumaryl, coniferyl and sinapyl alcohols, which are shown in Figure 1.1 (Buranov and Mezza , 2008).
Lignocellulosic materials are a good source for ethanol production (Taherzadeh and Karimi, 2007). The main objective of this chapter is to conduct a literature review on the mixing performance in wheat straw, which is applied in ethanol production. This literature review includes the ethanol production process, wheat straw suspension rheology, power consumption, impeller type, and cavern formation; finally, some ERT applications in mixing are presented.

1.1.1 Ethanol Production from Wheat Straw

Wheat straw is the most attractive low cost feedstock for production of fuel alcohol due to its abundance, renewability and low lignin content (Buranov and Mezza, 2008). Numerous studies were done on the bioconversion of lignocellulose to produce ethanol (Erdei et al., 2010; Talebnia et al., 2009; Kaparaju et al., 2009). This process contains three steps: (1) pre-treatment, to break down the recalcitrant structures of lignocellulose; (2) hydrolysis, to hydrolyze polysaccharides (e.g., cellulose, hemicellulose) into
fermentable sugars; and (3) fermentation, to convert sugars into ethanol (Hahn-Hagerdal et al., 2006; Jorgensen et al., 2007).

1.1.1.1 Pre-treatment

Pre-treatment is a significant process in the utilization of lignocellulosic material to achieve large amounts of fermentable sugars. Pre-treatment is performed to break the lignin seal, decrease crystallinity of the cellulose and solubilize hemicellulose (Patel et al., 2009). Pre-treatment techniques are categorized in four groups of physical, chemical, physicochemical, and biological.

**Physical pre-treatment**: chipping, milling and grinding are main types of physical pre-treatments. These treatments reduce both the crystallinity and the degree of polymerization (DP) of cellulose. In addition, they increase the specific surface area (Sun and Cheng, 2002).

Chipping reduces the biomass size to 10–30 mm while grinding and milling can decrease the particle size to 0.2–2 mm. Particle size and cellulose crystallinity are reduced in grinding and milling more than chipping probably because of the shear forces created during milling and grinding. Increasing specific surface area and reducing both cellulose crystallinity and degree of polymerization (DP) are all dependent on the type and duration of milling as well as the type of biomass.

**Chemical pre-treatment**: chemicals such as acids, alkali, cellulose / organic solvents, and ionic liquids can affect lignocellulosic biomass structure (Swatloski et al., 2002). In acid pretreatment (typically H$_2$SO$_4$), most of the hemicellulose is removed and converted to soluble sugars (Gil et al., 2010; Guo et al., 2008). Alkali pre-treatment such as NaOH,
KOH, Ca(OH)$_2$, hydrazine and anhydrous ammonia can break the lignin structure, increase the internal surface of biomass and reduce both the degree of polymerization and crystallinity (Chandra et al., 2007; Chang and Holtzapple, 2000; Galbe and Zacchi, 2007). The most effective chemical pre-treatment for biomass with low lignin content such as wheat straw is alkali pre-treatment (Agbor et al., 2011). Combined cellulose/organic solvent pre-treatment separates lignocellulose components by using a cellulose solvent such as concentrated phosphoric acid, organic solvent like acetone, and water (Zhang et al., 2007; Zhu et al., 2009). Ionic liquids (ILs) have been used as novel non-derivatizing media for the dissolution of carbohydrates including cellulose (Swatloski et al., 2002; Zhao et al., 2008). Many ILs, especially those containing halide, acetate, formate, and phosphate anions, dissolve cellulose quickly (Ohno and Fukaya, 2009).

**Physicochemical pre-treatment**: physicochemical pre-treatments are combinations of physical and chemical pre-treatments. They include steam pre-treatment (or steam explosion), liquid hot water pre-treatment, wet oxidation pre-treatment, ammonia fiber expansion (AFEX), ammonia recycle percolation, aqueous ammonia pre-treatment and organosolv pre-treatment (Zhu et al., 2006; Zhu et al., 2009).

**Biological pre-treatment**: fungi are used in biological pre-treatment. Fungi are able to produce enzymes that degrade lignin, hemicellulose, and polyphenols. White and soft-rot fungi are capable of degrading lignocellulose material. However, brown rot fungi can degrade cellulose structure. White-rot fungi are known as the most effective biological pre-treatment (Lee, 1997; Sun and Cheng, 2002). This method is not used in industry due
to several factors such as the need for careful growth environment, a residence time of 10–14 days and the need of large biological reactors (Agbor et al., 2011).

1.1.1.2 Hydrolysis

**Enzymatic Hydrolysis**

Cellulose slowly degrades into glucose by a group of enzymes (cellulases) with various functions during enzymatic hydrolysis of pre-treated lignocellulosic biomass. Cellulase refers to a group of enzymes produced by fungi, bacteria, and protozoans that catalyze cellulolysis (i.e. the hydrolysis of cellulose) (Watanabe et al., 2010). All these enzymes can hydrolyze cellulose by creating new attainable sites for each other. The incomplete conversion of cellobiose to glucose and inhibition of cellulbiohydrolase (CBH) are happening because *Trichoderma reesei* secretes low levels of β-glucosidase enzyme. Therefore, in order to obtain complete conversion of cellobiose to glucose, it is always required to use supplemental β-glucosidase, such as Novozyme 188 as shown in Table 1.1 (Zhang et al., 2010; Kumar and Wyman, 2009).

**Acid Hydrolysis**

Dilute acid hydrolysis is also another way to cleave ether bonds between hemicellulose and lignin complexes. Dilute acid (0.75% H$_2$SO$_4$) at 120–180 °C can both solubilize hemicellulose and convert solubilized hemicellulose to fermentable sugars (Grohmann et al., 1985; Saha et al., 2005). Studies show that during the organosolv and aqueous ethanol delignification of wheat straw, a major factor in lignin breakdown is the cleavage of α-
aryl and β-aryl ether linkages in lignin precursors. The cleavage of α-aryl ether bonds is faster than that of β-aryl ether bonds when acid catalyst is added (Papatheofanous et al., 1998; Xu et al., 2006; Hongzhang and Liying, 2007). Experiments show that during organosolv pulping of wheat straw in presence of formic–acetic acid–water (30/60/10) system, more than 94.1% of original lignin is removed (Xu et al., 2006).

Table 1.1. Summary of some multi-enzyme complexes and the role of supplemental enzymes

| Multi-enzyme complex                  | The role of supplemental enzymes                                                                 | Reference                      |
|---------------------------------------|---------------------------------------------------------------------------------------------------|--------------------------------|
| Cellulase+β-glucosidase               | Eliminate the inhibition of cellobiose to cellulase                                               | Zhang et al., 2010 and Kumar and Wyman, 2009 |
| Cellulase+β-glucosidase+xylanases     | Hydrolyze the xylan and make the cellulose more accessible to cellulase                           | Zhang et al., 2010; Kumar and Wyman, 2009; Berlin et al., 2007 |
| Cellulase+β-glucosidase+pectinases    | Remove the pectin that coat cellulose fibers                                                      | Zhang et al., 2010 and Berlin et al., 2007 |
| Cellulase+xylanase+β-xylosidase        | Hydrolyze the xylan and eliminate the inhibition of xylobiose and higher xylooligomers          | Kumar and Wyman, 2009          |
| Cellulase+endoxylanase+α-L-arabinofuranosidase | Remove the arabinofuranosyl group that limits the access of xylanases to xylan backbone | Sorensen et al., 2007 and Alvira et al., 2011 |
1.1.1.3 Fermentation

Ethanol fermentation is a biological process in which sugars such as glucose, xylose, and sucrose are converted into cellular energy and thereby produces ethanol and carbon dioxide as metabolic waste products. Several studies have been done to develop efficient pentose (especially xylose) fermenting microorganisms, such as recombinant *Saccharomyces cerevisiae*, *Zymomonas mobilis* and *Escherichia coli* strains (Hahn *et al.*, 2007; Yonge *et al.*, 2010).

Figure 1.2 shows three main strategies for strain improvement in cellulosic ethanol production; (1) pentose utilization, (2) direct cellobiose fermentation and (3) tolerance enhancement (Renliang *et al.*, 2011).

![Figure 1.2. Three main strategies for strain improvement in cellulosic ethanol production](image)
Literature reviews show that one of the important steps for the fermentation of xylose to ethanol is the transport of xylose in *S. cerevisiae* especially at low xylose concentrations. This transport is significant because it appears through nonspecific hexose transporters. Recently, some heterologous xylose transporters have been found in recombinant *S. cerevisiae*. These transporters such as Gxf1 (Hagerdal, 2009), Sut1 (Katahira *et al.*, 2008) are used to increase the absorption of xylose. Ethanolgenic microorganisms are useful to convert cellulosic biomass into ethanol (Figure 1.2). There are two ways to convert cellulosic biomass into ethanol. The first way is to use both cellobiose transporter and intracellular β-glucosidase into microorganisms (Galazka *et al.*, 2010) while the second way is to produce extracellular β-glucosidase from ethanologenic microorganisms (Nakamura *et al.*, 2008).

### 1.2 Wheat Straw Suspension Rheology

One important factor in the mixing of non-Newtonian fluids is the rheological behaviour of the fluid (Pakzad *et al.*, 2008). Rheology is the study of deformation and flow of matter, especially in soft solids and liquids with a complex flow behavior (Viamajala *et al.*, 2009). The rheological behavior is significant in the pulp and paper and in the biomass processing industries.

