Separation of Fibre and Core from Decorticated Hemp

by

Shahnaz Parvin

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Department of Biosystems Engineering
University of Manitoba
Winnipeg

ABSTRACT

Separation of fibre from decorticated hemp mixture is important for fibre being use in diverse applications. The main goal of the study was to develop effective and efficient processes to obtain clean hemp fibre. Aerodynamic properties of hemp fibre and core were measured using aerodynamic method to separate fibre and core. Carding method was also used to obtain clean fibre under three different carding durations and five different feeding masses. The third method was the floatation method using water for separating fibre and core.

For aerodynamic properties, fibre showed lower terminal velocity and higher drag coefficient than core. The differences in terminal velocity would allow fibres to be separated from core. Using the carding method, the fibre purity was increased from 55% up to 70%. Using the floatation method, the resultant fibre purity ranged from 85 to 90%. Present study discovers some promising methods for hemp fibre cleaning.

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1. INTRODUCTION

1.1 General

Industrial hemp (*Cannabis sativa*) is one of the oldest cultivated plants in the world. Natural hemp fibres are light and durable. There have been many different textile products made of hemp fibre, and the use of hemp fibre is being expanded to papers, composites, and construction materials and many other applications. Demand for natural fibre is increasing. Most of fibre industries generally require high-quality fibres. However, existing mechanical fibre processing methods have very limited capability for producing clean hemp fibre.

Hemp fibre processing includes mainly two parts: decortications and cleaning. Decortication involves breaking process in which machines (e.g. hammer mills, roll crushers, and cutterheads) generate forces to break the bonds between fibre and core. This process is also termed as detaching (detaching fibre from hemp stem) process. The output material from breaking process is a mixture of fibre bundles, core, and fines. The mixture is further cleaned to remove cores and fines with the intention to obtain cleaner fibre. Different types of cleaning methods have been used for hemp fibre cleaning, including screeners, straw walkers, and comb shakers. But all of these machines resulted in low fibre purity (lower fibre purity means high core content in the fibre), ranging from 50 to 70% (Fürll and Hempel 2000; Baker 2009; Gratton and Chen 2004). The major problem was the fibre entanglement nature which is complex. The low fibre purity has limited applications of hemp fibre for industrial products. Therefore, it can be concluded that alternative cleaning methods are needed for hemp fibre cleaning.

In this study, three alternative cleaning methods were explored: aerodynamic, carding, and floatation methods. It was expected that fibre tangling problem would be reduced when using those methods. In an aerodynamic process, lighter particles are separated from heavier particles by air flow. Carding process removes cores by opening tangled fibres with its stripping action. Floatation process uses density difference to separate materials, with lower density material remaining afloat and higher density material being sunk. These methods can be potentially used to separate fibre and core to obtain cleaning fibre.

These methods have been used in the past for cleaning other materials. Pneumatic cleaning has been commonly used in separation processes of agricultural materials (Gorial and O'Callaghan 1990; Khoshtaghaza and Mehdizadeh 2006). Grains can be separated easily from lighter particles such as dust and chaff through pneumatic cleaning (Simonyan and Yiljep 2008). Pneumatic method can also be combined with a mechanical process to improve the effectiveness of cleaning (Hollatz and Quick 2003). Carding is one of the widely used techniques in cotton processing industries. Several researches have been conducted on cotton fibre cleaning by using carding machines. Garcia-Jaldon et al. (1998) recommended using a carding treatment to separate the single fibres from semi-retted hemp bundles. Floatation is an extensively used method for waste treatments (Pongstabodee et al. 2008). However, little has been done in using these methods for hemp fibre separation from core.

1.2 Objectives

The primary objective of the study was to experimentally study alternative methods for separation of fibre and core to improve the fibre quality, in term of its purity. More specifically, the objectives of this study were

1. to determine the aerodynamic properties of hemp fibre and core and its application on hemp fibre and core separation;
2. to investigate fibre purity as affected by carding parameters, and
3. to measure the fibre purity resulting from the floatation method.

1.3 Thesis Structure

This thesis has been structured in paper formats. A general introduction and literature review are presented in Chapters 1 and 2, respectively. Chapters 3 and 4 are the parts of the thesis written in paper formats and they respectively address objective 1 and objectives 2 and 3. General Conclusions and recommendations are presented in Chapter 5. References have been summarized in Chapter 6.

2. LITERATURE REVIEW

2.1 Hemp plant

2.1.1 General Hemp (*Cannabis sativa)* is a bast fibre plant similar to flax, kenaf, jute and ramie. It is one of the fast-growing plants with a wide tolerance of environmental condition. Hemp can be grown either as a dual crop or as a single crop (Chen et al. 2004). Dual crop means that both fibre and seed are to be harvested, whereas single crop is for fibre only or seed production only. Several varieties of hemp are industrially grown, and they have different morphological and agronomic characteristics. Hemp is legally cultivating at least in 30 countries in the world. China, Russia, Chile, Netherlands, Canada, and Korea are the leading producers of hemp in the world (MAFRI 2011).

2.1.2 Background of hemp in Canada As a part of fibre crops program, Agriculture Canada was involved in hemp research in the 1920s (MAFRI 2011). During that period a small commercial hemp crop was grown in Manitoba and the cordage was the main fibre product. However, the species, *Cannabis sativa*, was banned in 1930s to cultivate in North America. Later it was internationally banned in 1961 under the United Nations' Single Convention on Narcotic Drugs. The main reason was the drug content named delta-9-tetrahydrocannabinol (THC) in its leaves and flowers. People often confuse hemp with marijuana (which has same genus and species like hemp, though different cultivar) regarding THC content. In 1998, certain varieties of hemp were allowed to be grown in Canada. Thus the 60-year ban was lifted and the licensed commercial production of hemp in Canada was re-established. But one of the limiting factors was the concentrations of delta-9-tetrahydrocannabinol (THC). Accepted THC level of hemp cultivar should not exceed 0.3%.

Industrial hemp is viewed as a new alternative crop in Canada, The cultivation of hemp in Canada is a growing industry. In 2001, the number of licensed acres in Canada for hemp cultivation was 3,250 and by 2009 this number increased by 13,760 (MAFRI 2011). Industrial hemp acres in Manitoba demonstrated the similar growth trend for those years. In the year 2001, the number of licensed acres in Manitoba for hemp cultivation was 1307 and this number increased in 4875 by the year 2009 (MAFRI 2011).

2.1.3 Hemp physiology Hemp is an annual broadleaf plant with a taproot and is capable of very rapid growth under ideal growing conditions. This plant consists of two major parts; one is a hollow inner layer which is known as core and the other is outer thin layer of bast fibre (Bócsa and Karus 1997). Depending on the seed variety and planting density, bast fibre accounts for 20-30 percent of hemp stalk whereas cores make up remaining 70-80 percent (Anonymous 2005). Cores are made with libriform fibres which are high in lignin content. Hemp fibre consist of approximately 65% cellulose, 15% hemicelluloses, and 4% lignin. On the other hand, hemp core consisted of 37% cellulose, 35% hemicelluloses, and 21% lignin (Bócsa and Karus 1997).

Different varieties of hemp are available in Canada. Each hemp variety has its own set of characteristics. For example: small or large seed; higher or lower oil content; different oil composition, etc. Varieties grown for fibre production may contain from 15%-25% bast fibres (MAFRI 2011). USO 14 and USO 31 are the most common varieties whereas Alyssa is a new variety licensed in 2004 in Canada. The height of USO 14 and 31 may reach up to 1.5 to 2.5 m and have an average stem diameter of 7 to 16 mm (Gratton and Chen 2000). Alyssa variety may reach a height of 1.5 to 1.8 m (MAFRI 2011). Planting density, variety, sun exposure, nutrient availability all these factors affects plant height (Bócsa and Karus 1997). Precipitation is another important factor for height. Bócsa and Karus (1997) mentioned that, a minimum of 250 mm of precipitation is required during vegetative period to achieve an optimal height. Proper height of hemp plant is effective tool of killing tough weeds in farming by minimizing the pool of weed seeds of the soil (Lotz et al. 1991).

2.1.4 Agronomic aspects of hemp Hemp is an annual crop. For its proper growth appropriate climate, soil condition, seedbed, seeding rate, plant population, fertilizer, weed, and disease and pests control are required. For fast germination, optimum soil temperature is 8-10°C, even though the hemp seed will germinate at 4-6 °C. Hemp responds well to a properly drained, loam soil with a pH 7.0 to 7.5. Hemp plants are very sensitive to clay soils due to compaction. Wet soils and flooding result in weedy, uneven and poor crop (MAFR 2011). For fibre production, hemp seed is usually sown at 20-30 mm depth and row spacing is maintained at 150 to 180 mm. Recommended seeding rate is 250 seeds per m^2 (MAFR 2011). According to seed size and density and application seeding depth and rate can be changed. Planting rate is recommended at 45 kg/ha. Industrial hemp is day-length sensitive. Longer day length provides more vegetative growth and triggered flowering. As a result, plants become taller with higher fibre yields.

Hemp requires approximately 110 kg/ha of nitrogen, 40-90 kg/ha of potash for fibre hemp depending on soil fertility and past cropping history. Weed control is another important segment for hemp production. Research in northwestern Ontario indicates that plant populations as low as 50-100 plants/m^2 may give adequate weed control (MAFR 2011). Cross seeding may be another way for weed control by improving canopy distribution. Yet now, no herbicides have been approved for industrial hemp. Hemp crop can be affected with more than 50 different viruses, bacteria, fungi, insect and pests. No pesticides or fungicides are registered for weed control yet on hemp cultivation. Furthermore hemp's rapid growth rate and vigorous nature allow it to overcome the attack of most diseases and pests (MAFR 2011).

Hemp fibre yield largely depends on proper harvesting. Harvesting time varies according to plant varieties and uses. Suitable harvesting time for male plant is during flowering whereas for female plants, it is at the first appearance of flowers (Bócsa and Karus 1997). Researchers feel higher yields can be obtained by earlier planting, optimum production management and using more suitably adapted varieties (MAFR 2011).

2.2 Use of hemp plant

All parts of this plant can be used for different purposes. Hemp seeds can be used for low cost high quality food and fodder for humans and animals. Hemp plant produces approximately10 tons of biomass with in 90 to120 days. Hemp biomass is a source of fuel production. Hemp provides approximately 75 percent of cellulose, whereas it only amounts to 60 percent for trees. Hemp stalk can be converted into 500 gallons of methanol/acre (Anonymous 2005). As a renewable resource from living plants hemp does not contribute to the greenhouse effect. The growing plants absorb as much CO_2 as will later be released when oil or other plant matter is burnt.

Hemp stalks have been traditionally used in homes for cooking and heating. The hemp stalk can be incorporated into building materials to increases tensile and compressive strengths which will reduce shrinkage and cracking of the structure. Hemp building materials require less processing than timber based building materials. Additionally, hemp as a building material provides insulation, elasticity, and breathability. Hemp paper is more durable compared with tree based paper, and requires no chlorides or bleaches. It also doesn't turn yellow or creak like tree based paper (Merfield 1999). In many non-writing paper industries, hemp paper can be used as cigarette paper, tea bags and filters.

Merfield (1999) mentioned that coarse fibres of hemp can be used for underlay materials or backing for carpets. On the other hand, finer fibres can be used in mixtures with wool or synthetics to produce super characteristics carpets that include non-piling, less wear and biodegradability (Merfield 1999). Natural fibre also results in better performances in terms of toughness, thermal comfort and indoor environmental quality (Bócsa and Karus 1997). Fabrics with at least 50 percent of hemp block the sun's UV rays more effectively than do other fabrics (Merfield 1999). In comparison with cotton, hemp fibres are longer, stronger, more lustrous and absorbent, and more mildew resistant. It is longer lasting than other natural fibres and so is economically better.

