DESIGN AND EVALUATION OF AN ON-FIELD

HEMP FIBRE PROCESSING MACHINE

BY

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Biosystems Engineering
University of Manitoba
Winnipeg, Manitoba

April, 2002

0-612-76952-6

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

Machinery to process bast fibre from hemp stalks directly on the field is currently non-existent or unavailable to hemp producers in Canada. It is believed that having such machinery available to producers would improve the overall efficiency and economics of bast fibre separation, and would help create new opportunities and markets for hemp fibre. The main objectives of this study were to design, build, and test a prototype of an on-field hemp fibre processor. The research was focused on building a mechanical means of picking up raw hemp stalks directly from the field in a harvested condition, and to perform separation of bast fibre and core in a continuous process.

The prototype used in this study was designed by analyzing the major functions of existing hemp processing machinery. The prototype was then constructed by modifying a conventional forage harvester to perform separation by breaking and scutching. A straw walker from a conventional combine was attached to this machine to separate loose core in the processed raw material by shaking and screening.

The prototype was tested under field conditions for several different treatments. The experimental factors considered were forage harvester configuration, straw walker speed, retting time, and material feedrate. Analysis of variance was performed on the field test variables and a factorial model was applied to determine significant effects of the different treatments.

The variables obtained from the field tests consisted of measurements of the amount of bast fibre and core in samples obtained from the two different outlets of the prototype. These measurements were obtained using a flotation method to separate bast fibre and core from samples of material obtained at each outlet of the prototype.

A maximum of 71 % of the core was removed from the raw material by the prototype. The modifications made to the forage harvester also proved to be significant in yielding a maximum of 10% more fibre and removing a maximum of 20% more core from raw material. Increases in time were found to have a positive effect on separation effectiveness of the prototype, and the reason for this was speculated to be the higher level of retting existing in the stalks that were processed 7 d after the initial harvest. Increases in feedrate of the material into the prototype up to a value of 18 t/h were found to have a detrimental effect on the separation efficiency of the prototype. Differences in straw walker speeds from 150 – 200 rpm did not prove to have an effect on the performance of the prototype. Significant bast fibre losses (i.e. a minimum of 36%) occurred. These losses were found to be in part due to a high fraction of these fibres (i.e. a maximum of 16%) which measured 38 mm in length, fell through the holes of the straw walker due to their length.

ACKNOWLEDGMENTS

I would like to thank the Manitoba Rural Adaptation Council for the financial support obtained in conducting this research.

I would also like to thank the following individuals for their contribution to this research.

- Dr. Ying Chen, for her generous support and guidance as my advisor;
- Dr. Martin King, for his generous support and guidance and also for serving as member of my thesis committee;
- Dr. Daniel Mann for serving on my thesis committee;
- My family, and Shanon, for their love and support;
- The technical support staff of Biosystems Engineering; Matt McDonald, Dale Bourns, and Gerry Woods, for their contributions to the work in this project;
- Jim Philp and Jack Putnam for sharing their ideas, knowledge and expertise
- Miroslav Bednař and colleagues at VULV S mperk, for their generous contribution in knowledge;
- The Institute of Natural Fibres, in Poznan, Poland, and;
- Van Doan, and David Thiele, for their help on this project.

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1. INTRODUCTION

1.1 General

Modern hemp production requires methods of mechanization which are currently either non-existent or unavailable on a commercial scale in North America. Such machines are needed for the harvesting of all individual parts of the hemp plant; seeds, leaves, and bast fibre. The research undertaken in this study attempted to develop and evaluate a mechanized system for processing the bast fibre from raw hemp stalks directly on the field. Such machinery would provide Canada's hemp producers with an effective means to harvest bast fibre from hemp stalks.

This system would be better than current existing hemp processing machinery because its ability to operate directly in the field would reduce the transportation costs associated with moving raw hemp stalks off the field. This would result from the ability to obtain bast fibres separate from the core of the stalk and to transport these materials to two different processing facilities. This would also help reduce the amount of warehouse space needed to house the raw material. Such a process would ensure optimal returns for each producer because it is suspected that the value of the raw material obtained using this technology would be increased.

Making such machinery available to producers on a commercial scale would also create many manufacturing opportunities. Profit and jobs would be generated by industries manufacturing this machinery and selling it to producers. Since hemp and other similar fibre crops are grown in countries all around the world, the potential for export sales of the fibre processing machinery to other countries is a distinct possibility.

The realization of an on-field hemp fibre processing machine would also help create new markets for hemp fibre and help encourage the use of hemp in areas where cost has been a prohibitive factor. Generally, high costs are encountered when hemp is processed in centralized processing facilities due to the high investment and overhead capital of such facilities, as well as high costs associated with transporting the material to and from the facilities. On-field fibre processing machinery would help eliminate these costs resulting in a more affordable resource for industrial use, thus promoting its use and activity.

1.2 Objectives

Primary objective: The primary objective of this study was to design and build a prototype of an on-field hemp fibre processor. This included building a machine capable of picking up raw hemp stalks from a windrow lying in a field, and then separating bast fibre and core in a continuous process. It was also desired that the prototype would deliver the separated materials to different outlets so that both could be collected individually.

Secondary objective: The secondary objective of this study was to determine the effectiveness of the prototype under actual field conditions. This was to indicate whether the designed functions of the prototype were working as expected. The field tests would also serve to identify optimal operational parameters of the prototype and assess the effectiveness of the prototype under different field conditions.

2. REVIEW OF LITERATURE

2.1 Hemp plant

2.1.1 General The plant species Hemp, or *cannabis sativa*, is a herbaceous annual plant native to Asia that is most commonly known as the source of marijuana (Encarta online). Several cultivars of hemp exist, all of which vary in morphological and agronomic characteristics. The cultivars native to latitudes between 28 and 58° are typically adopted for the cultivation of Hemp in the European Union (EU) and Canada because of the products which may be produced from seed and stalk and due to the fact that they have low concentrations of tetrahydrocannabinol THC, the active drug in marijuana (de Meijer 1995).

2.1.2 Physiology In Canada, the varieties grown attain an average height of 2.5 m. The stem averages 7 mm in diameter and consists of an inner hollow core with an outer tissue consisting of long bast fibres (Fig. 2.1). The inner core consists mainly of parenchyma cells and is composed of 38% cellulose, 31% hemi cellulose, and 18% lignin (Bócsa and Karus 1997). These values vary slightly from variety to variety, and are presented here for an Italian cultivar. Fibres found in the core are thin-walled and have a length of 0.55 mm. The bast fibres are generally much longer (5-40mm) and have a composition of 67% cellulose, 13% hemi cellulose, and 4% lignin.

The proportions of bast fibre in hemp stalks also vary between cultivars. Values of bast fibre mass proportions range from 16-35% among different cultivars, while core fibre proportions range from 52-68% (de Meijer 1995).

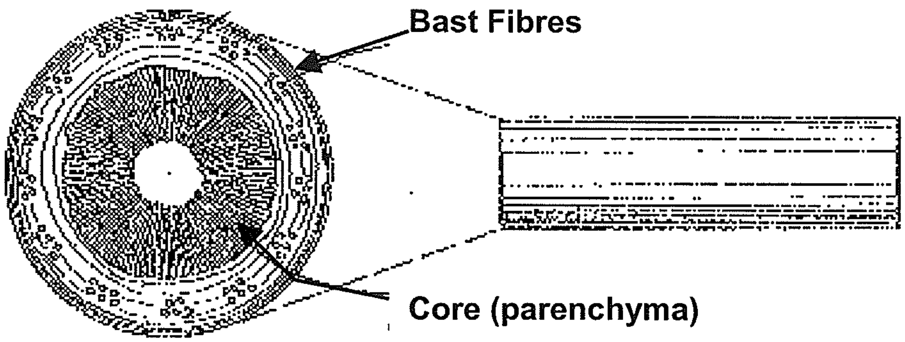

Fig. 2.1 Structure of hemp stalk (Adopted from Armstrong 1957)

2.2 History of hemp cultivation in Canada

In most western countries, the cultivation of hemp has been prohibited since the 1930s (Kearns 1996). In the early 1990s, certain varieties of hemp were allowed as crops in the EU. In 1998, Canadian federal legislation was evoked under the amendment of bill C-8, to allow the cultivation of hemp for industrial purposes under a specially acquired permit. Since then, varieties approved for production in the EU have been grown on a commercial scale here in Canada.

The cultivation of hemp in Canada achieved a peak in 1999 when approximately 14,500 ha of hemp received approval for cultivation (Alberta Agriculture 2000). Since then this number has decreased. In 2001, Health Canada approved only 1300 ha of hemp (Health Canada).

The reason for this rapid decrease is being blamed on a lack of a market for hemp based products. In Manitoba, the production of hemp seed exceeded the actual market demand. There is presently little demand for hemp bast fibre (Alberta Agriculture 2000). However, many in the industry feel that the future is still promising for the years ahead.

2.3 Uses of hemp bast fibre

2.3.1 Current markets The market opportunity for hemp bast fibre comes from products which can be made with both the bast fibre and core fibre, or either of the two components separately. Very little market presently exists for hemp straw in Western Canada (Alberta Agriculture 2000). There exists two processing facilities in central Canada which manufacture pure hemp products: Hempline Inc. (Hempline Inc. 11157 Longwoods Road, Delaware, ON N0L 1E0), and Kenex (Kenex LTD., Winter Line Road, Chatham, ON N7M 5J8) (Manitoba Agriculture 2000).

Hempline processes raw hemp stalks into both bast fibre products and core fibre products (Hempline inc 2001). Of the bast fibre products, Hempline produces fibre with levels of purity (free from core components) ranging from 85—99%. As well, fibre is also made available in staple lengths of 12.5—125mm. The fibre is marketed for applications ranging from composite materials for automotive and furniture components, nonwoven mats, paper, cement, and plaster filler.

With the core fibre products, Hempline produces quality animal bedding, and also grinds down the fibre for use in thermoplastics. Kenex produces a similar product line and markets bast fibre under the same uses as Hempline, but adds that its use can be adopted in wallpaper, acoustics, and friction materials (Kenex 2001). For a schematic of the markets for Kenex hemp products, refer to Fig 2.2.

2.3.2 Potential market uses of hemp fibre Most of the interest in hemp fibre comes from its potential as a replacement or additive fibre source in products that already use other natural or man-made fibres. This potential exists due to the fact that hemp fibre has many desirable properties that can be exploited to improve the products in which they are used.

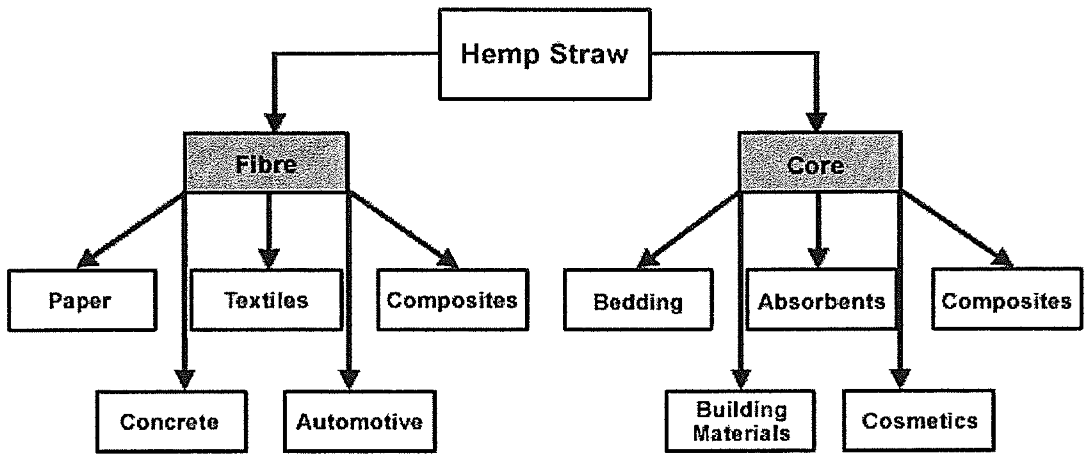

Fig. 2.2 Kenex marketing for hemp fibre products (Kenex 2001)

These properties are as follows:

- Biodegradability;
- High strength to mass ratio;
- High modulus of elasticity (stiff);
- Production is more ecologically sound than man made fibres;
- Non toxic and non abrasive, and;
- Fibres are generally longer than other natural fibre sources.

Hemp fibre use in fibre reinforced composite materials is an area of growing interest in Canada and in several other countries. The use of hemp in these applications is thought to capitalize on the advances that the flax fibre industry has been making in Europe (Manitoba Agriculture 2001). There, flax fibre has been used successfully in compression moulding of automobile components. Components such as side door panels and rear window panels are made of flax fibre reinforced plastics for manufacturers such as Volkswagen, Audi, Mercedes, Opel GM, Ford, Fiat, Renault, Peugeot, and Volvo. Flax fibre provides advantages for use in these products due to the fact that it is biodegradable, has good sound absorption characteristics, is lighter than the glass fibres presently used, and does not crack in compression moulds (Šmirous and Krmela 1994). Hemp is similar in physical and chemical composition to flax, thus its adoption in these processes are envisioned by many.

2.4 Hemp cultivation

Hemp may be sown successfully using conventional seeding equipment (i.e. air seeders, disk-press drills, hoe-press drills) (Manitoba Agriculture and Food 2001). Suggested seeding rates for a hemp fibre crop should be approximately 50 kg/ha, while for a seed or grain crop the seeding rate should be approximately 18 kg/ha. Seeding depth should be as shallow as possible, but into moisture which is typically 19– 70 mm (Manitoba Agriculture and Food 2001). Greater depths are possible, however, they have been found to delay emergence, and thus reduce the competitiveness of the stand. Fertilizer is generally not required for hemp, if it is planted in a suitable rotation, however, good results have been found in Manitoba soils containing total amounts of 100, 50, 67, 17 kg/ha of N, P_2O_5, K_2O, and S respectively (Manitoba Agriculture and Food 2001).

Hemp is a photosensitive crop, and thus the time that it will take to mature varies with the time that the crop is planted. This time period also typically varies between cultivars (de Maijer 1995). Recommended maturing times for most varieties are within 120-150 days (Manitoba Agriculture and Food 2001). Hemp grows well on various soil types, however, the crop is very sensitive to saturated soils. Prolonged exposure to wet soil conditions results in stunted growth, yellowing, and death of plants (Manitoba Agriculture and Food 2001).

2.5 Harvesting practices

The time of harvest is dependent on the specialized end use of hemp. For fibre, the best quality is obtained by harvesting at the flowering stage. On average this occurs 50 d before maturity (de Maijer 1995). If seed is desired, harvesting should occur when the first signs of shelling are found on the seed head of the plant. In Manitoba, this normally occurs 120-150 d after seeding. Harvesting for seed is typically performed in Manitoba by direct combining with a cutter head raised 1.2-1.5 m above the ground (Manitoba Agriculture 2001). This process attempts to harvest only the top portion of the plant where the seed is found and prevents excess plant material from flowing through the combine. As a result, the remainder of the plant stalks remain planted in the ground, and thus the integrity of stalks is preserved except for those that are run over by the combine. Consequently, the fibre is normally harvested using a conventional swather with a cutterhead width of approximately 7 m, or a mower conditioner (Cloutier 1999).

The swaths are then allowed to dry on the field to a typical moisture content of 15% w.b. and then baled with a conventional round baler (Bocsa and Karus 1997). The bales are then transported off the field for storage. The use of mower conditioners is preferred by many Manitoba producers because the stalks dry faster than if they were unconditioned. This is especially important when considering the seasonal temperature is generally colder and more humid at the time of seed harvest. Liu et al. (2000), found that drying of plant stalks in early fall was improved dramatically as a result of conditioning. In their experiment, conditioned hemp was dried to a safe moisture content for baling within 72 h. The control, or unconditioned plot, never achieved safe drying moisture content during the entire length of the experiment (i.e.168 h). Another advantage to conditioning is that hemp stalks pack better in a round bale after being crushed by the conditioning rolls. This results in tighter bales and thus more material can be transferred off the field with fewer trips.

A conventional windrow harvester was modified by Chen et al. (2002), to test a new method of harvesting hemp stalks. In their study, a conventional windrower was modified to achieve a maximum cut height of 1.58 m. This allowed the cutting of seed heads off hemp stalks higher than would be obtained by a conventional combine. The windrower had the ability to cut and place seed heads in a separate windrow. In the same operation, the cutter bar on the windrower would then be lowered and would cut the remainder of the standing stalks and place these in a separate windrow. This allowed two separate operations to be performed on the two different windrows (i.e., combining and baling).

2.6 Fibre processing

2.6.1 General In this study, it was important to review the existing techniques and practices of hemp fibre processing, to design a new field technology. This led to the examination of many existing processing developments in Europe and North America. They are presented in this section to gain an insight into some of the machinery used and the principles adopted in the processing of fibre.

The scope of this analysis is not limited to hemp. Many of the techniques presented in this section deal primarily with the processing of flax fibre. They are presented here because they offer significant background knowledge in the development of new techniques for processing hemp fibre due to the fact that both hemp and flax have similar physical and chemical characteristics. In most cases, hemp has already been successfully processed either on a commercial scale or experimental scale with these techniques.

2.6.2 Traditional processing of fibre flax The fine linen industry has been present in Europe for several decades. This has led to the development of specialized machinery to produce clean, fine fibre from flax straw for the spinning of linen yarn. Over the past 30 years however, the cultivation of fibre flax suitable for wet spinning of linens has declined substantially in several countries in Europe (van Soest 1993). Consequently, new harvesting and processing techniques for this industry have not been developed, and most of the techniques and machinery date back to earlier times.

In preparation for processing, flax is de-rooted and laid on the field in swaths perpendicular to the machine's travel. They are left on the field for 5—6 weeks. During this time, fungal agents are permitted to grow on the stalks and degrade parenchyma tissues to isolate fibres (Akin et al. 1998). This process is commonly known as dew retting, and is most successful in a temperate climate with little precipitation (Šmirous and Krmela 1994). This effectively provides separation of the bast fibres from themselves and the core of the stalk. Special care must be taken so that stalks are not over retted. This occurs when field conditions are too moist, and it may lead to destruction of the fibres. A part of the retting process, the stalks are turned or raked 2—3 weeks after harvest which aids in the uniformity of the retting.

