MECHANICAL DEWATERING OF CHOPPED ALFALFA

A Thesis

Submitted to the College of Graduate Studies and Research

in Partial Fulfilment of the Requirements

for the Degree of

Master of Science

in the

Department of Agricultural and Bioresource Engineering

University of Saskatchewan

Saskatoon, Saskatchewan

by

Sandeep Sinha

Fall, 1995

PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in any part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or part should be addressed to:

The Head
Department of Agricultural and Bioresource Engineering
University of Saskatchewan
Saskatoon, Saskatchewan, S7N 5A9

ABSTRACT

Mechanical dewatering of cut alfalfa could replace the traditional method of field drying and would also be cheaper than total thermal dehydration in dryers. Juice from alfalfa also contains several compounds that would meet the growing demands of a low-calorie-fed population and also, provide compounds that could find a cure to some of the fatal communicable diseases.

The major objective of this research is to find the pressure levels required to remove some of the initial moisture from shredded alfalfa and the quality of the pressed pulp and juice if alfalfa is mechanically dewatered in a pressure cell. The results from dewatering using the pressure cell are used to simulate the working of a continuous screw press for process optimization purposes.

Experiments on dewatering of alfalfa were done on a screw press which is originally designed for extracting oil from oilseeds. The screw press was modified to simulate the field conditions of a continuous dewatering process for cut alfalfa. Measurements were done for dewatering power consumption and the pressed pulp was pelleted on a pilot scale pelleting mill. The quality of pressed pulp and expressed juice was analyzed at different screw speeds and choke openings.

Using the available data from the above experiments, a quasi-mechanistic model was developed for the continuous dewatering process in a single-screw press. The model is based on a semi-empirical relationship given by Koegel et al. (1972) for dewatering of alfalfa in a batch-type hydraulic press. The model was tested against the experimental data and a sensitivity

analysis was done by changing the variables. The agreement for predicted power and pressure is very poor.

The results show that once the initial moisture is removed from fresh alfalfa at a low pressure of 2-4 MPa, further moisture removal from the dewatered pressed pulp becomes difficult even at considerably higher pressures. The efficiency of juice extraction can be enhanced by delaying the onset of the 'steady equilibrium moisture content state'.

Comparison of energies using three different methods of pelleting shows that field drying can save energy by 13% over combination of mechanical dewatering and thermal drying. Combination of mechanical dewatering and thermal drying can save energy by 45% over total thermal dehydration. However considering the numerous value-added products obtained from the alfalfa juice and the fact that mechanical dewatering is a weather independent system, it seems to be a promising technology for the future.

ACKNOWLEDGEMENTS

I am grateful to my supervisor, Professor Shahab Sokhansanj, for his guidance, encouragement, constructive criticism and patience throughout the graduate program.

Sincere gratitude to the members of my advisory committee - Professor S. Yannacopoulos, Professor E.M. Barber and Professor R.J. Ford, for their suggestions, guidance and time for making this thesis successful.

Sincere thanks are extended to Mr. Louis Roth and Mr. Wayne Morley for their assistance in instrumentation of the experimental set-up.

My gratitude is due to Mr. Vernon Racz for analyzing the samples for protein and beta-carotene in his laboratory.

I am thankful to Tisdale Alfalfa Dehy Limited for providing financial assistance for the project.

Sincere thanks are extended to all my friends and colleagues for their encouragement and cooperation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a,b	=	measure of chroma of a sample
D_s	=	shaft diameter, mm
D_c	=	diameter of the choke ring, mm
D_{sc}	=	screw diameter, mm
D_b	=	barrel diameter, mm
E	=	energy, J
E_v	=	bulk modulus of elasticity, MPa
H	=	thickness factor, lb of solids per sq. ft. of screen
k	=	drying constant, s^{-1}
L	=	measure of brightness of a sample
m.c.	=	moisture content, % w.b.
M	=	moisture content at any instant of time, % w.b.
M_e	=	equilibrium moisture content, % w.b.
M_o	=	initial moisture content, % w.b.
N	=	speed of the screw in revs/min
p	=	pressure, MPa
t	=	time, s
T	=	time interval, s
t_f	=	thickness of the flight, mm
v	=	rate of advance of material, m/s
V_c	=	volume of the material in the expansion zone, m^3/s
V_o	=	initial volume of the material fed into the screw press, m^3/s
V_r	=	volume of the material in the choke ring of the screw press, m^3/s

V_s	=	volume of the material in the pressure section of the screw press, m^3/s
w.b.	=	wet basis, %
w_i	=	initial mass, g
w_f	=	final mass, g
x	=	distance along the screw axis, mm
W_{sv}	=	weight of solids per unit volume, g/cm^3
YI	=	yellowness index
Δw_w	=	mass of water removed, g
ΔW	=	power, kW
Δp	=	pressure, MPa
λ	=	pitch of the screw, mm

Chapter 1

INTRODUCTION

Fresh alfalfa has a moisture content ranging from 70% to 85% at the time of cutting. This moisture content has to be reduced to about 8% for alfalfa to be pelleted. Currently moisture is removed by an initial sun-curing and then dehydration in thermal dryers or by a total dehydration in thermal dryers. Typically it takes about 3450 kJ of heat energy to remove a kilogram of water from alfalfa. Though the use of sun-curing as preliminary drying technique reduces the cost of drying, it results in both quantitative and qualitative losses because of detrimental effects of weather.

Considerable work has been done on artificial drying of alfalfa with an objective to improve drying efficiency. Reducing the moisture content of fresh alfalfa by mechanical means might also reduce the total drying costs by removing some of the initial moisture. The pressed pulp which is high in fiber can be dried thermally and made into feed pellets. The juice can be processed into value-added products of commercial importance to the food, feed and pharmaceutical industries.

Mechanical dewatering of alfalfa consists of two processes namely, maceration and juice expression. Maceration involves rupture of plant cells while juice expression is the flow of water and associated solids through and out of the fibrous matrix. The dewatering process should proceed with the view of preventing excessive loss of nutrients, to a level that will allow economic thermal dehydration. The specific nutrients of interest in dewatering of alfalfa are beta-carotene and protein content in the dewatered pulp.

The amount of moisture to be removed from alfalfa at 80% m.c. (w.b.) in order to produce 1 t of alfalfa at 8% m.c. is about 3.6 t. If this alfalfa is dewatered mechanically to 60% m.c., the amount of moisture to be removed in the dryer will be 1.4 t, a reduction of about 62% in the amount of water to be removed thermally.

The idea is then to dewater alfalfa mechanically immediately following the cutting. The dewatered pulp is dried to the desired moisture content. The question which remains to be addressed is, "What is the maximum amount of moisture that can be removed mechanically by applying pressure and what will be the quality of the pulp and the juice?" An important engineering question is the development of a continuous press to do the job cost effectively. With this in mind, the following objectives were established.

1.1 Objectives

The overall objective of this research is to investigate the technical feasibility of continuous extraction of juice from fresh alfalfa. The following sub objectives were set:

1. to study the degree of mechanical dewatering of an alfalfa variety grown in Saskatchewan using a pressure cell.
2. to determine the specific energy requirement and residence time for dewatering of alfalfa in a continuous press.
3. to develop a mathematical model that describes a continuous screw press and test the model against the experimental data.
4. to conduct a sensitivity analysis using the simulation model.

Chapter 2

REVIEW OF LITERATURE

Mechanical pressing of plant material has been practiced for centuries. Mechanical dewatering of alfalfa has been studied previously by several researchers. In this chapter, the available information on pressing of alfalfa for the purpose of juice extraction is reviewed in the context of the objectives of this research.

2.1 Types of Presses

The types of presses as used for mechanical dewatering of alfalfa may be divided into two broad categories: the batch type and the continuous type. A batch type press is used on laboratory or small scale operations where the sample size is small and the effect of pressing a sample of alfalfa is monitored for a given set of operating conditions. Continuous type presses are used for field operations where large amounts of alfalfa are dewatered immediately after harvesting. Among the batch type are the hydraulic presses and among the continuous type are the screw presses, belt presses and roller presses . Some of the presses used in the past are reviewed in this section.

The feasibility of an experimental machine to cut forage from the standing position, macerating it, squeezing out part of the juice, and blowing the forage into a self-unloading wagon was studied by Hibbs et al. (1968). They showed that the dewatering process eliminated an average of 60% of the water in the standing crop. The percent protein in the dry matter of the dewatered alfalfa averaged 3.2% lower than the standing crops. In the wilting process, the percent protein difference between the standing crop and the wilted alfalfa dry matter averaged 1.8%. The loss of protein in the wilted material was more variable than dewatered alfalfa, perhaps due to leaf loss caused by raking and from wind during chopping and loading.

Holdren et al. (1972) used a hydraulically powered press to study the relationships between relative residual volume, compressive stress and dwell time to describe the dejuicing process. Fresh forage was cut and chopped to about 7 mm length. The range of compressive stress varied from 1.4 to 13.8 MPa. The duration of dwell time varied from 0.5 to 10 min. The physical form of charge material was either minced or chopped alfalfa. Their results showed that the juice separation was a linear function of relative residue volume, which in turn was a function of amount of initial charge, compressive stress and dwell time. The other non-quantitative factors influencing the residual volume were forage species, maturity and physical form. It was also seen that less compressive stress and dwell time were required to squeeze minced forage than were required to squeeze chopped forage to the same relative volume. The juice characteristics showed that the dry matter content of the juice remained constant irrespective of the quantity of juice expressed. They reported that the juice from minced alfalfa contained about 50% more dry matter than juice from chopped alfalfa. From their experiments, they suggested that the chopped alfalfa could be a better source for reducing the moisture content in fresh alfalfa to minimize dry matter losses in the discarded juice. However for extraction of protein from the juice, minced alfalfa would be a better source. For practical purposes, they suggested the use of a roll or wringer-type press to minimize the dry matter losses in the juice.

Koegel et al (1972) used a hydraulic press to study the effect of pressure, hold time and thickness factor on the moisture content remaining in the dewatered press pulp. Based on the results of their experiments, they proposed empirical relationships to describe the dewatering process for macerated alfalfa. These mathematical relationships are discussed in section 2.5 of this chapter.

Screw presses for dewatering alfalfa are being manufactured commercially by Stord Bartz Industri A/S, Bergen, Norway. The Stord twin screw press has been reported to be available in six sizes with capacities between 1 and 20-25 t/h, depending on the quality of the input raw material. The weight of the press ranges from 2.5 to 30 t and, the power requirement is from 12 kW to 120 kW (according to sales literature).

Mathismoen (1974) reported the results of two sets of experiments with the Stord screw press - one on fresh alfalfa and the other on steamed fresh alfalfa. On fresh alfalfa, he reported that the screw press reduced the moisture content of fresh alfalfa initially at 80% to 65%-70%. The dry matter in juice of the fresh alfalfa was up to 10% of the total weight. The protein content of the dry matter in juice was 30% or about 35% of the total protein content in the fresh plant. In the second set of experiments, in order to minimize the loss of proteins in the juice, tests were done on fresh alfalfa heated to about 90 ^{o}C by direct steam treatment or by immersion in hot water. The results showed that about 30-50 percent increase in capacity could be achieved as compared to using cold alfalfa. For fresh alfalfa having a moisture content of 80%, moisture content of about 60% in the press cake was achieved. Dry matter in the juice was about 5-7 percent with a true protein loss of less than 10% of the protein in fresh alfalfa. The power consumption for a press with a capacity of 25-30 t/h was about 3 kWh/t of fresh alfalfa.

Edwards et al. (1977) used a horizontal twin screw press to dewater field chopped alfalfa. The press consisted of two intermeshing counter rotating main screws 229 mm in diameter and a single cake discharge screw 159 mm in diameter at right angles to the main screws. The screw press was stepped-pitch type having three flighted sections with pitches of 152 mm, 102 mm, and 76 mm from the feed end to the discharge end. The main screws were operable over the range of 22 to 130 revs/min and were driven by a 14.9 kW variable speed drive unit. The cross discharge screw was driven by a 3.7 kW variable speed drive unit operable over the range of 8 to 37 revs/min.

Savoie et al. (1990) used a system of roller macerators and belt-type press for macerating and forming alfalfa into thin mats to expedite field drying. The macerator unit consisted of 7 steel rollers having longitudinal grooves. The top three rolls rotated at 1250 revs/min while, the bottom three rolls rotated at 1850 revs/min. The feed roll rotated at 1000 revs/min. The fresh alfalfa was fed into the maceration unit from a conveyor belt. Maceration occurred due to differential tangential speeds between the rolls. After passing through the rolls, juice was extracted due to compression of alfalfa between two belts - a rubber belt and a perforated nylon belt over a 120^{o} arc along a slotted cylinder. The juice squeezed was collected in the cylinder. They studied the effect of initial moisture content, density and number of macerations on the juice quality. The original purpose of the machine was to macerate alfalfa for fast field drying.

2.2 Energy Requirement

Studies on energy required for fractionation of alfalfa suggest different levels during maceration and juice expression. Pirie (1971) reported an upper limit of 37 kWh/t of green plant material to avoid coagulation of protein. Hollo and Koch (1971) reported an energy requirement of 45-55 kWh/t of green plant material for the fractionation process. Koegel et al. (1973) reported an energy consumption of only 2.6 kWh/t of green plant material for maceration when alfalfa was extruded through a 3 mm orifice at a pressure of 13.8 MPa, which is considerably lower than those reported for conventional maceration methods.

2.3 Factors Affecting Mechanical Dewatering

Koegel et al. (1973) performed three sets of experiments to study the effect of uniaxial force on the rupture of plant cells in alfalfa. In the first set of experiments, pressure was applied to the sample by means of a roller press. Due to a difference in the cellular structure of leaves and stems, samples of leaves and stems were tested separately. Tests done at 0.35, 6.9, 13.8 and 27.6 MPa showed no difference in the cellular structure after pressing. In another test using steel rollers, alfalfa stems were passed through the rollers subjecting the stems to peak pressures of 22.2 MPa and 44.1 MPa at the rate pressure gradient of 49 MPa/cm. They found that the moisture content of both the samples was reduced by 12% points. Koegel et al. concluded that pressure alone was not responsible for cell rupture in stems and leaves of alfalfa. In the second sample set, alfalfa was passed through a set of rotating steel rollers to achieve the required pressure gradient. The peak pressure was adjusted by changing the force holding the rollers while the maximum pressure gradient was adjusted by regulating the elasticity of the system. The stems were subjected to a peak pressure of 6.3 MPa at two levels of pressure gradients- 5.6 MPa/cm and 13.2 MPa/cm. A reduction of 2% moisture units in the first case and 4.5% moisture units in the second case showed that the degree of cell rupture was more in the second case. They concluded that maximum pressure gradient and not the peak pressure was the decisive factor in determining the degree of cell rupture in alfalfa. They performed a third set of experiments to study the rupture of plant cells by extrusion through orifices. Chopped alfalfa was extruded through a 3.18 mm orifice when a pressure of 13.8 MPa was applied. A high pressure gradient was achieved due to a sudden drop of pressure in a short distance. However on the basis of limited testing, they suggested that this extrusion method was better and less energy consuming than the conventional methods of maceration due to certain inherent advantages. Further studies were recommended to find the effect of orifice diameter, configuration and extrusion rate on the degree of cell rupture and power requirement.

Edwards et al. (1977) studied the effect of twin screw speed on press capacity, juice yield, and dry matter content of press cake. Their results indicated a positive correlation between screw speed and feed rate, while a negative correlation was determined between screw speed and juice yield. The correlation between screw speed and dry matter content in the press cake was also negative. As an example, when the screw speed was increased from 39 revs/min to 55 revs/min, the feed rate increased from 3135 kg/h to 4385 kg/h; juice yield decreased from 54.5% to 50.4% of the total weight; dry matter content in the press cake decreased from 37.6% to 33.2%. In the above example, the feed material was at 78.5% m.c. (w.b.). They also showed that the dry matter content in juice increased with a decrease in the moisture content of fresh chopped alfalfa. Also a higher moisture content in the feed material gave a higher juice yield. They suggested that a lower moisture content in the press cake was favored by a low moisture feed material. However Holdren et al. (1972) reported that the dry matter content of juice remained constant irrespective of the quantity of juice expressed. In another experiment with fresh alfalfa having 80 % m.c. and pressed at 55 revs/min, they found that the press cake was reduced to a moisture content of 68%, and had an average protein content of 18%. It was suggested that the press cake could be used as dehydrated product as it would conform to the industry standards of 15% protein in dehydrated alfalfa. When the press cake was mixed with the solubles, it would also conform to the 17% protein requirement in the dehydrated alfalfa.

In a later study, Edwards et al. (1978) used both ground alfalfa and chopped alfalfa to understand better the factors affecting the dewatering process. Fresh alfalfa having 80% m.c. and protein content of 21% was pressed in the screw press at 55 revs/min using chopped and ground forms. The juice yield increased by 22%, juice dry matter content increased by 16% and the press cake dry matter content increased by 13% for results on pressing of ground alfalfa against chopped alfalfa. However there was a significant reduction of protein content in the press cake by 21% in the above case. The yield of press cake however reduced to 66% of the dry matter initially present for ground alfalfa as against 77% of the dry matter for chopped alfalfa. Also the final moisture content in the press cake was 63% (w.b.) for ground alfalfa as opposed to a final moisture content of 68% (w.b.) for chopped alfalfa. From the results of Edwards et al. (1977, 1978), it appears that chopped alfalfa is a better form of feed material as compared to ground alfalfa if the objective of dewatering is to have a minimum loss of dry matter in the juice expressed. A higher protein content in the press cake of chopped alfalfa also makes the press cake conform to the required industry standards of guaranteeing a minimum protein content in the dehydrated products to be used as feed.

Savoie et al. (1990) reported the results of their experiments on the effect of initial moisture content, density and number of macerations on the juice quality of alfalfa compressed through a belt-type press. The material was first macerated through a set of rollers (described in 2.2). They reported that the amount of juice extracted varied between 6% to 25% of the fresh weight. The proportion of juice extracted increased from 10% to 21% when moisture content in alfalfa was increased from 80% to 84%. The average value of juice dry matter was 9.5%. The juice had a protein content of about 34% and an ADF (acid detergent fiber) content of about 5%. Acid detergent fiber represents the lignocellulose content of the plant matter. Lignocellulose is insoluble in water and its quantity shows loss of insoluble solids in the juice. Increasing the number of macerations from 1 to 2 increased the juice extracted from 13% to 16%. A reduction in density from 1.2 to 0.4 kg dry matter per square meter of screen increased the proportion of juice from about 13% to 16%, but the amount of juice extracted was higher for higher density.

2.4 Mathematical Models

Several researchers have developed mathematical models to describe the pressing process in hydraulic press, screw extruder and screw press.

The model to be used for describing independent and dependent variables of a screw press should account for throughput, pressure profile, juice expression rate and reduction in moisture content in the pressed pulp. The models developed for screw presses and other presses are described in the following sections.

2.4.1 Model for belt press

Savoie et al. (1990) proposed the following empirical relationship for dry matter released (equation 2.1) and quantity of water extracted (equation 2.2) for alfalfa macerated through a set of rollers followed by juice expression in a belt-type press.

$$DME = -4.3 + 0.93\ MAC + 2.74\ IMC - 2.5\ DEN \tag{2.1}$$

$$WTE = -99.37 + 18.18\ MAC + 36.4\ IMC - 21.96\ DEN \tag{2.2}$$

where

DME = quantity of dry matter released in the juice (g/100 g d.m.)

WTE = quantity of water extracted (g/100 g d.m.)

MAC = number of macerations

IMC = initial moisture content (g of water /g d.m.)

DEN = forage density into the press (kg d.m./m^2)

Equations 2.1 and 2.2 appear to be developed from experimental data specific to a type of macerator. They cannot be used in a continuous press.

2.4.2 Models for hydraulic press

The pressing process in a hydraulic press is a batch-type process in which the material contained in a cylinder is pressed by a plunger. Hydraulic presses have been used to study the properties of time dependent materials which are not possible to monitor in a continuous-type press. Empirical relationships are then developed to describe these properties for different combinations of pressure, loading rate and hold time. Mathematical models developed for pressing of alfalfa in a hydraulic press are described in this section.

Koegel (1972) suggested three empirical models for juice expression from macerated alfalfa. These models were based on data of juice expressed by considering three different approaches for pressure changes,

- constant pressure
- pressure varying with time
- pressure changes due to volume varying with time

For the constant pressure approach, macerated alfalfa samples were pressed in a cylinder-piston setup under a hydraulic press. The pressure was held constant for a given length of time called the hold time. The moisture expressed at pressures from 0.7 to 7 MPa, held from 0 to 150 s, was predicted for macerated alfalfa having a thickness factor varying from 0.25 to 2. The thickness factor was defined as pound of solids present in the sample per sq. ft. area of screen openings. The moisture remaining in the pressed pulp was given as

$$M = M_e + \left(M_o - M_e\right)\left\{\exp\left[-\left(P^{-0.2875} t^{0.2648} H^{-0.07759}\right)\right]\right\} \tag{2.3}$$

where

M = moisture content (% w.b.)

M_e = equilibrium moisture content (% w.b.)

M_o = initial moisture content (% w.b.)

P = pressure (psi)

t = hold time (s)

H = thickness factor (lb solids per sq. ft. screen)

For practical purposes, it was suggested that a model based on pressure changes with time would be most useful. The total pressing time was divided into small finite time increments during which the pressure was thought to increase to a value equal to the average of the value at the beginnning and at the end of the time increment. On the basis of pressure-time data, a time increment of 2 s was chosen for simulation. They proposed the following model to predict the final moisture in the fibrous residue at the end of each time increment.

$$\frac{M - M_e}{M_o - M_e} = \exp\left[-\left(P^{-0.0444} T^{-4.37} H^{-0.12}\right)\right] \tag{2.4}$$

where

T = time increment (s)

Koegel et al. (1972) also proposed a model to calculate the final moisture in the pressed pulp by considering the pressure changes due to volume varying with time. This model was proposed to be good for designing a press for practical considerations. Volume-time data was used to predict the moisture remaining in the pressed pulp. The change in pressure was related to change in volume as

$$\Delta P = E_v \frac{\Delta V}{V} \tag{2.5}$$

where E_V is the bulk modulus of elasticity and is analogous to the Young's modulus of elasticity. Koegel et al. (1972) determined the values of E_V as a function of solids content and the bulk density of the solids in alfalfa. The following equation was developed to fit their experimental data.

$$E_v = a + b(W_{sv})^c \left(\frac{W_s}{W_s + W_w}\right)^d \tag{2.6}$$

where w_{sv} is the weight of solids per unit volume and a,b,c,d are constants.

In addition to the solids content, $\left(\frac{W_s}{W_s + W_w}\right)$, the above equation also takes into account the incompressibility of the liquid contained in alfalfa.

Two sets of values of a,b,c,d were proposed. The first set consisted of values that gave the best prediction for pressures while the second set gave the best prediction for moisture. These constants are summarized in Table 4.1 of chapter 4. The moisture remaining in the pressed pulp was then calculated from equation 2.4.

2.5 Summary

From the research work reviewed to date, the following major conclusions can be drawn:

1. The factors affecting mechanical dewatering can be divided into quantitative and non-quantitative. The quantitative factors are pressure, hold time, thickness factor (or the amount of initial charge). The five major non-quantitative factors are forage species, maturity, physical form of the initial charge, pre-treatment, type of press and press configuration.
2. The extent of mechanical dewatering and hence, the nutrient composition in the juice and the press pulp can largely be controlled by monitoring the above quantitative and non-quantitative factors. Moreover the entire process will depend on the objective of fractionation - isolation of value added products from juice or utilization of press pulp as feed after further thermal drying. A proper combination of these factors will meet the requirements of the objective of the process.
3. It would be useful to have a system which could utilize both the juice and the press pulp for isolation of value added products from them.
4. The economic feasibility of mechanical dewatering will depend upon the eventual use of the specific value added product(s). Economics will have to be worked out to find whether,

(i) the juice expressed should be further processed or added to the dewatered press pulp, and

(ii) maceration should be carried out separately or combined as a single unit operation with pressing.

5. It seems that the power required will depend on the specific objective of fractionation and the initial treatment given to fresh alfalfa. A value of 40 kWh/t might be a reasonable estimation for the power requirement.

6. A higher dry matter content in the press cake at low speeds suggests a greater extent of dewatering than at higher speeds.

Considerable scope exists in exploiting the nutrient characteristics of alfalfa. Mechanical dewatering can be used as a process preceding dehydration. Little published data were available on the extent of mechanical dewatering and its energy requirement in a horizontal single-screw press. Also the relationship between dry matter content in the juice and juice yield is not reported. Hence a study was done to find the factors affecting the dewatering characteristics of chopped alfalfa in a single-screw press.

Chapter 3

EXPERIMENTAL MATERIALS AND METHOD

Experiments on mechanical dewatering of alfalfa were conducted in two phases. In phase I, a cylinder-piston system was used to determine the relationship between pressure and the amount and quality of juice extracted. In phase II, a continuous screw press was used to determine the residence time, speed and power requirements. In this chapter, the equipment and procedures used in these experiments are presented.