Bio-composites can be produced from hemp which is relatively new. Moulded or pressed hemp textiles are currently used by car manufacturers such as Mercedes, BMW, Audi, Cadillac to make a wide range of parts and accessories. Among these parts, headliners, rear window shelving, dashboards, door panels, trunk/boot liners and air bag are considerable (Fortenbery and Bennett 2003). The European Commission ruled some criteria on car manufacturers. Such as 70 percent of a car's parts should be made from recyclable material which creates more pressure on car manufacturers to use hemp and other plant fibre (composites) in their manufacturing process. Many technologies that have been developed for automotive applications can be used to make consumer composites from hemp fibre. Various types of consumer goods such as furniture (chair backs or seats), sporting stuffs, and luggage and musical instruments can be made from hemp fibre composites.

2.3 Hemp fibre processing

Some literature has been studied on flax processing (Anthony 2002). But very little has been done for hemp processing. Hemp handling is not easy like handling of other conventional crops. Some of the main reasons are its long, rigid stems, and wrapping tendency associated with processing it for bast fibre. Raw material transportation causes high cost beside investment in fibre processing. Warehouse space is another issue before processing (Fürll and Hempel 2000). Spreading of chaff (waste material, consisting of small fibre and core particles) on agricultural land also add extra cost. All of these factors increase the cost of fibre processing. But the most critical issue is the quality of fibre, especially the purity of fibre.

2.4 Decortication

Decortication is one of the most crucial parts of fibre processing. This is the process of removing the outer fibrous layer from the inner core layer, also named as detaching process (detaching fibres from hemp stems). Decortication process can be done biologically, chemically, or mechanically. Hann (2005) mentioned that physical process of decortications includes both biological and physical techniques. Immersion of plants into non-turbulent water sources is a traditional physical method of decortications. Nowadays temperature is controlled artificially while stems are soaked in water tank. Natural retting is one of the mostly known biological processes. In this process plants are exposed in a swath to dry and wet conditions in order to weaken the chemical bonds between bast fibre and core with the help of microbiological action (Bruce et al. 2001).

Natural retting normally does not separate fibre and core completely, and further decortication mechanically is often required. Preretting of hemp stalk will reduce the effort of mechanical decortication (Chen et al. 2004). However, retting is not always possible due to the high risk of rotting, fungal or mold attack (Münder et al. 2004). Mechanical decortication is the most comment method for fibre processing in developed countries and it is discussed in details in the following section.

There have been different decorticators for hemp fibre processing, such as hammer mills, cutterheads, and crushing rollers. Raw materials which are fed into decorticators are subjected to various mechanical forces such as compress, shear, and impact. These mechanical forces break the bond between bast fibre and core, i.e. detach bast fibre from the core. Hammer mills use the impact and shear forces for decortication. Screen size of the hammer mill, moisture content, bulk and particle density of hemp material, and feed rate all affect the performance of a hammer mill (Yu et al. 2006; Lopo 2002; Shi et al. 2003). Hammer mills are preferred for applications of unretted hemp, low fibre purity, and high processing capacity (Chen et al. 2004). It produces more chaff comparing with scutching blades and roller crushers.

By using modified cutterhead which was adopted from forage harvester, Gratton and Chen (2004) tried to separate hemp stalk using an in-field hemp decorticator. The modified cutterhead was fitted with three cutting knives instead of twelve in the original forage harvester. Nine scuthching bars were fitted for decortications as an alternative of removed knives. Another type of decorticator is crushing rollers. This is mainly used in flour milling industries to grind wheat into flour (Fang et al. 1997). This machine was adopted for hemp decortications. Crushing rollers with fluted, pinned, or flat surface crush hemp stock using mainly compression force in detaching bast fibre from the core. Roller speed and roll gap are two major parameters for hemp decortication (Hobson et al. 2001). Crushing rollers are suitable for retted hemp and produce cleaner and longer fibre when compared to hammer mills.

Furthermore, decortication may be also achieved by ball mills which have a wide range of research applications on processing other materials, for example of preparing dry powder for vaccine (Garmise et al. 2006). Ball mill was adopted for hemp decortications under different grinding durations and speed by Baker (2009). Maximum fibre yield was obtained 43.3% by using this ball mill. Material is placed into a specific size and type of grinding bowl along with an appropriate size, type, and number of grinding balls. The bowl is operated in a circular motion, and the centrifugal forces cause collision between grinding balls (Prasad et al. 2005) which impacts the material through impact and shear forces. As the result, bast fibre is detached from the core.

2.5 Cleaning

The output of a decorticator is a mixture of fibre and core as well as chaff (fine particles). In general decorticators are not able to separate fibre from the mixture. Subsequent cleaning is very essential to meeting the requirement by fibre industries.

2.5.1. Cleaning through particle size difference For material cleaning, sieving or screening is one of the oldest types of technique. There have been many types of screen being developed for separating particles with different sizes and other properties (Cleary et al. 2009a; Vorster et al. 2002). Dass (2004) mentioned that the ultimate screener is an extensively used cleaning method for dry fine materials. It imparts multi frequency vibrations which vibrates various part of the screen with different frequency. In some industrial applications, decorticated hemp was feed into a multiple ultra cleaner to eliminate cores. The multiple ultra cleaner shakes the material intensively, and short fibres and cores are being separated from the long fibres (Münder et al. 2004). Pecenka and Furll (2008) reported about a special screening device that consists of a fixed screen with oscillating comb mounted above the screen as transport aid. The comb helps to untangle fibre by loosening the fibre and core mixture. The fibre purity was improved by reducing significant amount of core content (from 50% to 7%) from a mixture. However, it proved successful only in traditional long fibre cleaning. Most of screening machines are found ineffective when they are used for fibre cleaning.

2.5.2. Cleaning through scutching Another popular method of fibre separation is scutching. The scutching is a process for separation of fibre in industrial lines (Akin et al. 2005). A large rotating scutching wheel is enclosed within a metal housing and transports materials over grid bars. The fibers are stroked over grid bars to separate fibre bundles and further remove cores. This method does not work well for unretted hemp (Akin et al. 2005).

2.5.3 Combined technique for cleaning Liu (2009) found that sieving, combined with winnowing or air flows can categories particles more effectively than sieving alone in separating dried distillers grains with soluble. Gratton and Chen (2004) used a straw walker from a combine for fibre cleaning in an in-field fibre processing machine. The straw walker was fitted to a modified decorticator from a forage harvester. During passing over the straw walkers, the decorticated hemp material experienced both vertical and horizontal movement, which causes small particles fall through the screens of the straw walker. At the same time, very fine particles were blew away by the fan beneath the straw walker. The cleaned fibre had purity ranged from 35% to 52% with this in-field fibre processing unit. On average 45 % of fibre was lost into the chaff outlet (Gratton and Chen 2004). In that study, the air flow was designed for grains, which might not be appropriate for hemp materials.

2.5.4 Cleaning through density difference A grain cleaning method with the aerodynamic process has been well documented (e.g. Hollatz and Quick 2003; Gorial and O'Callaghan 1990; Khoshtaghaza and Mehdizadeh 2006). Hollatz and Quick (2003) pointed out that aerodynamic characteristic of particle mixtures are important for cleaning as desirable products are separated from unwanted material due to the differences of aerodynamic properties. Innocentini et al. (2009) mentioned that for designing and operating a pneumatic device, aerodynamic knowledge of individual particles of a mixture is also necessary. Therefore, when using aerodynamic method for fibre cleaning, aerodynamic properties of fibre and core are needed to be studied. Main parameters of aerodynamic properties are terminal velocity, drag force, and drag coefficient.

2.5.5 Aerodynamic properties Sturos (1972) discussed that, terminal velocity of an object is the velocity when it starts to move. On the other way, a free-falling object achieves its terminal velocity when the downward force of gravity (F_g) equals the upward force of drag if the buoyancy is negligible. Hollatz and Quick (2003) also pointed out that like an aspiration process, the cleaning process can be done and in this process, when air speed is high, grains and chaff is separated through the differences in terminal velocity and drag coefficient. For a particle suspended in a vertical air stream, the particle weight acting downwards balances the buoyancy and drag forces acting upwards (Persson 1991).

Terminal velocity varies directly with the ratio of weight to drag. More drag means a lower terminal velocity, while increased weight means a higher terminal velocity. An object moving downward with greater than terminal velocity will slow until it reaches the terminal velocity.

Hemmat et al. (2007) mentioned that agricultural materials are non-uniform in shape, size and density which cause instability in aerodynamic behaviour of materials. Bilanski (1971) stated that individual materials are unstable in aerodynamic behaviour and therefore a large number of replications are required to draw statistical interferences.

Aerodynamic properties of various agricultural products, mainly seeds were measured in different studies. In a wind tunnel by providing air flow, aerodynamic properties of cottonseed and sunflower seed were measured by Tabak and Wolf (1998) and Gupta et al. (2007). Terminal velocity of cotton seed ranged from 5.8 to 10.0 m/s for the mass of 0.08 to 0.15 g and drag coefficient ranged from 0.6 to 0.8. On the other hand, terminal velocities for three different varieties of sunflower seed were noticed 2.93 to 3.28, 2.54 to 3.04 and 2.98 to 3.53 m/ s respectively and the corresponding value of drag coefficient varied from 0.18 to 0.24, 0.20 to 0.31 and 0.17 to 0.40 respectively. Similarly by introducing air flow in a transparent tube coffee cherries demonstrated terminal velocity from 11.03 to 15.47 m/s whereas coffee beans had 8.72 to 11.44 m/s. Drag coefficient was observed 0.32 to 0.41 for coffee cherries and 0.45 to 0.51 for coffee beans (Ju´nior et al. 2007). By following the similar method, Zewdu (2007) revealed that terminal velocity of straw demonstrates decreasing trend with the increasing of straw length. For example, node free straw showed that terminal velocity decreased from 3.08 to 1.70 m/s with increasing straw length from 1 to 100 mm. By using a combine straw walker for corn plant, Uhl and Lamb (1966) showed that, terminal velocities of corncob pieces ranged from 6.7 to 13.4 m/s while corn stalk pieces ranged from lower to higher velocities than cobs. Farran and Macmillan (1979) concluded that higher air velocities are required to separate chaff from grain than to suspend chaff on its own. Gorial and O'Callaghan (1990) and Song and Lichfield (1991) also determined drag coefficient for various agricultural products including seeds, beans, nuts, kernels etc. Though several studies have been conducted on aerodynamic properties of agricultural products, no study was found on hemp fibre and core. In present study the behaviours of the terminal velocity and drag coefficient of hemp fibre and core was determined to develop a process line for fibre cleaning.

2.5.6 Cleaning through carding technique Carding is the most commonly used method in industries for cotton processing. Among several types, drum carding machine is the simplest one. Generally this machine has two cylinders: licker-in and a larger one, main cylinder. Other components include feeding tray, rotating handle and chain drive. Material is fed through the feeding tray, and as the cylinder rotate, the material travels through the cylinders where carding action occurs. In this mechanical process fibre clumps (A number of fibres in contact with each other) are opened, disentangled, and cleaned. Cores, short fibres, dust and dirt are removed through this process. Important task of carding is to open fibers, which enables to eliminate impurities and provide cleaner fibres. The degree of cleaning is claimed to be high in carding. In this study, carding method was also tried for hemp fibre cleaning.

Carding parameters, such as cylinder rotating speed, carding duration, and feeding mass play important role in fibre cleaning. Gangwar (2009) studied the influence of carding parameters on cotton fibre openness and cleaning. It was found that fibre openness and cleaning efficiency increases with increasing licker-in speed. Göktepe et al. (2003) mentioned that the enhancement of licker-in speed increased amounts of short fibre and reduced fibre strength. Higher licker-in speed also produced more waste. Fibre transfer in carding machine was studied by Lee and Ockendon (2006).

2.5.7 Cleaning through floatation method Floatation method is a process of separation that is widely used in industries mainly in water treatment. Pongstabodee et al. (2008) separated mixed post-consumer plastic waste with combination of three-stage sink-float method and selective floatation technique. In each case, materials were separated through density difference. Carvalho et al. (2010) also separated packaging plastics by froth floatation in a continuous pilot plant. Water separation is one of the common processes where materials can be separated through density differences. Water acts as a separating layer between the light and heavy materials. In this study, an attempt was taken to separate decorticated fibre from its mixture by using water. Additionally, behaviours of individual fibre and core as well as the mixture in water were observed.

