

HEAT CONTENT OF VARIOUS AGRICULTURAL RESIDUES

by

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A Thesis  
presented to the University of Manitoba  
in partial fulfillment of the  
requirements for the degree of  
MASTER OF SCIENCE  
in  
DEPARTMENT OF AGRICULTURAL ENGINEERING

Winnipeg, Manitoba, 1980

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## ABSTRACT

Availability of energy and its cost are the principal factors to determine any strategic measures that will be taken to change existing practices or to use alternate energy sources. Agricultural residues may be considered as alternate energy sources as they are abundant in nature and produce heat energy equivalent to lignite coal when burned. The heat content of combustible material is related to its moisture content and specific data has not been available to compare and select the most desirable of the agricultural residues. The residues of agricultural products, such as, wheat straw, barley straw, alfalfa, oat straw, peat, flax straw, corn silage and sunflower hulls and pulp were burned at different levels of moisture in a Parr Plain Jacket Calorimeter to find their higher heat values, from which the lower heat values of these residues were calculated.

The curves for heat value versus moisture content were drawn and their regression equations were found.

Based on the experiments it was found that the mixture of sunflower hulls and pulp had the highest heat content but the most adaptable fuel is wheat straw, due both to its availability and high heat values. Oat straw had the lowest

heat content of the residues tested at a typical storage  
moisture content of 20%.

#### ACKNOWLEDGEMENTS

The author gratefully acknowledges his indebtedness to Prof. L.C. Buchanan for the guidance in conducting this project. Sincere thanks are due to Prof. H.M.Lapp for his valuable suggestions. Sincere thanks are extended to Dr. A.B.Sparling, Dr. G.E. Laliberte and Dr. W.E.Muir for their interest and involvement in the project.

The author is grateful to the Manitoba Department of Agriculture for financial support to this project.

Thanks are also extended to Mr. J.G.Putnam for the excellent photography for this project.

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## Chapter I

### INTRODUCTION

Demands for energy are increasing with the rapid development in industry, mechanization and transportation. The entire world is dependent on petroleum as a source of energy consuming about 20 billion barrels in a year. The diminishing supply of liquid petroleum is forcing the scientists and engineers to look into the future for alternate energy sources. The known reserves of petroleum in Canada have dropped by about 35% since 1969 and presently Canada is importing about 25% of its total oil consumption. World Energy Outlook, published by the Organization for Economic Cooperation and Development (OECD, 1977) indicated that there may be great risks in permitting the current energy trend to continue. It stated that the demand for imported oil by OECD countries may rise to 35 million barrels per day by 1985 from the 23.4 million barrels per day in 1975 due to the present energy policies. The result, when supported by similar circumstances in other countries will undoubtedly lead to higher prices or shortage or both. While it may not be practical to reduce energy consumption because of a slow-down in development, the adoption of new sources of energy is a logical step. It may not be possible to have

total energy independence from fossil fuels, but production routines can become energy self sufficient by alternate energy sources such as utilizing solar or biomass energy.

Until recently many solid wastes were classed as disposal problems but many forms such as straws, wood chips, peat and sewage sludge contain abundant quantities of heat energy. These forms of energy are inexpensive and are readily available if collection and handling systems can be developed. ASAE public policy issues report (1979) reported that 4 quads of energy from crop residues and 2 quads from manure can be produced by U.S. farmers annually. Crop residues which are not required for erosion control can be converted into usable energy by burning them in a furnace. In the past, small grain's straw was used to fire steam traction engines in the areas where there was a scarcity of coal and wood.

The term agricultural residues can be referred to all crop residues; barley straw, sunflower seed hulls, and some other wastes, like peat, wood chips etc. According to Schwab (1979), the total residue yield from crops vary with their varieties, for example with wheat, the grain to straw ratio is 1:1.5, while for oats it is 1:2. Barley has a 1:1 ratio. The total yield of organic material in the United States from crops and food are about 390000000 tons per year, from logging and the wood industry, about 55000000 tons annually

and from manure, 200,000,000 tons per year (Larry, 1972). According to Knight et al (1974) in terms of energy one ton of organic material is equivalent to one barrel of crude oil.

The fuel required for drying crops is a major component of the total energy requirement in agriculture in certain areas. For drying corn with an initial moisture content of 30% down to 14% the liquid petroleum gas requirement is about 280 litres per hectare. Because of this high energy requirement, use of crop residues for drying purposes was investigated by Kajewski et al (1977). Presently the energy cost for collection of straw for the industrial manufacture of hydrocarbon fuels is not economical and the most practical route is to burn and use the heat energy on the farms. In the United Kingdom a number of farmers are using straw in addition to logs and papers in their slow burning furnaces.

The residues of agricultural products can be converted into usable energy forms by combustion and by biological and chemical processes. By burning the residues heat energy is obtained, while through their biological and chemical processes, storable energy can be obtained.

The direct burning heat available through the agricultural residues is convenient as the heat can be obtained from the present available state of the residues and no change is required as is the case with some other forms, for

example to get producer gas it requires a chemical process and a certain degree of supervision. The heat generated by agricultural residues can be economically utilized in home heating, livestock barn heating and drying of crops.

No work has been done in the past on the heat values of agricultural residues at different moisture contents. The research work to determine heat values of agricultural residues at various moisture levels was conducted at the Department of Agricultural Engineering, University of Manitoba. It was conducted with some crop residues and peat with the following

objectives.

1. To find the higher heat values of various agricultural residues at different levels of moisture content.
2. To find the lower heat values of these residues at different moisture contents.
3. To find regression equations to calculate the heat values of different residues at any level of moisture.
4. To compare the heat values of all these residues amongst each other at the highest permissible storage condition of 20% moisture content.

5. To determine the heat content relationship of other agricultural residues compared to wheat straw.

## Chapter II

### REVIEW OF LITERATURE

#### 2.1 ENERGY RECOVERY FROM AGRICULTURAL RESIDUES

Many forms of waste material such as wheat straw, barley straw, brome grass, alfalfa, sunflower seed hulls etc. contain abundant quantities of energy. This energy can be converted into usable heat energy by the use of an appropriate burner.

The major problem associated with burning agricultural residues is its excessive smoke which contributes to air pollution. According to Thompson, Miller and Goss (1975) rice straw burning reduced the visibility in the Sacramento valley in California during October 1971 to less than seven miles, while the state minimum visibility standard is 10 miles. According to field burning data reported by Thompson, Miller and Goss (1975), the straw should be burned at 10-12% moisture content to produce the least amount of smoke.

##### 2.1.1 Energy From Cereal Crop Residues

Kanoksing and Lapp (1975) reported on energy recovery from oat straw through pyrolysis and anaerobic digestion. They found that the energy content of the crop residues can be an



attractive source of energy and it can substitute for fossil fuel. White (1979) indicated in his article "Efficient Use of Energy in Agriculture and Horticulture" that the conflict with the requirements of food and fibre production is less likely to arise if the residues of food crops are used for energy purposes instead of growing special crops.

In the United Kingdom farmers are now using crop residues in slow burning furnaces to heat water. High density straw bales were used in a grain drier in Germany, Gogerty (1978). White (1979) reports on the possibilities of grain drying and heating of controlled environment houses with straw as a fuel.

#### 2.1.2 Energy From Sewage Sludge

The heat values obtained from crop residues will be different for different fields from where they are obtained (Downing, 1973). Based on this fact LaRue (1977) tested some crop residues and sewage sludge to find their heat values. The residue samples were taken from one place only. He found that the heat obtained from sewage sludge and crop residues was much more than from lignite coal. Sunflower stocks produced the greatest amount of heat in his combustion tests. LaRue found that sewage compost contained large quantities of inorganic material and if this could be eliminated the compost would be a much more efficient fuel source.

### 2.1.3 Energy Recovery From Wood Waste And Peat

The use of wood waste as a energy source is an old practice. In the early days people burned wood to cook and to heat their houses. It still is a common fuel in some developing countries. Watson (1978) discussed the possibility of using a wood waste fired plant to provide a low cost energy source for large scale drying of timber. The modern process of high temperature drying of exotic pines requires kiln temperatures of about 150C (degree Celcius) and primary temperatures of 204C. A wood mill at Morwell, Victoria used a heater having serpentine shaped coils, with a fluid having a high boiling point flowing in these coils. The fluid works as a heat transfer media and produces the required temperature. These coils were heated by wood wastes and so the timber drying operation, formerly taking two days, has been reduced to eight hours by this method.

Svenska (1978) discussed a new bark drying process in which raw bark, normally having 60% water content, is dried in a stream of hot gas and simultaneously ground in a mill, to form a fine, uniform powder with only 10 to 15% water content. This powder can be used directly in burners for pulverized fuel. Peat can also be treated in this way.

Holmes (1980) defined peat as a combustible substance produced by the incomplete decomposition of vegetable matter under conditions where atmospheric oxygen is excluded, usu-

ally in water. According to Steklasa (1980) the character of peat depends upon the conditions under which it has been formed and the nature of vegetation which has contributed to its formation.

Othmer (1978) used peat for energy recovery and found that the full heat of peat can be recovered by wet air oxidation. When the raw wet peat in the closed vessel is heated to the lower range of temperatures for wet carbonization and oxygen is supplied, a rapid oxidation takes place. The excess oxygen will oxidize all of the carbonaceous material of the peat and the final products are carbon dioxide and water. This heat compared on a dry weight basis with coal, amounts to two thirds to an equivalent heating value.

#### 2.1.4 Energy Recovery Through Pyrolysis

Pyrolysis can be defined as the chemical decomposition of a material by the action of heat in the absence of oxygen. This process was first used in the making of charcoal. Riddle (1972) used pyrolysis as a method of solid waste disposal and found that since the pyrolysis units operate at lower temperatures than the incineration system they are cheaper to build and less critical to operate.

Since the crops are harvested at particular times of the year, it seems important to convert wastes of different composition and quantity into a form that may approach compati-

bility with industrial firing practices. Schlesinger et al (1974) suggested the conversion of agricultural wastes into a usable energy form by pyrolysis. Materials that can not be burned cleanly in incinerators can be converted to gas, oils and solids that can be burned cleanly by known methods.

Knight et al (1974) reported that the steady flow, low temperature pyrolysis process is capable of converting the agricultural wastes into fuels. They found that the char and pyrolytic organic liquid represent useful solid and liquid fuels that can be transported economically. Agricultural wastes are very low in sulfur, and therefore the fuels obtained by pyrolytic conversion are also low in sulfur. The exhaust gas from burning this fuel therefore is low in sulfur dioxide.

#### 2.1.5 Energy Recovery Through Anaerobic Digestion

Anaerobic digestion is the biological decomposition of organic material in a controlled environment without the presence of oxygen. Kanoksing and Lapp (1975) applied anaerobic digestion and pyrolysis to oat straw to find the energy content of cereal crop residues. In their experiment with anaerobic digestion, the gas yield ranged from 0.38 to 0.41 L/g (litres per gram) containing 52 to 56% methane and 32 to 48% carbon dioxide. In the pyrolysis process the gas obtain ranged from 0.09 to 0.11 L/g and contained 13 constituents, out of which 30% was methane and 40% was carbon

dioxide. They concluded that the energy recovery from cereal crop residues was technically feasible by both pyrolysis and anaerobic digestion.

#### 2.1.6 Present Energy Sources

There is a great concern that petroleum reserves are depleting thereby requiring a new form of portable energy for mobile power units and other vehicles of the future.

##### 2.1.6.1 Sunflower oil as a fuel source

Goodier et al (1980) reported the tests conducted by the United States Department of Agriculture (U.S.D.A.) on sunflower oil used as a mixture with diesel fuel in a John Deere 4020 diesel tractor. The results showed that the two fuels mixed easily and exhibit no tendency to separate when left undisturbed for several days. The no load engine speed was 2350 rpm (revolutions per minute). Under load at this speed the sunflower mixtures emitted a small amount of smoke, while under no load conditions and with pure diesel fuel no emission of smoke was visible.

##### 2.1.6.2 Alcohol as a fuel

Interest first began in utilization of alcohol as a fuel, due to surplus grain production in Canada and the United States, but it never received much attention because of the low petroleum prices. Renewed interest has been prompted by the

sharp jump in prices and forecast shortages of petroleum fuel. Brazil has developed the alcohol industry because of the lack of oil as a natural resource.

Alcohol has certain properties as an engine fuel which give it particular value as a blending agent with petroleum, spirit, benzol and diesel. The alcohols which are of interest as motor fuels are only the first few members of monohydric series, being methyl, ethyl, n-propyl and n-butyl. The reason is that their boiling points which are 65C, 78C, 97C and 97C respectively.

Wrage and Goering (1979) tested ethanol and diesel mixture for fuel in a diesel engine. They used a three cylinder diesel engine with a distributor type injector pump for the engine tests. The fuels used in tests were No.1 diesel fuel, No.2 diesel fuel and diesohol. A blend containing 10% (by volume) anhydrous ethanol and 90% No.2 diesel fuel was called diesohol. They found that engine performance was good with diesohol and it produced approximately 30% less smoke compared to No.2 diesel fuel. Since ethanol had a much lower boiling point than diesel fuel, a closed container was required for storing ethanol - diesohol fuel blends, otherwise the ethanol evaporated from the blend.

Bayh (1980) in his article "Fuel alcohol production", reported that the National Alcohol Fuels Commission (NAFC) has underway a series of studies to examine all aspects of ethanol and methanol for use as fuel.

## 2.2 COMPRESSING OF RESIDUES

Crop residues are abundant in nature and contain energy which is sufficient to make their use as a fuel source feasible. But their low density creates a problem in their handling and transportation. Baling and pelleting provide a means of increasing the density of these residues.

Stone (1949) tested wheat straw for energy recovery after briquetting and he found that fifty times as much heat energy may be obtained from the briquettes by burning, as is necessary to produce them. He also recommended a minimum temperature of 220C and a minimum pressure of 5000 psi (pounds per square inch) for briquetting making.

Dobie and Carnegie (1972) found that some waste materials require some binding agent to make a cube of good density and durability for handling. Laboratory tests indicated that binders that will dissolve well enough to make a 40% or more solution in water give the best results when applied as a liquid.

LaRue (1976) conducted experiments to find the physical properties of briquetts made from sunflower stalks. Asphalt was added to the organic material at different percentages and mixed with a stirring device on an electric drill. The asphalt was thinned with the addition of 10 percent turpentine by volume. This improved the mixing qualities of the asphalts. He found that carbonizing could improve briquetts using an asphalt binder.

### 2.3 SIZE REDUCTION OF STRAWS

Agricultural residues, like wheat and oat straw and sunflower stalks, can be used as a heating source in a better way when they are properly briquetted. LaRue (1976) stated that briquetting is a method to increase the density of crop wastes so that these can be burnt in the most efficient way. The crop residues that are available from the fields are bulky to briquette, so it is necessary to reduce their size. The size reduction can be done by the use of a hammer mill. On a commercial basis The Prairie Agricultural Machinery Institute (PAMI) tested different varieties of tub grinders for efficient grinding. Burrows Enterprises, Inc. also tested Roto Grinders to grind the big bales into a granular form.

### 2.4 UTILIZATION OF RESIDUAL HEAT

Fuels are the source of energy, which when burned serves the purpose of raising the temperature in a furnace. In West Germany a straw fired furnace is used for heating a 44000 bird broiler house plus a large farm dwelling. In Denmark farmers estimate a thousand square bales will heat a farm house for the winter.

Kajewski et al (1977) designed a furnace to burn corn stalks to provide heat for drying high moisture grains. They found that the crop residues can provide a reliable, low cost source of heat for grain drying and grain quality was not damaged by this method of drying.



Singh et al (1980) designed several kinds of furnaces to burn rice husks and groundnut shells to provide heat energy required for artificial drying of raw or parboiled paddy and for generating steam which can be used in the parboiling process and for power generation to operate the rice mills.

Alleman (1979) reported on a crop residue burner manufactured by Middle States Mfg. Co. which replaced costly propane fuel with corn stalks, milo stubble, corn cobs, wood or hay; for drying corn. This residue burner is also applicable to the hot air turbine engine in supplying the primary heated air necessary for a high performance operation.

## Chapter III

### THEORY

#### 3.1 DEFINITION OF TERMS

Some basic terms which are frequently used in this thesis are defined here.

##### 3.1.1 Moisture Content

The moisture content of different residues has a considerable effect on the heat values. Moisture present in the residues can be determined by different ways but in the present experiment the oven drying method was used. Moisture content can be determined either wet basis or dry basis as follows.

