OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialized" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

FAIR USE POLICY

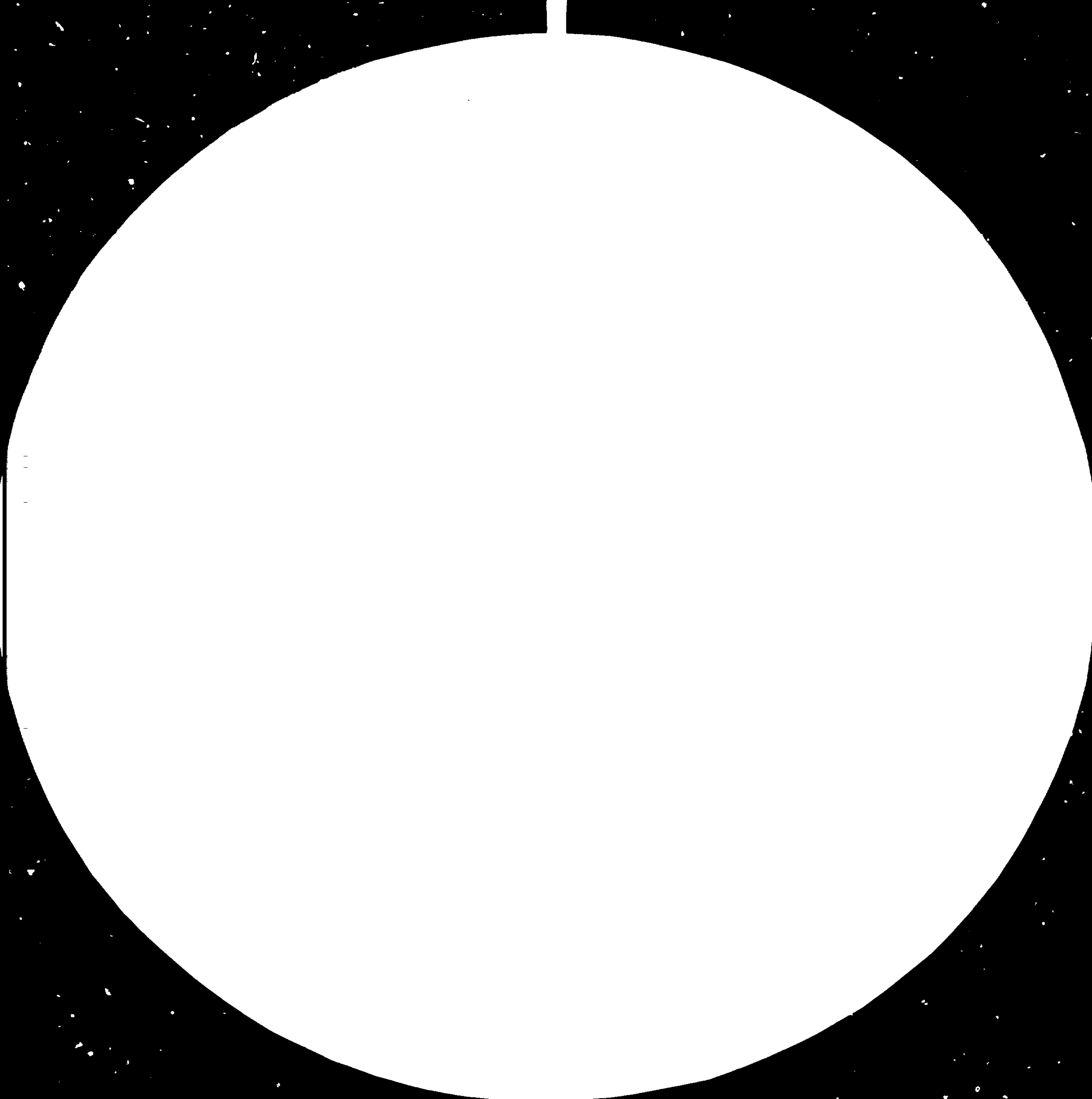
Any part of this publication may be quoted and referenced for educational and research purposes without additional permission from UNIDO. However, those who make use of quoting and referencing this publication are requested to follow the Fair Use Policy of giving due credit to UNIDO.