In summary, hemp is a very valuable crop and hemp fibre can be used in many applications, such as bio-composites and textile. However existing fibre processing machines do not generate clean fibres to meet the requirements of fibre industries. The main problem was the ineffectiveness of the equipment and lack of understanding of the cleaning process. In this study, three different cleaning methods, including aerodynamic separation, carding, and floatation, were investigated with the intention to obtain fibres with high purity.

3. AERODYNAMIC PROPERTIES OF HEMP FIBRE AND CORE AND ITS APPLICATION ON FIBRE CLEANING

3.1 ABSTRACT

Separation of the core from the fibre is very important to obtain clean fibre. This study explored the potential of using the aerodynamic method for removing fibre from a mixture of fibre and core. In this study, a testing apparatus (wind tunnel) was designed to measure the aerodynamic properties (mainly terminal velocity) of fibre and core. An experiment was carried out using the apparatus to separate fibre and core particles from the mixture. Treatments included the combinations of two types of materials (fibres and cores) and two retting conditions (retted and unretted). Each treatment was replicated for particles of different projected areas and masses. Terminal velocities were measured and the results showed that retting condition did not have any effects on the terminal velocities in all cases. However, core particles had higher terminal velocities than fibre particles. The ranges of the terminal velocity of core particles were 1.28 - 3.52 m/s and 0.56 - 1.36 m/s for fibre particles over all treatments. This differences in terminal velocity implied that fibre and core particles could be separated aerodynamically. However, when applying the aerodynamic method to mixtures of fibre and core, separation of fibre and core particles could not be achieved, as fibre and core particles were tangled together.

Keywords: hemp, fibre, core, separation, terminal velocity, drag coefficient, air flow.

3.2 INTRODUCTION

Hemp (*Cannabis sativa)* is one of the strongest sources of natural fibre. Hemp fibre has similarity with jute, flax, kenaf, and ramie. Durable and soft hemp fibre has an extensive usage in textile industry (Ranalli and Venturi 2004) in the past centuries. Good properties of hemp fibers lend themselves to new applications such as composites, reinforcements, fibreglass alternatives, automobile parts, fuel and paper (Foulk et al. 2002). Hemp fibre has low density, satisfactory specific strength; excellent thermal insulation criteria, recyclability, and biodegradability (Park et al. 2006; Lilholt et al. 2000; Van de Weyenberg et al. 2003; Gassan 2002; Baiardo 2004). All of these properties have increased the interest in hemp fibre.

All industrial applications require clean fibre. Fibre cleanness depends on the effectiveness of hemp processing. Hemp is typically processed mechanically and this process is termed as decortication. Decortication breaks the bond between outer layer (fibre) and the inner layer (core) of hemp stem. Different types of machines have been used for hemp decortication, including hammer mills, crushing rolls, and cutterheads. Through those machines, hemp stalk is broken into pieces of fibres and cores. The mixture of fibres and core pieces then subjects a cleaning process where the mixture is separated into fibres (main product) and cores (by-product). Existing fibre product from decortication often contains high percentage of cores, which is not desired for many industrial applications of fibre. Therefore, it is an immediate need to improve the effectiveness of existing fibre cleaning process.

Very few cleaning machines have been developed specially for separating hemp fibre from core. In most cases, cleaning equipment was adopted from other applications.

Gratton and Chen (2004) used straw walkers from a combine for cleaning decorticated hemp materials and found 52 % fibre purity (the other 48% was cores). In another study, decorticated hemp materials were fed in a multiple ultra cleaner and short fibres and cores were being separated from the long fibres (Munder et al. 2004) and the resultant fibre purity was 26-28%. Comb shakers, air blasters sieving with winnowing, and scutching methods have also used for separating cores from fibres in the past (Cleary et al. 2009a; Vorster et al. 2002; Liu 2009). However, fibres from those cleaning processes are not as clean as required by fibre industrials. Alternative cleaning processes need to be explored for hemp fibre cleaning.

Pneumatic cleaning has been used in separation processes of agricultural materials (Gorial and O'Callaghan 1990; Khoshtaghaza and Mehdizadeh 2006). Pneumatic process was also combined with mechanical process for grain cleaning (Hollatz and Quick 2003). By means of air flow, lighter particles such as chaff and dusty materials can be easily eliminated from grain materials (Simonyan and Yiljep 2008). Pneumatic cleaning may have potential for separating fibre and core. This study initiated some efforts towards using the pneumatic technique for fibre cleaning.

For designing and operating a pneumatic device for handling a material, it is essential to understand the aerodynamic characteristics of individual particles in the material (Innocentini et al. 2009) and the mixture of the particles (Hollatz and Quick 2003). Aerodynamic properties of a material include terminal velocity, drag force, and drag coefficient. Tabak and Wolf (1998) mentioned that when a particle starts to suspend in a vertical airflow, the speed of the airflow holding this position is called the terminal velocity. Drag force refers to forces that oppose the relative motion of an object through a fluid (a liquid or gas). It acts in a direction opposite to the oncoming flow velocity. Drag coefficient is dimensionless and is used to quantify the drag or resistance of an object in a fluid environment such as air (Tabak and Wolf 1998). Lower drag coefficient indicates the object will have less aerodynamic drag. For a particle suspended in a vertical air stream, the particle weight acting downwards balances the buoyancy and drag forces acting upwards (Persson 1991). Terminal velocity varies directly with the ratio of weight to drag. More drag means a lower terminal velocity, while increased weight means a higher terminal velocity.

Separation of different particles can be achieved using the differences in terminal velocity between the particles. Hollatz and Quick (2003) found that, grain and chaff can be separated through the differences in terminal velocity and drag coefficient in a combine cleaning process with the combination of aerodynamic and mechanical process. The mechanical process included mainly a centrifugal fan which provided air flow to chaff and grain. Farran and Macmillan (1979) concluded that higher air velocities are required to separate chaff from grain than to suspend chaff on its own.

Agricultural materials are non-uniform in shape, size and density and all these affect aerodynamic behaviours of the materials (Hemmat et al. 2007). There are several ways to measure aerodynamic properties of a material. By recording the rate of acceleration of a particle which is falling in an enclosed tube, terminal velocity can be measured. It can also be determined by measuring the air velocity required to suspend a particle in a vertical air stream (Persson 1991). The latter one is used to determine the terminal velocity of small size particles. Bilanski (1971) stated that individual materials are unstable in manner and therefore a large number of replications are required to draw statistical interferences.

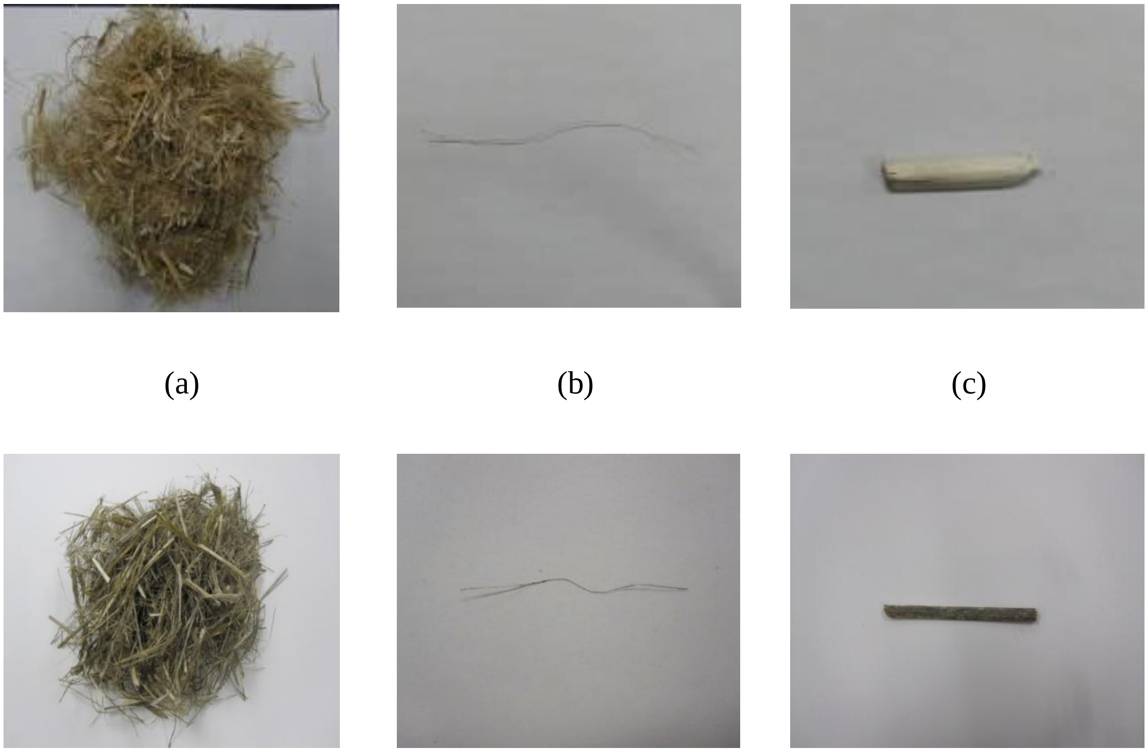
Zewdu (2007) measured aerodynamic properties of tef straw by using a wind tunnel where air was introducing for pneumatic separation. The study revealed that terminal velocity of straw demonstrates decreasing trend with the increasing of straw length. For example, node free straw showed that terminal velocity decreased from 3.08 to 1.70 m/s with increasing straw length from 1 to 100 mm. By following the similar method, aerodynamic properties of cottonseed and sunflower seed were measured by Tabak and Wolf (1998) and Gupta et al. (2007). Terminal velocity of cotton seed ranged from 5.8 to 10.0 m/s for the mass of 0.08 to 0.15 g and drag coefficient ranged from 0.6 to 0.8. On the other hand, terminal velocities for three different varieties of sunflower seed were noticed 2.93 to 3.28, 2.54 to 3.04 and 2.98 to 3.53 m/ s respectively and the corresponding value of drag coefficient varied from 0.18 to 0.24, 0.20 to 0.31 and 0.17 to 0.40 respectively. Furthermore Ju´nior et al. (2007) showed that terminal velocity of coffee cherries ranged from 11.03 to 15.47 m/s whereas coffee beans had 8.72 to 11.44 m/s. Drag coefficient was observed 0.32 to 0.41 for coffee cherries and 0.45 to 0.51 for coffee beans. By using a combine straw walker for corn plant, Uhl and Lamb (1966) showed that, terminal velocities of corncob pieces ranged from 6.7 to 13.4 m/s while corn stalk pieces ranged from lower to higher velocities than cobs. Gorial and O'Callaghan (1990) and Song and Lichfield (1991) also determined drag coefficient for various agricultural products including seeds, beans, nuts, kernels etc.

For pneumatically cleaning hemp material, aerodynamic properties of fibre and core are needed to be investigated. Though several studies have been conducted on aerodynamic properties of agricultural products, no study was found on hemp fibre and core. The primary objective of the present study was to investigate aerodynamic properties of hemp fibre and core with different sizes. The secondary objective was to apply the measured aerodynamic results in cleaning the mixture of fibre and core.

3.3 MATERIALS AND METHODS

3.3.1 Hemp material

An aerodynamic experiment was carried out using hemp material collected from a hemp processing plant in Manitoba, Canada. The material was from both unretted hemp (Alyssa variety) and retted hemp (USO 31 variety), and both have been decorticated prior to the experiment. The decorticated hemp material was a mixture of fibre and core (figs. 3.1a and 3.1d). From the mixtures, single fibre bundles and cores (named as fibre and core particles hereafter) were selected randomly for the experiment, and they are shown in figs. 3.1b, 3.1c, 3.1e, and 3.1f.



(a) (b) (c)

(d) (e) (f)

Fig. 3.1. Hemp materials used for the experiment; (a), (b), and (c) mixture, fibre particle, and core particle of unretted hemp respectively; (d), (e), and (f) mixture, fibre particle, and core particle of retted hemp respectively.