Following the retting phase, the fibre is then round baled and transported to a scutching mill. There, specialized machinery opens the bale and feeds the material into a turbine scutcher. In the first stage of this process, the stalks are passed between two indented rollers, which effectively crush and break the stalk at regular intervals. The machine then grips the material at the centre of the stalk with a belt and transports it through a series of intermeshing, rotating, paddled rolls (Fig 2.3). The paddles on the rolls beat the stalks and effectively scrape the bits of core off the fibres. This action is effectively known as scutching. Once the material has passed through the machine, the bast fibres of the stalk are entirely clean of any core fibres. Because the material is gripped at the centre, only the fibres gripped by the belt remain attached to it as the material is passed through the machine. The shorter fibres are removed from the stalk ends and carried away with the core fibres in what is referred to in the industry as "tow". These fibres are generally coarser and are retained for use in lower valued products, such as coarse yarns.

A Belgium company, Depoortere, manufactures turbine scutching machinery. These turbine scutchers can process 1.1 t/h of raw material. Typical output of long fibres from these machines is 13.5% of total stalk mass and 16.5% for tow fibres (Šmirous and Krmela 1994). It is important to note, however, that these levels may vary depending on whether the stalks were properly retted.

In previous research, hemp stalks were processed using a Depoortere turbine scutcher (Bioregional Development Group 1994). Prior to feeding into the scutcher, the stalks were cut into 1.5 m lengths to fit of these stalks into the machine. The experiment yielded approximately 8.5% of long fibre suitable for spinning into yarns.

2.6.3 Processing of fibre using decortication machinery Over the last few decades in Europe, the focus on processing fibre flax for textiles has changed dramatically due to new flax fibre spinning technologies and new end uses for flax fibre. One new spinning technology is the process of cottonizing flax fibres, where the processed

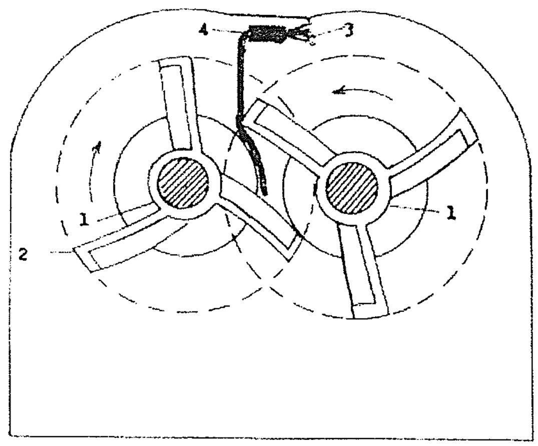

Fig. 2.3 Turbine scutcher (Mojžíše 1988)

fibres are cut into lengths of approximately 25 mm and then combed finer to resemble the same properties as cotton fibres. This process allows the spinning of flax textiles in more commonplace cotton spinning mills.

The advantages that the flax industry receives from this process is that the machinery used to spin flax textiles no longer needs to be as specialized as before and can be used for the spinning of other textiles. The length of the fibres also allows the blending of flax fibres with other natural fibres or synthetic fibres in these machines. Another significant advantage is that instead of partitioning the fibre in the primary processing stage between long fibre and tow, all of the fibre may be used, thus increasing the average return of processed fibre.

A decortication machine performs primary processing of flax fibre for use in a cottonization process. These machines process raw flax stalks or scutching tow into a clean useable fibre source for cottonization processes. These machines have also gained popularity for areas where non-textile applications of processed fibre are desired because this machinery provides a higher yield of useable fibre and the condition of the processed fibre is often suitable for these applications. Decorticating machinery also has the advantage that the material fed into the machine does not need a parallel orientation. Consequently, the process of harvesting stalks is greatly simplified because special machinery is not needed to keep the de-rooted stalks in a perpendicular arrangement in swaths before and after seed extraction. As well, retting time is generally shorter than that needed for scutching machinery; therefore, the risk of spoilage caused by over retting on the field is reduced.

Decortication machinery uses a series of intermeshing fluted rolls to crush and break flax straw in order to release bast fibres from core fibres (Fig 2.4). These machines typically consist of eight pairs of rolls. Material is unloaded from a bale at one end of the machine, and is moved along the line by movement between the top and bottom rolls. The rolls have a diameter of 180 mm and, depending on their position in the series, they have different types of teeth (Charle and Temafa 1997). At regularly spaced intervals along the line, a shaking apparatus is used to separate loose core from the bast fibres (Fig 2.5). The shakers consist of a series of fingers which move back and forth, which agitate the material and allow the core to fall through the holes of the perforated screen below.

At the end of the shaking apparatus, a series of feed rolls grip the material and present it to the blades of a turbine scutcher. The scutcher consists of a rotating drum, 1.5 m in length, with typically 12 or 24 blades (Charle and Temafa 1997). This process allows the material to be metered in at a constant rate and presents it to the scutching blades so that the blades can systematically scrape off bound core fibres from the bast fibres (Fig 2.6). The number of these shaking and scutching units in the line varies from 3 to 4 depending on the level of cleanliness that is desired of the fibres (Charle and Temafa 1997).

One manufacturer of such equipment is Charle and co., of Belgium (Charle & co. Driekerkenstraat 74/1 B-8501, Bissegem-Kortrijk, Belgium) and its German subsidiary, Temafa (Temafa Maschinenfabrik GmbH, Postfach 20 09 07, D-51439, Bergisch Gladbach, Deutschland). They market their decorticating line under the name "Lin-Line" and claim that it is suitable for processing fibre flax as well as hemp straw (Charle and

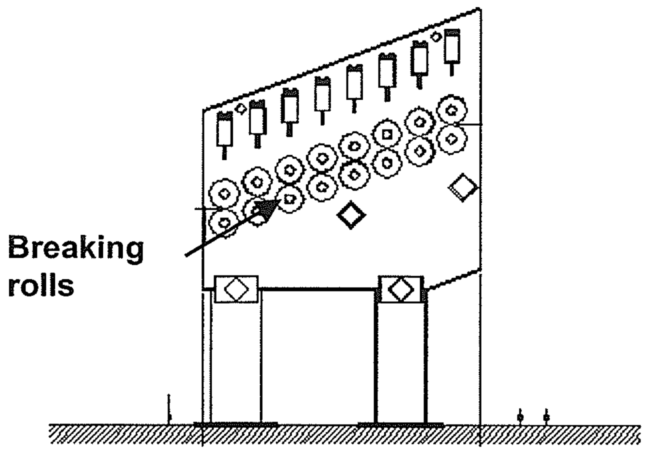

Fig. 2.4 Schematic of flax straw breaker (Charle and Temafa 1997)

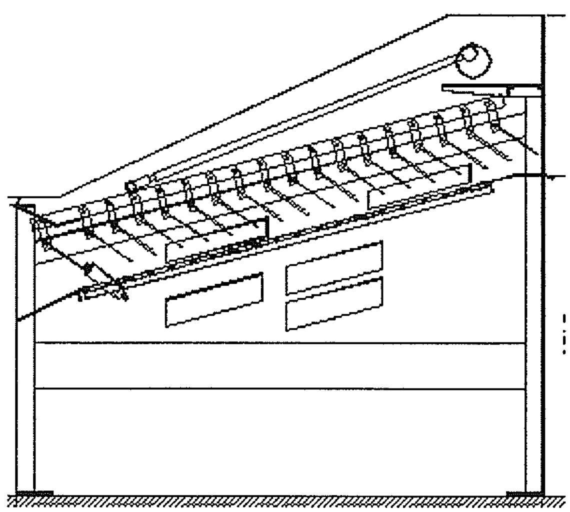

Fig. 2.5 Schematic of flax shaker (Charle and Temafa 1997)

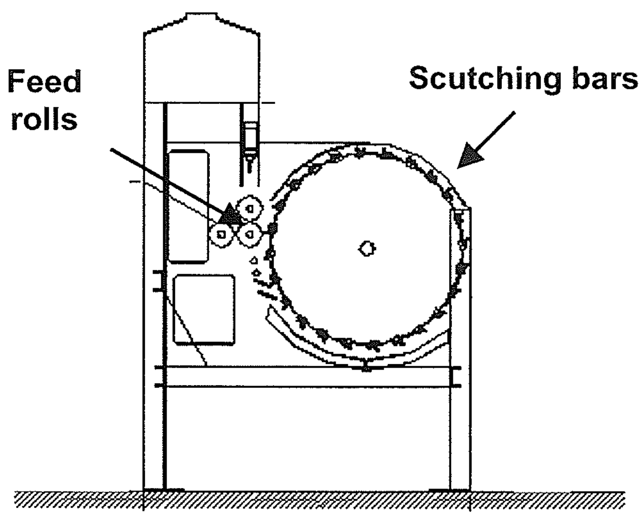

Fig. 2.6 Schematic of fibre scutcher (Charle and Temafa 1997)

Temafa 1997). The processing line has a length of approximately 20 m and can process 2 t/h or raw material (Charle and Temafa 1997).

Another model has been developed by the Silsoe Research Insititute in the United Kingdom (Silsoe Research Institute, Wrest Park, Silsoe, Bedford MK45 4HS UK). This model is called the "Fibrelin" and has been used successfully to process hemp straw. The model uses a series of breaking rolls to crush stalks and release fibres which is then followed by a high speed rotor with steel pins, which effectively refines the fibres and releases core fibres from them (ACTIN 1999). This machine has been successful in producing yields of 20-25% hemp fibre from raw straw (Bioregional Development Group Surrey UK 1994).

2.6.4 Non-textile methods Many recent developments have been made for the processing of hemp fibre in which the quality of the fibre produced is focused on a non-textile application. While textile quality hemp receives the highest price due to its quality and versatility, its use in quality textiles is limited by the greater availability of fibres that are better for these uses. Also, as mentioned in previous sections, there exists much interest in using hemp fibre in many different types of applications, ranging from nonwoven mats for composite materials, fillers, and paper. For use in these applications, hemp often does not need to be processed to the same quality as for textiles. Generally, the fibres do not need to be as clean, and the fibres do not need to be of a specific length and fineness. For these reasons, many efforts are being made to find less complex and more efficient processing procedures.

One such development is being realized at the Institut fur Agrartechnik in Germany (Institut fur Agrartechnik, Potsdam-Bornim, Germany). In this study, a modified hammer mill was used to process raw, un-retted hemp stalks (Fig 2.7) (Furl and Hempel 2000). The unit consists of a rotor with several hammer blades attached to it (1), which rotates in a cylindrical casing (2), with an inlet at the top of the unit (3), a perforated screen at the bottom of the casing (4), and a tangential outlet at the bottom of the casing (5). The perforated screen has rectangular holes, which measure 32 mm by 6 mm and have the long end of the holes oriented perpendicular with the tangential motion of the hammers. There are also special impact elements (6), which could be introduced in the casing to improve the effectiveness of the unit.

Material is introduced at the top of machine by a metering device, and the fibres are separated by impact of the material by the hammers against the inside of the casing. The stalks were pre-cut to a length of 80 mm prior to feeding into the machine. Performance trials were completed by introducing different kinds of impact elements into the casing, and also by operating the hammers at tangential speeds ranging from 33 to 66 m/s (Furl and Hempel 2000). Trials were also repeated for material feed rates of 0.5 to 1.5 t/h. Separation efficiency was measured for each trial, along with fibre length, fibre fineness, and fibre tenacity (strength).

Separation efficiency was measured by taking three ratios for the material output; the ratio of separated output fibres to the input mass, the ratio of the mass of core in the core output flow to the input mass, and the ratio of fibres in the core output flow. When an impact plate element was used in the casing, 60% of the core was separated from the output fibre.

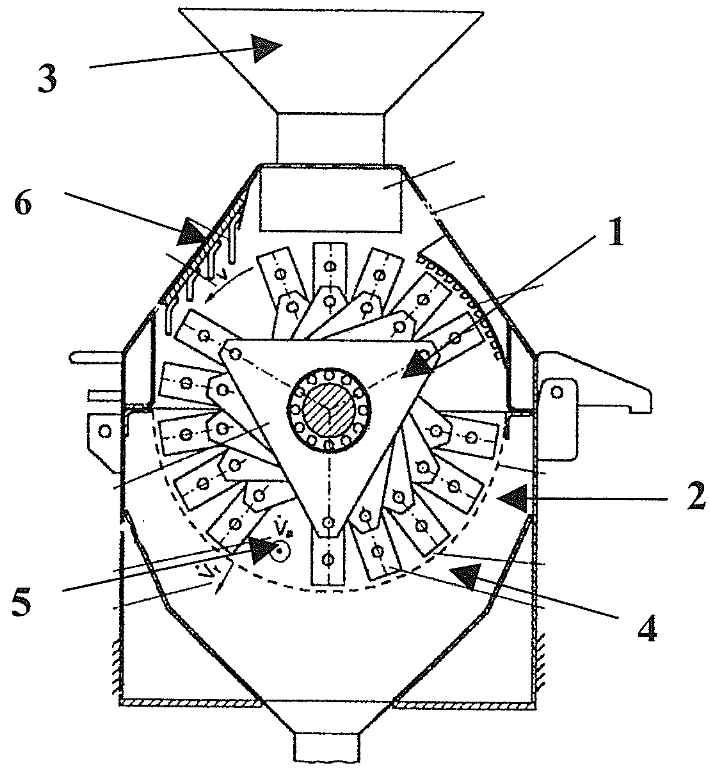

Fig. 2.7 Modified hammer mill (Furl and Hempel 2000)
1-Rotor, 2-Casing, 3-Inlet, 4-Screen, 5-Outlet, 6- Impact elements

In the hammer speed trials, between 38-61% of core was removed from the material as a result of the speeds tested. In these trials, the ratio of fibre in the core output ranged from 1-4%.

Fibre length was measured for treatments of hammer speed. Results from these trials were presented as cumulative frequency distribution curves for each trial. Fibre fineness was measured for different hammer speeds and was found to vary between 9.36 tex at a tangential speed of 33 m/s and 6.35 tex at 57 m/s. Units of tex are commonplace in the textile industry for describing fibre fineness; 1 tex equals the equivalent mass of 1 km of material in g (Morton and Hearle 1962). Fibre tenacity did not differ significantly from hammer speed treatments. As well, the fibre tenacities observed (0.39-0.43 N/tex) were not significantly different than that of un-processed hemp fibre.

Other similar developments can be found by major manufacturers such as Charle and co. This company also manufactures a 'hammer mill-line' that is suitable for processing hemp and flax for non-textile applications (i.e., cellulose for the paper-industry, technical applications, and cheap non-wovens) (Charle and co. 2002).

2.6.5 On-field processing technology Research has been performed in Germany for the development of an on-field processing technology for the processing of fibre flax for textiles (Šmirous and Krmela 1994). This research has been spearheaded by a co-operative effort between the German government and international machinery manufacturer CLAAS (CLAAS-Gruppe Öffentlichkeitsarbeit, Postfach 11 63, 33426 Harsewinkel, Deutschland). This effort attempts to improve the economics and reduce the risk of growing fibre flax for textiles. It hoped by doing this that the cultivation of fibre flax will be more widespread in Germany, which would provide producers with an alternative to highly subsidised grain production (Šmirous and Krmela 1994).

A mobile processing unit has been manufactured and tested and is called the "Flax-processor". The machine itself is a modified grain combine, with a square baler incorporated on the rear of the machine (Fig. 2.8). Material is picked up from the field and fed into the machine by a conventional pick up and drag chain conveyor located at the front of the unit. The combine itself has two modified threshing cylinders mounted in series (1), which receive stalks from the pick up, and then act to break the stalk to release fibres (Fig 2.9). The broken stalks are then passed through a rotary chaff separator (2) which separates the loose core from the fibres, and the separated core is returned to the field. The separated fibres are loaded into the baler (3), compressed into a 200 kg bale, and then dropped behind the machine. The baled fibre, which has a 50% reduction in core, is then transported to a centralized processing facility whereas the fibre is further refined by a Temafa "Lin-line" system.

Prior to this process, flax stalks are de-rooted when the seeds are ripe and then laid on the field for retting. After 10-15 d the stalks are combined to remove the seedpods and seeds. The stalks are then returned to the field in an un-oriented swath, and are left to dry to suitable moisture content for baling. Because the stalks have been threshed, the drying process occurs more rapidly than regular stalks. Shortly after this, the CLASS flax processor is employed to pick up and processes the material.

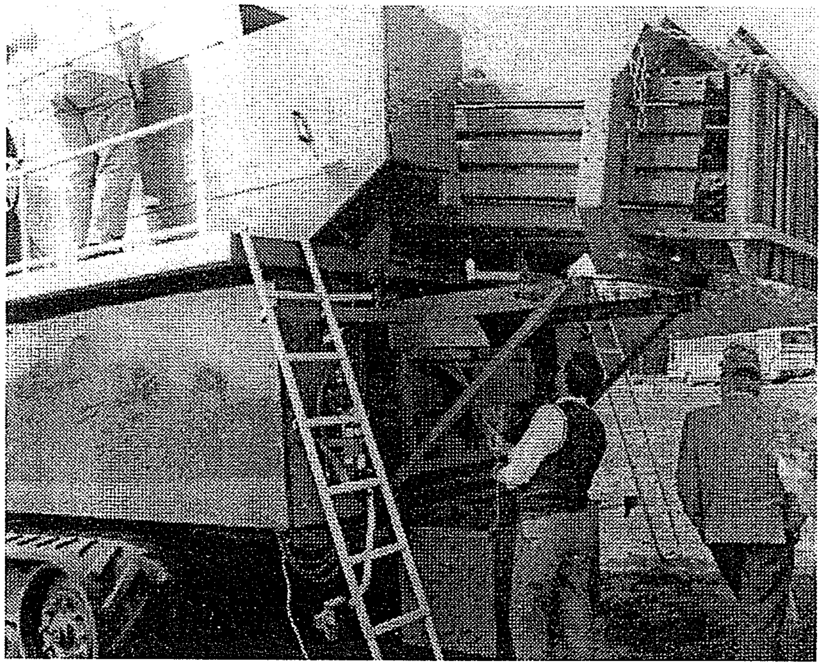

Fig. 2.8 CLAAS Flax processor (Šmirous and Krmela 1994)

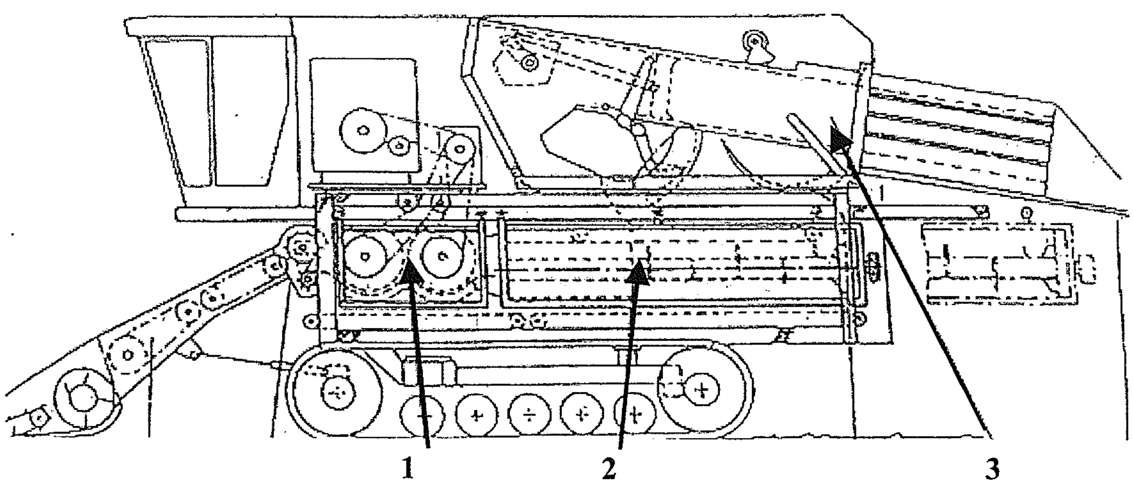

Fig. 2.9 Schematic of CLAAS Flax processor (Šmirous and Krmela 1994)
1 –Threshing cylinders, 2-Rotary chaff separator, 3-Square baler

This technique has several advantages over the conventional method of processing fibre flax. The harvest time is reduced by a factor of 3, which significantly reduces the risk of fibre being spoiled on the field. As well, the stalks may be combined using conventional machinery instead of the specialized flax combines, which reduces the investment cost of flax processing. The reduction in core in the fibre significantly reduces the costs of transportation and storage of the material, because 50% of the mass of the material is left on the field. The square baled form also allows for efficient packing on a truck trailer and in a storage warehouse.