In the experiment of finding heat values of different residues moisture contents were determined on the wet basis. Hereafter the moisture content on wet basis will be written moisture content only.

$$MC(wb\%) = (\text{wt. of wet sample} - \text{wt. of dry sample}) \times 100$$

---

Weight of wet sample

and

$$MC(db\%) = (\text{wt. of wet sample} - \text{wt. of dry sample}) \times 100$$

---

Weight of dry sample

where,

MC (wb%) = Moisture content, wet basis, percent

MC (db%) = Moisture content, dry basis, percent

### 3.1.2 Heat of Vapourization And Condensation

Heat of vapourization is the amount of heat in Joules required to turn 1 kg. of liquid at its boiling point into 1 kg. of vapour at the same temperature.

Heat of condensation is the heat liberated in Joules when 1 kg. of vapours are turned into 1 kg. of liquid at that temperature.

When a vapour condenses, its latent heat is transferred to the surface on which the liquid droplets are deposited. Heat is also set free when a liquid solidifies. On account of this, the total amount of heat set free or absorbed when a compound is formed depends upon the physical state of the product.

### 3.1.3 Standardization

The term standardization is used to denote the operation of the calorimeter on a standard sample from which the energy equivalent or effective heat capacity of the system can be determined.

For standardization purposes Benzoic acid of known heat value is used. Benzoic acid is usually compressed into tablet or pellet form because the pellets are easy to handle

and they burn more slowly than the loose samples, thereby ensuring complete combustion.

#### 3.1.4 Standard Solution

Any solution whose strength is accurately known is called a standard solution. In the experiment of heat value determination the standard solution of sodium carbonate of 0.0725 normality was used to find the value of nitric acid formed in the burning process.

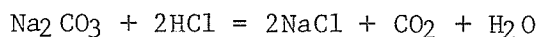
To prepare a 0.1 N sodium carbonate solution the following calculations were used.

The molecular weight of sodium is 23, carbon is 12 and oxygen is 16. Therefore, the gram molecular weight of sodium carbonate ( $\text{Na}_2\text{CO}_3$ )

$$= 2 \times 23 + 12 + 3 \times 16$$

$$= 106 \text{ g}$$

When sodium carbonate combines with hydrochloric acid, the chemical reaction takes place is



Since two molecules of hydrochloric acid react with one of sodium carbonate, the gram equivalent weight of sodium carbonate =  $106/2 = 53 \text{ g}$

To make one litre decinormal solution 5.3 grams of solid sodium carbonate will be required. Thus, to make 0.0725 N

solution, the amount of anhydrous sodium carbonate =  $53 \times 0.0725$

$$= 3.8425 \text{ g}$$

Therefore, 3.8425 gram of sodium carbonate was dissolved in one litre of water and the solution was used for the titration.

### 3.1.5 Energy Equivalent Factor

It is the energy required to raise the temperature of the calorimeter to one degree celcius expressed as the Joules per degree celcius. This factor represents the combined heat capacity of the water bucket of the water itself, of the bomb and its contents, and of parts of the thermometer, stirrer, and supports for the bucket.

In the experiments, the energy equivalent factor denoted by  $W$  is calculated as

$$W = \frac{Hm + e_1 + e_3}{t}$$

where,

$H$  = Heat of combustion of standard benzoic acid

$$= 26452202 \text{ Joules/Kg.}$$

$m$  = Mass of standard benzoic acid in Kg.

$e_1$  = Heat liberated by the Nitric acid formed by chemical reactions in burning, in Joule.

$$= \frac{4.1868 \times \text{Vol. of Sodium Carbonate} \times N \text{ of Sod. Carbonate}}{0.0725}$$

$$0.0725$$

Units of  $e_1$  are energy units as a unit volume of nitric acid liberates units of energy. 4.1868 is a constant to convert calories into joules.

$$e_3 = \text{Heat produced by the burning of fuse wire}$$

$$= 9.62964 \times (10 - \text{Length of wire left after burning})$$

The constant factor 9.62964 is used because one centimeter of fuse wire after burning gives 9.62964 joules of heat.

$t$  = Temperature difference

$$= t_f - t_a$$

$t_f$  = Final maximum temperature, degree celcius

$t_a$  = Initial temperature, degree celcius.

### 3.1.6 Higher Heat Value

When a substance is burned in a closed chamber, the heat of vapourization of water vapours and the heat of condensation of water vapours formed by the combination of hydrogen and oxygen are added into the heat of combustion of the solid material. The heat value obtained is the higher heat value of that substance. It is obtained by any sort of fuel calorimeter.

The higher heat value, denoted by HHV is calculated as

$$\text{HHV} = \frac{tW - e_1 - e_2 - e_3}{M}$$

Where,

$t$  = Temperature difference, degree celcius

$$= t_f - t_a$$

$W$  = Energy equivalent factor

$e_1$  = Heat produced by the nitric acid formation

$e_2$  = Heat of combustion of sulfur

$e_3$  = Heat produced by burning of fuse wire

$M$  = Mass of sample burned in Kg.

While calculating the higher heat value, the heat of combustion of sulfur is disregarded because the residues used in the experiment here contain such a small amount of sulfur, less than 0.5% in all cases (Morrison, 1956), that it contributes very minute amount of heat after burning, which can be neglected. In addition determining the sulfur content in a sample is a very time consuming process, so the small error which the sulfur correction will produce, is insignificant and so  $e_2$  disregarded.

### 3.1.7 Lower Heat Value

When a substance burns in open air, the heat value obtained is lower than that of the higher heat value. The water vapours which are formed by the hydrogen present in the sample combined with oxygen present in the air, escapes so it does not contribute any heat. Also the heat of vapourization of water present as the moisture content of the sample is also lost in open air burning. The heat value thus obtained is called the lower heat value.

Lower heat value, denoted as LHV, can be calculated as

$$\text{LHV} = \text{HHV} - \text{Heat of condensation of water vapours}$$

formed by the hydrogen - heat taken by the water to raise its temperature to boiling point-Heat taken in evaporation of water.

therefore,

$$\text{LHV} = \text{HHV} - 285.95844 \times \text{H}_2 \times (1.0 - \text{MC}) - \text{MC} \times \text{S} \times (100 - t_a) - \text{MC} \times \text{L}$$

Where,

HHV = Higher heat value

H<sub>2</sub> = Amount of hydrogen present in the sample

MC = Moisture content of the sample

S = Specific heat of water = 1

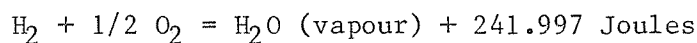
L = Latent heat of steam = 2260872.0 J/kg. (Joules per kilogram)

An average value of 6.5% of dry matter is used for the hydrogen content of all the agricultural residues.

The constant 100 is used as the temperature of boiling water.

The constant 285.95844 is the Joules of heat liberated when the steam formed by the reaction of hydrogen and oxygen, condenses.

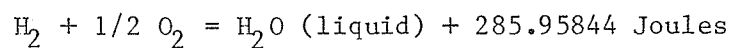
When the hydrogen burns in the presence of oxygen, the chemical reaction is





This 241.997 Joules of heat is always produced no matter whether there is closed burning or open air burning.

If the steam formed in this reaction is allowed to condense, the reaction is



When the burning of the sample is in open air, i.e., when calculating lower heat value, the water vapours formed by hydrogen and oxygen does not condense but escapes out and so this amount of heat is subtracted.

## Chapter IV

### METHODS AND MATERIALS

The heat values of different agricultural residues were determined by using a Parr 1341 plain jacket calorimeter (figure 1). The heat values were estimated at different moisture contents of these residues.

#### 4.1 SAMPLE COLLECTION

The samples of wheat, oat, barley, flax and alfalfa were collected from the Glenlea research station farm, south of Winnipeg, whereas corn silage samples were collected from Carman (south west of Winnipeg). The peat samples were from manitoba forest peat, the coal sample was brought from 200 miles north of Winnipeg near the Pine River and sunflower hulls and pulp samples were collected from a sunflower processing plant at Altona. These samples were all kept in polyethelene bags and the bags were tied properly to make them air tight. These bags were then kept in a refrigerator at a constant temperature to avoid their moisture loss and also to prevent any fungus development in the residues. For testing puoses, samples were taken out one at a time from the refrigerator.

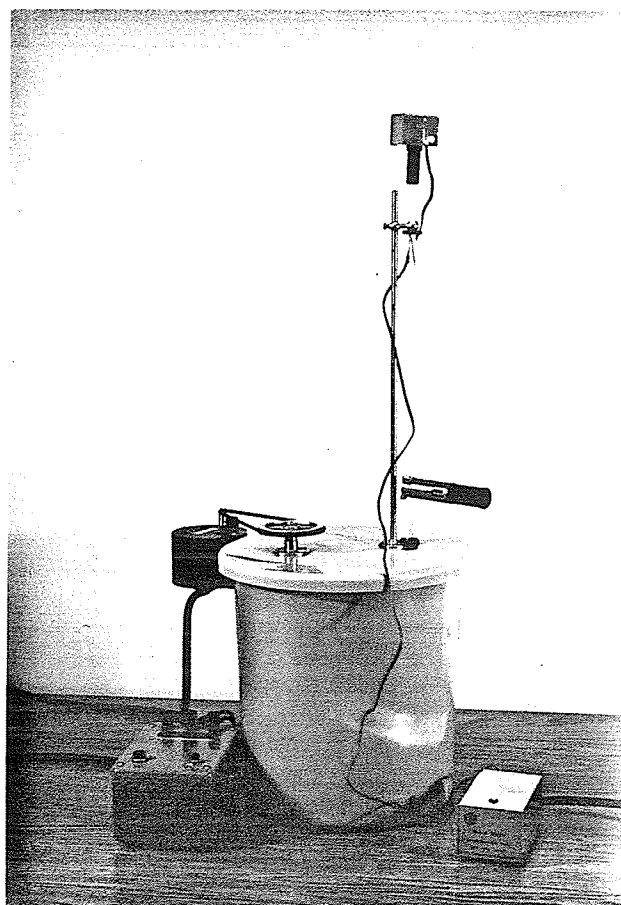


Figure 1: Parr Plain Jacket Calorimeter

## 4.2 MOISTURE CONTENT DETERMINATION

The samples as brought from the field were too large to test in small capsules for heat content and for the moisture content test, so after taking out the crop sample from refrigerator, they were finely cut by a scissors. The grains from the crop were separated out while the remaining part of that crop was used for the heat and moisture tests.

### 4.2.1 Finding Total Moisture Contents

For finding total moisture content, three aluminum containers kept in the oven, were taken out, allowed to cool, weighed and recorded. The same process was repeated to make sure that their weight was constant. The empty weights were noted down by weighing them on a balance (figure 2), accurate upto four decimal places. Residue samples of 15 to 25 g were put in the containers and the containers were weighed. All the three containers were kept in an air oven for 24 h, 48 h, or 72 h depending on the residue, and the temperature of the oven was set at 65c to 103c again depending on the residue kept inside. After this time the samples were taken out from the oven and kept in a desicator. When they were properly cooled, their weights were taken and the moisture contents on wet basis were determined. The average of three replicates was taken as the total moisture content of a residue sample.

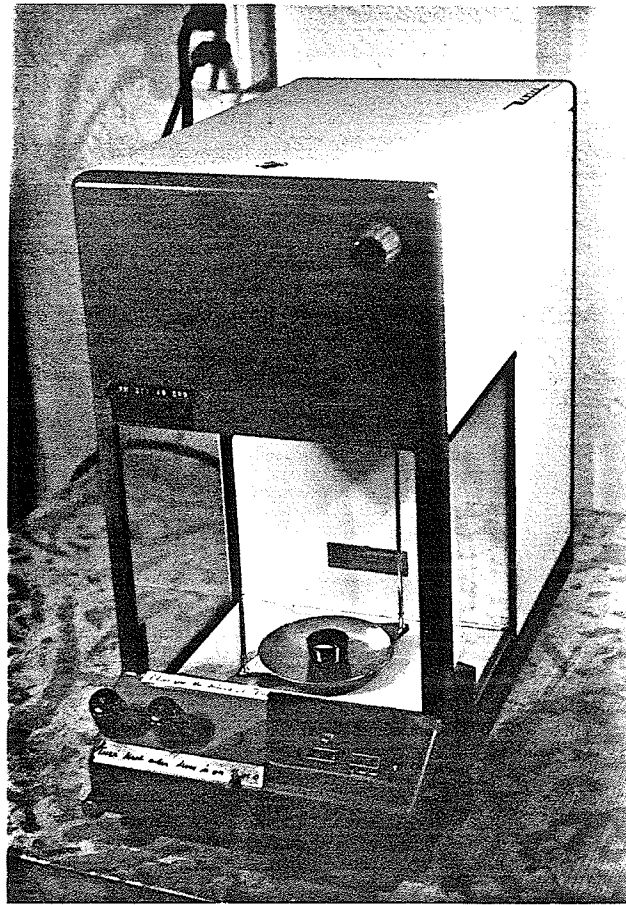


Figure 2: The weighing balance

#### 4.2.2 Varying The Moisture

To find heat values at different moisture contents, it was required to vary the moisture content of residues. For this purpose the samples from one residue were kept in about 15 aluminum containers previously tared. These containers were kept in an oven for different length of time. The containers were then cooled in a desiccator and weighed. Their loss of moisture were determined and so their moisture content were computed. These containers with the desired moisture content were kept air tight in polyethelene bags in in a refrigerator, at a constant low temperature. One at a time containers with polyethelene bags were taken out from the refrigerator for conducting the heat value test, kept for some time to reach room temperature, removed from the polyethelene bags and then weighed again to make sure of their moisture content. From this container samples were made into capsules for conducting the heat value determination test.

#### 4.3 MAKING THE PELLETS

Parr instruction manual no. 147 indicates that the powdered samples should be compressed into tablet or pellet form for easier handling and also pelleted samples burn more slowly, thereby reducing the chances for incomplete combustion. For making pellets the Parr 2811 pellet press (figure 3) with a

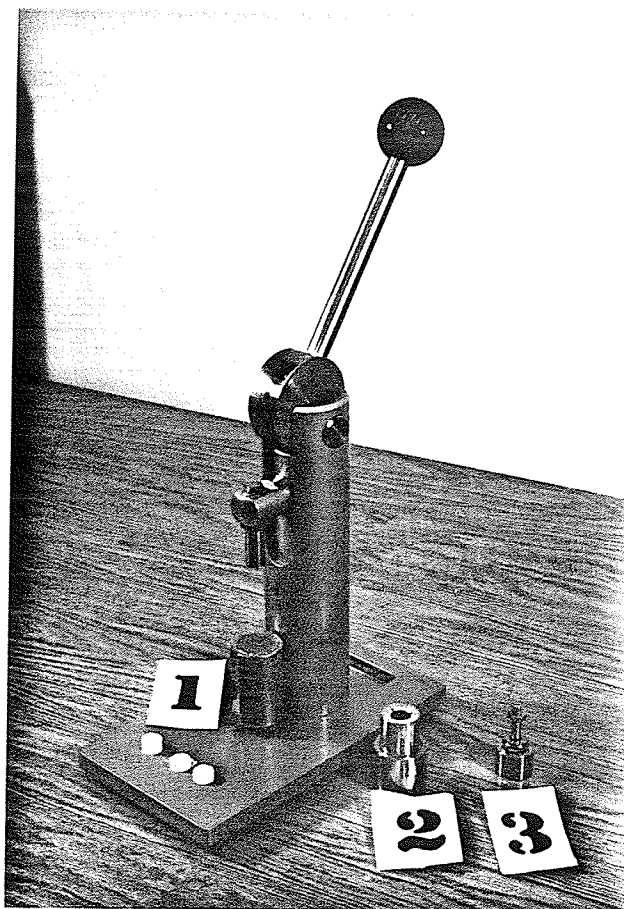


Figure 3: Pellet press

1. Pellet press and pellets
2. 1.2 cm. volatile sample holder
3. 0.6 cm. volatile sample holder

volatile sample holder was used. The loose sample material was put in the sample holder and this holder was placed on the platform of the pellet press, then by pressing the handle downward, sufficient force was applied on the loose sample so that it is compressed into tablet form. After making the pellets, they were stored in the capsules.

In the case of straw, it was impossible to make pellets as it does not contain any binding material. Also if the pellets were made, some moisture would have been lost during the pellet making process. All the straw samples were placed in the capsules in loose form and were covered by petri dishes (figure 5) to keep the moisture level constant.