3.3.2 Wind tunnel

A wind tunnel (fig. 3.2) was designed and constructed for the aerodynamic experiment. The wind tunnel consisted of a blower, a vertical tube, a flow straightener, a wire mesh screen, and a supporting wooden frame. The blower was attached with the frame and provided air flow in the upward direction to the vertical tube. The blower had a capacity of 0.05 m^3/s and its speed was adjusted by using a variable transformer to change the velocity of the air flow. The vertical tube was made of transparent plexi glass (thickness: 10 mm), 910 mm in height, and 139 mm in diameter (ID). The honey comb plastic flow straightener was 19 mm thick and its cell opening was 3 mm in diameter. It was placed at 100 mm above the base of the tube. Its function was to provide uniform air velocity distribution in the tube. The 8-mm wire mesh screen was positioned at 400 mm above the flow straightener. In the experiment, hemp particle would be placed on the screen; air flow was provided by the blower, passing through the straightener and the mesh screen to the particle. The transparent tube allowed observing aerodynamic behaviours of the particle.

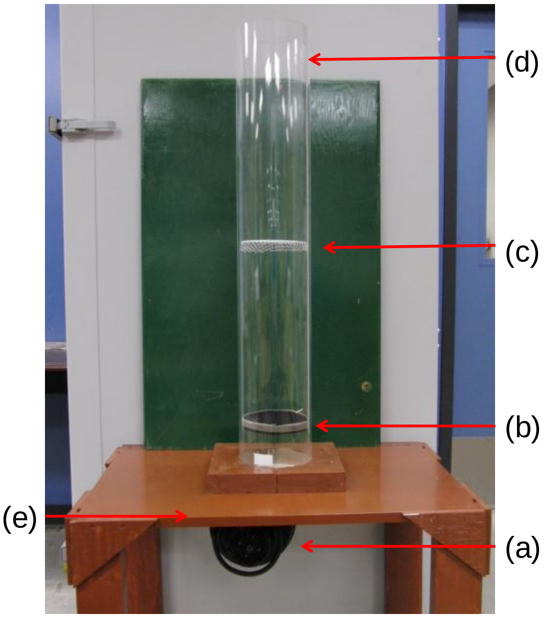


Fig. 3.2. Wind tunnel used for the aerodynamic experiment: (a) blower (b) flow straightener (c) wire mesh screen (d) transparent tube, and (e) supporting frame.

3.3.3 Calibration of air velocity

The blower was calibrated for its air velocity which was controlled by the input voltage to the blower. The input voltage was adjusted by a variable transformer (volt- pac 9T92A86, USA). The purpose of the calibration was to establish the relationship between the input voltage and the air velocity. Preliminary testing showed that the blower started to provide air flow when the voltage was set to about 30 volt, and a sufficient air flow was provided when the voltage was set to 80 volt. Thus, the calibration of air velocity was performed in a voltage range of 30 to 80 volt.

For the calibration, air velocity was measured at the centre of the transparent tube at 910 mm height from the base of the tube using an anemometer (Bacharach- Florite 800, PA). Measurements were carried out at voltages varying from 30 to 80 volt with 5 volt intervals. The calibration data has shown in fig. 3.3. The relationship between the transformer voltage and the air velocity could be represented by a linear regression equation with a high coefficient of determination (R^2 = 0.974). Based on this equation, the desired air velocity was achieved by adjusting the input voltage during the aerodynamic experiment.

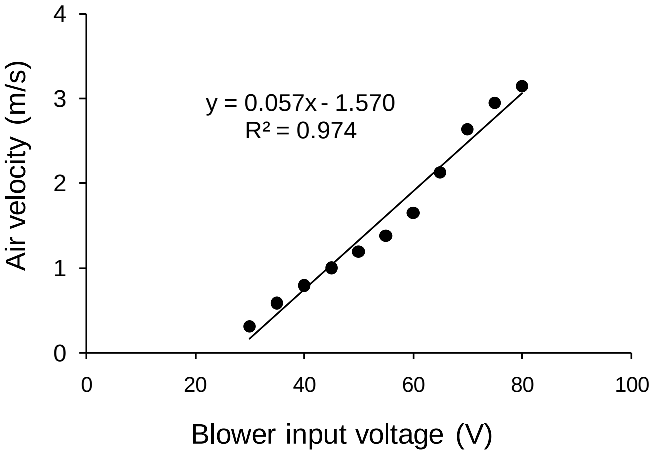


Fig. 3.3. Calibration of air velocity with the input voltage of the blower.

Then, whether the flow straighterner could provide uniform air velocity across the diameter of the transparent tube was examined. Air velocity distribution in the tube was measured using the anemometer at 11 different positions along the diameter of the tube.

The measurement was performed at the 50 volt settings of the input voltage. The results showed that the velocity was quite uniform along the cross-section of the tube within the 50 mm distance from the centre (fig. 3.4), as indicated by the low standard deviation (0.12 mm). This indicated that the straightener was reasonably effective.

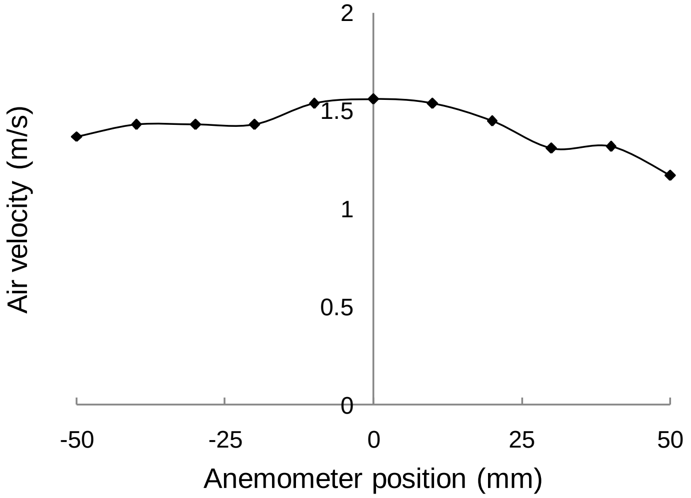


Fig. 3.4. Air velocity distribution across the diameter of the transparent tube.

3.3.4 Experiment design

Aerodynamic behaviours of a single fibre particle and a single core particle were examined using the wind tunnel in a completely randomized design (CRD). The experimental factors were two types of hemp particles (fibre and core) with two retting conditions (retted and unretted) which gave four treatments for the experiment. For each treatment, samples were picked up from the hemp material shown in fig. 1 and they were divided into five different groups from short, mediums, and long particles. For fibre samples, the particle length in the short group was around 20 mm; that in the long group was around 100 mm; and the particles of the other three groups were around 40, 60, and

80. Similarly, for core samples, the groups had particle lengths of approximately 20, 30, 40, 50, and 60 mm. This sampling procedure was to ensure that particles size to be tested would be representative. The actual length of each fibre simple was measured and used to determine the projected area of the particle. For the test, 10 samples were selected from each group. Thus 200 tests (2 type particles x 2 retting conditions x 5 lengths x 10 samples) were performed in the experiment.

3.3.5 Measurements

3.3.5.1 Physical properties The dimensions of 200 particles prepared for the aerodynamic experiment were characterized. The diameters of fibre particles were measured using a slide calliper. Projected area of a fibre particle was estimated from the measured length and diameter, assuming fibre particle has a circular cross-section. Core width was also measured using the slide callipers. Projected area of core was estimated from the measured length, and width. By using an analytical balance (Cole - Parmer Symmetry, PA), the mass of each fibre and core particle was also measured.

3.3.5.2 Terminal velocity For measuring terminal velocity, a particle of fibre or core was placed at the centre on the screen in the wind tunnel. The air velocity of the blower was being increased slowly during test. When the particle was just about to float away from the screen, the air velocity was recorded as the terminal velocity of the particle.

3.3.5.3 Drag coefficient With the measured terminal velocities, drag coefficients of fibre and core particles were calculated using the following equation:

$$c_d = \frac{2mg}{\rho A V_t^2} \tag{3.1}$$

Where

C_d = drag coefficient, dimensionless;

V_t = terminal velocity (m/s);

m = mass of the particle (kg);

g = acceleration due to gravity (9.8 m^2/s);

ρ = density of the air through which the particle is falling (kg/m^3);

A = projected area of the particle (m^2).

3.3.6 Application of the terminal velocities

After terminal velocities of single fibre and core particles were obtained, they were applied to mixtures of fibre and core for separating fibre and core particles. In the application, three types of mixture samples were tested and they were: a) one fibre particle and one core particle, b) two fibre particles and two core particles, and c) 3g mixture randomly taken from the material shown in fig. 3.1d. For each mixture, three tests were performed. Tests were performed using the same wind tunnel following the same procedure as in the single particle tests. A mixture was placed on the screen inside the wind tunnel tube and the air velocity was slowly adjusted to the required terminal velocities. The movement of samples was captured by using a high speed camera (Casio EX-F1, JP) and later was visually observed.

3.3.7 Statistical analysis

Analysis of variance (ANOVA) was performed on the data of the experiment using statistic software, SAS (version 9.1.3). T-test was conducted to compare treatment differences in aerodynamic properties between fibre and core particles and between retted and unretted particles. To examine aerodynamic properties as affected by particle physical properties, particle mass and project area were combined as one factor which was the ratio of mass and project area (M/A). The rationale was that terminal velocity is proportional to M and inversely propositional to A, as stated in Eq. 3.1. It would be better to combine these two parameters as a ratio, M/A to avoid one parameter confounding with the other. Similarly, drag coefficients were also examined for the effects of M/A. Linear regression was done to determine if terminal velocities and drag coefficients were significantly affected by M/A.

3.4 RESULTS AND DISCUSSION

3.4.1 Physical parameters

Masses and projected areas of the 200 hemp fiber and core particles used for the tests are summarised in table 3.1. Only the minimum and maximum values are presented as background information. The particles covered a wide range of masses and projected areas, which reflected well the reality, and therefore, the data would give good assessment on the feasibility of using the aerodynamic method in the application of separating fibre and core particles.

Table 3.1: Ranges of physical properties measured for the hemp fibre and core particles.

Sample	Mass (mg)		Projected area (mm^2)	
	Min	Max	Min	Max
Retted core	30	130	83.3	352.1
Unretted core	30	110	98.4	301.1
Retted fibre	0.7	3.56	6.96	34
Unretted fibre	0.61	6.53	8.94	52.9

3.4.2 Aerodynamic properties

3.4.2.1 Terminal velocity

Retted particles Figure 3.5 shows the trend of terminal velocity for different ratios of mass and projected area (M/A) for the retted fibre and core particles. In both cases, terminal velocity increased slightly with the increasing M/A. Terminal velocities of the retted fibre varied within a narrower range (0.68 to 0.88 m/s) than those of the retted core (1.28 to 3.35 m/s). Overall, the retted fibre had lower terminal velocities than the retted core as illustrated by the two nearly parallel regression lines. Terminal velocities of retted fibre and core did not overlap for any point. Statistically, retted fibre and core particles showed significant differences from each other ($p<0.05$). The ANOVA showed that terminal velocities of retted core were significantly affected by the M/A ($p<0.05$) whereas retted fibre did not affect significantly ($p>0.05$).

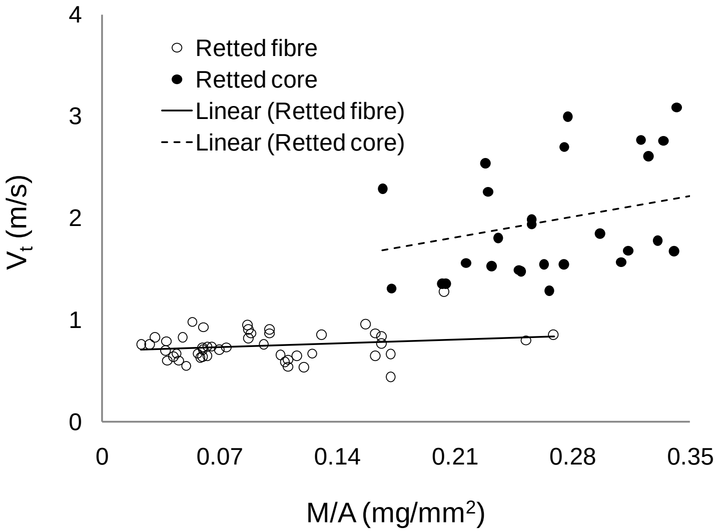


Fig. 3.5. Effect of the mass and projected area ratio (M/A) on terminal velocity (V_t) for the retted fibre and core particles.