Some studies have been done so far on the rheological properties of cellulose fiber suspensions (Chaussy *et al.*, 2011; Derakhshandeh *et al.*, 2010; and Hui *et al.*, 2009) and
also pre-treated lignocellulosic materials, especially corn stover (Primenova et al., 2004). Yield stress is one of the most important rheological properties of pulp suspensions in designing process equipment for the pulp and paper industry (Derakhshandeh et al., 2011). The yield stress of a fiber suspension is a key parameter in pulp manufacturing since the suspension flows once the yield stress is overcome.

Rheological studies on the slurries of pre-treated corn stover and various pulp fibers have also shown that the yield stress is a function of the fiber mass concentration through a power-law relationship as shown in Equation (1.1) (Lavenson et al., 2011):

\[ \tau_y = aC_m^b \]  

(1.1)

where \( a \) and \( b \) are empirical constants. Lavenson et al. (2011) compared fiber types to observe the direct effect of fiber properties on rheology.

Bennington et al. (1990) measured the yield stress of pulp and synthetic fiber suspensions using an equation based on network theory, which included fiber aspect ratio and Young’s modulus:

\[ \tau_y = cEA^2C_v^3 \]  

(1.2)

where \( A \) is the fiber aspect ratio, \( E \) is the fiber’s Young’s modulus, \( c \) is a constant and \( C_v \) is the volume concentration of the pulp suspension.
Chen et al. (2002) studied the flow behavior of pulp suspensions and identified three flow regimes. In the first regime, Newtonian flow was observed at low shear rates. Unstable flow was found in the second region, with jumps in the shear stress dependent on shear rate. In the third region, Newtonian behavior at high shear rates was observed, which was called dynamic equilibrium zone. This kind of behavior requires a flexible mixing system to cover the wide range of rheological behavior.

Hui et al. (2009) studied pulp fiber suspensions with concentrations from 1.0 wt% to 5.0 wt%. They found that the pulp fiber suspensions displayed non-Newtonian rheological behavior with yield stress. This finding was in contrast with Chen et al. (2002), who mentioned that the rheological behavior of pulp suspension is flow dependent.

Derakhshandeh et al. (2010b) studied the flow behavior of 0.5-5.0 wt% of pulp suspensions, using both conventional and coupled UDV-rheometry techniques. They observed that by increasing the fiber mass concentration, the apparent yield stress and the consistency index ($K$) in the Herschel-Bulkley model increased, while the power–law index ($n$) in the Herschel-Bulkley model decreased. They explained that these materials show a Newtonian behavior at high shear rates, which is referred to the turbulent regime. The shear stress values at which this regime begins were measured and reported as the critical shear stress for the onset of turbulence.

Chaussy et al. (2011) examined the rheological behavior of fiber suspensions using the Carreau-Yasuda model. This model does not show discontinuities and enables the description of the pulp suspensions behavior for the entire domain of shear rates up to $2.1 \times 10^6$ s$^{-1}$. They concluded that the pulp suspensions behave as a Newtonian fluid at the
lower shear rates and as a shear thinning fluid at the higher shear rates. They also observed that the suspension viscosity increased with fiber concentration, fiber length, and pH of the suspension.

Viamajala et al. (2009) examined the rheology of acid hydrolyzed corn stover at concentrations between 10.0-40.0 wt%. These slurries behaved like yield stress fluids. With increasing hydrolysis temperature and decreasing particle size, the yield stress decreased. They believed that with solids concentration up to a point, yield stress increased and then became independent of concentration at the high concentrations. The reason for the plateau at high concentrations is not clear.

The study of pre-treated lignocellulose (sawdust slurries) by Dasari and Berson (2007) showed that the rheology of pre-treated lignocellulose is affected by the fiber size. They reported that the yield stress of the slurry increased with an increase in fiber length.

Rosgaard et al. (2007) investigated the effect of solids content and enzymatic hydrolysis on the apparent viscosity of barley straw biomass slurries, with solids mass fraction varying from 5 wt% to 15 wt%. It was proved in this study that the apparent viscosity increased with solids mass fraction, and decreased with time during enzymatic hydrolysis.

Bashir (2008) measured the rheological properties of wheat straw suspensions at concentrations between 5.0-20.0 wt%. Wheat straw fibers were made by grinding wet or dry wheat straw and were divided into four sizes: 8, 12, 20, and 40 mesh. The yield stress was found to increase with concentration as well as with the size of the wheat straw fibers as shown in Table 1.2. The yield stress data were fitted to the power law equation
proposed by Kerekes et al. (1985) for pulp fibers. It was found that only the yield stress of the slurry of 40 mesh size wheat straw fibers agreed with this power law correlation.

Table 1.2. Yield stress values at various concentrations of wheat straw for mesh sizes of 40, 20, 12 and 8

| Concentration (% w/v) | Yield Stress (Pa) (40 mesh) | Yield Stress (Pa) (20 mesh) | Yield Stress (Pa) (12 mesh) | Yield Stress (Pa) (8 mesh) |
|-----------------------|-----------------------------|----------------------------|-----------------------------|----------------------------|
| 5                     | *                           | 171                        | 399                         | 411                        |
| 10                    | 153                         | 195                        | 426                         | 739                        |
| 15                    | 354                         | 405                        | 516                         | 765                        |
| 20                    | 462                         | 510                        | 684                         | 1035                       |

*Sedimentation effect was prominent only in 5 wt% (40 mesh) wheat straw suspensions, where no yield stress was found (Bashir, 2008).

1.3 Fiber Networks

The large aspect ratio of pulp fiber brings significant contact among fibers (Derakhshadeh et al., 2011). This has a strong effect on suspension rheology. For fibers to form flocs or coherent networks, every fiber must be in contact with at least three other fibers (Dodson, 1996; Meyer and Wahren, 1964; Soszynski and Kerekes, 1988a). This contact regime has been described by a crowding number (N), which is the average number of fibers in a spherical volume swept out by the length of the single fiber (Kerekes et al., 1985). The concentration of fiber suspensions can be characterized by the crowding number (Kerekes and Schell, 1992; Dodson, 1996).
Samaniuk et al. (2011) study showed that cellulose fibers in water form networks that give rise to an apparent yield stress, especially at high solids contents.

1.4 Power Consumption

Power consumption is a significant parameter for mixing system. It can be defined as the energy transformed from an impeller to a fluid per unit time (Tatterson, 1991). Having knowledge about power consumption is very important in order to operate the impeller (Chhabra and Richardson, 1999). The impeller power in a homogeneous liquid depends on the geometry of impeller and tank, the density and viscosity of the fluid, the impeller speed and the gravitational force as shown in the following equation (Tatterson, 1991):

\[ P = f(\mu, \rho, N, D, T, g) \]  

(1.3)

where \( P, \mu, \rho, N, D, T, \) and \( g \) are power, fluid viscosity, fluid density, impeller speed, impeller diameter, tank diameter, and gravitational acceleration, respectively. Applying the dimensional analysis, Equation (1.4) is obtained (Skelland, 1967):

\[ \frac{P}{\rho N^3 D^5} = f\left( \frac{\rho N D^2}{\mu}, \frac{N^2 D}{g} \right) = f(\text{Re}, \text{Fr}) \]  

(1.4)

This equation shows that the dimensionless power coefficient \( P/\rho N^3 D^5 \) depends on both Reynolds number and Froude number for a fluid. The dimensionless groups are as follows:
\[ P_o = \frac{P}{\rho N^3 D^5} \]  
(1.5)

\[ Fr = \frac{DN^2}{g} \]  
(1.6)

\[ Re = \frac{\rho ND^2}{\mu} \]  
(1.7)

1.4.1 Power Requirements for Mixing of non-Newtonian Fluids

The key objective of any mixing process is to maximize the degree of homogeneity of a property such as concentration, viscosity, color, and temperature (Chhabra and Richardson, 2008). For a stirrer system and for a non-Newtonian fluid, the Reynolds number is defined as Equation (1.8):

\[ Re = \frac{\rho ND^2}{\mu_{app}} \]  
(1.8)

In non-Newtonian fluids, apparent viscosity depends on the shear rate. Shear rate decreases with the distance from the impeller. It may fall to zero in stagnant zones (Gabelle et al., 2011).
Metzner and Otto (1957) believed that the fluid motion near the impeller could be explained by averaged shear rate, $\gamma_{ave}$, which is linearly related to the rotational speed of the impeller as in equation (1.9):

$$\gamma = k_s N$$  \hspace{1cm} (1.9)

The constant $k_s$ depends on the impeller and tank configuration. The value of $k_s$ reported by Metzner and Otto (1957) was 13 for a disk flat-blade turbine. Skelland (1967) reported the experimental values for $k_s$ for different kinds of impellers such as turbines, propellers, paddles, and anchors. In case of pseudoplastic fluids, for most of the impeller types, $k_s$ was in the range of 10-13, while for anchors and helical ribbons larger values of 25-30 was reported (Bakker and Gates, 1995).

### 1.5 Impeller Type

The selection of a suitable impeller is a critical design parameter for mixing processes utilized in chemical industries (Tahvildarian, 2010).

Mixing is used in the process industries to achieve different objectives such as blending miscible liquids in reactors, dispersing of gases or immiscible liquids into a liquid phase, and suspension of solids. Impellers related to the generated flow are classified into three groups of axial-flow, radial-flow, and close-clearance impellers.

Axial-flow impellers such as marine propellers and hydrofoil impellers discharge flow along the axis of the impeller as shown in Figure 1.3a (Oldshue, 1983). These types of
Impellers are used for blending, solid-liquid suspension, and heat transfer (Paul et al., 2004).

Radial-flow impellers such as disk turbines (Rushton) and hollow blade turbines (Scaba) release fluid to the wall of the tank in radial direction as shown in Figure 1.3b (Oldshue, 1983). Radial flow impellers exert shear stresses to the fluid to remove the boundary layer between various phases such as the mixing of immiscible fluids (Thring and Edwards, 1990).