3.1 Cylinder-piston Equipment and Procedures

In the following sections, three sets of experiments are described. The first set was a preliminary study to analyze the effect of pressure on the moisture content of press pulp. The second set was a repetition of the first set to get a better trend of the data by minimizing experimental error which seemed to have been present in the first experiment. The third set was performed to study the quality attributes, namely the moisture, the protein and the beta-carotene contents in the press cake at different range of pressures.

3.1.1 Effect of pressure on degree of dewatering of macerated alfalfa for one pass through grooved rollers

The equipment used in experiment set one consisted of a stainless steel cylinder-piston-flange assembly. The plan and elevation of the assembly are shown in figures B.1, B.2 and B.3. Figure 3.1 shows the pictorial view of the cylinder, piston and flange used for the experiment. The cylinder was fitted with a removable flange at the bottom. A drainage hole was provided 10 mm above the lower end of the cylinder to drain off the expressed juice through rubber tubing. Three 50 mm diameter bronze porous stones were placed on top of each other to prevent any pressed material from passing through the drainage hole. Previous tests done in the Agricultural and Bioresource Engineering Department, using alundum (aluminum oxide) stones showed that they could not be used at high pressures. A mild steel screen was placed on the top of the coarse stone to prevent any blockage of the porous stones which might occur due to choking of the pores by press cake. A plunger was used to press the material inside the cylinder. A clearance of 0.2 mm between the piston base and cylinder was provided to fit the piston snugly into the cylinder, and also, to allow an easy movement of the piston during pressing.

Alfalfa cut at first stage on 16 June 1993 was brought into the laboratory the same day and was put in the cold store at -30 ^{o}C. The moisture content was measured by the oven method using ASAE Standard S358.2 (ASAE 1993) by drying about 25 g of sample in a convection oven at 103 ^{o}C for 24 h.

Frozen alfalfa was thawed and cut into chops of about 5 cm length. The chops were then put in moisture proof polyethylene bags of size 27 cm × 27 cm. After preparing sufficient amount of chops, they were macerated by

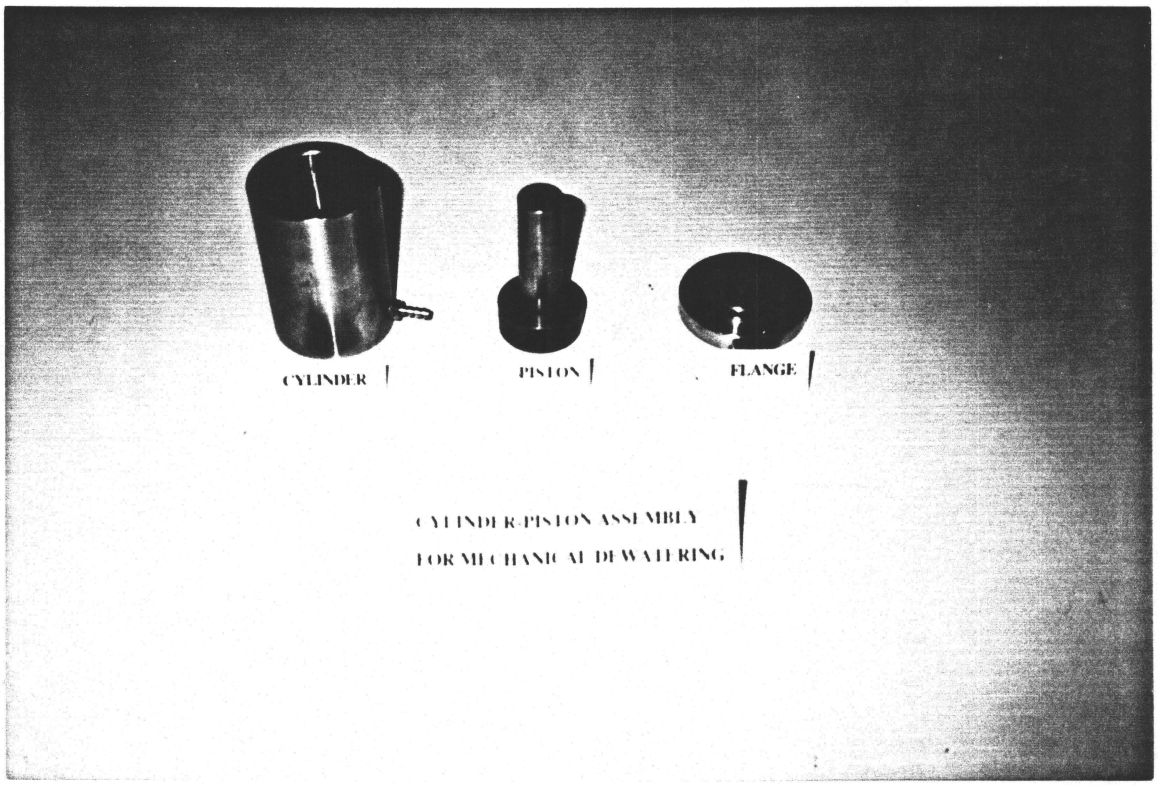


Figure 3.1 Cylinder, piston and removable flange used for experiments 1, 2 and 3

passing them through a pair of grooved rollers 15.1 cm in diameter. The rollers were about 0.18 mm apart. The rollers rotated at 440 and 443 revs/min. The grooves were 1 mm wide and spaced 1 mm from each other. The chops were macerated by passing them once through the rollers. The macerated alfalfa was thoroughly mixed and put back into polyethylene bags.

Macerated samples about 60 g were placed in the cylinder above the screen and porous stones. The piston was placed on the sample in the cylinder and pressure was applied on the piston by a hydraulic press. Figure 3.2 shows the cylinder containing alfalfa being pressed under a hydraulic press. The following pressure levels (MPa) were applied and recorded for the experiment : 0, 1, 2, 3, 4, 5, 6, 8, 10, 13, 14.5, 16.5, 18.6, 20.6, 30.8

The expressed juice was collected in plastic cups. The press cake was removed from the cylinder. The press cake and juice were weighed separately and samples of each were analyzed for moisture content. Figure 3.3 shows the samples of fresh alfalfa chops, macerated alfalfa, press cake and juice. The moisture content in the press cake was found by the oven method using ASAE Standard S358.2 while the moisture content in the juice was found by drying it at 103 ^{o}C for about 4 h.

3.1.2 Effect of pressure on degree of dewatering of macerated alfalfa for two passes through grooved rollers

Problems encountered during tests described in 3.1.1 included loss of residual juice that remained in the cylinder and in the hose. These problems were addressed in preparing for the second set of experiments.

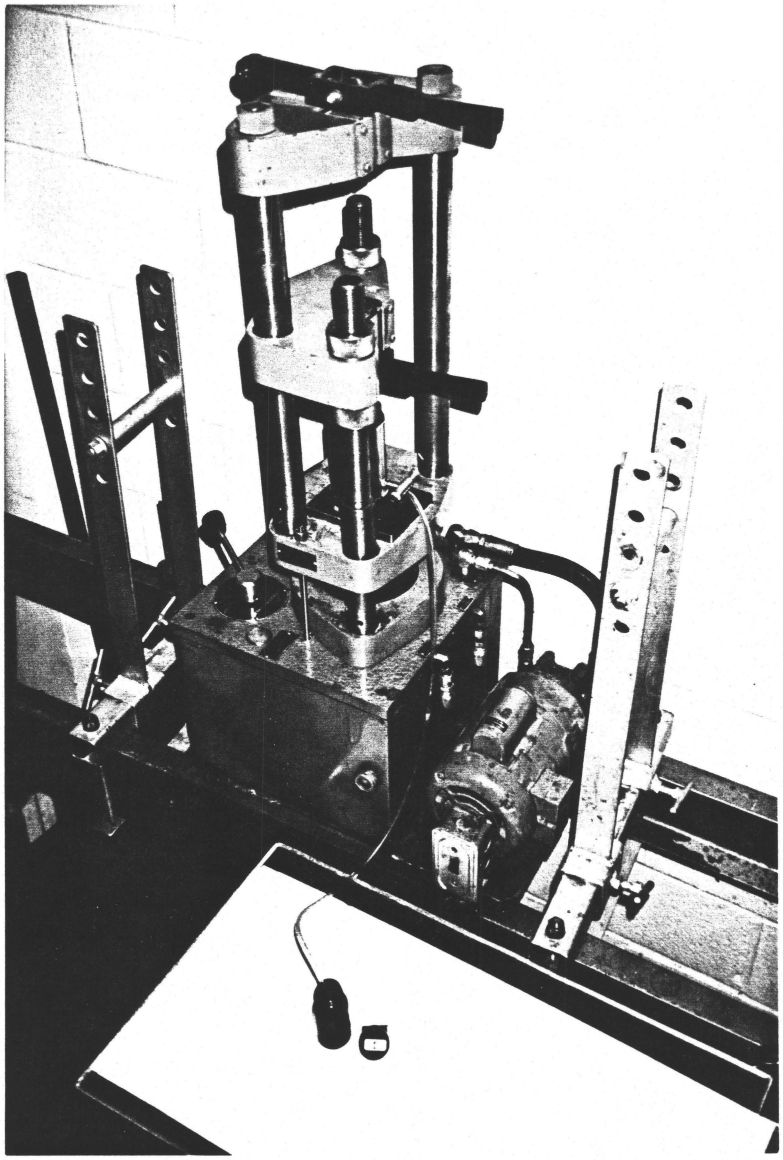


Figure 3.2 Hydraulic press showing the test cylinder, piston and collection of juice

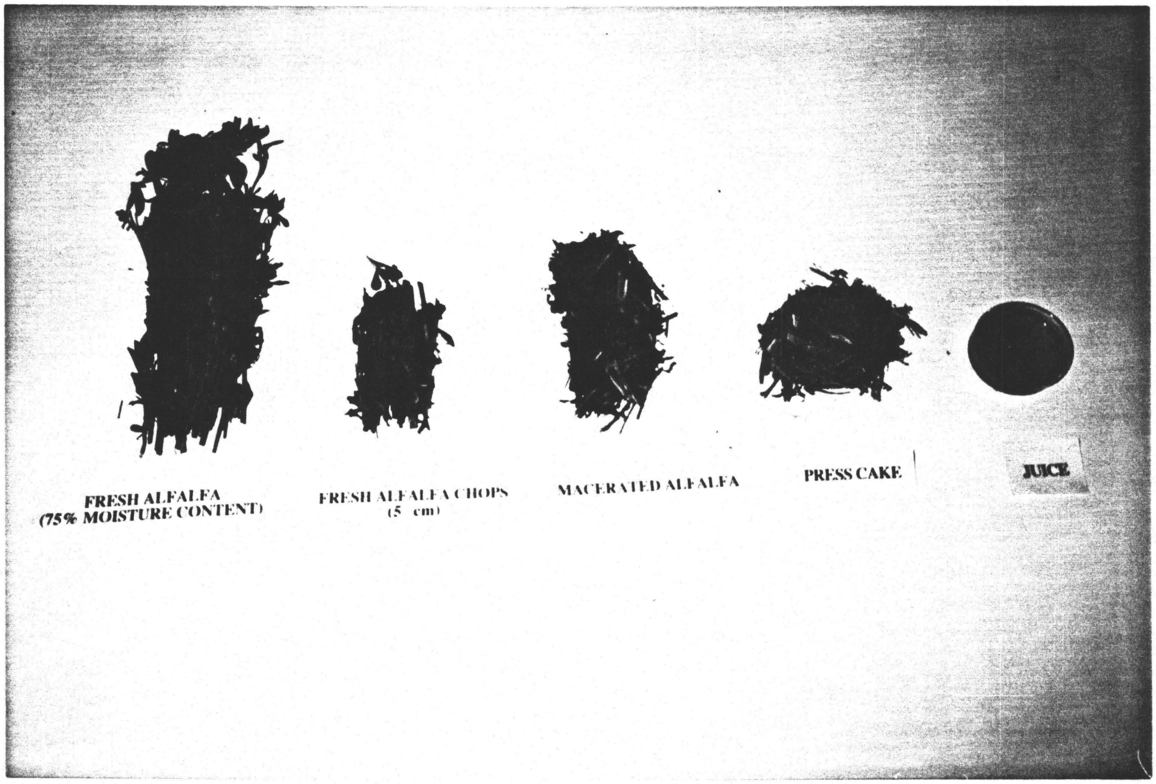


Figure 3.3 Alfalfa before the test and the resulting pressed pulp and juice

(i) A sponge was placed above the base of piston to absorb most of the otherwise escaped juice.

(ii) The rubber tubing used in 3.1.1 was replaced by a 48 mm × 16 mm flexible latex rubber tubing.

(iii) A pinch cock was installed on the latex rubber tubing at the hole end immediately when the pressure was released to ensure that no liquid re-entered the drainage hole after release of pressure.

Alfalfa chops used for this experiment were macerated by passing twice through the macerating rollers. Visual examination showed that the material was macerated well after two passes. The macerated alfalfa was mixed and placed in the moisture proof polyethylene bags. Since the material was macerated better, it was possible at this time to accommodate more amount of sample in the cylinder, increasing from 60 g in the experiment described in section 3.1.1, to 65 g in the present experiment. The following pressure levels (in MPa) were applied and recorded for the experiment: 0, 2, 4, 6, 8, 10, 12, 14, 16.5, 18.6. The expressed juice was collected in plastic cups and the press cakes were taken out after removing the flange and then they were placed into polyethylene bags. The total juice was found by summing the expressed juice and escaped juice. The press cake was weighed and stored in a refrigerator at 4 ^{o}C. When all the samples of press cake were collected, they were analyzed for their moisture contents using ASAE Standard S358.2.

Since the results from experiment set two were satisfactory, the same assembly was used for the subsequent experiment to analyze the quality of the press cake and juice.

3.1.3 Emulation of continuous dewatering process on a batch type hydraulic press

A third set of experiments with the piston and cylinder were performed to determine the quantity of juice and its quality under progressively increasing pressures. The reason for these experiments was to simulate the fact that the material in a screw press undergoes compression in stages of progressively increasing pressure. At each compression stage, the material is compressed between the barrel and the screw where the juice is squeezed from material. The pressed material advances forward to the next stage of higher pressure while the juice expressed is collected through the screens at the bottom. The process was simulated on a hydraulic press. The pressure ranges of 0-2, 2-4, 4-6, 6-8, 8-10 MPa were used to study the quality of press cake and juice expressed.

To prepare for the experiment, about 65 g of macerated alfalfa chops were removed from storage. The chops were placed in the cylinder. For 0-2 MPa, the sample was pressed from 0 to 2 MPa. The press cake was placed in polyethylene bags and stored in the refrigerator at 4 ^{0}C. The juice was collected in an ultraviolet resistant dark colored bottle and frozen at -24 ^{O}C to prevent any oxidation of beta-carotene. Two replications were taken for this range of pressure. It was made sure that the sample quantities were sufficient for moisture, protein and beta-carotene analysis.

For 2-4 MPa range, the amount of alfalfa sample was first pressed to 2 MPa and the expressed juice was collected in a plastic cup. The pressure on the piston was held at 2 MPa until all the expressed juice was collected. The pressure was then increased to 4 MPa and the expressed juice was collected in the bottle. Since a very small amount of juice was expressed in the 2 to 4 MPa range, this experiment was repeated several times in order to get sufficient juice for analysis. The press cake samples were again kept at 4 ^{o}C while juice samples were frozen at -24 ^{o}C. The pressing procedure was repeated for pressure ranges of 4-6, 6-8 and 8-10 MPa.

All of the samples of press cake, juice and fresh alfalfa were analyzed for protein, beta-carotene and moisture content. The time lag between dispatch of samples and the conduct of the analysis was about 3 to 4 days. For determination of protein content, the samples of fresh alfalfa chops, press cake and juice were sent to the Saskatchewan Feed Testing Laboratory, University of Saskatchewan, Saskatoon.

3.1.4 High pressure cylinder-piston assembly

In order to study the effect of higher pressures on the extent of dewatering, a larger cylinder-piston assembly with a screw arrangement for removing the piston from the cylinder was used. In the experiments described in sections 3.1.1-3.1.3, it was found difficult to remove the flange by hand from the cylinder. The modified assembly shown in Figure 3.4 was used to find the moisture content in the press pulp at pressures as high as 110 MPa. Different filters such as filter paper, cotton and nylon cloth were used separately as well as in combination with the porous stones to prevent the choking of the drainage hole which occurred at high pressures.

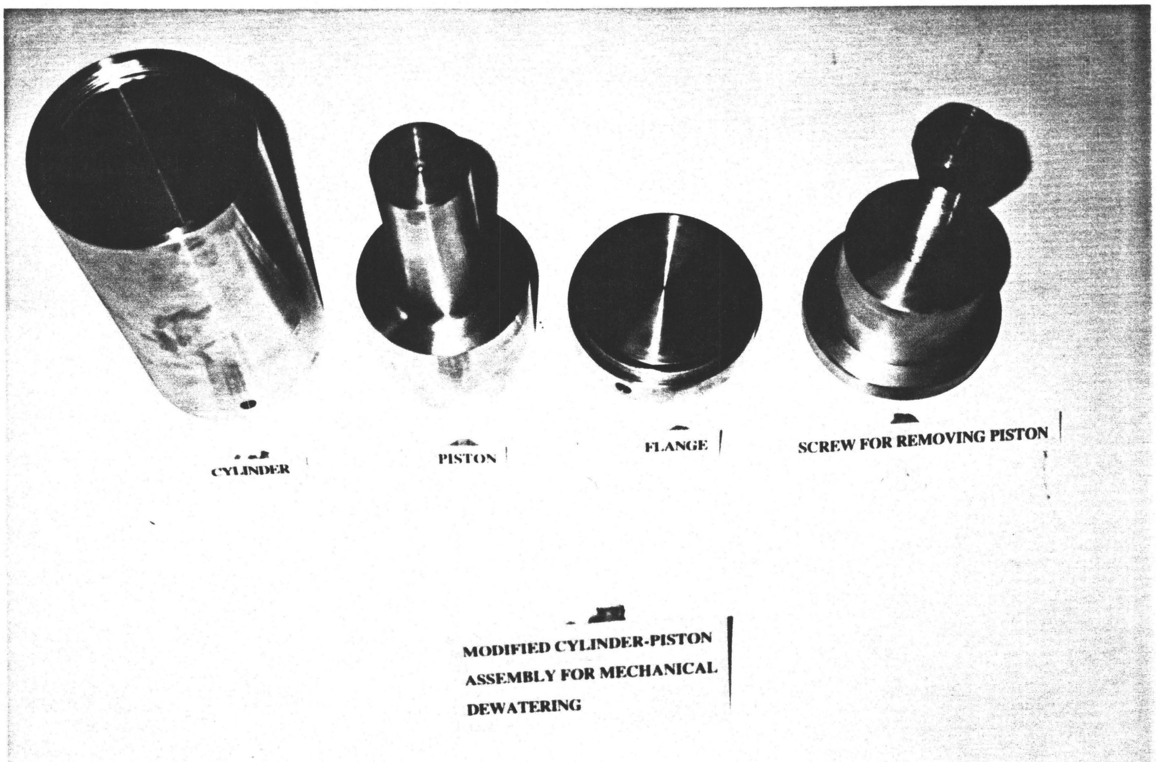


Figure 3.4 Modified cylinder-piston assembly with a screw for removing piston used for pressing alfalfa chops at high pressures

3.2 Screw Press

In order to study the dewatering characteristics of alfalfa for a continuous field operation, a screw press was purchased. Figure 3.5 shows the machine which is model-Super Delux, Table oil expeller. The unit was manufactured by M/s S.P. Engineering Corporation, Kanpur, India. The dimensions of the press were 137 cm x 53 cm x 69 cm and it weighed 270 kg. The screw press was designed for extracting oil from oilseeds with a rated capacity of 18 kg/h.

3.2.1 Installation of the screw press

The screw press was installed on a steel stand measuring 122 cm x 57 cm x 45 cm to make the unit portable as well as strong enough to absorb the vibrations of the screw press under operation. A 3.5 kW motor was selected to run the screw press. The drive had a variable pitch pulley to vary the pitch for providing different speeds and also it could be adjusted lengthways to vary the belt tension. The V-belts connecting the motor pulley and the driven pulley were protected for safety by means of a protective guard. To vary the speed of the screw, the unit was connected to an ac inverter which was connected to the main supply through a power measuring system. This system will be discussed in 3.2.3 and 3.2.4.

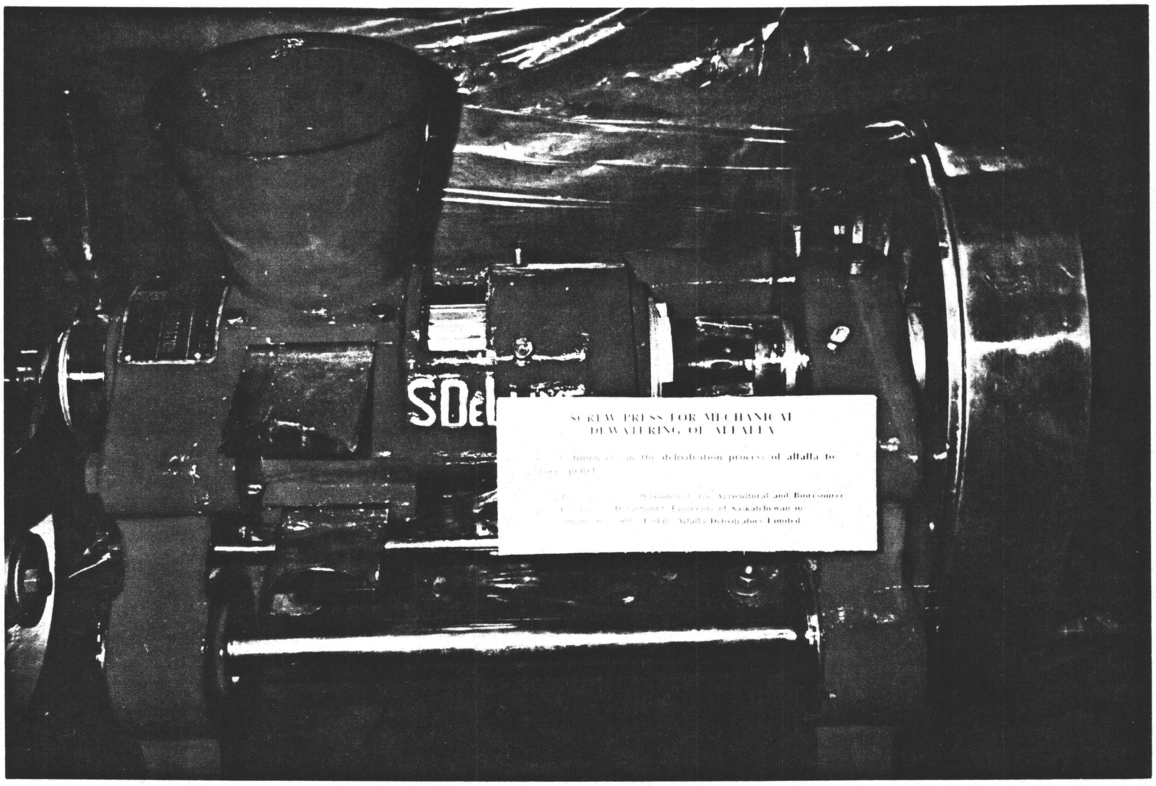


Figure 3.5 a   The overall view of the screw press

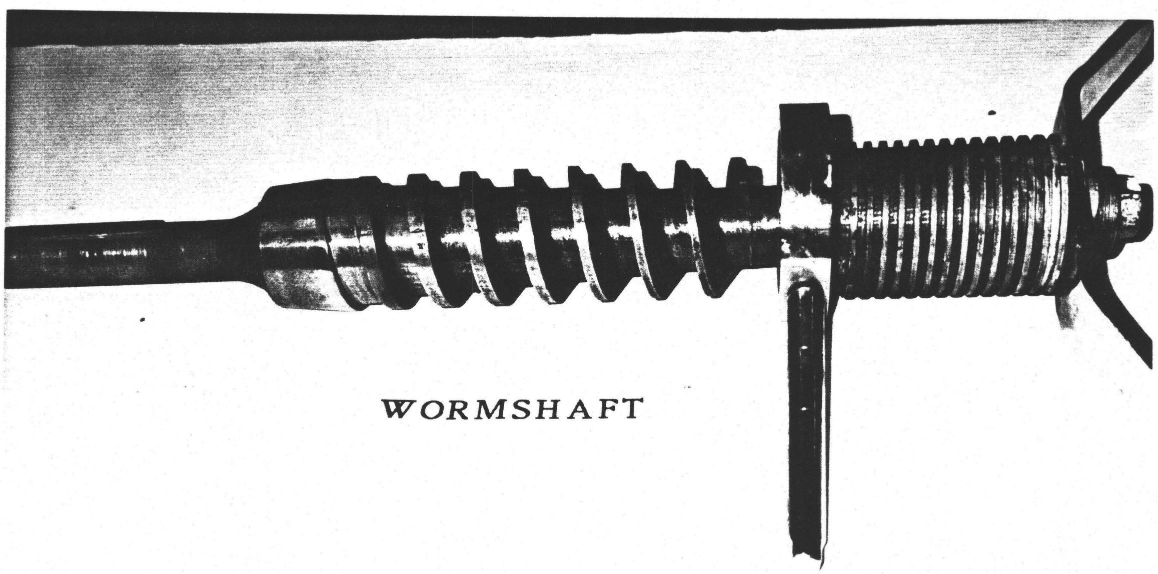


Figure 3.5 b   The screw auger of the screw press

3.2.2 Calibration of the screw press for clearance between the screw and choke ring

The diameter of the screw at the choke end was 72 mm. Since the choke ring tapered from 78 mm to 72 mm, a maximum clearance of 6 mm could be achieved. The adjusting handle was rotated anti-clockwise to move the screw in until the screw no longer could go through the choke ring. At this point, the clearance was zero. Corresponding to an increase in clearance from 1 mm to 6 mm, there would be a horizontal movement of the shaft. Thus there would be an increase in clearance of (78-72)/37 mm i.e. 0.162 mm per mm of horizontal shaft movement. As an example, at a clearance of 2 mm, horizontal shaft movement will be 2/0.162 = 12.3 mm. For the sake of convenience, the protruding key on the shaft was marked to indicate various clearances. Table 3.1 shows the position of the screw and the key at various clearances.