Unretted particle Terminal velocities of the unretted fibre and core particles followed a sharp increasing trend with M/A (fig. 3.6). Overall, the unretted core particles had higher terminal velocities than the unretted fibre particles. Likewise retted particles, terminal velocities of unretted particles did not coincide for any values. Highest terminal velocity of unretted fibre was 1.36 m/s whereas terminal velocity of unretted core started from 1.64 m/s . The differences in terminal velocity between unretted fibre and core particles were significant ($p<0.05$). The ANOVA showed that M/A had a significant effect on the terminal velocity for botht unretted fibre and core particles ($p<0.05$).

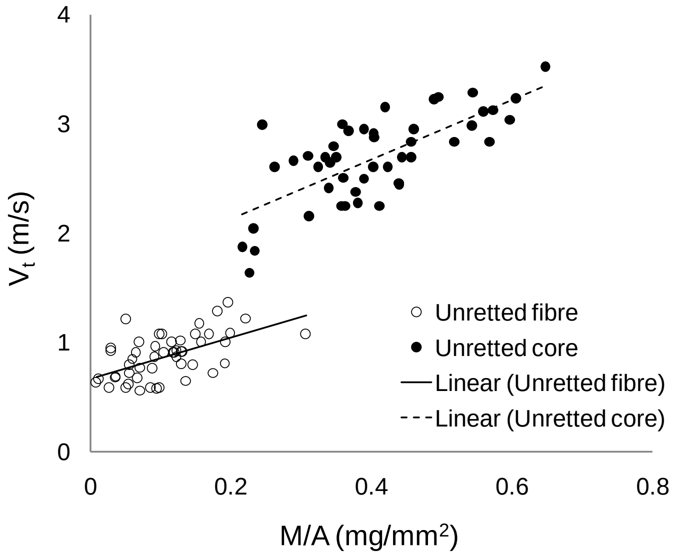


Fig. 3.6. Effect of the mass and projected area ratio (M/A) on terminal velocity (V_t) for the unretted fibre and core particles.

3.4.2.2 Drag coefficient

Retted particles Figure 3.7 shows the trend of drag coefficients for different ratios of mass and projected area (M/A) for the retted fibre and core particles. Though drag coefficients showed increasing trend with M/A for both cases, retted fibre increased sharply whereas drag coefficients of retted core were fairly constant over all the values of M/A measured. Overall, the retted fibre particle had higher drag coefficient than the retted core (fig. 3.7), which was signinficantly different ($p<0.05$). The higher drag coefficients of the retted fibre particles explained their lower terminal velocities. Drag coefficients of the retted core particles were also more scattering around the average when compared to those of the unretted core particles. The average drag coeficient of the retted fibre particle was 3.17 and that of the core particles was 1.37. Values of M/A had significant effects on the drag coefficients for retted fibre whereas retted core showed non significant effects according to the ANOVA (p>0.05) of linear regression.

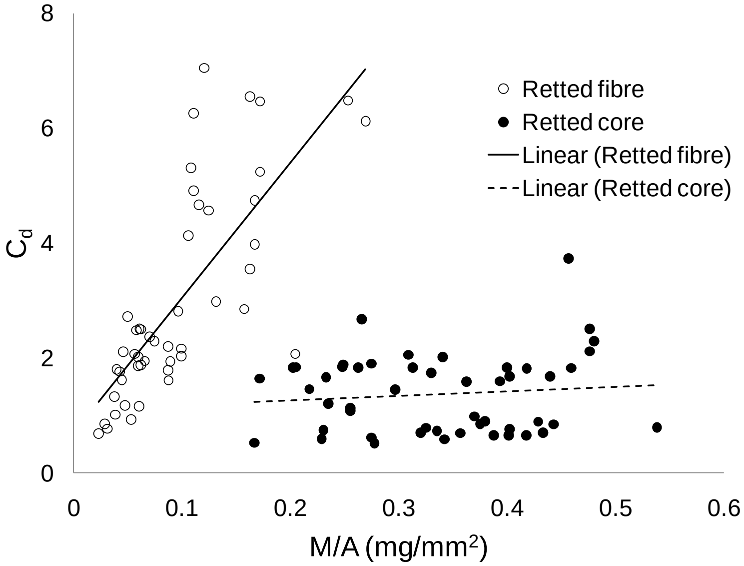


Fig. 3.7. Effect of the ratio of mass and projected area (M/A) on drag coefficient (C_d) for retted fibre and core particles.

Unretted particle Likewise retted fibre and core particles, drag coefficients of unretted fibre and core particles also increased with the increasing M/A (fig.3.8). Drag coefficients of unretted fibre particles were clustered together at low values of M/A. Unretted core showed nearly constant values of drag coefficients over all the values of M/A measured. The average drag coefficient of the unretted fibre particle was 2. 37, and that of the unretted core particle was 0.93. Drag coefficients between the unretted fibre and core particles were significantly different (p<0.05) from each other. Furthermore, from ANOVA it was found that, M/A made significant differences in the drag coefficients of unretted fibre particles but unretted core showed non significant effects.

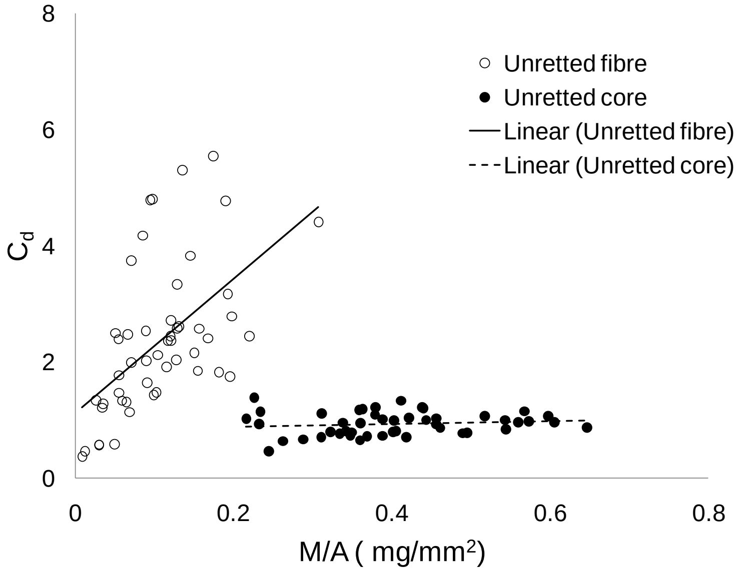


Fig. 3.8. Effect of the ratio of mass and projected area (M/A) on drag coefficient (C_d) for unretted fibre and core particles.

The value of drag coefficient of various agricultural products mainly seeds were measured in previous studies. Tabak and Wolf (1998) found the drag coefficient ranged from 0.6 to 0.8 in cottonseed. Ju´nior et al. (2007) showed that drag coefficient ranged 0.32 to 0.41 for coffee cherries and 0.45 to 0.51 for coffee beans. But hemp fibre and core showed little higher values of drag coefficient comparing these literature values due to very lightness of the particles.

3.4.3 Comparisons of terminal velocities of hemp fibre and core

From the magnitudes of terminal velocities for hemp fibre and core particles it is noticed that core particles had higher terminal velocities than fibre particles. Terminal velocity of core and fibre was significantly different from each other both for retted and unretted case ($p<0.05$). In retted condition, terminal velocity of core ranged from 1.28 to

3.35 m/s whereas it was 0.68 to 0.88 m/s for fibre. On the other hand, in unretted condition, , terminal velocity of core ranged from 1.64 to 3.52 m/s whereas it was 0.56 to 1.36 m/s for fibre. No literature has been reported on terminal velocities of hemp fibre and core. However, Zewdu (2007) measured the terminal velocity (1.70 to 3.08 m/s) of straw which can be considered as a supportive value with core. Additionally Gupta et al. (2007) determined terminal velocity of sunflower seed which ranged from 2.93 to 3.28, 2.54 to 3.04 and 2.98 to 3.53 m/s for three different varieties respectively.

From the magnitudes, it is noticed that the range of terminal velocities of fibre and core are quite different from each other both for retted and unretted case. Therefore, by observing these values, one can decide to apply it in practical field for separating hemp fibre and core from its mixture. With this intention measured terminal velocities of this study were applied for hemp fibre and core separation.

3.4.4 Application of the results

From the tests results of applying the measured terminal velocities on three mixtures of fibre and core, one found that using the terminal velocity differences, the fibre and core particles could be separated. In fig. 3.9a it was clearly showed that as air was being supplied to the wind tunnel tube, the fibre particle started floating and the core particle was sitting on the screen. Similar observations were found for the mixture of two fibre particles and two core particles. With the increasing air velocity, fibre particles started floating while core particles were staying on the screen (fig. 3.9 b).

(a) (b)

Fig. 3.9. Tests of hemp mixtures at the predetermined terminal velocity: a) the mixture of one fibre particle and one core particle and (b) the mixture of two fibre particles and two core particles.

However it did not work for the 3 g fibre and core random mixture. As the air velocity was being increased, some fibre particles intended to move, but they could not as some core particles were holding them back. The further increase in air velocity resulted in the tangled fibre and core particles floated away together (fig. 3.10). The results indicated that using the aerodynamic method, untangled fibre and core particles could be separated as they had different ranges of terminal velocity. However, mixtures of these particles would be difficult to be separated due to the tangling problem of fibre.

Fig. 3.10. Test of the 3 g random hemp mixture at the predetermined terminal velocity.

3.5 CONCLUSIONS

Aerodynamic properties were measured for retted and unretted hemp fibre and core particles with various sizes. In general, terminal velocities of fibre and core particles increased with the ratio of the particle mass and project area. Similar trend was observed for the drag coefficients. Retting of hemp did not affect the terminal velocities of hemp particles. Core particles had significantly higher terminal velocities than fibre particles. In retted condition, terminal velocity of core ranged from 1.28 to 3.35 m/s whereas it was 0.68 to 0.88 m/s for fibre. In unretted condition, terminal velocity of core ranged from 1.64 to 3.52 m/s whereas it was 0.56 to 1.36 m/s for fibre. Significant differences in terminal velocities between terminal velocities were noticed for core and fibre. If core and fibre particles were free of each other, they would be separated using the aerodynamic method. However, fibre and core particles could not be separated due to the entanglement problem when applying this method to a random mixture of fibre and core particles.

3.6 ACKNOWLEDGEMENTS

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4. CLEANING OF HEMP FIBRE USING CARDING AND FLOATATION METHODS

4.1 ABSTRACT

Carding and floatation experiments were conducted in separating fibre from processed hemp material to obtain clean fibre. The processed hemp material was a mixture of fibre, core, and fibre-attached-with-core with a fibre purity of 55%. Using the hemp material, a carding experiment and a floatation experiment were conducted to improve the fibre purity. Results showed that carding durations and feeding mass did not significantly made differences in the purity of the resultant fibre. Overall, carding improved the fibre purity. The highest fibre purity was 70%. Carding also caused losses on fibre yield. However, there were no significant differences in fibre purity among different carding durations and feeding masses. Results from the floatation experiment showed that fibres sunk and cores floated in water, which were desired for separation of fibre and core. To obtain higher fibre purity and to increase the efficiency of the floatation method, agitation of the water was necessary. With agitation, the resultant fibre purity could be as high as 90%. However, high fibre losses were also observed when using this method. **Keywords**: hemp, fibre, core, cleaning, carding, floatation, purity, water, agitation, yield.

