

Analysis and Design of Hemp Fibre Decorticators

by

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GENERAL ABSTRACT

Hemp (*Cannabis sativa L.*) fibre is a natural renewable material which has been used in important areas closely related to people's daily life. The increasing need of hemp fibre of high quality requires better fibre processing methods, more advanced facilities with higher machine performance and efficiency. Decortication is the key procedure to extract hemp fibre, and it significantly affects the output fibre quality and purity. The machine used for this process, known as a decorticator, needs to be well designed. The energy requirement is worth being evaluated for decorticators.

This study consisted of two parts. In the first part, the specific energy of using a hammer mill for decorticating hemp was examined. The experimental data (three hammer mill screen scenarios and three feeding masses) were used to fit modified size-reduction theories (Kick's, Rittinger's and Bond's laws). The experimental data were also used to develop a linear regression model to predict the specific energy from the ratio of initial and final fibre lengths. Results showed that all modified laws and the linear model performed equally well for specific energy prediction, and they had better prediction accuracy at a higher feed rate.

In the second part of the study, integrated with virtual reality (VR) technology, TRIZ ("Theory of Inventive Problem Solving" in Russian) method was used for designing and evaluating a new hemp scutcher prototype in virtual environments. An evaluation system was developed for making comparison of the new design and the traditional scutchers. The new design is expected to have a better performance in

terms of scale, product quality and energy efficiency. The TRIZ-VR integrated design has great potential to be a fast, reliable and low-cost design trend.

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1. General Introduction

1.1 INTRODUCTION

Hemp plants have been cultivated since ancient time, benefiting human beings in different aspects. The use of hemp as medicine can be traced back to around 2300 B.C. in China. Hemp cloth is known as the oldest sample of cloth. Hemp cores (also named as hurds) are able to be converted to paper products. Hemp seeds can be used for oil extraction. With the improvement of processing techniques, hemp oil has become an important original material for biodiesel production in recent years (Wikipedia Online 2009).

Modern industries require sustainable and ecological development in order to face the challenge of environmental issues. “Green” production and natural materials have gained more and more attention from people all over the world. Hemp fibre, as an important natural material, has been studied and used in different areas. Hemp fibre is stronger than flax and cotton fibre, and it is believed that hemp fibre may substitute carbon fibre and glass fibre in composite manufacturing (Munder and Fürll 2004; Mwaikambo 2006). Good thermal insulation property makes hemp fibre be widely used as thermal insulating materials (Munder and Fürll 2004). Hemp fibre also plays an important role in textile industry which is closely related with our daily life.

Fibre processing equipments and methods are worth being studied to elevate the quality of fibres and meet various needs. Decortication which detaches fibres from cores is an important procedure affecting fibre quality. The machine used to achieve

decortication is known as a decorticator. Two types of most commonly used decorticators are hammer mill and roll crusher. Hammer mill has the advantage in decorticating short fibres and its capacity is relatively high, while roll crusher is capable of extracting long fibres (Munder and Fürll 2004; Hobson et al. 2000). In some of the main producing areas, hemp fibre extraction is still a labor-intensive work. Current technology of hemp fibre processing is not very efficient. For instance, hammer mill processing has high energy requirement (Baker 2010), so it may decrease the economical value of the fibre product. In order to select the suitable decorticators according to their demand, users need to know the analytical data of energy requirement to operate the decorticators in an efficient way.

Developing new high-standard decorticators is one of the main goals in improving hemp fibre processing. Incorporating advanced designing methods and tools, such as TRIZ (“Theory of Inventive Problem Solving” in Russian) method, may bring novel ideas and prompt the development of fibre processing facilities. TRIZ is a logic methodology which can be applied in different areas including machine design. By analyzing the problems of the current decorticators, TRIZ can provide general solutions to improve the function of the machine. The new designed prototype can be evaluated in virtual environment instead of building a real model. This trend is able to achieve the preliminary decorticator design and evaluation with low cost.

1.2 GENERAL OBJECTIVES

The general objective was to provide fundamental knowledge and tools for developing hemp decortication machinery in the future. The specific objectives of this study were: 1) to investigate the relationship between the specific energy requirement of fibre decortication by hammer mill and the fibre length change; 2) to fit the experimental data with the modified size reduction theories (Kick's, Rittinger's and Bond's laws); and 3) to develop a fast conceptual design trend incorporating TRIZ design method with virtual reality (VR) technology in hemp decorticator (scutcher) designing.

The results of specific energy requirement of hammer mill will be helpful to estimate the energy consumption in using or designing hemp fibre decorticators. The TRIZ/VR method has the potential be used as a tool for modifying and improving the hemp processing line in the future.

1.3 THESIS STRUCTURE

This thesis has been structured around two stand-alone engineering papers. Chapter 1 includes the general introduction and objectives of the study. Chapter 2 consists of general literature review on hemp processing and machinery. Chapter 3 and Chapter 4 focus on energy requirement of hammer mill decortication and TRIZ design of hemp scutcher in virtual environment respectively. Chapter 5 summarizes the results and conclusions. References (for Chapter 1, Chapter 2 and Chapter 5) are presented in appendix.

2. Literature Review

2.1 HEMP PLANT

Hemp (*Cannabis sativa L.*) is the common name for plants of the entire genus *Cannabis*. *Cannabis sativa L.* is often referred to as true hemp to distinguish it from other fibre crops. Hemp is frequently confused with marijuana, because of their similar leaf shapes. THC (delta-9-tetrahydrocannabinol) is the active ingredient in marijuana as well as a material for making drugs. However, hemp contains virtually no THC (less than 0.3%), while the content of THC in marijuana can reach from 6 or 7% up to 20%. Therefore hemp cannot be used as a drug (Wikipedia Online 2009).

The innermost layer of hemp plant is the pith, surrounded by woody material known as core. The separated core is also called as “hurd” in some papers (Declerck et al. 2008). Outside of this layer is the growing tissue which develops into core on the inside and into the bast fibres on the outside (Beckermann 2007). Figure 2-1 shows the non-scaled simplified scheme of a hemp stem cross section.

Hemp can be grown on a range of soils, but tends to grow best on land that produces high yields of corn. The soil must be well drained, rich in nitrogen, and non-acidic. Hemp grows fast and it requires limited pesticides and attracts few pests. In northern latitudes, hemp is usually planted between early March and late May. Hemp averages between 2-4 m in height in about four months of growth. The stem diameter can range from 6-16 mm in the field according to a research conducted by Chen et al. (2004).

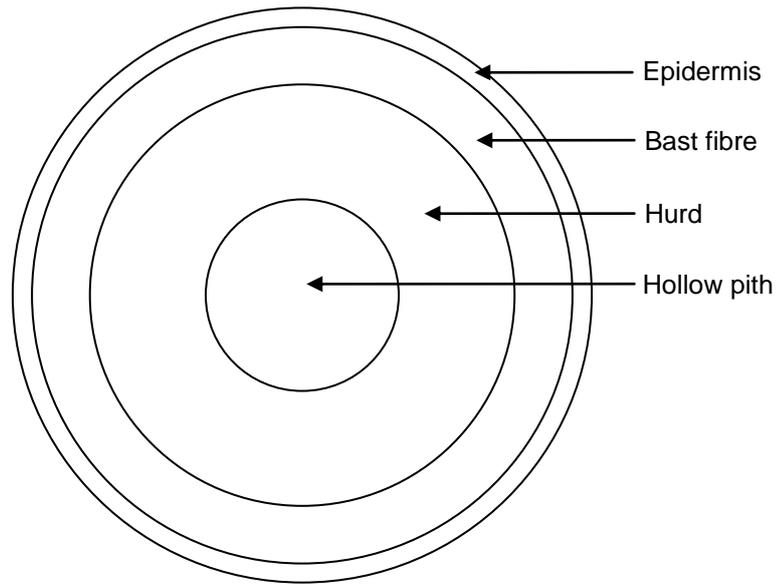


Fig. 2-1. Simplified scheme of a hemp stem cross section (not to scale).

Hemp is sensitive to day length. The plant matures (sets seed) as days get shorter in the fall. The seeds of hemp are smooth. The seeds usually contain from 29-34% oil. The composition of the oil mainly consists of three fatty acids: linoleic (54-60%), linolenic (15-20%), and oleic (11-13%) (Wikipedia Online 2009). There is a wide range of applications on both the fibre and seed.

2.2 HEMP FIBRE PROCESSING

Basically, processing hemp for the purpose of fibre needs to follow the procedures of harvesting, retting, baling, pre-cutting, decorticating and cleaning. Retting in the field helps later decorticating. But recent research has proved that “green decortication” without retting is also acceptable for some industrial applications (Munder and Fűrll 2004; Hobson et al. 2001; Riddlestone et al. 2006). However, decortication of green hemp required more power and energy than that of retted hemp, and decortication of green hemp was less effective when a hammer mill was used, when compared to decortication of retted hemp (Baker 2010).

2.2.1 Harvesting

Hemp crops are harvested at different times for different hemp products. When grown for textile fibre, the crop should be harvested when the fibre is at its highest quality. The best time to harvest stalks for high quality primary fibre is when crop is in flower. Harvesting for seed production and stalks occurs 4-6 weeks after flowering, when male plants begin to shed pollen. Hemp harvest is usually performed with the use of general-purpose agricultural harvesting machines such as haybines and

combines. Because of the large biomass, the whole plant cannot be fed into the harvester such as a conventional combine machine (Chen and Liu 2003). For the hemp cultivated for single-purpose (fibre) only, haybines can be used for swathing. For the hemp cultivated for dual-purpose (seed and fibre), a windrower has been developed by Chen and Liu (2003) for swathing seed and fibre separately.

2.2.2 Retting

For high-quality applications, the bast fibres should be separated from the retted stalks. Munder and Füll (2004) reported that the tensile strength and modulus of elasticity of hemp fibres from retted plants were higher compared with the ones from unretted hemp. Retting can also greatly improve the fineness and the stability of the hemp fibres (Munder and Hempel 2004).

Traditionally, the hemp stalks are laid in the field to dry for a couple of days after swathing. This kind of retting is called “dew retting”. The combined action of bacteria, sun, air, and dew produces fermentation, dissolving much of the stem material surrounding the fibre bundles. This type of retting is highly depended on the climate of the location and the weather situation. Over retting may destroy the structure of the stems and decrease the mechanical properties of the fibres (Akin et al. 2000). Though varying weather conditions affect the quality of fibres, retting process in the field is still commonly used especially in European countries because it is inexpensive and environment friendly.

Instead of leaving the stalks in the field, another retting method is to use water. Water retting provides more uniform and high-quality fibres. Currently, most hemp

fibre used in textiles in China is water retted. Stems can be immersed in rivers or tanks. Hot water is sometimes used for special fibre quality requirements.

In recent years, chemical retting and enzymatic retting methods have been developed by some researchers. Akin et al. (2005) compared the effect of a pilot plant for processing both dew-retted and enzyme-retted flax. The enzyme retting followed the previous method reported by Akin et al. (2000). The results showed that dew-retted flax fibres had higher strength than enzyme-retted ones. However, enzyme retting provided better fineness and higher fine fibre yield.

2.2.3 Baling

Baling is the process which gathers the harvested individual hemp plants into bales. It can be done by most types of balers. The straws of flax and linseed are shorter and are usually formed into rectangular bales. Different from that, the hemp straws are better to be collected into round bales. Round bales have larger surface area than square bales with the same volume, and they are easier to release moisture and are able to keep the bales dry during storage. Bales are then sent to the central unit for further processing.

2.2.4 Pre-cutting

Hemp stalk length can be up to 3 m. Such long straw may cause wrapping of machine rotating parts in the following decorticating and cleaning procedures. Thus, pre-cutting may be necessary before processing for fibre. Hemp was cut into a length of about 300-400 mm previously by Munder and Hempel (2004). A commercial bast fibre processing line designed by Van Dommele Engineering (VDE) can accept the

maximum straw length of 600 mm (Declerck et al. 2008). In order to protect the machine, the optimum fibre length for decortication was selected from 80-200 mm by Munder et al. (2003). Pre-cutting length of hemp straws also affects the average product length. The results have shown that longer cutting length can produce longer fibre at the end of the process. Baker et al. (2009) processed the feed hemp stock with a pre-cutting length of 40 mm in a planetary mono mill because this length was considered as the most suitable length for the production of biocomposties.

For different agricultural applications, some machines have been used to cut cereal straws and hays, such as linear knife grid, bale slicer, tub grinder and shredder (Igathinathane et al. 2006). Many of them are either length-uncontrolled or energy consuming, and they are not recommended to be used for industrial hemp pre-cutting. Rotary cutter is more energy saving than linear cutter (Persson 1987). Munder et al. (2003) used a driven knife disk co-operated with a bale holding and turning device to pre-cut the straws into 400 mm. A commercial hemp fibre processing line called Temafa GmbH Lin Line has a bale opener which is able to treat round as well as rectangular bales (Temafa GmbH 2004).

2.2.5 Decortivating

Decortivating is the most important procedure of hemp fibre processing. An effective decortication can make the following cleaning process simpler, and can elevate the fibre quality significantly. Generally, the machine used for decortication is called “decorticator” by researchers. One important principle on using the decorticator is that the process should not adversely influence the mechanical properties of the

fibre, so that the design of the machines and the choice of operational parameters should be considered before the process. Decortication machinery is discussed in details in the following sections.

With the increasing need for long fibres and the development of decorticators, the cutting procedure has been eliminated in some processing methods. Most of these decorticators are roll crushers, which have a horizontal path for straws passing through (Hobson et al. 2001; Booth et al. 2004; Akin et al. 2005). Such methods treat the whole plants in the format of bundles without cutting, so that longer fibres can be separated from the straws. Long fibres are useful for textile purpose and mat manufacturing (Munder and Hempel 2004).

2.2.6 Cleaning

The decortication procedure can separate most of the fibres from the cores. But there are still free cores and cores attached to the fibres which need further cleaning. Multiple ultra cleaner was applied in a laboratory line developed by Munder and Hempel (2004). Free cores may be sieved out using vibratory screens or rotary screens. Cores which are attached to the fibres are more difficult to clean. Hobson et al. (2000) used high speed pinned rotor to purify the fibre ejected from the rollers. Akin et al. (2005) reported the use of scutching wheel to stoke flax to shorten and clean fibres. The scutching wheel had a diameter of 1168 mm and a rotational speed of 263 rpm. Lin-Comb Shakers was used for separating loose shives in a commercial line (Temafa GmbH 2004).

2.3 DECORTICATION MACHINERY

2.3.1 Roll crusher

One commonly used decorticator is roll crusher. A simple roll crusher consists of a pair of rolls rotating in opposite directions. Material is fed in between the rolls and crushed by forces of the rolls. If the rolls rotate at the same speed, compression is the primary force. Shearing and compression are the primary forces on the materials when the rolls rotate at different speeds. If the rolls are grooved, a tearing or grinding action is introduced. Roll crushers are mainly used for ore and rock comminution in the industrial sectors such as mineral processing, chemistry, cement, and building material. Currently, the commercial machines have different scales to meet the different demands of customers.

Roll crushers have the potential to be used as the decorticators to separate fibres and cores. An example of a roll crusher model is shown in Fig. 2-2. Cores of the bast fibre plants are brittle and can be easily broken by pressure. The roll crusher normally has no effect on the length of fibres. Industrial flax manufacturing applies fluted rolls to crush and break the woody core into short pieces and then separates them from the remained fibres. This procedure is generally called as “scutching” in flax industry. In fact, the designing concept is similar to the roll crushers. Some roll crushers are also called as scutchers.

When designing the parameters of a roll crusher, the ratio of length to diameter of the rollers can reach to 4:1 (Feedmachinery 2009). Many lab-scaled machines were designed based on the structure of roll crushers to separate fibre from core of hemp

and flax. Hobson et al. (2001) developed a modified lab-scale flax decorticator to separate fibres from unretted hemp straws. The decorticator had four pairs of rollers (Fig. 2-2). Akin et al. (2005) used a pilot plant called Flax-PP to process flax. The line consisted of scutching roller combines. The sequence of the elements in the line was: 9-roller calender, top shaker, scutching wheel, top shaker, 5-roller calender and top shaker. The component called scutching wheel removed the shives greatly for unretted Neche and dew-retted Natasja, but was less effective on enzyme-retted Jordan. A lab decorticator “Bahmer-Flaksy” was used by Amaducci et al. (2008) to scutch the hemp stalks, in order to investigate the decorticability of hemp stems obtained at different plant densities and harvesting times. The hemp bundles were repeatedly put through the decorticator six times for each test. The results showed that scutching was more efficient in the lower part of the stems and long stems. Low plant population was suitable to reduce the loss of smaller and thinner plants during processing. Kovur et al. (2008) also used lab-scale Bahmer-Flaksy decorticator to extract hemp fibres. The pressure of the breaking rolls was 10 N, with the linear feeding speed of 13 m/min.