#### 4.4 STANDARDIZING THE CALORIMETER

The calorimeter with all its parts is shown in figure 6. Two thousand ml. (milli-litre) of distilled water was placed in the oval bucket. This amount of water was found sufficient to immerse the oxygen bomb completely. A 10 cm long nickel alloy fuse provided by Parr Instrument Co. was attached to the bomb head terminals for ignition purposes. A standard benzoic acid pellet was used for standardization. An empty capsule was weighed on the balance shown in figure 2, and then again weighed with the benzoic acid pellet. The



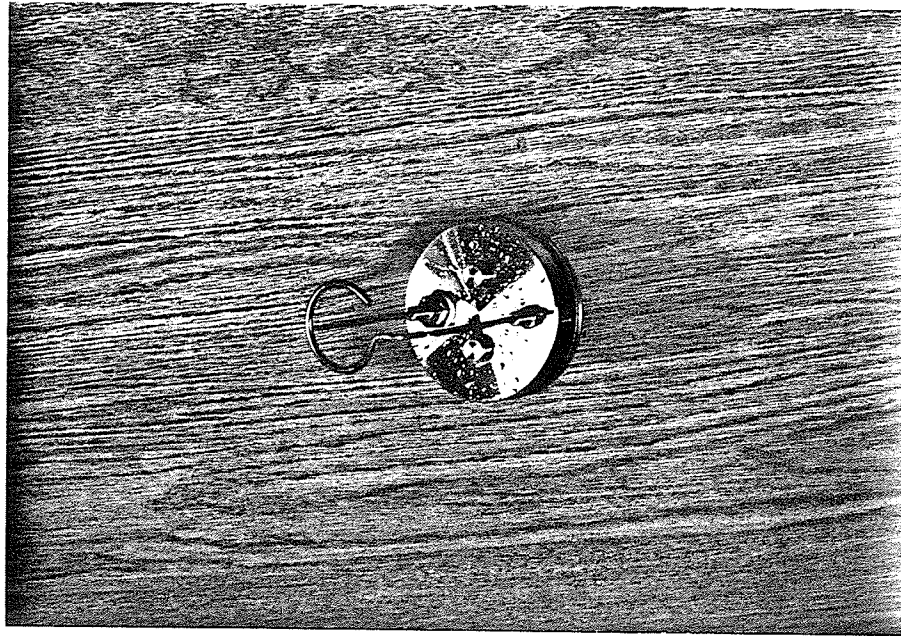


Figure 4: Water droplets deposited on the bomb head after burning the sample

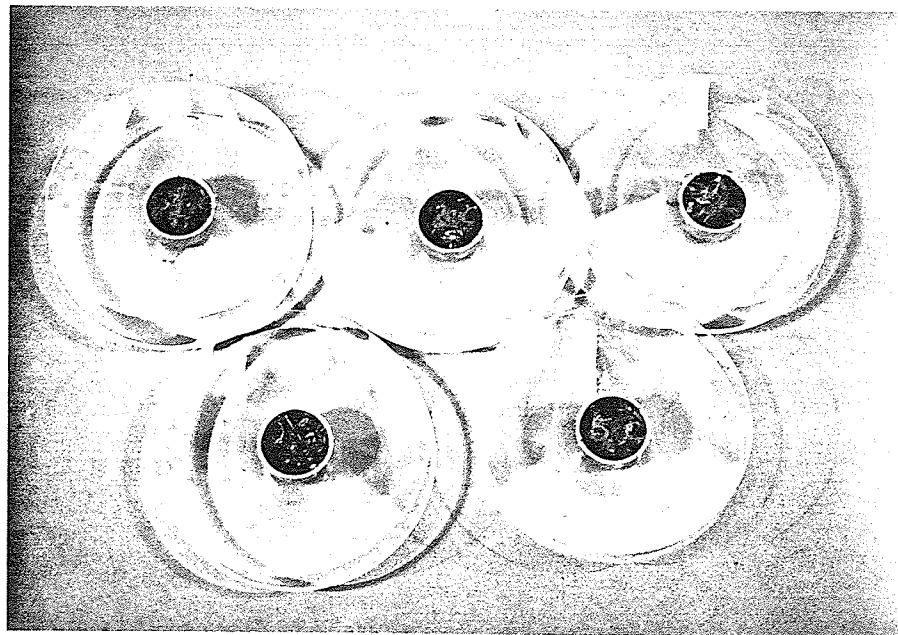


Figure 5: Loose samples in capsules covered by petri dishes

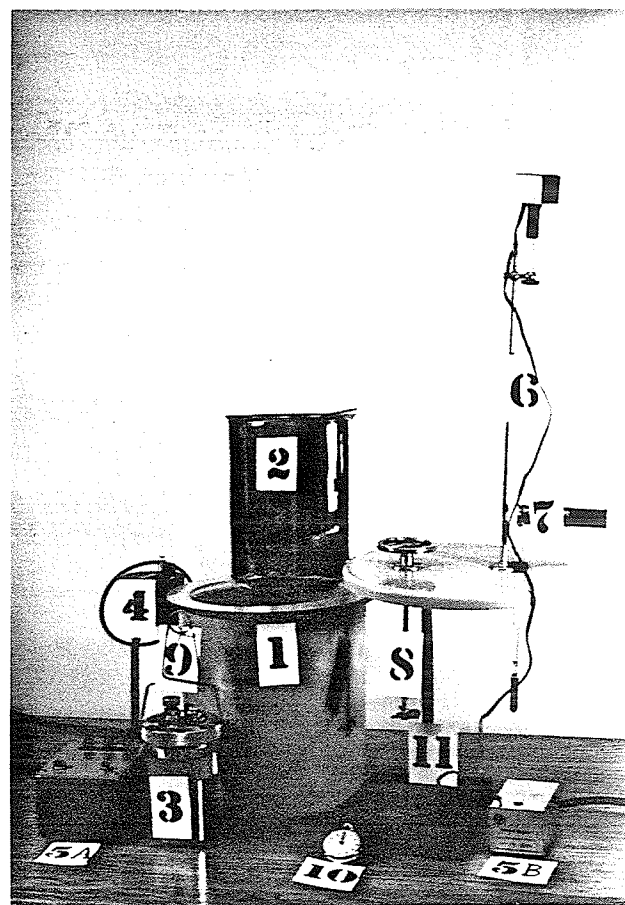


Figure 6: Oxygen bomb calorimeter

1. Plain jacket calorimeter
2. oval bucket for water
3. Oxygen bomb
4. Stirrer driving motor
- 5a. Ignition unit
- 5b. Vibrating unit
6. Thermometer
7. Thermometer reading lens
8. Stirrer
9. Bomb holder tong
10. Stop watch
11. Calorimeter cover stand

benzoic acid pellets were provided by Parr Instrument Co. This capsule was placed on the stand attached to the bomb head and the fuse wire was adjusted so that it just touched the sample. One ml. of distilled water was added to the bomb with a pipette to saturate the combustibles formed during the burning process. The bomb was closed by turning the nut and tightened by hand only. Oxygen was added to the bomb by a oxygen filling unit shown in figure 7. The bomb was lowered down into the distilled water in the oval bucket and the calorimeter was closed by putting on its cover. The stirrer drive belt was connected between the drive wheel and driving motor. A thermometer was lowered down into the bucket water to sense the temperature rise. This thermometer was accurate to two decimal places, and an estimate was possible for the third place. A reading lens was used to read the thermometer accurately. A vibrating unit (No. 5B in figure 6) was connected with the thermometer so that by pressing its button, it vibrates the thermometer. When there is rise in temperature the mercury some times sticks at one place so, by vibrating it, this possibility is avoided.

All electric connections were connected and the stirrer was started. The starting temperature was recorded and at minute intervals a reading was taken until it became constant. This process usually take 5 minutes. When the thermometer reading was constant the ignition button was

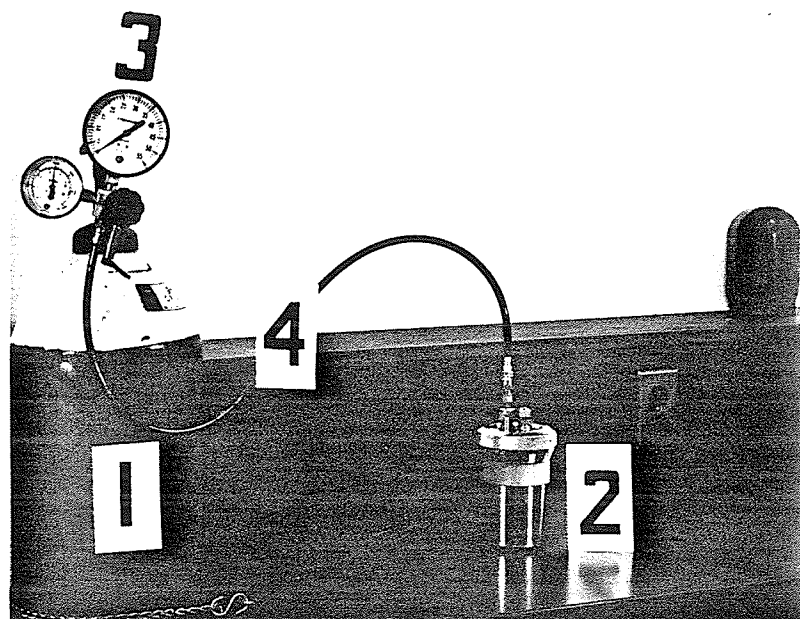


Figure 7: Oxygen filling unit

1. Oxygen cylinder
2. Oxygen bomb
3. Gas pressure indicator
4. Oxygen filling pipe

pressed allowing an electric current to pass through the fuse wire. Due to its resistance, the wire gets red hot. In the presence of oxygen the benzoic acid pellet burns and the heat is liberated throughout the bomb. The heat is taken up by the bucket water and so the thermometer shows a temperature rise. Initially the rise in temperature is very rapid so the first two minutes of thermometer readings were observed at 15 second intervals. Thereafter these readings were observed every minute. These readings were taken until the thermometer shows no more rise in temperature. At this stage the experiment was stopped. after taking out the electric plugs, the calorimeter cover was opened up and placed on its stand. The oxygen bomb was taken out from the bucket with the help of a tong and by opening the safety valve, its gas pressure was slowly released. When all the gas escaped, the bomb was opened and the head taken out. The capsule was taken out from its stand and kept in a beaker. The fuse wire left over after burning was carefully removed from the terminals and its length was measured. The inside of the oxygen bomb and terminals were washed with a jet of distilled water which was collected and poured into the beaker in which the capsule was placed. In this beaker two drops of methyl orange indicator were added and the solution was titrated against a 0.0725 N Sodium carbonate solution on a titration unit shown in figure 8. This is done to determine the volume of nitric acid formed. Then the value

of the energy equivalent factor,  $W$ , was calculated according to the formula described in chapter 3.

#### 4.4.1 Measuring The Fuse Wire

After burning, the left over fuse wire is not straight and it is almost impossible to straighten it completely. So it can not be measured very accurately by a scale. For this reason, it was tried to establish a relationship between mass and length of fuse wire so that by weighing the fuse wire the length could be computed. It was a time consuming process compared to the error provided in the heat value calculation. So the wire was measured by the length only.

#### 4.4.2 Pressure In The Bomb

Parr instruction manual no. 147 gave the maximum oxygen pressure limit in the bomb, of 3040 kPa (kilo Pascal) but when using loose samples, this pressure was too high. The safe pressure at which the loose sample did not fall down from the capsule was found to be 2230 kPa. so, in all the heat value measurement experiments, the oxygen pressure in the bomb was kept at 2230 kPa.

#### 4.5 HEAT VALUE DETERMINATION

To find the heat values of different residues at different moisture contents the residues were chopped into smaller

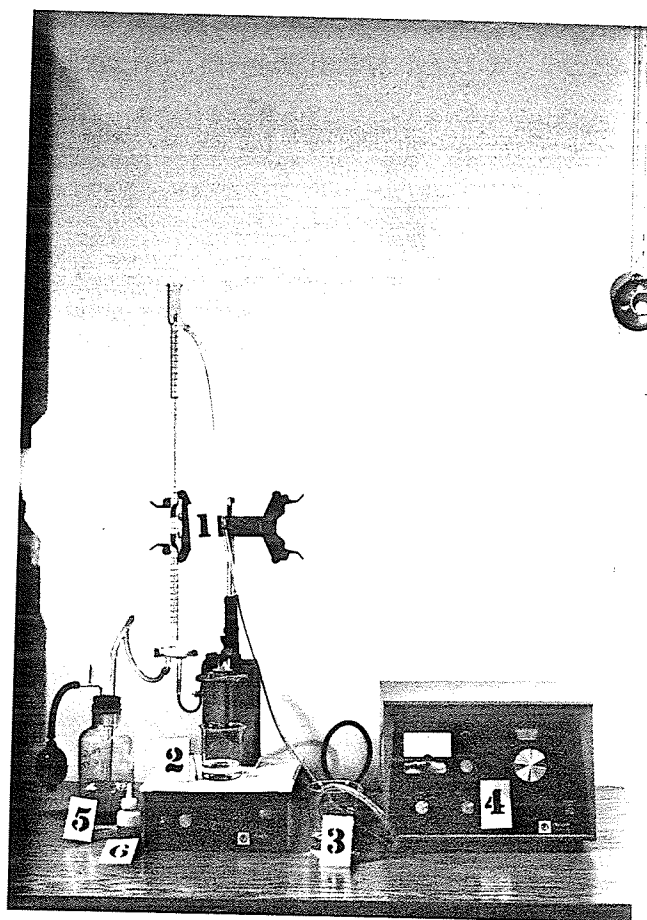


Figure 8: Titration unit

1. Burette with stand
2. Nitric acid solution received from oxygen bomb after burning the sample
3. Overflowed sodium carbonate
4. Titration control unit
5. Solution of sodium carbonate
6. Methyl orange indicator

sizes and brought upto the desired moisture content by drying in the air oven. Then for one moisture content, the known weight of the residue was placed in the capsule and allowed to burn in the oxygen bomb in the presence of oxygen, and the temperature rise was observed. The whole procedure for burning the sample was exactly the same as described in the standardization paragraph. After finding the temperature rise, the volume of nitric acid formed and length of left over wire after burning, the heat value for each residue at one moisture content was calculated according to the formula described in chapter 3. At one moisture content five replicates were taken and the mean of all five values was reported as the heat value at that moisture content. The calculations for heat value were done with the help of a computer program given in appendix A. The graphs relating heat value and moisture content for each residue were drawn and the equations for finding heat value at a particular moisture content for each residue were found by using a computer program given in appendix B.

#### 4.6 MOISTURE CONTENT REGULATION

Some residues, for example, sunflower hulls and pulp, coal and alfalfa had very low moisture contents when collected. To find the nature of the curve and also to find the equations, it is necessary to have at least four readings, which can be obtained only when the samples have higher moisture



content. To increase the moisture content in the residues a device known as a "Moisture Adding Unit", was constructed during the experiment. This unit, shown in figure 9, consisted of a garbage container, a centrifugal fan, one perforated flexible pipe, wire mesh buckets and some polyethelene covers. The residues that required an addition of moisture were kept in wire mesh buckets inside the can and covered by polyethelene papers to avoid the drip of water, deposited on top cover of the container due to condensation. A flexible perforated pipe was fitted at the suction side of a fan so that when the fan starts, circulation of wet air takes place inside the can so that the sample gets uniform moisture exposure. The samples were kept in this container for about 50 hours. It was found that fungus started growing if the samples were kept for a greater length of time.

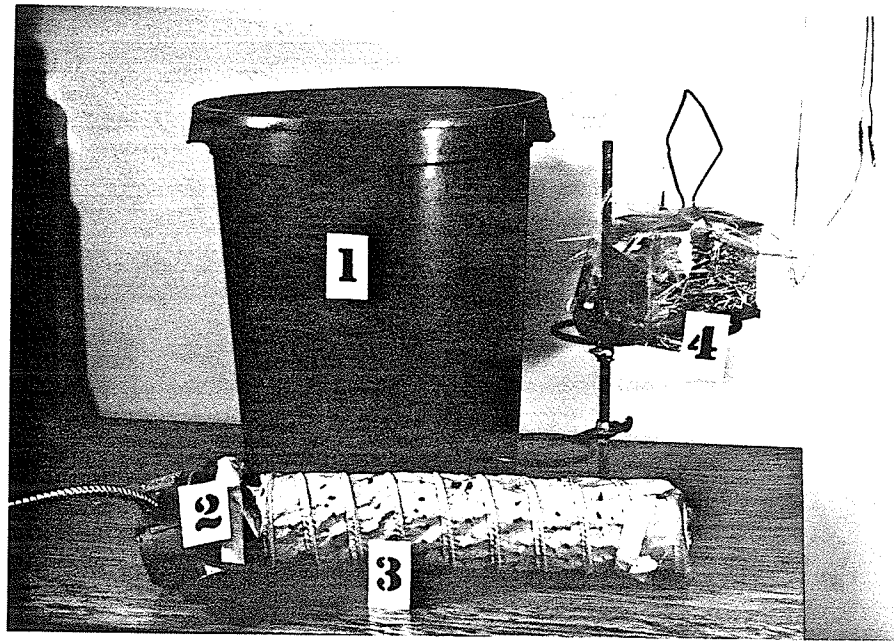


Figure 9: Moisture adding unit

1. Container for keeping samples, water and fan
2. Centrifugal fan
3. perforated flexible pipe
4. Samples in a wire mesh bucket

## Chapter V

### RESULTS AND DISCUSSIONS

Based on the procedure described in chapter 4, readings with alfalfa, barley straw, corn silage, flax straw, forest peat, oat straw, sunflower seed hulls and pulp mixture, wheat straw and coal were taken. At each moisture content, five replicates were taken and their average was recorded as the heat value at that moisture content.