The effect of two choke openings, 4 mm and 6 mm, was studied on the dewatering characteristics of chopped alfalfa. The position of the flights in the feed section, pressure section and the choke section for a choke setting of 4 mm and 6 mm is described below:

3.2.2.1 Choke opening of 4 mm

The length of the screw before the feed section was 35 mm. The feed section starts after first flight. There were three flights in the feed section. The length of the feed section was 87 mm. The pressure section starts after 122 mm from the beginning of the screw. There were four flights in the pressure section. The diameter of the screw at the start of the pressure section was 61

Table 3.1 Calibration of the screw for choke clearance

Clearance (mm)	Horizontal screw movement (mm)	Key out (mm)
0	0	11
1	6.2	18
2	12.3	23
3	18.5	30
4	24.7	35
5	30.9	41
6	37	47

mm. After adjusting for a choke opening of 4 mm, the length of the choke section of the screw in the barrel was calculated to be 23 mm. The total length of the screw in the pressure section was 143 mm. Thus the length of the screw in the choke ring was 12 mm.

3.2.2.2 Choke opening of 6 mm

The length of the screw before the feed section was 50 mm. The feed section starts just before the start of the second flight. There were three and one-half flights in the feed section. The pressure section starts after 137 mm from the beginning of the screw. There were three and one-half flights in the pressure section. The diameter of the screw at the start of the pressure section was 63 mm. After adjusting for a choke opening of 6 mm, the length of the choke section of the screw in the barrel was 35 mm. Thus no part of the screw protruded into the choke ring.

3.2.3 Calibration of the screw speed

A literature review showed that for fibrous materials having high moisture content, the speed of the screw should be considerably lower than the one used for extracting oil from oilseeds (Edwards, 1977 and Vadke, 1987). At the supply frequency of 60 Hz, the speed of the screw was measured to be 147 revs/min. To find an optimum speed for dewatering alfalfa, an ac inverter (model E-TRAC, manufactured by T.B. Wood's Sons Company, Pennsylvania) was used to step down the ac frequency from 60 Hz to 10 Hz. The speeds for this frequency range were found to vary between 147 and 24. Table 3.2 shows the calibration of screw for revs/min.

Table 3.2 : Variation of screw speed with ac frequency under no load

Inverter frequency (Hz)	Screw speed (revs/min)	Power (Wattmeter) (kW)
10	24	0.21
12	30	0.21
14	34	0.24
16	39	0.24
18	44	0.27
20	49	0.27
22	53	0.3
24	58	0.3
26	63	0.33
28	68	0.33
30	73	0.36
32	78	0.36
34	82	0.39
36	88	0.39
38	93	0.39
40	98	0.42
42	102	0.42
44	107	0.45
46	112	0.45
48	117	0.48
50	122	0.48
52	127	0.51
54	132	0.51
56	137	0.54
58	142	0.54
60	147	0.57

3.2.4 Measurement of power

In order to record the power required for dewatering, a digital wattmeter was used (0-100 kW). The power required for dewatering was calculated as the difference between the power consumed by the screw press when alfalfa was being pressed and the power consumed by the press under no-load condition. The energy required for dewatering was calculated as the product of power and total time required for dewatering a given amount of sample.

3.2.5 Determination of screw speed

Fresh alfalfa cut at its second stage on September 19, 1993 was left overnight in the field. The alfalfa was chopped into 5 cm length the next morning and brought to the laboratory where it was put into cold storage at -30 ^{o}C. The frozen lot was thawed on December 24, 1993. Six samples each of about one kg were prepared and sealed in moisture proof polyethylene bags. The moisture content of each sample was determined using the ASAE Standard S358.2 method. Two replications were taken for finding the moisture content.

The speed of the screw was varied from 147 to 24 revs/min corresponding to an ac frequency of 60 Hz to 10 Hz. Measurements for the revs/min of motorshaft, jackshaft and screw, and measurements for power were recorded under the no-load condition. Alfalfa chops were put in the feed hopper to the brim and a wooden stick was used to force feed the chopped alfalfa samples through the feed hopper. Readings were again recorded for power and total time for dewatering when alfalfa chops were fed into the screw press until a given sample of one kg passed through the barrel. Since the power consumed during the pressing operation was found to fluctuate with time, peak values of power were recorded.

The juice expressed through the cage bars was collected in high density polyethylene containers while the press pulp emerging from the choke ring was collected in a plastic tub. The amount of juice expressed and the quantity of press pulp discharged were weighed. Five replications were taken for determination of moisture content in the press pulp. Since very little amount of juice was expressed from alfalfa pressed at 147 revs/min and 6 mm choke opening, only one reading was recorded for solids content of juice by drying it at 103 ^{o}C for 15 h. For the remaining samples of alfalfa pressed at 122, 97, 73, 49, 24 revs/min; 1, 1, 3, 2, 4 replications were taken respectively for the determination of the solids content of the juice.

Since complete data could not be recorded due to human error for 73 revs/min and 49 revs/min, a second set of experiments were performed, which were a repetition of the first set of experiments. For this set of experiments, five replications were taken for moisture determination of the press pulp and 1, 2, 3, 4, 4, 5 replications were made for determination of solids content of juice corresponding to the speeds of 149, 122, 97, 73, 49, 24 revs/min.

The screw press was thoroughly cleaned with water after pressing samples of chopped alfalfa after each set of experiments.

The above experiments showed good results for the dewatering characteristics of chopped alfalfa. On the basis of these results, an optimum revs/min was found at which the maximum amount of moisture could be removed from fresh chopped alfalfa. The optimum speed was then used to find the dewatering characteristics of press pulp, juice and the power required at different choke openings.

3.2.6 Modifications in feeding chopped alfalfa into the screw press

Certain modifications were made to the method of feeding chopped alfalfa on the basis of observations made in the last two experiments. These modifications would simulate the field method of feeding chopped alfalfa. It was observed that feed rate was dependent on the method of feeding chopped alfalfa into the feed hopper. The two methods of feeding studied were:

(i) Chopped alfalfa was fed to the brim of the feed hopper and then a wooden stick was used to press and stir the material into the screw barrel housing.

(ii) A small quantity of chopped alfalfa was put in the feed hopper and left to be conveyed into the barrel and when the sample disappeared, more quantity was added.

Since about 20% of the charged material still remained in the feed section, it was decided to dewater about 2 kg of chopped alfalfa in the press and collect the juice and pulp. The remaining material was allowed to stand in the press. Then fresh samples of chopped alfalfa were fed into the press and, the expressed juice and press pulp collected separately. In order to simulate field operation of a screw press, the above mentioned modifications in (ii) were done to study the effect of choke opening on the dewatering characteristics of chopped alfalfa.

3.2.7 Choke opening

The effect of two choke openings, viz. 6 mm and 4 mm, was studied in determining the dewatering characteristics of chopped alfalfa. First, 2 kg of chopped alfalfa was dewatered in the press and the juice and pulp was collected. The remaining material was allowed to remain in the press. Then about 3 kg of chopped alfalfa was fed into the press and, the expressed juice and press pulp were collected separately. The power and the total time for dewatering were recorded. The sample size was chosen as 3 kg to allow a longer time for continuous dewatering process that would minimize variations. Three replications were taken for the data at 24 revs/min and 6 mm choke opening. Samples of press pulp were taken for determination of moisture content, cake thickness and color. Samples of juice were taken for determination of solids content and color.

Before starting the next set of experiments at 24 revs/min and 4 mm, the screw press was washed to make sure that no juice or pulp remained in the barrel. The choke opening was adjusted to 4 mm. Three replications were taken for the data in the same way as was done for the 6 mm choke opening.

3.3 Pelleting of fresh chops and press pulp

Depending on the raw material used for pelleting, two different methods were used to make pellets.

In the first method, chopped alfalfa having 75% moisture content and cut at its first stage was first dewatered at 24 revs/min and with a 6 mm setting of the screw. The press pulp was then left for natural drying for two days until the moisture content was reduced to about 8%. The dried pulp was then ground in a hammer mill. The meal was checked for moisture content to make sure that it was below 8% moisture content. This was done to prevent plugging of the pelleting mill, which occurs at moisture contents above 8%. The pellets made were cooled to the room temperature.

In the second method of pelleting, chopped alfalfa was naturally dried from 75% to 8% for about 2 days until the moisture content was about 8%. The dried chops were then ground in the hammer mill. The meal was checked for moisture content to ensure that it was below 8% for safe running of the pelleting mill. The pellets made were cooled to room temperature.

3.4 Quality determination of pellets

The quality of the pellets was determined in terms of moisture content, durability and color. Moisture content was found by ASAE Standard S358.2 which involves drying whole pellets at 103 ^{o}C in a convection oven for 24 h. The test procedure for durability and color of the pellets is discussed in the following sections.

The durability of pellets was measured in the DURAL tester. Figure 3.6 shows the tester. The tester consisted of four impeller blades at 45^{o} to each other rotating at 1600 revs/min. The procedure for testing the durability of alfalfa pellets was developed by Larsen et al. (1993). Alfalfa pellets were screened through 5.9 mm (15/64 in) round hole sieves. A sample of 100 g of pellets was put in the DURAL tester. The residence time for alfalfa pellets was 30 s. During this time, the pellets were subjected to impact and shear forces. Pellets were sieved again through the 5.9 mm sieve and durability was found as the ratio of the weight of pellets on the sieve after testing to the weight of pellets before testing. Durability expressed as percentage was then compared for two types of pellets - pellets made after natural drying only and the pellets made by a combination of mechanical dewatering and natural drying.

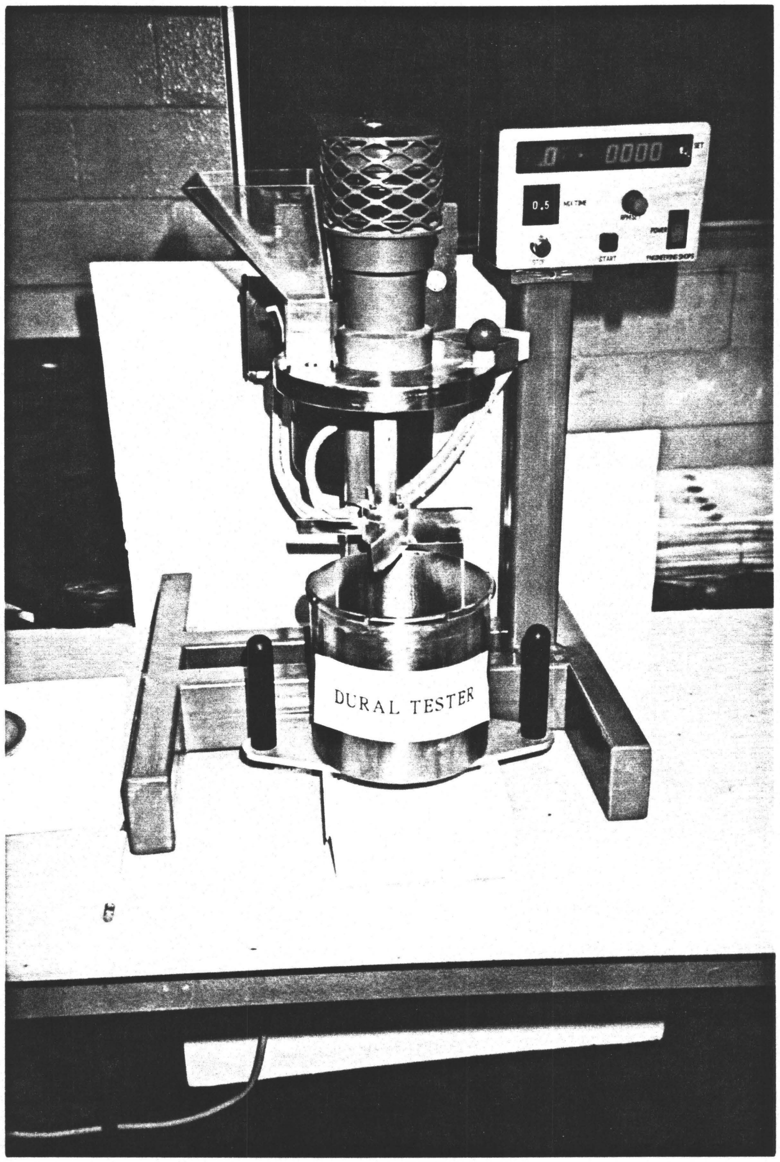


Figure 3.6 Dural tester showing the impellers with the canister removed

For color measurements of alfalfa samples for this study, Hunter L,a,b color scale was used. The illuminant used was D65 with a 10^{0} standard observer. The significance of L,a,b values is explained below.

L measures lightness and varies from zero for black, 50 for gray and 100 for perfect white

a measures redness when plus, gray when zero, greenness when minus

b measures yellowness when plus, gray when zero, blueness when minus

Before making color measurements, the instrument was standardized to a bottom scale value of zero for black color and a top scale value set for white calibrated standard. The L,a,b values give measurement of color in units of approximate visual uniformity throughout the color solid. These values are relative to the absolute value of the perfect white diffuser as measured under the same geometric conditions.

3.5 Summary

Experiments with piston-cylinder press and screw press were done to study the process and the machine variables influencing the dewatering characteristics of alfalfa. On the basis of these experiments, optimum pressure and screw speed were chosen which were ideal for removing some of the initial moisture from alfalfa. The results from the experiments are discussed in Chapter 5.

Chapter 4

Computer simulation for mechanical dewatering of chopped alfalfa in a single-screw press

In a screw press, changes occur in the press pulp discharged and in the juice expressed. In order to model the performance of a screw press, the flow characteristics of the material through the constricted space between the barrel and the shaft and the expression of juice through the compressed material have to be studied. This can be done by

(i) modifying the expression equation for uni-directional pressing in a cylinder-piston assembly

(ii) modifying and combining the axial flow equation in a screw extruder and the expression equation for uni-directional pressing

(iii) modifying and combining the axial flow equation in a screw extruder and the filtration equation, and

(iv) using a set of theoretical and empirical equations for pressing in a cylinder-piston assembly and modifying it along with the theoretical and empirical relationships for pressing in a screw press

The mathematical modelling of the dewatering process in a single screw press is based on scheme (iv). The model is based on the mathematical relationship developed by Koegel et al. (1972) for mechanical dewatering process of chopped and macerated alfalfa in a cylinder-piston press. With some modification to meet the objectives of this research, the model was applied to study the continuous dewatering process in a single-screw press.

Since this model was based on mechanistic and empirical relationships, the model was neither purely theoretical nor purely empirical. Hence it was decided to call it a 'quasi-mechanistic' model. Such a model should account for non-homogeneous and non-isotropic nature of alfalfa. The procedure describing the working of the model is given in this chapter.

4.1 Geometric Considerations

For simulation, the length of the screw is divided into three sections - the feed, the pressure and the choke sections. Figure 4.1 shows a diagram and a cross section of the single screw.

Feed section: The material is fed and conveyed to the barrel from this section.

The pressure and the choke sections are surrounded by an enclosure consisting of cage bars arranged along the inside circumference of the barrel.

Pressure section: Since the barrel has a constant diameter and the screw has an increasing root diameter and flighting thickness from the feed section, there is a reduction in clearance between the barrel and the screw. As a result, volumetric compression of the material occurs which causes the pressure to increase progressively to the end of the pressure section.

Choke section : The choke section is located at the discharge end of the screw. The choke has a tapering section, the diameter of which decreases towards the discharge end. The adjustment of the screw for choke opening changes the radial clearance. A decrease in choke opening corresponds to a decrease in radial clearance and an increase in pressure.

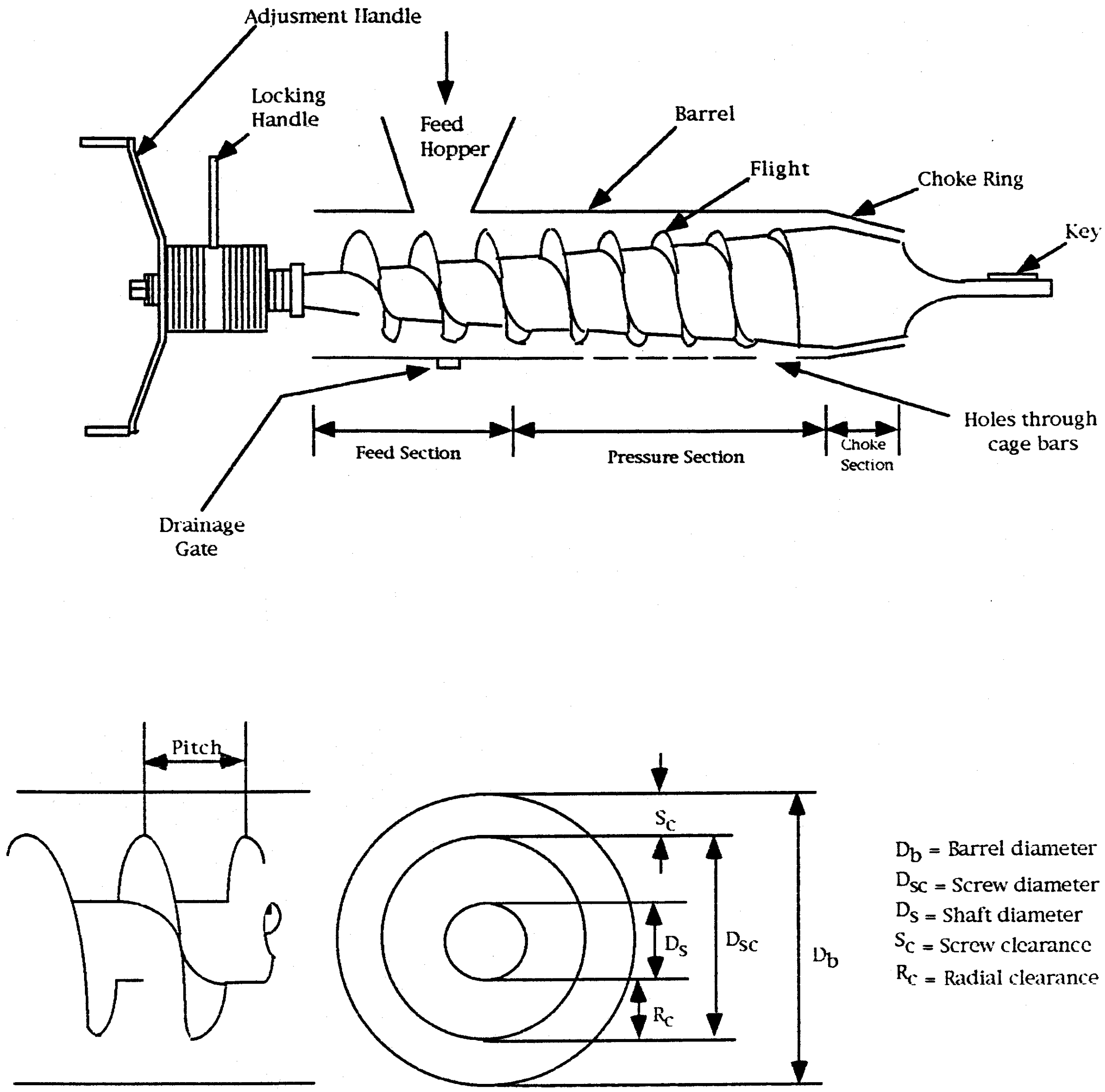


Figure 4.1 Diagram and cross section of the screw with nomenclature

Figure 4.2 shows the pictorial representation for mass balance of the material undergoing compression along the screw length.

If the total length from the feed section to the choke section is l, then

$$l = l_f + l_p + l_c \qquad (4.1)$$

where l_f, l_p , l_c are the lengths of feed, pressure and choke sections respectively.

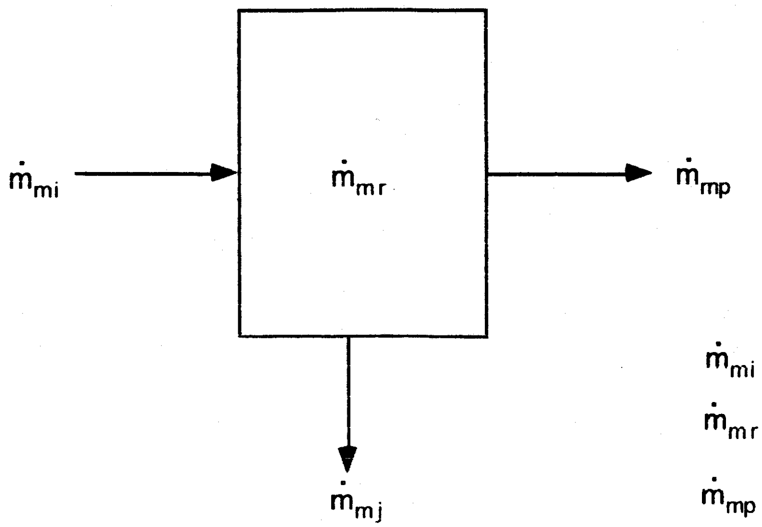
The pressure and the choke sections are located in an enclosure consisting of cage bars arranged along the inside circumference of the barrel.

In a screw press, maceration and juice expression occur simultaneously. Pressing is due to the compressive forces exerted by the screw normal to the material surface while, maceration is due to the shear forces on the material between the moving screw and the stationary barrel. The shear forces act parallel to the material surface. It is assumed that the nature of compressive forces is dilitational and that of shear forces is deviatoric.

The pressing process along the screw length can be explained by dividing the length of compression into a number of compression stages. The compression starts after the end of the feed section. Each stage can be viewed as causing compression of the sample of alfalfa for a pressing time, T. The total residence time will be the sum of all the pressing times along this length. During the time interval of T, the rate of advance of the sample is v such that

$$v = (\lambda - t_f)N \qquad (4.2)$$

where λ is the pitch of screw, t_f is the thickness of the flight and N is the speed of the screw in revs/min. The thickness t_f of the screw increases from the feed side to the choke side.



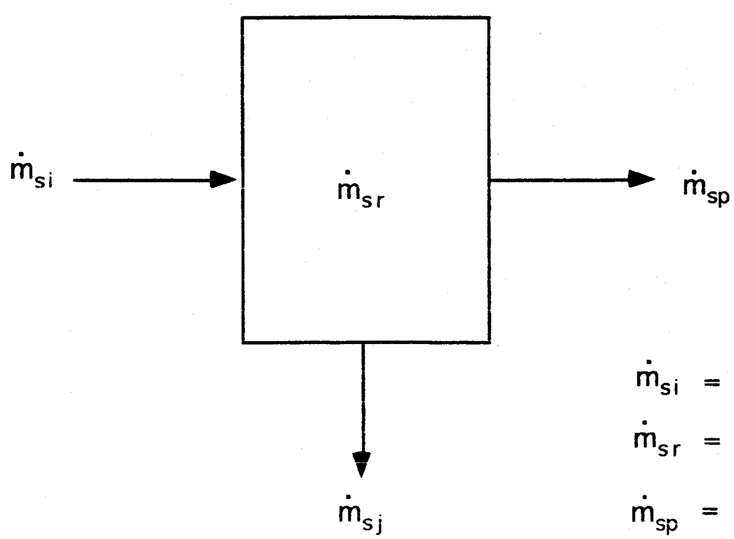
Moisture balance

$\dot{m}_{mi}$ = moisture rate, input

$\dot{m}_{mr}$ = moisture rate, retained

$\dot{m}_{mp}$ = moisture rate, pulp

$\dot{m}_{mj}$ = moisture rate, juice



Solids balance

$\dot{m}_{si}$ = solids rate, input

$\dot{m}_{sr}$ = solids rate, retained

$\dot{m}_{sp}$ = solids rate, pulp

$\dot{m}_{sj}$ = solids rate, juice

Figure 4.2 Mass balance of material in a screw press

The equation for the thickness of flight along the axis of the shaft is

$$t_f = -0.0002\ x^2 + 0.09\ x - 0.004 \qquad (4.3)$$

where 'x' is the distance along the screw axis in mm.