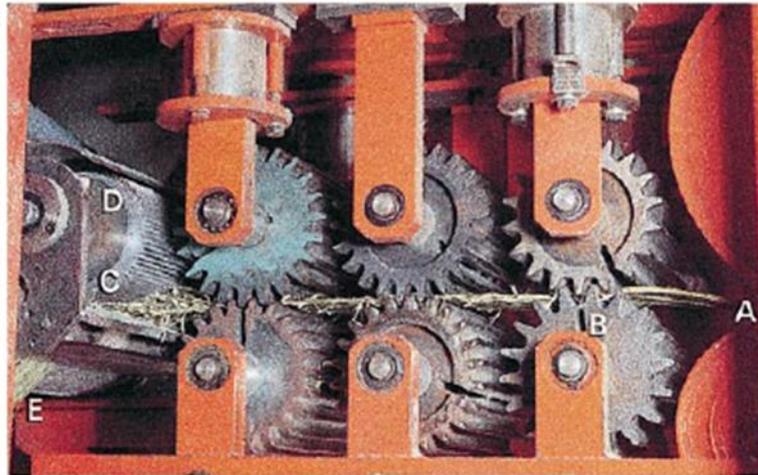


Fig. 2-2. Working elements of the roller machine used for decortication (Hobson et al. 2001).
(A) pair of smooth-faced rollers; (B) three pairs of fluted rollers follow; (C) shell feed; (D) feed pinned rotor; (E) main pinned rotor.

2.3.2 Hammer mill

Another type of fibre decorticator is hammer mill. Hammer mills are widely used in size reduction processes such as flour grinding and biomass industry. Hammer mills have large capacity and high energy efficiency compared with other size reduction equipments (Miu et al. 2006). The basic structure of a hammer mill is that a steel drum with a vertical or horizontal cross-shaped rotor in it (Fig. 2-3). The purpose of hammer mills is to shred material into small particles. Pivoting hammers are mounted on the rotor. The bottom mounted screen controls the product size. Hammers used inside the hammer mill can have a huge range of configurations, shapes, facings, and materials. Sometimes a hammer will be designed to have two holes. When one end is worn, the hammer can be used if sides are switched. The screen design should allow the greatest amount of open area. Holes will be aligned in a 60-degree staggered pattern.

When the hammers rotate with the rotor, the ends of them impact on the material and shred them into smaller particles until the particle size is smaller than the screen-hole-size. Not like roll crushers, hammer mills can grind fibrous materials. In such case, a screen with cutting edges will be employed. The design of the hammers attached to the rotor should meet the requirement of maximum contact with the feed ingredient. Hammers should be balanced and not trail each other. The common tip speeds for hammer mills are 5000-7000 m/min, and usually 8500-10000 rpm.

Munder et al. (2003) developed a pilot plant for hemp, flax, and oil seed linen with the co-operation with the Kranemann Gartenbaumaschinen GmbH. The pilot

plant can achieve a capacity of 3 t/h of straw. The decorticator used in this plant was a modified swing-hammer mill. Figure 2-3 shows the structure of the hammer mill (Munder and Fürll 2004). The rebound stress of the hammers on the straw stems separated the fibre from the brittle core. During the decortication process, about 45% of the shives arose at the decorticator. The final fibre purity of the retted hemp could reach to over 99%.

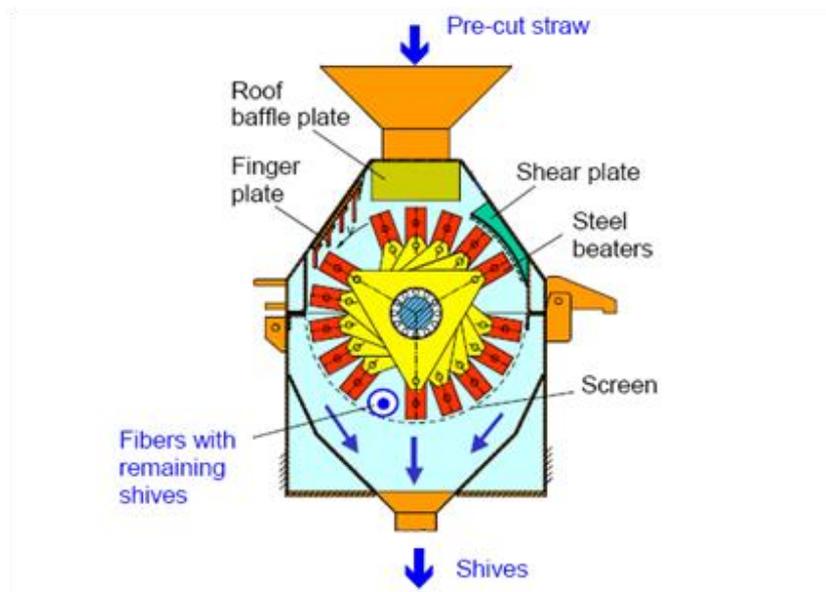


Fig. 2-3. Structure of the hammer mill used for decortication (Munder and Fürll 2004).

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2.3.3 Other machines used for decortication

Besides roll crushers and hammer mills, researchers also reported fibre decortication using other machines. Gratton and Chen (2004) applied modified cutterhead and scutching bars to decorticate hemp feedstock. The maximum fibre yield and purity were 61% and 52% respectively. Anthony (2002) used different types of cotton gin machines to separate fibre from seed flax straw. The results indicated that the range of the content of pure fibre was from 7.1% to 12.8%. Also, the author concluded that the raw material had to be retted before decortication. Baker et al. (2009) conducted a series of hemp decortication experiments using a lab-scale planetary mono ball mill. The results showed that higher grinding speeds and longer grinding time could separate more fibres from the cores.

2.4 FIBRE PROCESSING LINES

Some fibre processing lines have been constructed for laboratory tests or industry manufacturing. A flax fibre pilot plant was developed by USDA and Czech Flax Machinery (Akin et al. 2005). This line had good product quality and great commercial potential. A commercial “Lin Line” developed by Temafa GmbH had a capacity of 2 t/h, and was able to process both hemp and flax straws (Temafa GmbH 2004). A successful commercial line built by VDE had the capability to handle 6.6 t/h straw bales and technically get 1.92 t/h maximum output fibres (Declerck et al. 2008).

In summary, the hemp fibre decortication consists of field handling and central unit processing. The field handling includes harvesting, retting, and baling.

Mechanisms of pre-cutting, decortication, post-decortication are the main components in central unit line. Other components such as metal detector, conveyor, and output fibre baler may be varied in different lines. Munder and Hempel (2004) reported the use of a pilot-scale fibre processing line which consisted of all necessary functions from bale opening to product packaging (Fig. 2-4).

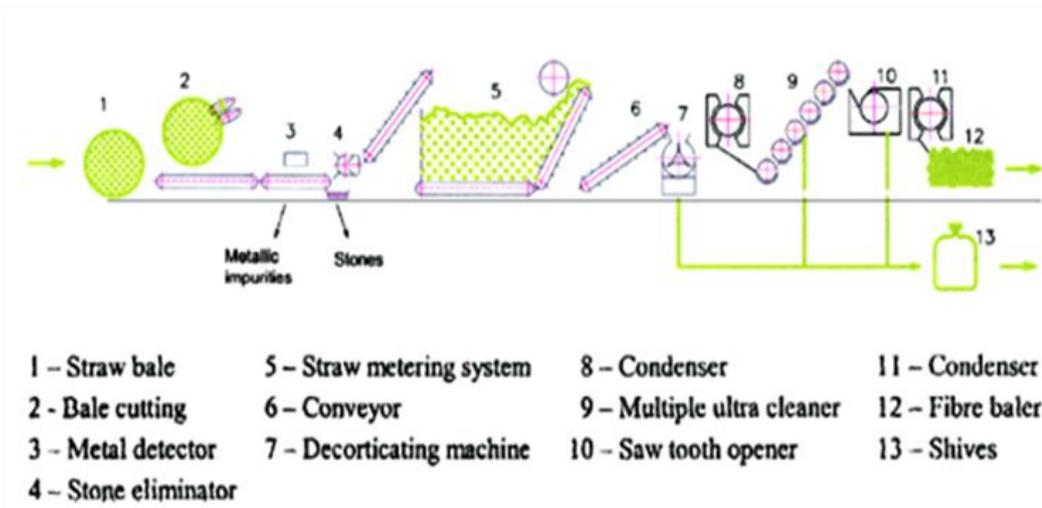


Fig. 2-4. Process flow sheet for processing hemp (Munder and Hempel 2004).

3. Analysis of Energy Requirement for Hemp Fibre Decortication Using a Hammer Mill

3.1 ABSTRACT

Hemp fibre decortication is an important procedure in hemp fibre processing. The cost of energy during decortication affects the commercial value of hemp fibres for industrial production. This study investigated specific energy requirement for hemp decortication using a hammer mill, and the length distribution of output fibre based on the tests with three screen opening sizes (19.28 mm, 25.74 mm, and no-screen scenario) and three feeding masses (200 g, 125 g, and 75 g). Results showed that 200 g feeding mass and small screen-hole size required the highest specific energy (73.84 J/g). Screen size affected the length distribution, and for all three feeding mass scenarios, more short fibres were produced when small size screen was used. Modified Kick's, Rittinger's and Bond's laws and a linear model were developed to fit the experimental data in regard to relating specific energy with initial and final fibre lengths. Results showed that all modified laws and the linear model performed equally well for specific energy prediction, and they had the best prediction accuracy at the highest feeding rate. **Keywords:** hemp, decortication, fibre, energy, hammer mill.

3.2 INTRODUCTION

Hemp (*Cannabis sativa L.*) fibre is a renewable and environmentally friendly natural material. The material has been used for different applications since early ages because of its outstanding mechanical and physical properties, such as high tensile strength and good thermal insulation character (Kozowski 2000). Because of the advantages, it becomes an important industrial starting material applied in textile, pulp and paper manufacturing, biocomposites, automobile accessories, and thermal insulation materials (Fortenbery and Bennett 2004; Van Wyk 2007). Hemp fibre has the potential to substitute carbon fibre and glass fibre (Munder and Fűrll 2004).

A hemp stem basically consists of the outer layer of fibre and inner layer of hollow cores. To extract the fibres from the fibre-core attachment, decortication is required. Decortication is the process that mechanically separates fibre and core. The equipment used for decortication is called a decorticator. Various types of equipment have been used to decorticate hemp. Hobson et al. (2000) modified a roll crusher (scutcher) which was originally for flax and retted hemp decortication to extract long fibre bundles from unretted hemp. The roll crusher had three pairs of fluted rollers running at different speeds, followed by a high speed pinned rotor to remove the remaining cores attached to the fibres. The fibre yield reached up to 30% by mass. Gratton and Chen (2004) developed a field-going unit with a cylindrical cutterhead to provide fibres for non-textile applications. The cutterhead from a forage harvester was modified and installed right after the pick-up entrance, and it shortened the cores by breaking and scutching of the hemp stalks. Longer fibres and shorter cores were then

delivered to a straw walker for cleaning. A processing line which featured a modified hammer mill as the decorticator was developed by Munder and Fürll (2004) for fibre production. They obtained a good decorticating effect from the impact stress of the hammers on the hemp straws and gained the fibre yield of 22-24%. This mechanism also worked well with the input materials of flax and linseed. Baker (2009) investigated the effect of low moisture (9.7%) hemp decortication using a lab-scale planetary mono ball mill. The results showed that grind speed and duration affected the properties and purity of the outputs. The combination of 200 rpm with 4-min duration gave the greatest long fibre yield of 51%.

Among the above mentioned equipments, hammer mill and roll crusher are most commonly used for commercial fibre decortication. For decortication purpose, hammer mills are more suitable for short fibre production which could be used in industrial composites or pulp manufacturing, while roll crushers have the potential to provide long fibres for textile products. A hammer mill requires relatively low initial and maintenance cost, and can work with large capacity of various materials.

Hammer mills are generally serving as size reduction machine in a wide range of applications such as biomass handling and flour grinding (Mani et al. 2003; Fang et al. 1998). Using hammer mill as a decorticator could achieve the separation of fibres and cores, but at the same time, both fibres and cores are shortened. Hammer mill is an energy consuming device with lower energy efficiency (Lobo 2002; Baker 2010). For this reason, energy requirement of hammer mill has been studied by many researchers in different application areas. The major energy input of hammer milling is consumed

on size reduction of the feed. The factors affecting the energy requirement include both material properties of the feed and machine geometrical parameters.

Normally, specific energy is used to assess the energy consumption of hammer mill. Specific energy is defined as the energy consumed per unit feeding mass. Vigneault et al. (1992) compared the specific energy, grinding rate, particle size, and hammer lifetime using a hammer mill with two hammer thickness scenarios: 3.2 mm and 6.4 mm. The average specific energy for thin hammer tests was 10.2 kW h t^{-1} , which was 13.6% less than that of thick hammer (11.8 kW h t^{-1}). The grinding rate was higher for thin hammer scenario. A relationship of wheat moisture, debranning rate, screen size and the energy requirement of grinding was investigated by Dziki and Laskowski (2005) based on the experiments using a laboratory hammer mill. The hammer mill was equipped with a current recorder to calculate the electrical energy during the grinding process. A multiple linear regression was built to relate specific energy with the variables of grain moisture, mass of grain, and diameter of screen openings. They found that higher debranning degree caused a decrease of specific energy, and more specific energy was required for higher moisture grain. Smaller screen size led to higher specific energy requirement. Similar results in terms of screen size were also reported by Arthur et al. (1982) and Mani et al. (2004). Mani et al. (2004) compared the specific energy of grinding wheat and barley straws, corn stover and switchgrass by a hammer mill with 22 swinging hammers. A negative correlation between the specific energy consumption and the hammer mill screen size was found for each material with the moisture content of 8% (w.b.) or lower. Moisture

content affected the specific energy at the same time, that the higher the moisture content, the higher was the specific energy. Ghorbani et al. (2010) tested the specific energy of reducing the size of alfalfa chops on a hammer mill. The average specific energy ranged from 5.65 kJ kg⁻¹ to 30.51 kJ kg⁻¹ over different hammer mill screen sizes and initial material sizes. Holtzapple et al. (1989) reported that a two-stage hammer mill required 0.18 MJ kg⁻¹ electrical energy for reducing initial wood chip length of 25.4 mm into final length of 2 mm.

Researchers have presented different models to simulate the energy requirement of hammer mill comminution (Austin 2004; Shi et al. 2003). Theories were developed relating the specific energy of size reduction to the initial and final sizes of the material. Among these theories, Kick's, Rittinger's and Bond's size reduction laws are most famous and widely accepted (Lowrison 1974; Henderson and Perry 1976; Pfof and Swinehart 1970). Their theories are presented as the following equations:

$$E_K = C_K \times \ln \left(\frac{L_1}{L_2} \right) \quad (3-1)$$

$$E_R = C_R \times \ln \left(\frac{1}{L_2} - \frac{1}{L_1} \right) \quad (3-2)$$

$$E_B = C_B \times \ln \left(\frac{10}{\sqrt{L_2}} - \frac{10}{\sqrt{L_1}} \right) \quad (3-3)$$

where E_K , E_R and E_B stand for the specific energy of each law. L_1 and L_2 are the initial size and the final size of the material respectively. C_K , C_R and C_B are constant factors.

If the constant factors are known, specific energy requirement can be estimated based on the initial and final material sizes. For example, Ghorbani et al. (2010) calculated the constant numbers in Kick's, Rittinger's and Bond's laws respectively according to the regression of the experimental data in alfalfa comminution by a

hammer mill. Rittinger's law fitted the data best.