2.6.6 Patents Several patents were found for previous inventions of fibre processing units for either flax or hemp. These deal with variations of techniques, which either consist of one of the methods explained in the previous section, or a combination thereof. Detail on these is omitted in this section due to the large number of these inventions, and the fact that they cover techniques already discussed. A comprehensive list of these patents, however, is presented in Appendix A.

2.7 Hemp fibre quality and measurement

Many industrial applications of natural fibres require the measurement of several key properties of the fibres to identify physical characteristics and to assess quality. Such measurements include fibre length and fibre fineness. Experimental methods exist for the measurement of these properties for a wide variety of natural and synthetic fibres, and are well documented (Morton and Hearle 1962, Booth 1968).

The ASTM standard D 519 method uses a comb sorting device to sort fibre samples into groups of different lengths. A comb sorter consists of a bed evenly-spaced parallel combs mounted on a frame. The needles of the combs face upwards, and a sample of fibre is inserted over the combs and rendered parallel with the combs in such a manner that their coterminous ends are almost flush with an outer comb (ASTM 1995). Fibres at this end are then secured by another comb, with needles pointing down, which is placed over top of the outer comb securing the ends of the fibres in place. The fibre sample is then combed to remove the lengths of fibre that are not secured by the outer comb. The other combs are then secured with their own corresponding top comb. Following this, the end comb at the fixed end is removed and all fibres that are shorter than the next corresponding comb are removed. This procedure is repeated until all combs have been removed. The fibres removed from each length interval are then weighed. A suggested interval for the measurement of the length of bast fibres is 25 mm for the first two combs on the apparatus, and a spacing 51 mm for every successive comb after (L.I.R.A).

Fibre fineness is a measure of the cross-sectional thickness of fibres and is obtained by counting the number of fibres in each length group and then dividing by the mean length of the weight group (Morton and Hearle 1962). Fibre fineness is expressed in units of tex which is equal to the equivalent mass in g of 1 km of material. Hemp processed from traditional methods normally has a minimum length of 100 cm and a maximum length of approximately 200-300 cm (Doberczak et al. 1964). Average fineness is 2.2 tex.

3. FUNCTIONAL ANALYSIS AND DESIGN METHODOLOGY

3.1 General

This chapter presents methods used to achieve the primary objective of this study; the design and construction of an on-field hemp processing prototype. As a first step in achieving this objective, the mechanics of bast fibre separation are observed. This information is presented as a functional analysis of previous hemp fibre processing machines and several assumptions of the physical mechanisms of bast fibre separation are made. This chapter then presents the specific functions which are identified for the prototype to achieve. Details are then presented on the techniques and materials used to design and build the prototype. The anticipated functions of the prototype are then discussed to explain how the prototype is expected to separate bast fibre from raw hemp stalks.

3.2 Functional analysis

In the previous chapter, several inventions and processes were presented which have already been used on a commercial and experimental scale for the processing of flax and hemp. At the time of this study, no theoretical information could be found outlining the principles in which these machines operate to separate hemp bast fibre from stalks. Consequently, the work undertaken in this study was limited to observing the processes created by these machines as the basis of the new design. These sections also include assumptions made on the physical mechanisms of bast fibre separation and are presented in the following sections as well.

3.2.1 Bast fibre separation by breaking It was observed upon review of the literature that most of the inventions were separating bast fibre from the stalks by breaking the stalks using some form of bending stress. Armstrong (1957) explains that the separation of bast fibres from the core is achieved when the bond between bast fibre and core is broken. He explains that repeated bending of stalks at high rates of speed and high frequencies is one method in which this can be achieved. While this comment provides some insight on the process, some more specific knowledge on this process was desired to maximize the efficiency of this process in the design. The following hypothesis is presented in order to elaborate on how the mechanism of breaking causes bast fibre separation.

3.2.2 Delamination model By comparing a flattened segment of hemp stalk to a composite laminate beam subjected to static bending, some understanding of bast fibre separation by breaking may be obtained. This is especially important in considering that the structure of a hemp stalk itself is like a composite laminate beam consisting of parallel layers with different elastic modulii. Most notably, this structure consists of a thin layer of bast fibres on the outermost surface of the composite, and has several layers of equal thickness of core fibres forming the remainder of the composite. Typically the modulus of bast fibres is higher than that of core.

A composite beam consisting of several parallel laminates, when bent around an axis, develops a linear strain variation throughout each layer (Fig. 3.1). If the individual layers consist of different elastic modulii in the axial direction, a discontinuous variation in stress state will exist throughout the layers (Daniel and Ishai 1994). These two different levels of stress experienced in each layer contribute to a net difference in stress between the two

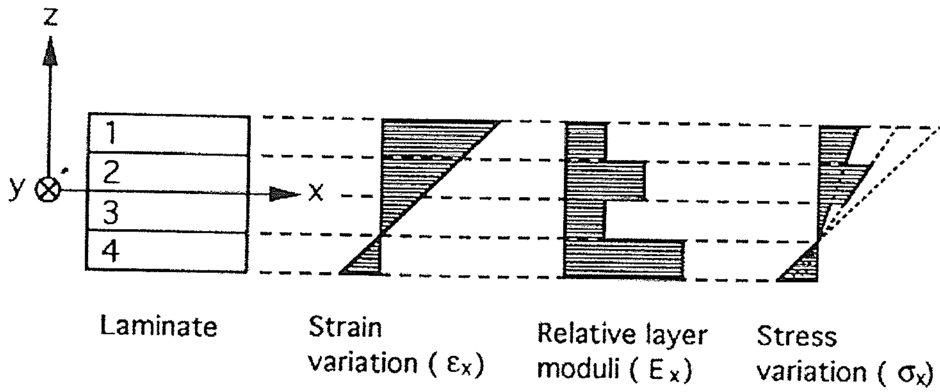

Fig. 3.1 Composite laminate beam subjected to bending (Daniel and Ishai 1994)

layers. For the two layers to be in static equilibrium, a shear stress exists between the two fibre layers to balance out the stress difference. Shear stress between the fibre layers will continue to increase with further increases in bending stress until the physical bond between the two layers is broken. This phenomenon is called delamination.

By comparing the bond between the two layers of the composite example to the bond existing between bast fibres and core layers of a hemp stalk, some understanding of fibre separation by breaking was obtained. At the time of this study, no information on the strength of the bond between the bast fibre and core layers was found. However, it was presented in chapter 2 that this bond is degraded with retting, and thus weakened.

It is possible that the bond between bast fibres and core is strong enough to resist delamination, as in the case of poorly retted stalks. In this case, failure of the bast fibres will be experienced before delamination, and no fibre separation will result. If we consider that shear stress is a function of the area in which the bast fibres cover the surface of the core layer, then a method to create delamination in poorly retted stalks may be obtained. If the area in which the bast fibres cover the core is reduced, then the strength of the bond between layers would be lowered and delamination would be more likely to occur. This could be achieved by breaking the stalk at very short intervals. The effectiveness of separating hemp fibre by subjecting the stalks to a high frequency of breaks in a decorticating machine may be an indication of the significance of this assumption.

3.2.3 Bast fibre separation by scutching Inventions using scutching blades as a means of primary removal of core, or as an added cleaning step, were presented in chapter 2. In the case of a turbine scutcher, it was observed that scutching blades remove bast fibres from core by scraping off core from the bast fibres. In the case of a decorticating machine, scutching is employed after the stalks have been broken by the rolls. This step effectively helps to scrape off any core that may still be bound to bast fibres after the breaking step has been performed.

The scutching process requires a certain amount of energy to be exerted as the core is peeled off the fibres. The energy required is a function of the strength of the bond between core and bast fibres and the distance through which the force is exerted. Again, the strength of the bond between bast fibres and core is affected by the amount of retting. This assumption is supported by the observation of the traditional scutching machines. These machines require stalks to be very well retted before scutching can be performed. Another factor affecting the bond strength is the area of the bast fibre bond. If the area is too large, then the energy exerted may then be transferred to the bast fibres, and failure of the bast will occur.

3.2.4 Fibre separation by impact Impact forces, such as high velocity, high kinetic energy forces, may provide the energy necessary to cause the bending and scutching forces needed for bast fibre separation as discussed above. However, impact forces alone may play a role in separation of bast fibres from the core. For instance, energy perpetrated into the stalk from inertia and vibrations created by high-speed impact forces may improve separation.

3.2.5 Fibre separation by shaking and screening Shaking and screening provide a means to remove core that has been separated from bast fibres by breaking and scutching. After being broken and scutched, the bast fibres often hold the separated core loosely. To remove the loose core, shaking effectively helps to dislodge any core particles that are entangled in the bast fibres. The shaking table consists of a series of perforated holes which permit the broken core to fall through. Because the bast fibres are on average longer, little fibre passes through the screen, and core separation is achieved.

3.3 Design methodology

3.3.1 Functional identification To maximize the efficiency of the design, the field-processing prototype should perform all of the aforementioned functions for fibre separation. The prototype was designed to provide a means to break stalks and to provide impact forces while breaking that material. As well, the prototype was designed to have the ability to scutch the broken stalks, and then to shake out loose core from fibres.

In addition, several new functions were identified as necessary for the prototype to be able to operate in the field. This included providing a mechanism for crop pick up and feeding, as well as providing delivery systems for separated fibre and core. Figure 3.2 shows a schematic for the order of the functions of the prototype, and the material flow through the prototype.

3.3.2 General design criteria Special considerations were made related to the prototype design. They are as follows:

- The prototype should not alter current hemp harvesting practices dramatically. This would be avoided by not introducing any additional steps between the windrowing and baling processes;

- The prototype should have a high capacity. This would ensure that the crop could be harvested in a timely manner, which in turn minimizes the risk of spoilage and maximizes efficiency;

- The prototype must be able to pick up a windrow created using conventional windrowing equipment to eliminate the need for any specialized crop windrowers;

- For simplicity in design and construction, the prototype should be pulled by a tractor, and;

- The power needed to drive the prototype should be low enough that a conventional power source can be used (i.e., Tractor power take off).

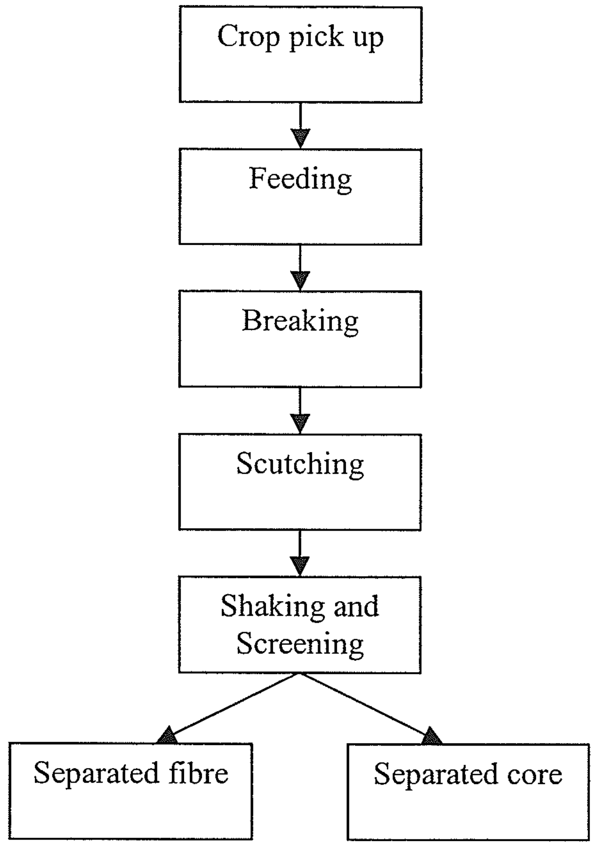

Fig. 3.2 Function order of prototype and material flow

3.4 Prototype design

3.4.1 Forage harvester The prototype (Fig. 3.3) was designed using a conventional forage harvester as the basis of achieving the pick up, feeding, beating, and scutching functions. The forage harvester used was a 1978 New Holland 782 forage harvester (Fig. 3.4) (New Holland North America, 411 Diller Avenue, New Holland, PA 17557). This model is a side blow type with a cutterhead that had 12 knives. The cutterhead itself had a diameter of 378 mm and a width of 476 mm.

The unit had a hitch and power-take off shaft (1) for towing and powering the unit, respectively. As well, the unit had a windrow pickup (2) suitable for picking up various types of crops. The forage harvester also had a series of feedrolls (3) for feeding material to the cutterhead. The speed of the feedrolls on the unit was adjustable by selecting a 195:135:75 gear ratio.

3.4.2 Forage harvester modifications The original forage harvester cutterhead was modified to form a breaker/scutcher for the design by removing nine of the knives and inserting nine straight steel scutching bars in between the three equally spaced knives remaining on the original cutterhead. The bars were made from 38 x 38 mm angle steel and were mounted on support blocks. Figure 3.5 demonstrates a schematic of the cutterhead assembly with the original knives (1) and the scutcher bars (2) introduced. The support blocks (3) of the scutcher bars were designed to fit into the existing holes of the cutterhead flanges(4). This resulted in the bars having a helical angle similar to the original knives.

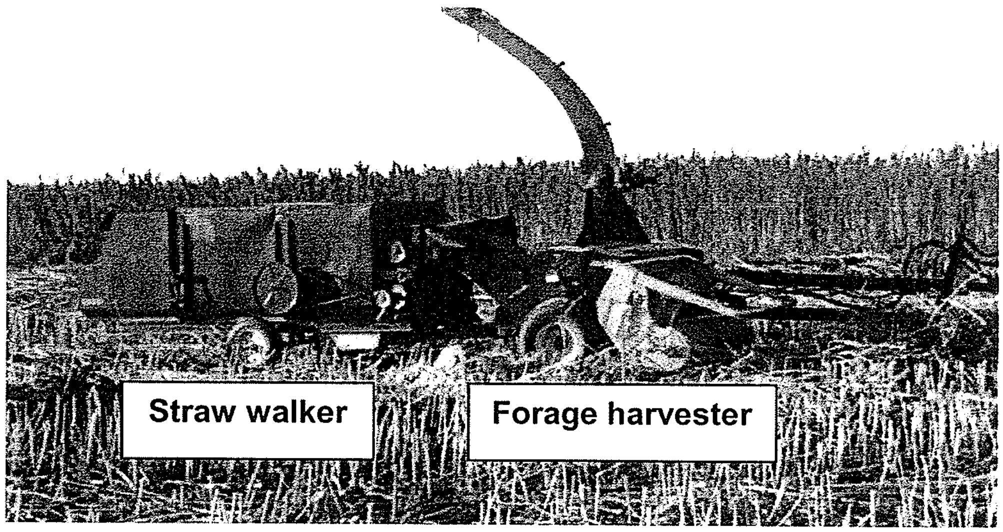

Fig. 3.3 Hemp processing prototype

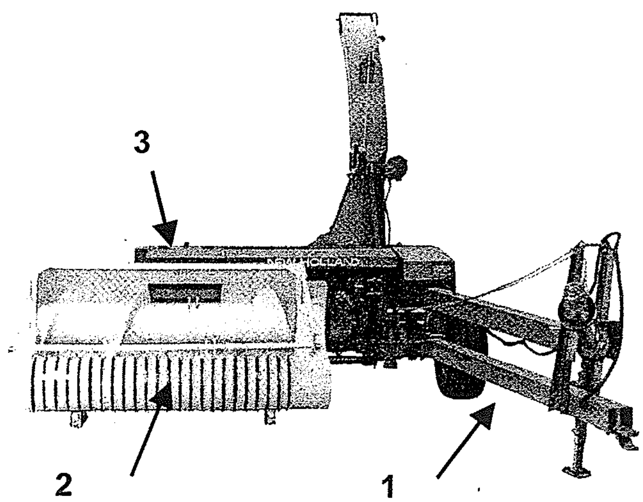

Fig. 3.4 Original forage harvester (New Holland 1978)
1- Hitch and power take off, 2-Windrow pick up, 3-Feed rolls

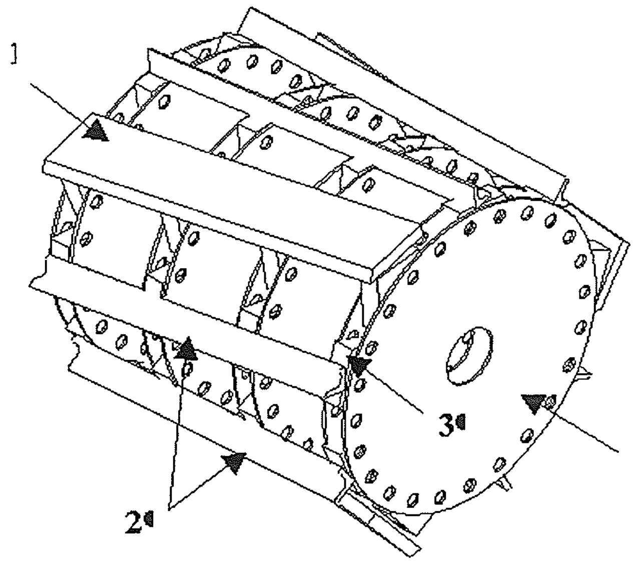

Fig. 3.5 Schematic of modified cutterhead
1 – Original knives, 2-Scutcher bars, 3-Support blocks, 4- Cutterhead flanges

The speed of rotation of the cutterhead was specified at 850 rpm. The speed of the feedrolls was adjusted using the gears provided on the original rotor. This was done in order to provide a theoretical length of break of stalks in intervals of 10 mm. This was based on the same theoretical length of cut if there were 12 knives present on the cutterhead. With this setting, the three remaining knives provided a theoretical length of cut of 38 mm. This was the maximum cut length that could be achieved from the forage harvester without changing the original gears.