Close-clearance impellers such as anchors, helical ribbons, and helical screws are used in high viscosity applications (Chhabra and Richardson, 2008). Patel et al. (2012) suggested that the rapidly emerging Maxblend impeller is more efficient than conventional close-clearance impellers for mixing of Newtonian and non-Newtonian fluids. Fradette et al. (2007) conducted some experiments with viscous Newtonian and shear-thinning fluids and proved that the Maxblend impeller provided efficient mixing with lower power consumption.
Figure 1.3. Flow patterns in a baffled tank, generated by: (a) axial-flow impeller, and (b) radial-flow impeller.

1.5.1 Impeller Clearance

The distance between the bottom of the tank and the impeller is called clearance.

A large clearance creates a huge vortex, which results in air entrainment into the system and also causes the splash of fluid around (Paul et al., 2004). When an impeller is placed very close to the bottom of the vessel, the axial-flow pattern created with the downward pumping impeller is similar to the radial-flow pattern. In this situation, the bottom of the vessel becomes clear from the suspension of the particles and it leads to the reduction of the level of homogeneity in whole vessel.
1.5.2 Impeller Diameter

Impeller to tank diameter ratio (D/T) is a significant ratio in mixing tank design. Normally this ratio is selected inside a range of 0.16-0.98 (McCabe, 2005).

The diameter of the impellers which produce bulk motion such as helical ribbons, screws, and anchors should be close to the tank diameter (Tatterson, 1991).

1.6 Fiber Suspension Mixing

Mixing is a process which increases the degree of homogeneity and the rate of mass transfer (Paul et al., 2004; Bhole and Bennington, 2010). To optimize the fiber suspension mixing process, many design parameters such as the type of impeller, impeller clearance, impeller diameter, impeller speed, fiber concentration and fiber size must be considered (Samaniuk et al., 2011).

Hui et al. (2009) used a side-entering Maxflo impeller to measure the cavern size of several pulp fiber suspensions (hardwood and soft wood pulp) with suspension mass concentration from $C_m = 1\%$ to $5\%$.

Bhole and Bennington (2010) explored the performance of four axial-flow impellers (Maxflo, marine propeller, focused flow (FF), and A-312 impellers) in the mixing of hardwood bleached kraft pulp suspensions with mass concentration of $3\%$. They reported that the Maxflo impeller showed better performance compared to the other three impellers.
Pimenova and Hanley (2003) measured the viscosities of corn stover using a helical ribbon impeller viscometer. Corn stover suspensions of 5, 10, 20, and 30 wt% were used in their experiments. The viscosities of the corn stover suspensions were determined for concentrations up to 30 wt%. The helical impeller method was ineffective at corn stover concentrations more than 30 wt%.

Two impellers, Rushton and helical, were utilized by Zhang et al. (2010) for the simultaneous saccharification and fermentation process (SSF) under a high solids loading of pre-treated corn straw. The pre-treated corn straw contained approximately 40.0 % dry solids matter (DM), and was ground in a juice blender. The results showed that the feeding time of pre-treated corn straw using the helical impeller was at least 2 hours shorter than that using the Rushton impeller. Thus, the shorter feeding time indicated that the mixing using the helical impeller was better than that using the Rushton impeller.

1.6.1 Effect of Fiber Size

The size of fiber has a prominent effect on the mixing performance. Samaniuk et al. (2011) measured the rheological properties of concentrated lignocellulose biomass, corn stover. They observed that the yield stress increased with the fibre length. Chaussy et al. (2011) examined the rheological behavior of cellulose fiber suspensions; they also observed that the suspension viscosity increased with the fiber length. Viamajala et al. (2009) assessed the rheology of acid hydrolyzed corn stover and reported that the yield stress decreased with a decrease in fiber size. Bashir (2008) measured the rheological
properties of wheat straw slurries at different concentrations. Based on his results, the yield stress increased with the size of the wheat straw fibers. Dasari and Berson (2007) examined the rheology of the corn stover and observed that with increasing fiber size, the yield stress increased.

1.6.2 Effect of Fiber Concentration

The literature review showed that the fiber concentration has a significant effect on the rheology of fibrous suspensions. Chaussy et al. (2011) examined the rheological behavior of fiber suspensions and reported that the suspension viscosity increased with the fiber concentration. Derakhshandeh et al. (2010b) studied the flow behavior of pulp suspensions as a function of the fiber concentration and found that by increasing the fiber mass concentration, the apparent yield stress and the consistency index in the Herschel Bulkley rheological model ($K_s$) increased.

Bashir (2008) measured the rheological properties of the wheat straw slurry at different concentrations and showed that the yield stress of the slurry increased with the fiber concentration. Pimenova and Hanley (2003 and 2004) measured the rheological properties of the corn stover suspensions at different concentrations. The viscosity and the yield stress of the suspension increased as the fiber concentration increased.
1.7  **Cavern**

The formation of cavern around the impeller is a characteristic of the mixing of viscoplastic fluids with yield stress such as pulp suspensions, polymers, and ceramic pastes. This class of fluids has a relatively high apparent viscosity at low shear rates. Therefore, the region around the impeller has intensive motion while elsewhere in the mixing tank is almost stagnant (Wichterle and Wein, 1975). The presence of the stagnant zones in non-Newtonian fluids are harmful to the mixing process since it leads to poor heat and mass transfer (Amanullah, 1997). Therefore, it is important to determine the cavern size and shape in these mixing operations (Adams and Barigou, 2007).

Several techniques have been used and reported in the literature for the assessment of cavern size and shape. The most significant techniques are laser Doppler anemometry (LDA), hot-wire anemometry (HWA), ultrasonic Doppler velocimetry (UDV), positron emission particle tracking (PEPT), electrical resistance tomography (ERT) and numerical techniques such as computational fluid dynamics (CFD).

1.7.1  **Laser Doppler Anemometry (LDA)**

This technique was first developed by Yeh and Cummins in 1964. LDA is used for measuring velocity in a non-intrusive manner by using seeded particles conveyed by a fluid flow (Drain, 1980). This is based on the measurement of laser light scattered by particles that pass through a pattern of light and dark surface. LDA measures the velocity at one point or in a very small volume, which is formed by the cross section from two-laser beams (Chaouki *et al.*, 1997). Laser Doppler anemometry has been used to characterize the flow structure in stirred vessels since late 1970s (Durst *et al.*, 1976;
Drain, 1980). The earlier works on caverns, using LDA, had considerable practical value to industry (Etchells et al., 1987; Jaworski et al. 1993). However, some of the fundamental concepts and the definition of the cavern boundary based on LDA measurements (Hirata et al., 1991) require reconsideration. The spatial and temporal resolution for this technique is very high and it can cover a huge range of flow velocities (magnitude and direction). Hirata et al. (1994) measured the cavern size using LDA in a shear-thinning plastic fluid agitated by the Rushton turbine. They observed the cavern shape as a circular cylinder.

1.7.2 Ultrasonic Doppler Velocimetry (UDV)

Ultrasonic Doppler Velocimetry (UDV) is a non-invasive fluid flow measurement technique, which has been used for the measurement of fluid velocity profiles (Williams, 1986; and McClements et al., 1990). Pulsed ultrasound echography and detection of the instantaneous Doppler shift frequency are applied in UDV to measure fluid velocity (Takeda, 1991). This technique gives an exact determination of the flow curves of complex fluids such as pulp suspensions (Derakhshandeh et al., 2010).

Ein-Mozaffari et al. (2007) examined the ability of UDV to measure the cavern size in the mixing of pulp suspensions in a rectangular tank equipped with a Maxflo impeller. Hui et al. (2009) also used UDV to determine the cavern dimensions in the mixing of pulp suspensions in a cylindrical tank. The UDV probes were placed at various locations around the vessel periphery to locate the points at which the suspension velocity approached zero. In this method, the data collection and analysis are time consuming compared to ERT technique.
1.7.3 Positron Emission Particle Tracking (PEPT)

Positron emission particle tracking (PEPT) is a relatively new technique allowing the quantitative study of flow phenomena in three dimensions in opaque systems that could not be studied by optical methods such as laser Doppler anemometry (LDA). Chiti et al. (2011) showed that the PEPT technique could be used to obtain accurate velocity data throughout the entire complex three-dimensional turbulent flow field in an agitated baffled vessel. The PEPT technique was successfully employed to visualize the cavern formed during the mixing of a slurry using a 250 µm neutral density tracer (Adams et al., 2008).

1.7.4 X-Ray Technique

The X-ray technique is utilized to visualize the flow patterns in the mixing of opaque fluids. Elson and Cheesman (1986) used the X-ray technique to study the flow patterns and cavern size during the mixing of opaque fluids exhibiting yield stress. Absorption of what happens when only a fraction of the radiation passes through an absorber (a heavy metal tracer). Therefore, a number of photons are lost in the absorption process. In order to use X-ray, an absorber should be added to the mixing tank. Elson (1986) measured dimensions of the cavern created around a disc turbine impeller in the mixing of xanthan gum solutions and characterized the shape of the cavern using a right circular cylinder.
1.7.5 Electrical Resistance Tomography (ERT)

ERT is a non-invasive imaging technique that measures the distribution of conductivity within a region of interest (Mann et al., 1997). This technique has been used in several studies, such as the formation of cavern in the mixing of pseudoplastic fluids (Pakzad et al., 2008), investigation of mixing processes (Kim et al., 2006), solid-liquid filtration processes (Vlaev et al., 2000), multiphase processes like solid-liquid (Lucas et al., 1999; Recard et al., 2005), gas-liquid (Wang et al., 2000), and liquid-liquid (Kaminoyama et al., 2007).