In summary, when hammer mill is used as a decorticator, energy requirement is an important factor to be considered. Little research has been done in the aspect of specific energy of decortication. No literature was found in relating specific energy to hemp fibre lengths before and after decortication. The objectives of this study were: 1) to theoretically modify Kick's, Rittinger's and Bond's laws and relate the specific energy with the initial and final fibre lengths; 2) to fit the modified laws with the experimental data to determine the constant factors; and 3) to develop a regression model of specific energy and the ratio of initial and final fibre lengths based on the experimental data.

3.3 MATERIALS AND METHODS

3.3.1 Experiments

3.3.1.1 Hemp samples, equipment and experimental design

The experiment was carried out as a part of another study by Baker (2010) on hemp fibre decortication using a hammer mill. Details on hemp samples, equipment (hammer mill) and experimental design have been described in Baker (2010). Here these are briefly summarized. The hemp samples (variety: USO 31) were from a farm in western Manitoba (Canada). The hemp stalks were retted in field for six weeks and then baled and stored outside. The moisture content of the samples was 9.7%. Before being loaded into the hammer mill, hemp samples were cut into segments using a heavy-duty paper cut in order to prevent wrapping in hammer mill (Fig. 3-1).

A swing hammer mill (Model E221.5 – TFA, Bliss Eliminator, Oklahoma, U.S.A) was used as the decorticator to decorticate the hemp samples (Fig. 3-2). The hammer mill had 24 swinging hammers symmetrically installed on the rotor. The scale of each hammer was $175 \times 50 \times 7$ mm. Hammer mill was installed with staggered perforated plate screens with round openings. The hammer rotor rotating at a speed of 3600 rpm was driven by a 22 kW motor.

The treatments of the decortication experiments were: three screen scenarios 19.28 mm (Fig. 3-3a), 25.74 mm (Fig. 3-3b), and no screen; three feeding masses 75 g, 125 g, and 200 g. Each treatment was conducted with four replications, which gave a total of 36 tests (3 screen scenarios \times 3 feeding masses \times 4 replications).



Fig. 3-1. Retted hemp sample precut into segments.



(a)

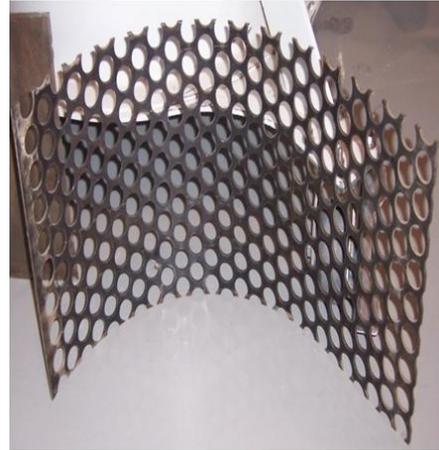


(b)

**Fig. 3-2. Decortication equipment (Baker 2010).
(a) hammer mill; (b) swing hammers.**



(a)



(b)

**Fig. 3-3. Staggered perforated screen of the hammer mill (Baker 2010).
(a) opening size 19.28 mm; (b) opening size 25.74 mm.**

3.3.1.2 Specific energy measurement

A sensor kit was linked to the hammer mill, transmitting data including the motor torque, speed, power, current, and voltage to a laptop computer every 0.1 second. 9000XDrive Software was applied to record data. The power data recorded from the sensors were translated and plotted into power-time curves (Fig. 3-4). The ascent of the bell shape curve was because of the increasing power during decortication. The power value decreased as the decortication completed gradually. The decortication process ended within approximately 5 seconds. For each power-time curve, 5-seconds width of the curve containing the peak was selected to calculate the energy. The following equation was used to evaluate total decortication energy input during the 5 seconds:

$$E_{\text{total}} = \left(\frac{y_2 + y_1}{2}\right) \times \Delta t + \left(\frac{y_3 + y_2}{2}\right) \times \Delta t + \dots + \left(\frac{y_n + y_{n-1}}{2}\right) \times \Delta t \quad (3-4)$$

where:

E_{total} = total energy (J);

y_1 = the power value of the first data point (W);

y_2 = the power value of the second data point (W);

y_n = the power value of the n^{th} data point (W); and

Δt = time interval (s).

The horizontal line before the bell shape curve shown in Fig. 3-4 represented for the no-load power, which was 594 W. This no-load power was translated to a no-load energy of 2970 J (for 5 seconds). To determine the net energy, the no-load energy was deducted from the total energy obtained from the above equation. The specific energy

was calculated as dividing net energy by the feeding mass (Eq. 3-5).

$$E_s = \frac{E_{\text{net}}}{M} \quad (3-5)$$

where:

E_s = specific energy (J/g);

E_{net} = net energy (J); and

M = feeding mass (g).

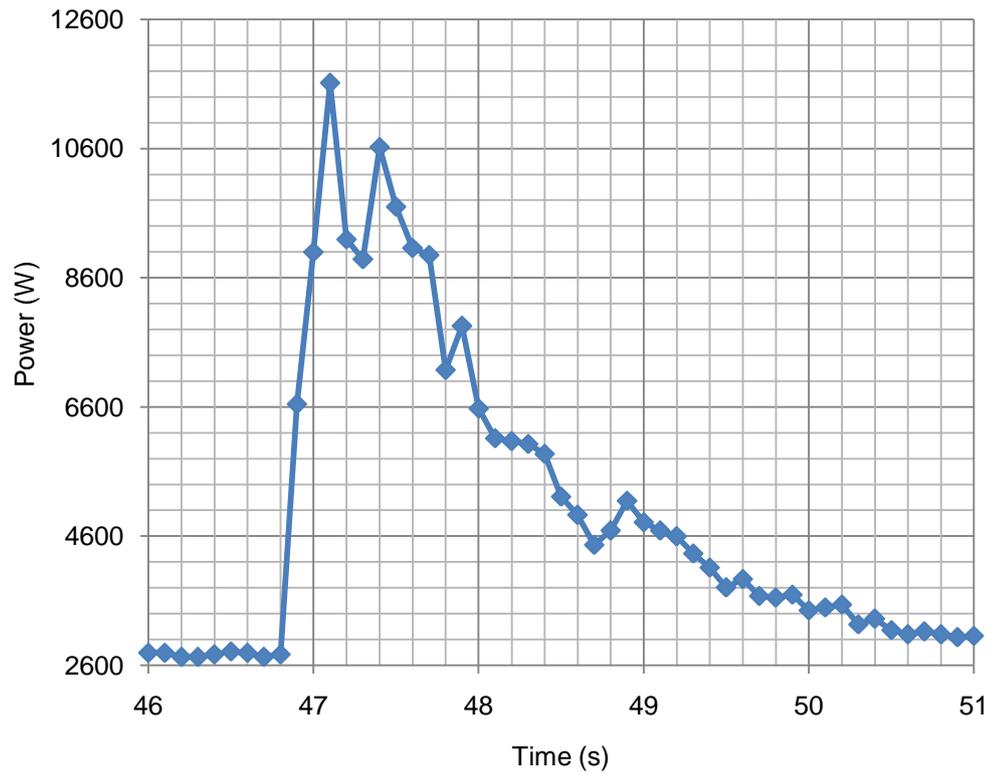


Fig. 3-4. Typical power-time curve; data from the treatment: 25.74 mm screen with 200 g feeding mass.

3.3.1.3 Fibre length analysis

To determine the initial fibre length, ten fibres from the initial sample without decortication were randomly chosen and measured. As the hemp fibres were always tangled, the length distribution of the output hemp fibres was done manually. After each decortication test, the fibres from the output (mixture of fibres and cores) were collected, and the final length was characterized with six length categories, and they were used: 0-20 mm, 20-40 mm, 40-60 mm, 60-80 mm, 80-100 mm, and longer than 100 mm. Each fraction was weighed by Mars digital scale (MS200, North York, Canada) and the proportion value of each fraction was recorded for fitting energy models as described below.

3.3.2 Modified size reduction laws

Kick's, Rittinger's and Bond's size reduction laws can achieve good simulation when the material consists of single component. However, the outputs from the hammer mill consisted of two components: fibres and cores, and the properties of these two components were quite different. The three existing laws could not be used directly. A theoretical modification was made to simply relate the specific energy with the initial and final lengths of fibres without considering the sizes of the cores. This was because most cores were rejected (commonly by air flow) to a waste stream during decortication process and their length distribution cannot be quantified.

To describe the procedure of the modification, a list of nomenclature parameters is shown in Table 3-1. The initial lengths of fibre and core were assumed to be the same controlled by the pre-cutting procedure. The ratio of final core and fibre lengths

was considered as constant due to the assumption that the ratio was one inherent character of the hemp samples. The proportions of core and fibre contents were assumed to be uniform of all samples. These assumptions are:

1) the initial length of the core L_{1c} equals to the initial length of the fibre L_{1f} ;

2) the relation between final length of the core and fibre is $L_{2c} = r \times L_{2f}$, where r is a constant;

3) the proportion of core μ_c and the proportion of fibre μ_f are constants.

The total specific energy could be simplified in two parts: specific energy of fibre and specific energy of core. Thus:

$$E_K = \mu_c E_c + \mu_f E_f \quad (3-6)$$

Table 3-1. Nomenclature for deducing modified laws.

Nomenclature			
L_{1c}	initial core length (mm)	E	total specific energy (J/g)
L_{1f}	initial fibre length (mm)	E_c	specific energy of core (J/g)
L_{2c}	final core length (mm)	E_f	specific energy of fibre (J/g)
L_{2f}	final core length (mm)	C_c	constant factor for core
μ_c	mass proportion of core fraction	C_f	constant factor for fibre
μ_f	mass proportion of fibre fraction	r, C, b	constants

*Subscripts K, R, B and L stand for Kick, Rittinger, Bond, and the linear regression model developed respectively.

Taking the fibre and core fractions separately, the original Kick's law (Eq. 3-1)

would be expressed as:

$$E_c = C_{Kc} \times \ln \frac{L_{1c}}{L_{2c}} \quad (3-7)$$

$$E_f = C_{Kf} \times \ln \frac{L_{1f}}{L_{2f}} \quad (3-8)$$

Substituting L_{1c} and L_{2c} by the terms of L_{1f} and L_{2f} , the relationship could be presented as:

$$\begin{aligned} E_K &= \mu_c \cdot C_{Kc} \cdot \ln \frac{L_{1f}}{r \cdot L_{2f}} + \mu_f \cdot C_{Kf} \cdot \ln \frac{L_{1f}}{L_{2f}} \\ &= (\mu_c \cdot C_{Kc} + \mu_f \cdot C_{Kf}) \ln \frac{L_{1f}}{L_{2f}} + \mu_c \cdot C_{Kc} \cdot \ln \frac{1}{r} \end{aligned} \quad (3-9)$$

The final fibre length might vary in a large range. For instance, in this study, the final fibre length varied from shorter than 20 mm to longer than 100 mm. To consider the length distribution of the final fibre, E_K could be calculated as:

$$E_K = (\mu_c \cdot C_{Kc} + \mu_f \cdot C_{Kf}) \times \ln \left(\sum_{i=1}^n \delta_i \frac{L_{1f}}{L_{2fi}} \right) + \mu_c \cdot C_{Kc} \cdot \ln \frac{1}{r} \quad (3-10)$$

where δ_i is the mass proportion of the i^{th} length category, n is the number of length categories, and L_{2fi} (mm) is average output fibre length of the i^{th} length category. The Eq (3-10) is rewritten in the following general form:

$$E_K = C_K \cdot X_K + b_K \quad (3-11)$$

where C_K is a constant factor to be determined by the experimental data. b_K (J/g) is a constant term according to the assumptions. X_K represents $\ln \left(\sum_{i=1}^n \delta_i \frac{L_{1f}}{L_{2fi}} \right)$, and it was the independent variable in the modified Kick's law. Equation 3-11 was the modified Kick's law for assuming hemp decortication specific energy. This modified law related the total specific energy with the initial and final length of the fibre fraction only.

Similarly, the modified Rittinger's and Bond's laws are as follows:

$$E_R = \left(\frac{\mu_c \cdot C_{Rc}}{r} + \mu_f \cdot C_{Rf} \right) \cdot \sum_{i=1}^n \delta_i \left(\frac{1}{L_{2fi}} - \frac{1}{L_{1f}} \right) + \left(\frac{\mu_c \cdot C_{Rc}}{L_{1f} \cdot r} - \frac{\mu_c \cdot C_{Rc}}{L_{1f}} \right) \quad (3-12)$$

$$E_R = C_R \cdot X_R + b_R \quad (3-13)$$

$$E_B = \left(\frac{\mu_c \cdot C_{Bc}}{\sqrt{r}} + \mu_f \cdot C_{Bf} \right) \cdot \sum_{i=1}^n \delta_i \left(\frac{10}{\sqrt{L_{2fi}}} - \frac{10}{\sqrt{L_{1f}}} \right) + \left(\frac{10 \cdot \mu_c \cdot C_{Bc}}{\sqrt{L_{1f}} \cdot \sqrt{r}} - \frac{10 \cdot \mu_c \cdot C_{Bc}}{\sqrt{L_{1f}}} \right) \quad (3-14)$$

$$E_B = C_B \cdot X_B + b_B \quad (3-15)$$

Variables b_R and b_B (J/g) were coefficient factors related to the initial fibre length.

In this study, the initial fibre length was considered as unchanged. The expressions of C , X , and b for the three modified laws are summarized in Table 3-2. To determine the unknown factors in the modified models, linear regression was conducted based on the experimental data of specific energy and length distribution.

3.3.3 Development of a size reduction model

A linear model was developed relating the specific energy of decortication and the ratio of initial and final fibre length. For simplicity, the average final fibre length $\overline{L_{2f}}$ (mm) was used and it was calculated by the following equation:

$$\overline{L_{2f}} = \sum_{i=1}^n \delta_i \cdot L_{2fi} \quad (3-16)$$

The slope of the regression equations C_L (J/g) represents the constant factor in the relationship (equivalent to C_K , C_R and C_B). A constant term b_L was included. The relationship could be expressed as:

$$\begin{aligned} E_L &= C_L \cdot \frac{L_{1f}}{\overline{L_{2f}}} + b_L \\ &= C_L \cdot X_L + b_L \end{aligned} \quad (3-17)$$

where X_L was the independent variable in the model, representing for $\frac{L_{1f}}{L_{2f}}$.

Table 3-2. Summary of C, X, and b expressions in three modified laws.

Modified law	$C_{(K, R \text{ or } B)}$	$X_{(K, R \text{ or } B)}$	$b_{(K, R \text{ or } B)}$
Kick's	$\mu_c \cdot C_{Kc} + \mu_f \cdot C_{Kf}$	$\ln \left(\sum_{i=1}^n \delta_i \frac{L_{1f}}{L_{2fi}} \right)$	$\mu_c \cdot C_{Kc} \cdot \ln \frac{1}{r}$
Rittinger's	$\frac{\mu_c \cdot C_{Rc}}{r} + \mu_f \cdot C_{Rf}$	$\sum_{i=1}^n \delta_i \left(\frac{1}{L_{2fi}} - \frac{1}{L_{1f}} \right)$	$\frac{\mu_c \cdot C_{Rc}}{L_{1f} \cdot r} - \frac{\mu_c \cdot C_{Rc}}{L_{1f}}$
Bond's	$\frac{\mu_c \cdot C_{Bc}}{\sqrt{r}} + \mu_f \cdot C_{Bf}$	$\sum_{i=1}^n \delta_i \left(\frac{10}{\sqrt{L_{2fi}}} - \frac{10}{\sqrt{L_{1f}}} \right)$	$\frac{10 \cdot \mu_c \cdot C_{Bc}}{\sqrt{L_{1f}} \cdot \sqrt{r}} - \frac{10 \cdot \mu_c \cdot C_{Bc}}{\sqrt{L_{1f}}}$

*The units of C, X, and b are determined by the parameter units listed in Table 3-1.

3.4 RESULTS AND DISCUSSION

3.4.1 Fibre length analysis

The average initial fibre length was 111 mm. The manually separated output fibre samples in different length categories are shown in Fig. 3-5. Average fractions for each screen scenario under different feeding masses are presented in Fig. 3-6. Results indicated that for screen opening size of 19.28 mm and 25.74 mm, majority fraction of the output was short fibres in the range of 0-20 mm. With the screen size of 19.28 mm, all fibres were shorter than 80 mm, while product from the 25.74 mm screen scenario contained only small proportion (less than 3%) of fibres longer than 80 mm. The no-screen scenario produced fibres spreading in all length categories, and approximately half of the fibres were within 40-80 mm. With screens (19.28 and 25.74 mm), the decortication process produced more short fibres comparing with the no screen scenario. This result agreed with conclusions from other studies that smaller screen opening size provided finer products (Ghorbani et al. 2010; Mani et al. 2003). Feeding mass in the range from 75 g to 200 g did not show obvious effect on the final fibre length.