In the original forage harvester, the material cut by the cutterhead was conveyed to the other side of the machine with the use of a screw conveyor and a blower. It was suspected that some long fibres would be exiting the cutterhead, thus creating the potential that they would wrap around the conveyor and blower parts. Because of this possibility, the conveyor was removed, and a spout was installed at the exit of the cutterhead (Fig. 3.6). A curved plate was inserted into the original cutterhead chamber so that the material could be accelerated around the plate and be exited up the spout by a tangential velocity.

3.4.3 Straw walker A component added to the modified forage harvester was a straw walker/beater assembly from a 1962 Massey Ferguson Super 92 combine. This was done to perform the shaking and screening functions of the prototype. This straw walker consisted of six channels mounted to two perpendicular crankshafts (Fig. 3.7). Each channel measured 0.19 m wide and 2.5 m in length. The channels had two vertical slopes each and a 13 mm gap existed between each channel. The channels also had rectangular holes, measuring 32 x 25 mm. The long side of the holes were orientated perpendicular to the long side of the channels. There were also ribs placed perpendicular to the length of the channels, which

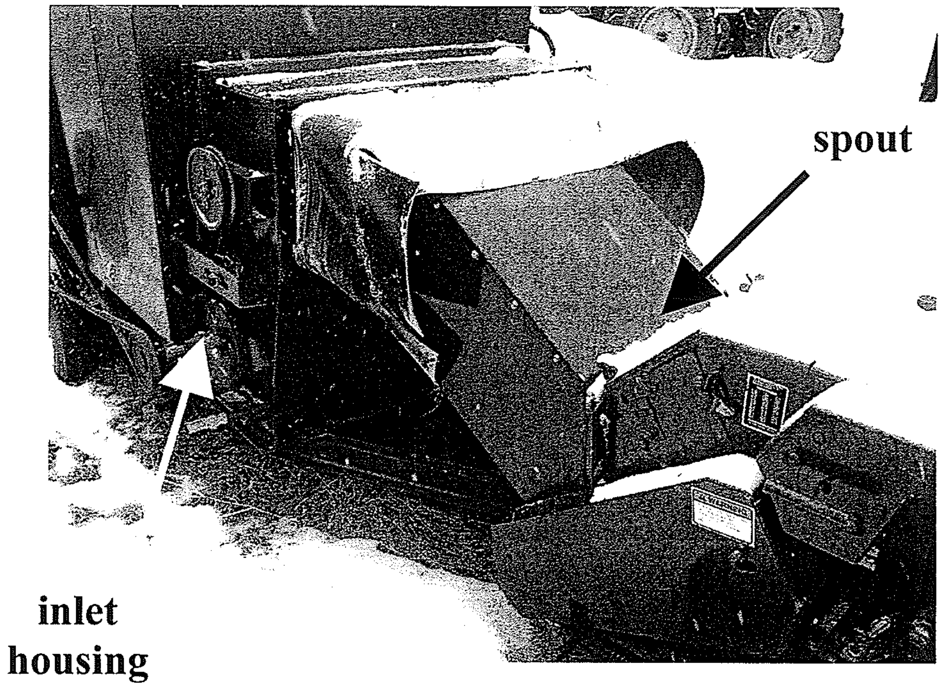

Fig 3.6 Spout placed at exit of forage harvester cutterhead

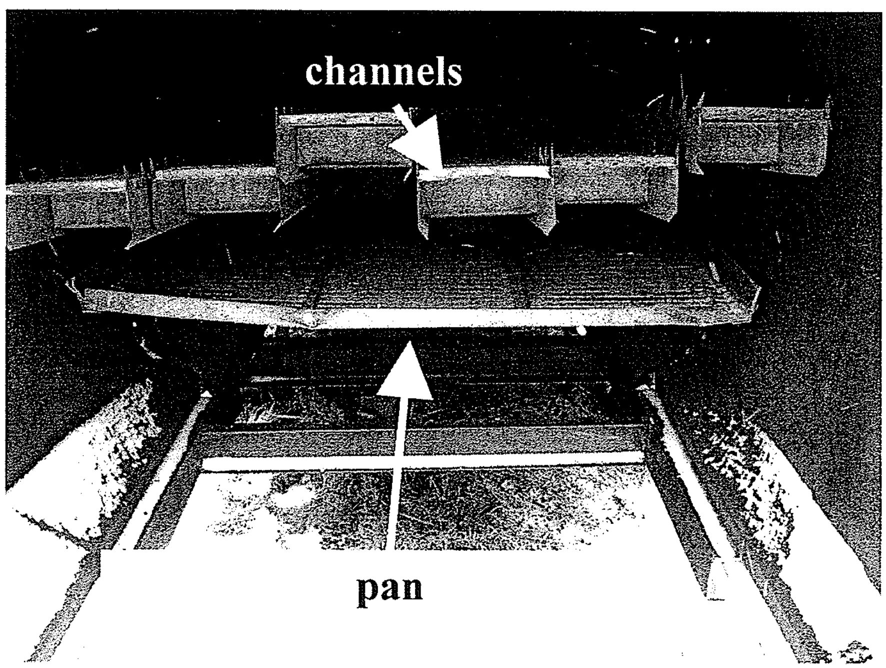

Fig. 3.7 Straw walker channels and pan

spanned the width of the channels, and were spaced at equal distances between the holes. The ribs each had a height of 6.4 mm and were spaced 32 mm apart.

The straw walker assembly consisted of a 1.2 x 2.5 m pan (Fig. 3.7), placed below the straw walker channels. The pan was attached to two rocker shafts. These shafts were connected to one of the oscillating shafts of the straw walker channels by means of a rocker arm.

The straw walker assembly itself was connected to the modified forage harvester by means of a rigid frame (Fig 3.8). The frame had a single axle and wheels (1) mounted at the bottom for mobility. The straw walker assembly was mounted on top of this frame, and the frame was pulled behind the forage harvester by means of a hitch (2) attached to the frame.

An inlet housing was constructed at the input end of the straw walker (Fig. 3.6). This was done to accommodate the output spout of the forage harvester so that processed material could move onto the straw walkers. The housing hosted the original beater (3) from the Super 92 (Fig 3.8). This was done to provide a means to push the material onto the straw walker channels once it moved out of the spout. Two collection bins were constructed at both the straw outlet (4) and the chaff outlets (5) of the straw walker.

3.4.3 Power delivery system A separate drive system was constructed to power the straw walker/beater assembly. This was achieved by using a 6 kW hydraulic motor (Series DH 160, Sauer-Danfoss (US), 2800 East 13th Street, Ames, Iowa, 50010). The motor had a maximum speed of 486 rpm, and had a maximum operating pressure of 13.8 MPa. Hydraulic power was supplied to the motor by the output ports on the tractor used in the experiments.

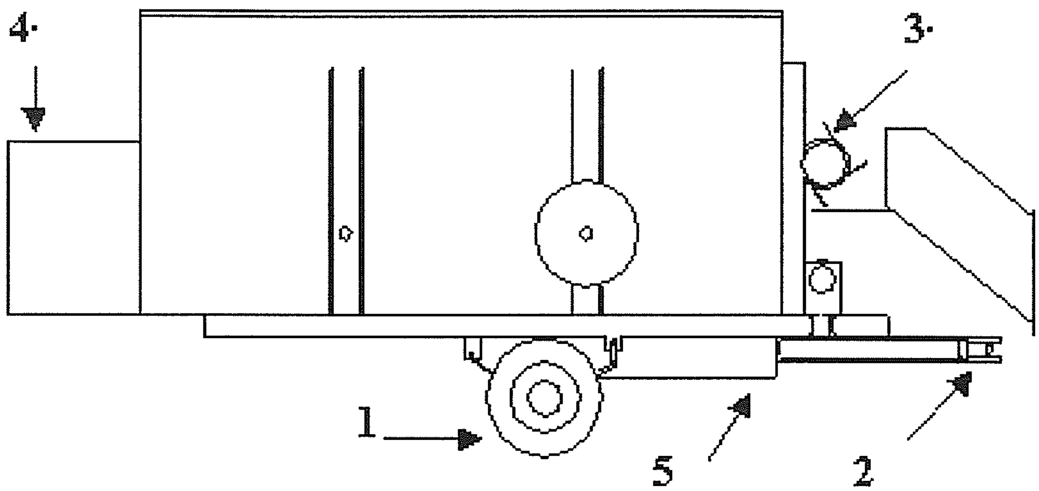

Fig. 3.8 Schematic of straw walker assembly (inlet housing not shown)
1- Axle and wheels, 2-Hitch, 3-Beater, 4-Straw outlet bin, 5-Chaff outlet bin

The motor was mounted on the straw walker/beater assembly frame in a position below the inlet housing (Fig. 3.9). The motor was connected to the beater shaft by chain and sprocket. The sprocket on the motor shaft consisted of 44 teeth, and the sprocket on the beater shaft had 20 teeth.

The power transmitted from the motor was also used to drive the straw walker crankshaft (Fig. 3.10). In order to do this, a 203 mm pulley was connected to the other end of the beater shaft. The pulley was then connected by a belt to a transmission shaft, which provided a means to transfer power to the straw walker crankshaft. The transmission shaft consisted of two 152 mm pulleys and was connected to the original 460 mm pulley of the crankshaft via a crossed over belt. The overall configuration resulted in the beater rotating approximately 2.3 times faster than the straw walker crankshaft. This ratio was chosen because it approximated the original relative rotating speeds of both components when mounted on the original combine.

As part of the design requirement, it was desired that the speed at which the straw walker operated be variable. Therefore, a variable flow rate valve was placed in series with the input line of the hydraulic motor. The valve also had a pressure relief valve which helped protect the motor from pressure surges. For a schematic of the hydraulic circuit, refer to Fig. 3.11.

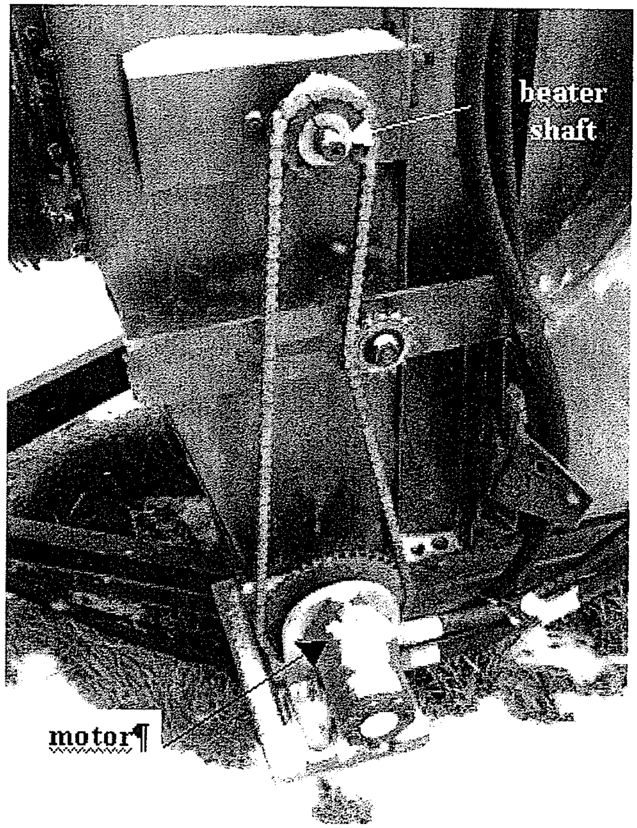

Fig. 3.9 Hydraulic motor and connection

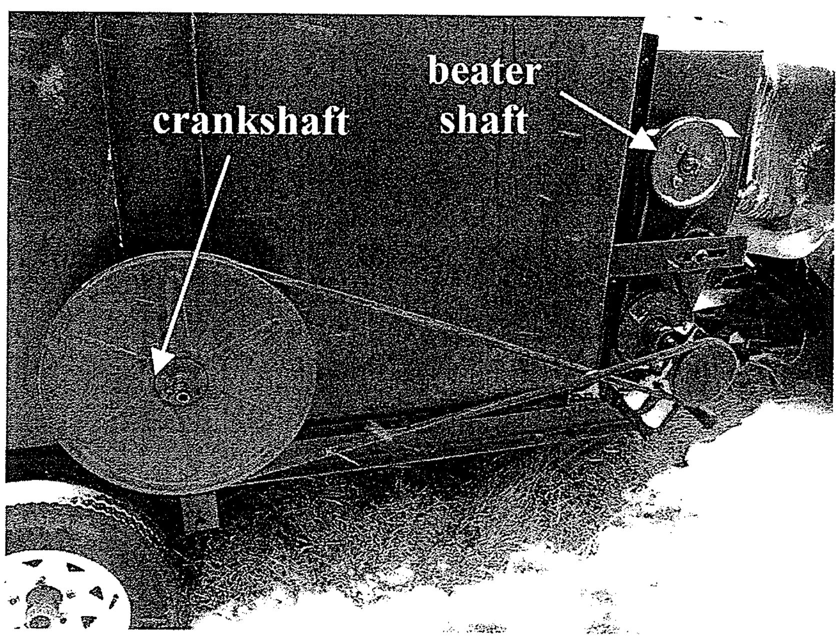

Fig. 3.10 Power transmission to straw walker

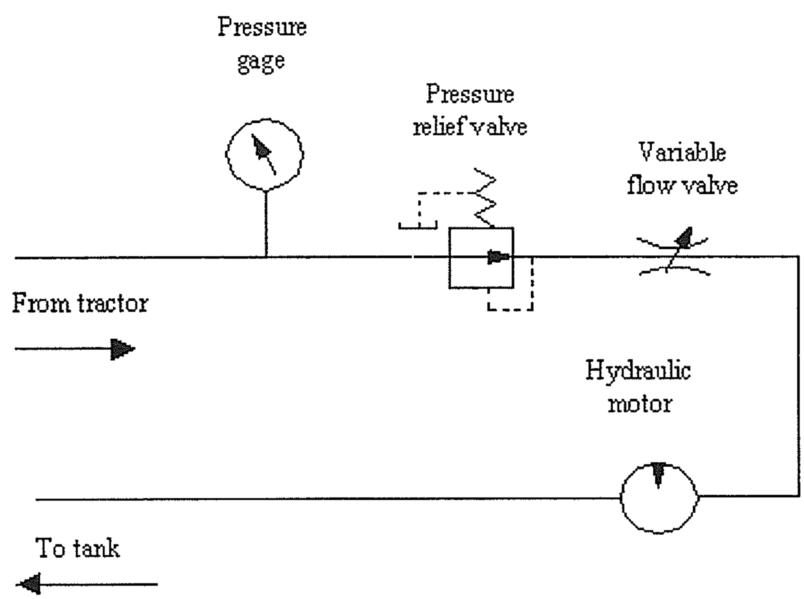

Fig. 3.11 Hydraulic circuit for straw walker power delivery system

3.5 Anticipated functions of the prototype

3.5.1 Windrow pick-up and feeding mechanisms It was anticipated that the original pick-up on the forage harvester would pick up the hemp windrows and present the material to the feedrolls of the machine. The feed rolls would then grab the stalks and feed them into the machine in a parallel orientation. The feed rolls would also have a dual purpose; the grooves present on the rolls and the pressure applied between the rolls would help to pre-break the stalks at regular intervals.

3.5.2 Breaking / scutching mechanisms Stalks that have been picked up and fed in the machine would be fed into the modified cutterhead assembly of the forage harvester. The cutterhead itself was cylindrical in shape and its centre axis was orientated perpendicular to the stalk's travel into the machine.

It was anticipated that contact between the material and the scutching bars would occur as stalks were fed into the machine at a constant rate. The stalks would then bend around the original shearbar, which provides lower support for the stalks coming out of the feed rolls of the forage harvester. The constant rate of rotation of the feeding rolls and the modified cutterhead would allow the material to be broken at regular intervals (i.e., 10 mm). The breaking of the stalk would release the core from the bast fibres, but bast fibres themselves would remain attached to the stalk. The scutching bars placed on the forage harvester cutterhead would also serve to scrape the bits of core that had not been removed by breaking. Core particles would be carried away at a high velocity due to the high speed of rotation of the cutterhead.

The remaining bast fibres would then be cut when the knives make contact with the material at the shearbar. The separated bast fibres would be cut loose at a length of 38 mm and then be carried away by the knives. This is especially important when considering that the length of bast fibres in raw stalks can extend to the entire length of the stalk. It was suspected that feeding whole stalk lengths in the modified forage harvester would lead to a build up of material at the shear bar before they could be moved out of the device. It was suspected that this could lead to plugging of the modified cutterhead due to wrapping of bast fibres around it. Theoretically, cutting the fibres would eliminate this problem.

3.5.3 Shaking and delivery systems Once the material is carried through the forage harvester cutterhead, it was anticipated that the material would consist of a mixture of separated bast fibres and loose core. As the material was fed into the straw walker, it would be shaken and the loose core (expected to be <10mm in length) would fall through the holes in the straw walker onto the pan beneath. It was anticipated that the bast fibre (expected to be 38 mm in length) would not to fall through the holes of the straw walker and would be retained on top.

The straw walker channels oscillate in a manner in which the material presented on top of the channels experiences both vertical and horizontal movement, which in turn aids in separation. The movement also helps to move the material from the inlet of the straw walker to the opposite end. A specially designed bin was constructed at the latter end of the straw walker of the prototype, and it was anticipated that the bast fibre retained over the straw walker channels would be collected in this bin (Fig. 3.8). Since the material flowing out of the straw walker outlet in the original combine would have consisted of straw, the same outlet on the prototype was denoted as the straw outlet (*so*).

The pan below oscillated laterally in a direction opposite to the shaking table. The pan itself had small undulations, which help facilitate the movement of the material across the pan. The separated core fallen onto the pan would effectively be collected and delivered at the end of the pan in a separate bin. This end corresponded to the inlet end of the straw walker and since at this end the product collected in a combine would consist of chaff, the outlet on the prototype would be denoted as the chaff outlet (*co*).

4. MATERIALS AND METHODS

4.1 Experimental design

4.1.1 General To achieve the secondary objective of this study, it was necessary to test the prototype under actual field conditions. It was anticipated that results from these tests would confirm some of the assumptions made on the anticipated functions of the prototype. These tests also provided an opportunity to examine the effectiveness of the prototype under different field conditions, as well as to understand some of the prototype's limitations. These tests also served to identify some optimal conditions under which the prototype should be operated.