#### 5.1 HEAT VALUE OF RESIDUES

##### 5.1.1 Alfalfa

For alfalfa the higher and lower heat values in MJ/kg (Mega joules per kilogram) at different moisture contents are recorded in Table 5.1.

Based on the data recorded in Table 5.1 a curve for heat value versus moisture content was drawn (figure 10). The solid lines in the curve are for experimental values. These values were obtained by burning alfalfa in the presence of oxygen in a calorimeter. The curve shows the highest of higher and lower heat values were at 0% moisture content and those were 18.46 and 18.44 MJ/kg respectively. At 20% moisture content (figure 10) the higher heat value was 12.78 MJ/kg and the lower heat value was 12.40 MJ/kg. The curve

TABLE 5.1

Heat values of Alfalfa at different

moisture contents

Moisture %	Experimental Values		Calculated Values from regression equation	
	Higher Heat	Lower Heat	Higher Heat	Lower Heat
	value, MJ/kg	value, MJ/kg	value, MJ/kg	value, MJ/kg
0.0	18.46	18.44	18.46	18.44
6.43	16.33	16.14	16.33	16.14
11.93	14.43	14.11	14.43	14.11
33.74	12.15	11.26	12.15	11.26



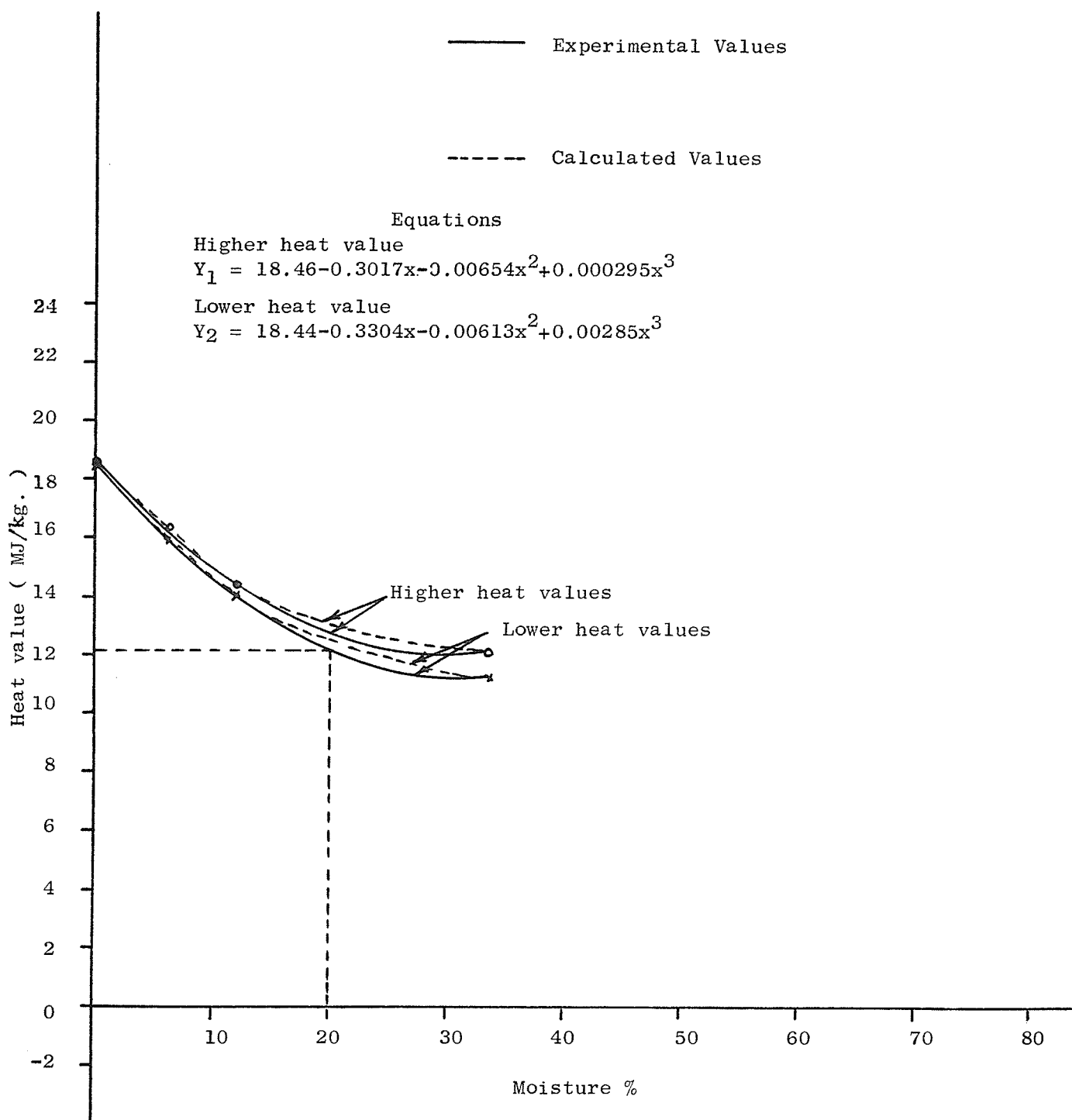


Figure 10: Heat value vs. moisture content for Alfalfa

shows that as the moisture content in the sample increases, the heat value decreases as well as the difference between the higher and lower heat value keep on increasing with the increase in moisture content. This is because at the high moisture content, total solids are less and so contribute less heat while at low moisture content the converse is true. In the case of lower heat value at low moisture content of the crop residue, loss of heat due to vapourization of water is less but loss of heat due to evaporation of water vapours, formed by the reaction of hydrogen and oxygen, become more significant because the hydrogen present is represented as the percentage of dry matter. At low moisture content the total solids are relatively large, hydrogen present is also greater and consequently the losses are greater. At high moisture content the heat loss due to vapourization becomes quite high and so the lower heat value is considerably lower than the higher heat value.

Based on the experimental values which are the solid lines on the graph, the curve was drawn and by the nature of the plotted points, a polynomial curve was found most appropriate. A computer program (appendix B) was used to find the degree of polynomial and the coefficients. In that program the degree of polynomial were varied from 2 to 9 to find the most appropriate one. For alfalfa, the degree of 3 was found most appropriate for the experimental values, as

the value of Beta, the regression coefficient, was zero. The program has given the coefficients by which the regression equations for higher and lower heat values were found by rounding some figures. These equations are:

Higher heat value

$$Y_1 = 18.46 - 0.3017x - 0.00654x^2 + 0.000295x^3$$

Lower heat value

$$Y_2 = 18.44 - 0.3304x - 0.00613x^2 + 0.00285x^3$$

where x is the moisture percent in alfalfa.

From the equations the higher and lower heat values were calculated at different moisture contents and the values are reported in Table 5.1 under the heading of "Calculated values from regression equation". By comparing the experimental and calculated values, it was found that both of them are exactly the same indicating the regression equation is accurate.

#### 5.1.2 Barley Straw

When the barley straw was burned in the calorimeter at 0% moisture content, the heat value obtained was 17.54 MJ/kg by which the lower heat value comes out to be 17.52 MJ/kg. The tests were conducted at different moisture contents upto a maximum moisture content of 70.54% on wet basis. The details of heat values obtained at different moistures are given in Table 5.2. From these values the curves drawn between heat

value and moisture content is shown in figure 11. The solid lines are for experimental values. According to this curve the highest heat values are at 0% moisture and decreases rapidly with increase in moisture content. Between 20% to 33% moisture content the decrease in heat values was low and the curve flattens in this region. After 33% moisture the heat values again decreases very rapidly. Above 57% moisture content the lower heat value becomes negative while the higher heat value remains positive. It shows that the higher heat value obtained by burning barley straw which is over 57% moisture, was only due to the condensation of water vapour present in the sample. Also the higher heat was obtained from condensation of water vapours formed by the interaction of hydrogen and oxygen. The solid matter at such a high moisture content does not burn at all. When it is a closed burning system the heat value obtained is positive but in open air burning all the heat of condensation can not be recovered and so instead of giving off heat the residue starts taking heat from the surroundings and shows the negative value.

For barley straw the equations for finding the higher heat value and lower heat value were found by a polynomial curve fit using the computer program (Appendix B). In this case the curve fit at a 4th degree polynomial for both higher and lower heat values. In the case of higher heat value, beta, the regression coefficient, for the 4th degree



TABLE 5.2

Heat values of Barley Straw at different

moisture contents.

Moisture %	Experimental Values		Calculated Values from regression equation	
	Higher heat	Lower heat	Higher heat	Lower heat
	value, MJ/kg	value, MJ/kg	value, MJ/kg	value, MJ/kg
0.0	17.54	17.52	17.60	17.58
8.13	11.55	11.32	11.82	11.60
15.30	11.34	10.93	9.89	9.49
21.49	9.13	8.56	9.31	8.76
23.85	7.85	7.30	9.18	8.57
30.79	8.17	7.37	8.68	7.89
35.28	8.41	7.49	8.07	7.17
40.68	6.87	5.81	6.93	5.88
46.06	7.09	5.90	5.36	4.16
51.76	3.21	1.86	3.39	2.04
56.94	0.29	-1.19	1.61	0.13
65.66	0.14	-1.56	-0.18	-1.89
70.54	0.35	-1.47	0.28	-1.54

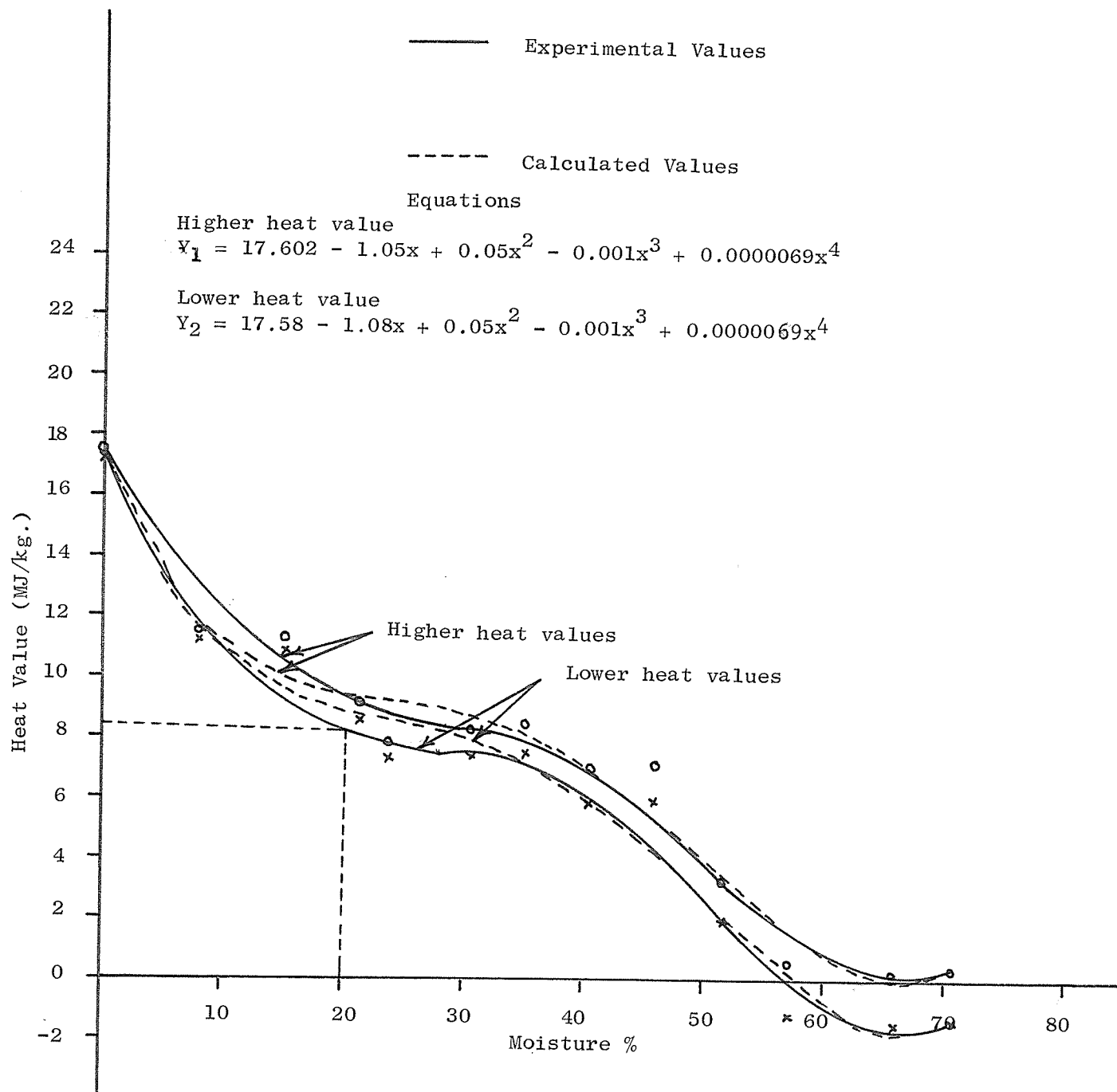


Figure 11: Heat value vs. moisture content for Barley Straw

equation is 0.000466. For the 3rd degree equation the coefficient is 0.1507269 and for the 5th degree it is 0.0071112, i.e. beta is minimum at 4th. In the case of lower heat value beta is a minimum at 0.0004219 for degree 4, going higher at 3 and 5 and increases even more as it goes for higher degree polynomial. Therefore, the equations obtained for:

Higher heat value

$$Y1 = 17.602 - 1.05x + 0.05x^2 - 0.001x^3 + 0.0000069x^4$$

Lower heat value

$$Y2 = 17.58 - 1.08x + 0.05x^2 - 0.001x^3 + 0.0000069x^4$$

From these equations the heat values were calculated by putting a value of moisture percent in place of x and reported in Table 5.2 under the heading of calculated values from regression equation. In figure 11 the dotted lines show the calculated higher and lower heat values. By comparing the solid and dotted lines in the curve, it is seen that both follow the same trend and the difference between the solid and dotted line is very minute. This shows the equations obtained are correct and can give accurate heat values if the moisture content of the barley straw is inserted into the equation.

### 5.1.3 Corn Silage

The heat values obtained by experiments on corn silage show that the higher and lower heat values are quite close at low moisture contents and the difference between the two values increases with increase in moisture content. The moisture content variation was from 0% to 65.07% On a wet basis so that the lowest of higher and lower heat values were 3.93 and 2.25 MJ/kg respectively at 65.07% moisture. The highest of these values were at 0% and amounted to 17.80 MJ/kg and 17.78 MJ/kg respectively. The curve relating heat value and moisture percent show the rapid reduction of heat values from 0 to 25% moisture content after which the rate of reduction becomes comparatively low. In the case of barley straw the lower heat value went to a negative value after 57% moisture but in this case both the heat values remain positive upto much higher moisture values. The trend of the curve indicates that above 70% moisture content the lower heat value may go below the x-axis. The higher heat value will always be positive, because there is always some condensation of water vapours formed by oxygen and hydrogen which contributes to the higher heat value.

The results of heat values obtained at different moisture contents are given in Table 5.3 and based on these values the curve is shown in figure 12.

The curve fitting was done by polynomial curve by varying the degree of polynomial from 2 to 9. For higher heat value at the 6th degree equation the regression coefficient of 0.0000003 was found minimum. for the 5th degree it was 0.0000030 and for the 7th it was 0.0000041. Its value increases even more on both sides. Therefore, the equation for higher heat value for corn silage was obtained as

$$Y1 = 17.69 - 0.446x + 0.0126x^2 - 0.00048x^3 + 0.000015x^4 \\ - 0.00000022x^5$$

where x is the moisture percent in the sample.