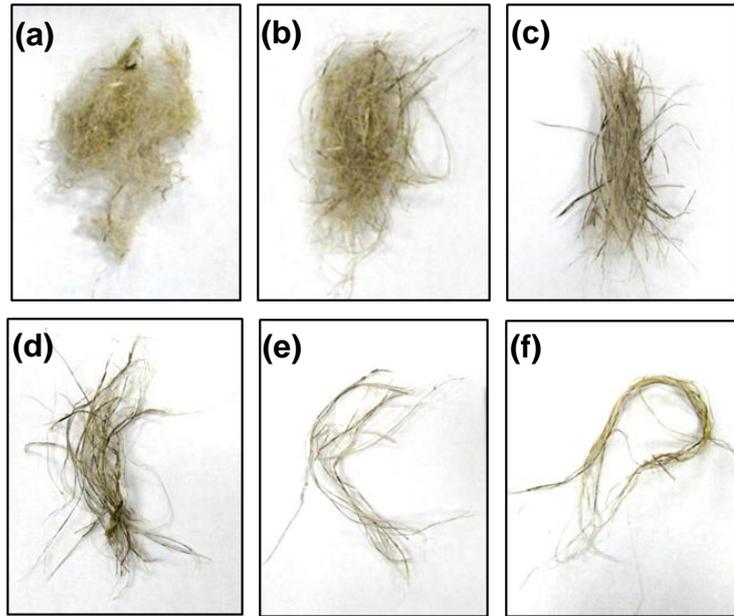
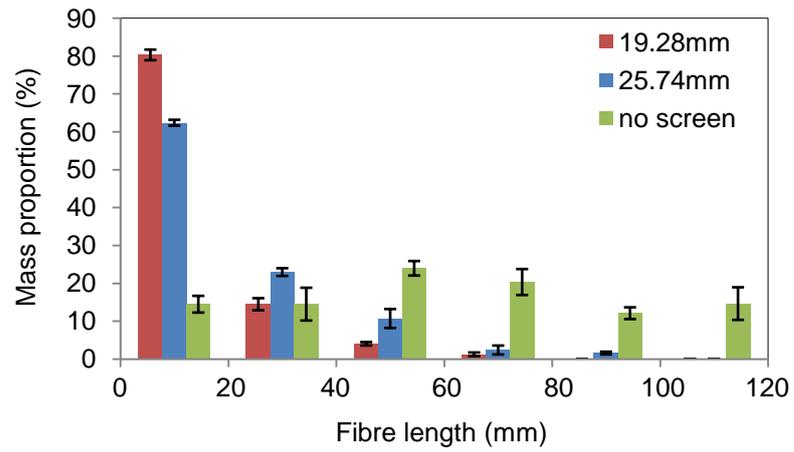
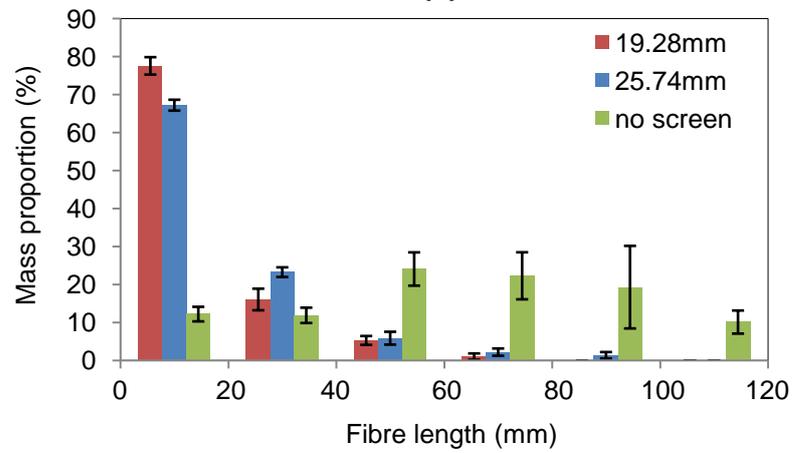


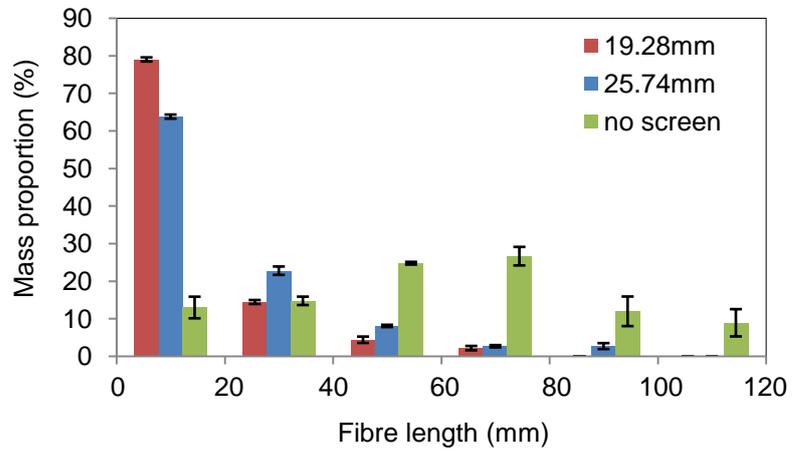
Fig. 3-5. Output fibres in different length categories.
(a) 0-20 mm; (b) 20-40 mm; (c) 40-60 mm;
(d) 60-80 mm;(e) 80-100 mm; (f) > 100 mm.



(a)



(b)



(c)

Fig. 3-6. Length distribution of different feeding masses. (a) 200 g; (b) 125 g; (c) 75 g.

3.4.2 Specific energy requirement

The highest net energy and the highest specific energy was 14.77 kJ and 73.84 J/g respectively when the small opening size (19.28 mm) screen was used to decorticate 200 g feeding hemp sample (Table 3-3). The no screen scenario with 75 g feeding mass required both lowest average net energy (0.70 kJ) and lowest average specific energy (9.31 J/g). The trends of specific energy were that higher feeding mass resulted in higher specific energy and smaller screen opening resulted in higher specific energy to complete decortication. Similar trends were observed for net energy. This result agrees with the conclusions of some studies using hammer mill in size reduction of crops, grains, and residues (Mani et al. 2004; Ghorbani et al. 2010; Arthur et al. 1982; Dziki and Laskowski 2005).

The standard errors of average specific energy for 75 g feeding mass cases were relatively high. It might be because that machine energy output was not stable when processing smaller amount of feeding mass, and it would cause fluctuant of motor torque and data transmitted to the recording facility. With higher feeding mass, the recorded energy data approached to a relatively stable status for each replication.

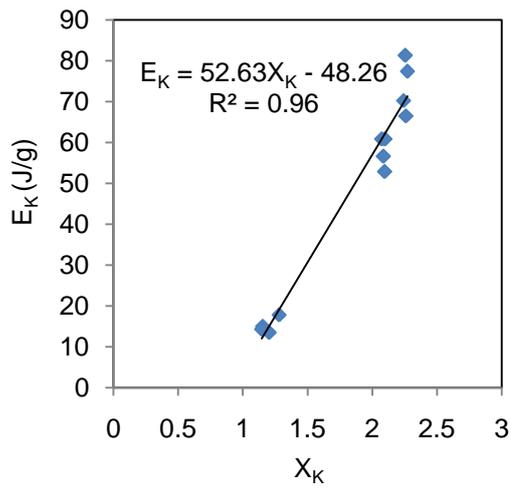
3.4.3 Fitting modified Kick's law

In the modified Kick's law shown in Eq. 3-11, the values of specific energy E_K were measured, and X_K were derived from the data of fibre length. Thus, values of C_K and b_K were obtained through linear regression of E_K versus X_K . Feeding mass had little contribution on the final fibre length distribution as discussed above, meaning that the feeding mass had little effect on the value of X_K (i.e. $\ln\left(\sum_{i=1}^n \delta_i \frac{L_{1f}}{L_{2fi}}\right)$) for a

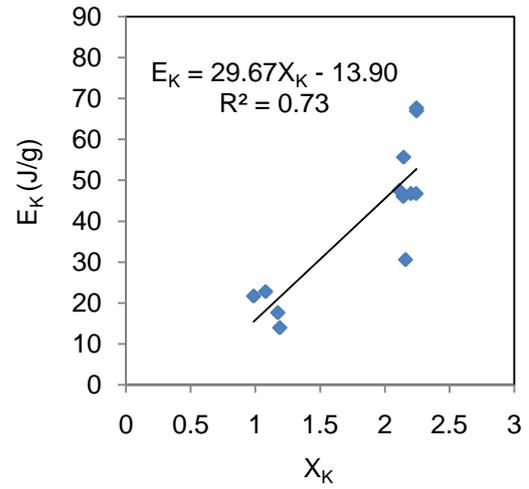
given screen scenario. However, feeding mass affected the specific energy, and it in turn affected the regression coefficients: C_K and b_K . For this reason, linear regressions for three feeding masses were conducted separately to exhibit the effect of screen opening size (Figs. 3-7 (a), (b) and (c)). A combined data regression including data points over all feeding masses is also shown in Fig. 3-7 (d). Values of C_K were taken as the slopes of the regression equations and values of b_K were taken as the intersection. They are summarized in Table 3-4.

Table 3-3. Specific energy of decortication.

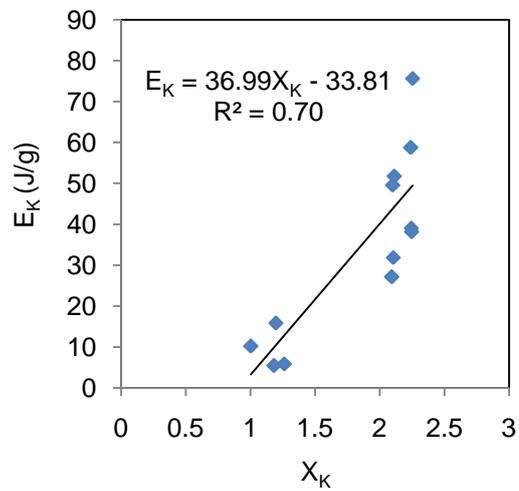
Screen scenario (mm)	Feeding mass (g)	Average net energy (kJ)	Average specific energy E_s (J/g)	Standard errors (J/g)
19.28	200	14.77	73.84	± 5.80
	125	7.13	57.02	± 10.29
	75	3.97	52.90	± 15.52
25.74	200	11.56	57.78	± 3.31
	125	5.62	44.95	± 9.08
	75	3.01	40.06	± 10.73
no screen	200	3.03	15.17	± 1.63
	125	2.38	19.00	± 3.51
	75	0.70	9.31	± 4.19



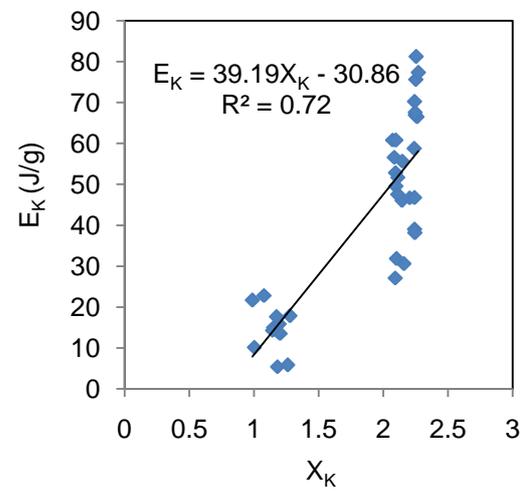
(a)



(b)



(c)



(d)

Fig. 3-7. Linear regression for fitting modified Kick's law.

(a) feeding mass 200 g; (b) feeding mass 125 g;

(c) feeding mass 75 g; (d) combined all feeding rates.

Table 3-4. Summary of C_K and b_K values.

Feeding mass (g)	C_K (J/g)	b_K (J/g)	R^2 value	Domain of X_K
200	52.63	-48.26	0.96	$1.15 \leq X_K \leq 2.27$
125	29.67	-13.90	0.73	$0.99 \leq X_K \leq 2.25$
75	36.99	-33.81	0.70	$1.00 \leq X_K \leq 2.25$
Combined data	39.19	-30.86	0.72	$0.99 \leq X_K \leq 2.27$

The value of coefficient of determination (R^2) varied from 0.72 to 0.96 with the feeding mass of 200 g giving the highest R^2 value. Ghorbani et al. (2010) reduced the size of alfalfa using a hammer mill and fitted the experimental data with Kick's law. Their regression gave a 0.87 R^2 value.

The negative values of b_K indicated that the r value is greater than 1, according to Table 3-2. If the extreme condition is considered where there is no size reduction, no specific energy would be cost, and the value of b_K would be zero. This is consistent with the theory. Under such condition, the ratio of L_{2c} and L_{2f} is 1 (i.e. $r=1$), so that the term b_K is zero. The modified Kick's law (Eq. 3-11) fit by the hemp decortication data can be rewritten, for example, for the combined feeding rates, as the following format:

$$E_K = 39.19 \times \ln \left(\sum_{i=1}^n \delta_i \frac{L_{1f}}{L_{2fi}} \right) - 30.86 \quad (3-18)$$

where L_{1f} and L_{2fi} are in mm, and E_K is in J/g.

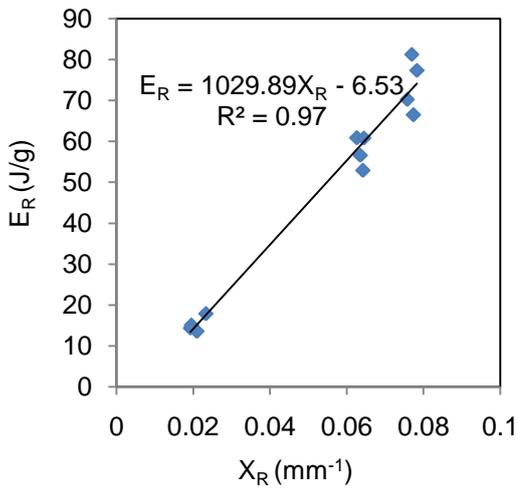
3.4.4 Fitting modified Rittinger's law

As shown in Eq. 3-12, the b_R in the modified Rittinger's law was related to the initial fibre length L_{1f} . As the L_{1f} was constant (the average L_{1f} was measured as 111 mm), the value of b_R should be a constant. Similar to the fitting exercise of modified Kick's law, linear regression was performed between E_R and X_R (i.e. $\sum_{i=1}^n \delta_i \left(\frac{1}{L_{2fi}} - \frac{1}{L_{1f}} \right)$) to determine the C_R and b_R variables under each feeding mass case and the combined data. Table 3-5 summarized the values of C_R and b_R , and R^2 values. Similarly, data from high feeding mass (200 g) scenarios had better fitness with the regression, giving a R^2 value of 0.97.

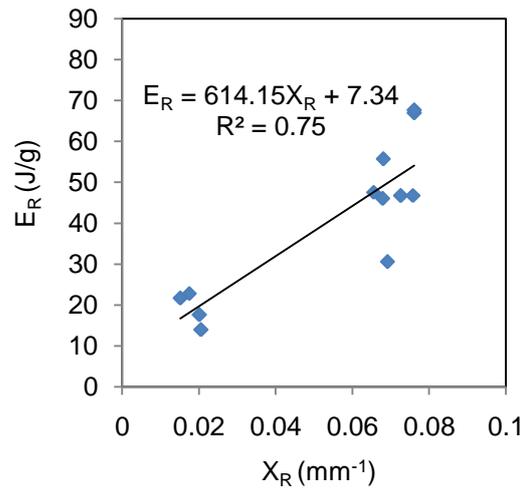
Theoretically, if extreme condition is considered, b_R should be zero. This can be interpreted as that when there is no size reduction (i.e. $L_{2fi} = L_{1f}$), the r (the ratio of final core length to fibre length) will be 1, so the b_R in Eq. 3-13 should be zero, meaning that there is no energy consumed. Having determined the unknown coefficient factors in Eq. 3-13, the modified Rittinger's law can be expressed by the following equation for the combined data:

$$E_R = 793.04 \times \sum_{i=1}^n \delta_i \left(\frac{1}{L_{2fi}} - \frac{1}{L_{1f}} \right) - 1.47 \quad (3-19)$$

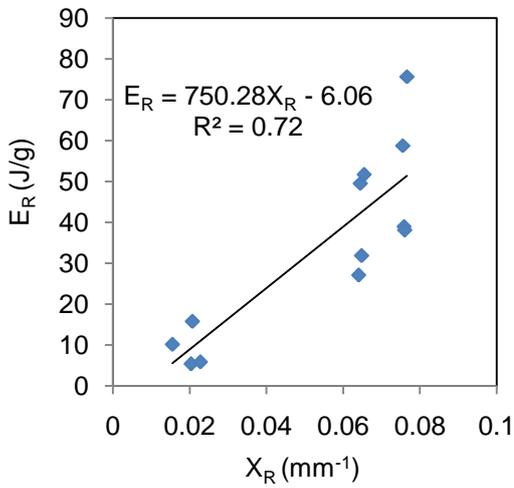
where L_{1f} and L_{2fi} are in mm, and E_R is in J/g.