To determine whether the scutching bars added to the forage harvester cutterhead actually helped in the separation of bast fibres, field tests were designed to examine results from operating the prototype with both the original and modified forage harvester cutterhead configurations separately. Another consideration was whether the prototype would be effective in separating bast fibres in a relatively short period of time following harvest to avoid the risk of spoilage due to bad weather. The field tests were therefore designed to address this question by performing the tests on raw material exposed to different retting times.

Another question that was addressed by the field tests was the capacity of the prototype. It was understood that processing high volumes of raw material would add to the prototype's efficiency, however, it was important to determine if the effectiveness of the prototype was influenced by its capacity. The field tests subjected the prototype to different raw material feed rates in order to address this question. It was also not clear at the time of design the speed at which the straw walker on the prototype should be operated. Because this was suspected to have an influence on the separation effectiveness of the prototype, the field tests attempted to address this question by obtaining results after operating the prototype at different straw walker speeds.

4.1.2 Test plot To test the prototype under actual field conditions, a test field was grown on field 19W at the University of Manitoba Glenlea research station. The field had an area of 8 ha.

The field was divided into three plots of equal area and seeded at different rates with the cultivar Felina 34 on May 16, 2000. This cultivar was chosen because it is a late maturing variety that is commonly grown in Manitoba for the harvest of seed. Plot 1 was seeded at the recommended seeding rate for a grain crop of 18 kg/ha. Plot 2 was seeded at 24 kg/ha and Plot 3 was seeded at the recommended seeding rate for a fibre crop of 50 kg/ha. Fertilizer was added at rates of 90, 31, 13, and 0 kg/ha for N, P_2O_5, K_2O, and S fertilizers, respectively. Seeding depth was set at 19 mm and rows were spaced at 230 mm.

It was anticipated that the prototype would be tested on all three different plots. However, heavy rains occurred immediately following seed planting, and other heavy rains were experienced in the following month. This resulted in significant flooding of Plots 2 and 3, and a section of Plot 1. Many of the plants in these areas did not survive.

As a result, only one section of Plot 1 was used in the experiments. The area of this plot measured approximately 2.5 ha.

4.1.3 Plant population sampling Prior to conducting field tests, nine areas of the field were sampled by placing a quadrate (1m x 1m) in a randomly selected area of the field, followed by cutting all the stalks present inside the quadrate. The stalks were then counted to determine the plant population per m^2 area of the field.

4.1.4 Harvest Prior to the field trials, hemp was windrowed using the modified windrower presented in chapter 2 (Chen et al. 2002). In this operation, seed heads were cut off the plants at a height of approximately 1.2 m above the ground, and placed in a windrow. This operation was performed on October 12, 2000. The stalks were cut and placed in a separate windrow, named the stalk windrow. Trials in this experiment were performed only on the stalk windrows. Windrows with variable cut widths were created for the experimental purpose as discussed below. The variable cutting widths were achieved by cutting the stalks with only a partial header width of the windrower.

4.1.5 Treatments The information presented in section 4.1.1 led to the identification of treatments that were applied in the field experiments. The first treatment consisted of different configurations of the beater/scutcher (SC) of the prototype to assess the effectiveness of scutching bars added to the forage harvester cutterhead. The two levels in these treatments were identified as KO, for the cutterhead configuration with knives only, and BK for the cutterhead configuration with knives and scutching bars. Another treatment, with only scutching bars placed on the cutterhead was attempted, however, it was excluded as severe wrapping of the long fibres around the cutterhead was quickly observed in the field tests.

The time at which the field tests were performed (T) was also included as a treatment to assess the effect of retting on the separation efficiency of the prototype. The treatment times identified were T = 1d, which occurred 24 h after windrowing, and T = 7d which occurred 7 d after windrowing. Subsequent trials were halted due to heavy rains experienced in the following weeks.

Treatments related to feed rate were formed by cutting different widths of field area, to form stalk windrows of different sizes. The size of windrow cut *w* was chosen as either 3.5 or 7 m. Feed rates were estimated using the following equation, Eq.1.

$$FR = w \bullet v \bullet y \qquad (1)$$

where:

FR = rate of material flow into the prototype (t/h)
w = effective width of cut (m)
v = forward travel velocity of prototype (m/h)
y = yield of hemp stalks (t/m^2)

The average plant population density was 47 plants/m^2. Standard deviation of this population was 7.66. This information was used to find the yield in (t/ha) of hemp by multiplying the value of average plant population to the average linear density of hemp stalks (15 g/m, reported in Gratton and Chen (2000)). This value was then multiplied by the length of stalks, which was assumed to be approximately 0.97 m. This length was calculated by the average length of stalks which remained after the seed heads were removed by the windrower 1.2 m, minus an assumed stubble height of 230 mm. This resulted in an estimated plant yield of $y = 0.68$ kg/m^2.

By entering a value for the forward travel speed of the prototype (v= 3000 m/h), the feed rate (FR) into the prototype was obtained for both cut widths w. For $w = 3.5$ m, FR was estimated at 7 t/h. In the case where $w = 7$ m, FR was estimated at 14 t/h. These values were used to denote the levels of the feed rate treatment in the experiment.

Three different straw walker speeds (WS) were selected as treatments (100, 150, and 200 rpm) to determine the effect of straw walker speed on the separation of fibre. However, while conducting the field trials, it was observed that the lowest speed was not sufficient to keep up with the material flow into the prototype. Severe plugging was experienced at the forage harvester rotor and thus this treatment was abandoned. The two remaining treatments were identified as WS: 150 rpm and WS: 200 rpm.

4.1.6 Experimental layout A split-plot experimental design was used in which Plot 1 was divided into sub-plots and each sub-plot consisted of a section of a windrow of harvested hemp stalks. One level of each of the four treatments was assigned randomly to each sub-plot. This was performed until all combinations of treatment levels existed throughout all sub-plots. This resulted in a total number of sub-plots equal to 16.

In the instance where the treatment level was one of the different feed rates, the sub-plot selected had one of the two different windrow sizes. The time treatment was differed by performing the actual tests at the different times after initial harvest on each sub-plot.

4.1.7 Testing procedure The prototype was operated on each sub-plot by a 86 kW tractor. For each sub-plot, the prototype was towed at a speed of 3.0 km/h and directed to pick up the windrow in a continuous line. Once the outlets of the prototype became full, the prototype was stopped, and the material collected at each outlet of the prototype was removed and stored for analysis.

4.2 Measurements

4.2.1 General A material flow chart is presented in Fig. 4.1 to demonstrate the material flow through the prototype as the field trials were carried out. Several variables were obtained from the different partitions of processed raw material. These are presented in Fig. 4.1 and will be explained in detail in the following sections.

In general, these variables corresponded to measurements of the amount of bast fibre and core in the material collected at the prototype outlets after each field test. It was anticipated that these results would help determine the yield of separated bast fibres at the straw outlet of the prototype. As well, the measurements would indicate how "contaminated" the bast fibres would be with un separated core at the straw outlet. By measuring the percentage of bast fibre at the chaff outlet, this would also help determine how much fibre is "lost" in the process.

In order to obtain these variables, a method was developed to sample the mass of the material presented at each outlet of the prototype and then to separate the bast fibre and

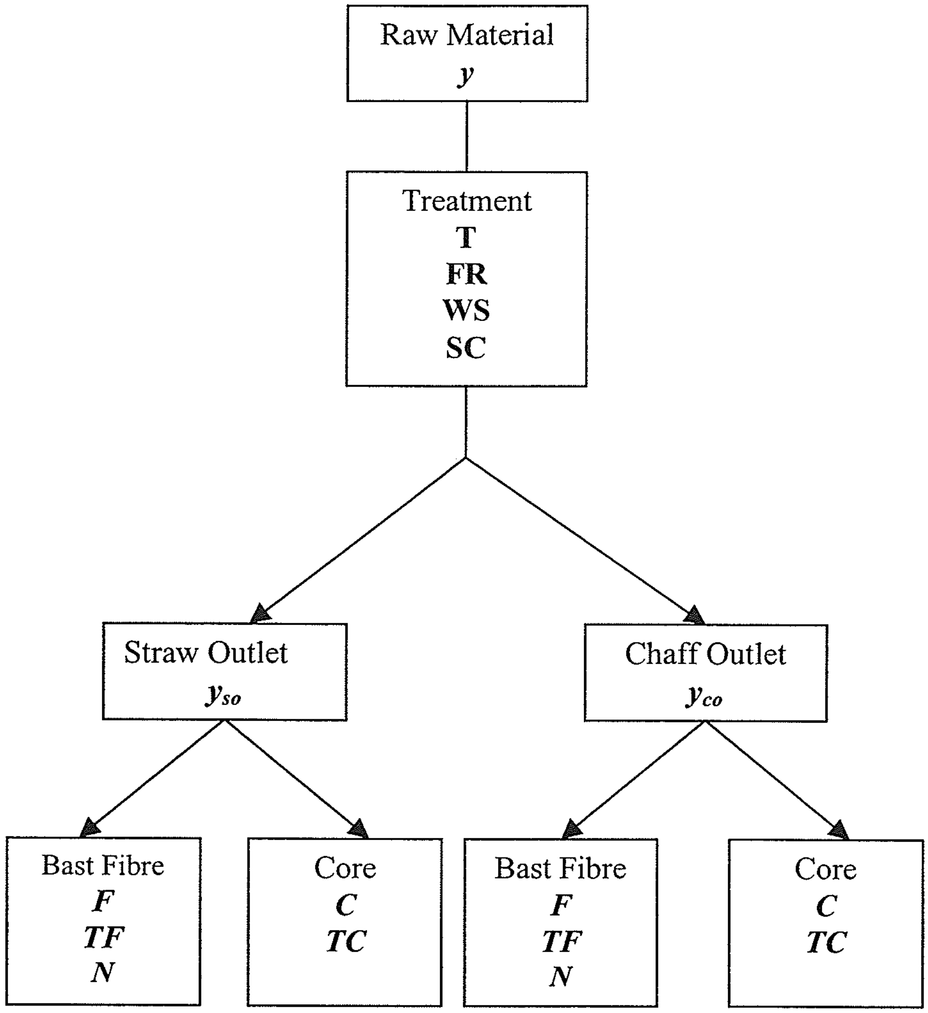

Fig. 4.1 Material flow chart

core so that the two could be measured separately. The individual amounts of bast fibre and core obtained were then used to find the ratio of both of these constituents to the total mass of raw material. This was done by considering the yield of material at each outlet as a fraction of the total mass of raw material. By determining these ratios, variables obtained could be compared to those of other treatment groups directly.

Statistical tests were performed on this data to assess whether the different treatments had an effect on the values observed. This would identify which treatments had a direct influence on the performance of the prototype with respect to the above criteria.

In depth analysis of the results obtained in the field tests was also performed to identify the ratio of the bast fibres that were completely loose of any core in the material collected at both outlets of the prototype. This helped examine the quality of the separation obtained by the various treatments and helped to explain the significance of some of the treatments. This was performed by developing a method of determining the ratio of loose fibres from samples obtained at both prototype outlets, and determining the ratio of fibres that were not loose in the same samples.

As another step in this analysis, the length of loose fibre and core obtained from each outlet was measured to obtain information on the condition of the fibre and core collected at each outlet. This information helped to explain the significance of some of the treatments and to understand the functioning of the prototype. For this analysis, a separate method was developed to determine the lengths of both bast fibre and core presented at each outlet. As a qualitative measurement, the fineness of separated fibres was also measured. This was performed as an added step in the length analysis.

4.2.2 Sampling The material obtained at both the straw and chaff outlets of the prototype were sampled to form a smaller sample for analysis. This was done because the amount of material collected after each trial was too large to perform an efficient analysis. The material from each of the prototype outlets was sampled by drawing material from random locations of the bulk until approximately 25% of the total mass was obtained. The bulk was then mixed together in a plastic bag and three smaller samples were drawn from the bulk for analysis. The approximate mass from each smaller sample was 100 g.

4.2.3 Outlet yield ratio Prior to sampling, the mass of the total amount of material removed from each outlet was recorded. The results were expressed as the ratio of mass of sample collected at the straw or core outlet to the total mass collected at both outlets of the prototype (Eqs. 2a and 2b).

$$y_{so} = \frac{m_{so}}{m_{sc}} \qquad (2\text{ a})$$

and,

$$y_{co} = \frac{m_{co}}{m_{sc}} \qquad (2\text{ b})$$

where:

y_{so} , y_{co} = straw and chaff outlet yield ratios, respectively (%)
m_{so} , m_{co} = total mass of material collected at straw and chaff outlets, respectively (kg)
m_{sc} = total mass of material collected from both prototype outlets (kg)

4.2.4 Sample bast fibre and core ratios To determine the ratio of both fibre and core in samples obtained at each outlet of the prototype, a procedure had to be developed to measure the mass of both fibre and core in the sample. A method was developed for this study using the basis of flotation to separate both fibre and core components. This approach was inspired by De Maeyer and Huisman (1994), who used flotation as a means of separating bast fibres from core of chopped hemp stalk. They reported that when introduced in a bath of slow moving water, loose bast fibres sank to the bottom of the bath, while loose core floated to the surface.

In the procedure used to process the samples of this study, the samples were introduced into a 910 x 406 x 318 mm basin of warm water (i.e., water temperature was 45°C). Prior to introducing the samples into the water basin, the samples were chopped using a household blender for approximately 10 s. This effectively helped to reduce the length of bast fibres and core, so that they would move better in the water. As well, chopping also served to remove bast fibre from the core, which was not separated by the prototype. The samples were pre-cut with scissors to a length of approximately 25 mm, to avoid fibres wrapping around the moving parts of the blender.

The chopped sample was placed in the water basin. The surface was manually agitated using a rod for approximately 10 min to separate bast fibres, which would become tangled with loose core at the surface. After this, the surface was skimmed with a number 60 mesh sieve, and the removed core was collected. Following this step, the remainder of the water was drained, and the bast fibre was collected from the bottom of the basin. Both bast fibre and core were oven dried at 105°C for 24h (ASAE Standard S269.4 2001) and then weighed.

This procedure was repeated for each of the three samples obtained at the two outlets of the prototype. This resulted in replicate measurements of the amount of fibre and core in each prototype outlet for each treatment group.

Overall, the flotation approach proved to be just as efficient as hand separation. Both outlet samples were significantly cross-contaminated with either bast or core, and separating the two by hand was a tedious and long process. As well, the flotation technique removed any bias that may have been presented due to human interaction.

Results from the flotation procedures were expressed as the ratio of fibre mass to the total mass of the raw material by considering the yield ratio at each prototype outlet (Eq. 2). This was performed so that variables would be obtained which could later be tested against other treatments statistically. This was calculated with the following relationships (Eq. 3 and 4).

$$F = \frac{mf}{mt} \bullet y_i \qquad (3)$$

and,

$$C = \frac{mc}{mt} \bullet y_i \qquad (4)$$

where:

i = denotes the straw outlet (so) or chaff outlet (co)
F, C = ratio of bast fibre or core in sample expressed as a percentage of the total mass of raw material, respectively (%)
mf, mc = mass of bast fibre and core in sample respectively (g)
mt = total mass of bast fibre and core in sample (g)

It was also important to express the variables obtained in Eqs. 3 and 4 as ratios of the total amount of fibre or core present in the raw material, respectively. This was performed to provide a clearer picture of how the fibre and core is partitioned into each prototype outlet. This is expressed by the following relationships (Eqs. 5 and 6).

$$TF = \frac{F}{\Sigma F} \quad (5)$$

and,

$$TC = \frac{C}{\Sigma C} \quad (6)$$

where:

TF, CF= ratio of fibre or core collected at each outlet of the prototype, expressed as a percentage of the total mass of fibre or core, respectively (%)
ΣF, ΣC= sum of fibre or core ratios of each prototype outlet, respectively (%)

This information is presented in the next chapter in summary form only, as statistical analysis of treatment effects on these results were difficult to perform due to the division of the variables F and C with ΣF and ΣC. A method of maintaining the variance for individual replicates of these values was not found at the time of the study, and therefore average values of F and C were used to determine the ratios of TF and TC, Five control samples of unprocessed stalks were also collected from random locations of the test field and the mass of bast fibre and core of these samples was obtained using the same flotation method. This was performed to have a measure of the bast fibre content in the hemp stalks prior to processing. The results in this analysis were simply expressed as the percentage of bast fibre mass to the total mass of the tested stalks.

4.2.5 Outlet sample constituents The material collected at each prototype outlet for each field trial generally consisted of a mixture of loose bast fibres (*l*), and bast fibres still bound to pieces of core (*b*). It was desired in this study to determine the fraction of each of these constituents to further investigate the significant effects of the treatments applied to each field trial.

The size of each sample selected for this analysis was 200 g, and was obtained from the same sampling bulk described in section 4.2.2. Each sample was hand separated by picking out all the loose bast fibres from the sample. A loose fibre was considered to be one entirely free of core. The fraction of loose fibre obtained in each sample was then oven dried at a temperature of 105°C for 24 h and weighed. The remainder of the fibre, which was bound to core particles, was extracted using the flotation method. The following ratio of the mass of loose or bound fibre to the total fibre mass of the raw material was found by considering the ratios obtained in Eqs. 5 and 6, and are presented in the following relationships (Eq. 7and 8).

$$LF = \frac{mfl}{mf} \bullet TF \qquad (7)$$

and,

$$BF = \frac{mfb}{mf} \bullet TF \quad (8)$$

where:

LF, BF = ratio of loose or bound fibre in sample, respectively (%)
mfl, mfb= mass of loose or bound fibre in sample, respectively (%)
mf =mass of fibre in sample (g)

These calculations were performed for samples obtained at each prototype outlet. Results were expressed in this manner to provide a clear picture of how much the total fibre mass of the raw material is partitioned into loose and bound fibre. More information on this is presented in the next chapter.

4.2.6 Fibre length distribution and fibre fineness Lengths of loose bast fibres from the constituent measurements above were separated into length categories, which ranged from 0-25 mm, 25-51 mm, 51-102 mm, 102-152 mm, 152-203 mm, 203-254 mm, 254-305 mm, and 305-356 mm. The length categories were selected from the suggested category spacing of the fibre sorting method outlined in chapter 2.

Fibres under 51 mm were typically measured by hand with a ruler. For fibres that were longer than 51 mm an apparatus similar to a comb sorter was constructed and used (Fig. 4.2). The apparatus consisted of fibre grips, which could be opened and closed separately, each spaced at the required category spacing. The fibre sample was introduced in the apparatus by selecting a sample of loose fibres and aligning the fibre ends together at one end. The fibre ends were then secured by the first grip on the apparatus.