The diameter of the shaft increases from the feed section to the pressure section and then decreases along the choke section.

The equation describing the diameter of the shaft in the pressure section is

$$D_s = 46 + 0.018\ x + 0.00038\ x^2 \qquad (4.4)$$

The equation for the diameter of the shaft in the choke section is

$$D_s = 123 - 0.17\ x \qquad (4.5)$$

The initial volume of the material fed will be

$$V_O = \frac{\pi}{4}\left(D_{SC}{}^2 - D_S{}^2\right)\left(\lambda - t_f\right)N \qquad (4.6)$$

where D_{sc} is the screw diameter and D_s is as defined in 4.4

Due to non-uniform feeding in the feed section, equation 4.6 was multiplied by a dimensionless constant β_O. This should account for the shape of the feed hopper, variable moisture content, chop length, thickness of alfalfa and the presence of weeds coming from the field. Thus 4.6 can be modified to 4.7 as

$$V_O = \beta_O \frac{\pi}{4}\left(D_{SC}{}^2 - D_S{}^2\right)\left(\lambda - t_f\right)N \qquad (4.7)$$

β_O in equation 4.7 was called 'feed factor'. The volumetric change in the feed section will be

$$\frac{dV_o}{dx} = -\frac{\pi}{4}N\left[\left(D_{sc}^2 - D_s^2\right)\frac{dt_f}{dx} + 2D_s\frac{dD_s}{dx}\left(\lambda - t_f\right)\right] \tag{4.8}$$

The negative sign shows a decrease in feed volume along the shaft axis.

When the material enters the pressure section, a volumetric compression is caused by a reduction of the clearance between the shaft and the barrel.

If D_b is the diameter of the barrel, then the volume of the material undergoing compression in each stage in the pressure section will be

$$V_s = \frac{\pi}{4}\left(D_b^2 - D_s^2\right)\left(\lambda - t_f\right)N \tag{4.9}$$

The change in V_s in the pressure section along the shaft axis will be

$$\frac{dV_s}{dx} = -\left(\frac{\pi}{4}\right)N\left[\left(D_b^2 - D_s^2\right)\frac{dt_f}{dx} + 2D_s\left(\lambda - t_f\right)\frac{dD_s}{dx}\right] \tag{4.10}$$

Equation 4.10 was modified by incorporating a constant β_1. However it was not clear about its physical significance. But it seems that the chops in the pressure section undergo progressive compression and relaxation cycles between the flight land and the channel depth. The forces acting on the chops depend on their length, thickness and orientation. Hence the pressure and residence time will be affected by these factors. The modified equation is

$$\frac{dV_s}{dx} = -\beta_1\left(\frac{\pi}{4}\right)N\left[\left(D_b^2 - D_s^2\right)\frac{dt_f}{dx} + 2D_s(\lambda - t_f)\frac{dD_s}{dx}\right] \tag{4.11}$$

When the choke opening is such that no compression occurs in the choke ring, then there is a sudden expansion of the material following the pressure section. However when the choke opening is such that compression occurs in the choke ring also, then there is compression of the material following expansion.

The volumetric change of the material in the expansion zone will now be

$$V_c = \frac{\pi}{4}\left(D_b^2 - D_s^2\right) l_c N \tag{4.12}$$

where D_s is as defined in 4.5 and l_c is the length of the choke section. The change in volume of the material in this section will be

$$\frac{dV_c}{dx} = -\frac{\pi}{2} l_c N \left(D_s \frac{dD_s}{dx} \right) \tag{4.13}$$

The volumetric change of the material in the choke ring will be

$$V_r = \frac{\pi}{4}\left(D_c^2 - D_s^2\right) l_c N \tag{4.14}$$

where D_c is the diameter of the choke ring as defined in 4.15.

$$D_c = 78 - 0.17\,x \tag{4.15}$$

The change in volume of the material in the choke ring will be

$$\frac{dV_r}{dx} = \frac{\pi}{2} l_c N \left(D_c \frac{dD_c}{dx} - D_s \frac{dD_s}{dx} \right) \tag{4.16}$$

Equation 4.14 was modified by incorporating a constant β_2. This constant may be related to physical characteristics of the pressed pulp which now undergoes compression after the creep stage. Thus the modified equation becomes

$$\frac{dV_r}{dx} = \frac{\pi}{2} l_c \beta_2 N \left(D_c \frac{dD_c}{dx} - D_s \frac{dD_s}{dx} \right) \tag{4.17}$$

4.2 Simulation of juice extraction

If the volume at the end of each compression stage is V, then the volumetric compression ratio is defined as $\Delta V/V$. For a sample having an initial moisture content M_o,

$$M_o = w_w/(w_w + w_s)$$

w_w = mass of water

w_s = mass of solids

Assuming no loss of solids in the juice, w_s is thus constant in each stage. A volumetric compression causes an increase in pressure by ΔP. The change in pressure can be related to the change in volume by,

$$\Delta P = E_v \frac{\Delta V}{V} \tag{4.18}$$

where E_V is the bulk modulus of elasticity and is analogous to the Young's modulus of elasticity. Koegel et al. (1972) determined the values of E_V as a function of solids content and the bulk density of the solids in alfalfa. The following equation was developed by Koegel et al. (1972) to fit their experimental data,

$$E_v = a + b(W_{SV})^c \left(\frac{W_S}{W_S + W_W} \right)^d \tag{4.19}$$

,

where w_{SV} is the weight of solids per unit volume and a,b,c,d are constants.

In addition to the solids content, $\left(\frac{W_s}{W_s + W_w} \right)$, equation 4.19 also takes into account the incompressibility of the liquid contained in alfalfa.

Two sets of values of a,b,c,d were proposed. The first set was values that gave the best prediction for pressures while the second set gave the best prediction for moisture. These constants are summarized in Table 4.1.

The pressure at the end of each compression stage is the sum of pressures at the beginning of the stage and the change in pressure.

Let the material be in the first compression stage. The maximum amount of juice, if expressed, will depend on M_e, the equilibrium moisture content in the pulp which in turn is a function of the pressure applied on the sample. Koegel et al. (1972) developed the following expression for M_e as a function of pressure

$$M_e = 116\ p^{(-0.1746)} \tag{4.20}$$

where p is the pressure in psi. The factor 116 was erroneously reported as 0.116 in the original paper.

The expression for finding the moisture content in the pulp can be represented by the equation proposed by Koegel at al. (1972). The equation is analogous to Page's equation for the drying process. The equation given by Page (1949) was

$$\frac{M - M_e}{M_o - M_e} = \exp(-kT^n) \tag{4.21}$$

where k is the drying constant

The equation developed by Koegel for dewatering process is similar to 4.21 where k is replaced by a function of pressure, p, and thickness factor, H, such that

$$k = p^{(-0.0444)} H^{(-0.12)} \tag{4.22}$$

Table 4.1: Constants for prediction of pressure and moisture

	Range of W_{sv}	Constants			
		a	b	c	d
Pressure prediction	$W_{sv}<30$	-19.14	2.097×10^{-10}	6.179	5.955
	$W_{sv}>30$	1158 2358*	5.187×10^{-9}	2.912	10.56
Moisture prediction	$W_{sv}<30$	58.40	2.97×10^{-9}	5.91	8.59
	$W_{sv}>30$	-113.9	6.059×10^{-7}	2.90	12.65

* constant for the expansion cycle

The thickness factor, H, is defined as pounds of dry matter per square feet of screen. The screen was located at the bottom of the cylinder in which the alfalfa was pressed. To apply this concept to a continuous screw, the screen is considered to be the barrel area.

Thus the moisture content after time interval, T, will be

$$M = M_e + \left(M_o - M_e\right)\left[\exp\left(-p^{-0.0444}T^{-4.37}H^{-0.12}\right)\right] \tag{4.23}$$

Equation 4.23 describes the effect of time dependent pressure on dewatering of alfalfa. The equation shows that pressure, time and thickness factor are three important process variables influencing the dewatering process for a given initial moisture content of alfalfa. Among these variables, the thickness factor is the least important.

Water removed in each stage can be calculated by $\Delta w_w = w_i - w_f$ where w_i is the initial weight of water in the sample before compression and w_f is the final weight of water remaining in the pulp after juice expression.

In order to calculate the total power for dewatering, the power required in each stage is added.

Power for dewatering in each stage = ΔW

$$\Delta W = (\Delta p)\ (V) \tag{4.24}$$

where Δp is the pressure difference and V is the volumetric flow rate in each stage.

The rotation of the screw causes the material to move forward to the next stage where the radial clearance further decreases. Equations 4.1-4.24 were used step by step for stage 2 and for successive stages to calculate the total amount of water expressed and the total power required for dewatering from a given sample of chopped alfalfa undergoing compression in a screw press.

Total water expressed will be the sum of water expressed in each stage and total power will be the sum of the power components in each stage. The mechanical energy, E, consumed for the dewatering process will be

E = Total power x residence time/throughput

A time increment of 2 s was chosen for simulation. The constants a,b,c,d were as shown in Table 4.1. However in order to correctly predict the pressure and moisture for different screw speeds and choke openings, certain constants were introduced for the initial volumetric flow rate, for the changes in volume in the pressure and choke sections and during compression in the choke ring. These constants that were found by trial and error are listed in Table 4.2.

4.3 Summary

The objective of developing this simulation model was to predict the response of the system to the changes causing this response. The changes may be either a natural type or an enforced type. Among the natural type of changes is the initial condition of alfalfa fed into the screw press like physical properties of alfalfa and any pre treatment. Among the enforced type changes are the machine variables of screw press that govern the physical properties of alfalfa to meet specific objectives of dewatering. The response of the system for these natural and enforced changes affecting the dewatering process is discussed in chapter 5.

The simulation model was used to predict the moisture remaining in pressed pulp, pressure profile, throughput and specific energy required for mechanical dewatering of alfalfa chops. The model simulates the pressing process in a screw press for a material that is not only variable in quality

Table 4.2: Dimensionless constants for calculation of volumetric feed rate, change in volume and moisture expressed from alfalfa at 75% m.c.

Speed (revs/min)	Choke opening (mm)	Constants for Bo	B1	B2	Moisture expressed
24	6	80/120*	40	-	4.37
49	6	100/120*	60	-	4.37
73	6	500	70	-	4.37
97	6	1000	120	-	4.37
122	6	1000	30	-	4.37
147	6	1000	80	-	4.37
24	4	90/120*	40	1000	3.5
49	4	90/120*	40	1000	3.5
73	4	90/120*	40	1000	3.5
97	4	90/120*	40	1000	3.5
122	4	90/130*	40	1000	3.5
147	4	90/130*	40	1000	4.37

* refer to the constants for alfalfa at 85% m.c.

when fed into the press but also explains the changes the material undergoes during progressive pressing stages along the screw.

Chapter 5

RESULTS

The equipment and procedures used in the tests were described in chapter 3. Experiments were conducted in two phases of preliminary experiments with the piston and cylinder; then the dewatering characteristics of a continuous screw press were examined. A computer simulation for the dewatering process in a screw press was described in chapter 4. The results from the experiments done on the hydraulic press and the screw press and those obtained from computer simulation are described in this chapter.

5.1 Experimental Results

5.1.1 Test results with the cylinder-piston press

Table 5.1 lists the results of experiment 3.1.1 with the piston-cylinder press including the solids content of the juice and the moisture content for the press pulp at different pressure levels. Typical yields obtained from about 60 g of alfalfa chops were 36 to 41 g in the form of pressed pulp and from 12.4 to 23 g in the form of juice. The sum of juice weight and press pulp weight did not make up the original chop weight. This indicated loss of material, especially juice, during the extraction process.

The moisture content of the alfalfa pulp ranged from 53.2% to 92.0%. About 40% of the total plant moisture, which may be a combination of the moisture that became free as a result of thawing, the surface moisture that

Table 5.1 : Mass balance, moisture content of pulp, solids content of juice after pressing alfalfa at 75.7% m.c. in experiment 3.1.1

Run No.	Pressure (MPa)	Initial mass (g)	Press pulp mass (g)	Juice mass (g)	Press pulp moisture (% wb)	Solids content of juice (%)
1	1.0	60.4	38.1	19.1	84.0	13.4
2	2.1	60.6	39.7	12.7	67.3	13.1
3	3.1	60.8	39.5	19.3	66.6	12.8
4	4.0	60.3	39.4	18.8	92.0	12.4
5	5.1	60.6	40.2	18.0	84.8	14.1
6	5.9	60.4	40.6	16.9	67.2	15.6
7	8.3	60.3	38.2	19.0	67.1	14.7
8	10.2	60.1	35.7	21.5	66.8	13.1
9	13.2	60.7	37.9	20.6	67.4	12.4
10	14.5	60.3	39.1	19.1	64.2	16.9
11	16.5	60.4	34.4	22.8	66.7	12.6
12	18.6	60.2	36.8	20.6	68.4	14.3
13	20.7	60.7	40.0	19.6	53.2	13.1
14	30.8	60.2	36.9	19.9	74.3	13.5

was loosely bound, and some of the bound moisture that was released due to maceration, could be removed at very low pressures up to 2 MPa. A further increase in pressure did not increase the juice yield.

The solids in the juice were measured by evaporating the moisture. The juice solids content ranged from 12.4% to almost 17% of the juice weight. The loss of solids was 7% to 13% of the total solids in fresh alfalfa.

It can be seen that the data did not show a strong correlation between the pressures and the solids content of the juice. The calculated correlation coefficient was 0.38. The correlation between pressure and moisture content in the pulp was higher than that for solids in the juice. The calculated correlation was -0.63. However upon ignoring the data for samples 1,4,5 and 14, the shape of the correlation between pressures and solids content and, pressure and moisture content improved somewhat. The correlation between the juice weight and solids content was -0.2.

From the mass balance for solids and the moisture and from the experimental observations, it was inferred that the unexpected high values for moisture content in the pulp could have been due to the following sources of experimental error.

Error due to escape of juice: Some of the juice that escaped through the clearance and got collected above the base of the piston might have entered the press cake when pressure was being applied. This resulted in higher moisture content in the press pulp.

Error due to inability to collect all of the expressed juice: Some of the expressed juice in the rubber tubing might have re-entered through the drainage hole when the pressure was released. Also some of the juice remained in the tube.

Table 5.2 shows the data for dewatering of alfalfa under compression in the cylinder-piston-flange assembly for experiment 3.1.2 to study the effect of maceration level on juice yield. In these experiments, about 65 g of chop masses were used. The juice yield increased with pressure as one expected. It was observed that at 8.26 MPa (run 4) and higher pressures, the juice escaped through the clearance between the piston and the cylinder. The escaped juice was however absorbed by a sponge. The variation in moisture content of press pulp with pressure showed that the moisture content in press pulp decreased from 75.7% to 61.8% on increasing the pressure from 0 to 6 MPa. The correlation between pressure and moisture content in the pressed pulp was -0.81. Table 5.2 also shows that the sum of press pulp and juice was not equal to initial mass of the chops. The loss of material either in the form of juice or solids amounted to, in some cases, 10% of the initial mass of chops. However the moisture content of the pulp is fairly constant and it appeared to be independent of the level of pressures beyond 6 MPa.

Since the solids content in the juice was not found experimentally, they were calculated by mass balance as shown in Table A.3. The solids content in the juice ranged from ranged from 9% to 14% of the juice weight. A low correlation coefficient of -0.3 between the solids content and the amount of juice expressed shows that the solids content in the juice does not depend on its weight. However the mode of the population for the solids content ranged between 10-11% of the juice weight. The loss of solids in the juice was 8% to 14% of the total solids in fresh alfalfa.

The above results showed that after macerating alfalfa chops twice through the rollers, more of the bound moisture became available in the free state. About 50% of the total plant moisture could now be expressed at pressures up to 6 MPa. Pressure up to 2 MPa could remove 40% of the

Table 5.2 : Mass balance and moisture content of press pulp after pressing alfalfa at 75.7% m.c. in experiment 3.1.2

Run No.	Pressure (MPa)	Initial mass (g)	Press pulp mass (g)	Juice mass (g)	Moisture content (% wb)
1	2.06	65.9	39.4	18.9	66.1
2	4.13	66.2	39.9	23.9	65.5
3	6.19	65.6	34.5	27.2	61.8
4	8.26	65.7	37.9	23.7	63.3
5	10.32	66.0	32.4	31.0	60.3
6	12.39	65.6	31.9	30.7	60.5
7	14.45	65.3	32.3	31.1	61.4
8	16.52	65.5	31.3	29.8	60.0
9	18.58	66.0	32.4	31.6	61.1

totalplant moisture. However a further increase in pressure did not increase the juice yield appreciably.

Table 5.3 lists the pressure ranges, the quantity of chops and the amount of press pulp and juice for experiment 3.1.3. Similar to experiment 3.1.2, full recovery of material was not possible. The number of samples used in each pressure range was selected in order to collect adequate juice for analysis. In run 1, two samples each at about 65 g yielded a total of 41.5 g of juice. In the subsequent samples at higher pressures, the yield of juice was small only 1-2 g from the pressed pulp of about 30 g.

Table 5.4 shows the data for moisture, protein and beta-carotene contents when macerated alfalfa was pressed to various pressure ranges (shown in table 5.3). The continuous dewatering process in a screw press can be represented by the batch process of dewatering in a hydraulic press. The screw length can be considered as consisting of a number of compression stages. Fresh alfalfa at 75.7% moisture had 20.6% crude protein and 18.88 mg/kg (31500 IU/kg) of beta-carotene. The material enters the first compression stage (0-2 MPa) at 75.7% m.c. and leaves at 68.3% m.c. The pressed material from stage 1 then enters stage 2 at 68.3% m.c. and after compression leaves at 65.9% m.c. The drop in moisture content from stage 1 to stage 2 is 2.4 points. The process continues until the pressed material enters stage 5 (8-10 MPa) at 64.4% and leaves at 63.8%. The drop in moisture content during five stages is 11.9 points. This shows that as the pressure was increased further, the moisture content decreased, but the decrease in moisture content became lesser with a progressive increase in the compression stages. Crude protein content varied from about 22 to 24%. Beta-carotene content varied from 26.4-33.6 mg/kg (43000-56000 IU/kg).

Table 5.3 : Quantity of press pulp and juice expressed from alfalfa chops at various pressure ranges in experiment 3.1.3

Run No.	Pressure range (MPa)	Sample No.	Initial mass (g)	Press pulp mass (g)	Juice collected (g)
1	0.00-2.06	1	65.7	35.3	24.5
		2	65.3	37.4	17.0
	Total		131.1	72.7	41.5
2	2.06-4.13	1	65.8	32.2	1.8
		2	65.7	31.8	1.9
		3	65.6	32.7	2.7
		4	65.0	31.9	1.8
		5	65.7	31.6	1.9
	Total		327.9	160.3	10.1
3	4.13-6.19	1	65.3	31.5	1.6
		2	65.4	30.7	1.6
		3	65.2	32.9	1.5
		4	65.7	32.1	1.7
		5	65.6	32.1	2.1
		6	65.9	32.0	1.7
	Total		393.1	191.4	10.2
4	6.19-8.26	1	65.6	30.4	1.4
		2	65.9	30.7	1.6
		3	65.1	31.3	0.0
		4	65.8	33.0	1.4
		5	65.6	31.3	1.7
	Total		327.9	156.7	6.0
5	8.26-10.32	1	65.6	31.3	1.5
		2	65.4	31.6	1.6
		3	65.7	32.2	1.8
		4	65.9	31.7	1.6
	Total		262.5	126.7	6.5

Table 5.4 : Quality of press pulp and juice expressed at various pressure ranges for following initial conditions of fresh alfalfa in experiment 3.1.3

Moisture : 75.7%
Protein : 20.6%
Beta-carotene : 18.88 mg/kg (31500 IU/kg)

		Press pulp			Juice		
Run No.	Pressure range (MPa)	m.c. (% wb)	Protein (%)	Beta carotene (mg/kg)	Solids content (%)	Protein (%)	Beta carotene (mg/kg)
1	0.00-2.06	68.3	7.3	10.16	12	2.2	3.31
			23.1*	32.08*		18.1*	27.62*
2	2.06-4.13	65.9	8.3	10.42	10.5	1.60	2.25
			24.3*	30.61*		15.6*	21.45*
3	4.13-6.19	65.0	7.8	11.79	10.5	1.50	2.29
			22.2*	33.68*		14.2*	21.74*
4	6.19-8.26	64.4	8.0	9.39	10.4	1.60	1.01
			22.4*	26.38*		14.9*	9.72*
5	8.26-10.32	63.8	8.6	10.67	10.4	1.60	1.01
			23.7*	29.41*		15.3*	9.80*

* based on dry matter

Samples of juice analyzed for solids, protein and beta-carotene contents showed that the solids content in juice decreased from 12% to 10.5% of the juice weight as the material was compressed from 0-2 MPa to 2-4 MPa. From stage 1 (0-2 MPa), the juice expressed had a solids content of 12%. The juice from stage 2 had a solids content of 10.5%. On going from stage 2 to stage 5, there was not significant change in the solids content of the juice expressed and, it remained almost steady at an average of about 10.4%. Crude protein content of juice expressed from stage 1 was 18.1%. On going to stage 2, it decreased to 15.6%. However further advancement of the pressed material to higher stages 3, 4 and 5 did not show a significant difference in the protein content and, it might be taken as an average of about 14.8%. The beta-carotene content in the juice samples showed that the juice from stage 1 had the highest beta-carotene content of 27.62 mg/kg (46000 IU/kg). As the material progressed to stage 2, juice expressed had 21.45 mg/kg (35800 IU/kg) beta-carotene. Further advancement of the material to stage 3 did not show significant change in beta-carotene content of the juice as it was 21.74 mg/kg (36200 IU/kg). However as the material advanced to stage 4 with a resulting 9.72 mg/kg (16200 IU/kg) beta-carotene, there was a significant decrease in beta-carotene content by 12.02 mg/kg (20000 IU/kg). The juice expressed from stage 5 (9.8 mg/kg or 16300 IU/kg) showed only a slight increase in its beta-carotene content by 0.08 mg/kg (100 IU/kg).

These results show that the quality of pressed pulp and juice was good till the second stage where the pressure was 2 MPa. The loss of solids in the juice was rather high at 18% of the total solids in fresh alfalfa. The loss of protein in juice was 15% of the total protein in fresh alfalfa and that of vitamin A was 30% of the total vitamin A in fresh alfalfa. Although further advancement of the material to higher stages caused moisture reduction, the decrease was not significant considering the pressure levels achieved. The protein and the vitamin A in the pressed pulp did not show much change in higher stages. The juice also had a steady solids and protein content in higher stages except for a significant loss in vitamin A.

5.1.2 Tests results with the screw press

Table 3.2 showed the data for calibration of the screw revs/min at different ac frequencies. An inverter frequency of 10 Hz yielded 25 revs/min for the screw.

To meet our objective of removing the maximum quantity of water from fresh alfalfa, it was decided to find the speed at which maximum moisture reduction would occur.

Table 5.5 shows the results of experiment set 4 described in 4.2.6 for the effect of screw speed and the quantity of juice extracted at 6 mm clearance on the dewatering characteristics of chopped alfalfa. It can be seen from the data that on lowering the speed from 147 to 24 revs/min, the weight left in the feed section increased from 15% to 30% of the total weight. This material was not conveyed forward to the compression section. The proportion of pulp discharged decreased from 75% to about 41% of the total weight while, the juice yield increased from 0.3% to 17%. For frozen alfalfa chops at 75% m.c., the moisture content in the press pulp was reduced to 72% at 147 revs/min and 64% at 24 revs/min. Thus the amount of moisture removed increased from 2% points to 11% points as a result of decreasing the screw speed. The solids content of the juice did not show any trend and varied between 11% to

Table 5.5 : **Effect of speed of screw press at a constant clearance of 6 mm on dewatering characteristics of fresh alfalfa having an initial moisture content of 75% in experiment 4, replica 1**

Screw speed	Initial	Final				Mass left in press	Energy for dewatering	Throughput
		Pulp		Juice				
	Mass	Mass	Moisture content *	Mass	Solids content **			
(revs/min)	(g)	(g)	(% wb)	(g)	(%)	(g)	(kWh/t)	(kg/h)
147	1000	747	72.5	4	11.7	153	20.8	31
122	1001	781	72.4	25	13.8	166	25.8	22
97	1001	689	71.4	59	12.8	162	35	21
73	1000	642	71.0	94	11.1	188		28
49	1000	573	67.7	147	11.6	213		
24	1000	408	63.8	169	11.5	300	34.7	18

* Average of two replicates
** Average of five replicates

14% of the juice weight. The loss of solids in juice was 0.2% to 8% of the total solids when the speed was decreased from 147 to 24 revs/min. The throughput at the above revs/min were 31 kg/h and 18 kg/h respectively and the energy for dewatering was 21 and 35 kWh/t.