For finding the equation of lower heat value again the 6th degree of polynomial gives the lowest beta value which is 0.0000003, and shows the best fit with the equation given below

$$Y2 = 17.67 - 0.47x + 0.013x^2 - 0.00051x^3 + 0.000015x^4 \\ - 0.00000024x^5.$$

By these two equations the heat values are tabulated at different moisture content and in the curves they are shown by the dotted line. In figure 12 it is seen that for higher heat value, the calculated and experimental values are exactly the same upto 15% and above 55% moisture whereas from 15 to 55% there is a slight variation in two values.

For lower heat values the experimental and calculated values are exactly the same upto 7% and above 56%. Between

TABLE 5.3

Heat values of Corn Silage at different

moisture contents

Moisture %	Experimental Values		Calculate Values from regression equation	
	Higher Heat	Lower Heat	Higher Heat	Lower Heat
	Value, MJ/kg	Value, MJ/kg	Value, MJ/kg	Value, MJ/kg
0.0	17.80	17.78	17.69	17.67
5.07	15.23	15.09	15.69	15.55
10.37	14.50	14.22	14.03	13.75
14.75	13.33	12.94	12.86	12.48
18.99	11.26	10.76	11.89	11.40
25.59	10.16	9.49	10.67	10.01
29.22	9.94	9.18	10.14	9.38
32.77	11.28	10.43	9.70	8.85
39.54	7.85	6.83	8.97	7.91
48.73	8.31	7.05	7.85	6.51
53.10	6.88	5.51	7.05	5.75
65.07	3.93	2.25	3.93	2.24

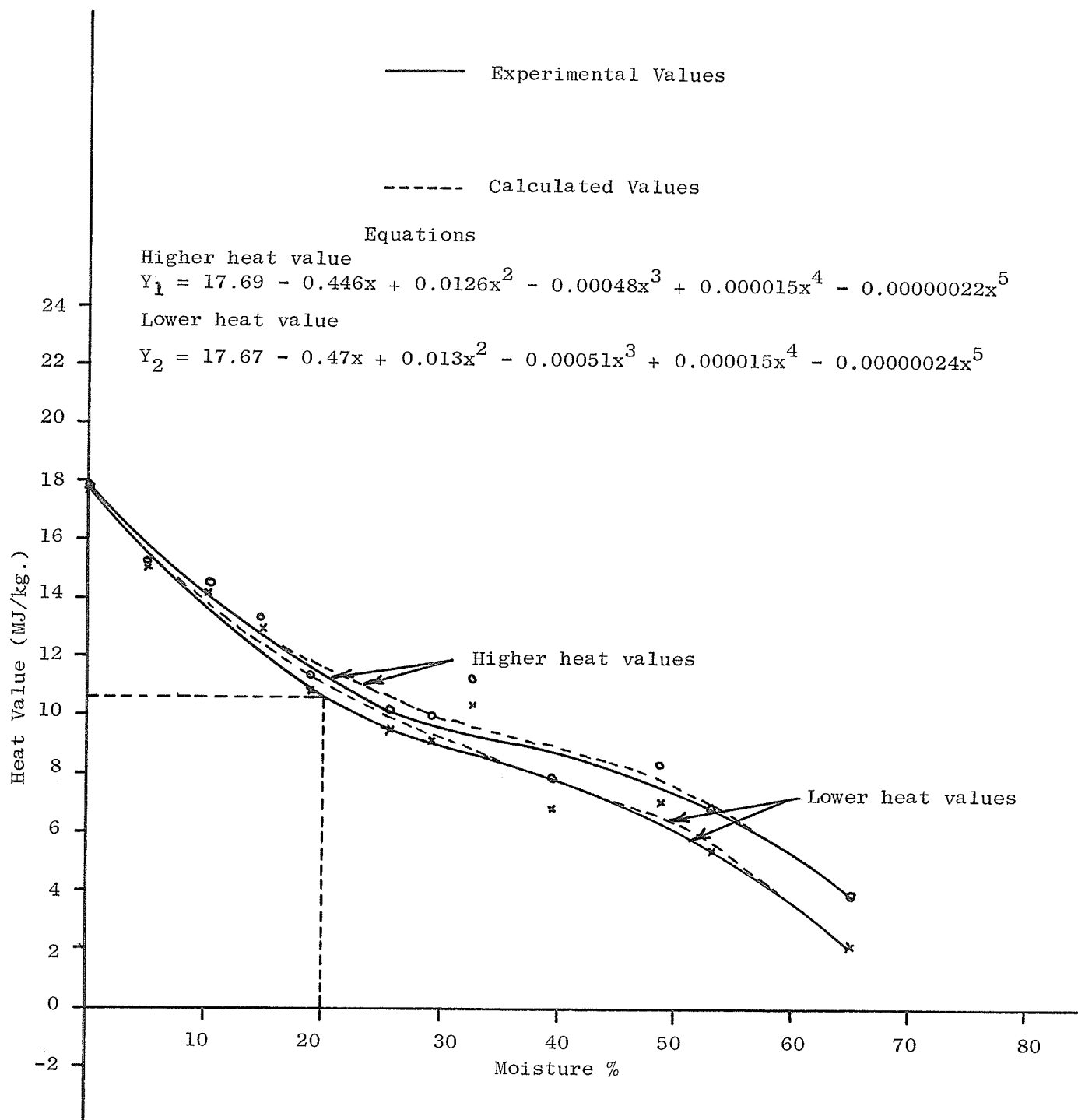


Figure 12: Heat value vs. moisture content for Corn Silage

these the heat values have little variations. Both the higher and lower heat values follow the same trend in the calculated values curve and experimental values curve.

#### 5.1.4 Flax Straw

The moisture content for flax straw tests was varied from the completely dried stage upto a maximum of 83.14% on wet basis. The difference between experimental higher and lower heat value was 0.02 MJ/kg at 0% which increased with an increase in moisture content and goes upto a maximum of 2.14 MJ/kg at 83% moisture. The maximum of higher and lower heat values were obtained at 0%, where they were 19.99 and 19.97 MJ/kg respectively. Both the heat values decrease more rapidly between 0 to 17% moisture, after which the rate of reduction becomes a little bit lower. The higher heat value always remain positive; as some hydrogen is liberated, combining with oxygen to form water vapour which in turn condenses and contributes heat. The lower heat value above the 52% moisture level goes to the negative value. This negative value increases with an increase in the moisture content of the sample. The heat values at different moisture contents are shown in Table 5.4 and the curve drawn for heat value versus moisture content is shown figure 13 in which the solid lines are for experimental values.

For flax straw the curve fitting was done by the power curve and by polynomial curve. The power curve fit gave the equations for higher and lower heat values as shown below:



Higher heat value

$$Y1 = 0.00014x^{2.7} \quad \text{for } r2 = 0.98$$

and lower heat value

$$Y2 = 0.3x^{1.03} \quad \text{for } r2 = 0.97$$

Where  $r2$  is the regression coefficient and the closer it is to 1.0, the more accurate is the equation. In both the equations the value of  $r2$  is quite close to one.

When the computer program was used for the polynomial curve fit (Appendix B), the equations obtained were:

Higher heat value

$$Y1 = 20.15 - 1.38x + 0.07x^2 - 0.0014x^3 - 0.00000634x^4 \\ + 0.00000042x^5$$

$$Y2 = 20.13 - 1.4x + 0.07x^2 - 0.0014x^3 - 0.0000063x^4 \\ + 0.00000041x^5$$

In the polynomial curve fit for the higher heat value, the minimum value of beta, the regression coefficient, was obtained at the 8th degree polynomial. This value of beta was 0.0000032. Beta should be as close to zero as possible for the best curve fit and the above value of beta was the closest to zero. Similarly for lower heat value the above mentioned equation was obtained at the 8th degree polynomial at a minimum beta value of 0.0000027.

TABLE 5.4

Heat values of Flax Straw at different

moisture contents

Moisture %	Experimental Values		Calculated Values from regression equation	
	Higher Heat	Lower Heat	Higher Heat	Lower Heat
	Value, MJ/kg	Value, MJ/kg	Value, MJ/kg	Value, MJ/kg
0.0	19.99	19.97	20.15	20.13
6.15	14.42	14.24	14.01	13.84
13.04	11.06	10.71	11.00	10.65
17.13	10.16	9.70	10.17	9.71
22.53	8.34	7.74	9.36	8.76
32.47	7.97	7.12	7.16	6.31
39.27	5.89	4.86	4.96	3.94
42.86	3.06	1.95	3.76	2.65
47.41	1.99	0.76	2.40	1.17
54.93	0.81	-0.62	0.91	-0.52
61.10	0.67	-0.92	0.44	-1.15
69.10	0.15	-1.64	0.17	-1.62
83.14	0.04	-2.10	0.05	-2.09

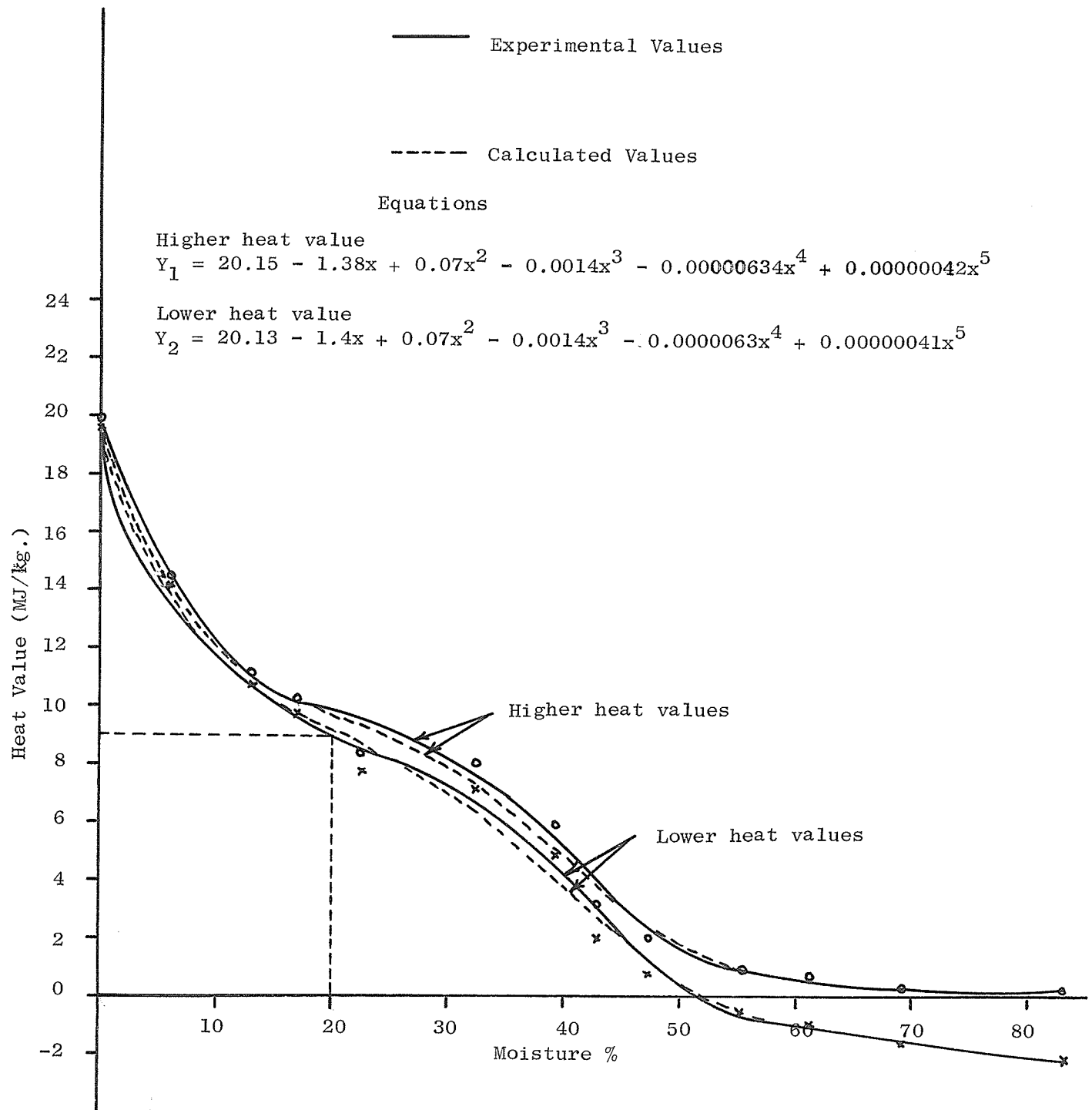


Figure 13: Heat value vs. moisture content for Flax Straw

When the equations obtained by the power curve fit are compared with the equations obtained by the polynomial curve fit, it is found that the power curve equations are very simple and short. The power curve equations have a number of limitations, which restrict its use for heat value calculation for flax straw. The first limitation is that the y axis of the curve has to be changed from left to right of the x axis, secondly these equations are good only for the positive heat values and does not give accurate results when the curve goes below the x axis. These limitations are very major and so with this consideration the equations obtained by the polynomial curve fit, though long, were used as the equations of flax straw and so by these equations, the higher and lower heat values were calculated and reported in Table 5.4 under the heading of calculated values from regression equation. From these calculated values, the curve drawn is shown in figure 13 by a dotted line. This figure shows the nature of the curve for both the experimental and calculated values is the same. The calculated values are exactly the same as experimental values between the moisture contents of 13 and 17.5%, 45 to 47% and after 61% for higher heat value and between 7.5 to 17%, 45 to 52% and over 57% moisture for lower heat value. In other moisture ranges also they are quite close to the experimental values.

#### 5.1.5 Forest Peat

Steklasa (1980) and Othmer (1978) put a great deal of emphasis on using peat as a combustion fuel. Over 200 million tons of peat is produced annually world wide and Canada has an abundant supply. Usually peat has a low or negligible sulfur content so no injurious combustion gases are released into the environment. To use peat as a fuel it was found necessary to test for its heat content. Tests were conducted on forest peat named here as only peat.

When peat was burned in a calorimeter, in the presence of oxygen, it gave a maximum heat of 17.76 MJ/kg at 0% and a minimum of 0.03 MJ/kg at 78.98% moisture. After subtracting the heat of condensation of water vapours, the lower heat value obtained was a maximum of 17.74 MJ/kg at 0% moisture content. The details of heat values are given in Table 5.5. the curve drawn for these values between heat value and moisture content is shown in figure 14. From the curve it is seen the heat value decreases rapidly from 0 to 30% moisture. From 30 to 37% the rate of reduction is very low after which this rate again increases. At more than 60% moisture the curve becomes almost flat for both the heat values. At 55% moisture content, the lower heat value becomes negative, i.e., at more than 55% peat instead of giving heat starts taking heat from surroundings.