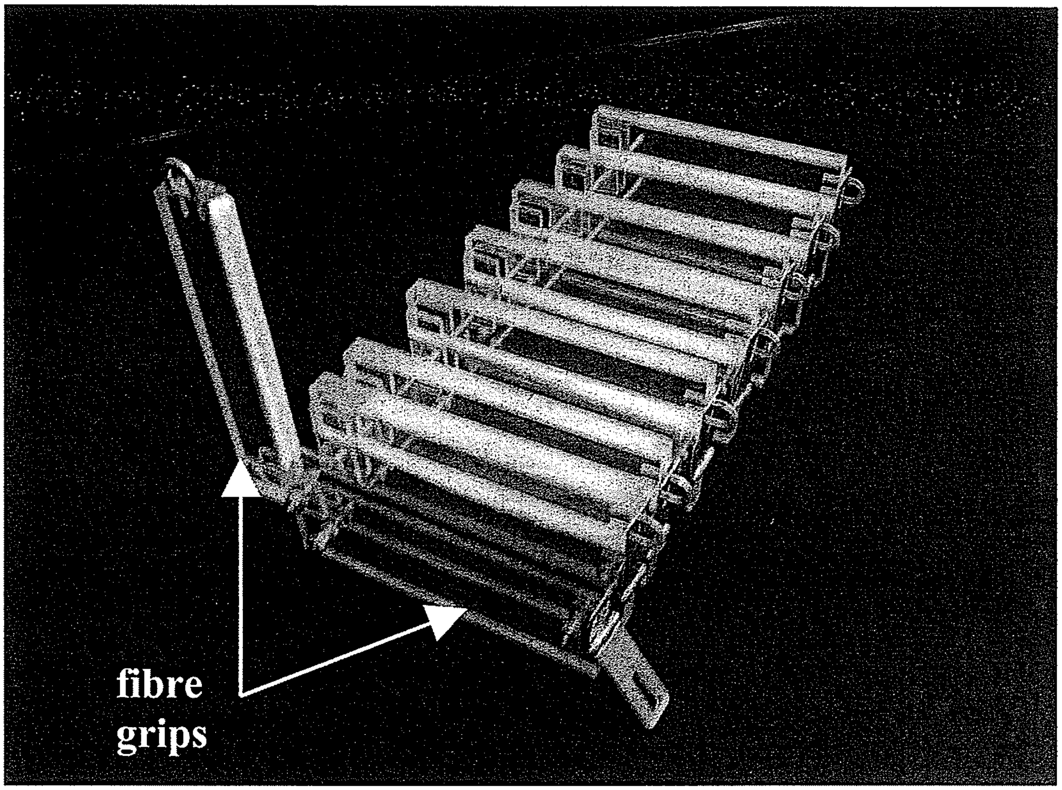

Fig 4.2 Fibre length sorter

The fibre was then straightened using a handheld comb and pulled over each successive grip in the apparatus. The comb itself consisted of steel needles spaced approximately 3 mm apart. Once the fibres were combed over a grip, the grip was fastened until all fibres were held by the grips. Fibres were then sorted by removing the first grip and combing out the loose fibres that are released by the grip. The remainder of the fibres are removed in this fashion for each successive grip. This effectively resulted in all fibres being sorted in the proper length categories.

Once the loose fibres were sorted, the fibres in each length category were oven dried at 105°C for 24h and then weighed. The mass of loose fibres *mf* obtained in each length category were expressed as a fraction of total mass of fibre obtained at both prototype outlets *TF* using Eqs. 3 and 5.

The number of individual fibres in each category were also counted to determine fibre fineness for each length category. The following relationship was used to calculate fineness (Eq. 9).

$$N = \frac{m \bullet n}{lav} \qquad (9)$$

where:

N = fibre fineness (g/km = tex)
m = mass of fibre in each length category (g)
n = number of fibres in each length category
lav = average length represented by each length category (km)

4.2.7 Core length distribution The length distribution of core was also determined for each sample. The length of core particles was determined by measuring particles by hand with a ruler. The core particles were then classified under the following specific length categories: 0-25 mm, 25-51 mm, 51-72 mm, 72-102 mm, 102-127 mm, 127-152 mm, 152-178 mm, and 178-203 mm. The core obtained in each interval was oven dried at 105°C for 24 h and then weighed.

The results from this analysis were expressed by calculating the ratio of core mass *mc* in each length interval to the total mass of core in the outlet sample *TC* from Eqs. 4 and 6.

4.2.8 Statistical analysis Statistical analysis was performed on the ratios obtained from fibre content analysis *F* and *C* separately to determine significance of any of the treatments on these variables. This was performed using analysis of variance with a 2^4 factorial model using the different treatments in the field test as factors in the model.

A multivariable analysis of variance (MANOVA) was performed on the values of the variables obtained at both prototype outlets for each separate analysis on variable *F* or *C*. This procedure was used to reduce the number of individual analyses that had to be performed on the data. To ensure that this method could be adopted successfully, basic assumptions about the two variables had to be verified.

One of the assumptions that have to be true to use MANOVA is that dependent variables must not be too highly correlated. A correlation coefficient of 0.3 is suggested to be low enough for the use of MANOVA (Sherry 1997). This was verified by calculating the

Pearson correlation coefficient of the two dependent variables of the analysis. As well, it was assumed that a significant multivariate F ratio would indicate significant effects in the model. This assumption was verified by performing univariate tests on each dependent variable separately. The F ratio was obtained by the Wilk's lambda criterion because it is suggested that this criterion minimizes the chance of committing a type I error, and is the most immune to violations of assumptions (Sherry 1997). To further reduce the chance in committing errors in interpreting the results in this analysis, the significance level was chosen as 0.01.

Analysis of significance on the means of treatments with significant effects was performed using Duncan's multiple range test with a significance level of 0.05.

Frequency analysis was performed on each length distribution obtained for the ratios of *TF* and *TC*. Data was organized into a two-way contingency table with the data from each treatment group arranged in rows of the table, and data from each length category arranged in columns. A Chi-square statistic was calculated using maximum likelihood to determine if the frequency distributions varied according to the different treatments. The level of significance chosen for the Chi-square statistic was 0.05.

5. RESULTS

5.1 Fibre content

Results from the MANOVA analysis of the fibre ratio *F* is presented in Table 5.1. The only significant factors observed were T and the interactions T*SC and FR*SC*WS. The Pearson correlation coefficient between the values of *F* for the straw outlet and chaff outlets was found to be 0.38.

The WS factor alone was not significant in the analysis. As a result, means were only presented for the treatment groups with straw walker speeds of 150 rpm (Tables 5.2 and 5.3). Excluding the values for the straw walker speed 200 rpm reduced the number of comparisons which had to be made between means, and thus reduced the overall complexity of the interpretations that were made for the other factors. The results from both straw walker speeds are summarized in Table 5.4 as the average value of the ratios *F* and *C* obtained from each prototype outlet for all treatment groups.

Upon analysis of the means of the straw outlet (Table 5.2), it was found that there were significant differences in the factor T between the means of the treatment groups 7 t/h - BK, 14 t/h - BK, and 14 t/h - KO respectively. In general, the means were higher for the level 7 d in each pair. In the case of the interaction T*SC, means were significantly different. The means were highest for the levels 7 t/h and BK combined.

The means from the chaff outlet of the prototype were also observed (Table 5.2), and means from 7 t/h - BK and 14 t/h - BK groups were found to be significantly different for the T

Table 5.1Multivariable analysis of variance results from fibre content analysis

Model (Full factorial)	Source	Degrees of Freedom	Dependent Variable, DV			
			Fibre ratio, *F* (%)		Core Ratio, *C* (%)	
			F	Prob<F	F	Prob<F
DV(*so*) DV(*co*)[†] =	Whole Model	47	6.94	<0.0001	78.82	<0.0001
	T	1	54.83	<0.0001	2.30	0.1389
T	FR	1	0.4548	0.5049	150.51	<0.0001
FR	T*FR	1	0.1336	0.7172	4.24	0.0478
T*FR	SC	1	0.0350	0.8527	868.33	<0.0001
SC	T*SC	1	26.77	<0.0001	18.39	0.0002
T*SC	FR*SC	1	1.21	0.2801	3.69	0.0637
FR*SC	T*FR*SC	1	0.78	0.3833	0.40	0.5294
T*FR*SC	WS	1	0.57	0.4547	4.57	0.0403
WS T*WS	T*WS	1	0.01	0.9116	3.61	0.0667
FR*WS	FR*WS	1	4.59	0.0398	22.43	<0.0001
T*FR*WS	T*FR*WS	1	1.31	0.2603	16.75	0.0003
SC*WS	SC*WS	1	1.60	0.2156	0.71	0.4043
T*SC*WS	T*SC*WS	1	0.12	0.7359	2.84	0.1015
FR*SC*WS	FR*SC*WS	1	11.27	0.0020	1.88	0.1803
T*FR*SC*WS [††]	T*FR*SC*WS	1	0.38	0.5438	0.00	0.9880

[†] *so* = Straw outlet; *co* = Chaff outlet

[††] T = Trial time [1 d and 7 d]; FR=Material feed rate [7 t/h and 14 t/h]; SC = Scutcher configuration [BK and KO]; WS=Straw walker speed[150 rpm and 200 rpm]

Table 5.2 Fibre ratio *F* of test groups with significant effects in MANOVA model

Treatment			*F* at straw outlet (*so*) (% of total raw material mass)			*F* at chaff outlet (*co*) (% of total raw material mass)			$\Sigma F = F_{so} + F_{co}$	
FR	T	SC								
Level	Level	Level	y_{so}	Mean††	SD†	y_{co}	Mean††	SD†	Mean††	SD α
7 t/h	7 d	BK	40.09	20.88 c	0.83	59.91	12.15 b	1.11	33.03 bc x	1.21
		KO	46.72	17.81 ab	0.75	53.28	15.12 a	1.52	32.93 bc x	1.47
	1 d	BK	38.45	17.53 ab	1.29	61.55	17.39 a	0.96	34.92 a x	1.39
		KO	45.04	16.46 b	0.47	54.96	15.43 a	1.06	31.89 c	1.01
14 t/h	7 d	BK	40.51	18.58 a	1.03	59.49	14.58 ab	2.37	33.16 bc x	2.24
		KO	53.74	18.92 a	0.64	46.26	14.58 ab	2.34	33.50 abc x	2.10
	1 d	BK	34.44	14.04 d	0.83	65.56	20.22 c	1.42	34.26 ab x	1.42
		KO	47.22	16.97 b	0.51	52.78	15.07 a	0.55	32.04 c	0.65
CONTROL†††				-	-	-	-	-	34.25 x	1.86β

† S.D. = Standard deviation based on n=3, unless noted otherwise [α (n=9), β (n=5)]
†† Means followed by same letters (a,b,c,d) in each column are not significantly different (P>0.05) Duncan's multiple range test
††† Means followed by letter (x) are not significantly different from control (P>0.05) Dunnett's Method (|d| = 2.75)

Table 5.3 Fibre ratio *C* of test groups with significant effects in MANOVA model

Treatment			*C* at straw outlet (*so*) (% of total raw material mass)			*C* at chaff outlet (*co*) (% of total raw material mass)			$\Sigma C = C_{so} + C_{co}$	
FR	T	RC								
Level	Level	Level	y_{so}	Mean††	SD†	y_{co}	Mean††	SD†	Mean††	SD α
7 t/h	7 d	BK	40.09	19.22 e	0.83	59.91	47.76 a	1.11	66.97 ab x	1.21
		KO	46.72	28.91 ab	0.75	53.28	38.16 c	1.52	67.07 ab x	1.47
	1 d	BK	38.45	20.92 cd	1.29	61.55	44.16 b	0.96	65.08 c x	1.39
		KO	45.04	28.56 b	0.47	54.96	39.54 c	1.06	68.10 a	1.01
14 t/h	7 d	BK	40.51	21.93 c	1.03	59.49	44.91 b	2.37	66.84 ab x	2.24
		KO	53.74	34.82 f	0.64	46.26	31.67 d	2.34	66.50 abc x	2.10
	1 d	BK	34.44	20.40 d	0.83	65.56	45.34 ab	1.42	65.74 bc x	1.42
		KO	47.22	30.25 a	0.51	52.78	37.71 c	0.55	67.96 a	0.65
CONTROL†††				-	-	-	-	-	65.75 x	1.86β

† S.D. = Standard deviation based on n=3, unless noted otherwise [α (n=9), β (n=5)])]
†† Means followed by same letters (a,b,c,d,e,f) in each column are not significantly different (P>0.05) Duncan's multiple range test
††† Means followed by letter (x) are not significantly different from control (P>0.05) Dunnett's Method (|d| = 2.75)

Table 5.4 Means of treatment groups from both straw walker speeds

Ratio	Outlet	Straw walker speed			
		150 rpm		200 rpm	
		Mean[††]	S.D.[†]	Mean[††]	S.D.[†]
F	*so*	17.65 a	2.02	18.16 a	2.67
	co	15.56 b	2.60	15.21 b	3.03
C	*so*	25.62 c	5.52	26.03 c	6.28
	co	41.16 d	5.23	40.60 d	6.37

[†]S.D. = Standard deviation based on n = 24
[††] Means followed by the same letter (a,b,c,d) in columns are not significantly different (P>0.05) Duncan's Multiple range test

factor. In this case the level 7 d yielded means that were lower than those of the level 1 d. For the interaction T*SC, means were found to be significantly different. In general the means with levels 7 d and BK were found to be the lowest. The interaction FR*SC*WS could not be explained because the FR and WS factors alone were not significant.

The yield fractions presented in Table 5.2 were used to calculate the values of F used in the analysis (Eq. 3). The total values of ΣF of the straw and chaff outlets were obtained by taking the sums of the values of F for each outlet. All possible combinations of these values were calculated and this resulted in a sample size of nine for the new variable, ΣF. This was performed to properly represent the variance of the new variable. The values of ΣF were then compared to the control using Dunnett's method. Means that were significantly different from the control belonged to the treatment group levels 1d- 7 t/h - KO, and 1d – 14 t/h - KO. This may have indicated errors encountered in the measurements of these variables, as the total of both outlets should equal control values, in order to account for all the fibre passed through the prototype. Specifically, errors may have occurred in the collection of the material from the outlet bins, as well, errors may have also occurred in the flotation measurement of the outlet sample mass.

5.2 Core content

Table 5.1 presents the results from MANOVA analysis for the core ratio *C*. The factors FR, SC, T*SC, FR*WS and T*FR*WS were found to be significant at the significance level <0.01. The Pearson correlation coefficient between the values of *C* obtained from the straw and chaff outlet was found to be 0.26.

The means for the straw outlet (Table 5.3) indicated that only the means from 1d - KO were not significantly different for the two levels in the factor FR. Generally, the value of the means for level 14 t/h of this factor was slightly greater. As well, all of the pairs of means for the SC factor were significantly different. The means for the BK level were lower than the KO level. For the interaction of T*SC, the means that were significantly different were lowest for treatment levels 7 d and BK combined.

Upon analysis of the means for the chaff outlet (Table 5.3), the means from 7 d - KO and 7 d - BK were significantly different for the factor FR. In general the means were slightly greater for the level 9 t/h. As well, significant differences were found for all pairs of means for the SC factor. The means for the BK level were significantly greater than those of levels KO. For the interaction T*SC, the means that were significantly different from each other were highest for the treatment levels 7 d and BK combined. The interaction FR*WS, and T*FR*WS were significant. Again it was difficult to address these significant effects because the WS factor alone was not significant in the analysis.

The sum of the core fractions presented at each prototype outlet was determined and presented in Table 5.3 by the variable ΣC. This variable was obtained using the same method as was performed for the variable ΣF. Means that were significantly different from the control belonged to the treatment group levels 1d – 7 t/h - KO, and 1d – 14 t/h - KO.

5.3 Summary of prototype outlet yields

Table 5.5 presents calculated values of *TF* and *CF* from the variables *F* and *C* calculated for the MANOVA analysis in Table 5.1. What is observed in this table is the highest percentage of total bast fibre (i.e., 63.15%) is presented in the straw outlet for treatment group 7 d – 7 t/h – BK. The same treatment group has the lowest percentage of total core in the same prototype outlet, (i.e., 28.68%). The same treatment group also had the lowest percentage of fibre in the chaff outlet (i.e., 36.85%) and the highest percentage of core in the chaff outlet (i.e., 71.32%).

5.4 Outlet sample constituents

5.4.1 Treatment group selection Based on the results of the previous section, a decision was made on which treatment groups would be selected for use in the constituent and fibre length distribution analyses. Not all treatment groups were considered in this analysis due to the amount of work and results which would have been presented by performing these tests on all the significant treatments. In order to simplify the constituent analysis, results from the significant treatment of feedrate were excluded. Because this treatment only had a small role in the differences of means observed, it was suspected that the exclusion of this treatment would not result in a significant loss of information on the performance of the prototype.

Table 5.5 Summary of fibre and core yields at both prototype outlets

Treatment			Straw outlet		Chaff outlet	
FR Level	T Level	SC Level	*TF* (% of total mass of fibre)	*TC* (% of total mass of core)	*TF* (% of total mass of fibre)	*TC* (% of total mass of core)
9 t/h	7 d	BK	63.15	28.68	36.85	71.32
		KO	54.08	43.10	45.92	56.90
	1 d	BK	50.20	32.15	49.80	67.85
		KO	51.64*	41.94*	48.36*	58.06*
18 t/h	7 d	BK	56.03	32.80	43.97	67.20
		KO	56.48	52.38	43.52	47.62
	1 d	BK	40.98	31.04	59.02	68.96
		KO	52.97*	44.51*	47.03*	55.49*

*Results were significantly different from control (Tables 5.2 and 5.3).

It was observed that the factors T and SC caused the greatest difference in the value of means. At least one of these two factors was significant in all three MANOVA analyses described above. As well, the interactions of these two factors, when significant caused the greatest difference in the value of the means for all the significant interactions encountered. The treatment groups 1d – 7 t/h - BK, 1d – 7 t/h - KO, 7d – 7 t/h - BK, and 7d – 7 t/h - KO were thus selected for constituent and fibre length distribution analysis.

5.4.2 Fibre constituents Figure 5.1 demonstrates the ratios of *TF* for loose and bound bast fibres obtained for each prototype outlet. This figure represents mosaic bars for each treatment group selected. Within the bars are the individual values of *TF* obtained from the constituent analysis procedure outlined in the previous chapter. One noticeable feature of this plot was the amount of loose fibre obtained in the straw outlet (*so*) for each treatment group. This fraction seemed to exhibit a slight increase when the treatment T increased from 1 d to 7 d. Another feature was the amount of bound fibre in each treatment group. This fraction did not seem to change very dramatically with changes of the treatment T, however, a difference appeared to exist in between the treatment SC for BK and KO levels. A lower fraction of bound fibre was observed for the BK level.