4.2 INTRODUCTION

Hemp plant is an excellent source of natural fibre which has been widely used in the production of textiles, paper, food and fuel, composites, construction materials, and automobile parts. There is an increasing demand for hemp fibre due to its high strength and light weight. However, most existing hemp processing equipment can not generate fibres as clean as industries require. Improvement of existing machines and development of new machines for hemp processing are essential. The first step is to understand different processes which can be potentially used for hemp processing, which was the focus of this study.

Hemp processing includes two main steps: detaching and cleaning. Detaching is the technique of removing outer fibre from inner woody core of hemp plant. In this process, the bond between fibre and core is broken mechanically, resulting in fibre being detached from the core, and at the same time, hemp stalk is broken into pieces as well (Baker 2009). Thus the output of a detaching process is a mixture of different sizes of fibre, core, and chaff. Further cleaning is required to separate fibre from the mixture. Cleaning process is very important, as the cleaner the fibre is, the higher is the value. However, most existing cleaning machines are not effective. As the result, the end fibre has low purity (cores in fibre are considered as impurities). The lower purity means the higher core content in the fibre. Furl and Hempel (2000) reported 48-61% cores in a hemp mixture from a hemp processing line with a hammer mill. Using a field fibre processing machine, Gratton and Chen (2004) reported fibre purities ranging from 35% to 52%. These low fibre purities indicate that necessity of improving the effectiveness of fibre cleaning.

Sieving or screening is a traditional technique for general material cleaning. This technique separates material mainly with different particle sizes. The general structure of a sieve consists of several decks with different screen openings. Material is loaded onto the upper deck, small particles are separated through falling through the deck, and they can be further separated by additional decks placed beneath. Improvements in the separation efficiency of sieving methods have been done over the years, for example, introducing vibration action to the decks (Sweco 2003), fitting a Kroosher unit (a mechanical converter which converts monoharmonic oscillations to amplified polyharmonic oscillations) on the screen surface for seperating dry material (Vorster et al. 2002), and combining with air flows in separating grains with soluble (Liu 2009). Special attentions have been given to meet specific needs of an application. For example, double deck banana screens are an example that has been used for high capacity separation of iron ore and coal (Cleary et al. 2009a) and the ultimate screener which imparts multi frequency vibrations was developed for dry fine materials (Dass 2004).

Münder et al. (2004) has used a multiple ultra screen cleaner to clean hemp fibre, and the resultant fibre purity was 24-26%. A vibratory screen has been used for hemp fibre cleaning by Sadek (2010). The results showed that the screen method could remove the chaff and some small cores, but the resultant fibre still contained high percentage of cores. The reason was that hemp fibre tended to tangle together, which blocked the screen openings. Also, some cores were held within the tangled fibre and did not fall through the screens. Pecenka and Furll (2008) reported about a special screening device that consists of a fixed screen with oscillating comb mounted above the screen as transport aid. The comb helps to untangle fibre by loosening the fibre and core mixture. The fibre purity was improved by reducing significant amount of core content (from 50% to 7%) from a mixture. However, it proved successful only in traditional long fibre cleaning and its capacity, in terms of tones per hour, is low.

Carding is the most commonly used method for cotton processing industries. There are several types of carding machine used in industries. Carding is a mechanical process in which fibre clumps (A number of fibres in contact with each other) are opened, disentangled, and combed. Drum carding machines, consisting of a licker-in and main cylinder with wire grips, have been used for fibre carding. Carding parameters like cylinder rotating speed, carding duration, and feeding mass play vital roles in fibre processing. Gangwar (2009) found that fibre openness and cleaning efficiency increases with increasing licker-in speed. Cleaning efficiency also increased with decreasing the gap between two cylinder settings. This was because the closer setting of cylinders improved fibre opening ability as wire grip penetrated inside the clumps of fibres and removed trash particles. Göktepe et al. (2003) mentioned that the enhancement of licker-in speed increases short fibre and reduce fibre strength. Higher licker-in speed also produced more waste. Fibre transfer in carding machine from licker-in cylinder to main cylinder is important in an industrial application (Lee and Ockendon 2006). For hemp fibre cleaning, it is expected that carding also detach fibres which remain attached with cores. However, there have been no studies in this regard.

Another technique for cleaning is the floatation method which separates particles through density difference using fluid (water and air). Water acts as a separating layer between the light and heavy materials. The floatation method has been widely used in industries mainly in waste water treatment. Pongstabodee et al. (2008) separated mixed post-consumer plastic waste with combination of three-stage sink-float method and selective floatation technique. Carvalho et al. (2010) separated packaging plastics by froth floatation in a continuous pilot plant. The floatation method has been also used for separate biomaterials. Simonyan and Yiljep (2008) mentioned that by density difference, lighter particles such as chaff and dusty materials can be easily eliminated from grain materials by providing air flow. In this process heavier materials move downward. However, no publications have been found regarding separating fibre from core using the floatation method.

In summary, fibre cleaning is crucial to obtain fibre with high purity to meet the demand of fibre industries. Mechanically processed hemp fibre has high percentage of core, and some cores still remain attached to fibre. Hemp fibre has tendency to tangle with each other and cores. This is a great challenge for fibre cleaning. Traditional sieving technology is ineffective for hemp fibre cleaning due to the tangling nature of hemp fibre. Other cleaning technologies, such as carding and floatation have not been studied or used for hemp fibre cleaning. The objectives of this study were to examine

1. the effectiveness of detaching hemp fibre and fibre purity as affected by the carding parameters;
2. the fibre purity resulting from the floatation method.

4.3 MATERIALS AND METHODS

4.3.1 Feed material

The feed material used for the cleaning experiments in this study was collected from a hemp processing industry in Manitoba, Canada. The material was from unretted hemp (Alyssa variety) which had been processed prior to the experiment. The material (fig. 4.1) contained impurities, such as core pieces and chaff (very small particles). The intention was to remove the impurities from the mixture to obtain cleaner fibre. Prior to the experiment, the material was passed through 20 mm size of sieve in a Retsch sieve shaker (model AS 400, PA, USA) to remove chaff. The composition of the feed material was analyzed by separating it manually into core (core free of fibre), fibre (fibre free of core), and fibre-attached-with-core (fibre was not detached from core in previous fibre processing process). Each fraction was weighed using a balance (Model MS- 2500, Mars, Canada) to determine the initial percentages of these fractions. The results showed that overall the material contained 55% of fibre, 37% of fibre-attached with core, and 8% of core, meaning a initial fibre purity of 55%.

Fig. 4.1. Hemp feed material used for the cleaning experiments.

4.3.2 Carding experiment

In the carding experiment, a lab scale drum carding device was used to clean the feed material, as a commercial scale carding equipment was not available for the experiment. Figure 4.2 shows different components of the drum carding device used for this experiment. Feed sample is to be spread in the feeding tray. The rotating handle is used to manually rotate the main cylinder's shaft which is connected to the shaft of the licker-in cylinder through the chain drive. Feed material travels along the circumference of the licker-in cylinder and is transferred to the main cylinder surface. The material is cleaned by the stripping action occurred between two cylinders. Table 4.1 lists the geometric dimensions of the components of the carding device.

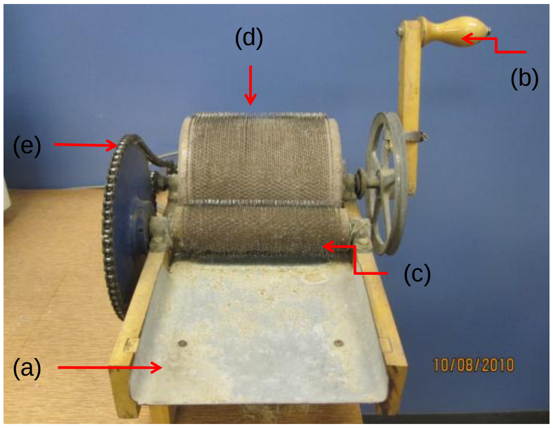


Fig. 4.2. Drum carding device: (a) feeding tray, (b) rotating handle (c) licker-in cylinder (d) main cylinder, and (e) chain drive.

Table 4.1: Geometry of the carding device.

Component	Specification
Feeding tray	Length: 250 mm
	Width: 210 mm
Licker-in cylinder	Diameter: 54 mm
	Spacing of hook: $8/\text{cm}^2$
	Height of each hook: 5 mm
Main cylinder	Diameter: 185 mm
	Spacing of hook: $9/\text{cm}^2$
	Height of each hook: 5 mm
Gear ratio	7:1, main cylinder to licker-in cylinder

4.3.3 Experimental design

A completely randomized design was considered for the experiment. From the feed hemp material, five different masses were taken, and they were 10, 20, 30, 40, and 50g, labeled as M1, M2, M3, M4 and M5 respectively. The licker-in cylinder of the carding device was manually operated for three different durations (2, 4, and 6 min.), labeled as T1, T2 and T3 respectively. Values of masses and duration were selected based on preliminary trials. Five different masses and three different durations gave 15 treatments for the experiment. For each treatment, three replications were performed. Therefore a total of 45 tests were conducted in the experiment.

4.3.4 Sample preparation

To ensure that all feed material samples were uniform and representative, the feed materials were first divided randomly into nine groups. Then five samples were taken from each group, giving a total of 45 samples for carding tests.

4.3.5 Test procedure

A feed sample with the desired mass was spread in the feeding tray as a “flat sheet” (Fig. 4.3a). Care was taken when rotating the handle to ensure a nearly constant rotational speed (approximately 50 rpm) for all tests. Waste (mixture of very tiny fibre, and core) was generated as the sample traveled along the circumference of the licker-in cylinder and nep formation was reduced as well. After traveling through the licker-in cylinder, the sample was transferred to the main cylinder surface (Fig. 4.3b). Material distribution was both transversely and longitudinally on the main cylinder. Between the licker-in and main cylinders, stripping action occurred. In both sections, inclined wire grip were noticed at the same direction (clockwise) of material movement. This is known as point to back arrangement which facilitated shredding of fibre from the licker-in cylinder to the main cylinder. Through the observation, one found that carding cleaned the fibre by two types of actions occurring simultaneously: 1) separating free cores from the feed sample and 2) detaching fibre which were originally attached to core in the feed sample. Figure 4.3c shows the end products (carded material removed from the cylinder and waste fell down at the bottom of carding device).

(a) (b) (c)

Fig. 4.3. Fibre cleaning tests using the carding device: (a) initial stage; (b) middle stage; and (c) end products.

4.3.6 Measurements

4.3.6.1 Composition of the feed material and carded material The composition of the carded material was analyzed by separating it manually into core, fibre, and fibre-attached-with-core. Each fraction was weighed to determine the percentage of each fraction. These fractions were used to determine the performance indictor of the carding, as described in the following sections.

4.3.6.2 Final fibre purity After fibre was carded, its purity was measured again, so that comparisons could be made between fibre purities before and after carding. Final fibre purity was defined as the mass of fibre in a carded sample divided by the total mass of the carded sample using the following equation:

$$f_a = \frac{(m_f)_a}{M - m_w} * 100 \tag{4.1}$$

Where,

f_a = fibre purity after carding (%);

$(m_f)_a$ = mass of fibre after carding (g);

M = total mass of feed sample (g);

m_w = waste from carding (g).

Similarly, equation (4.1) was used for calculating final core and fibre-attached-with-core fractions after carding.

4.3.6.3 Fibre yield Carding process also generated chaff and fine particles, i.e. waste. Percentage of the waste generated from the carding process affected the fibre yield. Fibre yield was calculated by using the following equation:

$$Y = \frac{1 - m_w}{M} * 100 \tag{4.2}$$

Where,

Y = fibre yield (%);

m_w = mass of waste from carding (g);

M = Total mass of sample (g).

4.3.6.4 Detaching effectiveness Another function of carding was further detaching fibre in the feed material which was attached with core. The detaching effectiveness was expressed by the following equation:

$$E = \frac{(m_{f/c})_b - (m_{f/c})_a}{(m_{f/c})_b} * 100 \tag{4.3}$$

Where,

E = Detaching effectiveness (%);

$(m_{f/c})_a$ = mass of fibre-attached-with-core after carding (g);

$(m_{f/c})_b$ = mass of fibre-attached-with-core before carding (g).