It was observed that at 73, 49 and 24 revs/min, there was juice flow through the choke ring and through the drainage gate at the bottom of the feed section. The reason for juice flow through the choke ring might have been that there was some expressible moisture in the press pulp being discharged at the high pressure end. This pressure was not achieved at speeds higher than 73 revs/min. The reason for backflow of juice through the drainage gate located at the bottom of the feed section may be cited as due to a high positive pressure difference at the choke end against the feed section. The same pressure difference exists for the press pulp in the choke section. But it is conveyed forward due to the forward rotation of the flights of the screw. The juice along the surface of the cage bars is pushed back.

Since the solids content in the juice did not show any trend and, the power could not be recorded at 73 and 49 revs/min, the experiment was repeated.

Table 5.6 is the data from the experiment set 5 done as a repetition to experiment set 4. The fraction of weight left in the feed section increased from 16% to 26% of the total weight on decreasing the speed from 147 to 24 revs/min. The pulp yield decreased from 75% to 38% while, the juice yield increased from 1.5% to 25% of the total weight. For fresh alfalfa at about 75% m.c., the press pulp had a moisture content between 73% to 62% at 147 and 24 revs/min respectively. This corresponded to a drop in moisture points ranging from 1.6% to 13%. The solids content in the juice increased from 10.8% to 12.3% of the juice weight when speed was lowered from 147 to 49 revs/min.

Table 5.6 : **Effect of speed of screw press at a constant clearance of 6 mm on dewatering characteristics of fresh alfalfa having an initial moisture content of 75% in experiment 5, replica 2**

Screw speed	Initial	Final				Mass left in press	Energy for dewatering	Throughput
		Pulp		Juice				
	Mass	Mass	Moisture content *	Mass	Solids content **			
(revs/min)	(g)	(g)	(% wb)	(g)	(%)	(g)	(kWh/t)	(kg/h)
147	1000	755	72.4	16	10.8	165	21.6	33
122	1001	714	73.3	38	11.2	199	13.5	36
97	1000	658	71.3	109	11.8	186	21.6	33
73	1000	607	68.9	151	12.1	178	20.6	33
49	1000	536	66.7	186	12.3	231	25.9	27
24	1001	383	61.5	251	11.4	256	33.0	20

* Average of two replicates
** Average of five replicates

However at 24 revs/min, there was a drop in solids content to 11.4% rather than showing an upward trend. This can be explained on the fact that at 24 revs/min, a large amount of juice flowed through the choke ring and the drainage gate at the bottom of the feed section. At higher speeds, there was less flow of juice through the two sections. The loss of solids in the juice was in the range of 0.7% to 11.4% of the total solids. On the basis of the results of these experiments, it was concluded that maximum moisture reduction occurred at 24 revs/min. Since there was not a significant difference between the solids lost in the juice at the speeds studied, it was decided to choose 24 revs/min as the speed for further studies for the given screw press.

Table 5.7 shows the data for experiment set 6 for dewatering of alfalfa chops at 24 revs/min and a choke clearance of 6 mm. It can be seen that after simulating field conditions for feeding chopped alfalfa (discussed in 3.2.7), the amount left in the feed section was only about 7% of the feed input (against 25% in experiment 4). The amount of press pulp discharged was about 50% of the feed input (against 40% in experiment 4). The juice yield was about 41% of the feed input (against 25% in experiment 4). This is also due to a larger sample size of 3 kg in contrast to 1 kg in the previous experiment. For fresh alfalfa chops at 77%, the pressed pulp had an average moisture content of 64%. The average solids content in the juice was about 9.5%. The loss of solids was 17.5% of the total solids in fresh alfalfa. The average energy required for dewatering was 37.7 kWh/t. The average throughput was 15.4 kg/h. This is slightly lower than the rated throughput of 18 kg/h for oilseeds for this press as was specified by the manufacturer. The average thickness of the press pulp measured with vernier calipers was close to 6 mm.

Table 5.8 shows the dewatering of alfalfa chops at a speed of 24 revs/min and a choke clearance of 4 mm. The mass of chops left in the feed

Table 5.7 : **Dewatering characteristics of fresh alfalfa having an initial moisture content of 77% in a screw press at 24 revs/min and 6 mm clearance in experiment 6**

Replica	Initial		Final				Mass left in press	Energy for dewatering	Throughput
			Pulp		Juice				
	Mass	Moisture content *	Mass	Moisture content **	Mass	Solids content ***			
		(g)	(g)	(% wb)	(g)	(%)	(g)	(kWh/t)	(kg/h)
1	2772	76.7	1410	64.1	1150	9.4	212	41.6	15.1
2	2820	76.5	1466	64.6	1173	9.5	181	34.9	15.6
3	2754	76.9	1328	64.5	1234	9.7	192	36.7	15.5
							Average	**37.7**	**15.4**
							Std. deviation	**3.45**	**0.24**

* Average of three replicates
** Average of three replicates
*** Average of five replicates

Table 5.8 : **Dewatering characteristics of fresh alfalfa having an initial moisture content of 76.5% in a screw press at 24 revs/min and 4 mm clearance in experiment 7**

Replica	Initial		Final				Mass left in press	Energy for dewatering	Throughput
			Pulp		Juice				
	Mass	Moisture content *	Mass	Moisture content **	Mass	Solids content ***			
		(g)	(g)	(% wb)	(g)	(%)	(g)	(kWh/t)	(kg/h)
1	2780	76.2	1122	60.0	1418	9.54	240	50.1	15.3
2	2800	75.9	1224	59.0	1306	10.5	270	60.1	13.6
3	2707	77.3	1156	62.5	1378	10.0	173	51.0	11.5
							Average	**53.7**	**13.5**
							Std. deviation	**5.5**	**1.9**

* Average of three replicates
** Average of three replicates
*** Average of five replicates

section was about 8% of the total mass fed into the press. However the amount of pressed pulp discharged decreased to 42% of the feed input in contrast to 50% for 6 mm clearance. This was justified by an increase in the juice yield to 50% of the feed input against 40% as for 6 mm clearance. For fresh alfalfa at 76%, the press pulp showed a further decrease by 3 moisture units to 60% while, a solids content of 10% in the juice did not show an appreciable change over 9.5% for 6 mm. Irrespective of the juice yield, the solids content in juice remained steady. However the loss of solids was higher in this case and was 21.5% of the total solids in fresh alfalfa. The energy required for dewatering increased by 16 units to 53.7 kWh/t. The throughput decreased by about 2 units to 13.5 kg/h.

Limited test trials with a 2 mm choke opening showed relatively higher loss of insoluble solids in the juice. These were mostly from the leafy portions of alfalfa.

Table 5.9 shows the effect of a number of passes on the moisture remaining in the pressed pulp at a speed of 24 revs/min and a choke setting of 6 mm and 4 mm. In order to see whether further moisture could be removed from the press pulp after first the pass through the press, the pulp discharged at 6 mm clearance from replica 1 was pressed for the second time. The press pulp showed no change in the moisture content as it remained at 64%. However a third pass through the press decreased the moisture content in the pulp to 62%. For a 4 mm clearance, the pulp after the first pass had a moisture content of 60%, which was reduced to 58.6% and 55.4% after the second and third passes respectively.

Table 5.9: **Effect of number of passes of alfalfa at 76% on moisture remaining in the pressed pulp through the screw press operating at 24 revs/min**

Choke opening (mm)	No. of passes		
	1	2	3
4	60%	58.70%	55.40%
6	64.10%	64.10%	62%

Note: Moisture determinations are average of 3 replcations

5.1.3 Quality of pressed pulp, juice and pellets

The processed products from fresh alfalfa, namely, pressed pulp, pellets and juice were analyzed for their quality. The quality factors analyzed were color of fresh alfalfa, pressed pulp, and juice. The pellets were analyzed for their durability. These quality attributes are discussed below.

5.1.3.1 Color

Table 5.10 shows the color analyses for fresh alfalfa, pressed pulp and juice for a screw speed of 24 revs/min and a choke opening of 4 mm and 6 mm. Fresh alfalfa used for 24 revs/min and 4 mm choke tests had a color index of -6 and a yellowness index of 56.7. Color index is represents the chroma and brightness of the sample, and is defined in section 6.4.3. After dewatering the pressed pulp had a color index of -7.8, showing an improvement in color. The color index change calculated was 54.1. There was an increase in the 'a' value from -2 to -2.4. Although the 'b' value increased from 6.8 to 8.1, the yellowness index decreased from 56.7 to 53.1. Juice had a color index of 1.2 and the color index change calculated was 36.5. The 'a' value decreased from -2 to 0.4. There was a decline in the 'b' value from 6.8 to 5.9 although the yellowness index increased from 56.7 to 76.5. These results show that after mechanical dewatering, the pulp has a deeper green color than fresh alfalfa. The increase in greenness may be attributed to the release of chlorophyll through the cell sap. The juice had a shift in the 'a' value towards the red side of the spectrum. This shows the presence of some red coloring pigments. These could be the carotenoids.

Table 5.10 Color measurement for fresh alfalfa, pulp and juice

24 revs/min; 4 mm

Sample	L	a	b	Color Index	Color Index Change	Percentage Greenness	Yellownwess Index
Fresh alfalfa	20.6	-2	6.8	-6	0	100	56.7
	0.46	***0.36***	***0.63***	***0.75***			
Pulp	26.5	-2.4	8.1	-7.8	54.1	119	53.1
	1.19	***0.11***	***0.15***	***0.3***			
Juice	15	0.4	5.9	1.2	36.5	-122	76.5
	1.14	***0.42***	***0.69***	***1.13***			

24 revs/min; 6 mm

Sample	L	a	b	Color Index	Color Index Change	Percentage Greenness	Yellownwess Index
Fresh alfalfa	20.2	-2.1	7	-6.2	0	100	58.4
	0.71	***0.04***	***0.37***	***0.22***			
Pulp	25.6	-2.5	8.4	-7.7	63.4	120.3	56.3
	0.13	***0.07***	***0.07***	***0.32***			
Juice	15.7	-0.1	6.3	-0.3	30.4	6.1	74.4
	1.34	***0.86***	***0.88***	***2.21***			

Figures in bold italics are standard deviations

For the case of 24 revs/min and 6 mm clearance, similar results were obtained except for the juice. There was a drop in 'a' value from -2.1 for fresh alfalfa to -0.1 for the juice.

5.1.3.2 Durability of pellets

Table 5.11 shows the results for the comparison on the durability of pellets made from two different raw materials. In the first case, pellets were made from first cut alfalfa chops that were dried naturally. In the second case, pellets were made from second cut alfalfa chops that were dewatered and then dried naturally. These limited number of tests showed a drop in durability from about 83% to 79% for the first and second cases respectively. Since the raw materials in the two cases were from two different cuts, a firm conclusion cannot be drawn for the difference in durabilities.

5.2 Computer Simulation Results

The simulation results for mechanical dewatering of chopped alfalfa in a single screw press are summarized in Tables 5.12-5.15. The machine parameters are the screw speed and choke opening. The material parameter is the initial moisture content of alfalfa.

Table 5.12 shows the effect of screw speed for a choke opening of 6 mm when alfalfa having an initial moisture content of 75% is dewatered. At this choke setting, compression occurs in two sections. The first compression occurs in the pressure section for a length of 128 mm while the second compression occurs in the choke section for a length of 35 mm. During compression in the pressure section, there is an increase in volumetric compression ratio. After

Table 5.11 Comparison of durability of pellets made from chops after natural drying and from press pulp

Dried chops

Replica No.	Durability (%)	Average durability (%)	Std. Dev.	C.V.
1	83.1			
2	83.0	83.1	0.33	0.004
3	83.9			

Press pulp

Replica No.	Durability (%)	Average durability (%)	Std. Dev.	C.V.
1	80.2			
2	80.5	79.4	1.58	0.02
3	77.6			

Table 5.12: Simulation results for dewatering of alfalfa at 75% m.c. pressed at different screw speeds and a choke opening of 6 mm

Speed (revs/min)	Residence time (s)	Pressure (MPa)	Moisture reduction in pulp (% units)	Power (kW)	Throughput (kg/h)
24	18	48.8	14.2	12.8	9.4
49	10	30	9.3	18.4	31.8
73	8	2.5	6.1	3.3	55.7
97	6	1.6	4.2	6.7	92.3
122	6	1.6	4	0.8	115.7
147	4	1.1	3.1	15.0	138.5

choosing the constants from Table 4.1, the calculated value of E_v is 7.9 MPa.

When the screw speed is 24 revs/min, the pressure increases to 48.8 MPa. The sample resides in this section for 14 s and the moisture is reduced by 11% points. When the sample enters the choke section, a relative expansion occurs due to a relative increase in the radial clearance after the pressure section. Thus there is a drop in volumetric compression ratio and the sample undergoes stress relaxation. After choosing the constants from Table 4.1, the calculated value of E_v is 16.1 MPa. The pressure in this section drops by 0.3 MPa. But it can be seen that although there is a drop in pressure, there is still a moisture reduction by 3.2% points. This is because even at a lower pressure, the sample resides for another 4 s, thereby causing further moisture reduction. Thus there is a total moisture reduction of 14% points in a time of 18 s. The pressure required for dewatering is 48.8 MPa. The power required is 12.8 kW. The throughput of the screw press is 9.4 kg/h. Since the screw does not protrude in the choke ring, entire compression occurs in the barrel only. Juice along with the solids flow through the cage bar holes.

Table 5.13 shows the effect of changing the initial moisture content of alfalfa to 85% on the output variables for the same choke setting of 6 mm. Pressure as well as power could not be predicted accurately.

Table 5.14 summarizes the simulation results when the choke opening is changed to 4 mm. The initial moisture content of alfalfa is 75%. At a screw speed of 24 revs/min, the moisture content is reduced by 17.4% points in the press pulp. The compression process now occurs in three sections. The first compression in the pressure section occurs for a length of 143 mm. The residence time for this section is 14 s. There is an increase in volumetric compression ratio. The calculated value of E_v is 7.9 MPa. The pressure increases to 32 MPa. The moisture is reduced by 10.6% points. The second

Table 5.13: Simulation results for dewatering of alfalfa at 85% m.c. pressed at different screw speeds and a choke opening of 6 mm

Speed (revs/min)	Residence time (s)	Pressure (MPa)	Moisture reduction in pulp (% units)	Power (kW)	Throughput (kg/h)
24	18	10	17.2	1.3	12.3
49	10	27	12.1	18.9	30.9
73	8	2	7.8	3.3	60.5
97	6	1	5.9	3.2	91.1
122	6	0.5	4.7	0.4	122.5
147	4	1.1	4.4	11.0	141.2

Table 5.14: Simulation results for dewatering of alfalfa at 75% m.c. pressed at different screw speeds and a choke opening of 4 mm

Speed (revs/min)	Residence time (s)	Pressure (MPa)	Moisture reduction in pulp (% units)	Power (kW)	Throughput (kg/h)
24	20	45	17.4	5.4	9.9
49	12	43	12.2	15.2	27.4
73	10	38.4	11.1	11	46.3
97	8	38.2	9.8	64	72.6
122	8	29	9.7	53.6	75
147	6	23	6.5	97.4	125.1

compression occurs in the choke section of the screw. Due to a relative decrease in radial clearance, there is a relative expansion of the material. The calculated value of E_V is 16.1 MPa. The pressure in this section drops by 1.2 MPa. The sample resides for 2 s in this section. However there is still a moisture reduction of 1.6% points. The above compression which occurs in the barrel allows the juice to flow through the cage bar holes. The third volumetric compression occurs in the choke ring where the clearance is 4 mm. There is an increase in volumetric compression ratio. The calculated value of E_V is 7.9 MPa. The pressure increases by 14 MPa in this section. It is assumed that the residence time for this section is 4 s. Thus juice is expressed and the moisture is reduced by 5.3% points in the choke ring. Hence there is a total reduction of 17.4% points in a residence time of 20 s. The pressure required is 45 MPa and the power required is 13.1 kW. The throughput of the screw press is 9.9 kg/h. It seems that the pressure predictions were good while the power predictions were not as good since the correlation between speed and power was a high positive value.

Table 5.15 shows the results when the initial moisture content is increased to 85%. The pressure was not predicted accurately as a positive correlation of 0.71 was obtained. It can be seen that at 147 revs/min, the predictions for pressure, power and throughput were 190 MPa, 1637.7 kW, 214.3 kg/h, which appear to be rather high.

5.3 Comparison of Experimental Results with Simulation Results

Tables 5.1-5.8 described the experimental results on mechanical dewatering of chopped alfalfa. The simulation results are summarized in Tables 5.13-5.15.

Table 5.15: Simulation results for dewatering of alfalfa at 85% m.c. pressed at different screw speeds and a choke opening of 4 mm

Speed (revs/min)	Residence time (s)	Pressure (MPa)	Moisture reduction in pulp (% units)	Power (kW)	Throughput (kg/h)
24	20	14	21.5	2.2	11.3
49	12	18	15.2	8.8	32.6
73	10	12	13.5	10.4	50.2
97	8	38	12.5	83.2	95.9
122	8	24	12.4	64.6	123.3
147	6	190	8.8	1569.6	214.3

It is clear from the tables that the drop in moisture points in the pressed pulp was predicted with good accuracy for all screw speeds and choke openings. However the throughput of the screw press was predicted with some accuracy only at lower speeds. At higher speeds, deviations of the simulated values over the experimental values were as high as 330%. It was noted, though from limited tests, that at higher speeds the variation between the replicates for recording throughput was itself large. However there was not much variation at different choke openings. Hence more data will be required for simulating the throughput at different speeds.

5.4 Response of the System to the Changes as Explained by Computer Simulation

5.4.1 Effect of initial moisture content

On increasing the initial moisture content, the model predicts an increase in the number of moisture units removed in the pressed pulp during the initial stages of pressing. This is due to a considerable increase in the surface moisture and loosely bound moisture near the surface. In order to remove this moisture from low moisture alfalfa chops, higher pressure is required. This shows that forces holding moisture near the surface are stronger and have higher affinity for it at low moisture contents. These forces could be the adhesive forces between the water molecules on the surface and the surface of alfalfa and, the forces just below the surface.

For alfalfa chops having initial moistures from 80% to 90%, application of 4 MPa pressure could remove only 50% of the total moisture expressible in the given length of pressure section. Whereas for alfalfa chops having initial moistures from 70% to 80%, pressure moisture was only 25-30% of the total moisture that could be expressed in the pressure section. This moisture was the surface, loosely bound and part of the bound moisture that became free from within the cell walls due to maceration. Maceration is due to shear forces acting on the material between the moving screw and the stationary barrel surface. The direction of shear forces is parallel and perpendicular to the material surface. At the same time, the material is being pressed due to compressive forces acting normal to the material surface. As a result of these two forces, juice along with the solids flows through the ruptured fibrous matrix. Application of pressure alone now may remove this free moisture.

As the material proceeds through the screw, pressure keeps on increasing and the equilibrium moisture content keeps on decreasing. However after a certain time and during a certain length of pressure section, the equilibrium moisture content does not decrease significantly and approaches an asymptote even though considerable pressure is exerted on the material. Hence after this stage, pressure ceases to be the significant variable causing juice expression. The moisture that could be expressed in the initial stages by using pressure alone was called 'pressure moisture'. Further removal of moisture was low and even higher pressures could not remove moisture any more. The equilibrium moisture value after which pressure alone does not favor juice expression was called 'steady equilibrium moisture content' in the present work.

An important inference that may be drawn at this point is that any factor that will prolong the onset of steady equilibrium moisture content will favor juice expression. This can be done by three ways.

(i) increasing the pressure in the initial stages gradually

(ii) having a system in the pressure section that will continuously macerate the material

(iii) increasing the residence time for the material in the pressure section after all the pressure moisture is removed

The residence time can be increased by placing baffles along the surface of cage bars and by increasing the length of pressure section. Thus the pressure required to remove the same number of moisture units will decrease.

Experiments with the cylinder-piston assembly also showed that pressures up to only 2-4 MPa were required to remove 40% of the total plant moisture from alfalfa at 75% initial moisture content macerated through grooved rollers. For higher degree of maceration, the amount of this moisture did not increase. This moisture could thus be the pressure moisture. This pressure is about 4 MPa. The equilibrium moisture content corresponding to this pressure from the data of Koegel (1972) is 40%. Though as stated earlier, the degree of maceration will affect the steady equilibrium moisture content, its value may be taken to be in proximity to 40%. Thus in order to remove further moisture, the residence time will have to be increased along with a higher degree of maceration in the pressure section. The associated loss of dry matter in the juice at this pressure level was 10-12% of the juice weight and 15-18% of the total dry matter in fresh alfalfa (experiments 3.1.1-3.1.3).

5.4.2 Effect of screw speed

The model predicts an increase in the moisture units removed in the pressed pulp when the screw speed is reduced. This was verified from the experimental results. At lower screw speeds, a higher pressure is achieved in the barrel and the material is pressed for a longer residence time. These two factors favor higher moisture reduction. However at low speeds, throughput is reduced. The power predictions did not show any trend.

5.4.3 Effect of choke opening

The model predicts that higher moisture can be expressed on reducing the choke opening. This was also verified from the experimental results. This can be attributed to a higher pressure and a longer residence time attained by reducing the choke opening.

The screw press performed well for expressing juice from alfalfa. Since the screw press used was designed for extracting oil from granular oilseeds, it was felt that the press could be better designed for expressing juice from fibrous alfalfa. The modifications following in section 5.5 are recommended and their effect on press performance is predicted using the simulation model.

5.5 Modifications to the Screw Press for Better Performance

5.5.1 Feeding Mechanism

Since alfalfa chops are fibrous materials and are not free flowing like grains, it was difficult to convey them from the feed section and the feed hopper was found to be frequently blocked. A wooden stick was used to implement forced feeding in the hopper. However in order to simulate field conditions where the hopper is continuously fed with the chops, a motor driven vertical auger in the feed section may prevent the blockage of chops.

Blockage of chops in the feed hopper may be prevented by having a vertical screw auger in the feed hopper to force feed the material. Equation 4.7

in the simulation incorporates a dimensionless constant, B_O. A higher moisture reduction in the pressed pulp is predicted when B_O is increased.

It was also felt that a change in the shape of feed hopper could improve the press performance.

Zhong et al. (1989) discussed the effect of the shape of the feed opening on the performance of a horizontal screw conveyor. They reported that for a screw operating at 40 revs/min, increasing the casing angle from 0 to 28.5^o increased the throughput by 30% and decreased the specific energy requirement by 1%. The casing angle is defined as the angle between the normal to the casing and the feed hopper incline. Further increase in casing angle from 28.5^o to 35.5^o increased the throughput by another 20% and decreased the specific energy requirement by another 10%. At a screw speed of 60 revs/min, increasing the casing angle from 0 to 28.5^o increased the throughput by 30% and decreased the specific energy requirement by 12%. However when the casing angle was increased further from 28.5^o to 35.5^o, the throughput increased by 9% and the specific energy requirement increased by 3%. They also reported that an increase in the casing angle beyond 45^o decreased the throughput and increased the specific energy.

The casing angle for the given screw press was 30^o. In the range of screw speeds ideal for dewatering of alfalfa chops, it seems that increasing the casing angle will improve the press performance. This is because an increase in casing angle allows the inlet of the casing to form an acute angle with the flight, thereby reducing sliding of the chops along the casing edge and allowing a cutting action between the edge of the flight and the edge of the casing, Zhong et al. (1989). Thus blockage of the chops in the feed hopper may be prevented.

Hence increasing the casing angle and having a forced feeding system should improve the press performance.

5.5.2 Juice collection

When the choke opening is set such that no compression occurs in the choke ring, then juice is collected through the cage bar openings and the drainage gate below the feed hopper. However when the choke opening is set such that compression occurs in the choke ring as well, then juice is collected through the discharge end also. The present set-up had the juice spout under the cage bar openings. In order to collect the juice from beneath the drainage gate, another juice spout was provided. To collect the juice from the discharge end, another collection system will have to be provided. It was seen that the juice collected through the drainage gate and the discharge end had a lot of insoluble solids, mostly the leaf portions. To get a clear filtrate, screens can be provided under the drainage gate and at the discharge end. However the juice collected through the drainage gate and the discharge end is only a small fraction of the juice collected through the cage bar openings.

5.5.3 Use of trapezoidal teeth-baffles in the pressure section

The teeth in the pressure section of the screw can be mounted on the inside surface of cage bars. The purpose of teeth is threefold:

trapezoidal cross section - pressure application

teeth - maceration

baffle - increase in residence time

The trapezoidal section of teeth should have a decreasing taper along the screw axis. A higher volumetric compression ratio will be achieved resulting in an increase in pressure.