The amount of loose fibre in the chaff outlet (*co*) of the prototype appeared to increase slightly with changes in the treatment T from 1 d to 7 d. However, the most significant changes seemed to occur with the change of the treatment SC. Larger increases in loose fibre in the core outlet were observed when the treatment SC changed from KO to BK. The fraction of bound fibre in the core outlet of the prototype increased with changes in the

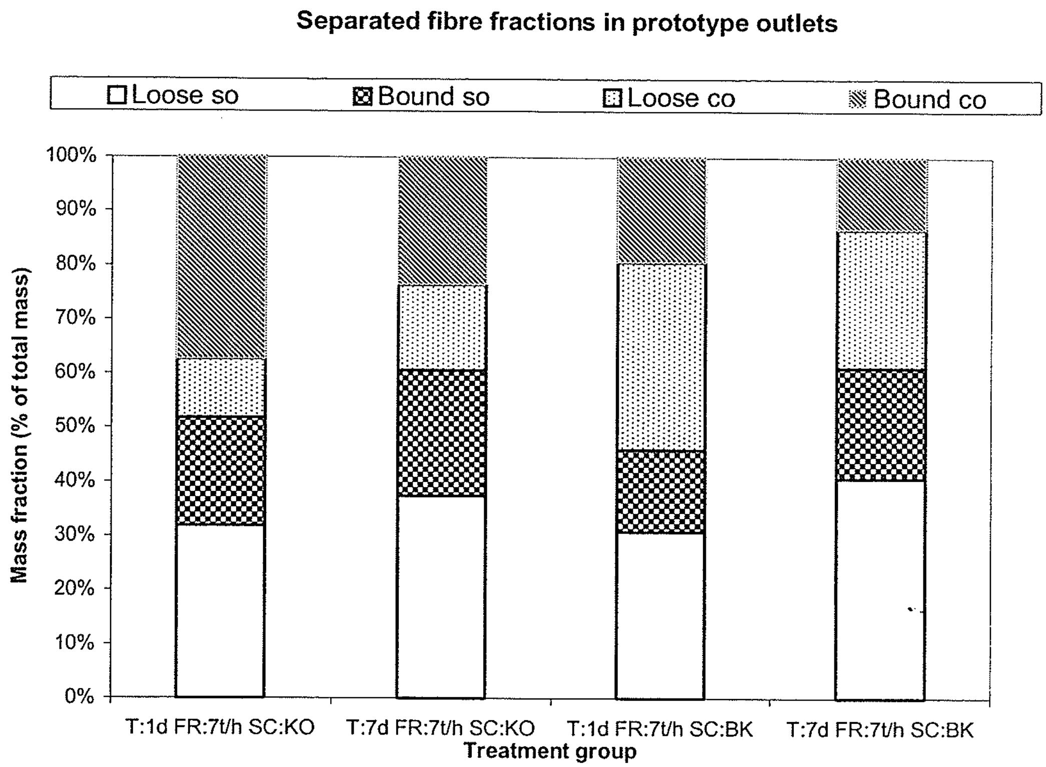

Fig. 5.1 Mosaic plot of fibre ratios (*TF*) obtained from constituent analysis

treatment T from 1 d to 7 d, and with changes in the treatment SC from KO to BK. Overall, the change appeared to be more significant for the factor SC.

5.4.3 Core constituents The value of *TC* obtained from the constituent analysis samples at each outlet is presented in Fig. 5.2. This was provided to better visualize the effects of the treatment groups on the presence of core in each outlet. An increase in core content in the straw outlet was observed with changes in T from 1 d to 7 d. As well a decrease in core content was observed for changes in the factor SC from KO to BK. The amount of core in the chaff outlet had an inverse relationship of the core at the straw outlet.

5.5 Loose fibre and core length distribution

Tables 5.6 and 5.7 present the results of the values of *TF* and *TC* obtained for each treatment group. Data were presented in each table for values obtained in both straw (*so*) and chaff outlets (*co*). Corresponding values from each prototype outlet were then added to form a total length distribution (*tot*) for each treatment group.

Table 5.8 presents the results from frequency analysis performed separately on all three distributions of *TF* and *TC* obtained for all four treatment groups. From these results it was possible to determine that significant differences existed in *TF* for the chaff outlet (*co*) and straw outlet (*so*) length distributions. From the results in Table 5.8 it was also possible to determine that significant differences existed in the *TC* values, for chaff outlet (*co*) and total (*tot*) length distributions.

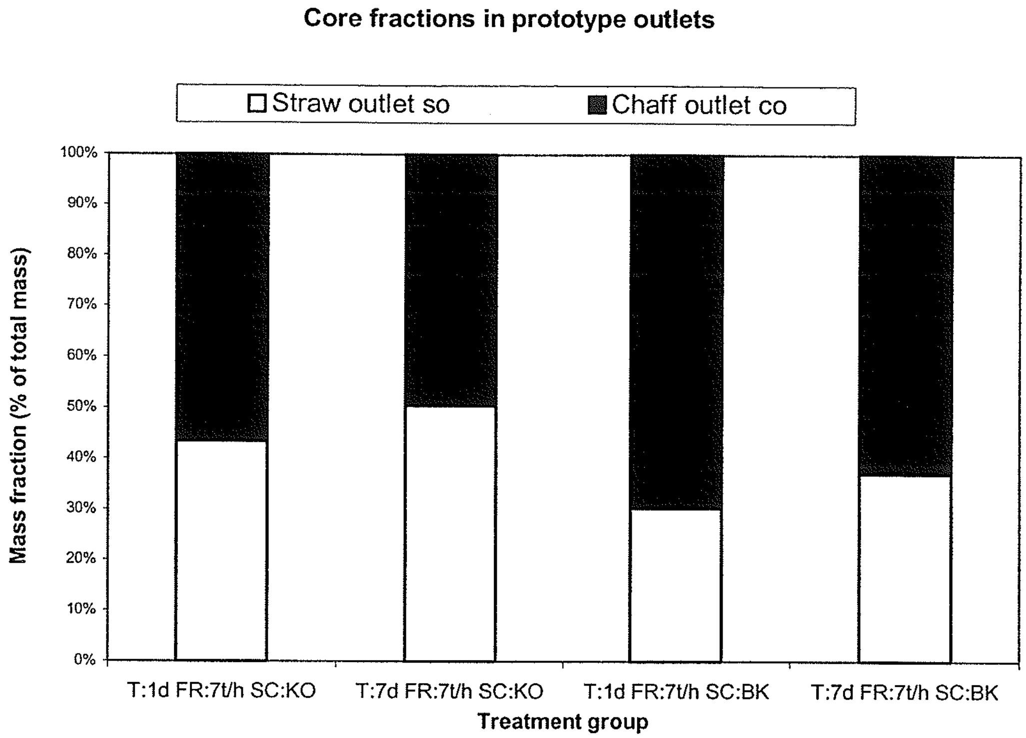

Fig. 5.2 Mosaic plot of core ratios (TC) obtained from constituent analysis

Table 5.6 *TF* length distributions for loose fibre

T Level	FR Level	SC Level	Outlet†	0-25 mm	25-51 mm	51-102 mm	102-152 mm	152-203 mm	203-254 mm	254-305 mm	305-356 mm
Treatment††				*TF* (% of fibre total mass)							
1d	7 t/h	KO	*so*	0.47	3.51	7.61	6.56	4.67	3.59	2.79	2.74
			co	0.63	6.97	0.80	0.44	0.16	0.08	0.00	0.00
			tot	1.11	10.47	8.41	7.00	4.83	3.68	2.79	2.74
1d	7 t/h	BK	*so*	0.84	5.35	7.16	5.38	3.16	3.21	1.46	4.22
			co	9.98	14.20	6.59	2.01	1.15	0.79	0.00	0.00
			tot	10.82	19.55	13.75	7.39	4.31	4.00	1.46	4.22
7d	14 t/h	KO	*so*	0.54	9.07	6.46	6.72	5.19	2.47	2.70	4.30
			co	1.59	11.49	1.91	0.20	0.59	0.00	0.00	0.00
			tot	2.13	20.56	8.37	6.93	5.77	2.47	2.70	4.30
7d	14 t/h	BK	*so*	0.54	3.51	6.83	7.62	6.28	4.02	2.78	3.88
			co	5.20	15.64	4.30	1.44	0.16	0.00	4.10	0.00
			tot	5.74	19.15	11.14	9.06	6.43	4.02	6.88	3.88

† *so* = Straw outlet; *co*= Chaff outlet; *tot* = Total straw outlet and chaff outlet
†† Treatment groups with different FR and WS levels were intentionally excluded from these tests

Table 5.7 *TC* length distribution

T Level	FR Level	SC Level	Outlet†	0-25 mm	25-51 mm	51-72 mm	72-102 mm	102-127 mm	127-152 mm	152-178 mm	178-203 Mm
Treatment††				*TC* (% of core total mass)							
1d	7 t/h	KO	*so*	4.24	29.00	6.25	2.16	1.53	0.00	0.00	0.14
			co	12.13	42.30	1.79	0.00	0.11	0.28	0.00	0.00
			tot	16.38	71.35	8.05	2.16	1.64	0.28	0.00	0.14
1d	7 t/h	BK	*so*	5.59	11.24	5.97	4.29	2.30	0.76	0.00	0.00
			co	30.96	22.54	11.99	4.34	0.00	0.00	0.00	0.00
			tot	36.55	33.79	17.97	8.63	2.30	0.76	0.00	0.00
7d	14 t/h	KO	*so*	5.69	28.78	7.33	2.49	1.18	2.28	0.52	2.13
			co	11.81	33.99	3.33	0.49	0.00	0.00	0.00	0.00
			tot	17.50	62.77	10.66	2.98	1.18	2.28	0.52	2.13
7d	14 t/h	BK	*so*	1.44	12.15	5.72	2.72	1.90	1.42	2.09	0.00
			co	31.90	26.62	3.50	0.97	0.00	0.00	0.00	0.00
			tot	33.35	38.77	9.22	3.69	1.90	1.42	2.09	0.00

† *so* = Straw outlet; *co*= Chaff outlet; *tot* = Total straw outlet and chaff outlet
†† Treatment groups with different FR and WS levels were intentionally excluded from these tests

Table 5.8 Results from frequency analysis

Group	Outlet†	Degrees of freedom	Chi square	Prob>ChiSq
Loose fibre	*so*	82	25.58	0.0427
	co	131	63.43	<0.0001
	tot	212	15.46	0.7993
Core	*so*	229	44.41	<0.0001
	co	140	25.39	0.2303
	tot	377	58.54	<0.0001

† *so* = Straw outlet; *co*= Chaff outlet; *tot* = Total straw outlet and chaff outlet

Figure 5.3 is presented to observe the differences in treatment group length distributions *TF* at the chaff outlet of the prototype. We can see here that a significant difference existed in the shape of the distribution curve of the treatment group 1d – 7 t/h - BK. This appeared to occur because of a higher fraction of fibre mass existed in the length category 0-25 mm over all other distributions. The shape of the distribution also appeared different because of a higher fraction of fibre mass in the length category 72-102 mm for this treatment group. The distribution of the treatment group 7d – 7 t/h - BK appeared to differ from the other distributions slightly. The difference observed was a slightly higher fraction of fibre in the length categories, 0-25 mm and 72-102 mm. The highest proportion of fibre in all the treatment group distributions were concentrated within the length category 25-51 mm.

The most obvious difference in length distribution for the ratios of *TF* at the straw outlet of the prototype occurred for the treatment group 7d – 7 t/h - KO (Fig 5.4). In this distribution, there was a much larger fraction of fibre mass in the length category 0-25 mm. Otherwise, the treatment groups 1d – 7 t/h - BK and 7d – 7 t/h - BK seemed to differ slightly in the length categories 0-25 mm and102-152 mm, respectively.

The difference in the length distribution of *TC* at chaff outlet of the prototype was significant upon analysis of Fig. 5.5. The differences in these distributions occurred between the different treatments of SC. In the treatment groups 1d - 9t/h - BK and 7d - 9t/h - BK, a significant difference of core mass fraction was observed in the length category 0-25mm. Other differences lied in the slow decay of the distribution in the treatment group 1d - 9t/h - BK.

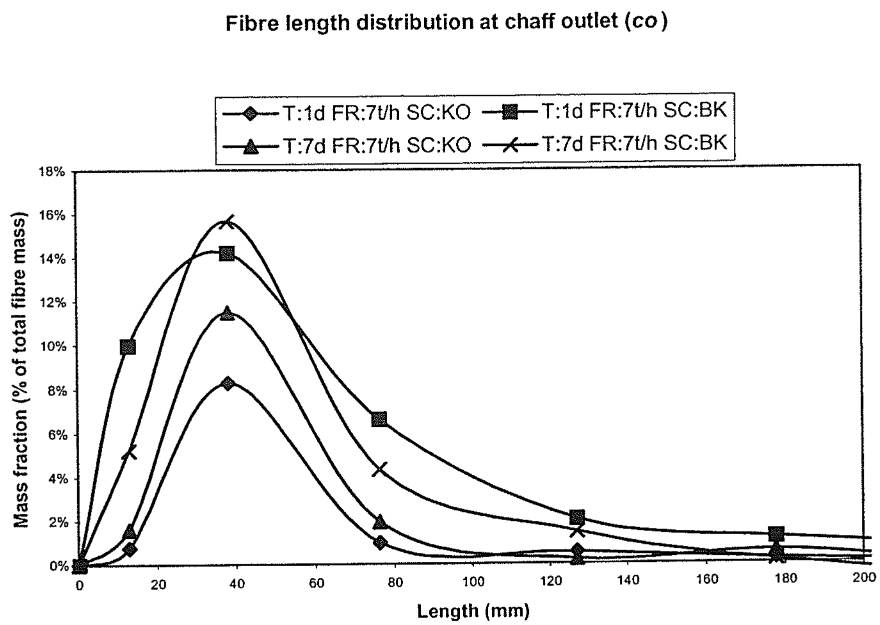

Fig. 5.3 Loose fibre length distribution for chaff outlet of prototype

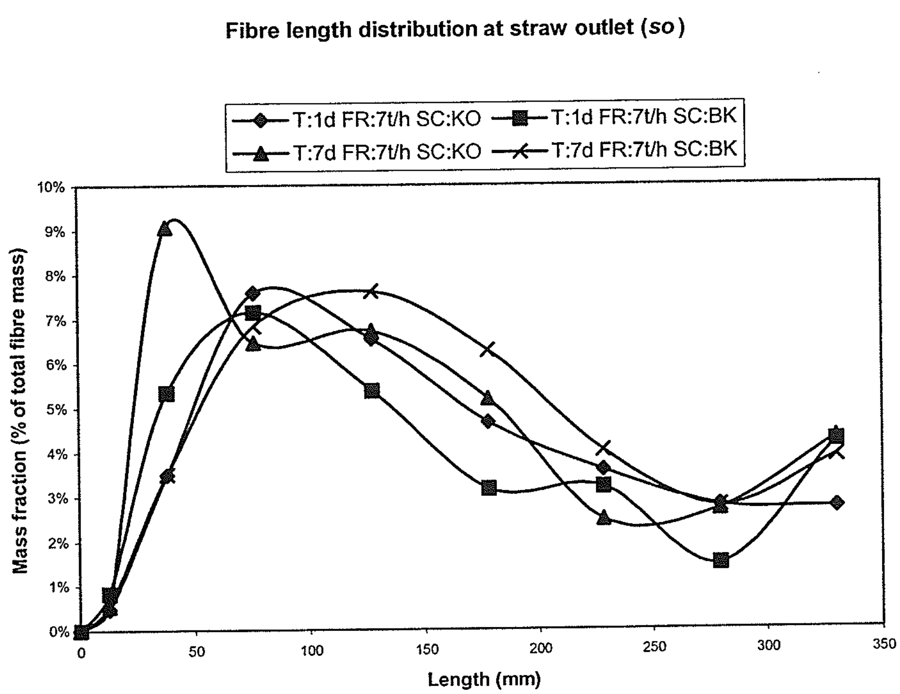

Fig. 5.4 Loose fibre length distribution at straw outlet of prototype

5.5.1 Fibre fineness The results from the fibre fineness tests are presented in Table 5.9. The means were not significantly different from each other, except for the treatment group 1d - 9t/h - BK. The value of the mean for this group was found to be lower than the other means.

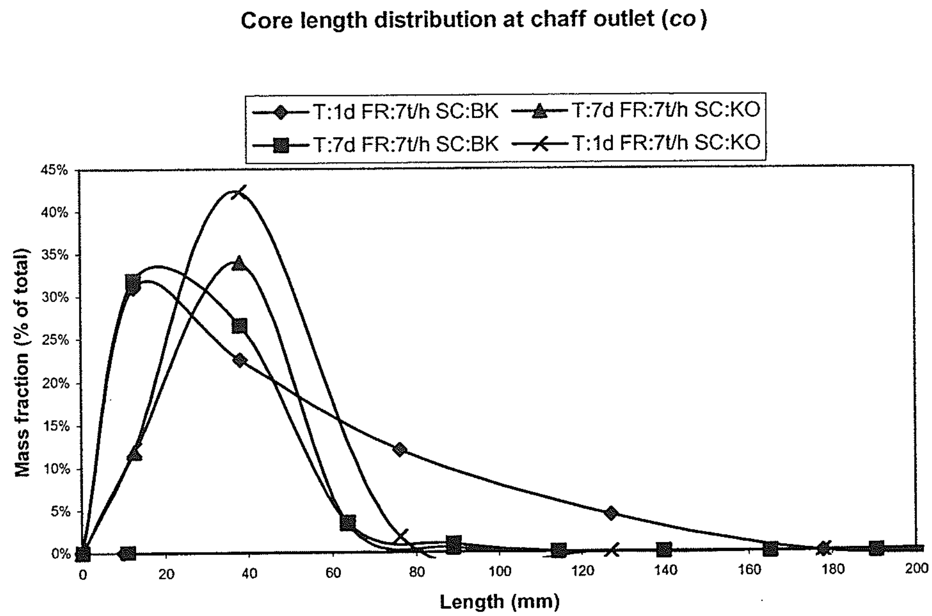

Fig. 5.5 Core length distribution at chaff outlet

Table 5.9 Mean fibre fineness (tex)

Treatment			Number of samples	Mean†	SD††
T Level	FR Level	SC Level			
1 d	7 t/h	KO	8	159.7 a	23.0
		BK	8	126.9 b	32.2
7 d	7 t/h	KO	8	178.1 a	27.3
		BK	8	169.6 a	21.8

†Means followed by the same letters (a,b) are not significantly different
††SD = Standard deviation

6. DISCUSSION

6.1 The effect of retting time

It was found that for the dependent variable *F*, the treatment time T was significant for values obtained at both the straw and chaff outlets. The amount of bast fibre obtained at the straw outlet was higher when the level of the treatment T was 7 d. As well, the amount of bast fibre lost to the chaff outlet was lower for the treatment level 7 d.