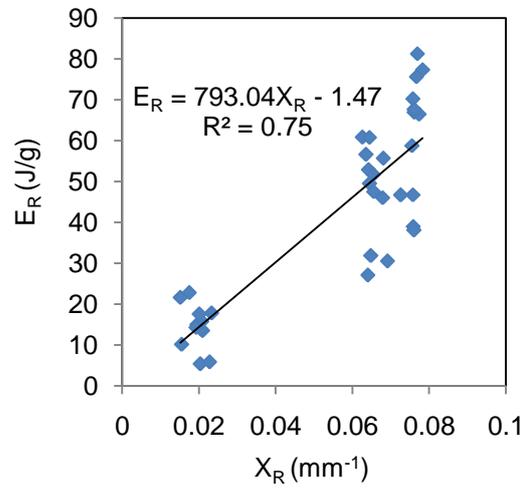
(a)



(b)



(c)



(d)

Fig. 3-8. Linear regression for fitting modified Rittinger's law.

(a) feeding mass 200 g; (b) feeding mass 125 g;

(c) feeding mass 75 g; (d) combined all feeding rates.

Table 3-5. Summary of C_R and b_R values.

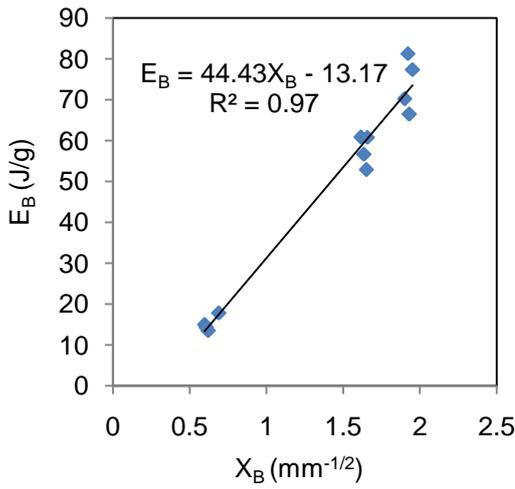
Feeding mass (g)	C_R (J · mm g ⁻¹)	b_R (J/g)	R^2 value	Domain of X_R (mm ⁻¹)
200	1029.89	-6.53	0.97	$0.019 \leq X_R \leq 0.078$
125	614.15	7.34	0.75	$0.015 \leq X_R \leq 0.076$
75	750.28	-6.06	0.72	$0.016 \leq X_R \leq 0.077$
Combined data	793.04	-1.47	0.75	$0.015 \leq X_R \leq 0.078$

3.4.5 Fitting modified Bond's law

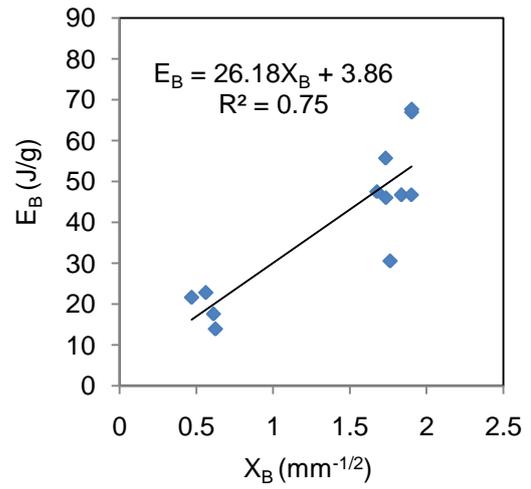
The linear regression results of fitting Bond's law are shown in Fig. 3-9, in respect of 200 g, 125 g, 75 g feeding masses, and the combined data. Similar to the modification procedures of Kick's and Rittinger's laws, the term $\sum_{i=1}^n \delta_i \left(\frac{10}{\sqrt{L_{2fi}}} - \frac{10}{\sqrt{L_{1f}}} \right)$ as a whole was calculated as dependent variable, X_B . The regression results showed that high feeding mass again led to a more accurate regression with R^2 of 0.97. The modified Bond's law for the combined data is presented in Eq. 3-20:

$$E_B = 34.11 \times \sum_{i=1}^n \delta_i \left(\frac{10}{\sqrt{L_{2fi}}} - \frac{10}{\sqrt{L_{1f}}} \right) - 6.44 \quad (3-20)$$

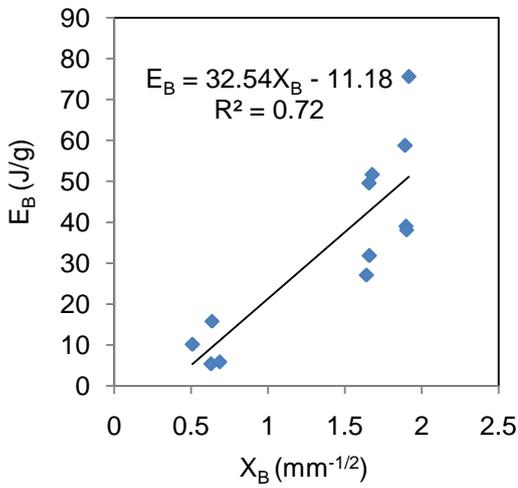
where L_{1f} and L_{2fi} are in mm, and E_B is in J/g.



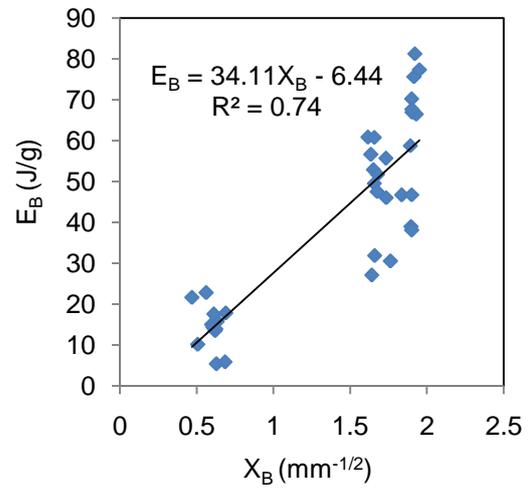
(a)



(b)



(c)



(d)

Fig. 3-9. Linear regression for fitting modified Bond's law.

(a) feeding mass 200 g; (b) feeding mass 125 g;

(c) feeding mass 75 g; (d) combined all feeding rates.

Table 3-6. Summary of C_B and b_B values.

Feeding mass (g)	C_B (J mm ^{1/2} /g)	b_B (J/g)	R^2 value	Domain of X_B (mm ^{-1/2})
200	44.43	-13.17	0.97	$0.60 \leq X_B \leq 1.95$
125	26.18	3.86	0.75	$0.47 \leq X_B \leq 1.90$
75	32.54	-11.18	0.72	$0.51 \leq X_B \leq 1.92$
Combined data	34.11	-6.44	0.74	$0.47 \leq X_B \leq 1.95$

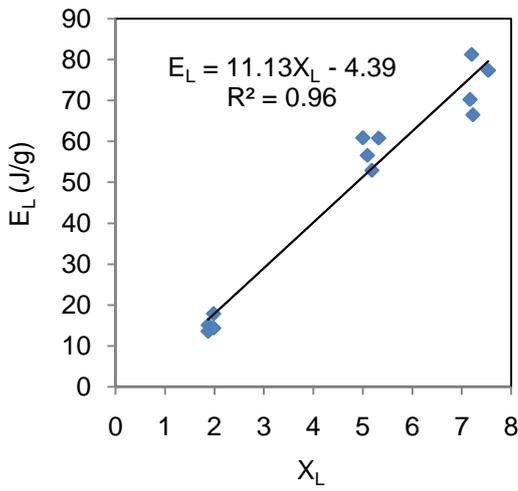
3.4.6 Fitting a linear model

Results of regression are shown in Fig. 3-10. The values of C_L are summarized in Table 3-7. According to the results of the combined data, the relationship between decortication specific energy E_L (J/g) and the ratio of initial and average final fibre length for the combined data was expressed by the equation below:

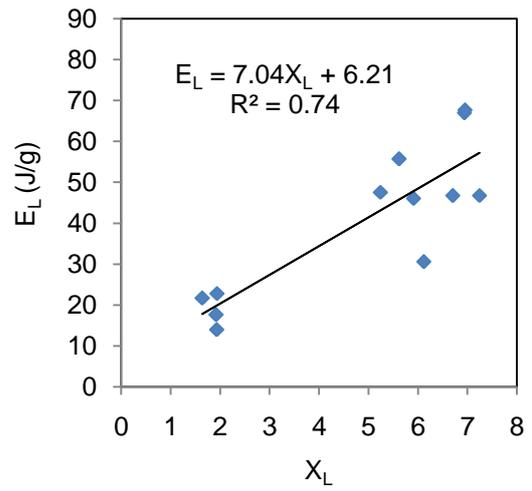
$$E_L = 9.11 \times \frac{L_{1f}}{\overline{L_{2f}}} - 2.43 \quad (3-21)$$

where L_{1f} and $\overline{L_{2f}}$ are in mm, and E_L is in J/g.

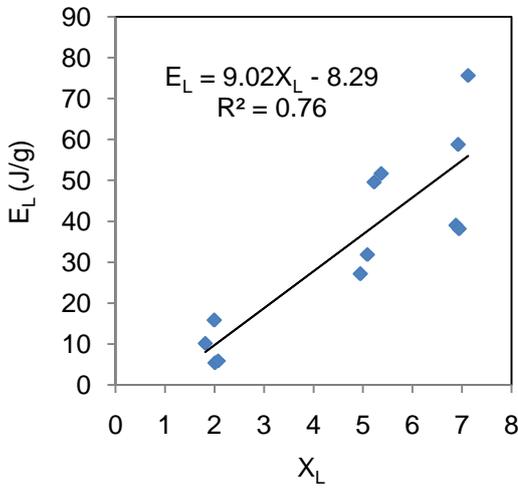
The R^2 values of the linear regression model were similar to the three modified laws. The advantage of the linear model is that the model uses the average final fibre length and no fibre length distribution analysis is required.



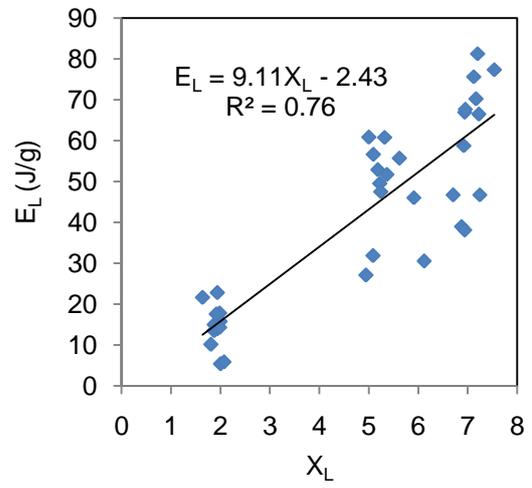
(a)



(b)



(c)



(d)

Fig. 3-10. Regression for fitting linear model of specific energy and the ratio of initial and average output fibre length.

- (a) feeding mass 200 g; (b) feeding mass 125 g;
(c) feeding mass 75 g; (d) combined all feeding rates.

Table 3-7. Summary of C_L and b_L values.

Feeding mass (g)	C_L (J/g)	b_L (J/g)	R^2 value	Domain of X_L
200	11.13	-4.39	0.96	$1.87 \leq X_L \leq 7.54$
125	7.04	6.21	0.74	$1.64 \leq X_L \leq 7.25$
75	9.02	-8.29	0.76	$1.81 \leq X_L \leq 7.12$
Combined data	9.11	-2.43	0.76	$1.64 \leq X_L \leq 7.54$

3.5 CONCLUSIONS

Length distribution of the output fibres from decortication using a hammer mill with screen scenarios of 19.28 mm and 25.74 mm opening indicated that majority fibres were shorter than 20 mm. Small screen opening size produced more fine fibres than larger sized screen and no-screen cases. Feeding mass had little effect on length distribution. The highest specific energy (73.84 J/g) was required when using small opening size screen (19.28 mm) to process 200 g retted hemp. The modified Kick's, Rittinger's and Bond's laws could determine specific energy requirement of decorticated hemp material which consists of both fibre and core. Those modified laws also could address different length fractions of hemp fibre. The three modified laws and the linear model developed described the hemp decortication data using a hammer mill with the R^2 value as high as 0.97 in the case of 200 g feeding mass. Lower R^2 values (0.70-0.76) were observed for the two lower feeding masses. The linear model was simpler and had comparable accuracy as the other three modified laws.

The modified laws and the linear model were developed based on certain assumptions and data from a given hammer mill and a given hemp feedstock. These may affect the accuracy of the models in energy prediction. Caution should be taken when using the results.

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4. Integration of TRIZ and Virtual Environments for Hemp Scutcher Design

4.1 ABSTRACT

TRIZ (“Theory of Inventive Problem Solving” in Russian) method provides useful theory for users to analyze and solve problems using a logic manner. It is widely used in different fields and has gained great success in machine design. Virtual reality (VR) is a computer generated environment with features of visualization and users’ interaction, which provides a cost-effective tool for product evaluation and design improvement. In this research, TRIZ is applied in the design of a new hemp scutcher prototype. With the assistance of VR technology, the design visualization and concept evolution are achieved in a virtual environment. A VR-based system is developed to evaluate the mechanism of the conceptual design, and to compare differences with traditional machines. The new design is supposed to have a better performance in terms of scale, product quality and energy efficiency. **Keywords:** hemp scutcher, design, TRIZ, virtual reality.

4.2 INTRODUCTION

Hemp (*Cannabis sativa*) fibre is a renewable and environmentally acceptable material. It has been used in different areas including textile industry, civil engineering industry and automobile industry. Hemp fibre can substitute glass and carbon fibres in a wide range of industrial products. With the increasing need of high quality hemp fibres, the processing methods of hemp fibres have been developed during the past decades. Because the properties of hemp are similar to other bast fibre plants such as flax and linen, some of the existing processing machines for hemp were modified based on those used for flax or cotton processing (Hobson et al. 2000; Akin et al. 2005).

The key procedure in hemp fibre processing is the decortication, which can detach the fibre (outer layer of hemp plant) from the core (inner layer). Scutching machines, or scutchers, are used by some industries to achieve this purpose. However, the effect of current scutching machines on hemp fibre processing is not satisfying. Problems such as large machine scale, waste of products and energy affect the economy of the production. An efficient machine should be designed to improve the processing quality.

Methods used by engineers to produce design ideas include brainstorming, axiomatic design, TRIZ (Teoriya Resheniya Izobretatelskikh Zadatch), etc (Shirwaiker and Okudan 2006; Pham et al. 2009). When engineers encounter a problem or an improvement issue, the most direct way to find a solution may be the trial-and-error method: try one thing, if it does not work, try something else (Mathis

2009). Mostly, people prefer to use brainstorming for quick and direct problem solving because it is a natural style of human mind. However, this kind of unstable and unpredictable way may require a significant time before a right solution is attained. TRIZ is the acronym for the “Theory of inventive problem solving” in Russian. It was originally developed by G. S. Altshuller and his colleagues between the 1940s and the 1980s (Barry 2009). Having reviewed more than 40,000 successful patents, they summarized the common features for different creative work and patterns to predict solutions of problems. The theory helps users to analyze problems and contradictions inside the problems, and provide reasonable directions for solutions with the assistance of tools. During the past decades, research in different fields involving TRIZ has improved the method by complementing the theory continuously. Nowadays, the theory is close to maturity and has been successfully applied in problem solving in a large range of areas.