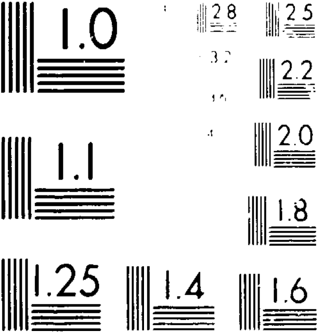
CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org





MICROCOPY RESOLUTION TEST CHART

[illegible]

VARIABLES AFFECTING THE PERFORMANCE OF SAWDUST AS A FUEL, AND ITS USE IN A SOLAR/SAWDUST CROP DRYER

MICHAEL W. BASSEY

Final Report
UNIDO RESEARCH PROJECT
Subject No: UN-K-12624-380
Contract No. 78/24

Department of Mechanical Engineering
Fourah Bay College
University of Sierra Leone
Freetown, Sierra Leone
May, 1980

VARIABLES AFFECTING THE PERFORMANCE OF SAWDUST AS A FUEL AND ITS USE IN A SOLAR/SAWDUST CROP DRYER

MICHAEL W. BASSEY

Department of Mechanical Engineering
Fourah Bay College
University of Sierra Leone
Freetown

MAY 1980

FINAL REPORT
UNIDO RESEARCH PROJECT
Subject N° UN-K-12624-380
Contract N° 78/24

ABSTRACT

This report presents the results of a program of study carried out in the Department of Mechanical Engineering, Fourah Bay College, University of Sierra Leone, on the use of sawdust as a fuel.

A survey of the availability of sawdust has been done and estimations show that there is about 2000 m^3/month of the fuel in Sierra Leone, the majority of sawdust being available in sawmills.

An experimental investigation was carried out to assess the effect of tree species and moisture content on the calorific value of sawdust. The variation of calorific value with moisture content can be predicted, for five main trees from which large amounts of sawdust are produced, using linear equations. A general equation for mixtures of the sawdust is recommended.

A method of burning sawdust was studied experimentally in order to determine the variation with time of variables involved in the burning process. The method of burning the sawdust consisted of making a hole through packed sawdust and lighting the sawdust within the hole. A wide range of experiments were carried out to determine the variation of the burner hole diameter, the mass of sawdust used and the effect of the height of packing of the sawdust. Equations are presented for the variation with time of the burner hole diameter and the mass of fuel consumed for various air inlet hole diameters. Analyses of the results have indicated further generalizations of the experimental data and two equations are recommended for use in the design of this type of burner.

A crop dryer capable of using solar energy and sawdust, individually or simultaneously as fuel, has been designed and tested. The dryer can be used under all weather conditions. The results of no-load tests show that temperatures of up to 90°C can be expected using solar energy and sawdust simultaneously, and temperatures of 80°C and 70°C can be expected using

solar energy and sawdust respectively. Tests under loaded conditions show that drying occurred at average temperatures of 50°C and 60°C using only sawdust and combined sawdust and solar energy respectively. Average temperatures of up to 60°C can be expected under load using only solar energy. The dried products, using the dryer, are better in quality compared to open air sun drying and the time of drying can be decreased by up to 50%.

ACKNOWLEDGEMENTS

This work was supported by a research grant from the United Nations Industrial Development Organization (UNIDO) under Subject N°: UN-K-12624-380, UNIDO Contract N° 78/24.

The author wishes to express his appreciation to the following people who contributed to this project: Mr. Apolo Bwogi, Mr. Sullay Kamara and Sylvester Tucker for participating as research assistants; Mr. Albert Harding, Mr. Palmson Williams, Mr. Roderick During for their assistance during the construction and testing phases of this project.

The support and encouragement given by my wife, Marie-Lise, during the work are gratefully acknowledged. Her patience and devotion during the preparation of this report are also highly appreciated.

TABLE OF CONTENTS

Page

1. INTRODUCTION

2. AVAILABILITY AND DISTRIBUTION OF SAWDUST IN SIERRA LEONE

3. CALORIFIC VALUE OF SAWDUST

4. CHARACTERISTICS OF SAWDUST BURNER

5. DESIGN OF SOLAR/SAWDUST CROP DRYER

6. PERFORMANCE OF SOLAR SAWDUST CROP DRYER

7. ECONOMIC ASPECTS OF CROP DRYER

8. CONCLUSIONS AND RECOMMENDATIONS

FIGURES

TABLES

NOMENCLATURE

CV	Calorific value of sawdust, kJ/kg
d	burner hole diameter, cm
t	time, min.
D_B	air inlet diameter, cm
m_f	mass of sawdust burnt in time t, gm
m_s	mass of steam, kg
S	slope of m_f versus t line, $\frac{gm}{min}$
m_w	mass of water evaporated from crops, kg
L	Latent heat of water, kJ/kg
G	Total radiation falling on dryer, J
η_o	overall efficiency, $m_w L/(m_f . CV + G)$
η_I	intermediate efficiency, $m_w L/(m_s L + G)$
η_B	burner efficiency, $m_s L/m_f . CV$
MC	moisture content

Chapter 1

INTRODUCTION

1.1 Background

Many developing countries have a substantial amount of residues from agricultural activities. In many cases, these residues are discarded as waste when they can be used as fuel. One of the reasons why these potential fuels are not used is because special systems are needed to burn them which are expensive for the potential users.