Sharp teeth will rupture the cells causing release of bound moisture and the associated solids through the fibrous matrix.

The teeth will act as a baffle to the flow of pressed pulp, thereby increasing the residence time of the pressed pulp in the pressure section.

5.5.4 Reduced pitch and/or a double screw in the pressure section

As discussed before, a longer residence time and a higher pressure are needed to remove the bound moisture from the compressed pulp. Kim (1994) reported from the results of Gu et al. (1982) that the relative order of importance of the variables affecting juice expression from thick mats of macerated alfalfa is - (i) pressing time (ii) degree of maceration (iii) pressure levels and (iv) thickness of pulp. Latter stages of dewatering in a screw press will require holding the well macerated pressed pulp for a longer time at a gradually increasing pressure. This can be achieved by reducing the pitch of the screw and/or having a double screw near the choke section. This was verified from equation 5.11. Increasing the values of B_1 increased the volumetric compression ratios and the corresponding pressures significantly. But it was interesting to note that very high compression ratios in the initial stages had an adverse effect on the dewatering process. In the initial stages, although the pressure increased, the amount of moisture removed in this stage was the same as without the reduced pitch and double screw. Moreover no more moisture could be released in further stages. This may be because of increased resistance to juice flow through the compressed mat. This shows that in the initial stages a low pressure should be applied and the increase in pressure in further stages should be gradual.

5.5.5 Cage bars with cut grooves and rounded off along the edges

It was observed that at screw speeds of 24 and 49 revs/min and a choke opening of 2 mm, the juice through the cage bar openings had some insoluble solids in it. This was because the cage bars that were arranged along the inside circumference of the barrel had a rectangular cross section which allowed some of the insoluble solids pass through the edges. The insoluble solids which were mostly the leafy portion, were torn apart from the pressed pulp and forced through the cage bar openings. Thus cage bars should be rounded off at the edges to have a minimum spacing between them when they are arranged along a circular cross section of the barrel.

The inside surface of the cage bars can be cut with grooves to provide for an enhanced shearing effect. Thus the degree of maceration will increase and higher juice yields can be anticipated.

5.6 Summary

From the above results and discussion, it is clear that maceration, pressure and residence time are the important factors favoring moisture reduction in the pressed pulp. This was also stated by Koegel et al. (1972), Holdren (1972) and Gu et al. (1982). For a given screw press geometry, it may be predicted that pressed pulp with a good feed value can be obtained for alfalfa chops low in moisture content (70-80%, w.b.) while both a good quality pressed pulp and a good quality juice may be obtained for alfalfa chops high in moisture content (80-90%, w.b.). This is because of filtering action of the compressed fibrous pulp needs a higher pressure to remove moisture from low moisture alfalfa. The computer model can be used to predict the performance of the screw press when the feed section and the pressure section are modified. The effect of pre-treatments on alfalfa can also be simulated. Based on the simulation model, an industrial scale press can be designed to meet the objectives of dewatering.

Chapter 6

DISCUSSION

Results from experiments done with the hydraulic press and the screw press and, those from computer simulation were described in chapter 5. The factors responsible for the predicted and the observed response of the system to the changes causing the response are discussed in this chapter.

6.1 Cylinder-piston Assembly

Results showed that increasing the degree of maceration increased the juice yield, the loss of solids in the juice and the number of moisture units removed in the pressed pulp. Figures 6.1-6.4 illustrate this fact.

It is seen that increasing the number of passes from one to two through a pair of grooved roller macerators resulted in higher loss of solids per unit weight of solids in fresh alfalfa. This was because of a higher degree of cell rupture which facilitated more solids to be expressed with the juice. However the loss of solids per unit weight of juice expressed is less when the degree of cell rupture is higher. This is because the proportion of water in the expressed juice is considerably higher than the associated solids. Since more amount of moisture was expressed at a higher degree of cell rupture, the number of moisture units removed in the pressed pulp was also more. For one pass through the rollers, the data for solids in the juice per unit weight of juice are scattered at different pressures. This shows that the degree of maceration was not complete. Whereas for two passes, the data follow a trend which shows

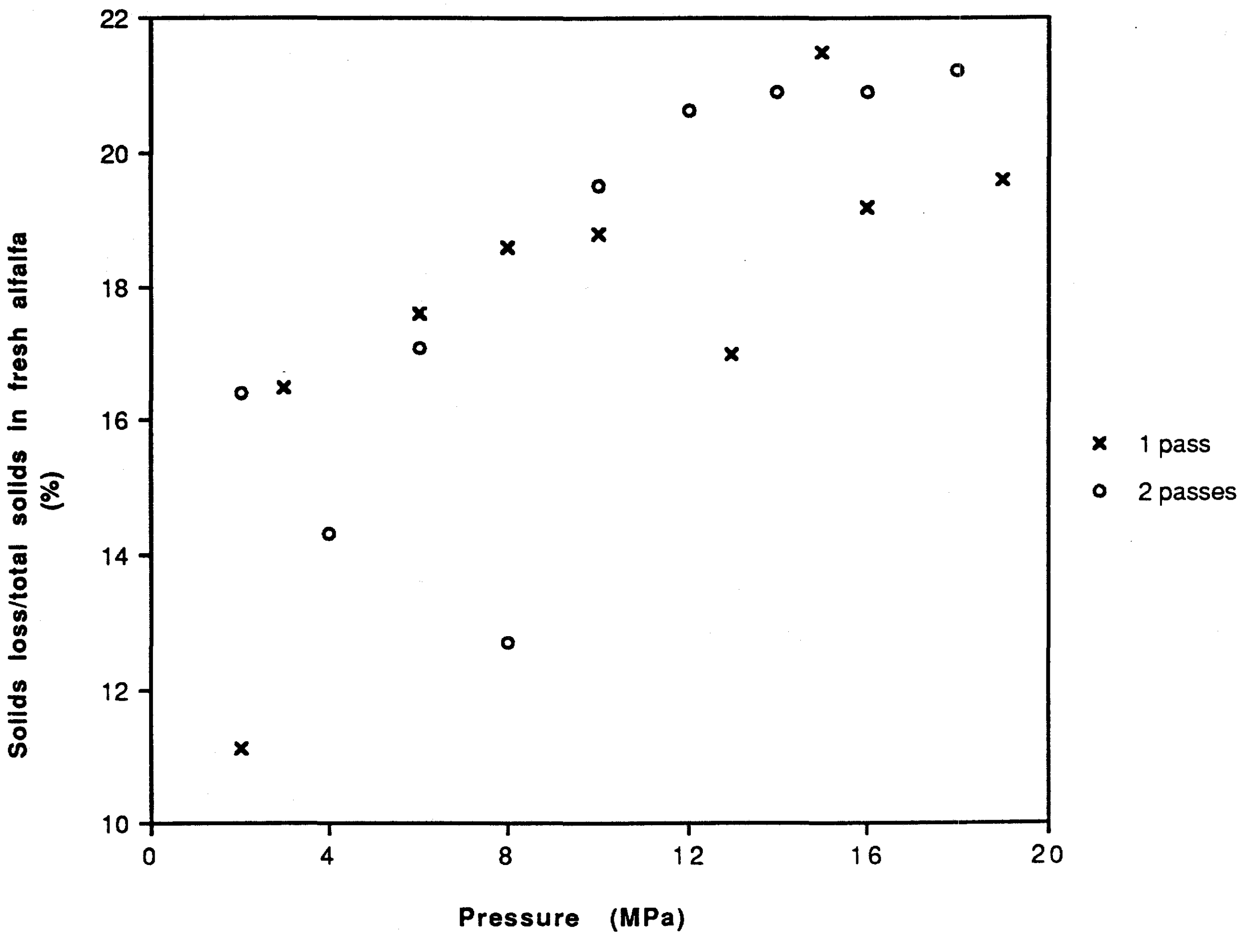


Figure 6.1: Effect of degree of maceration on solids loss in juice per unit solids in fresh alfalfa at different pressures

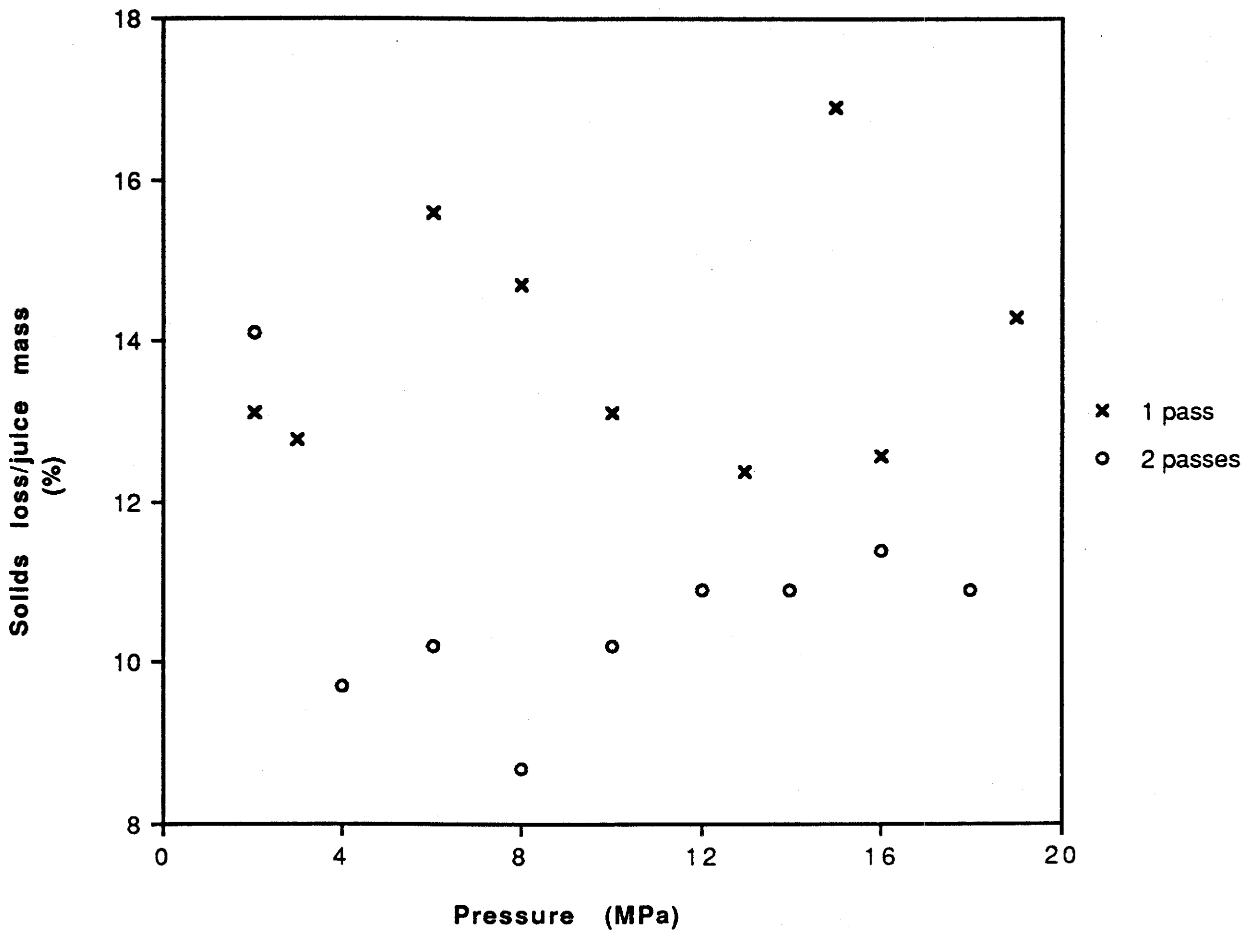


Figure 6.2: Effect of degree of maceration on solids loss in juice per unit mass of juice at different pressures

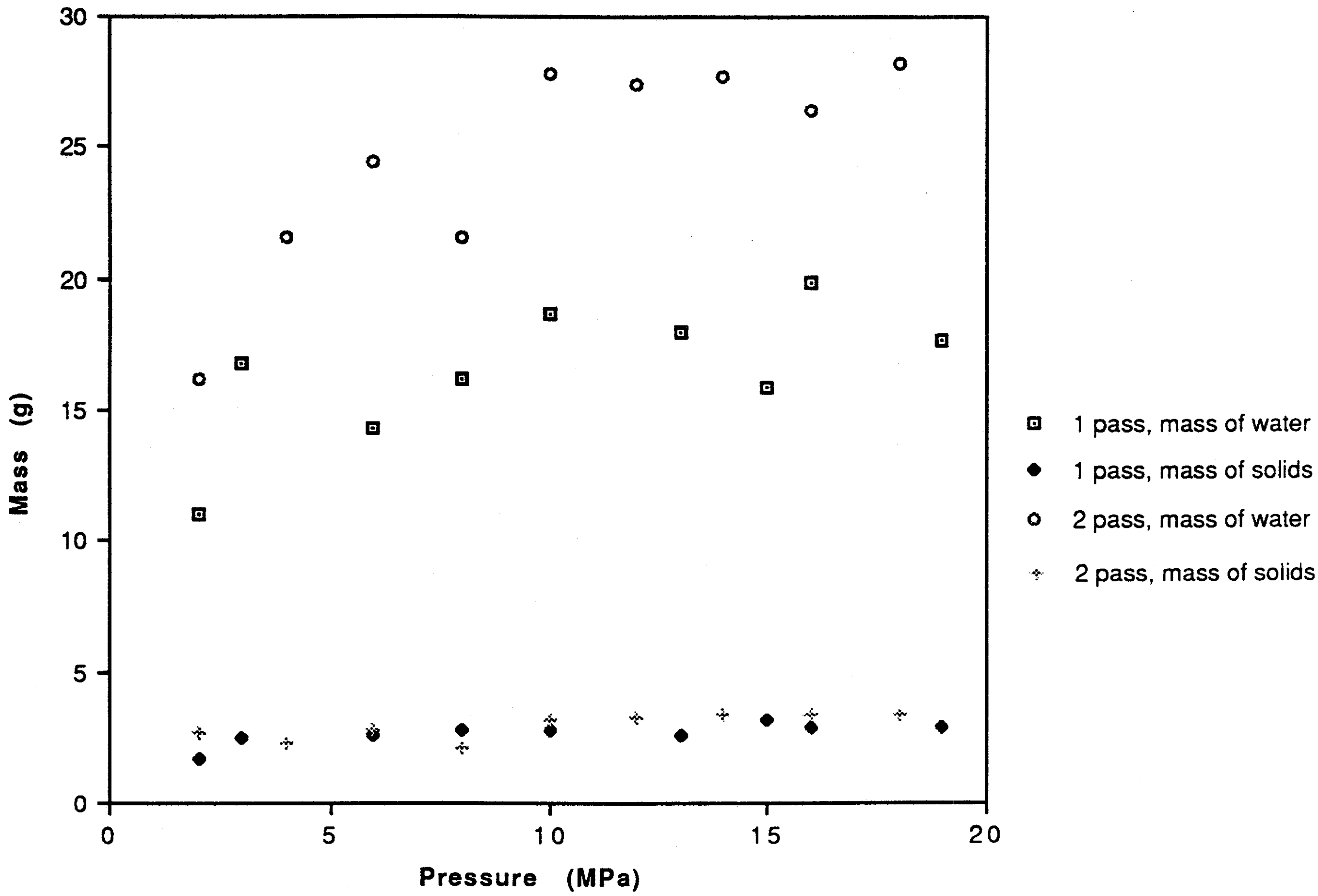


Figure 6.3: Water and solids expressed in juice as effected by pressure and degree of maceration

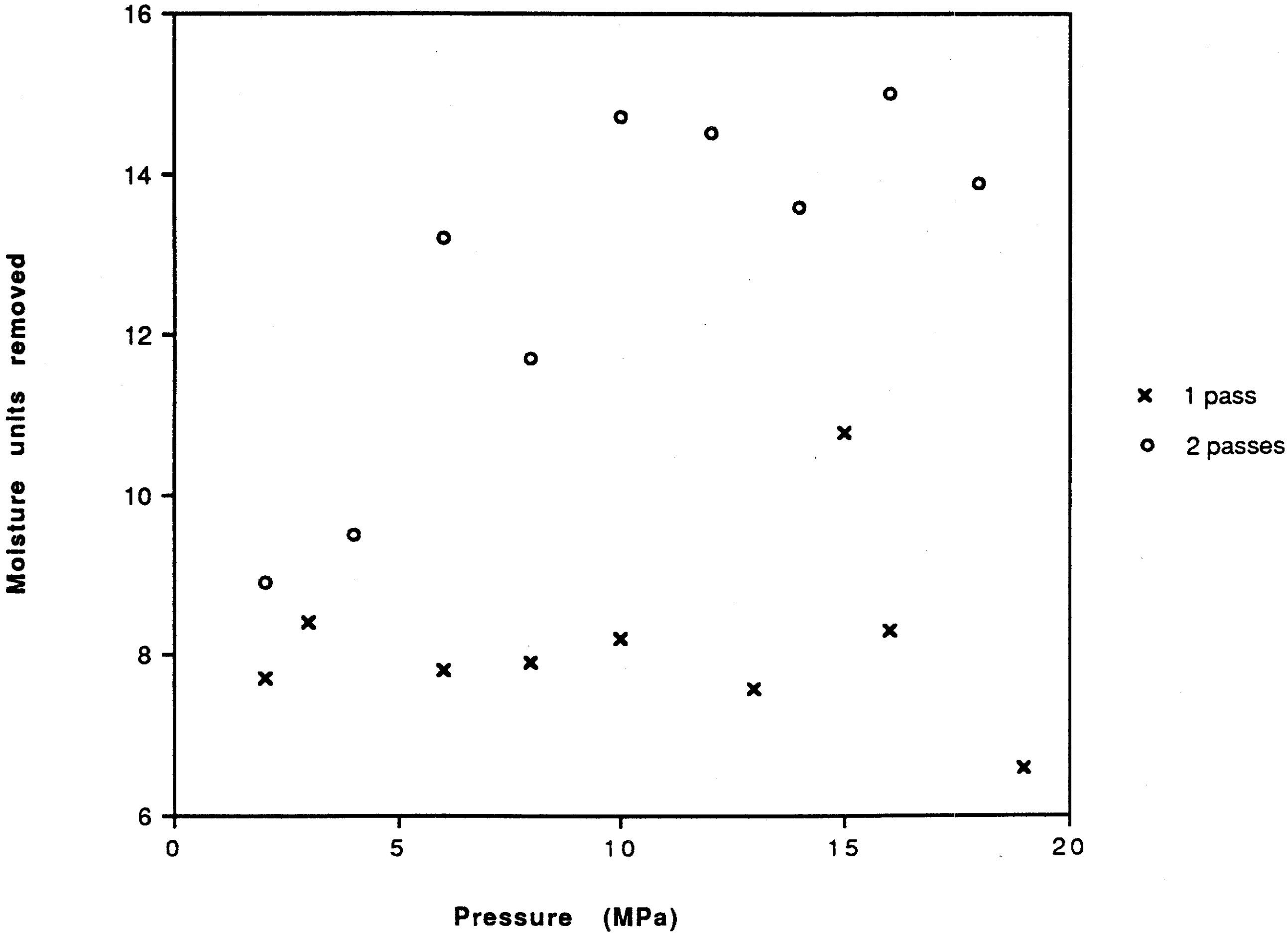


Figure 6.4: Effect of degree of maceration on moisture units removed in pressed pulp

that maceration was better in this case. However even this degree of maceration was not complete as is evident from Figure 6.2.

From the results described in section 5.1, it is clear that a pressure of 2-4 MPa is sufficient to remove the initial moisture from macerated alfalfa. The moisture so removed seems to be the surface moisture, loosely bound moisture and bound moisture that is released from within the cell walls after maceration. At this pressure level, the pressed pulp is high in protein and vitamin A. The juice expressed has also a high content of protein and vitamin A. During later stages of compression, the juice yield is very low. Although there is not much change in the quality of pressed pulp, the vitamin A content in the juice drops significantly at higher stages.

Further removal of moisture can be achieved by better maceration or by holding the sample for a longer time at a gradually increasing pressure. Although a higher degree of cell rupture will facilitate moisture removal and increase in juice yield, it will also result in higher loss of solids in the juice.

6.2 Screw Press

The screw press used was designed for oil extraction from oilseeds. Since the press was used for mechanical dewatering of alfalfa, which unlike oilseeds is not free flowing, modifications were done in the feeding method to simulate field conditions. These modifications were discussed in chapter 3. The feeding method recommended was the one that was considered to be closest to a continuous field operation.

The disadvantage of the first method described in section 3.2.7 is that the use of a stick compacts the alfalfa chops in the hopper at some points and loosens the chops at other points. This causes a variation in the bulk density of the sample fed. So the bulk density will be different at different revs/min and even at same revs/min for different replications due to non-uniform compaction.

The second feeding method of gradual feeding the sample into the feed hopper may be considered close to the field operation. The chops fed would be conveyed forward to the barrel and next lot of chops would then be fed into the hopper. The throughput of the screw press will influence the feed rate of the system used to discharge the chops into the press. In order to achieve a higher throughput of the screw press in the field, forced feeding into the screw press would be recommended. Thus the feed hopper could be provided with a vertical screw auger driven by a motor to facilitate forced feeding.

For the measurements of power in section 3.2.5, peak power was recorded from the watt meter. However it was noticed that the values for power fluctuated with time. Initially it was thought that these fluctuations were because of the fluctuations from the ac supply mains. In fact, these fluctuations were due to the changes in the feed rate in the feed section. Hence it is recommended that the instantaneous values for power with time should be recorded for accuracy.

Although the single screw press was able to remove considerable initial moisture, the pressed pulp, after the first pass, looked soggy. This shows that additional moisture could still be expressed from the pressed pulp. The incomplete moisture removal could probably have been due to two reasons:

(i) The residence time was not sufficient enough to favor juice expression,

(ii) The degree of maceration was not complete.

After the second pass through the screw press, the reduction in moisture in the pressed pulp was still not significant. However a third pass through the screw press reduced the moisture to some extent. In order to achieve a higher degree of cell rupture and hence more juice expression, it may be suggested that the samples be macerated separately before feeding into the screw press or the screw be designed as a better macerator with a longer screw. However Holdren et al. (1972) and Edwards et al. (1978) suggested that maceration should not be carried out separately before juice expression to avoid loss of nutrients in the juice. Hence the screw should be modified in light of the objectives of dewatering.

6.3 Computer Simulation

In order to correctly simulate the moisture expressed with the experimental values, certain constants were introduced while calculating the volumetric rates in the feed section, pressure section and the choke ring. These constants were listed in Table 4.2. The theoretical values in equations 4.7, 4.9 and 4.14 were multiplied by these constants. Also the constant 4.37 appearing in equation 6.20 was changed to a constant 3.5 for the 4 mm choke opening.

The constants for the model were different from the ones proposed by Koegel et al. (1972). This is because of the following differences in the two experimental methods:

(i) The model proposed by Koegel et al. (1972) was applicable to a hydraulic press which is a batch type process. Thus such a model may not be applicable to a continuous type screw press where the material is fed continuously, undergoes progressive compression and stress relaxation cycles in the pressure section, creep in the choke section, and compression in the choke ring. At the same time, juice is extracted and press pulp is discharged.

(ii) The forces acting on the sample under compression in a hydraulic press are assumed to be uni-axial while the forces acting on the sample in a screw press are assumed to be dilitational and deviatoric in nature.

(iii) Alfalfa used by Koegel et al. (1972) was macerated before dewatering while in this case chopped and unmacerated alfalfa was used.

(iv) Koegel et al. (1972) had thawed macerated alfalfa before dewatering. In this case, thawing of chopped alfalfa rather than macerated alfalfa was done prior to dewatering.

Due to a difference in the type of equipment and a difference in the material properties, the ease of release of moisture will be different at different combinations of pressure, time and thickness factor. This probably changes the values of the parameters.

From the simulation results it appears that the moisture content in the pressed pulp and the throughput were predicted with accuracy while the pressure and the power could not be predicted with accuracy at all speeds.

There are two broad objectives of mechanical dewatering of alfalfa in a screw press. The first objective is simultaneous utilization of pressed pulp and juice. Since juice has been found as a source of value-added products, the second objective is utilization of juice only. From these experiments and from the computer simulation, it is clear that the design criteria for a screw fulfilling these objectives will be based on the filtration characteristics of the fibrous pressed pulp. Keeping this in mind, the single screw should be modified.

6.4 Color

6.4.1 Yellowness Index (YI)

Yellowness in alfalfa and processed alfalfa products may be related to beta-carotene and product degradation due to biochemical oxidation reactions occuring because of light and the presence of oxygen. In the case of dehy pellets, a high yellowness index may be correlated with a high beta-carotene content. In the case of suncured pellets, this may represent product degradation.