1.7.6 Numerical Model

1.7.6.1 Computational Fluid Dynamics (CFD)

Computational fluid dynamics (CFD) is a technique to analyze a system involving fluid flow and other related phenomena through mathematical modeling based on computer programs (Hosseini et al., 2009). The CFD provides useful information regarding the impeller pumping capacity, flow pattern, and the formation of cavern around the impeller. Pakzad et al. (2008) employed CFD technique to analyze the formation of cavern around a Scaba impeller rotating in a yield-pseudoplastic fluid. The CFD results were in good agreement with the experimental data determined using the tomography technique.

Adams and Barigou (2006) studied the formation of caverns in a yield-stress fluid of the Herschel–Bulkley type and pseudo-cavern in a shear-thinning power-law fluid, both in the laminar and transitional flow regimes using a CFD model. They determined that CFD
predictions of cavern size agreed very well with experimental measurements at low Reynolds numbers.

1.8 **Cavern Mathematical Models**

Several mathematical models were developed over the years to predict the cavern size as a function of mixing conditions and fluid properties, such as spherical (Solomon *et al.*, 1981), cylindrical (Elson *et al.*, 1986 and 1988; Hirata and Aoshima, 1994 and 1996) and toroidal (Amanullah *et al.*, 1998; Wilkens *et al.*, 2005). In all cases, the models were developed for the isolated cavern that does not make contact with the vessel walls (Hui *et al.*, 2009).

For the models mentioned above, researchers considered different flow regimes inside the cavern as well as different forces (tangential and axial), and used different rheological models such as Herschel-Bulkley and Bingham plastic.

### 1.8.1 The Spherical Model

Solomon *et al.* (1981) developed a theoretical model for a spherical cavern. The basis of this model is that the shear stress equals the fluid yield stress at the cavern boundary. The model assumes that the predominant motion of the fluid within the cavern is tangential and is equivalent to the flow in an unbaffled vessel. The equation given by Solomon *et al.* (1981) is:

\[
\left( \frac{D_c}{D} \right)^3 = \left( \frac{4P_0}{\pi^3} \right) \left( \frac{N^2 D^2 \rho}{\tau_y} \right)
\] (1.10)
when \( D \leq D_C \leq T \) (Tank diameter), where \( D_C \) is the cavern diameter, \( D \) is the impeller diameter, \( P_o \) is the power number, \( N \) is the impeller speed, \( \rho \) is fluid density and \( \tau_y \) is fluid yield stress. The term \( N^2 D^2 \rho/\tau_y \) on the right hand side of the equation (1.10) is called the yield stress Reynolds number, and is usually shown as \( Re_y \) (Etchells et al., 1987).

### 1.8.2 The Cylindrical Model (Elson’s Model)

The cylindrical model was proposed by Elson et al. (1986 and 1988). The model indicates that the cubed cavern diameter ratio \( (D_C/D)^3 \) is proportional to the product of the power number and the “yield Reynolds number” as shown by equation (1.11):

\[
(D_C/D)^3 = \left[ \frac{1}{(H_c/D_c + 1/3)\pi^2} \right] \left( \frac{N^2 D^2 \rho}{\tau_y} \right) P_o \quad (1.11)
\]

where in this equation, \( D_c/D \) is dimensionless cavern diameter, \( N^2 D^2 \rho/\tau_y \) is the yield stress Reynolds number, and \( H_c \) is the cavern height, and \( P_o \) is the power number.

Amanullah et al. (1998) reported that both spherical and cylindrical models predicted the cavern diameter equally well. However, they believed that the cylindrical model was a better representation of the cavern shape.
1.8.3 The Torus-shaped Model

A mathematical (axial force) model was created by Amanullah et al. (1998). This model assumes entire momentum passed on by the impeller as the sum of both tangential and axial shear components, transmitted to the cavern boundary by the pumping action of the impeller. The equation given by Amanullah et al. (1998) is as follows:

$$\left(\frac{D_c}{D}\right)^2 = \frac{1}{\pi} N_f + \left(\frac{4P_0}{3\pi}\right)^2 \left(\frac{N^2 D^2 \rho}{\tau_y}\right)$$

where $N_f = F_a / PN^2 D^4$ is the dimensionless axial force number, $F_a$ is the axial force imparted by the impeller and $P$ is the power. This model can also be applied to the caverns generated by radial flow impellers if $N_f = 0$, as follows (Bhole and Bennington, 2010):

$$\left(\frac{D_c}{D}\right)^2 = \frac{1}{3} \left(\frac{4P_0}{\pi^2}\right) \left(\frac{N^2 D^2 \rho}{\tau_y}\right)$$

In the literature, there seems to be no study on the cavern evaluation of wheat straw suspensions. The recent and rapid development of non-intrusive ERT seems to provide an efficient tool for the analysis and control of mixing processes, especially in the case of non-Newtonian fluids (either opaque or transparent). Electrical resistance tomography (ERT), which is an emerging technology, can be the best alternative to measure the cavern size and analyze fluid flow in 2D and 3D.
1.9  **Research Objectives**

From the literature review, one can say that the information regarding mixing of wheat straw slurry is still inadequate. This study will try to employ ERT to study the mixing of this pseudoplastic fluid with axial impellers (A100, A200, and A310). The main contributions of this work are:

- To employ Electrical Resistance Tomography (ERT) to predict the cavern dimensions of the cavern formed around the impellers
- To study the effects of wheat straw slurry concentration on the cavern size
- To study the effects of wheat straw fiber size on the cavern size
- To understand the flow field generated by the A100, A200, and A310 impellers.
CHAPTER 2

Electrical Resistance Tomography (ERT)

As described in chapter 1, many techniques are available to measure the cavern size. However, those techniques have their own restrictions such as limitation in working with opaque fluids and changing the local flow field. To solve these issues, a non-intrusive technique called electrical resistance tomography (ERT) can be utilized to measure the cavern size.

ERT is a measurement technique which is used in several studies such as the investigation of mixing processes (Kim et al., 2006), examination of solid-liquid filtration processes (Vlaev et al., 2000), and also observation of multiphase processes such as solid-liquid (Lucas et al., 1999; Recard et al., 2005), gas-liquid (Wang et al., 2000) and liquid-liquid (Kaminoyama et al., 2007). This technique not only measures the mixing time but also allows observation of the dynamic of mixing for both transparent and opaque fluids. The ability of ERT to work in opaque fluids makes this technique very attractive from an industrial perspective since most of the fluids encountered in industrial mixing processes are opaque fluids such as pulp suspensions, ketchup, mayonnaise, paints, cement, pigment slurries, certain polymer and biopolymer solutions, and wastewater sludge (Ihejirika and Ein-Mozaffari, 2007).
2.1 **Principal elements of the ERT system**

The objective in electrical tomography technique is to measure electrical signals sent from sensing electrodes and to reconstruct the conducting properties of the fluid inside of the mixing vessel (William et al., 1993; Holden et al., 1998; and Tahvildarian et al., 2011).

The goal of ERT system is to obtain the resistance distribution in the domain of interest. The ERT system consists of three main components: the sensors, the data acquisition system (DAS) and the image reconstruction system.

2.1.1 **Sensing System**

Electrodes are the heart of the ERT system. They must be in continuous contact with the fluid inside the vessel. The position of the electrodes is important since the reconstruction algorithm is based on the electrodes being located at exactly defined intervals in order to outline the maximum amount of information from inside of the vessel (Kaminoyama et al., 2007). The size of the electrodes is another important factor in measuring the electric field distribution (Mann et al., 1996).

In this method, multiple electrodes are located around the wall of the mixing vessel (Zhao et al., 2008; Pakzad et al., 2008). An electrical current is applied to two adjacent electrodes and the voltages are measured between the other adjacent electrode pairs (Williams and Beck, 1995). To receive accurate measurement, the electrodes must be more conductive than the fluid (Tahvildarian et al., 2011). The electrodes, which are
located around the boundary of the vessel, make the electrical contact with the fluid inside the vessel and are connected to the data acquisition system (DAS) by co-axial cables to reduce electromagnetic noise and interference (Dickin and Wang, 1996).

Electrodes can be fabricated from gold, platinum, stainless steel, brass, or silver (Paulson et al., 1992).

2.1.2 Data Acquisition System (DAS)

A data acquisition system (DAS) is connected to the electrodes and communicates with the host image reconstruction computer.

DAS is responsible for signal measurement, filter and control, demodulation, multiplexer control, waveform generation, synchronization, and power supply (Holden et al., 1998). It is necessary to select the scheme that has a good distinguishability and high sensitivity to conductivity changes in the fluid. Figure 2.1 shows a schematic diagram of the ERT data acquisition system (DAS), made of six functional parts.

![Figure 2.1. Components of a typical data-acquisition system (Holden et al., 1998)
The digital “stir-case” generators are used to generate staircase wave. A high-speed digital to analogue converter (DAC) converts the digital pattern to analogue and subsequently filters to reduce unwanted harmonics. The major part of DAS is voltage generator. The output of this part is a sine wave voltage that is sent to a voltage-to-current convertor. Multiplexers (MUX) are necessary to share the current source and voltage measurement stages between any numbers of electrodes (Beck et al., 1993).

The data acquisition system is responsible to perform the desired measurement protocol. As can be seen in Figure 2.2, an adjacent measurement protocol is used to apply an AC current between two adjacent electrodes and to measure the voltage between all other pairs of adjacent electrodes. The AC current is then applied to the next pair of electrodes and the voltage is measured for all other electrode pairs (Barber et al., 1983).