4.3.7 Floatation experiments

Using the floatation method, one experiment was carried out on individual samples of the feed hemp material: i.e. single fibre, core and fibre-attached-with-core (fig. 4.4) and another experiment was performed on the original mixture of the hemp feed material (fig. 4.1). It was expected that fibre would sink while core would float. It was also expected that behaviours of a single sample and a mixture would be different due to the fact that fibre tangling is not a concern in the case of a single sample, while it would be a concern in the case of a mixture. By comparing the results from the two experiments, one would know the extent of fibre tangle effects in fibre cleaning using the floatation method. Water tanks were used for the experiments. The size of the tanks was 554x443x335 mm (length x width x height). For floatation tests, 42 L tap water was used to fill the tank.

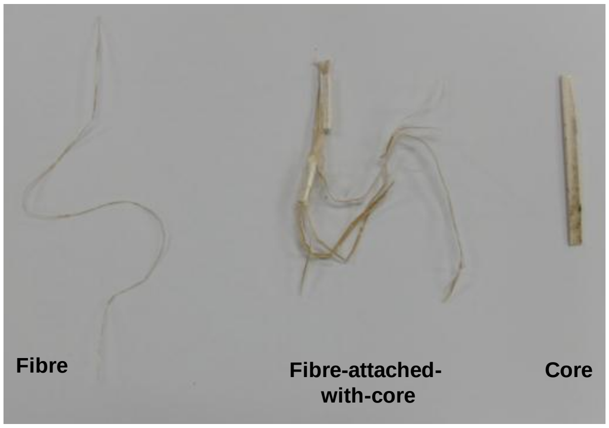


Fig. 4.4. Individual samples used for the floatation experiment.

4.3.8 Experiment using individual samples

4.3.8.1 Experimental design A completely randomized design (CRD) was applied for the experiment. Three sample categories (single fibre, core, and fibre-attached-with-core) and two agitating conditions (with agitation and without), forming six treatments. Three replications were done for each treatment, giving a total of 18 tests.

4.3.8.2 Experimental procedure and measurements For the experiment, single samples shown in fig. 4.4 were randomly picked from the hemp feed material and placed on the water surface at the centre of the water tank. For the agitation treatment, water was agitated manually by applying wave into water using a ruler. Care was taken to ensure the agitation action (moving the ruler for 120 circles) was nearly same for all tests. During each test, the sample in water was visually observed at 11 different times (0, 1, 2, 5, 10, 30 min, and 1, 2, 5, 8, and 24 hr). The observations were characterized by two simple scenarios: whether the sample floated or sunk, which was noted down as Float (F) or Sink (S).

Water absorption was also of interest as density of particle changes after particle absorbs water. In a case where fibre needs to be dried after being cleaned, the water absorption will give an indirect indication of energy requirement for the subsequent drying process. In applications of using hemp fibre for bio-composites, water absorption is also an important indicator of the bio-composites' quality (Kostic et al. 2008). For measuring water absorption in this study, the sample was taken out from water at the end of a test. After the free water was drained, wet mass of the sample was measured. Then it was dried by using a standard oven dry method (at 105 ºC for 24 hrs) (walker et al. 1993) in a dryer (SL FX14-2& FX 28-2, Oregon, USA). Wet and dry mass were measured using an analytical balance (Cole - Parmer Symmetry, PA). Water absorption was defined as

$$a_s = \frac{m_{wet} - m_{dry}}{m_{dry}} * 100 \tag{4.4}$$

Where,

a_s = Water absorption of single sample (%);

m_{wet} = Wet mass of single sample (g);

m_{dry} = Dry mass of single sample (g).

4.3.9 Experiment using a mixture

4.3.9.1 Experimental design Mixture of the hemp feed material shown in fig. 1 was used in this experiment. Three masses of mixture (10, 30, and 50 g) and two agitation conditions (with and without agitations) were used as treatments with three replications. Completely randomized design (CRD) was applied for the experiment.

4.3.9.2 Experimental procedure and measurements In a test, a mixture of hemp feed material with the desired mass was placed on the water surface at the centre of water tank. The agitation method was the same as that used in the experiment of single samples. Observations were made at different times: 0, 1, 2, 5, 10, 30 min, and 1, 2, 5, 8, and 24 hr. Floating materials (by-product) were collected with a sieve from the water surface, and then sinking material (product) were collected from the bottom of the tank. The collected floating materials and sinking materials were weighed, oven-dried, and weighed again separately. After drying, each of these two materials was manually separated into three fractions: fibre, core, and fibre-attached-with-core to evaluate the effectiveness of the floatation method for fibre cleaning, as discussed below.

Initial fibre purity of floatation experiment was measured similarly in carding experiment mentioned in section 4.3.1 in this chapter. Fibre purity of the product (sinking material) was determined as follows

$$f_p = \frac{m_{fs}}{m_s} * 100 \tag{4.5}$$

Where,

f_p = Fibre purity (%);

m_{fs} = Dry mass of fibre in sinking material (g);

m_s = Total dry mass of sinking material (g).

In similar way by following equation (4.5), core and fibre-attached-with-core fractions from sinking material were also calculated which were considered as impurities of the product.

The percentages of floating material and sinking material were determined by using the following equation:

$$F_m = \frac{m_f}{(m_f + m_s)} * 100 \tag{4.6a}$$

$$S_m = 100 - F_m \tag{4.6b}$$

Where,

F_m = Floating material (%);

S_m = Sinking material (%);

m_f = Dry mass of floating material (g).

m_s = Dry mass of sinking material (g).

4.3.10 Statistical analysis

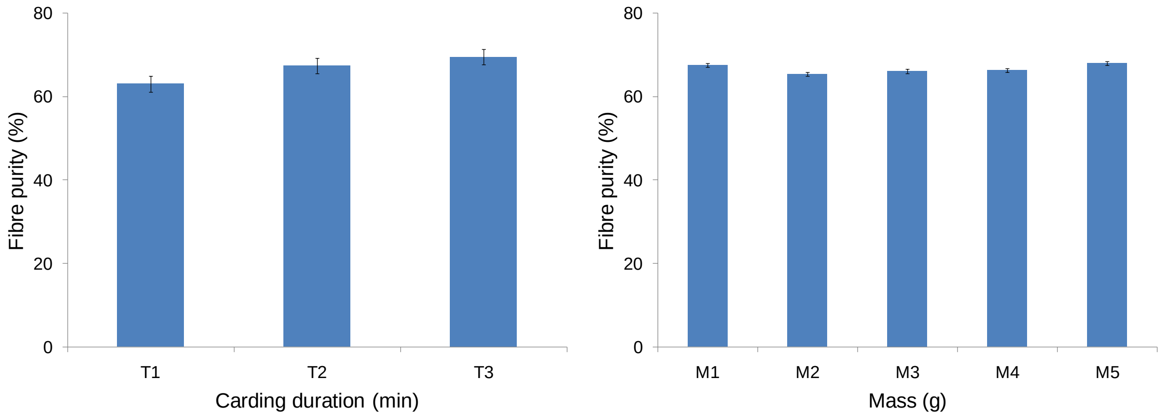
Statistical software SAS (version 9.1.3) was used to analysis the data both for carding and floatation methods. Two factor factorial analyses were performed. Analysis of variance (ANOVA) was carried out to see the level of significance of each factor and their interactions. It was found that interactions of the experimental factors were not significant. Therefore, main effects of each factor are presented in the following sections. Further t- test was conducted to see which factor varies significantly from others.

4.4 RESULTS AND DISCUSSION

4.4.1 Results from the carding method

4.4.1.1 Fibre purity from carding

Fibre purity for different carding durations after carding is presented in fig. 4.5a. Fibre purity showed a rising trend with the increasing carding duration. The highest fibre purity observed at the T3 treatment was 70%. Figure 4.5b shows fibre purities for various feeding masses, where similar purities were found for all different masses, and the average purity of overall masses was 67%. Although the data had very low standard errors, significant effects of treatments on fibre purity were not detected ($p > 0.05$). When compared with the initial purity of the feed material, 55%, carding improved the fibre purity up to 15%.

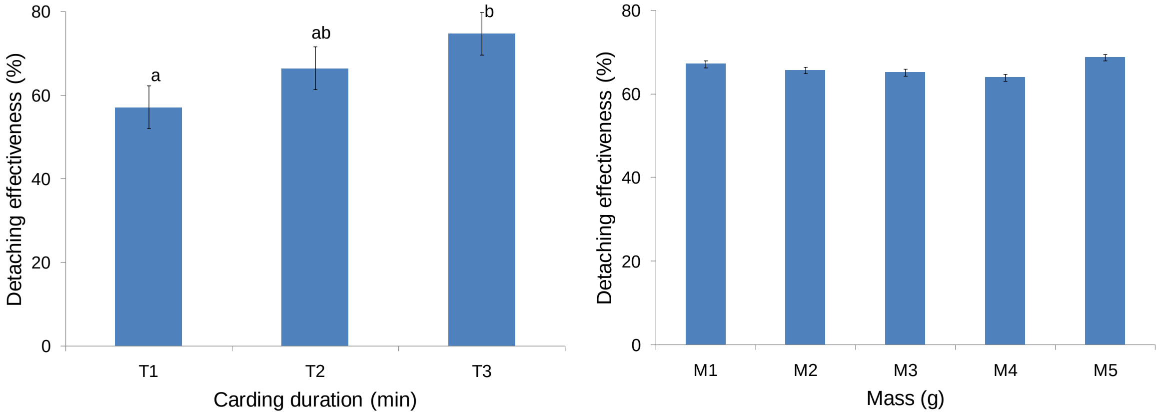


(a) (b)

Fig. 4.5. Means and error bars of fibre purity after carding: (a) for different durations; T1= 2 min; T2= 4 min; T3= 6 min; and (b) for various feeding masses; M1= 10g; M2= 20g; M3= 30g; M4= 40g; M5= 50g.

4.4.1.2 Detaching effectiveness of carding

The highest detaching effectiveness was noticed for the T3 treatment and it was 75%, the lowest detaching effectiveness was observed for the T1 treatment (fig. 4.6a). Longer duration allowed detaching more fibre from core; this effect was significant ($p < 0.05$). However, detaching effectiveness for various masses was not statistically different ($p > 0.05$), and average value of overall masses was 66% (fig. 4.6b).

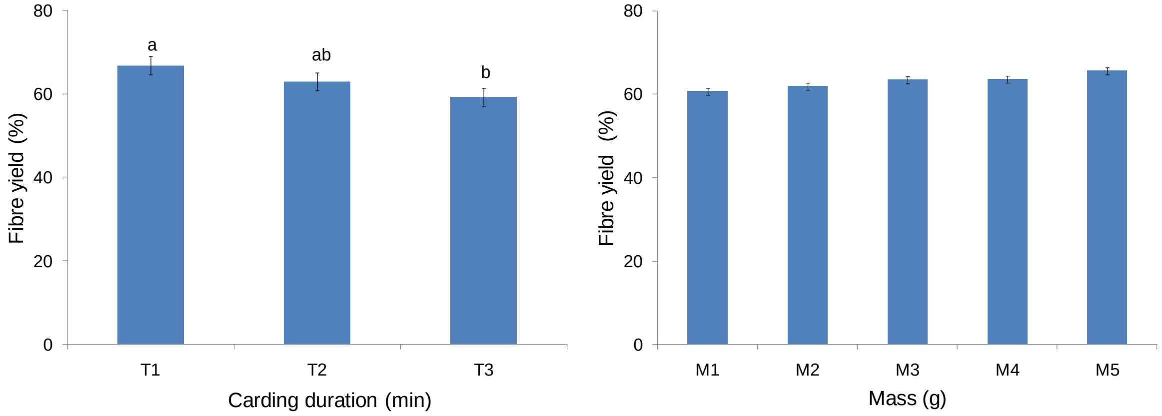


(a) (b)

Fig. 4.6. Detaching effectiveness of fibre from core after carding: (a) for different durations ; T1= 2 min; T2= 4 min; T3= 6 min; and (b) for various feeding masses; M1= 10g; M2= 20g; M3= 30g; M4= 40g; M5= 50g.