Yellowness index per ASTM D 1925-70* is given as (according to sales literature of HunterLab Associates Inc.),

$$YI = (100(1.274641506\ X - 1.057434092\ Z))/\ Y \qquad (6.1)$$

The equivalent values of Hunter L,a,b for CIE X,Y,Z values are given by,

$$L = 100\ (Y/Y_n)^{0.5} \qquad (6.2)$$

$$a = K_a\ (X/X_n - Y/Y_n)/(Y/Y_n)^{0.5} \qquad (6.3)$$

$$b = K_b\ (Y/Y_n - Z/Z_n)/(Y/Y_n)^{0.5} \qquad (6.4)$$

For D65 illuminant and 10^o standard observer,

$X_n = 94.825$

$Y_n = 100$

$Z_n = 107.380$

$K_a = 172.10$

$K_b = 66.70$

Substituting these values, we get X,Y,Z in terms of L,a,b as

$$X = 94.825\ (aL/17210 + L^2/10000) \qquad (6.5)$$

$$Y = L^2/100 \quad (6.6)$$

$$Z = 107.38 \ (L^2/10000 - bL/6670) \quad (6.7)$$

Thus yellowness index,YI, can be calculated by measuring the L,a,b values, calculating the X,Y,Z values, and using equation 6.1.

6.4.2 Greenness

One of the most important physical parameters in determination of quality of processed alfalfa products is greenness. Greenness in alfalfa and its processed products represents the chlorophyll content and its quality in terms of retention of freshness. The higher the greenness, the lesser the degradation of chlorophyll. Greenness can be quantified in terms of percentage greenness or the color index.

6.4.3 Color Index

The color index (I) takes into account the brightness and the chroma of the samples used for color analysis. Numerically the color index is given as (according to sales literature of HunterLab Associates Inc.),

$$I = aL/b \quad (6.8)$$

6.4.4 Color Index Change

The change in color index from one stage of processing to another stage is defined by ΔI, (Patil et al., 1994).

$$\Delta I=\left[\left(\frac{\partial I}{\partial a}\Delta a\right)^2+\left(\frac{\partial I}{\partial b}\Delta b\right)^2+\left(\frac{\partial I}{\partial L}\Delta L\right)^2\right]^{0.5} \tag{6.9}$$

where 'a' represents greenness, 'Δa' change in greenness, 'b' yellowness, 'Δb' change in yellowness, 'L' brightness and 'ΔL' change in brightness.

6.5 Energy Consumed for Pelleting Process by Using Three Different Methods of Dehydration

For the pelleting process, alfalfa is dehydrated to about 8% m.c. There are three alternatives for pelleting. One is total thermal drying from initial 75% (say) to 8%. The second alternative is a combination of field drying from 75% to 60%, followed by thermal drying to 8%. The third alternative is a combination of mechanical dewatering from 75% to 60%, followed by thermal drying to 8%. In order to compare the energies required for alfalfa to be pelleted for the above alternatives, experimental values from dewatering data were used. To calculate the thermal energy required for drying, values from Table A.1 were used.

(i) **Total thermal drying of alfalfa from 75% to 8%**

Heat energy required = 2805 kWh/t d.m.

(ii) **Field drying from 75% to 60% followed by thermal drying from 60% to 8%**

Heat energy required = 1377 kWh/t d.m.

(ii) **Mechanical dewatering from 75% to 60% followed by thermal drying from 60% to 8%**

Mechanical energy required = 200 kWh/t d.m.

Heat energy required = 1377 kWh/t d.m.

Total energy required = 1577 kWh/t d.m.

Field drying of alfalfa before thermal drying will save energy by 50% over total thermal dehydration and 13% over combination of mechanical dewatering and thermal drying. Mechanical dewatering preceding thermal drying will save energy by 45% over total thermal dehydration.

Thus field drying of alfalfa is the cheapest alternative. However considering the commercial benefits of mechanical dewatering and also, it being a weather independent system with no field losses as in field drying, dewatering looks to be the most promising technology.

Chapter 7

CONCLUSIONS

1. Macerated alfalfa chops were mechanically dewatered into pressed pulp at a low pressure of 2-4 MPa. An increase in the number of maceration passes from one to two through a pair of grooved rollers increased the juice yield. This was accompanied by an increase in the amount of moisture removed and an increase in the loss of dry matter in the juice. The loss of dry matter in the juice ranged from 7% to 18% of the total dry matter. A further increase in pressure above 4 MPa, did not increase the juice yield appreciably.

In order to monitor the quality of pressed pulp and juice that would be obtained in a continuous dewatering screw press, the process was simulated on a batch-type hydraulic press. Results showed that both the quantity and quality of pressed pulp and juice were at their peak in the initial stage of dewatering where the pressure achieved was 2-4 MPa. Further advancement of the material to higher pressure stages did not increase the juice yield appreciably. The quality of pressed pulp remained steady. However the vitamin A content in juice declined sharply at higher pressures.

Hence it can be concluded that to remove the moisture any further, the residence time should be increased along with a higher degree of maceration.

2. The extent of dewatering of alfalfa chops in a single screw press was maximum at low screw speeds and at reduced choke openings. The recommended screw speed ideal for dewatering alfalfa was found to be 24-49 revs/min. However the throughput of the press is low. Reducing the choke

opening increased the moisture removed, loss of dry matter in juice and the specific energy requirement but decreased the throughput of the press. At a screw speed of 24 revs/min, the loss of dry matter in the juice was 17-20% of the total dry matter. The specific energy required for dewatering was 35-55 kWh/t of fresh alfalfa.

The single screw which had a constant pitch and an increasing diameter did not macerate well as moisture could still be expressed from the pressed pulp fed back into the press. Thus to remove further moisture from the pressed pulp, the screw could be designed as a better macerator and with a longer pressure section to allow a prolonged steady equilibrium moisture range.

3. Koegel's relationship for the dewatering process in a batch-type hydraulic press was used to develop a quasi-mechanistic model to describe the continuous dewatering process in a single screw press. The model predicted the moisture remaining in the pressed pulp with accuracy. The throughput of the press could be predicted accurately only at low screw speeds. The pressure and the power could not be predicted with sufficient accuracy to warrant simulation.

4. The simulation model for the dewatering process in a screw press was used to account for the response of the system, which included the behavior of the machine and the material, to the cause of the changes occurring insitu. The throughput achieved and the specific energy required for dewatering would govern the behavior of the machine while the moisture removed from fresh alfalfa and the loss of solids in juice would govern the behavior of the material. The variables causing changes in the system would be initial

moisture content, screw speed, choke opening, screw configuration and pre treatment.

It was concluded that reducing the screw speed and choke opening would increase the amount of moisture removed. An increase in initial moisture content would also increase the amount of moisture removed by increasing the proportion of surface moisture and loosely bound moisture. It was also predicted that use of a forced feeding system with a screw auger will favor moisture removal.

Mechanical dewatering, as a process preceding thermal dehydration, offers a savings in energy by 45% over a total thermal dehydration process of making feed pellets. Besides juice expressed during dewatering can be utilized for extracting valuable products of commercial importance to the food, feed and pharmaceutical industries. There is also a possibility of direct utilization of pressed pulp as a feed to meet the demands for the domestic market. This is because of longer shelf life of pressed pulp due to reduced respiration rates. In order to meet the demands of export market, the pressed pulp can be suitably packed in modified atmosphere surroundings. Direct utilization of pressed pulp will be economically feasible for domestic market. However economics will have to be worked for the export market due to the additional cost incurred in packaging. Also handling cost will be substantially more due to low bulk density of pressed pulp.

CHAPTER 8

SUGGESTIONS FOR FUTURE RESEARCH

Further research could be carried on by considering the following points.

1. Since juice was still expressed and the pressed pulp moisture showed a decline on passing the pulp the third time through the screw press, it shows that further rupture of plant cells was still possible. Hence the single screw could be designed as a better macerator or maceration could be carried out separately before feeding in the screw press. Thus the effect of feeding macerated alfalfa chops into the screw press could be studied and compared with the performance of the press when the chops are fed unmacerated. However the modification should meet the specific objectives of dewatering.

2. In order to define the degree of maceration, the rate of respiration at different maceration levels may be used as a possible criterion. This is because at a higher degree of maceration, the cells that are ruptured will have lower respiration rates and retarded biochemical activity.

3. Since the values for power were found to fluctuate with time, a strip chart recorder may be used to record the instantaneous values of power.

4. Since the pressure and the power could not be predicted with accuracy, the computer simulation model needs further improvement. In doing so, the frictional power may be taken into account.

REFERENCES

1. Aboaba, F.O., H.D. Bruhn, R.G. Koegel and D.F. Livermore. 1973. Some fundamental principles of dewatering aquatic vegetation. *Transactions of the ASAE* 16(3):430-434.

2. ASAE. 1991. ASAE Standards 1991, American Society of Agricultural Engineers. St. Joseph, MI.

3. Bagnall, L.O. Intermediate-Technology Screw Presses for Dewatering Aquatic Plants, University of Florida, Gainesville, Florida 32611.

4. Bilanski, W.K. and V.A. Graham. 1984. Non-Linear viscoelastic behavior during forage wafering. *Transactions of the ASAE* 27(6):1661-1665.

5. Carlsson, R. 5/5 Wet Green Crop Fractionation. Department of Plant Physiology, University of Lund, Lund. Sweden.

6. Casselman, T.W., V.E. Green, R.J. Allen Jr. and F.H. Thomas, 1965. Mechanical Dewatering of Forage Crops. Technical Bulletin 694, Agricultural Experiment Stations, University of Florida, Gainsville.

7. Edwards, R.H., D. de Fremery, B.E. Mackey and G.O. Kohler. 1977. Factors Affecting Juice Extraction and Yield of Leaf Protein Concentrate from Chopped Alfalfa. *Transactions of the ASAE* 20(3):423-428.

8. Edwards, R.H., D. de Fremery, B.E. Mackey and G.O. Kohler. 1978. Factors Affecting Juice Extraction and Yield of Leaf Protein Concentrate from Ground Alfalfa. *Transactions of the ASAE* 20(1):55-59.

9. Faborode, M.O. and J.R. O' Callaghan. 1989. A Rheological Model for the Compaction of Fibrous Agricultural Materials. J. Agric. Eng. Res. 42:165-178.

10. Hibbs, J.W., R.H. Conrad and W.H.Johnson. 1968. Macerated, Dewatered vs. Wilted Alfalfa-Grass Silage for Dairy Cows. Research Bulletin 1013:3-9. Ohio Agricultural Research and Development Center, Wooster, Ohio.

11. Holdren, R.D., W.L. Harris and G.J. Burkhardt, 1972. Squeezing juice from forage. *Transactions of the ASAE* 15(6):1044-1048.

12. Hundtoft, E.B. and F.H. Buelow. 1971. An Axial Stress-Strain Relationship for Bulk Alfalfa. *J. Agric. Engng. Res.* 16(11):32-45.

13. Kim, J.Y. 1992. Mechanical dewatering characteristics of fibrous waste materials and macerated green alfalfa. Unpublished PhD. thesis. Department of agricultural engineering, University of Wisconsin, Madison.

14. Koegel, R.G. and H.D. Bruhn. 1972. Pressure fractionation characteristics of alfalfa. *Transactions of the ASAE* 15(5):856-860.

15. Koegel, R.G., V.I. Fomin and H.D. Bruhn. 1973. Roller maceration and fractionation of forages. *Transactions of the ASAE* 16(2):236-240.

16. Koegel, R.G., V.I. Fomin and H.D. Bruhn. 1973. Cell rupture properties of alfalfa. *Transactions of the ASAE* 16(4):712-716.

17. Koegel, R.G., H.D. Bruhn and V.I. Fomin. 1974. Instrumentation of crushing and dewatering rolls. *Transactions of the ASAE* 17(6):1099-1103.

18. Larsen, T.B., R.T. Patil and S. Sokhansanj. 1993. Microwave method for moisture content determination in alfalfa products. *ASAE Paper No.* RRV 93-301. St. Joseph, MI 49085-9659, USA.

19. Leonard Hill. Bulk Solids Handling-An Introduction to the Practice and Technology. Ed: Woodcock, C.R. and J.S. Mason. Chapman and Hall. New York.

20. Mathismoen, P. 1974. Stord Twin Screw Presses - Design and Application on Alfalfa. Proceedings of the 12th Technical Alfalfa Conference. Overland Park, KS.

21. Patil, R.T., S. Sokhansanj and T. Larsen. 1994. Effect of drying of alfalfa chop on color preservation. Drying '94, Vol. B (Eds V. Rudolph and R.B. Keey) :1037-1044.

22. Peterson, C.L., D.L. Auld, and J.C. Thompson. 1983. Experiments with Vegetable Oil Expression. *Transactions of the ASAE* 26(5):1298-1302.

23. Reece, F.N. 1966. Temperature, Pressure and Time Relationships in Forming Dense Hay Wafers. *Transactions of the ASAE* 9(6):749-751.

24. Rehkugler, G.E. and W.F. Buchele. 1969. Biomechanics of Forage Wafering. *Transactions of the ASAE* 12(1):1-8.

25. Savoie, P. and S. Beauregard. 1990. Potential in the Field Forage Juice Extraction. *ASAE Paper No. 90-1055*. St. Joseph, MI 49085-9659, USA.

26. Spencer, R.R., E.M. Bickoff, G.O. Kohler, S.C. Witt, B.E. Knuckles and A.C. Mottola. 1970. Alfalfa products by wet fractionation. *Transactions of the ASAE* 13(2):198-200.

27. Srivastava, A.C., W.K. Bilanski, and V.A. Graham. 1981. Feasibility of Producing Large Size Hay Wafers. *Canadian Agric. Eng.* 23(2):109-112.

28. Straub, R.J. and H.D. Bruhn. 1975. Mechanical Dewatering of Alfalfa Protein Concentrate. *ASAE Paper No. 75-6519.* St. Joseph, MI 49085-9659, USA.

29. Straub, R.J. and R.G. Koegel. 1983. Evaluation of a cone press for forage fractionation. *Transactions of the ASAE* 26(4):1016-1021.

30. Stroshine, R., R. Pitt and D. Hamann. 1992. Physical Properties of Agricultural Materials and Food Products. Agricultural Engineering Department, Purdue University, West Lafayette, IN.

31. Tang, J., J.C. Jofriet and B. Lelievre. 1987. Juice Flow From Silages. *Canadian Agric. Eng.* 30:99-106.

32. Zhong, Z and J.R. O'Callaghan. 1990. The effect of the shape of the feed opening on the performance of a horizontal screw conveyor. *J. Agric. Engng. Res.* 46:125-128.

APPENDICES

APPENDIX A

Theoretical Calculations

Table A.1 : Amount of water to be removed from fresh alfalfa to produce 1 t of dried chops at 8% and, heat energy required during the process

Initial m.c. (%)	Fresh alfalfa (t)	Water removed (t)	Heat energy (kJ/kg)	Heat energy (kW-h)
85	6.13	5.13	3448	4917
80	4.60	3.60	3457	3457
75	3.68	2.68	3467	2581
70	3.07	2.07	3478	1997
65	2.63	1.63	3491	1579
60	2.30	1.30	3507	1267
55	2.04	1.04	3527	1023
50	1.84	0.84	3551	829
45	1.67	0.67	3581	669
40	1.53	0.53	3622	537
35	1.42	0.42	3677	424
30	1.31	0.31	3756	328
25	1.23	0.23	3883	245
20	1.15	0.15	4116	172
15	1.08	0.08	4681	107
10	1.02	0.02	8073	50

Table A.2 To find the quantity of water expressed and the quantity of alfalfa needed (at given m.c.) to produce 1 t of alfalfa at 40% m.c.

Let

W1 be the weight of alfalfa at a moisture content, m1(%wb)

W2 be the weight of alfalfa produced at moisture content,m2(%wb)

For our problem, W2=1 tonne and m2=40%

Applying a mass balance for the above problem,

$$W1(100-m1) = W2(100-m2)$$

$$W1 = W2(100-m2)/(100-m1)$$

m 1 (%)	m 2 (%)	W 2 (tonne)	W 1 (tonne)	Water expressed (tonne)
85	40	1	4.00	3.00
80	40	1	3.00	2.00
75	40	1	2.40	1.40
70	40	1	2.00	1.00
65	40	1	1.71	0.71
60	40	1	1.50	0.50
55	40	1	1.33	0.33
50	40	1	1.20	0.20
45	40	1	1.09	0.09
40	40	1	1.00	0.00

Table A.3: Amount of solids in the juice expressed calculated by mass balance for solids in experiment 3.1.2

I.M.C. = 75.7%

Initial weight (g)	Pulp weight (g)	Juice weight (g)	m.c. in pulp (%)	Juice expressed (%)	Solids content in juice (%)
65.9	39.4	18.9	66.1	28.7	14.1
66.2	39.9	23.9	65.5	36.1	9.7
65.6	34.5	27.2	61.8	41.5	10.2
65.7	37.9	23.7	63.3	36.1	8.7
66	32.4	31	60.3	47.0	10.2
65.6	31.9	30.7	60.5	46.8	10.9
65.3	32.3	31.1	61.4	47.6	10.9
65.5	31.3	29.8	60	45.5	11.4
66	32.4	31.6	61.1	47.9	10.9

APPENDIX B

Cross sectional view of the equipment used

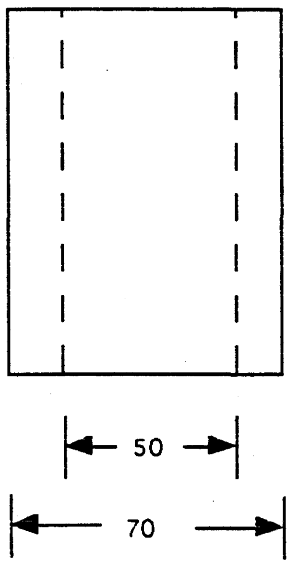


Fig. B.1a

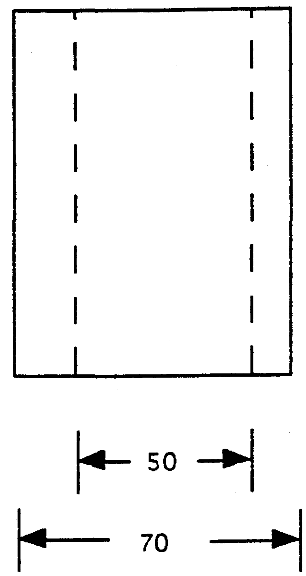


Fig. B.1b

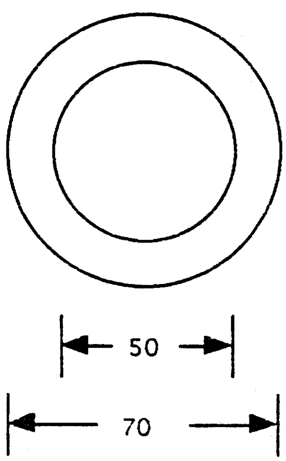


Fig. B.1c

Note : 1. All dimensions are in mm

2. Figures drawn are not to scale

Fig. B.1 : Elevation (B.1a), side view (B.1b) and plan (B.1c) of cylinder used in experiments 1, 2 and 3

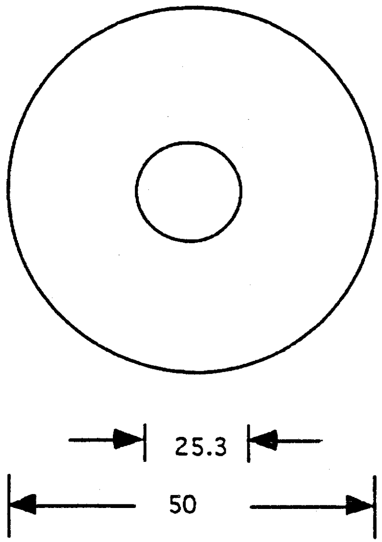


Fig. B.2a

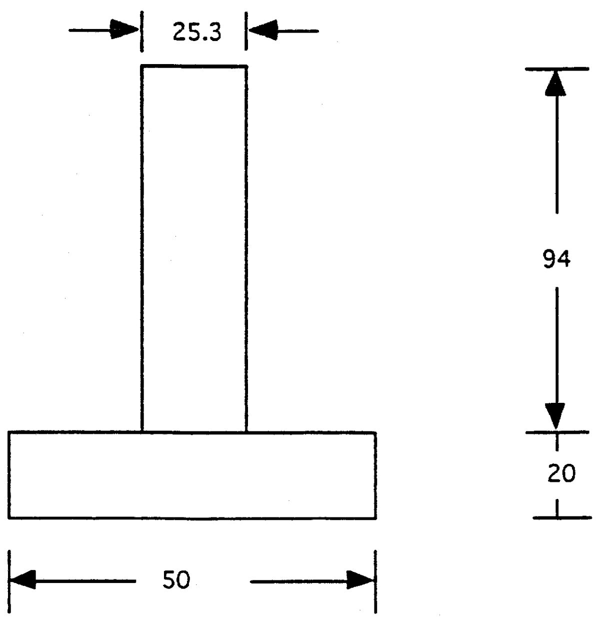


Fig. B.2b

Note : 1. All dimensions are in mm

2. Figures drawn are not to scale

Fig. B.2 : Plan (B.2a) and Elevation (B.2b) of piston used in Experiments 1, 2 and 3

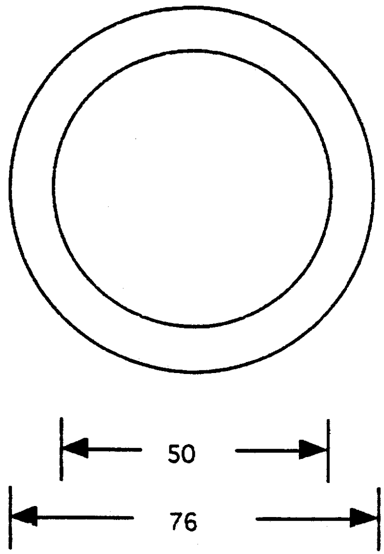


Fig. B.3a

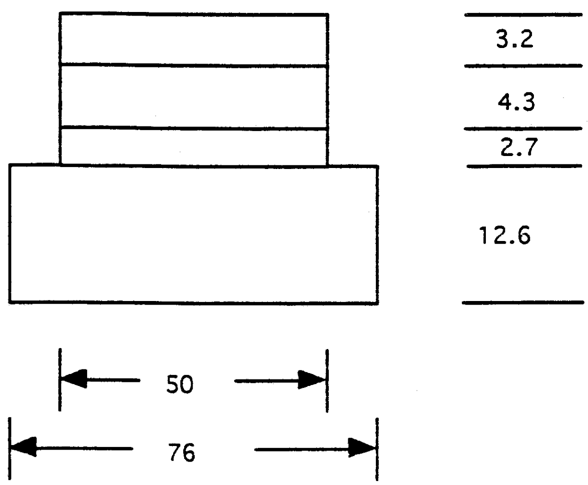
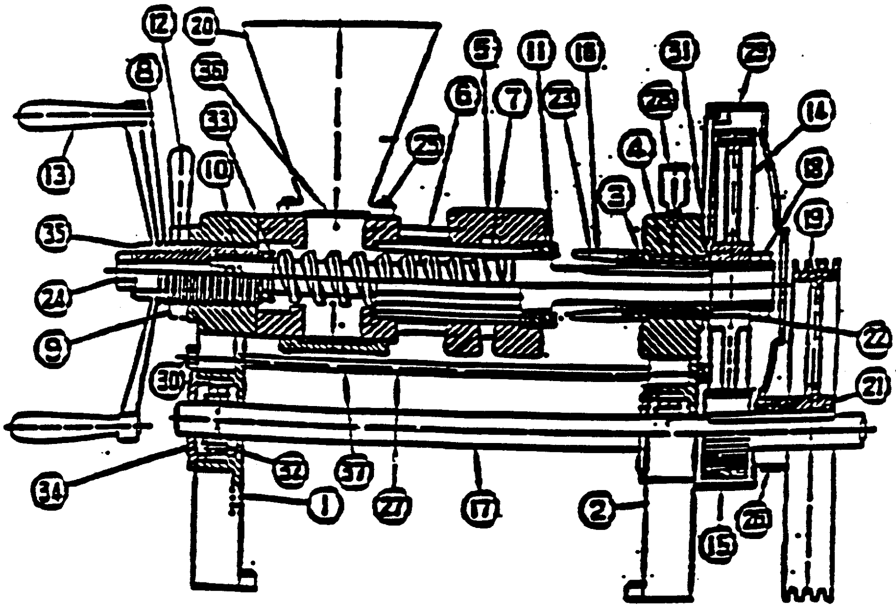


Fig. B.3b

Note : 1. All dimensions are in mm
2. Figures drawn are not to scale

Fig B.3 : Plan (B.3a) and Elevation (B.3b) of flange used in experiments 1, 2 and 3



Name of parts:

(1) Hopper Side Frame
(2) Gear Side Frame
(3) Sleeve
(4) Large Gunmetal Journal Bearing
(5) Drum
(6) Wormshaft
(7) Cage Bars
(8) Adjusting Screw
(9) Round Locking Nut
(10) Small Gunmetal Journal Bearing
(11) Ring
(12) Locking Handle
(13) Adjusting Handle
(14) Large Gear
(15) Pinion Gear
(16) Oil Cake Cutter
(17) Driving Shaft
(18) Round Sleeve Nut
(19) Pulley
(20) Hopper
(21) Key for Pinion Gear
(22) Key for Large Gear
(23) Key for Wormshaft
(24) Lock Bolt
(25) Hopper Attaching Screw
(26) Pulley Locking Screw
(27) Stay Bolt
(28) Oil Cup
(29a) Gear Cover
(29b) Inside Gear Back Plate
(30) Nuts for Stay Bolt
(31) Sleeve Ring
(32) Radial Ball Bearing
(33) Thrust Ball Bearing
(34) Bearing Cap
(35) Ring Washer
(36) Raw Materials Feed Regulating Gate
(37) Raw Materials Removal Plate

Fig B.4 : Drawing of the screw press
(Source: Sales Literature of M/s S.P. Engineering Corporation, Kanpur, India)

APPENDIX C

Color Measurement

Table C.1 - Color measurement for fresh alfalfa, pulp and juice expressed at 6 mm choke clearance

Sample type	Label	L	a	b
Fresh alfalfa	6/Rep1/Fr/C1	19.54	-1.56	6.33
used for 6 mm;	/C2	19.78	-2.59	6.72
24 rpm;	/C3	20.77	-2.31	7.28
Replica 1	/C4	20.76	-2.48	7.09
	/C5	20.48	-1.76	7.37
Average		20.27	-2.14	6.96
Std. Dev.		0.57	0.45	0.43
SEOM		0.26	0.20	0.19
Fresh alfalfa	6/Rep 2/Fr/C1	22.42	-1.91	7.92
used for 6 mm;	/C2	21.92	-1.79	7.54
24 rpm;	/C3	20.07	-2.16	7.09
Replica 2	/C4	20.63	-2.19	7.36
	/C5	19.55	-2.31	6.64
Average		20.92	-2.07	7.31
Std. Dev.		1.22	0.21	0.48
SEOM		0.54	0.10	0.22
Fresh alfalfa	6/Rep 3/Fr/C1	19.17	-2.25	6.33
used for 6 mm;	/C2	19.22	-1.94	5.93
24 rpm;	/C3	19.52	-2.08	6.71
Replica 3	/C4	20.17	-2	7.1
	/C5	19.42	-2.43	6.82
Average		19.50	-2.14	6.58
Std. Dev.		0.40	0.20	0.46
SEOM		0.18	0.09	0.20
Pulp from	6/Rep1/pulp/C1	24.61	-2.33	8.1
alfalfa pressed	/C2	24.98	-2.75	8.18
at 6 mm; 24 rpm;	/C3	25.36	-2.66	8.26
Replica 1	/C4	26.3	-2.3	8.75
	/C5	26.09	-2.59	8.66
Average		25.47	-2.53	8.39
Std. Dev.		0.72	0.20	0.29
SEOM		0.32	0.09	0.13
Pulp from	6/Rep 2/pulp/C1	25.27	-2.52	7.98
alfalfa pressed	/C2	24.72	-2.45	7.97
at 6 mm; 24 rpm;	/C3	26.52	-3.15	9.06
Replica 2	/C4	25.75	-2.67	8.5
	/C5	26	-2.36	7.94
Average		25.65	-2.63	8.29
Std. Dev.		0.69	0.31	0.49
SEOM		0.31	0.14	0.22

Sample type	Label	L	a	b
Pulp from	6/Rep 3/pulp/C1	24.36	-2.56	7.95
alfalfa pressed	/C2	25.73	-2.51	8.67
at 6 mm; 24 rpm;	/C3	24.71	-2.51	8.02
Replica 3	/C4	26.47	-2.43	9.12
	/C5	27.75	-2.39	9.28
Average		25.80	-2.48	8.61
Std. Dev.		1.37	0.07	0.61
SEOM		0.61	0.03	0.27
Juice from alfalf.	6/Rep 1/juice/C1	16.73	-0.24	7.24
pressed at 6 mm;	/C2	16.33	-0.27	6.85
24 rpm;	/C3	16.28	-0.93	6.65
Replica 1	/C4	16	-0.73	6.34
	/C5	15.61	-1.17	5.94
Average		16.19	-0.67	6.60
Std. Dev.		0.42	0.41	0.49
SEOM		0.19	0.18	0.22
Juice from alfalf.	6/Rep 2/juice/C1	16.05	-0.23	6.56
pressed at 6 mm;	/C2	15.66	-0.75	6.27
24 rpm;	/C3	15.76	-0.64	6.4
Replica 2	/C4	17.2	-0.16	6.95
	/C5	17.55	-0.59	7.31
Average		16.44	-0.47	6.70
Std. Dev.		0.87	0.26	0.43
SEOM		0.39	0.12	0.19

Sample type	Label	L	a	b
Juice from alfalf.	6/Rep 3/juice/C1	13.95	0.78	5.16
pressed at 6 mm;	/C2	14.09	0.9	5.34
24 rpm;	/C3	14.01	0.64	5.21
Replica 3	/C4	15.31	0.8	5.81
	/C5	15.39	0.57	5.79
Average		14.55	0.74	5.46
Std. Dev.		0.73	0.13	0.32
SEOM		0.33	0.06	0.14

Table C.2 - Color measurement for fresh alfalfa, pulp and juice expressed at 4 mm choke clearance

Sample type	Label	L	a	b
Fresh alfalfa	4/Rep1/Fr/C1	19.36	-2.4	6.69
used for 4 mm;	/C2	20.32	-2.63	7.03
24 rpm;	/C3	22.6	-2.04	7.96
Replica 1	/C4	20.68	-1.7	7.09
	/C5	21.5	-2.25	7.94
Average		20.89	-2.20	7.34
Std. Dev.		1.23	0.35	0.58
SEOM		0.55	0.16	0.26
Fresh alfalfa	4/Rep 2/Fr/C1	22.26	-1.98	7.73
used for 4 mm;	/C2	19.38	-2.15	6.52
24 rpm;	/C3	20.54	-2.2	6.89
Replica 2	/C4	21.02	-2.16	6.77
	/C5	20.43	-2.58	6.68
Average		20.73	-2.21	6.92
Std. Dev.		1.05	0.22	0.47
SEOM		0.47	0.10	0.21
Fresh alfalfa	4/Rep 3/Fr/C1	20.14	-1.54	5.93
used for 4 mm;	/C2	20.01	-1.62	6.24
24 rpm;	/C3	19.78	-1.58	5.92
Replica 3	/C4	19.15	-1.77	6.03
	/C5	21.09	-1.4	6.37
Average		20.03	-1.58	6.10
Std. Dev.		0.70	0.13	0.20
SEOM		0.31	0.06	0.09
Pulp from	4/Rep1/pulp/C1	26.29	-2.23	8.36
alfalfa pressed	/C2	27.97	-2.34	8.75
at 4 mm; 24 rpm;	/C3	28.16	-2.31	8.61
Replica 1	/C4	26.21	-2.29	7.68
	/C5	27.03	-2.13	7.68
Average		27.13	-2.26	8.22
Std. Dev.		0.91	0.08	0.51
SEOM		0.41	0.04	0.23
Pulp from	4/Rep 2/pulp/C1	27.07	-2.47	8.08
alfalfa pressed	/C2	25.21	-2.19	7.2
at 4 mm; 24 rpm;	/C3	28.07	-2.5	8.53
Replica 2	/C4	27.64	-2.44	8.41
	/C5	28.21	-2.46	8.58
Average		27.24	-2.41	8.16
Std. Dev.		1.22	0.13	0.57
SEOM		0.54	0.06	0.26

Sample type	Label	L	a	b
Pulp from	4/Rep 3/pulp/C1	23.66	-2.33	7.22
alfalfa pressed	/C2	26.13	-2.37	8.08
at 4 mm; 24 rpm;	/C3	25.03	-2.59	7.97
Replica 3	/C4	25.44	-2.67	8.29
	/C5	25.39	-2.42	8.09
Average		25.13	-2.48	7.93
Std. Dev.		0.91	0.15	0.41
SEOM		0.41	0.07	0.18
Juice from alfalf	4/Rep 1/juice/C1	15.44	0.52	5.84
pressed at 4 mm;	/C2	15.56	0.32	6.17
24 rpm;	/C3	15.91	0.34	6.51
Replica 1	/C4	16.16	0.59	6.39
	/C5	16.22	0.35	6.47
Average		15.86	0.42	6.28
Std. Dev.		0.35	0.12	0.28
SEOM		0.16	0.05	0.12
Juice from alfalf	4/Rep 2/juice/C1	13.36	1.05	4.79
pressed at 4 mm;	/C2	13.96	1.2	5.33
24 rpm;	/C3	13.41	0.95	4.83
Replica 2	/C4	13.26	1	5.02
	/C5	14.54	0.14	5.64
Average		13.71	0.87	5.12
Std. Dev.		0.54	0.42	0.36
SEOM		0.24	0.19	0.16
Juice from alfalf	4/Rep 3/juice/C1	15.85	0.1	6.59
pressed at 4 mm;	/C2	15.57	0.13	6.38
24 rpm;	/C3	15.1	-0.07	6.16
Replica 3	/C4	15.2	0.04	6.19
	/C5	15.51	-0.03	6.41
Average		15.45	0.03	6.35
Std. Dev.		0.30	0.08	0.18
SEOM		0.13	0.04	0.08

APPENDIX D

Computer Simulation

Table D.1: Simulation for mechanical dewatering of fresh alfalfa at 75% m.c. in a single screw press set at 6 mm choke opening and 24 revs/min

6 mm, pressure section = 128 + 35 mm, dia from 63 to 78, then 78 to 72

Suppose that the initial moisture content of the sample is 75%(wb). Let us start with an initial sample weight of 100 lb.

W = 100 lb
Ww = 75 lb
Ws = 25 lb

Barrel dia = 83 mm= 3.5inches=0.3 ft
Screw dia at the start of pressure section = 63 mm=2.5 inches=0.21 ft

Pitch = 32 mm = 1.26inches = 0.1 ft
Thickness of flight = -0.0002 x^2 + 0.09 x -0.004
N=24 r/min=0.4 r/s

Consider a time increment of 2 s for each compression stage.
v = (lambda-tf)*N
9.72 mm/s

So each compression stage is about 20 mm.

Time	Ww (lb)	Ws (lb)	Del x (mm)	x (mm)	Ds (mm)	tf (mm)	Vo (mm^3/s)	Del V (mm^3/s)	V (mm^3/s)	Vo (ft^3/s)	Del V (ft^3/s)	V (ft^3/s)	Del V/V	Wsv (lb /ft^3)	Ev	Delta P	P	Me	H	M	H2O	Power (kW)	Energy (kWh/t)
			87	137	56	8.6	9.25E+05																
2	75.00	25	20	157	58	9.2	9.25E+05	1.12E+05	8.13E+05	3.24E-02	3.93E-03	2.85E-02	1.38E-01	4.39E+02	1158	160.06	160.0586	47.82	0.1	73.67	1.33	0.99	
4	73.67	25	20	177	61	9.7	8.13E+05	1.16E+05	6.97E+05	2.85E-02	4.05E-03	2.44E-02	1.66E-01	5.12E+02	1158	192.16	352.2183	41.67	0.1	72.16	1.51	1.05	
6	72.16	25	20	197	64	10.0	6.97E+05	1.22E+05	5.76E+05	2.44E-02	4.26E-03	2.01E-02	2.12E-01	6.21E+02	1158	245.17	597.3863	37.99	0.1	70.59	1.58	1.15	
8	70.59	25	20	217	68	10.1	5.76E+05	1.32E+05	4.44E+05	2.01E-02	4.60E-03	1.55E-02	2.96E-01	8.04E+02	1158	343.00	940.3836	35.10	0.1	68.98	1.60	1.33	
10	68.98	25	20	237	72	10.1	4.44E+05	1.46E+05	2.98E+05	1.55E-02	5.10E-03	1.04E-02	4.88E-01	1.20E+03	1158	564.94	1505.319	32.33	0.1	67.36	1.62	1.68	
12	67.36	25	20	257	76	10.1	2.98E+05	1.64E+05	1.35E+05	1.04E-02	5.73E-03	4.72E-03	1.21E+00	2.65E+03	1158	1406.54	2911.861	28.81	0.1	65.70	1.66	2.82	
14	65.70	25	8	265	77	0.0	1.35E+05	1.05E+05	2.96E+04	4.72E-03	3.68E-03	1.04E-03	3.55E+00	1.20E+04	1158	4106.09	7017.953	24.71	0.1	64.00	1.70	3.72	
16	64.00	25	20	285	75	0.0	2.96E+04	2.79E+02	2.99E+04	1.04E-03	9.75E-06	1.05E-03	9.31E-03	1.19E+04	2358	21.95	6996	24.73	0.1	62.38	1.63	0.0044	
18	62.38	25	15	300	72	0.0	2.99E+04	2.69E+02	3.02E+04	1.05E-03	9.42E-06	1.06E-03	8.91E-03	1.18E+04	2358	21.01	6974.988	24.74	0.1	60.82	1.56	0.0042	
																					14.18	12.75	1.40

Table D.2: Simulation for mechanical dewatering of fresh alfalfa at 85% m.c. in a single screw press set at 6 mm choke opening and 24 revs/min

6 mm, pressure section = 128 + 35 mm, dia from 63 to 78, then 78 to 72

Suppose that the initial moisture content of the sample is 85(wb). Let us start with an initial sample weight of 100 lb.

W = 100 lb
Ww = 85 lb
Ws = 15 lb

Barrel dia = 83 mm= 3.5inches=0.3 ft
Screw dia at the start of pressure section = 63 mm=2.5 inches=0.21 ft

Pitch = 32 mm = 1.26inches = 0.1 ft
Thickness of flight = -0.0002 x^2 + 0.09 x -0.004
N=24 r/min=0.4 r/s

Consider a time increment of 2 s for each compression stage.
v = (lambda-tf)*N
9.72 mm/s

So each compression stage is about 20 mm.

Time	Ww (lb)	Ws (lb)	Del x (mm)	x (mm)	Ds (mm)	tf (mm)	Vo (mm^3/s)	Del V (mm^3/s)	V (mm^3/s)	Vo (ft^3/s)	Del V (ft^3/s)	V (ft^3/s)	Del V/V	Wsv (lb /ft^3)	Ev	Delta P	P	Me	H	M	H2O	Power (kW)	Energy (kWh/t)
			87	137	56	8.6	1.39E+06																
2	85.00	15	20	157	58	9.2	1.39E+06	1.23E+05	1.27E+06	4.86E-02	4.29E-03	4.43E-02	9.68E-02	1.69E+02	1158	112.09	112.094	50.89	0.1	83.20	1.80	1.04	
4	83.20	15	20	177	61	9.7	1.27E+06	1.26E+05	1.14E+06	4.43E-02	4.42E-03	3.99E-02	1.11E-01	1.88E+02	1158	128.19	240.28	44.54	0.1	81.24	1.97	1.09	
6	81.24	15	20	197	64	10.0	1.14E+06	1.33E+05	1.01E+06	3.99E-02	4.64E-03	3.52E-02	1.32E-01	2.13E+02	1158	152.58	392.8571	40.88	0.1	79.22	2.01	1.17	
8	79.22	15	20	217	68	10.1	1.01E+06	1.43E+05	8.64E+05	3.52E-02	5.00E-03	3.02E-02	1.65E-01	2.48E+02	1158	191.45	584.3054	38.14	0.1	77.21	2.01	1.29	
10	77.21	15	20	237	72	10.1	8.64E+05	1.58E+05	7.06E+05	3.02E-02	5.51E-03	2.47E-02	2.23E-01	3.03E+02	1158	258.27	842.5775	35.78	0.1	75.21	2.00	1.50	
12	75.21	15	20	257	76	10.1	7.06E+05	1.76E+05	5.30E+05	2.47E-02	6.17E-03	1.86E-02	3.33E-01	4.04E+02	1158	385.18	1227.755	33.50	0.1	73.23	1.98	1.83	
14	73.23	15	8	265	77	10.1	5.30E+05	7.36E+04	4.56E+05	1.86E-02	2.58E-03	1.60E-02	1.61E-01	4.69E+02	1158	186.82	1414.571	32.69	0.1	71.32	1.91	0.67	
16	71.32	15	20	285	75	0.0	4.56E+05	5.57E+03	4.62E+05	1.60E-02	1.95E-04	1.62E-02	1.21E-02	4.64E+02	2358	28.43	1386.14	32.80	0.1	69.50	1.82	0.09	
18	69.50	15	15	300	72	0.0	4.62E+05	4.04E+03	4.66E+05	1.62E-02	1.41E-04	1.63E-02	8.66E-03	4.60E+02	2358	20.42	1365.[illegible]25	32.89	0.1	67.78	1.73	0.06	
																					17.22	8.74	1.0

Table D.3: Simulation for mechanical dewatering of fresh alfalfa at 75% m.c. in a single screw press set at 4 mm choke opening and 24 revs/min

4 mm, pressure section = 143+ 23+12 mm, dia from 61 to 78, then 78 to 74, then 74 to 72

Suppose that the initial moisture content of the sample is 75%(wb). Let us start with an initial sample weight of 100 lb.

W = 100 lb
Ww = 75 lb
Ws = 25 lb

Barrel dia = 83 mm= 3.5inches=0.3 ft
Screw dia at the start of pressure section = 61 mm

Pitch = 32 mm = 1.26inches = 0.1 ft
Thickness of flight = -0.0002 x^2 + 0.09 x -0.004
N=24 r/min=0.4 r/s

Consider a time increment of 2 s for each compression stage.
v = (lambda-tf)*N
9.72 mm/s

So each compression stage is about 20 mm.

Dc = 78-0.17*x

Time	Ww (lb)	Ws (lb)	Del x (mm)	x (mm)	Ds (mm)	t f (mm)	Vo (mm^3/s)	Del V (mm^3/s)	V (mm^3/s)	Vo (ft^3/s)	Del V (ft^3/s)	V (ft^3/s)	Del V/V	Wsv (lb /ft^3)	Ev	Delta P	P	Me	H	M	H2O	Power (kW)	Energy (kWh/t)
			87	122	54	8.0	1.03E+06																
2	75.00	25	20	142	56	8.7	1.03E+06	1.11E+05	9.15E+05	3.59E-02	3.90E-03	3.20E-02	1.22E-01	3.90E+02	1158	140.90	140.90	48.89	0.1	73.73	1.27	0.97	
4	73.73	25	20	162	59	9.3	9.15E+05	1.13E+05	8.02E+05	3.20E-02	3.95E-03	2.81E-02	1.41E-01	4.45E+02	1158	163.18	304.08	42.75	0.1	72.28	1.45	1.00	
6	72.28	25	20	182	62	9.8	8.02E+05	1.17E+05	6.85E+05	2.81E-02	4.09E-03	2.40E-02	1.71E-01	5.21E+02	1158	197.76	501.83	39.17	0.1	70.76	1.52	1.06	
8	70.76	25	20	202	65	10.0	6.85E+05	1.24E+05	5.61E+05	2.40E-02	4.34E-03	1.96E-02	2.21E-01	6.37E+02	1158	255.75	757.58	36.45	0.1	69.22	1.55	1.18	
10	69.22	25	20	222	69	10.1	5.61E+05	1.35E+05	4.26E+05	1.96E-02	4.71E-03	1.49E-02	3.16E-01	8.38E+02	1158	365.47	1123.05	34.03	0.1	67.66	1.56	1.38	
12	67.66	25	20	242	73	10.1	4.26E+05	1.50E+05	2.77E+05	1.49E-02	5.25E-03	9.68E-03	5.42E-01	1.29E+03	1158	627.77	1750.83	31.49	0.1	66.08	1.57	1.80	
14	66.08	25	23	265	77	10.1	2.77E+05	1.96E+05	8.04E+04	9.68E-03	6.86E-03	2.81E-03	2.44E+00	4.44E+03	1158	2825.70	4576.53	[illegible]6.63	0.1	64.44	1.64	5.25	
16	64.44	25	23	288	74	0.0	8.04E+04	6.36E+03	8.67E+04	2.81E-03	2.23E-04	3.04E-03	7.34E-02	4.12E+03	2358	172.97	4403.56	26.81	0.1	62.87	1.57	0.09	
18	62.87	25	6	294	73	0.0	8.67E+04	3.06E+04	5.62E+04	3.04E-03	1.07E-03	1.97E-03	5.45E-01	6.36E+03	1158	630.92	5034.48	26.19	0.1	60.13	2.74	0.37	
20	60.13	25	6	300	72	0.0	5.62E+04	3.07E+04	2.54E+04	1.97E-03	1.08E-03	8.89E-04	1.21E+00	1.41E+04	1158	1401.54	6436.02	25.09	0.1	57.55	2.59	0.53	
																					17.45	13.10	1.6

Table D.4: Simulation for mechanical dewatering of fresh alfalfa at 85% m.c. in a single screw press set at 4 mm choke opening and 24 revs/min

4 mm, pressure section = 143+ 23+12 mm, dia from 61 to 78, then 78 to 74, then 74 to 72

Suppose that the initial moisture content of the sample is 85%(wb). Let us start with an initial sample weight of 100 lb.

W = 100 lb
Ww = 85 lb
Ws = 15 lb

Barrel dia = 83 mm= 3.5inches=0.3 ft
Screw dia at the start of pressure section = 61 mm

Pitch = 32 mm = 1.26inches = 0.1 ft
Thickness of flight = -0.0002 x^2 + 0.09 x -0.004
N=24 r/min=0.4 r/s

Consider a time increment of 2 s for each compression stage.
v = (lambda-tf)*N
9.72 mm/s

So each compression stage is about 20 mm.

Dc = 78-0.17*x

Time	Ww (lb)	Ws (lb)	Del x (mm)	x (mm)	Ds (mm)	tf (mm)	Vo (mm^3/s)	Del V (mm^3/s)	V (mm^3/s)	Vo (ft^3/s)	Del V (ft^3/s)	V (ft^3/s)	Del V/V	Wsv (lb /ft^3)	Ev	Delta P	P	Me	H	M	H2O	Power (kW)	Energy (kWh/t)
			87	122	54	8.0	1.37E+06																
2	85.00	15	20	142	56	8.7	1.37E+06	1.21E+05	1.25E+06	4.79E-02	4.25E-03	4.36E-02	9.73E-02	1.72E+02	1158	112.65	112.6463	50.84	0.1	83.22	1.78	1.04	
4	83.22	15	20	162	59	9.3	1.25E+06	1.23E+05	1.12E+06	4.36E-02	4.31E-03	3.93E-02	1.10E-01	1.91E+02	1158	126.95	239.5921	44.57	0.1	81.28	1.94	1.06	
6	81.28	15	20	182	62	9.8	1.12E+06	1.27E+05	9.96E+05	3.93E-02	4.46E-03	3.49E-02	1.28E-01	2.15E+02	1158	148.17	387.7597	40.97	0.1	79.29	1.99	1.12	
8	79.29	15	20	202	65	10.0	9.96E+05	1.35E+05	8.61E+05	3.49E-02	4.72E-03	3.02E-02	1.57E-01	2.49E+02	1158	181.26	569.0152	38.32	0.1	77.31	1.99	1.21	
10	77.31	15	20	222	69	10.1	8.61E+05	1.46E+05	7.15E+05	3.02E-02	5.11E-03	2.50E-02	2.04E-01	3.00E+02	1158	236.44	805.4565	36.06	0.1	75.34	1.97	1.37	
12	75.34	15	20	242	73	10.1	7.15E+05	1.62E+05	5.53E+05	2.50E-02	5.67E-03	1.94E-02	2.93E-01	3.87E+02	1158	339.19	1144.648	33.92	0.1	73.39	1.95	1.63	
14	73.39	15	23	265	77	10.1	5.53E+05	2.13E+05	3.40E+05	1.94E-02	7.46E-03	1.19E-02	6.27E-01	6.30E+02	1158	726.29	1870.941	31.13	0.1	71.45	1.94	2.70	
16	71.45	15	23	288	74	0.0	3.40E+05	6.36E+03	3.46E+05	1.19E-02	2.23E-04	1.21E-02	1.84E-02	6.19E+02	2358	43.31	1827.627	31.26	0.1	69.60	1.85	0.10	
18	69.60	15	6	294	73	0.0	3.46E+05	3.06E+04	3.16E+05	1.21E-02	1.07E-03	1.11E-02	9.69E-02	6.79E+02	1158	112.18	1939.80	30.93	0.1	66.41	3.18	0.26	
20	66.41	15	6	300	72	0.0	3.16E+05	3.07E+04	2.85E+05	1.11E-02	1.08E-03	9.98E-03	1.08E-01	7.52E+02	1158	124.90	2064.71	30.60	0.1	63.47	2.94	0.26	
																					21.53	10.48	926.4