The objective of this research was to design and evaluate a new hemp scutcher based on the TRIZ principle in virtual environments (VEs). Virtual Reality (VR) technology is capable of constructing a user-centered, three-dimensional (3D) environment in which abstract and complex information is visualized in an intuitive and realistic manner (Cobb et al. 1995; Shukla et al. 1996; Cecil and Kanchanapiboon 2007). It is an important tool for industry design to save the cost of physical prototypes. By using VR technologies, designers can build and test virtual prototypes to forecast usability problems in the design process.

In this research, the problems and weakness of current scutching machines were analyzed based on the investigation of several hemp and flax fibre scutcher patents. TRIZ specially concentrates on the use of the experience and knowledge to improve problems because it is a method developed based on a large number of patents (Pham et al. 2009). Therefore, TRIZ method was used to find solutions to overcome the bottlenecks of the design. The conceptual designs of a new hemp fibre scutcher were developed according to suggested principles by TRIZ. The prototype evaluation and design improvement are achieved using the VR technology. A VR tool, EON Studio 6.1, was applied to build the virtual environment to provide functions required for the design evaluation and improvement. The advantage of designing in the VE is that it is very easy to modify the conceptual model without spending a lot of money on constructing physical prototypes.

4.2.1 The TRIZ Theory

TRIZ is a type of logic and knowledge-oriented methodology (Hsieh and Chen 2009). One important principle of TRIZ is the use of evolution patterns. A pattern represents a direction to idealize the current problem. The first step of the solving problems using TRIZ is to idealize the problem without considering the weakness, cost or barricades (Cai et al. 2008). The ideal final result is defined as the point when users get all benefits they want without any of costs or harms (Mann 2004; Ma et al. 2006). Using patterns will help designers to forecast the future development and give the direction to follow to generate ideal final results. Direct evolution is one of the

ways to get the ideal final results before using TRIZ for further development (Barry et al. 2009; Cai et al. 2008; Ma et al. 2006).

Once ideal final results are settled by designers, TRIZ requires the encountered technical problems and difficulties be identified, which are in the formats of contradictions. The basis of the theory is the finding of contradictions in the converted TRIZ problems. It is believed that the fundamental concept of solving any problems is to eliminate the contradictions (Barry et al. 2009). Two groups of contradictions are classified in TRIZ problems: technical contradictions and physical contradictions. Technical contradiction is the classical engineering “trade-off”. When specific point of a system needs to be improved, some other parts will be affected and may get worse simultaneously. Physical contradiction is also called inherent contradiction which stands for the contradiction of an object with opposite requirements. After contradictions have been identified, the tools for eliminating contradictions can be applied. The powerful function of “TRIZ-contradiction matrix” can provide references as solutions which have been successfully used in patents on solving problems in specific areas. Using the contradiction matrix, designers can identify up to 39 engineering parameters summarized in TRIZ, both in improving and worsening directions. Contradiction matrix then provides the recommended “40 principles” for specific contradiction combinations. There are also “76 standard solutions” related to the 40 principles providing more detailed ways of contradiction elimination (Barry et al. 2009; Hsieh and Chen 2009; Domb 1999). With the development of the theory, the

39 improving and worsening features of TRIZ contradiction matrix have been increased to 48 features recent years (Pham et al. 2009).

Finally, based on the solutions provided by the matrix, TRIZ solutions can be transferred into a real design for solving actual problems. Figure 4-1 indicates a basic flowchart of TRIZ in solving problems. However, there are also some weaknesses of TRIZ method. When improving and worsening features are selected, some of the cells in the contradiction matrix are empty so that the matrix cannot provide recommendation for such situations (Pham et al. 2009). In such cases, single engineering inventive principle can be used (Hsieh and Chen 2009). The principles appearing most frequently in the contradiction matrix can be applied as the suggested principles. In addition, because of the complexity of translating the practical requirements, constraints or criteria of design problems in TRIZ problems, TRIZ contradiction matrix is known being difficult for applications (Pham et al. 2009).

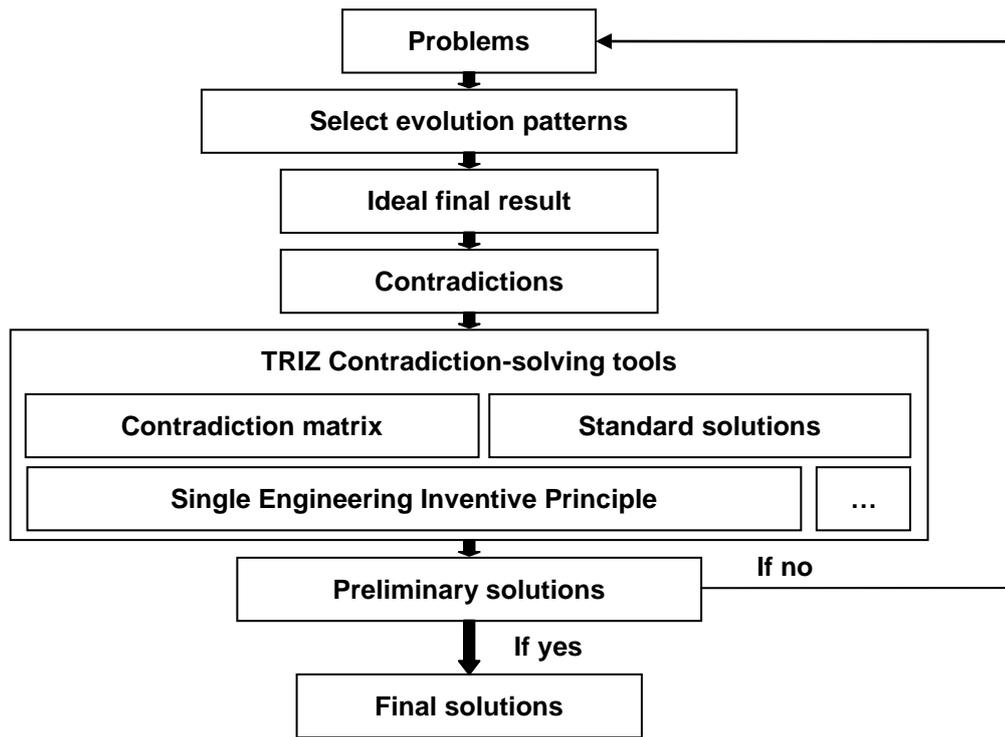


Fig. 4-1. Flowchart of TRIZ in problem solving.

4.2.2 TRIZ Applications

TRIZ-based studies on machine design have been conducted by many researchers. Design improvements are also achieved using TRIZ. Cai et al. (2008) applied the TRIZ method in analyzing the modular fixture design details and forecasting the development potential. The intelligent modular fixture is difficult to be produced because of the complexity of machining components. The controllability of automation degree and feedback has been improved using TRIZ. A conceptual design of the packaging machine for Chinese traditional medicine pill dropping was developed by Ma et al. (2006). The authors first converted the real problem into substantiate function diagram of the process using a substance-field analysis. Based on suggested solution principles given by the conflict matrix, a design of tumbling cylinder with filling mechanical structure was invented to meet the package requirement. A study on the effect of TRIZ to support designers using the descriptive design framework was conducted by Pham et al. (2009). The descriptive design framework was developed with TRIZ methodology as the core, which could help a designer to track his ideas throughout the design process. Shirwaiker et al. (2006) conducted a review on both TRIZ and axiomatic design and found that the compatibility of the two methods could be applied synergistically to achieve better solutions. TRIZ is considered to be capable to generate innovative solutions, while axiomatic design has the function to analyze the effectiveness of solutions.

A manufacturing process can be improved using TRIZ if the problems in terms of technical contradictions can be eliminated according to the recommended principles

by contradiction matrix. Hsieh and Chen (2009) conducted a research on the design of friction stir welding process using TRIZ as a problem analyzing and solving tool. According to the contradiction matrix, “Phase transitions” was selected as the solution orientation for improving the welding process. The rotating welding tool was designed as the heat generator by means of the friction between the head and materials. Additionally, the study conducted other process problems, and used TRIZ suggestions in the welding process such as a friction stir welding roller press to maintain a constant welding depth. Zhang et al. (2006) studied the development of the cutting technology and generated the evolutionary technology by means of TRIZ. Fresner et al. (2009) used TRIZ principles showing similarities and correspondence to the strategies of Cleaner Production so that the authors realized that the concept of the ideal final result and Laws of Evolution could be a framework for assisting Cleaner Production improvement. The effectiveness of TRIZ-based Cleaner Production concept on improving chemical process was proved by a practical application.

TRIZ has the potential in improving design, and managing the design process. Mathis (2009) reported an example using the TRIZ method to improve the design of candy pouch. The research used TRIZ as well as experiments to prove the effect of each design stage. In a non-technological area, Su et al. (2008) attempted using the TRIZ methodology to develop a systematic framework for service industry. The approach successfully supported resolving problems of service quality in the e-commerce sector.

4.3 METHODOLOGY

4.3.1 TRIZ Design integrated with VE

As shown in Fig. 4-1, TRIZ method provides designers the tools to gain reasonable solutions for design problems. However, not all the recommended solutions can fit the need for real problems. Before transferring TRIZ solutions to a real design, there should be a pre-testing procedure in order to evaluate the solutions. VR, as a visualization tool, can assist to get feedback from the evaluation of a design built in VEs according to TRIZ solutions. Comparing with common evaluation methods, VR has the advantage to check TRIZ solutions by users' interaction with the model in VEs. The users can evaluate a design by simulating its working processing for the feasibility. If the feedback proves that the model is working properly, then the design can go for manufacturing. If not, users can modify the design in VEs. Users can also go back to the TRIZ procedure to select other solutions for the problem based on the evaluation in VEs. The whole process is shown in Fig. 4-2. It includes TRIZ procedures shown in Fig. 4-1. This procedure is proposed for the methodology applied in this research.

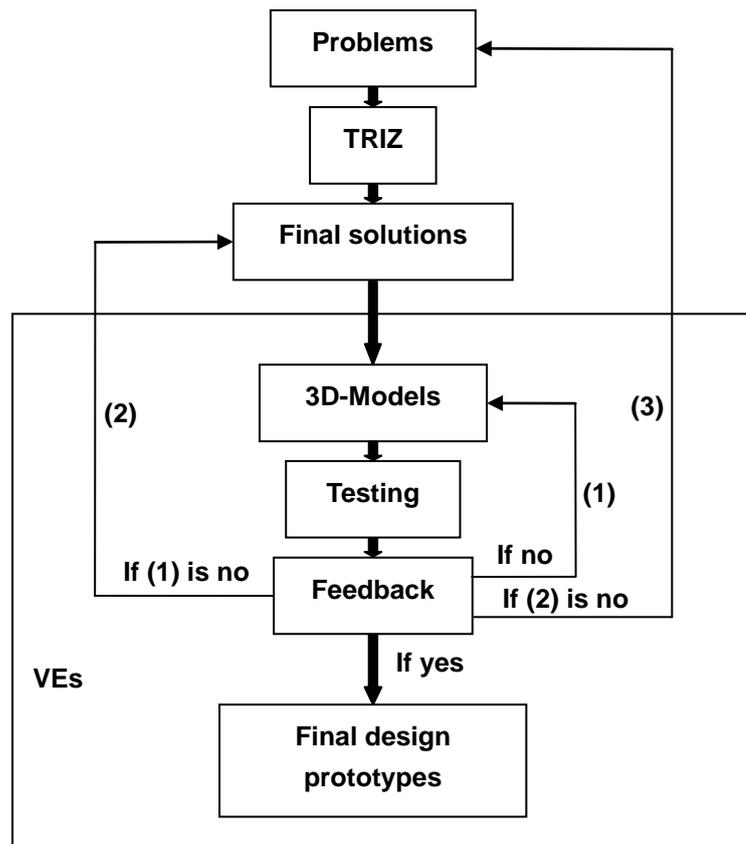


Fig. 4-2. Flowchart of TRIZ integrated with VE.

4.3.2 Problem analysis and design criteria for hemp scutchers

The principle of hemp fibre scutching is to bend the stalks sharply in one direction and then re-bend them in an opposite direction to break the brittle core, and simultaneously to comb the material by bars or brushes rapidly in order to remove the broken parts from the fibre (Johansen 1946). Many traditional scutchers used this principle for decortication machine designing and fibre processing (John 1941; Waldo 1956; Patterson 1949; Cary et al. 1956; Horine 1906). Some laboratory-scaled scutchers have been tested and their effects on the fibre decortication have been evaluated (Akin et al. 2005; Hobson et al. 2001). Mostly, gears and rollers with grooves are used to achieve this goal. The machine generally includes a horizontal path and a couple of roller pairs. When the stalks are introduced to pass between the roller pairs, the sharp teeth of the rollers bend the stems so that the brittle cores will be broken into smaller pieces as shown in Fig. 4-3. Some of them may fall down through the gaps between roller pairs, while others still attach to the fibre and should be removed by following procedures.

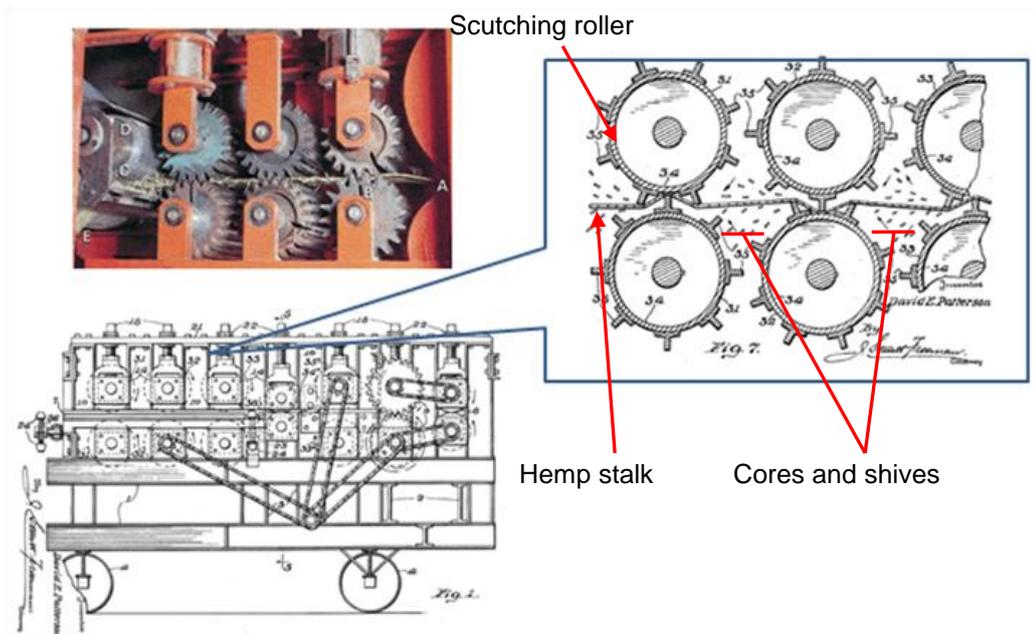


Fig. 4-3. Basic principle of the scutching procedure (Hobson et al. 2001; Patterson 1949).

By analyzing the existing methods, some problems of the scutcher design have been found. The main problem was that in order to gain clean fibre (fibre free of cores) after scutching, large numbers of roller pairs were required. For the horizontal arranged structure as shown in Fig. 4-3, this would increase the length of the horizontal path and at the same time increase the machine scale. Simultaneously, with the increasing roller pair number, the power and energy requirement for driving the rollers would be increased, making the procedure costly and less efficiently. In addition, for a single roller, the functioning part was only the touching point in-between the roller pair which is getting in touch with the stalk, while other teeth around this roller were running ineffectively. Productivity was also a factor need to be considered. Processing speed might be increased if the rotational speed of the rollers is increased. However, more energy was required to run the machine, and there might be more loss of the fibre due to the higher speed. More broken fibres could fall down with the shives and be collected as waste.

According to the above analysis, the new design should compromise the following criteria:

- Fewer roller pairs;
- Relatively smaller in machine scale and machine part dimensions;
- Less fibre waste along the processing line;
- Simple structure to achieve better maintenance ability;
- Better controllability for adjusting machine performance on different hemp varieties;

- Less chance of wrapping or entanglement.

Two evolution patterns were chosen in this study, including:

- Transition toward micro-level and increasing use of fields.
- Increasing dynamism and controllability.