![Figure 2.2. Data collection strategy; adjacent measurement strategy (Pakzad, 2007)](image)
2.1.3 Data Collection Strategies

There are four main strategies to examine conductivity distribution in a tank and to gain maximum information, as follow:

- Adjacent strategy
- Opposite strategy
- Diagonal strategy
- Conducting boundary strategy

2.1.3.1. The Adjacent Strategy

This strategy is used for sensors with insulating boundaries. In this strategy, current is applied through two neighbouring electrodes and the voltage differences are measured using all other pairs of neighbouring electrodes. To repeat this process, the current is applied to all other possible pairs of neighbouring electrodes. In this strategy, the total number of independent measurements \( (M) \) achieved is given by equation (2.1):

\[
M = \frac{N(N - 3)}{2}
\]

where \( N \) is number of electrodes.

This strategy entails minimal hardware to implement and image reconstruction. It is very delicate to measure error and noise, based on the non-uniformity of the current distribution and the low current density at the center of the vessel (Mann et al., 1997; Kaminoyama, 2005).
2.1.3.2. The Opposite Strategy

In this strategy, current is applied through diametrically opposed electrodes. The voltage reference is that to the electrode adjacent to the current-injecting electrode. The voltages are measured with respect to the reference, at all electrodes except the current-injecting ones. The whole process is repeated in the clockwise direction until all independent measurements have been made. In this case, the total number of independent measurements $M$ is calculated as follows (Viergever and Todd-Pokropek, 1988):

$$M = \frac{N}{4} \left( \frac{3N}{2} - 1 \right)$$

(2.2)

Compared to the adjacent strategy, the opposite strategy is less sensitive to conductivity changes at the boundary because most of the current runs through the central part of the region (Hua et al., 1993). The opposite strategy has less image resolution than the adjacent strategy, due to the reduced number of independent current projections (Abdullah, 1993).

2.1.3.3. The Diagonal Strategy

In this strategy, a current is applied between electrodes separated by large dimensions. Electrodes 1 and 2 are fixed as the current reference and the voltage reference, respectively. Then, the current is applied to electrodes 3, 5, 7, etc., and the voltage is measured from electrodes to the left of electrode number 2. Then the current reference and voltage reference are changed to electrode 4 and electrode 3, respectively. Sending
current through electrodes 2, 6, 8, etc., the voltage is measured on all other electrodes except the current-injecting ones. This strategy, compared with the adjacent strategy, has a good sensitivity over the entire vessel and gives better quality (Hua et al., 1993).

### 2.1.3.4. The Conducting Boundary Strategy

In this strategy, both current and voltage are used between two electrodes. The main benefit of this strategy is its low common-mode voltage component. The large surface area of the conducting boundary is used as the current sink to reduce the common-mode voltage across the electrodes doing the measurement (Gisser et al., 1987).

The common-mode voltage for conducting boundary strategy is greatly reduced compared with that of the adjacent strategy (Dickin and Wang, 1996).

### 2.1.3 Image Reconstruction System

The adjacent strategy provides 104 individual voltage measurements for each plane with 16 electrodes according to the equation \( n_e (n_e-3)/2 \), where \( n_e \) is the number of electrodes per plane. Eventually, the DAS communicates the quantitative data to the host image reconstruction computer, where data are processed using a suitable image reconstruction algorithm. An image reconstruction algorithm is applied to determine the interior distribution of the resistance in the process vessel after gaining the measurements from a set of electrodes sitting on the border of a vessel (Pinheiro et al., 1999; Mann et al., 1996). There are two types of algorithms: non-iterative and iterative. A non-iterative
image reconstruction algorithm (Linear Back Projection-LBP) is used to convert a voltage measurement to conductivity values of each plane (Barber and Brown, 1984). The linear back projection algorithm, compared to an iterative image reconstruction algorithm, has a low computational requirement (Wang, 2002). The iterative algorithm has high computational requirement and is too slow for real-time image reconstruction compared to the non-iterative algorithm (Madupu et al., 2005).

The P2000 system (Industrial Tomography Systems-ITS, Manchester, UK), used in this study, comes with a qualitative, non-iterative algorithm on linear back-projection.
CHAPTER 3

EXPERIMENTAL SETUP AND PROCEDURE

3.1 Material and Methods

In this study, we assessed the mixing of aqueous wheat straw slurries of 5 wt%, 7 wt%, and 10 wt% concentration. Wheat straw was generously donated by the Ontario Schomberg farm. In order to study the effect of the fiber length, two sizes (≤ 2 mm and (8 mm ± 0.014 mm) of the wheat straw were prepared. The Cutting Mill SM 100 (Master Craft, United States) grinded the wheat straw to ≤ 2 mm. Scissors were used to cut the wheat straw to 8 mm. During the experiments, the tank was filled with tap water to a height (H) of 400 mm.

For each test, the required amount of the wheat straw was loaded into the mixing vessel and the tap water was added to reach the desired slurry height (400 mm) inside the tank.

In this study, experiments were conducted using three impellers at many impeller speeds, and for two fiber sizes. Table 3.1 summarizes the operating conditions for all experiments conducted in this study.
Table 3.1. Experimental conditions

|                          |                                   |
|--------------------------|-----------------------------------|
| **Impeller Speed** N rpm | 30 - 120 rpm                      |
| Impeller Type            | A100, A200, and A310              |
| Fiber Size               | \( \leq 2 \text{ mm and } 8 \text{ mm} \) |
| Slurry Concentration     | 5 wt\%, 7 wt\%, 10 wt\%          |

3.2 Experimental Setup

Figure 3.1 shows the schematic diagram of the experimental setup utilized in this study.

Mixing system used in this study consists of a flat-bottomed cylindrical tank with a diameter of 400 mm and a height of 600 mm. The tank was equipped with two equally spaced baffles with a width of 30 mm.

The slurry height \( H \) in the tank was 400 mm. The tank consisted of four tomography sensor planes. The planes were 86 mm apart from each other with the bottom plane 74 mm from the bottom of the tank. The planes were numbered from top \( (P1) \) to bottom \( (P4) \). Each plane had 16 stainless steel electrodes, which were located equidistantly on the periphery of the vessel. The height, width, and thickness of the electrodes were 20 mm, 30 mm, and 1 mm, respectively. Each electrode was connected to the electrical resistance tomography system (Industrial Tomography Systems, Manchester, UK), which was connected to a computer for the image reconstruction.

---

1 The sample of detailed table and explanation regarding the experiments are placed in Appendix A.
The mixing tank was equipped with a top-entering impeller driven by a 2-hp motor. The impeller rotational speed was varied using a variable frequency drive. The impeller torque and speed were measured using a rotary torque meter (Staiger Mohilo, Germany) and a tachometer, respectively. In this study three impellers were used (A100, A200, A310), each with a 180 mm diameter \((D)\). Each impeller was located on plane \(P3\) with an off-bottom clearance of 160 mm.

**Figure 3.1.** Schematic diagram of the experimental setup used in this study (all units in mm)
A100 (marine propeller) is a three rounded and twisted blade impeller with a 45° blade angle (Figure 3.2). A100 impeller produces an axial flow directed to the bottom of the vessel and has a high discharge capacity with low head.

![Figure 3.2. Impeller A100 used in this study](image)

A200 (pitched blade turbine) is a four blade impeller with a 45° blade angle (Figure 3.3). This impeller generates an axial-flow pattern. Normally this impeller is used for low to medium viscosity flow.

![Figure 3.3. Impeller A200 used in this study](image)
A310 is a 45° blade angle with three twisted blade impeller (Figure 3.4). The blade tip of this impeller creates a consistent velocity across the entire discharge area. This impeller is very useful for low viscosity fluids.

![Figure 3.4. Impeller A310 used in this study](image)

### 3.2.1 Power Measurements

The power input to the impeller \( P \) was obtained from torque \( M \) and impeller rotational speed \( N \) measurements using:

\[
P = 2\pi NM
\]

(3.1)

Impeller torque and speed were measured using a torque sensor (Staiger Mohilo, Germany). The bearing friction was measured by operating the system with an empty vessel. This friction torque was subtracted from all subsequent measured torques.
3.2.2 Using tomography to measure the cavern size

In this study, electrical resistance tomography (ERT) was utilized to measure the cavern size. To achieve this goal, 30 mL of 20% saline solution (as a tracer) was injected into the wheat straw slurry near the impeller blade using a plastic syringe after the mixing system reached steady-state conditions. The injection took about 2-3 s for all experiments. A conductivity meter (PC10 portable meter, Oakton Instruments, USA) was employed to take an individual conductivity measurement before each experiment run to make sure that the conductivity of the wheat straw slurries were the same for all experiments. The size of the cavern was measured after the injection once the cavern size remained unchanged. The cavern boundary was determined as a position at which the tracer concentration was zero. Each tomography test was repeated three times. The standard deviation was found to be 0.56 % for cavern dimensions.

Colors in tomograms display the dispersion of the tracer in the vessel (Fig 3.5). The dark blue color in these tomograms demonstrates low-conductivity zones, which represents lower tracer concentration. The red color in the tomograms shows the high-conductivity regions, which indicates the higher tracer concentration in those zones. At the boundary of the cavern, the concentration of the tracer was zero. This means that the conductivity of the slurry at the cavern boundary was equal to the conductivity of the slurry before the injection of the tracer.