The equations for finding heat values at various moisture contents the heat values at corresponding moisture content, taken from the experiment, were put into the computer program. From this program the 9th degree polynomial looked to be the most suitable for the experimental curve drawn for higher heat value, as at this degree the lowest beta obtained was 0.0000162. At 68.04% moisture, the heat value obtained by the equation was negative, which is not true as the higher heat value is always positive. This can be taken as a limitation of this equation establishing that at 68% moisture, it does not give an accurate result. At more than this moisture level, values obtained were quite close to the experimental results and the same was true with lower than 68% moisture. The equation obtained for higher heat value is:

$$Y1 = 17.79 - 0.483x - 0.015x^2 - 0.00143x^3 - 0.000031x^4 \\ + 0.00000012x^5$$

For the lower heat value the polynomial curve gives the lowest beta of 0.0000155 at the 9th degree polynomial and so the equation obtained for this is:

$$Y2 = 17.77 - 0.5x - 0.016x^2 + 0.0015x^3 - 0.000032x^4 \\ + 0.00000012x^5$$

From these two equations the calculated values were obtained and the curve drawn from these values is shown by the dotted line in figure 14. This figure indicates that in

TABLE 5.5

Heat values of Peat at different moisture

contents

Moisture %	Experimental Values		Calculated Values from regression equation	
	Higher Heat	Lower Heat	Higher Heat	Lower Heat
	Value, MJ/kg	Value, MJ/kg	Value, MJ/kg	Value, MJ/kg
0.0	17.76	17.74	17.79	17.77
11.28	12.14	11.86	12.04	11.75
15.65	10.24	9.82	10.38	9.98
25.45	8.52	7.84	8.34	7.67
31.26	7.86	7.04	7.71	6.89
36.68	6.52	5.56	7.00	6.04
42.11	5.71	4.61	5.91	4.81
46.38	5.29	4.09	4.72	3.52
60.45	0.22	-1.34	0.49	-1.07
68.04	0.04	-1.72	-0.09	-1.85
78.98	0.03	-2.00	0.05	-1.99

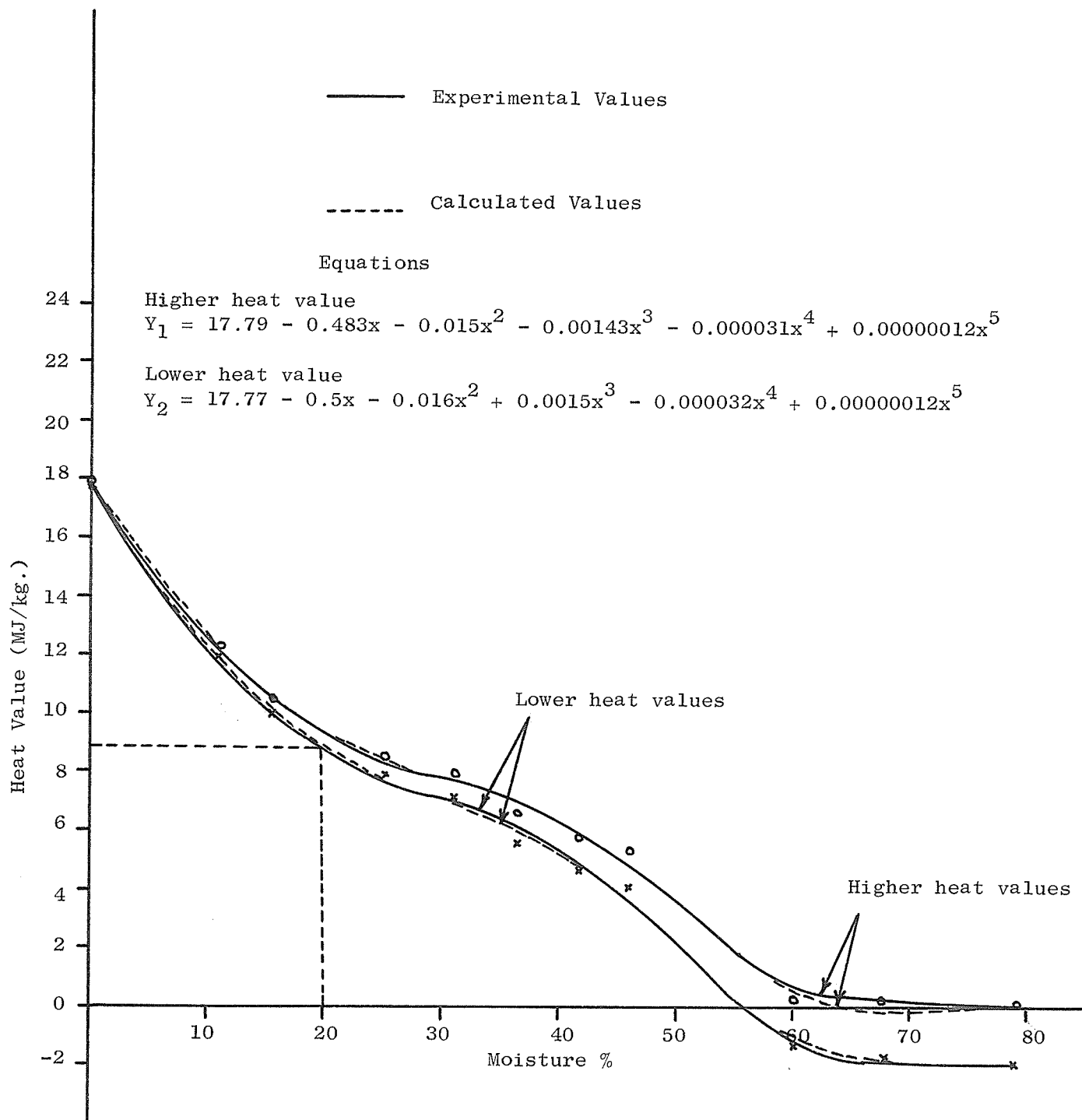


Figure 14: Heat value vs. moisture content for Forest Peat



most cases the calculated and experimental values are either very very close or they are exactly the same which indicates that the equations obtained for the two heat values are correct and have the most appropriate constants.

#### 5.1.6 Oat Straw

Oat straw samples were burnt at different moisture contents and the results show that it can give the maximum of higher and lower heat when it does not contain any water. At this stage these two heat values are 18.03 MJ/kg and 18.01 MJ/kg respectively. the results of heat values are reported in Table 5.6. The curve drawn for the experimental heat values at different moisture percent is shown by solid lines in figure 15. This figure shows the peak of both heat values at 0% moisture and they decrease sharply upto 20% moisture, such that at this moisture content the lower heat value is only 7.58 MJ/kg. From 20 to 30% of moisture, the rate of reduction of heat values is low and after that again the rate becomes very fast. After 46% of moisture level the lower heat value becomes negative.

At the 5th degree polynomial the value of beta obtained was 0.0001655 for higher heat value, which was the minimum. The resulting equation found from the coefficients at the 5th degree is:

$$Y_1 = 18.1 - 0.63x - 0.022x^2 + 0.0026x^3 - 0.000071x^4 + 0.0000006x^5$$

The higher heat values were calculated from this equation and from that the graph drawn is shown by dotted line in figure 15. It shows that from 30% to 45% moisture, the calculated higher heat value line is little apart than the line of experimental values; otherwise both of them coincide.

For the lower heat value the minimum beta was found to be 0.0001647 at the 5th degree polynomial and the equation is:

$$Y_2 = 18.08 - 0.65x - 0.02x^2 + 0.0026x^3 - 0.000071x^4 + 0.0000006x^5$$

The values obtained from this equation are drawn on the graph and show that the calculated and experimental lower heat values are very close.

#### 5.1.7 Sunflower Seed Hulls And Pulp Mixture

The sample was made up of the residue left after removing the oil from sunflower seeds. This waste ordinarily used as a livestock feed can be utilized for energy recovery purposes very well. The test results show that at 0% moisture the higher and lower heat values are 23.60 and 23.58 MJ/kg respectively. The heat values found at different moisture contents are shown in Table 5.7 and for these values the curve is drawn relating heat value and moisture content shown in figure 16. The curve shows both the heat values reduce with an increase in moisture content but the rate of

TABLE 5.6

Heat values of Oat Straw at different

moisture contents

Moisture %	Experimental values		Calculated values from regression equation	
	Higher Heat	Lower Heat	Higher Heat	lower Heat
	value, MJ/kg	value, MJ/kg	value, MJ/kg	value, MJ/kg
0.0	18.03	18.01	18.10	18.08
4.04	15.49	15.37	15.36	15.25
17.60	8.57	8.10	8.71	8.24
27.68	7.45	6.72	7.33	6.60
42.59	2.81	1.70	2.88	1.77
48.27	0.33	-0.93	0.30	-0.96

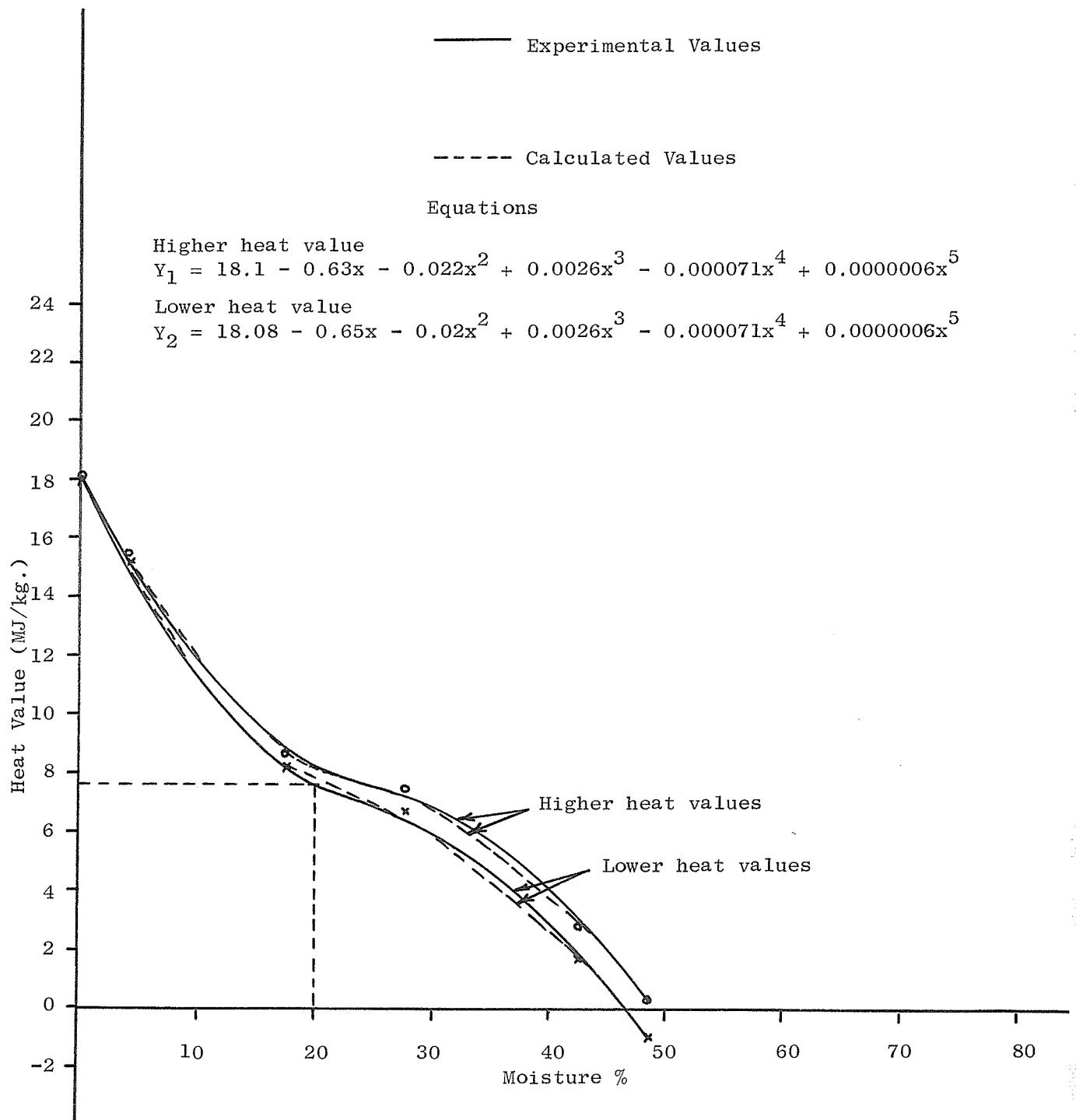


Figure 15: Heat value vs. moisture content for Oat Straw

reduction is low initially upto 8% of moisture and then the rate of heat value reduction is very high so that the curve between 8% moisture and 50% moisture is almost a straight line for both the heat values. After 50% moisture the rate of reduction of heat content reduces and over 60% moisture the curves become almost flat. The higher heat value is always positive but the lower heat value has a negative value when the moisture level rises above 55%.

The higher heat value curve fits the 3rd degree polynomial with a minimum beta of 0.0000050 and similarly the lower heat value curve fits a 3rd degree polynomial with beta equal to 0.0000036. The equations found from the coefficients obtained at this degree of polynomial are:

Higher heat value

$$Y_1 = 23.73 - 0.083x - 0.0127x^2 + 0.00013x^3$$

Lower heat value

$$Y_2 = 23.71 - 0.109x - 0.013x^2 + 0.00013x^3$$

From these equations the heat values were calculated and drawn on figure 16. For the higher heat value the curves show that the calculated and experimental values are exactly the same between the moisture region of 9% and 32%, otherwise in the other region these values are quite close. For lower heat calculated and experimental values coincide from 2% to 21% moisture. The curves for experimental and calculated values show the same trend.

TABLE 5.7

Heat values of Sunflower seed hulls and

pulp mixture at different moisture contents

Moisture %	Experimental values		Calculated values from regression equation	
	Higher Heat value, MJ/kg	Lower Heat value, MJ/kg	Higher Heat value, MJ/kg	Lower Heat value, MJ/kg
0.0	23.60	23.58	23.73	23.71
8.05	22.61	22.38	22.30	22.08
13.28	20.20	19.84	20.67	20.32
19.21	19.77	19.26	18.36	17.84
26.59	13.56	12.85	14.96	14.26
30.44	12.18	11.38	13.06	12.30
34.37	11.62	10.72	11.09	10.19
44.32	7.56	6.40	6.30	5.14
51.58	3.77	2.43	3.30	1.96
56.33	0.30	-1.16	1.73	0.27
66.27	0.20	-1.52	-0.14	-1.86
73.32	0.04	-1.87	0.03	-1.88

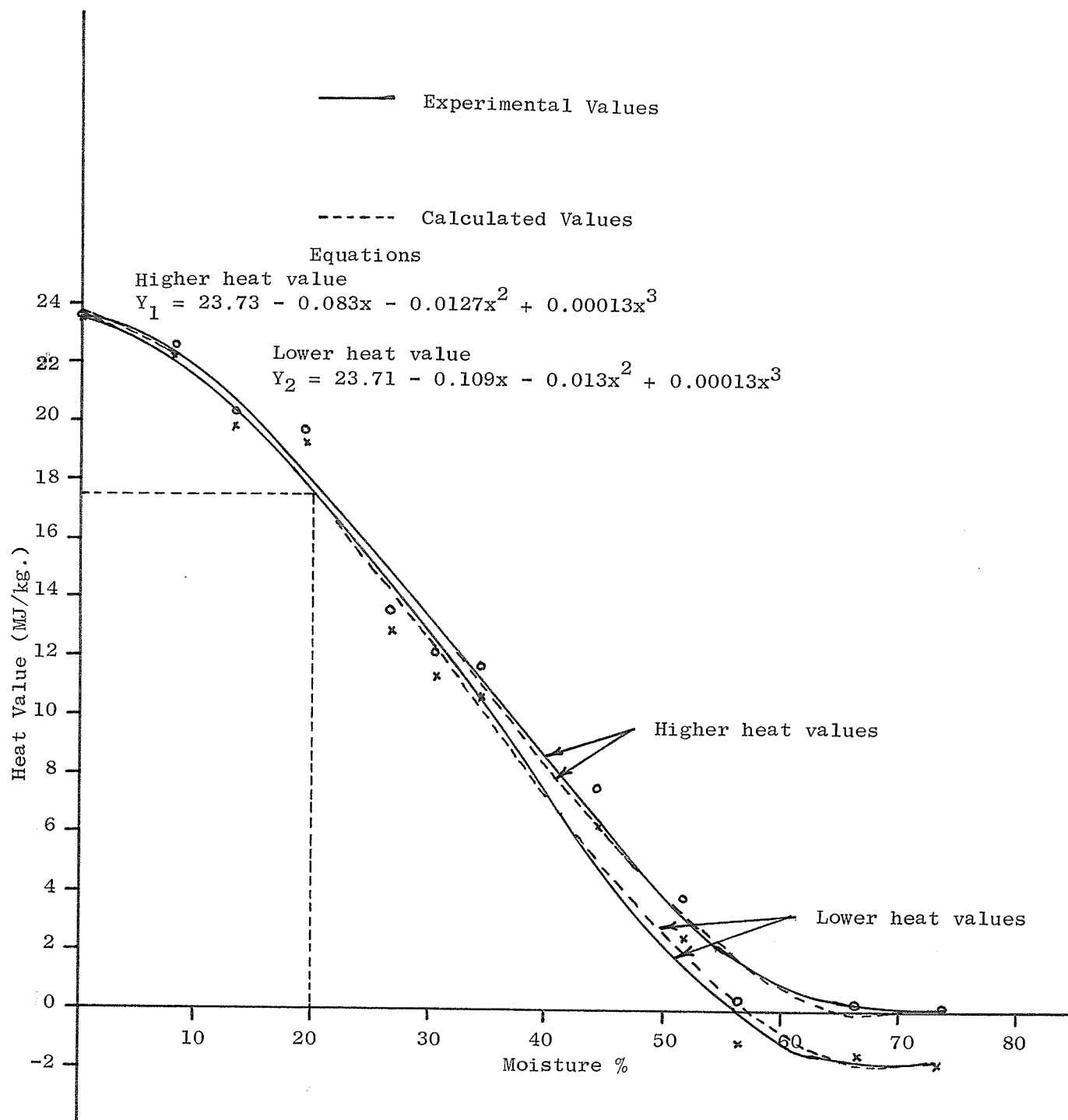


Figure 16: Heat value vs. moisture content for Sunflower Seed Hulls and Pulp mixture

Sunflower seed hulls alone were also tested for their heat content and they gave a higher heat value of 19.21 MJ/kg and a lower heat value of 19.19 MJ/kg, whereas, the mixture of hulls and pulp gave 23.60 MJ/kg and 23.58 MJ/kg respectively at the same moisture content. It shows, when the pulp is added to the residue of sunflower hulls, some extra heat is added into the mixture and thus it can be concluded that the mixture of hulls and pulp of sunflower is better fuel than sunflower hulls only. The details of sunflower hulls heat value are given in Table 5.8.