Four pairs of contradictions were abstracted from the real problems, as summarized in Table 4-1.

Table 4-1. Selected TRIZ contradictions and solutions from TRIZ contradiction matrix (TRIZ40 2010).

Improving feature	Worsening feature	Solution
#39 Productivity	#6 Area of stationary object	#17 Moving to a new dimension
#29 Manufacturing precision	#22 Loss of energy	#2 Extraction
#9 Speed	#22 Loss of energy	#35 Parameter change
		#14 Spheroidality – Curvature
		#20 Continuity of useful action
#9 Speed	#29 Manufacturing precision	#10 Prior action

4.4 PRELIMINARY DESIGN AND EVALUATION IN VE

Before the design prototype was evaluated in the VE, 3D CAD models of the possible design solutions were built using Auto CAD 2009. EON Studio 6.1, a VE modeling tool, was used to construct virtual environments for the concept testing and design evaluation. CAD models were imported into EON Studio in the format of .3ds for the VE modeling.

According to the TRIZ contradiction matrix, six solutions were selected to form the design concept as listed in Table 4-1. However, these solutions could only generate the design directions without exact ideas. Based on these proposed concepts, possible models were built in the VE, and then a preliminary evaluation was taken to assess the proposed conceptual model. At the design stage in the VE, no physical activities could be executed to test and evaluate the effect of the prototype. It was also difficult to simulate the hemp material reaction in virtual models due to the complexity of the bio-fibre material properties. The model evaluation was only based on the geometrical feasibility of machine operations. The machine structure was improved in the VE based on the simulation feedback. This procedure is illustrated as the route (1) in Fig. 4-2.

Taking the solutions “#17 Moving to a new dimension” and “#14 Spheroidality – Curvature” for instance, four alternative schemes of the roller layout were generated in VE as shown in Fig. 4-4. All of them were curve paths designed to achieve both space-saving and energy-efficient purposes. Comparing with traditional linear processing line, hemp cores should be removed more easily with fewer roller pairs

because the bending may effectively help to detach the cores from the fibres. Meanwhile, developed in a new dimension, the machine scale was expected to be limited to a reasonable size.

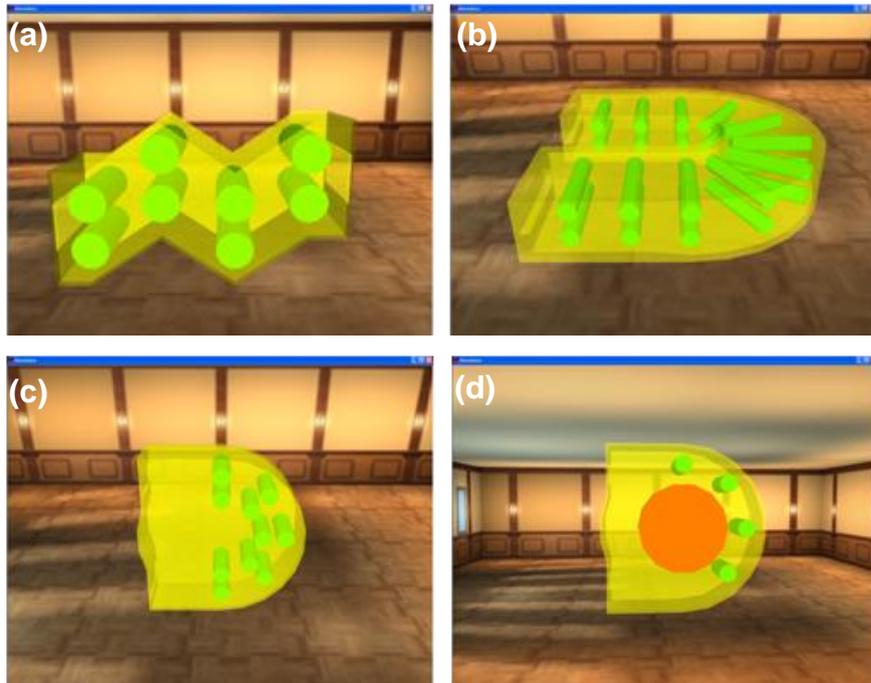


Fig. 4-4. Alternative schemes of roller layout.
(a) “S” shape; (b) “U” shape; (c) “C” shape; (d) improved “C” shape.

Figure 4-4(a) has an “S” shape curve with 4 pairs of rollers. Rollers with smaller radius were selected to decrease loading energy of the machine. The total horizontal length was decreased due to the curved line. The structure might achieve good bending and scutching force to break the cores, but the sharp turns might damage the fibre at the same time. It might cause wrapping and entanglement if the turning angle is not well designed. Figure 4-4(b) has a “U” shape curve, but it contained many pairs of rollers. It could save the horizontal length of the whole line, and generate horizontal bending by the side housing. However, the energy consumption might be high because many roller pairs were applied. Material might choke at the turn. Figure 4-4(c) applies 4 roller pairs to form a “C” shape curve. It was a relatively smoother curve compared with the previous two alternatives. The arrangement was in a vertical plane so that horizontally it would not take too much space. However, the large gaps between roller pairs might cause shorter fibres falling down as a waste. Figure 4-4(d) was evolved from the C shape scheme. This improved C shape consisted of one big roller at the centre, and in reaction with four assisting rollers around it. This design also followed the TRIZ solutions “#2 Extraction” and “#20 Continuity of useful action”. The central roller could be efficiently used without wasting much energy. So the improved C shape was selected as the basic scheme of rollers.

The improved C shape had the character of a “planetary layout”. Having selected the “planetary layout” as the proposed structure, housing was then designed step by step. Firstly, a simple sector housing was created (Type A in Fig. 4-5). It was noticed that the material path through the roller gaps could not be regulated, which might be a

reason for wrapping. Then the idea of adding a curved housing structure as shown in Type B came out from the TRIZ solution “#10 Prior action”. Such a structure could form a relatively stable working path for material. Additionally, high speed air flows were considered to help in leading material mass stream and remove the shives, so that three air flow inlets were created as shown in the circles in Type C in Fig. 4-5.

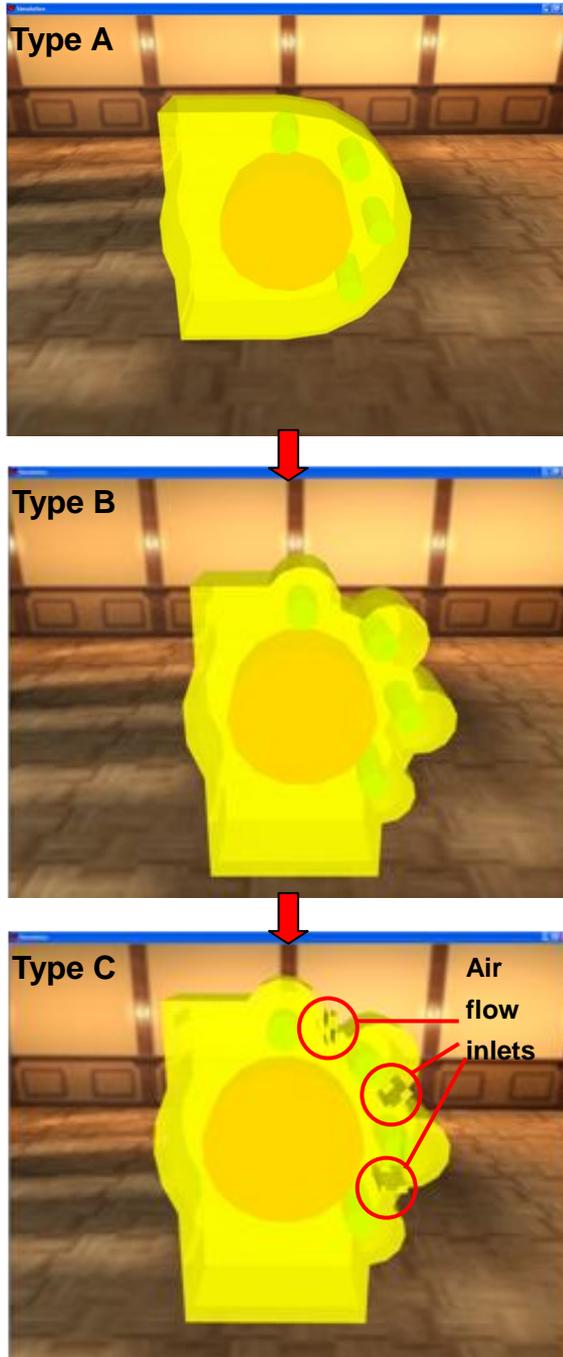


Fig. 4-5. Housing design evolution.

Using the similar procedure as mentioned, new design ideas could be evaluated, compared, and improved in the VE. Based on the feedback from the models according to the criteria, necessary modifications could be conducted easily. The detailed designs according to the TRIZ solutions in the VE are summarized below:

- Moving to a new dimension: Instead of traditional horizontal path, a curve path was designed to save the space taken by the machine.
- Extraction: One single functional roller was “taken-out”, with four smaller assisting rollers around it. This roller was placed at the centre, so that nearly half of its perimeter could function the scutching.
- Parameter change: Smaller rollers were chosen to achieve a faster speed and better controllability.
- Spheroidality: Rotational working mode was selected instead of linear one.
- Continuity of useful action: Around the central roller, four smaller rollers reacted with it together, making half of the central roller under working condition all the time. (The traditional designs just used one single working point between a roller pair.)
- Prior action: The housing of the machine contained curve structure around the four assisting rollers. The gap between two rollers was dominated by the housing, so that the path of the passing material was controlled, preventing wrapping and miss-introducing. Three high speed air flows were applied to lead the material, and they could help remove unwanted shives from the fibre to purify the product.

In addition, removable teeth on the rollers were designed to make the maintenance easier. Also, the changeable teeth could fit different plant varieties. For a variety of tougher stem property, original teeth could be substituted by the sharper teeth to satisfy the decortication effect expected. Figure 4-6 shows a 2D CAD model of the final proposed machine. A VR model of the complete machine was then developed to test and evaluate these concepts in the VE, which will be discussed in following sections.

4.5 VR MODELING AND PROTOTYPE EVALUATION

The user interface was designed with a menu, including four typical traditional scutchers and the proposed design. Users could select one of the models to view details of the structure. It made the comparison of the new design and the traditional machines in scale, structure, components and working principle. Figure 4-7 is the VE framework built. Figure 4-8 shows the user interface of the system.

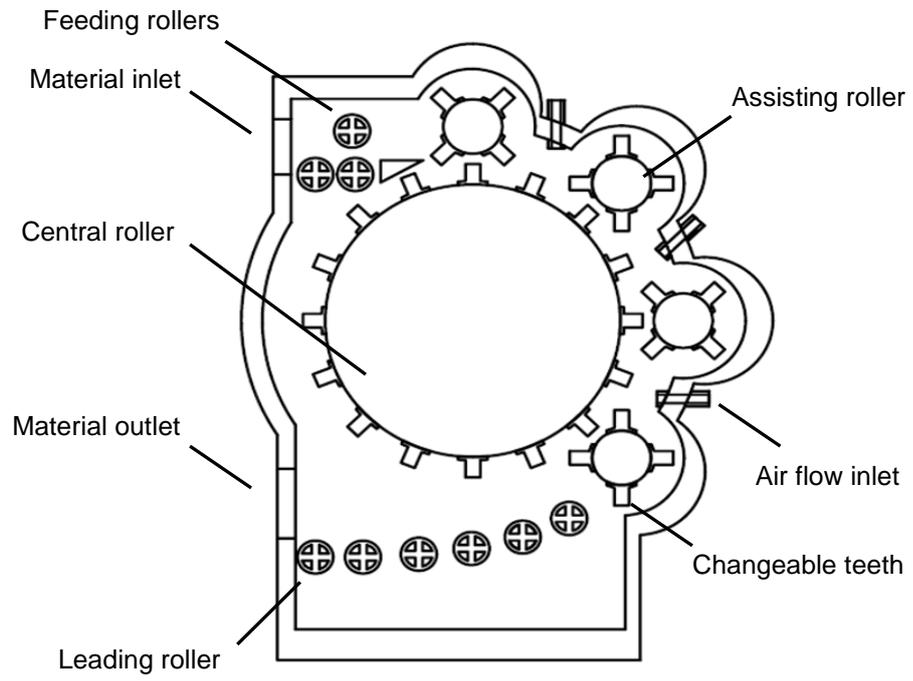


Fig. 4-6. 2D CAD Model of the new design.

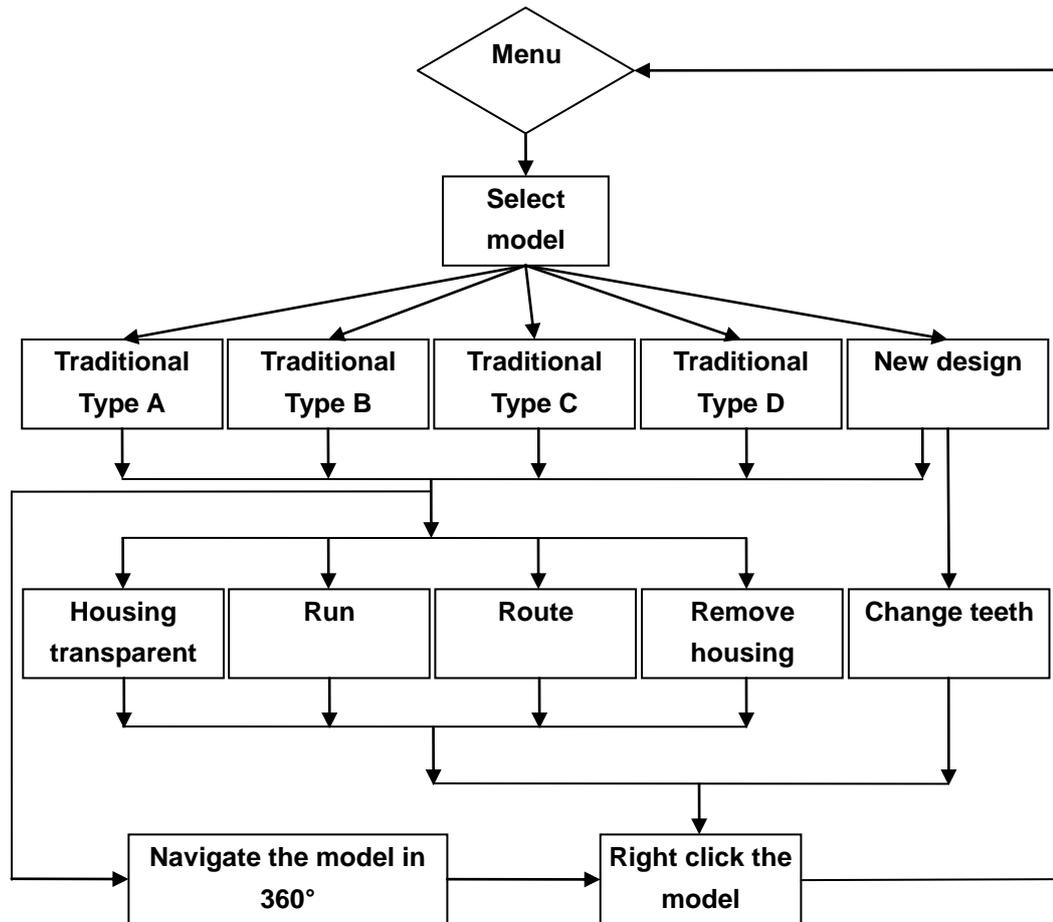


Fig. 4-7. The framework of the VE.