The 2D tomogram shows that the tracer injected near the impeller blade remained within the cavern and no tracer was found in the surrounding.
Figure 3.5. Tomogram of the cavern formation for 10 wt% wheat straw slurries (≤ 2 mm) agitated by the A100 impeller at 60 rpm

3.3 **Xanthan Gum as a Reference to Check the Accuracy of the Tomography Measurements**

In this study, an aqueous 0.5 wt% xanthan gum solution was used as a reference to check the accuracy of the ERT measurements. To prepare xanthan gum solutions, 2.5 kg of the xanthan gum powder was added slowly to water in the tank while the A310 impeller was working.

ERT was able to image the cavern formed around the impeller at 0.5 wt% xanthan gum solution once 30 ml of 10% saline solution tracer was injected near the impeller blade. Measurements of cavern were collected from the four planes of electrodes until the cavern size remained unchanged. These tomography images were then used to measure the cavern diameter ($D_c$) and cavern height ($H_c$), using 2D and 3D images respectively. Figure 3.6 shows the formation of cavern visualized using the two dimensional (2D)
tomograms generated after the injection of the saline tracer in the mixing of 0.5 wt% xanthan gum solution using A310 impeller. As shown in the figure, the impeller was located on the plane $P3$.

Figure 3.6. Cavern formation in agitation of 0.5 wt% xanthan gum solution at 30 rpm agitated by A310 impeller

The cavern dimensions obtained from the tomography measurements were then substituted into the cylindrical model proposed by Elson (Equation 1.11), and the yield stress for 0.5 wt% xanthan gum solution was calculated. As shown in Table 3.2, the yield stress estimated using the tomography images was in good agreement with that measured
using a Bohlin CVOR Rheometer 150 (Malvern Instruments, USA) as reported by Pakzad (2007). The relative error between the estimated values obtained from the rheometry and the tomography techniques was 0.61%.

Table 3.2. Comparison between the yield stresses measured using ERT and rheometer

| Xanthan gum yield stress (Pa) measured by Rheometer | Xanthan gum yield Stress (Pa) measured using ERT |
|--------------------------------------------------|------------------------------------------------|
| 1.79 (Pakzad, 2007)                              | 1.80±0.01                                      |
CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the experimental results are presented and discussed for the impeller torque, power consumption, yield stress, and cavern formation in the mixing of wheat straw slurries as a function of the impeller type, impeller speed, slurry concentration, and fiber size.

4.1 Torque and Power Measurements

4.1.1 Evaluation of the Torque Sensor Precision

The impeller torque was measured using a rotary torque meter (Staiger Mohilo, Germany) as a function of the impeller rotational speed. Each test was repeated 3 times and the standard deviation for the torque measurements was calculated using the following equation:

\[ \sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (M_i - \bar{M})^2} \]  

(4.1)

where \( N \) is the number of measurements, \( M_i \) is the torque measurement for sample i and \( \bar{M} \) is the mean value of the torque measurements.
Figure 4.1 shows the torque versus the impeller speed as a function of the slurry concentration for fiber $\leq 2$ mm. The figure shows spread of the torque about the mean value as indicated by the error bar obtained using the standard deviation. Based on the error bars, we can see that the errors were small enough ($\sigma < 0.01$) to be acceptable.

**Figure 4.1.** Torque versus impeller speed for 5, 7, and 10 wt% wheat straw ($\leq 2$ mm) agitated by A310 impeller

Figure 4.2 depicts the torque versus the impeller speed as a function of the slurry concentration for fibers of 8 mm. By increasing the fiber concentration and fiber size, the impeller torque increased. When fiber size and fiber concentration increased the strength
of the slurry networks increased as well. Therefore, the yield stress of the slurry increased and it caused an increase of the impeller torque.

![Torque versus impeller speed for 5, 7 and 10 wt% wheat straw (8 mm) agitated by A310 Impeller](image)

**Figure 4.2.** Torque versus impeller speed for 5, 7 and 10 wt% wheat straw (8 mm) agitated by A310 Impeller

As shown in Figure 4.3, for the same size and concentration of wheat straw at 80 rpm, impeller A100 shows highest torque compared to impellers A310 and A200. Impeller A200 has the lowest torque.
Figure 4.3. Torque versus impeller speed for 7 wt% wheat straw (≤ 2 mm) agitated by A100, A200 and A310 impellers
4.2 Cavern Formation in Mixing Wheat Straw Slurries

Several experimental methods have been employed to investigate the formation of cavern as discussed in literature review; each of these techniques has its own restrictions. In order to prevail over these limitations, electrical resistance tomography, which is an emerging technology, can be the best alternative to measure the cavern size and analyze fluid flow in 2D and 3D in this study.

4.2.1 Using ERT to Measure the Cavern Diameter and Height

In this study, the size of cavern formed around the impeller in the mixing of the wheat straw slurries was measured as a function of the impeller type and speed for two sizes of wheat straw fibres (≤ 2 mm and 8 ± 0.014 mm) with 5, 7, and 10 wt% fiber through the tomography images.

Figure 4.4 illustrates the formation of cavern based on the conductivity distribution visualized using the two dimensional (2D) tomograms generated after the injection of the saline tracer in the mixing of 10 wt% of wheat straw slurry (≤ 2 mm) agitated by A310 impeller at 60 rpm. The 2D tomograms provided the diameter of the cavern.
Figure 4.4. Cavern formation in 10 wt% wheat straw slurry (≤ 2 mm) agitated by A310 impeller at 60 rpm

The 3D images provided the height of the cavern. The cavern height was measured using the vertical slice images as shown in Figure 4.5.
Figure 4.5. Cavern height in agitation of 10 wt% wheat straw suspension (≤ 2 mm)
agitated by A310 impeller using 3D tomogram at 60 rpm.
4.2.2 Dimensionless Cavern Diameter \((D_c/D)\)

Various models have been recommended in the literature (Solomon et al., 1981; Elson et al., 1986 and 1988) to estimate the dimensionless cavern diameter \((D_c/D)\) versus the product of two dimensionless groups of \(P_o\) and \(Re_y = \rho N^2 D^2/\tau_y\). As mentioned before, \(Dc\) is the cavern diameter, \(D\) is the impeller diameter, \(P_o\) is the impeller power number, and \(Re_y\) is the yield stress Reynolds number. According to Elson’s model equation (1.11), a plot of the dimensionless cavern diameter, \(Dc/D\), versus \(P_o Re_y\) is a straight line with a slope of 0.33 in log-log scale. This model defines the formation of a cylindrical cavern centered upon the impeller. In the following sections, the cavern dimensions measured using tomography technique at different operating conditions were fitted to Elson’s cylindrical model.

4.2.2.1 Effect of Wheat Straw Concentration on the Cavern Dimensions

Figure 4.6 shows the effect of wheat straw concentration on the cavern diameter when a wheat straw slurry of \(\leq 2\) mm fiber size was agitated by the A200 impeller at 70 rpm. It shows the cavern diameter of 32 cm, 28 cm and 21 cm for wheat straw concentration of 5 wt\%, 7 wt\%, and 10 wt\% respectively.

The largest cavern diameter was measured for 5 wt\% wheat straw slurries. This finding is in agreement with those reported in the literature. For instance, Pakzad et al. (2008) showed that by increasing the yield stress, the cavern diameter decreased. In fact, the presence of the yield stress leads to the formation of stagnant regions outside the cavern in which the shear stress falls below the slurry yield stress.
Figure 4.6. The effect of wheat straw (≤ 2 mm) concentration on the cavern diameter agitated by the A200 impeller at 70 rpm for (a) 5 wt%, (b) 7 wt% and (c) 10 wt%.

Figures 4.7 to 4.9 show the dimensionless cavern diameter versus the product of $P_o$ (power number) and $\rho N^2 D^2/\tau_y$ (Reynolds yield stress) for the three impellers used in this study for all three concentrations. The slopes of the $D_c/D$ versus $P_o Re_\tau$ for A100, A200, and A310 impellers were 0.24, 0.26, and 0.29, respectively. These slopes are lower than that expected from Elson’s model (0.33). However, our results for these three axial-flow impellers were in good agreement with those reported in the literature. For example, Patel et al. (2012) reported a value of 0.23 for A310 while Saeed et al. (2008) reported a value of 0.24 for three axial-flow impellers (i.e. A200, A100, and A310 impellers) in mixing of xanthan gum solutions.
Figure 4.7. Dimensionless cavern diameter versus dimensionless stress ($P_oRe_y$) for 5, 7, and 10 wt% wheat straw slurry ($\leq 2$ mm) agitated by the A100 impeller.
Figure 4.8. Dimensionless cavern diameter versus dimensionless stress ($P_o\cdot Re_y$) for 5, 7, and 10 wt% wheat straw slurry ($\leq 2$ mm) agitated by the A200 impeller.
Figure 4.9. Dimensionless cavern diameter versus dimensionless stress ($P_o\cdot Re$) for 5, 7, and 10 wt% wheat straw slurry ($\leq 2$ mm) agitated by the A310 impeller

4.2.3 Cavern Height to Diameter Ratio ($H_c/D_c$)

Before the cavern touches the wall, the ratio of cavern height to cavern diameter ($H_c/D_c$) remains almost constant versus the impeller speed for each type of impellers (Figures 4.10 to 4.15 show ($H_c/D_c$)), when mixing of 5, 7, and 10 wt% wheat straw slurries of fiber sizes $\leq 2$ mm and 8 mm. It can be seen that the cavern height to cavern diameter ratios were constant at 0.78, 0.57, and 0.82 for the A100, A200, and A310 impellers, respectively. These results were in good agreement with those reported in the literature for these three types of impellers as demonstrated in Table 4.1.
Figure 4.10. $H_c/D_c$ versus the impeller speed for the A100 impeller, at 5, 7 and 10 wt% wheat straw slurries ($\leq 2$ mm)
Figure 4.11. \(H_c/D_c\) versus the impeller speed for the A200 impeller, at 5, 7 and 10 wt\% wheat straw slurries (≤ 2 mm)
Figure 4.12. $H_c/D_c$ versus the impeller speed for the A310 impeller, at 5, 7 and 10 wt% wheat straw slurries ($\leq 2$ mm)
Figure 4.13. $H_c/D_c$ versus the impeller speed for the A100 impeller, at 5, 7 and 10 wt\% wheat straw slurries (8 mm)
Figure 4.14. $H_c/D_c$ versus impeller speed for the A200 impeller, at 5, 7, and 10 wt% wheat straw slurries (8 mm)
\[ H_c/D_c = 0.82 \]