TABLE 5.8

Heat values of Sunflower hulls at

different moisture contents

Moisture %	Higher Heat Value MJ/kg	Lower Heat Value MJ/kg
0.0	19.21	19.19
10.95	17.79	17.49
24.16	12.03	11.39

#### 5.1.8 Wheat Straw

Wheat straw results show the maximum higher heat value is 17.88 MJ/kg and lower heat value is 17.86 MJ/kg, both at 0% moisture content. In this case the testing was done upto a maximum moisture content of 44.7% and upto this moisture



content no negative value of lower heat value was obtained. At 44.7% moisture the lower heat value is 9.67 MJ/kg and the nature of the curve (figure 17) shows no rapid reduction in heat value.

From the curve drawn it is seen that both higher and lower heat values for wheat straw, reduce slowly with an increase in moisture content. This is the only case where this occurred. The heat values at different moisture contents are shown in Table 5.9.

By the configuration of the curve it appears that the heat value of wheat straw at 0% moisture content should have been greater than the value obtained in the laboratory so as to conform to the same general pattern as of other residues. This value reported in Table 5.9 is the average of five replicates but only one sample was dried to get 0% moisture. An error may have occurred at this point. The data at 20% moisture content follows the normal pattern and it is at this condition the residue would likely be burned properly.

The polynomial curve fit gives the value of coefficients for finding the equations. For higher heat value at the 5th degree polynomial, the value of beta was 0.0000353 which was minimum. Similarly for the lower heat value the minimum beta was obtained at the 5th degree polynomial and it was 0.0000441. Based on the coefficients obtained at this degree the equations for wheat straw are:

TABLE 5.9

Heat values of Wheat Straw at different

moisture contents

Moisture %	Experimental Values		Calculated Values from regression equation	
	Higher Heat	Lower Heat	Higher Heat	Lower Heat
	value, MJ/kg	value, MJ/kg	value, Mj/kg	value, MJ/kg
0.0	17.88	17.86	17.50	17.48
3.45	16.65	16.55	17.38	17.27
11.38	17.92	17.61	17.52	17.22
15.55	17.27	16.85	16.96	16.54
17.16	17.24	16.78	16.61	16.15
19.02	14.97	14.47	16.13	15.63
23.44	15.00	14.38	14.87	14.25
30.86	12.98	12.17	13.20	12.39
34.15	13.22	12.33	12.85	11.96
40.03	12.24	11.19	12.37	11.33
44.70	10.86	9.67	10.82	9.65

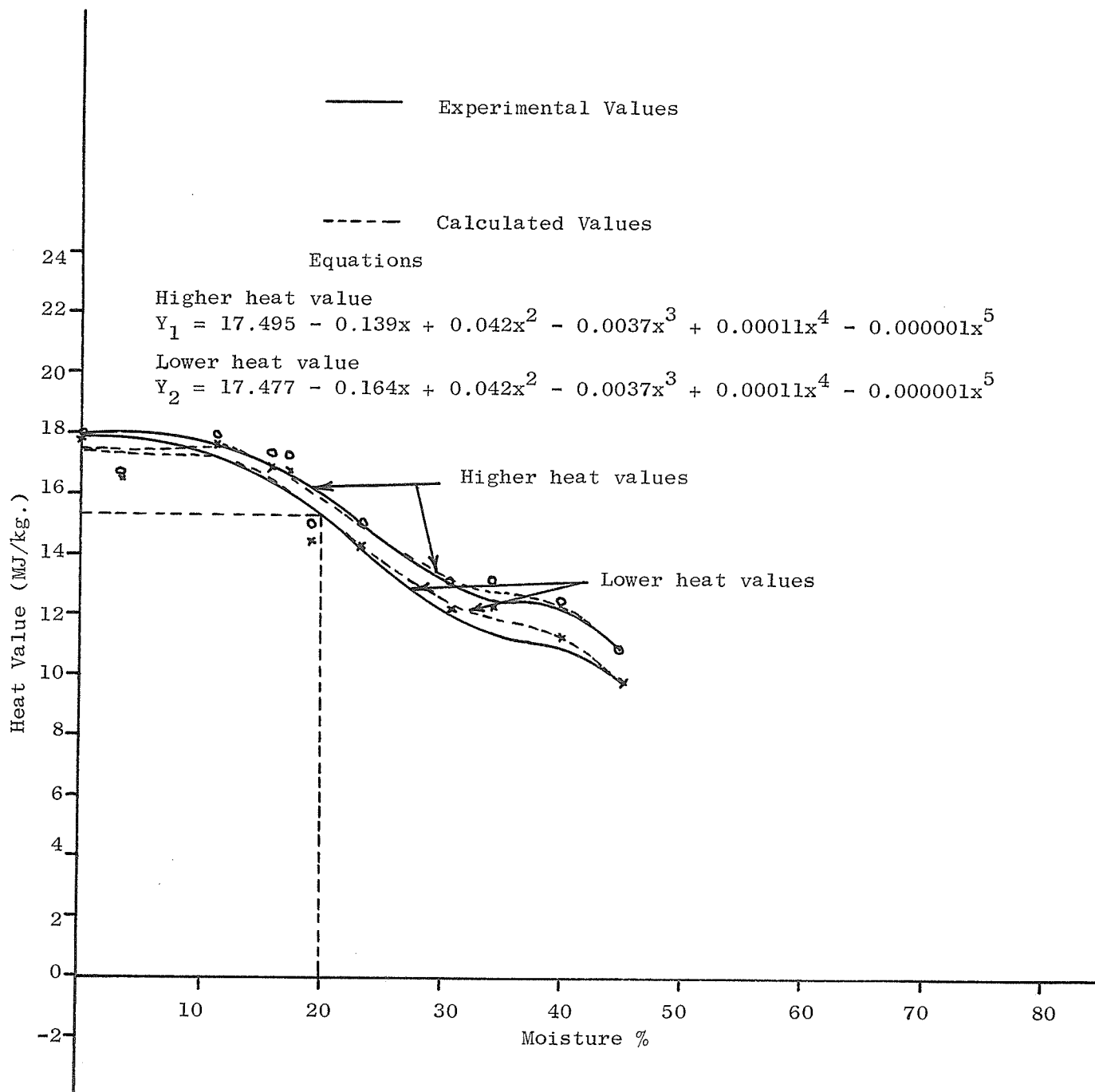


Figure 17: Heat value vs. moisture content for Wheat Straw

Higher heat value

$$Y_1 = 17.495 - 0.139x + 0.042x^2 - 0.0037x^3 + 0.00011x^4 \\ - 0.000001x^5$$

Lower heat value

$$Y_2 = 17.477 - 0.164x + 0.042x^2 - 0.0037x^3 + 0.00011x^4 \\ - 0.000001x^5$$

The curves drawn from the values calculated from these equations (dotted line in figure 17) show that the values of higher and lower heat obtained from the two equations are quite different from the experimental values. Beyond 10% moisture both the higher and lower heat values are quite close for calculated and experimental heat contents. This can be interpreted as a limitation for wheat straw, the equations are very accurate over 10% moisture content, while they are not so accurate below 10% moisture.

#### 5.1.9 Coal

The sample of coal, resembling low quality lignite, was taken from an outcropping in central manitoba. It was burned in the calorimeter at different moisture contents. The moisture content varied from 0% to 30.12% on a wet basis. The heat values obtained are shown in Table 5.10.

The curve drawn for these heat values at various moisture contents is shown in figure 18. The largest higher heat value obtained was 15.32 MJ/kg and lower heat value was

TABLE 5.10

Heat values of Coal at their different

moisture contents

Moisture %	Experimental Values		Calculated Values from regression equation	
	Higher Heat	Lower Heat	Higher Heat	Lower Heat
	Value, MJ/kg	Value, MJ/kg	Value, MJ/kg	Value, MJ/kg
0.0	15.32	15.31	15.32	15.31
12.83	12.88	12.54	12.88	12.54
16.96	11.27	10.82	11.27	10.82
30.12	7.28	6.95	7.28	6.95

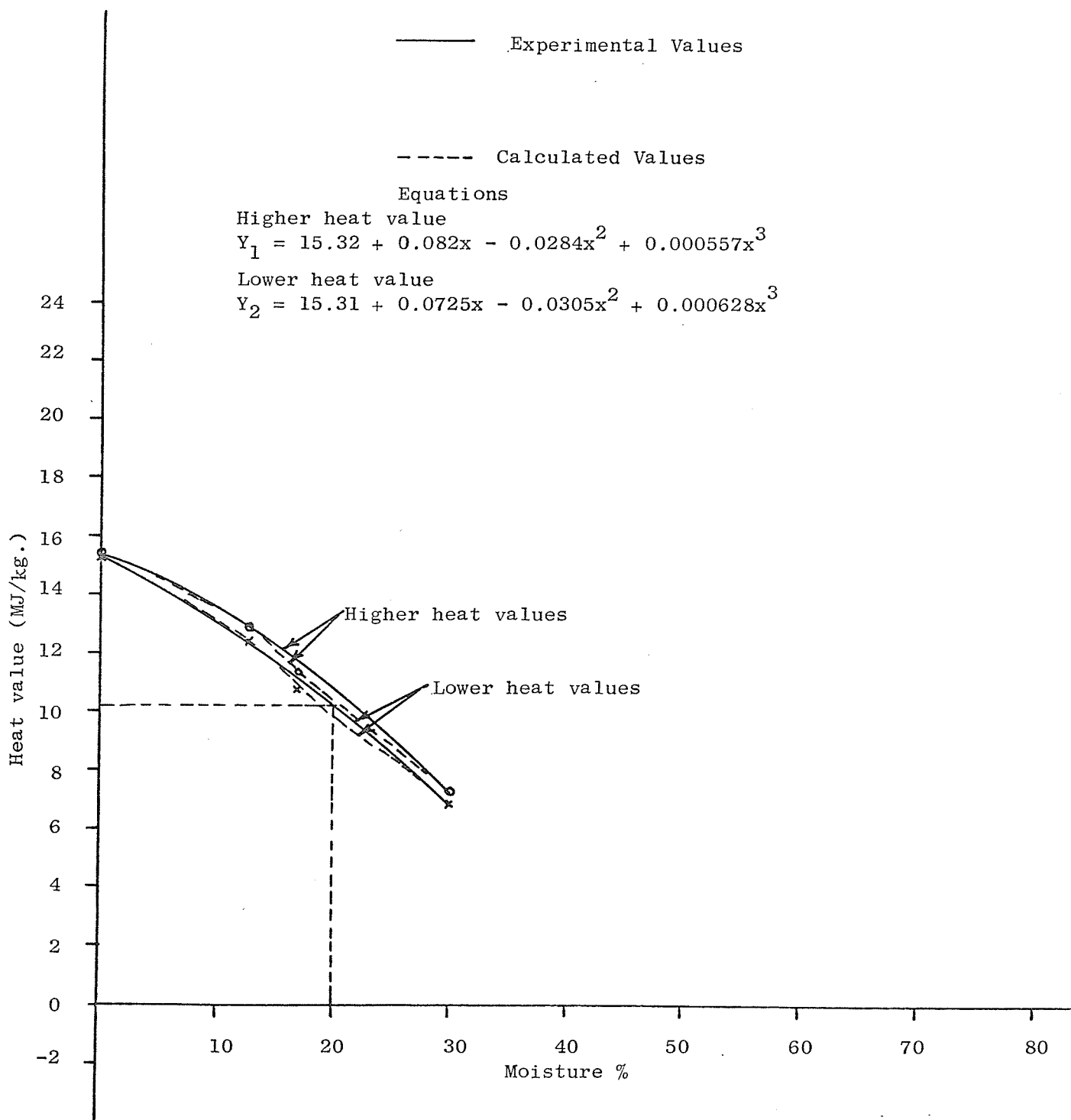


Figure 18: Heat value vs. moisture content for Coal

15.31 MJ/kg both at 0% moisture. As the moisture content was increased, the heat value decreased rapidly.

The curve of the experimental values for the higher heat values fits with a 3rd degree polynomial curve at which the value of beta was zero. Similarly for the lower heat value, equation coefficients were found. The two equations for coal are:

Higher heat value

$$Y1 = 15.32 + 0.082x - 0.0284x^2 + 0.000557x^3$$

Lower heat value

$$Y2 = 15.31 + 0.0725x - 0.0305x^2 + 0.000628x^3$$

The curve drawn by the dotted line in figure 18 show that both the experimental and calculated values are very close or some times even the same, so these two equations are the most appropriate equations for determining heat content of this coal.

## 5.2 COMPARISON OF RESIDUES FOR HEAT VALUES

All the residues examined were compared for their lower heat value by plotting heat values of all residues against moisture content on one graph as shown in figure 19. The lower heat value was chosen for comparison as it is the heat which can be utilized in a regular furnace. From figure 19 it is seen that the mixture of sunflower seed hulls and pulp is

the best source of heat energy almost at all moisture contents and it gives very high heat values compared to other residues. At 0% moisture content it gives 23.60 MJ/kg heat whereas other residues at the same moisture content give heat values ranging from 17.5 to 20 MJ/kg. Similarly at 20% moisture content sunflower hulls and pulp produces 17.60 MJ/kg of heat whereas at this moisture content wheat straw gives 15.30 MJ/kg, alfalfa 12.40 MJ/kg, corn silage 10.80 MJ/kg, barley straw 8.25 MJ/kg, peat 8.75 MJ/kg, flax straw 9.0 MJ/kg and oat straw gives the minimum heat value at this moisture content, 7.6 MJ/kg.

At moisture contents greater than 25% the heat value obtained by sunflower hulls and pulp mixture is lower than the heat obtained from wheat straw. At very high moisture levels, i.e. above 50%, it is not economical to burn as most heat is lost in the evaporation of water and also it is quite difficult to store high moistured residues. Flax straw can be a good heat source at 0% moisture, next to sunflower hulls and pulp. Peat is an excellent alternate energy source as it is available throughout the world in abundance. Barley straw, oat straw and alfalfa can also be used for heating purposes as they give satisfactory heat quantities when burned.