This indicates that increases in time had a positive effect on the efficiency of the prototype. This may have resulted from the fact that the longer the stalks had been left on the field, the greater they would have been subjected to retting. As a result, bast fibres would be removed from the core more easily. This was observed in Fig. 5.1, where the amount of loose fibres was slightly greater in treatments with higher retting times. As well, the amount of bound fibre in the chaff outlet was significantly lower for treatments with higher retting times. This indicates that, regardless of the scutcher configuration, bast fibres were removed from the core more easily as retting time increased.

The length of loose fibres measured seemed to be slightly longer for the treatment level 7 d. This is observed from Fig 5.4, where a higher percentage of fibre is found in the length category 102-152 mm for treatment 7 d – 7 t/h – BK. This may have helped increase the amount of fibre observed in the sample. The longer fibres would not have fallen through the holes in the straw walker and would thus have been remained retained. Longer fibres may have been a result of improper cutting of loose fibres at the shearbar.

Because a small gap existed in between the knife blade and the shearbar of the rotor assembly, the fibres may have simply bent around the bar in the space between the shearbar and the knife and may not have been cut until sufficient build-up was present at the bar. This effect may have been more significant at the 7 d level. Because there would have been less core to cut in the material, and thus less support for the fibres not to bend around the shearbar.

6.2 The effect of feedrate

The effect of feedrate was significant for the dependent variable C for both straw and chaff outlets. Generally, the amount of core separated from the bast fibres in the straw outlet was lower for the higher feedrate of 14 t/h. This may have been caused by the larger amount of material flowing over the straw walkers which may have inhibited the separation ability of the straw walker itself.

6.3 The effect of cutterhead configuration

The effect of cutterhead configuration was significant for the dependent variable C for both straw and chaff outlets. Significantly lower amounts of core at the straw outlet and higher levels of core at the chaff outlet were observed for the treatment level BK. In the length distribution (Fig. 5.5) it can be seen that the fraction of mass of core in the length range 0-25 mm was higher by approximately 18 to 20 % for the BK level, when compared to the distributions of the KO level treatments.

From these results, it was concluded that the scutcher bars placed on the cutterhead effectively reduced the length of core, to the theoretical length. This length of core was therefore appropriately sized to pass through the holes of the straw walker, and this resulted in a higher separation of core to the chaff outlet.

From these results it was suspected that the some of the core found in the straw outlet were not separated from the straw walker due to their size. It was observed from Table 5.7, that the majority of these particles measured within the range of 25-51mm. One of the reasons that these particles did not fall through the holes of the straw walker may have been due to their length. What this indicates is that the scutcher bars were not able to break the entire stalk into the theoretical length of 10 mm. Instead some of the stalks were cut along with the fibres at the theoretical cut length of 38 mm.

6.4 Interaction effects

Significant effects were observed for interaction of the time (T) and cutterhead configuration (SC) treatments for both dependent variables *F* and *C*. In the case of the dependent variables *F*, the means from the chaff outlet were significantly different from each other between the levels of T, 1d and 7d for the SC level BK. The means were also higher in the case where the level of T was 1d.

The length distribution of the treatment group 1d - 7 t/h - BK was significantly different from the other distributions because of the higher ratio of fibre in the length interval 0-25 mm (Fig. 5.3). This may have resulted from the interaction of the scutcher bars on the fibre. Because these stalks had not been retted, the bast fibres may have broken with the core before the knife blades were able to cut the fibre. The smaller fibres would then have fallen through the holes of the straw walker more readily than the fibres in the length range 25-51 mm, resulting in the slightly higher proportion observed in the chaff outlets. This is also supported by Fig. 5.1 where the amount of loose fibre observed in the chaff outlet is greater in the case of retting times of 1 d. The effect of shorter fibres was also present in the treatment group 7 d – 7 t/h – BK (Fig. 5.3). The significance of this effect was much lower. The effect barely existed at all in the other distributions, indicating that it is a characteristic of the BK level only.

The means of values of *C* at the straw outlets with significant differences were found to be generally lower for levels 7 d and BK combined when considering the interaction T*SC. The opposite of this was observed at the chaff outlet. This interaction can be explained by the information presented in Fig 5.1. It was observed that bound fibre ratios in the fibre outlet of the prototype decreased with increases in retting time from 1 d to 7 d and were lowest with the level BK. It was concluded from this result, that separation ability (i.e., fibre from core by the scutcher bars) is greatly improved by retting time.

6.5 Bast fibre loss

As pointed out in the previous chapter, the mass fractions of the loose bast fibre found in the chaff outlet were highest in the length range of 25-51 mm (Fig. 5.3). This demonstrates that the majority of the mass of fibres were cut to the theoretical length of cut of 38 mm. The values in this length range were compared to the values for the straw outlet distributions of the same length range (Table 5.6). In all cases, these values were higher in the chaff outlet of the prototype. The reason for this was suspected to be the size of the holes on the straw walker. Instead of being carried over the straw walkers as anticipated, these bast fibres passed through the holes of the straw walker due to their length.

The amount of bast fibre lost from this effect varied within the range of 8-16% of the total mass of fibres (Fig. 5.3) for different treatment groups. The highest values were found for the treatments of BK. This may have been a result of the scutcher bars' ability to separate more fibre from the core. This effectively contributed to more individual fibres of the length range 25-51 mm to fall through the straw walker. This was supported by Fig. 5.1 where it was observed that loose fibre was higher in the chaff outlet for treatment level BK. The effect of the retting time T was also suspected to contribute in the same manner.

It is suspected that the different amounts of fibre lost from each treatment played a significant role in the effects of the treatments observed for the variables F and C. However, it was difficult to model loss due to fibre length for these treatment effects and more work needs to be performed to properly address this.

6.6 Summary and comments

In general, the results obtained from the field tests provided information on the overall effectiveness of the prototype. Most notably, the maximum amount of core removed from the raw material by the prototype was approximately 70% (Table 5.5). This occurred when the prototype was operated on raw material 7 d after initial harvest, the feedrate was set at 7 t/h, and the forage harvester cutterhead had scutcher bars added to it. It is clear, therefore, that the prototype realized the statement in chapter 1; whereas the device itself would provide a benefit to the current cultivation practices of hemp by reducing the amount of raw material from the field. A reduction of 70% of core would reduce the mass to be transported off the field and the amount of space needed in to warehouse the material.

Overall, the modifications made to the original forage harvester were significant in the effectiveness of the prototype. This was observed in the significance of the cutterhead configuration treatments SC of the field tests. In general, more fibre was yielded (10%) and more core (20%) was separated from raw material compared to the same treatments performed without scutcher bars (KO) (Table 5.5). This occurred when the prototype was operated on raw material 7 d after harvest and the feedrate was set at 7 t/h. This helped to confirm the validity of some of the assumptions made on the anticipated function of the prototype pertaining to the addition of scutcher bars. Among these was the breaking of core into small lengths as a means to perform separation of the core from bast fibres which proved to be somewhat successful.

It was shown in this study that retting time had a positive effect on obtaining more fibres at the straw outlet of the prototype, and in reducing the amount of core at the same outlet. This suggests that the effectiveness of the prototype may be increased by allowing the stalks to ret in the field longer. Retting may not be beneficial to producers trying to remove the raw material from the field before spoilage occurs.

The increase in the rate of feed of material through the prototype was shown to have a detrimental effect on core separation. This demonstrates that the prototype's effectiveness is limited to lower feed rates. A feedrate lower than 7 t/h may be beneficial in improving separation of core in the prototype. Careful consideration must be made however, that the feedrate is not too low to render the prototype too inefficient.

In the experiments performed in this study, the speed of the straw walkers was varied on the prototype to determine the effect on the separation ability of the prototype. None of the treatments applied were found to be significant for this factor. This does not necessarily suggest that straw walker speeds do not have an effect; it is possible that the differences were too small to notice using the sampling methods in this study. This is especially true when considering that some interaction effects were observed for the analysis on the amount fibre and core in the prototype outlets. These could not be explained using the information obtained, and in general more work needs to be performed to address this effect.

The highest amount of bast fibre obtained from the straw outlet of the prototype was approximately 60%. This represents a total loss of bast fibres to the chaff outlet of approximately 40%. This is significantly high, and has a major detrimental effect on the overall effectiveness of the prototype. One major reason for fibre loss was found to exist because of the cut length of the majority of the fibres. While it was anticipated that fibres cut to the theoretical length of 38 mm would not pass through the holes present on the straw walker, this was not the case as shown in the experiments. In fact, the majority of the fibres for the treatment 7d – 7 t/h – BK (i.e., approximately 16%), were lost due to this effect.

7. CONCLUSIONS

7.1 Primary objective

The primary objective of this study was to design and construct an on-field hemp fibre processing prototype. This was achieved by the construction of the prototype presented in this study. The main function of the prototype was identified as picking up raw hemp material from the field, separating the fibre and the core of the raw material, and delivering both of these fractions separately to two different outlets in a continuous process.

The prototype design used information obtained by analyzing the major functions of several existing hemp and flax processing machines. Several assumptions were made to provide more detail on the actions of the functions observed in these machines.

The major components of the prototype were then designed based on the functional analysis performed. The prototype was physically constructed using existing agricultural equipment. The pick-up, feeding, breaking/scutching functions were achieved using a conventional forage harvester. The shaking/screening functions were achieved using a conventional straw walker from a combine. The straw walker also served to deliver the separated fibre and core material to two different outlets.

7.2 Secondary objective

Practical tests were conducted to achieve the secondary objective of this study; the evaluation of the prototype under field conditions. Specifically, the prototype was operated in the field on harvested windrows of hemp stalks. These tests provided a means to examine the performance of the prototype under several different operational conditions. This consisted of operating the prototype with the original forage harvester cutterhead configuration consisting of only knives and the operation of the prototype with scutcher bars added to the cutterhead. The prototype was also tested with two different straw walker speeds. The tests also provided a means of determining the effectiveness of the prototype under different field conditions. This was done by operating the prototype on material which had undergone two different retting times, and by subjecting the prototype to two different material feedrates into the prototype.

The results obtained from the field test were measurements of the bast fibre and core content of the processed material collected at both outlets of the prototype. These measurements indicated the overall effectiveness of the prototype in separating hemp bast fibre from the core. The measurement of the amount loose and bound bast fibres in samples also helped explain some of the significant treatments. The measurement of the length of loose bast fibres and core were also performed and aided in explaining the significance of treatments.

7.3 Field test results

The major findings of the field tests are summarized in the following points:

1. The maximum amount of core which was removed from raw material by the prototype was approximately equal to 70%.

2. The introduction of scutcher bars on the original cutterhead of the forage harvester improved the separation of fibre the most out of all other factors. The reason why this was more effective was that it broke 20% of the total mass of core particles into lengths <25mm which were then effectively screened by the straw walker.

3. Best results were obtained when operating the prototype 7 d after initial harvest. This was found to be more effective because of retting of hemp stalks when they are left in the field after harvest.

4. The yield of fibre at the straw outlet from field tests was a maximum of approximately 60% of the total mass of fibre. Consequently, it was concluded that large fibre losses were experienced, and that 8-16% of total fibre mass was lost because the fibre lengths were too short.

5. The prototype was more effective at a lower feedrate of 7 t/h than 14 t/h..

6. The speed of the straw walkers in the prototype did not prove to have an effect on separation. The lowest speed (100 rpm) was insufficient in allowing the proper

function of the prototype.

7. Fibres obtained from the prototype had a fibre fineness range of 126-178 tex.

7.4 Recommendations for future research

7.4.1 Delamination model To achieve a better understanding of the mechanics of fibre separation, practical tests could be performed on the breaking assumptions made in chapter 3 of this study. This would include testing the effect of fibre separation under practical situations using the delamination model presented. This could be achieved by determining the strength of the bond between the bast fibres and the core of a hemp stalk.

This procedure is commonly performed for reinforced fibre composites, to examine the strengths of inter-laminar bonds. One example of these tests is called a peel mode interlaminar fracture toughness test (Daniel and Ishai 1994). In this test, a fracture composite specimen is torn apart by grabbing the two ends of the composite on either side of the fracture and pulling the specimen apart (Fig. 7.1). The energy dissipated per unit area of the fracture growth is measured and recorded. In the case of hemp fibre, the same procedure could be repeated by pulling the bast fibre layer off the core. The energy measured here would help in determining the shear strength of the bond and can be repeated for samples subjected to different levels of retting.

7.4.2 Modifications to the prototype Because the theoretical cut length of fibres (38 mm) was found to result in major fibre loss (8-16%), it is suspected that this amount of fibre could be recovered by changing the cut length of the prototype. This could be achieved by reducing the number of knives on the modified cutterhead of the prototype to two so that a longer cut length could be achieved. In general, more work needs to be performed on this aspect. By conducting the field tests again using cut length as a treatment, an optimal cut length could be identified.

Because the prototype was to be used only on an experimental basis, the fibre and core delivered to each outlet of the prototype were collected in a bin. In actual field circumstances, a means of packaging the processed material would have to be done to efficiently remove the material from the field. In the case of the separated bast fibre, a square baler may be employed at the straw outlet of the prototype to package this material, and present it in a form which could be collected using conventional machinery. In the case of core at the chaff outlet, it may be desired to keep this material as a value added product. In this case, a larger collection bin than the one used may be placed on the prototype, and the means to empty this bin once full, may be incorporated onto the prototype. This would allow the operator to empty the bin into a truck, and the material could be carried off the field. Otherwise the material could be returned to the field directly.

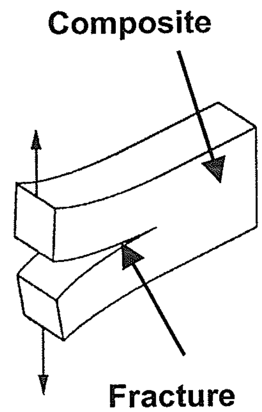

Fig. 7.1 Illustration of peel mode test

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APPENDIX A

Canadian Patent No.	Class/subclass	Title
2111458	A01F 12/44	METHOD OF DECORTICATING FLAX, AND FLAX-PROCESSING MACHINE DESIGNED TO CARRY OUT THE METHOD
369135	19/23	STAPLE FLAX FIBRE PRODUCING APPARATUS
350504	19/23	SCUTCHING MACHINE
345125	19/23	FIBROUS MATERIAL TREATING APPARATUS
345124	19/23	BAST FIBRE PRODUCTION
296353	19/23	HEMP MACHINE
294014	19/23	FIBRE CLEANING MACHINE
292463	19/23	FIBRE PROCESSING MACHINE
292247	19/23	TEXTILE BREAKER
285778	19/23	COTTONIZED FIBRE PRODUCTION
265140	19/23	FIBROUS MATERIAL MANUFACTURE
263395	19/23	HEMP CLEANING MACHINE
261004	19/23	DECORTICATING MACHINE
253125	19/23	MACHINE FOR DESINTEGRATING MATERIAL CONTAINING TEXTILE FIBRES
229876	19/23	MACHINE FOR SCUTCHING FIBROUS MATERIAL
218700	19/23	SCUTCHING OF FLAX
214658	19/23	MACHINE FOR BREAKING FIBROUS MATERIALS
206296	19/23	METHOD OF TREATING FLAX

US Patent No.	Class/Subclass	Title
5,970,582	19/5R	METHOD FOR SEPARATING KENAF INTO CORE AND FIBER
5,906,030	19/5R	APPARATUS FOR DECORTICATING PLANT MATERIAL
5,720,083	19/5R	DECORTICATING METHOD FOR SEPARATING BAST FROM CORE OF FORAGE CHOPPED KENAF OR THE LIKE
3,064,315	19/5R	APPARATUS FOR DECORTICATING FLAX
3,009,210	19/12	METHOD AND APPARATUS FOR THE AUTOMATIC DOSING OF BAST FIBRE STALKS
2,759,224	19/11	APPARATUS FOR EXTRACTING FIBERS FROM FIBER-BEARING PLANTS
2,747,232	19/9	PROCESS FOR DECORTICATING FIBROUS MATERIAL
2,685,108	19/5A	MECHANISM FOR PROCESSING VEGETABLE FIBERS
2,605,510	19/7	APPARATUS FOR CLEANING FIBROUS MATERIAL
2,231,040	19/5R	MACHINE FOR TREATING FLAX AND THE LIKE
2,231,039	19/5R	COMBINATION MACHINE FOR TREATING RAMIE, FLAX, AND HEMP
2,211,351	19/5R	THE SEPARATION OF FIBRE FROM FIBRE CONTAINING MATERIAL
2,208,287	19/5R	BAST FIBER PREPARATION
1,950,403	19/23	SCUTCHING AND CLEANING MACHINE
1,846,859	19/5R	PRODUCTION OF BAST FIBERS FROM VEGETABLE STALKS
1,795,530	19/5R	MACHINE FOR THRESHING AND SCUTCHING FLAX

1,716,589	19/24	METHOD OF AND MACHINE FOR CLEANING FLAX, HEMP, AND OTHER FIBERS
1,598,094	19/5R	METHOD OF CLEANING HEMP AND OTHER FIBROUS PLANTS
1,477,449	19/5R	MACHINE FOR TREATING FLAX STRAW
1,403,830	19/5R	DECORTICATING MECHANISM
1,241,703	19/5R	MACHINE FOR TREATING FLAX AND OTHER FIBRES
1,239,667	426/636	PROCESS OF REMOVING FIBRE FROM FLAX STRAW AND PREPARING RESIDUE
1,209,546	435/279	PROCESS FOR TREATING FLAX PLANTS
1,111,027	19/5A	METHOD OF SECURING VEGETABLE FIBER
988,151	19/5R	PROCESS FOR PREPARING FIBER FOR COMMERCIAL PURPOSES
962,783	19/5R	BREAKING AND SCUTCHING MACHINE
869,004	19/5R	HEMP BRAKE
839,198	19/5R	FIBER PREPARING MACHINE
826,014	19/5R	HEMP BRAKE
781,398	19/5R	HEMP BRAKE
761,311	19/5R	HEMP SHAKING MACHINE
749,475	19/5R	DECORTICATING MACHINE
701,183	19/25	METHOD OF PREPARING FLAX FIBER FOR SPINNING
464,308	19/5R	MACHINE FOR DECORTICATING VEGETABLE FIBERS
362,387	19/5R	TREATING RAMIE AND OTHER FIBERS