**Figure 4.15.** \( H_c/D_c \) versus impeller speed for the A310 impeller, at 5, 7, and 10 wt\% wheat straw slurries (8 mm)
**Table 4.1.** $H_c/D_c$ for the A310, A100, and A200 in agitation of non-Newtonian fluids

| Impeller type | Reference                     | $H_c/D_c$ |
|--------------|-------------------------------|-----------|
| A100         | Saeed *et al.*, 2008          | 0.75      |
|              | Elson, 1988                   |           |
|              | Solmon *et al.*, 1981         |           |
| A200         | Saeed *et al.*, 2008          | 0.55      |
|              | Elson, 1988                   |           |
|              | Solmon *et al.*, 1981         |           |
| A310         | Patel, 2012                   | 0.78-0.8  |
|              | Saeed *et al.*, 2008          |           |
|              | Elson, 1988                   |           |
|              | Solmon *et al.*, 1981         |           |

### 4.3 Effect of Impeller Speed on Cavern Diameter

In order to see the effect of impeller speed on the cavern diameter, two illustrative tomograms (as a sample of obtained tomograms) are shown in Figure 4.16. This figure shows the effect of impeller speed when it was varied from 70 rpm to 95 rpm, on the diameter of the cavern for 10 wt% wheat straw slurry ($\leq 2$ mm) agitated by A100 impeller. These images were obtained from tomography plane 3, which was located at the impeller position. These tomograms clearly show that the diameter of the cavern increased when the impeller speed increased to 95 rpm. Similar trends were also observed for other cases.
(a) Impeller speed: 70 rpm  (b) Impeller speed: 95 rpm

**Figure 4.16.** Effect of impeller speed on the diameter of the cavern for 10 wt% wheat straw slurries (≤ 2 mm) agitated by the A100 impeller for (a) 70 rpm and (b) 95 rpm

4.4  **Effect of Impeller Type on Cavern Diameter**

Figure 4.17 shows tomograms obtained from plane 3 for the A310, A200, and A100 at the rotational speed of 40 rpm and 7 wt% wheat straw slurry (≤ 2 mm). The results show the cavern diameter of 18.5 cm, 21 cm, and 21.5 cm for A310, A200, and A100, respectively.

The larger cavern diameter created by the A100 impeller and A310 resulted in the smallest cavern.
Figure 4.17. Tomograms obtained from plane 3 at 7 wt% wheat straw slurries (≤ 2 mm) for (a) A100, (b) A200 and (c) A310, at 40 rpm

4.5 Predicted Yield Stress of Wheat Straw Slurries Using Tomography Data

The yield stress of wheat straw suspensions for concentrations of 5, 7, 10 wt% and two fiber sizes were estimated using the cylindrical model of Elson (Equation 1.11). The term \(N^2D^2\rho/\tau_y\) on the right hand side of Equation (1.11) refers to the yield stress Reynolds number (\(Re_y\)) (Etchells et al., 1987).

As explained in the previous section, the diameter and height of the cavern were determined through ERT. These dimensions as well as the impeller speed and the power number were substituted into Equation (4.2) to obtain the slurry yield stress. The yield stresses calculated using three impellers at three concentrations (5, 7, and 10 wt%) for two fiber sizes (≤ 2 mm and 8 mm) are listed in Tables 4.2 and 4.3. It can be seen that the average yield stress for the fiber size of ≤ 2 mm at 5, 7, and 10 wt% were 1.3, 4.2, and
14.8 Pa, respectively. For the fiber size of 8 mm, the average yield stress was 3.4, 6.8, and 16.7 Pa for 5, 7, and 10 wt% concentrations, respectively.

**Table 4.2.** Yield stress of the wheat straw slurries for the fiber size of ≤ 2 mm calculated from cavern diameter and height

| Impeller type | [Wheat straw suspension] | Yield Stress (Pa) |
|---------------|--------------------------|-------------------|
| A100 5 wt%    | 1.41 ± 0.05              |                   |
| 7 wt%         | 4.05 ± 0.03              |                   |
| 10 wt%        | 15.07 ± 0.04             |                   |
| A200 5 wt%    | 1.35 ± 0.04              |                   |
| 7 wt%         | 4.13 ± 0.04              |                   |
| 10 wt%        | 14.70 ± 0.08             |                   |
| A310 5 wt%    | 1.19 ± 0.05              |                   |
| 7 wt%         | 4.37 ± 0.07              |                   |
| 10 wt%        | 14.68 ± 0.07             |                   |
Table 4.3. Yield stress of the wheat straw slurries for the fiber size of 8 mm calculated from cavern diameter and height

| Impeller type | [Wheat straw suspension] | Yield Stress (Pa) |
|---------------|--------------------------|-------------------|
| A100          | 5 wt%                    | 3.45±0.06         |
|               | 7 wt%                    | 6.76±0.05         |
|               | 10 wt%                   | 16.58±0.05        |
| A200          | 5 wt%                    | 3.46±0.09         |
|               | 7 wt%                    | 6.46±0.05         |
|               | 10 wt%                   | 16.68±0.29        |
| A310          | 5 wt%                    | 3.19±0.05         |
|               | 7 wt%                    | 6.61±0.03         |
|               | 10 wt%                   | 17.02±0.04        |

4.5.1 Effect of Fiber Length on Yield Stress

As shown in Tables 4.5 and 4.6, the yield stress of the wheat straw slurry with a fiber size of 8 mm was more than that for a fibre size of ≤ 2 mm, at all three concentrations. When the fiber size increases the fibrous network will be stronger, thus the yield stress will increase.

This result is in agreement with those reported in the literature. Samaniuk et al. (2011) observed that the yield stress of concentrated lignocellulosic biomass (corn stover) increased with particle length. In another study, Viamajala et al. (2009) reported that acid
hydrolyzed corn stover slurries behaved like yield stress fluids, at various concentrations, and that with increasing particle size, the yield stress increased. Bashir (2008) measured the rheological properties of wheat straw suspension at concentrations between 5.0-20.0 wt%. The yield stress was found to increase with the size of the wheat straw fibers. Rosgaard et al. (2007) investigated the effect of solids content and enzymatic hydrolysis on the apparent viscosity of barley straw biomass slurries, with solids fraction varying from 5 wt% to 15 wt%. They showed that the apparent viscosity increased with solids fraction. Pimenova and Hanley (2003 and 2004) measured the apparent rheological properties of corn stover suspensions of 5, 10, 20, and 30 wt% and showed that the viscosity and the yield stress of the suspensions enhanced as the fiber size increased.

### 4.5.2 Effect of Fiber Mass Concentration on Yield Stress

Several studies have been conducted to relate the yield stress ($\tau_y$) as a function of the mass concentration ($C_m$) in both pulp and biomass suspensions (Bennington et al., 1990; Dalpke and Kerekes, 2005; Knutsen and Liberatore, 2009; Stickel et al., 2009; Hue et al., 2009).

As was shown in Tables 4.5 and 4.6, by increasing fiber concentration, due to the fiber network strength the amount of yield stress is increased, which is in good agreement with Chaussy et al. (2011), Derakhshandeh et al. (2010b), and Bashir (2008) studies.
4.6 **Power Number versus Yield Stress Reynolds Number**

Typically, the power consumption of an impeller is presented using the power curve: power number versus Reynolds number. Since, in this study, we measured the yield stress of the wheat straw slurry, the yield stress Reynolds number (Equation 4.3), which is a function of the yield stress, was employed instead of Reynolds number.

\[
Re_y = \left( \frac{N^2 D^2 \rho}{\tau_y} \right)
\]  

(4.3)

Figures 4.18, 4.19, and 4.20 illustrate the power number versus the yield stress Reynolds number for A100, A200, and A310 impellers.

![Figure 4.18. Power number versus yield stress Reynolds number for the A100 impeller and the fiber size of ≤ 2 mm](image)

**Figure 4.18.** Power number versus yield stress Reynolds number for the A100 impeller and the fiber size of ≤ 2 mm
Figure 4.19. Power number versus yield stress Reynolds number for the A200 impeller and the fiber size of \( \leq 2 \) mm
Figure 4.20. Power number versus yield stress Reynolds number for the A310 impeller and the fiber size of ≤2 mm

These data show that the power number of the A100 impeller was the highest among the impellers employed in this study. These figures also show that the power number increased while the concentration of wheat straw slurry increased. It should be mentioned that yield stress Reynolds number decreased when the wheat straw slurry concentration increased.
CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Electrical resistance tomography (ERT) was used to measure the cavern diameter (2D) and cavern height (3D) in the mixing of non-Newtonian wheat straw slurries with yield stress, for the A100, A200, and A310 impellers.