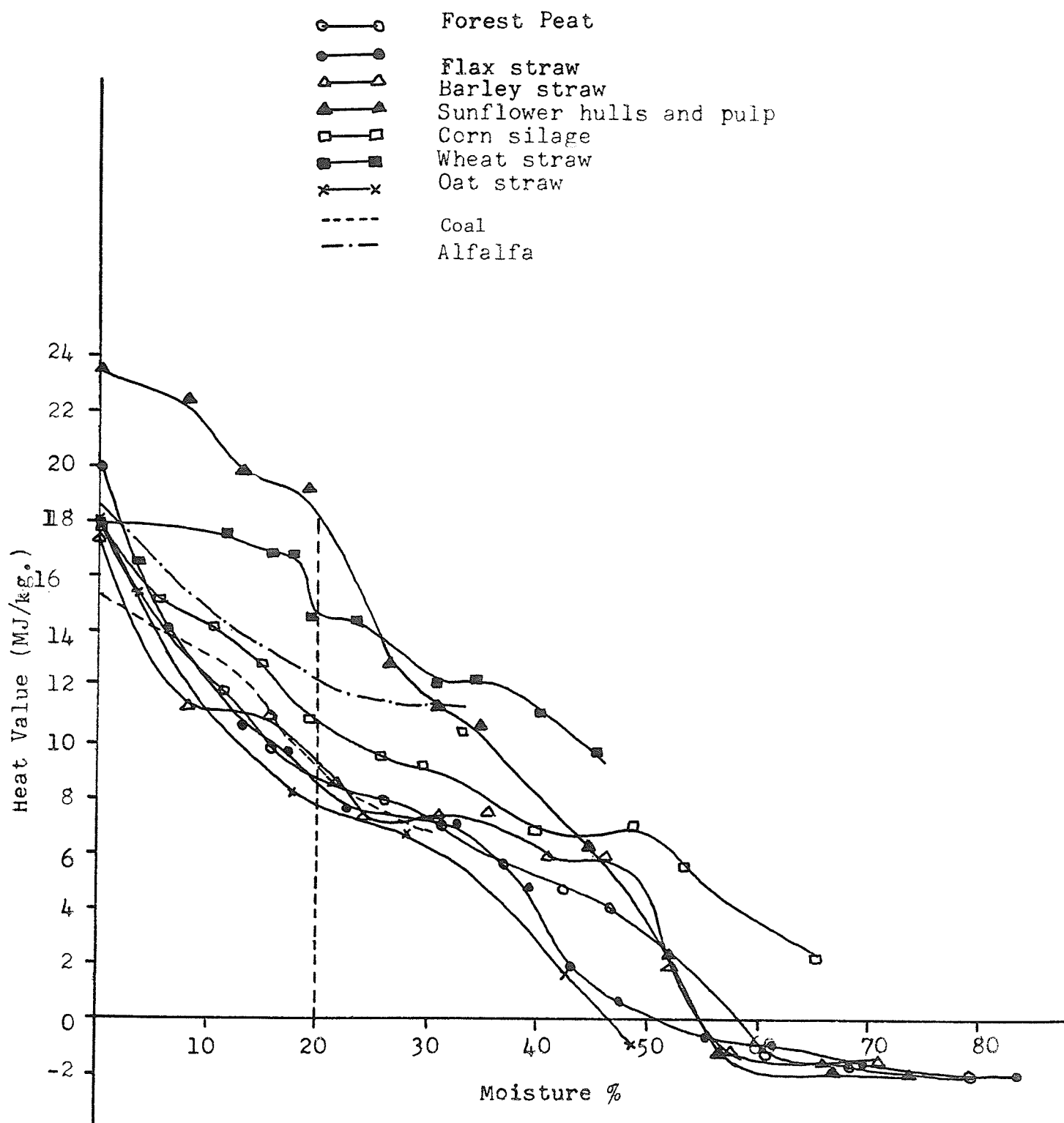


Figure 19: Experimental lower heat values of different residues at their different level of moistures

### 5.3 COMPARISON OF RESIDUES WITH WHEAT STRAW

All the agricultural residues tested for heat content were compared with wheat straw. The wheat straw was taken as the base for comparison because it is much more available throughout the world compared to any other residue. The comparison was done by finding the lower heat values of all residues at 20% moisture content from their curves. The heat value of wheat straw was divided by a particular residue's heat, and it gives the amount of that residue equal to one kilogram of wheat straw in terms of the heat values. In Table 5.11 the residues are kept in descending order of their quantities. From this table it was found that the sunflower hulls and pulp mixture is a better fuel than the wheat straw while the other residues are lower grade fuels.

TABLE 5.11

Comparison of heat obtained from residues

with wheat straw at 20% moisture level.

Name of residue	Heat value of residue at 20% moisture level (MJ/kg)	Heat value of wheat straw at 20% moisture level (MJ/kg)	Amount of residue equal to 1 Kg of wheat straw (kg)
Oat straw	7.60	15.40	2.03
Barley st	8.25	15.40	1.87
Peat	8.75	15.40	1.76
Flax st	9.00	15.40	1.71
Coal (low quality lignite)	10.20	15.40	1.51
Corn sil.	10.80	15.40	1.43
Alfalfa	12.40	15.40	1.24
Sunflower residue	17.60	15.40	0.88

## Chapter VI

### UTILIZING THE RESIDUES FOR HEATING PURPOSES

#### 6.1 STRAW HANDLING AND PROCESSING

Crop residues are usually bulky and difficult to handle, so it is desirable to reduce their size and/or increase their density. Size reduction can be accomplished by machines such as a hammer mill or tub grinder and density may be increased by the use of balers, wafers and pelleting machines.

Pelleting is a process to increase the density of crop residues. The baled wheat straw has a density from 0.16 g/cm<sup>3</sup> (gram per cubic centimetre) to 0.24g/cm<sup>3</sup>, whereas the density of lignite coal is usually 0.83 g/cm<sup>3</sup>. To make handling and transportation convenient, the straws may be pelleted. Bales are too large to be burned in a small furnace used for home heating, while in the pellet form any shape and size of cube can be utilized. Most of the residues require some form of binding material to hold the pellet together after forming. Alfalfa is one exception as it pellets well with no additives.

Selection of the crop residue for fuel depends upon various factors, but availability is one of major importance.

## 6.2 DESIGN OF A STRAW FIRED FURNACE

For the purpose of burning straw a furnace can be somewhat similar to a wood burning furnace. The main considerations influencing the design of a furnace are -

1. The kind, condition and characteristics of the fuel to be burned.
2. The properties of any ash or clinker that may be formed, like for wheat straw the ash content is 8.3%.
3. The normal, minimum and maximum loads to be carried, and their relative durations.
4. The size and relation of the furnace with respect to the boiler and other parts of the unit.
5. The method of firing.
6. The excess air coefficient which is desired to use.
7. The initial and operating cost.

## 6.3 STORAGE OF HIGH MOISTURE RESIDUES

Straw is usually baled from 20 to 30% moisture content. When the moisture content and the temperature is high, spoilage may occur due to the growth of mould. Microbiological deter-

ioration in the tropics is a greater problem because of the humid conditions. The development of fungi, in addition to microbial deterioration, severely reduces the heat value of straw since much of its heat is lost to the metabolism of the fungi.

In the mid 1960s B.P. Chemicals International Ltd. marketed pure propionic acid as a preventative of spoilage of moist grains. Its success in high moisture grain storage promoted interest in using it for preserving hay.

## Chapter VII

### CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were drawn from the experimental results-

1. The agricultural residues used in the experiment contain sufficient heat to be considered as an alternate energy source.
2. Of the residues tested at moisture content upto 25% the mixture of, sunflower hulls and pulp is the best heat source. The heat content was higher than sunflower hulls alone.
3. Above the 25% moisture content, wheat straw is preferable for heating purposes.
4. At approximately 50% moisture content, most of the residues when burned, start to absorb heat from the surroundings instead of producing heat.
5. Higher heat values for all the residues remain positive at any moisture content, whereas the lower heat value of most of the residues go towards a negative value after reaching a 50% moisture level.

6. For all the residues tested, the heat value is maximum at 0% moisture and decreases with an increase in moisture level.
7. The maximum higher and lower heat values, of all the residues tested, were obtained by sunflower hulls and pulp mixture. They were 23.60 MJ/kg and 23.58 MJ/kg respectively at 0% moisture content.
8. The difference between the higher and lower heat values increases with an increase in the moisture level.
9. Residues can burn more effectively if they are compressed to increase their density.
10. The residues can be utilized as a home heating fuel, if they are burned in a properly designed furnace.

#### 7.1 RECOMMENDATIONS

1. To determine average heat values, samples should be collected from different places as the heat value of certain residues differ with the source.
2. Research is required to design a furnace which can use residues with limited supervision.



3. More research is needed on high moisture straw storage.

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## Appendix A

### FORTRAN PROGRAM FOR HEAT VALUE CALCULATION

#### A.1 LIST OF VARIABLES

AVRAGE	Average of gross heat of combustion
BWL	Burnt Wire Length
CAP	Weight of empty capsule
CAPSAM	Weight of capsule with the sample of residues
CBAP	Weight of capsule with benzoic acid pellet
EEF	Energy equivalent factor
FBR	Final burette reading
FMTEMP	Final maximum temperature
FMTSCR	Temperature correction for final temperature
GHC(5)	One dimensional array containing five values of gross heat of combustion in cal/g
GHCJ(5)	One dimensional array containing five values of gross heat of combustion in Joules/Kg
H2	Hydrogen content
HCSBA	Heat of combustion of benzoic acid
I	Integer for Do loop
IBR	Initial burette reading
IFTEMP	Initial firing temperature
IFTSCR	Temperature correction for initial temperature
J	Integer for Do loop
K	Integer for number of replicates

L            Integer to give maximum value of Do loop  
              depending upon number of replicates

LHC(5)       One dimensional array containing five values of  
              lower heat values in Cal/g

LHCJ(5)      One dimensional array containing five values of  
              lower heat values in Joules/Kg

MC           Moisture content

MEAN         Average of lower heat values

SQRT         Square root

STD          Standard deviation

SUMSQ        Sum of squares of values

TOTGHC       Total of gross heat of combustion

TOTLHC       Total of lower heat values

## A.2 PROGRAM

\$job        WATFIV    PRADEEP,NOEXT

C PROGRAM FOR STANDARDIZATION, HIGHER, LOWER HEAT VALUE AND  
 C STANDARD DEVIATION

```

      REAL HCSBA, CBAP, CAP, IBR, FBR, BWL, FMTEMP, FMTSCR,
      *IFTEMP, IFTSCR, EEF, CAPSAM, GHC(5), LHC(5), TOTGHC, MC,
      *LHCJ(5), TOTLHC, AVRAGE, MEAN, SUMSQ, STD, SQRT, H2, GHCJ(5)

      INTEGER I, J, K, L

      K = 5

      READ, HCSBA, CBAP, CAP, IBR, FBR, BWL, FMTEMP, FMTSCR, IFTEMP,
      *IFTSCR

      EEF=(HCSBA*(CBAP-CAP)+(FBR-IBR)+2.3*(10.0-BWL))/(FMTEMP-FMTSCR
      *)-(IFTEMP-IFTSCR))

```

```

      PRINT
100, HCSBA, CBAP, CAP, IBR, FBR, BWL, FMTEMP, FMTSCR, IFTEMP,
      *IFTSCR
100  FORMAT('1', 10(F8.2, 2X))
      PRINT, 'ENERGY EQUIVALENT FACTOR = ', EEF
      L = 1
      DO 20 J = 1, L
      READ, MC, H2
      PRINT, 'MOISTURE CONTENT=', MC, 'HYDROGEN CONTENT =',
      *H2
      TOTGHC = 0.0
      TOTLHC = 0.0
      SUMSQ = 0.0
      DO 10 I = 1, K
      READ,
      CAP--
      SAM, CAP, FMTEMP, FMTSCR, IFTEMP, IFTSCR, FBR, IBR, BWL
      PRINT
      110,
      CAP--
      SAM, CAP, FMTEMP, FMTSCR, IFTEMP, IFTSCR, FBR, IBR,
      *BWL
110  FORMAT('--', 9(F8.2, 2X))
      GHC(I) = (((FMTEMP - FMTSCR) - (IFTEMP - IFTSCR)) * EEF - (FBR - IBR) - 2.3 *
      *(10 - BWL)) / (CAPSAM - CAP)
      LHC(I) = GHC(I) - 68.3 * H2 * (1.0 - MC) - MC * (100 - (IFTEMP - IFTSCR))
      *-MC*540
      GHCJ(I) = GHC(I) * 4186.8
      LHCJ(I) = LHC(I) * 4186.8
      TOTGHC = TOTGHC + GHCJ(I)

```



```

      TOTLHC = TOTLHC + LHCJ(I)

      SUMSQ = SUMSQ + GHCJ(I)**2

10  CONTINUE

      AVRAGE = TOTGHC/K

      MEAN = TOTLHC/K

      STD=SQRT((SUMSQ-(TOTGHC*TOTGHC)/K)/(K-1))

      PRINT 120, (GHC(I), LHC(I), I =1,K)

120  FORMAT('- ', 'GHC=', 15X, F8.2, 25X, 'LHC=', 15X, F8.2)

      PRINT 130

130  FORMAT('- ',15X,'UPPER HEAT VALUES WERE IN CALORIES
      *PER G.',/'-',25X,'HEAT VALUES IN JOULES PER KG',/
      *'0',25X,'HIGHER HEAT VALUE',25X,'LOWER HEAT VALUE')

      PRINT 135,(GHCJ(I), LHCJ(I), I=1,K)

135  FORMAT('0',25X,F15.2,25X,F15.2)

      PRINT,AVRAGE,MEAN,STD

20  CONTINUE

      STOP

      END

$ENTRY

```

## Appendix B

### FORTRAN PROGRAM FOR FINDING REGRESSION EQUATIONS

```

$JOB    WATFIV    PRADEEP,NOEXT

        DIMENSION X(13), Y(13), C(10), A(10,11), XN(13)
        READ,N
        READ,MS,MF
        READ,(X(I),Y(I),I=1,N)
        IF(MF.LE,(N-1) ) GO TO 5
        MF = N-1
        WRITE (6,200) MF
200    FORMAT(1H0,42HDEGREE OF POLYNOMIAL CANNOT EXCEED
        *N-1./1H,47HREQUESTED MAXIMUM DEGREE TOO LARGE-
        *REDUCED TO,13)
5      MFP1 = MF + 1
        MFP2 = MF + 2
        DO 10 I = 1,N
10     XN(I) = 1.
        DO 30 I = 1,MFP1
        A(I,1) = 0.
        A(I,MFP2) = 0.
        DO 20 J=1,N
        A(I,1) = A(I,1) + XN(J)
        A(I,MFP2)=A(I,MFP2)+Y(J)*XN(J)
20     XN(J) = XN(J)*X(J)

```

```

30  CONTINUE

    DO 50 I=2,MFP1
      A(MFP1,I) = 0.

    DO 40 J=1,N
      A(MFP1,I)=A(MFP1,I)+XN(J)
40  XN(J)= XN(J)*X(J)

50  CONTINUE

    DO 70 J=2,MFP1
      DO 60 I=1,MF
60  A(I,J) = A(I+1,J-1)

70  CONTINUE

      WRITE(6,201) ((A(I,J),J=1,MFP2),I=1,MFP1)
201  FORMAT('0',11E12.4)

      CALL LUDCMQ (A,MFP1,10)

      MSP1 = MS+1

      DO 95 I=MSP1,MFP1
        DO 90 J = 1,I
90  C(J) = A(J,MFP2)

        CALL SOLNQ (A,C,I,10)

        IMI= I-1

        WRITE(6,202) IMI,(C(J),J=1,I)
202  FORMAT(1H0,14HFOR DEGREE OF,12,17H COEFFICIENT ARE
          *,/1H,10X,6F18.8/5F18.8)

      PRINT 8

8  FORMAT('0',T16,'XDATA',T35,'YDATA',T55,'YPOLY')

    DO 2 JJ=1,N

      YY = 0.0

```

```

      DO 1 II=1,I
1    YY=YY*X(JJ)+C(I-II+1)
      PRINT 9, X(JJ),Y(JJ),YY
9    FORMAT(3F20.5)
2    CONTINUE
      BETA = 0.0
      DO 94 IPT =1,N
      SUM = 0.0
      DO 93 ICOEF = 2,I
      JCOEF = I-ICOEF+2
      SUM = (SUM+C(JCOEF))*X(IPT)
93   CONTINUE
      SUM = SUM+C(1)
      BETA= (Y(IPT)-SUM)**2
94   CONTINUE
      BETA = BETA/(N-1)
      WRITE(6,203)BETA
203  FORMAT(1H,10X,9H BETA IS, F10.7)
95   CONTINUE
      STOP
      END
      SUBROUTINE LUDCMQ (A,N,NDIM)
      DIMENSION A(NDIM,NDIM)
      DO 30 I=1,N
      DO 30 J=2,N
      SUM = 0.
      IF (J.GT.I) GO TO 15

```

```

      JM1 = J-1

      DO 10 K=1,JM1

10    SUM = SUM + A(I,K)*A(K,J)

      A(I,J) = A(I,J) - SUM

      GO TO 30

15    IM1=I-1

      IF (IM1.EQ.0.)GO TO 25

      DO 20 K=1,IM1

20    SUM=SUM+A(I,K)*A(K,J)

25    IF(ABS(A(I,I)).LT.1.E-10) GO TO 99

      A(I,J) = (A(I,J)-SUM)/A(I,1)

30    CONTINUE

      RETURN

99    WRITE(6,100) I

100   FORMAT(1H0,32H REDUCTION NOT COMPLETED BECAUSE,

      *38H SMALL VALUE FOUND FOR DIVISOR IN ROW, I3)

      RETURN

      END

      SUBROUTINE SOLNQ (A,B,N,NDIM)

      DIMENSION A(NDIM,NDIM), B(NDIM)

      B(I) = B(I)/A(I,1)

      DO 20 I=2,N

      IM1 = I-1

      SUM = 0.

      DO 10 K=1,IM1

10    SUM = SUM+A(I,K)*B(K)

20    B(I) = (B(I)-SUM)/A(I,I)

```

```
DO 40 J=2,N  
NMJP2 = N-J+2  
NMJP1 = N-J+1  
SUM = 0.  
DO 30 K = NMJP2,N  
30 SUM = SUM+A(NMJP1,K)*B(K)  
40 B(NMJP1) = B(NMJP1)-SUM  
RETURN  
END  
$ENTRY
```