4.4.1.3 Fibre yield

Maximum yield was noticed for the T1 treatment, whereas the T3 treatment resulted in the minimum yield and the differences between treatments were significant (Fig. 4.7a). This was expected as waste production would increase with increasing carding duration. The results implied that carding for higher fibre purity may be compromised with less fibre yield, as up to 40% of the total mass was rejected to the waste stream. Fibre yield showed an increasing trend with increasing masses (Fig. 4.7b), but the trend was not significant ($p > 0.05$).



(a) (b)

Fig. 4.7. Fibre yields resulting from carding: (a) for different durations; T1= 2 min; T2= 4 min; T3= 6 min; and (b) for various feeding masses; M1= 10g; M2= 20g; M3= 30g; M4= 40g; M5= 50g.

4.4.2 Results from the floatation method

4.4.2.1 Behaviour of hemp material in water

4.4.2.1.1 Individual samples For the single fibre without agitation, it floated over the entire observation period of 24 hours (Table 4.2). When agitation action was introduced, the single fibre sunk after approximately 5 minutes, and stayed at the bottom of the tank for the rest of the observation period. This showed that agitation made differences in the behaviour of single fibre in water. However, for the single core it floated on water over the entire observation period, regardless of the agitation condition. Interestingly, the single fibre-attached-with-core floated at all times, implying that the effect of core has overcome that of fibre. The observation of fibre sinking, core and fibre-attached-with-core floating was desired, as it demonstrates that fibre can be separated from the rest of hemp material, resulting in improvement in purity fibre.

Table 4.2: Behaviour of individual fibre, core and fibre-attached-with-core in water.

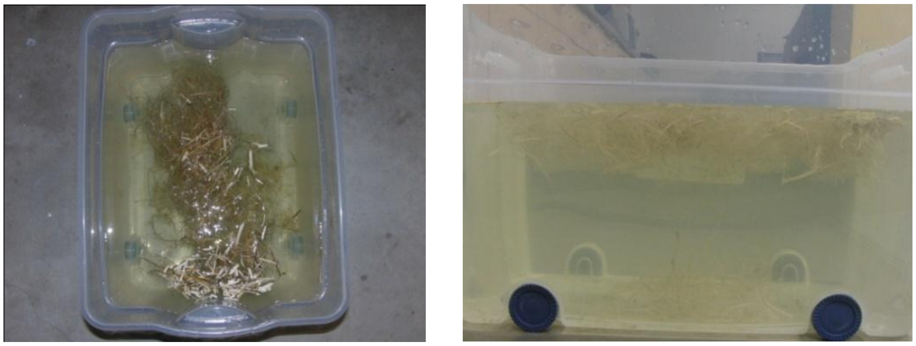
Sample	Agitation condition	Behaviour										
		0 min	1 min	2 min	5 min	10 min	30 min	1hr	2 hr	5 hr	8 hr	24 hr
Single fibre	Without	F	F	F	F	F	F	F	F	F	F	F
	With	F	F	F	F	S	S	S	S	S	S	S
Single core	Without	F	F	F	F	F	F	F	F	F	F	F
	With	F	F	F	F	F	F	F	F	F	F	F
Single fibre-attached-with-core	Without	F	F	F	F	F	F	F	F	F	F	F
	with	F	F	F	F	F	F	F	F	F	F	F

F= Float; S= Sink;

4.4.2.1.2 Mixture It is observed that without agitation the mixture remained afloat from 0 to 2 min (Table 4.3). Fibre started sinking after 2 min and kept on sinking until 10 min. After 10 min, it was noticed that both core and fibre-attached-with-core started sinking along with fibre and continued over the entire observation period. Finally after 24 hrs of observation, the whole mixture found in sinking condition except some cores which were free from entanglement. However, the mixture’s behaviour was different with agitation. After applying agitation, fibre started sinking after 1 min whereas core and fibre-attached-with-core was remaining float. Fibre kept on sinking up to 30 min. The sinking fibre stayed at the bottom of the tank on the entire observation period. After 30 min, no further movement was observed. This process is illustrated in fig. 4.8 where core and fibre-attached-with-core were floating on water (fig.4. 8a) and fibre sank at the bottom of the tank (fig. 4.8b) by making a clear difference.

Table 4.3: Mixture’s behaviour into water.

Time	**Without agitation**	**With agitation**
0 min	All float	All float
1 min	All float	Few fibres sunk, most core remained float
2 min	All float	Fibre kept on sinking, others remained same
5 min	Few fibres sunk	Mainly short fibre sank
10 min	Fibres kept on sinking	Short fibre remained sink
30 min	Few fibres sunk with little core and fibre-attached-with-core	No movement
1hr	Fibres kept on sinking with little core and fibre-attached-with-core	No movement, all samples remained stuck
2hr	Same as above	No movement, all samples remained stuck
5hr	Same as above	No movement, all samples remained stuck.
8hr	Same as above	Same as above
24hr	Sinking ended	Some long fibres started to sink



(a) (b)

Fig. 4.8. Hemp material behaviour in water tank with agitation (a) top view (b) side view.

4.4.2.2 Comparison between individual samples and mixture

From Tables 4.2 and 4.3, one can see that individual samples and mixture behaved differently without agitation. A single fibre floated at all times, whereas the mixture was sinking slowly over time. This difference may be explained by the fact that the fibres in the mixture tangled together as a heavier mass on the water, resulting in a better contact with the water and absorbing of more water. Thus, the density of the mixture would become greater than that of water, resulting in settling down to the bottom of the tank. However, with agitation, individual samples and mixtures showed same types of behaviour, i.e. fibre sunk after being agitated, and core and fibre-attached-with-core remained floated. This implies that agitation helped on untangling fibres for them to sink, and freed cores and fibre-attached-with-core for them to stay on the water surface. From the mixture’s behaviour with agitation, it was noticed that material movement in the mixture occurred within 30 min after agitation; and then all remained settled.

4.4.2.3 Fibre yield

Figure 4.9 depicts the product (sinking material) and by-product (floating) collected from the water tanks. These results reflect the fibre yields of different treatments. More sinking material would be desired under the same fibre purity. The amount of the floating material was found to be higher than that of the sinking material. For the 10g mass treatment, the fibre yield was 45.6 % of the total material mass. Lower yield (13.86 % and 10%) was observed for the 30 g and 50 g treatments. The possible reason might be the more entanglement of larger samples, which resulted in fibres being floating together with cores and fibre-attached-with-core.

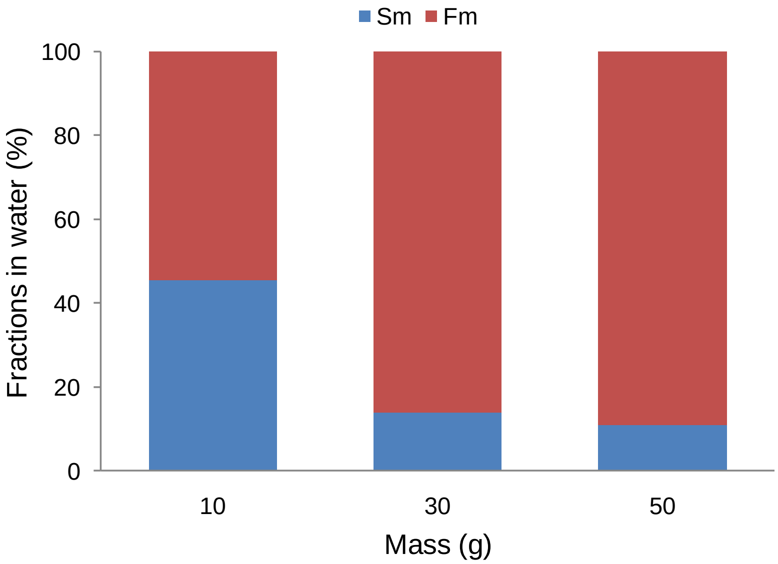


Fig. 4.9. Fractions of floating and sinking material in water tank with agitation.

4.4.2.4 Fibre purity from floatation method with agitation

For the treatments with different masses of mixture, various fractions in the sinking hemp materials are shown in Table 4.4. Fibre was found as the major part whereas fibre-attached-with-core and core was in very less amount for all treatments. The resultant fibre purity was as high as 90% for the two higher mass treatments. For the 10 g treatment, the fibre purity was slightly lower. These results indicated that the floatation method was very effective to obtain clean fibre. All treatments had similar amounts of impurities. Mass of the mixture did not show any significant effect ($p > 0.05$) on fibre purity and other impurity fractions. As compared with the initial fibre purity of 55%, the floatation method significantly improved the fibre purity. This method was more effective than the carding method, in terms of fibre purity. However, there were significant fibre yield losses when using this method.

Table 4.4: Fibre purity and impurity resulting from the floatation method with agitation.

Mass (g)	Fibre purity (%)	Impurity (%)	
		Core (%)	Fibre-attached-with-core (%)
10	85.58±4.68	3.93±0.97	9.61±5.51
30	89.94±6.93	4.46±3.47	8.62±2.92
50	89.92±3.81	3.70±2.54	6.19±2.11

4.4.2.5 Water absorption of individual samples

Fibre and core absorbed more water after agitation when compared to the treatments without agitation (Table 4.5). This was expected, as agitation could enhance the contact between hemp material and water. The water absorption of fibre was 17.22% over two agitation conditions, and that of core was approximately 12 times higher.

Table 4.5: Water absorption (%) of fibre and core.

Condition	fibre	core
Without agitation	7.16	188.20
With agitation	27.36	224.50

4.5 CONCLUSIONS

Carding and floatation methods were investigated to clean the hemp material which originally had 55% fibre purity. Through carding, the fibre purity was increased up to 70% and the highest fibre yield from the carding method was 67%. Longer carding duration could improve the effectiveness of detaching fibre which was originally attached to core. Carding duration did not affect the fibre purity. Longer duration caused higher fibre yield losses. Similarly, amount of material being fed into the carding device did not show any effects on the fibre purity and other measured variables. Data from the floatation tests of individual fibre and cores showed the nature that fibre sinks and core floats in water. This phenomenon justified the feasibility of using water to separate fibre from core. Through the floatation tests, one found that agitation of water enhanced the separation of fibre with the rest of hemp material. The resultant fibre purity ranged from 85 to 90%, depending on the amount of material being put in water. Higher feeding mass produced fibres with higher purity, but resulted in lower fibre yield. This needs to be further verified in the future. Regardless, the fibre purity has been significantly improved when compared to the 55% purity of the original feed material. This demonstrates that floatation method is a promising technique for fibre cleaning. However, the fibre yields were very low and need to be improved in the future. Also, the drawbacks of this method were the final fibre product being wet and the generation of waste water.

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5. CONCLUSIONS AND RECOMMENDATIONS

In this study, three different methods were investigated for cleaning a decorticated hemp material with a fibre purity of 55%. As a prerequisite of the aerodynamic method, aerodynamic properties (terminal velocity and drag coefficient) of fibre and core particles were measured. Terminal velocities of core particles were significantly higher than those of fibre particles. Based on the differences in terminal velocities, the aerodynamic method would be feasible for separating mixtures of fibre and core particles. However, after testing mixtures of fibre and core particles, one found that the method was effective only for individual fibre and core particles which were free of entanglement. The method did not work for a random mixture of fibre and core, which actually represent the reality, due to particles being tangled together. Using the carding method, a fibre purity of up to 70% could be achieved. Higher fibre purity (up to 90%) was obtained using the floatation method. From this study, one concluded that the aerodynamic method would not work for hemp fibre cleaning, unless the tangling problem is solved. Using the carding and floatation methods for fibre cleaning, fibre purity could be significantly improved. However, both methods would cause some losses of fibre into the waste streams.

Present study recommends some future works from three different methods of cleaning. The aerodynamic method should be tested further for bulk fibre and core. In case of the carding method, a larger scale carding machine should be used and tested with larger feeding mass and different operational speeds. For the floatation method, controlled mechanical agitation can be introduced to examine its effects on the separation efficiency.

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