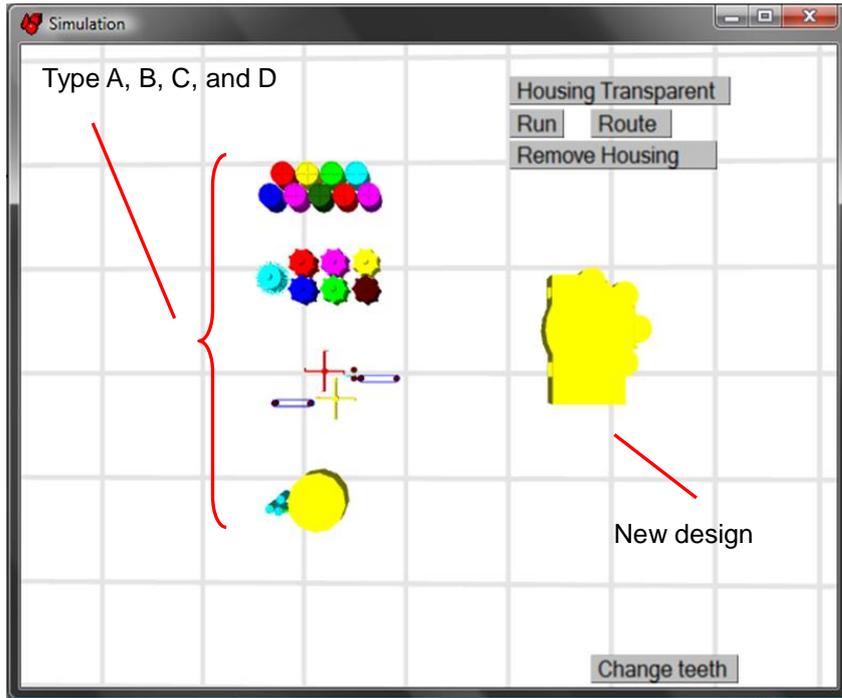


Fig. 4-8. Main menu of the system.

The model operation in VE was achieved using the prototypes of “*ObjectNavManager*” and “*ObjectNav*” provided in EON Studio. The trigger action was controlled by the “*ClickSensor*” connected to the prototypes in the route simulation shown in Fig. 4-9. When selecting one of the models by left clicking it, the view would focus on this single model, so that users could view it in detail as shown in Figs. 4-10 and 4-11. Also, dragging an object by clicking the right mouse button could provide 360 °view of the model from any angle.

There were two ways of showing details of the inner machine structure: making the housing transparent or removing the outer case. Both functions were programmed to be a textbox-button-controlled method. For the transparency function, a prototype called “*SmoothOperator*” was selected and connected to a textbox-button “Housing Transparent”. The texture property of the housing material was set to be 50% transparent once the “*SmoothOperator*” sending out an order signal. To remove the housing, “*Script*” node was edited to control the appearance of the objects connected to it as shown in Fig. 4-9. The commands were shown as follows:

```
function On_show()
{
    visible.value = false
}
function On_disappear()
{
    visible.value = true
}
```

Using dynamic models was the main character of the system. The running machine could provide a clear view of the working status of the models compared with static models, including the movement of the main working components and the

materials. Therefore it was easier for designers to evaluate and modify the preliminary design based on the visualization feedback. “*Rotate*” and “*Place*” nodes were used to dynamically display the models in VE. The main function parts in these scutching machines were the rotating rollers and gears. Textbox button “Run” was the central control of this function. “Change teeth” button was connected to a “*Place*” node. When it was clicked, the teeth around an assisting roller would be moved out of the machine, representing the changeable teeth structure as shown in Fig. 4-11 (c). Moreover, a time-step-motion was added to each model to present the material path through the scutcher. A red arrow was created as an object, and a “*KeyFrame*” node was taken to simulate the material path of each model as shown in Fig. 4-12. The position of each time step was set in the property of the “*KeyFrame*” node. The motion of the red arrow stood for the hemp stalk passing through the gap between rollers. Three green arrows were created to demonstrate the air flow direction of the new design.

Comparing with the traditional machines, the new design could compromise the designing criteria in terms of reduced scale, less energy consumption, and higher product quality, etc.

In summary, users could easily compare the differences of the new design and the traditional ones in VEs. With the help of the virtual environment, users could get a better understanding on the mechanism and working principle of the machine designed. The design feasibility could be easily analyzed due to the flexibility of modifying prototypes in VEs.

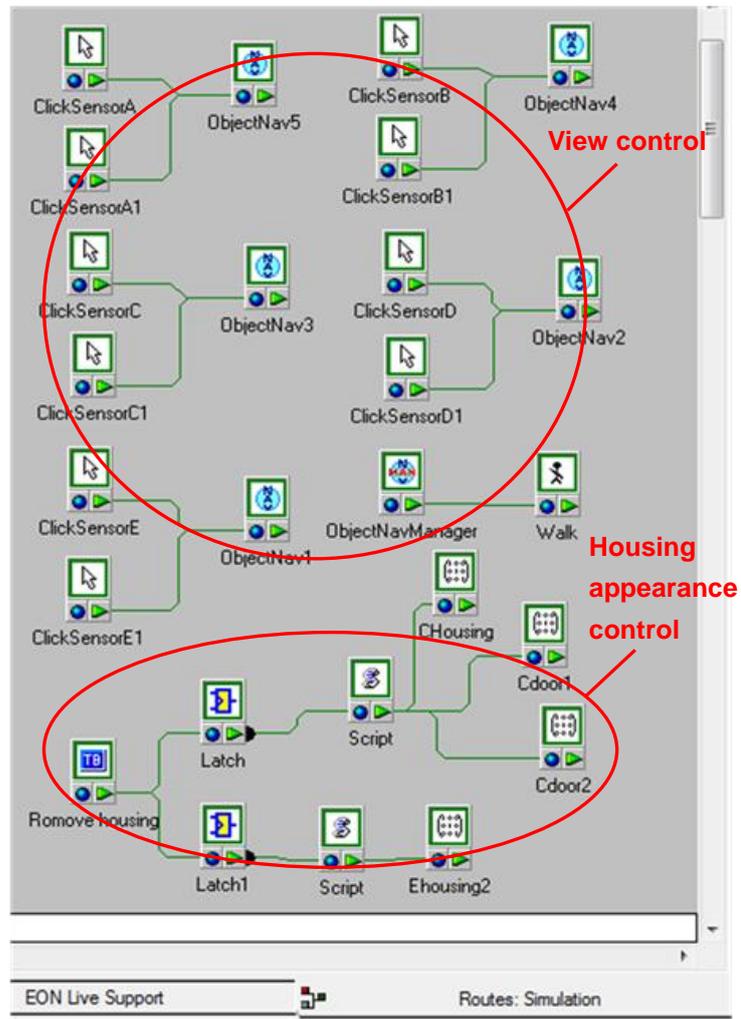


Fig. 4-9. Route simulation examples inVE.

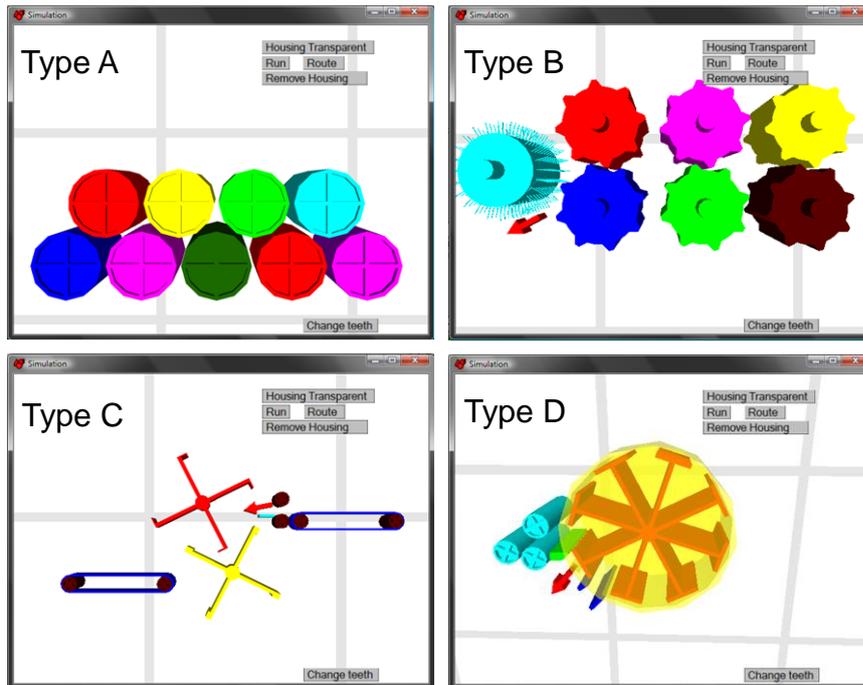


Fig. 4-10. The models of the traditional scutchers.

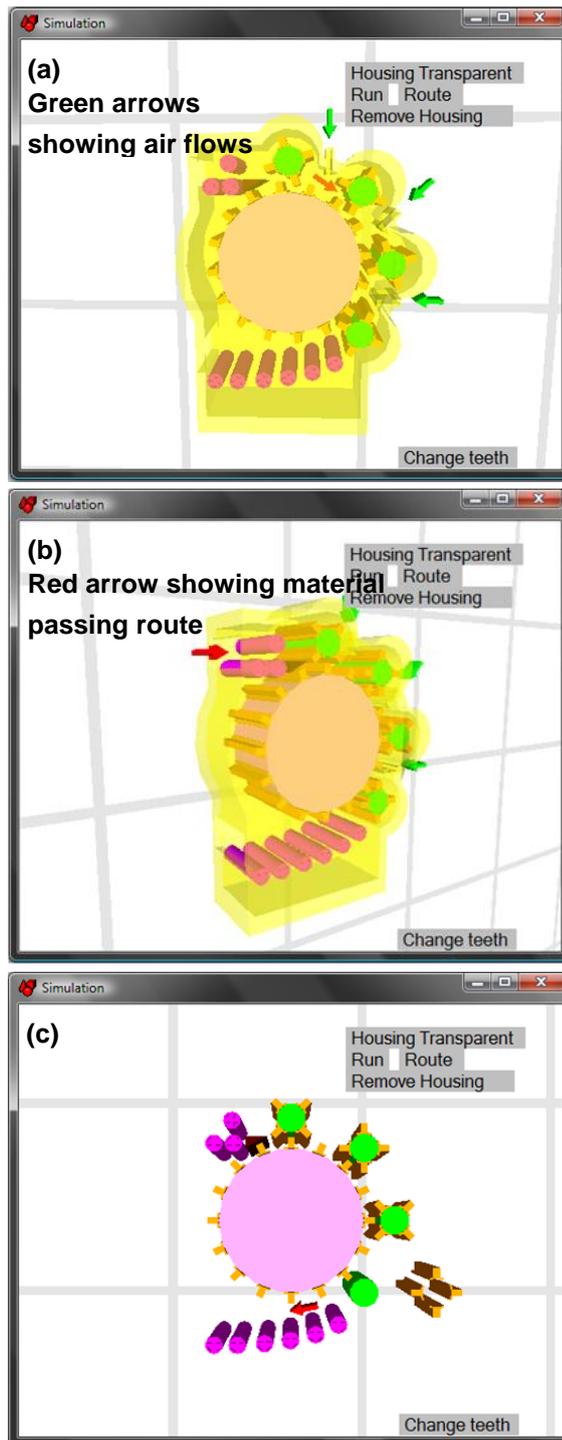


Fig. 4-11. The model of the new design in VE.
 (a) front view of the model with a transparent cast;
 (b) side view of the model with a transparent cast;
 (c) inner structure without cast.

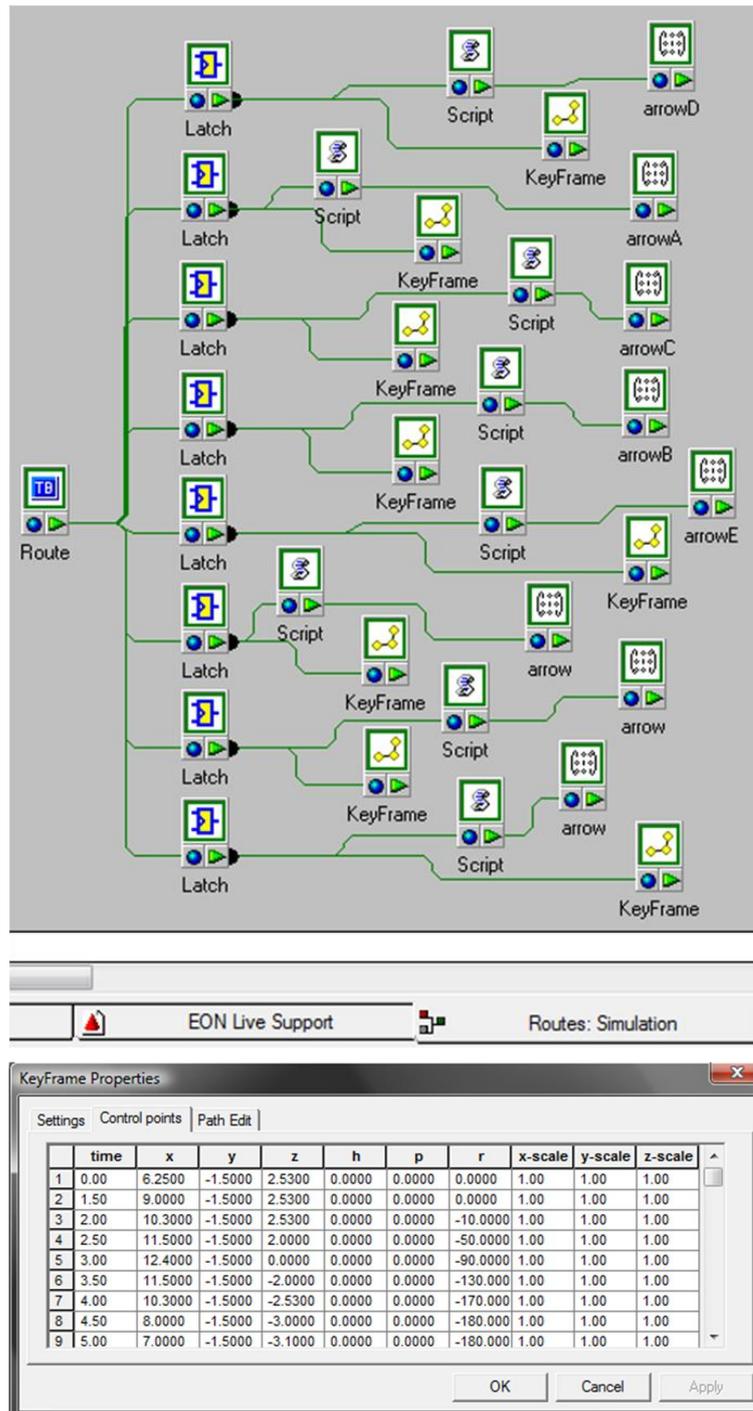


Fig. 4-12. *KeyFrame* Node to simulate material route.

4.6 CONCLUSIONS

The TRIZ method can be successfully used in designing conceptual prototypes of a hemp scutcher. The new design of the scutcher consisted of a “planetary layout” and air flow assistance. It will overcome some bottleneck problems of the existing machines in large scale, energy and productivity inefficiency. Design evaluation was conducted in a virtual environment without building physical models, and a dynamic model navigation which provided a straightforward view to the working status of the machine was developed. The use of TRIZ methods with assistance of virtual reality technology in the machine design is a new trend. It has a great potential for a fast, reliable and low-cost design evaluation.

4.7 ACKNOWLEDGEMENTS

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5. Summary

Hemp fibre can be widely used for various industrial applications. Hemp decorticator is an important component in a hemp processing line. Hammer mill and roll crusher (scutcher) are two types of decorticator, and their performance in fibre decortication is worth being studied. Energy requirement affects the cost of the process, which at the same time determines the availability of the processing method and equipment.

The results of this study provided analytical resource in estimating specific energy of hemp decortication using a hammer mill. One of the contributions of this study is that modified Kick's, Rittinger's and Bond's laws were developed. The second contribution is the development of a linear model. The constant factors in the modified laws and the linear model were determined based on the experimental data. All modified laws and the linear model fit the data equally well. They can be used to estimate specific energy of hammer mill decortication in the future if the output fibre length is known.

Another contribution of this study is the application of TRIZ-VR integrated method in designing a conceptual hemp scutcher. The new design has high potential to be used as long fibre processor in the future. This tool provides a useful trend of a fast, reliable and low-cost design evaluation.

For the future work, a physical prototype based on the conceptual design can be built and tested to evaluate the performance of the design. TRIZ-VR integrated

method has the potential to be used for designing other components of a hemp fibre processing line such as the cleaning component. Virtual environment as a platform can be integrated with data analysis functions. For instance, with the assistance of external numerical simulation software, energy or force data can be introduced to the prototype in the VEs, and the evaluation procedure can be supported by the data analysis results. Furthermore, the evaluation in VE can contain assembly-disassembly analysis, manufacturing efficiency assessment, and production cost calculation.

Appendix

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