In this study for the first time wheat straw slurry yield stress was estimated from the cavern size obtained from ERT tomograms for three concentrations of wheat straw slurry (5, 7, and 10 wt%) and two sizes of fiber (≤ 2 mm 8 ± 0.014 mm) with three types of axial impellers (A100, A200, and A310). The average yield stress of wheat straw slurries at 5, 7, and 10 wt% were 1.31 Pa, 4.2 Pa, and 14.8 Pa, respectively for the fiber size of ≤ 2 mm and were 3.4 Pa, 6.8 Pa, and 16.7 Pa, respectively for the fiber size of 8 mm. As expected, these values were irrespective of the type of impeller. As the slurry concentration and fiber size increased, the yield stress of the slurry also increased due to a stronger fibrous network structure.
Analysis using the 2D images at different slurry concentrations showed that the diameter of the cavern increased when the impeller speed increased for the three impellers, and that the highest ratio of the cavern height to the cavern diameter was achieved by using the A310 impeller.

5.2 **Recommendations for Future Work**

The results from experimental work in this study drew attention to areas for future considerations, as follows:

- Using computational fluid dynamics (CFD) to study the mixing of wheat straw slurries.

- Studying the performance of other mixing systems (e.g. the combination of a radial and an axial flow impellers, and the combination of a close clearance impeller and a central impeller) in the mixing of wheat straw slurries.

- Studying the rheological behavior of wheat straw slurry using the rheometry techniques.

- Exploring the mixing of other types of agricultural wastes used for the production of bioethanol.

- Assessing the effect of pre-treatment on the mixing of agricultural wastes.
## Nomenclature

| Symbol | Description |
|--------|-------------|
| $C_m$  | Mass concentration |
| $D$    | Impeller diameter (m) |
| $D_c$  | Cavern diameter (m) |
| $F_a$  | Axial Force (N m) |
| $g$    | Gravitational acceleration, (m/s$^2$) |
| $H$    | Fluid height in the vessel (m) |
| $H_c$  | Cavern height (m) |
| $K$    | Consistency index (Pa s$^n$) |
| $k_S$  | Metzner-Otto constant (-) |
| $M$    | Torque (N m) |
| $n$    | Power-law index (-) |
| $N$    | Impeller rotational speed (s$^{-1}$) |
| $N_f$  | Axial force number |
| $n_e$  | Number of electrodes (-) |
| $P$    | Power (W) |
| $P_o$  | Power number (-) |
| $P1$-$P4$ | Plane number (-) |
| $T$    | Tank diameter (m) |
| $V_c$  | Cavern volume (m$^3$) |
Greek Letters

\( \dot{\gamma} \)  
Shear rate \((s^{-1})\)

\( \dot{\gamma}_{avg} \)  
Average shear rate \((s^{-1})\)

\( \eta \)  
Apparent viscosity \((Pa\ s)\)

\( \rho \)  
Fluid density \((kg\ m^{-3})\)

\( \tau_s \)  
Shear stress \((Pa)\)

\( \tau_y \)  
Fluid yield stress \((Pa)\)

\( \mu \)  
Fluid viscosity \((Pa\ S)\)

\( \sigma_{mc} \)  
Conductivity \((mS/cm)\)

Abbreviations

2D  Two-dimensions

3D  Three-dimensions

ADC  Analogue to digital converter

AFEX  Ammonia fiber expansion

CFD  Computational fluid dynamics

CPU  Central processing unit

DAC  Digital analogue converter

DAS  Data acquisition system

DM  Dry solids matter

DP  Degree of polymerization

ERT  Electrical resistance tomography
LDA  Laser Doppler anemometer  
HWA  Hotwired anemometer  
MUX  Multiplexer  
PEPT  Positron emission particle tracking  
SSF  Simultaneous saccharification and fermentation  
UDV  Ultrasonic Doppler Velocimetry  

**Dimensionless Numbers**

\( Fr \)  Froude number  
\( P_o \)  Power number  
\( Re \)  Reynolds number
Appendix

Sample of Yield Stress Calculations for a 5 wt% Wheat Straw Slurry

Cavern dimensions were measured using ERT. For each impeller speed, the experiment was repeated 3 times. Table A.1 and A.2 show the average of cavern diameter and height measurement for each speed.

**Table A.1.** Cavern diameter average calculated for 5 wt% wheat straw slurry (≤ 2 mm) agitated by A200 impeller at 30, 55 and 70 rpm

| Impeller Speed (rpm) | Cavern Diameter (m) (Run 1) | Cavern Diameter (m) (Run 2) | Cavern Diameter (m) (Run 3) | Cavern Diameter (m) (Average) |
|----------------------|-----------------------------|-----------------------------|-----------------------------|-------------------------------|
| 30                   | 0.26                        | 0.25                        | 0.25                        | 0.25 ± 0.005                  |
| 55                   | 0.29                        | 0.29                        | 0.30                        | 0.29 ± 0.005                  |
| 70                   | 0.32                        | 0.31                        | 0.33                        | 0.32 ± 0.01                   |

**Table A.2.** Cavern height average calculated for 5 wt% wheat straw slurry (≤ 2 mm) agitated by A200 impeller at 30, 55 and 70 rpm

| Impeller Speed (rpm) | Cavern Height (m) (Run 1) | Cavern Height (m) (Run 2) | Cavern Height (m) (Run 3) | Cavern Height (m) (Average) |
|----------------------|---------------------------|---------------------------|---------------------------|-------------------------------|
| 30                   | 0.14                      | 0.15                      | 0.14                      | 0.14 ± 0.005                  |
| 55                   | 0.16                      | 0.16                      | 0.17                      | 0.16 ± 0.005                  |
| 70                   | 0.18                      | 0.17                      | 0.19                      | 0.18 ± 0.01                   |
Yield stress values, as shown in Table A.3., were calculated according to the steps presented after Table A.3.

**Table A.3.** Yield stress of 5 wt% wheat straw slurries for fiber size \( \leq 2 \text{ mm} \), agitated by A200 impeller at 30, 55 and 70 rpm

| \( N \) (rpm) | \( N \) (rps) | \( M \) (N.m) | \( P \) (J/s) | \( D \) (m) | \( \rho \) (kg/m\(^3\)) | \( P_0 \) (-) | \( D_e \) (m) | \( H_e \) (m) | \( \tau_y \) (Pa) | \( \tau_{y,\text{ave}} \) (Pa) |
|----------------|---------------|----------------|--------------|------------|-----------------|--------------|--------------|--------------|----------------|----------------|
| 30             | 0.500         | 0.031          | 0.097        | 0.18       | 1000            | 4.123        | 0.250        | 0.143        | 1.395          | 1.350 ± 0.04   |
| 55             | 0.916         | 0.046          | 0.264        | 0.18       | 1000            | 1.820        | 0.290        | 0.164        | 1.325          |               |
| 70             | 1.166         | 0.062          | 0.454        | 0.18       | 1000            | 1.514        | 0.320        | 0.183        | 1.330          |               |

**Step by step calculations for \( N = 30 \text{ rpm} \):**

1. Value of “\( N \)” (impeller speed) was measured using a tachometer; the value was read in revolutions per minute (rpm) and then converted to revolutions per second (rps). For \( N = 30 \text{ rpm} \), \( N = 30/60 = 0.5 \text{ rps} \)

2. Value of “\( M \)” (impeller torque) was measured using a torque meter in N.m. At \( N = 30 \text{ rpm} \), \( M \) was read as 0.031 N.m

3. Value of \( P \) (impeller power) was calculated using equation (3.1)

\[
P = 2\pi N M = 2 \times 3.14 \times 0.5 \times 0.031 = 0.097 \text{ J/s}
\]

4. Value of “\( D \)” (impeller diameter) for A200 was \( D = 0.18 \text{ m} \)

5. The density of the slurry was assumed constant at \( \rho = 1000 \text{ kg/m}^3 \)

6. \( P_0 \) (power number) was calculated using equation (1.5)

\[
P_0 = \frac{P}{\rho N^2 D^5} = \frac{0.097}{1000 \times 0.5^3 \times 0.18^5} = 4.123
\]
7. Value of yield stress was calculated by re-arranging equation (1.11)

\[
\left(\frac{D_c}{D}\right)^3 = \left[\frac{1}{\left(\frac{H_c}{D_c}\right)^{1/3}\pi^2}\right] \left(\frac{N^2D^2\rho}{\tau_y} \right) P_0 ,
\]

to give

\[
\tau_y = \frac{N^2D^2\rho P_0}{\left(\frac{H_c}{D_c}\right)^{1/3}\pi^2} \left(\frac{D}{D_c}\right)^3 = \frac{0.5^2 \times 0.18^2 \times 1000 \times 4.123}{\left(\frac{0.144}{0.250}\right)^{1/3}\pi^2} \left(\frac{0.18}{0.250}\right)^3 = 1.395 \text{ Pa}
\]

8. Standard deviation for the yield stress is calculated using

\[
\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\tau_{y,i} - \overline{\tau}_y)^2}
\]

where \(N\) is the number of measurements, \(\tau_{y,i}\) is the yield stress measurement for sample \(i\) and \(\overline{\tau}_y\) is the mean value of the yield stress measurements. So,

\[
\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\tau_{y,i} - \overline{\tau}_y)^2} = \sqrt{\frac{1}{3} \left[ (1.395 - 1.350)^2 + (1.325 - 1.350)^2 + (1.330 - 1.350)^2 \right]}
\]

\[
\sigma = \sqrt{\frac{1}{3} \left[ (0.002025) + (0.000625) + (0.000400) \right]} = \sqrt{\frac{1}{3} [0.003050]} = 0.031885 \text{ Pa}
\]

The margin of error, at 95 percent confidence level, was calculated using

\[
\pm 1.96 \frac{\sigma}{\sqrt{N}} = \pm 1.96 \left(\frac{0.031885}{\sqrt{3}}\right) = \pm 1.96 (0.018409) = \pm 0.04 \text{ Pa}
\]
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