One of the materials which can be utilized is sawdust. It is available in many countries which have timber industries. It would therefore be beneficial if simple methods of burning sawdust were developed in order to use the large amounts of sawdust which are available.

Many developing countries concentrate a large proportion of their manpower and energy resources in agricultural activities in the attempt to provide adequate food for consumption by the people within these countries and for export. In many cases, the agricultural product needs to be preserved in order to increase the storage time. It is obvious that the method of preservation must yield a good quality product in order that satisfactory prices are obtained both locally and on the export market.

A very common method of drying crops is by spreading them out under the sun until they are reduced to their respective equilibrium moisture contents. This method is of course not without problems as it exposes the crops to infestation by insects, contamination by dirt and spoilage and losses due to rain and wind.

Various improvements can be made to this traditional method of drying in order to improve the quality of the final product. But there still remains the frequent lack of solar energy due to cloud cover, the time of the year and time of day. This intermittent nature of solar energy prolongs the drying time and in many instances causes unnecessary spoilage of crops.

It would therefore be of benefit to the farmer if simple methods are developed to dry crops even under adverse weather conditions.

1.2 Aim of Work

The work outlined in this report partly involved, the experimental investigation of the parameters and factors which affect the use of sawdust as a fuel, and the analysis of the results to quantitatively describe the performance of burners using this fuel. The results obtained would be used to design burners for various domestic and small industrial applications suited to rural areas.

The other aspect of the project was to use results of the study mentioned above to design a crop dryer which would use both sawdust and solar energy as sources of heat. The dryer would be used to dry crops so as to evaluate its effectiveness under various conditions.

1.3 Literature Survey

There has been a lot of work done on solar crop dryers which have been reported in the literature. A survey of solar dryers has been presented in a report by the Brace Research Institute(1) which described work going on in various countries throughout the world. Dryers have been built for coffee, cacao, rice, tea, vegetables, grapes, herbs, apples, wheat, timber, etc. The design and performance of the dryers depend on the crop being dried, the building materials available and the meteorological conditions at the particular location in question.

Two types of solar dryers have been used for various crops: indirect and direct solar dryers. Direct dryers collect the solar radiation through transparent covers at the top of the dryers. Directly underneath the transparent cover is the crop which is heated by the accumulated heat in the dryer. The moisture which is driven off from the crop passes out of the cabinet, through vent holes on the side walls of the dryer. The sunlight is always on the crop being dried. Indirect dryers consist of a collector which heats up the ambient air, and the cabinet in which the crop is dried. The heated air is circulated by a fan or by natural convection through the crops. The sunlight does not come into contact with the crop in this type of dryer. Of course there are dryers which consist of a combination of direct and indirect heating by solar energy. In addition it is also possible to use a supplementary source of heat in these dryers, in case the available solar radiation is poor.

A typical direct solar dryer has been described in (2). The transparent cover was glass and the cabinet made of wood. The moist air escaped through holes drilled in the sides of the cabinet. Sawdust and wood shavings were used as thermal insulation for the vertical and bottom panels of the cabinet. The top of the dryer was sloped at an angle of α = latitude + 15 degrees for the winter and α = latitude - 15 degrees for the summer.

Experimental results were shown in (2) for the drying of peaches, prunes, peas and cauliflower. The average temperature in the dryer was 40°C above the ambient air temperature of 35°C. The rate of drying in the dryer was much faster than that compared to open air drying, and the products were more superior in color and odor. For example, peaches decreased in weight from 900 gm to 275 gm in 10 hours compared to the time of 16 hours in open air drying. The efficiency of the dryer under no-load condition was between 40% and 50%.

A dryer consisting of a flat plate collector, a drying cabinet and dehumidifier has been reported by Headley and Springer (3). The hot air from the collector was circulated by natural convection through the crops. The cooled air then fell to the bottom of the cabinet where the water was removed by condensation.

Four models were constructed and tested; some of them used the principle of indirect drying and the others the direct principle. Temperatures of 110°C were attained in three of the dryers under no-load conditions but changed under loaded conditions, ranging from 105°C at the top to 80°C at the bottom. The crops dried were yams, sorrel, sweet potatoes and grass. The percentage of water removed from these crops were 65% (yam), 55-60% (sweet potatoes) and 90% (sorrel and grass). These dryers appeared to have potential applications in tropical climates.

Selçuk et al (4) have developed a solar fruit and vegetable dryer comprising of a collector, a cabinet and a fan for circulating the warm air. Glass was used as the glazing material and metal chips as the absorber, in the flat plate collector. The ambient air flowed through the metal chips and through the trays containing the crops. The top of the drying cabinet was covered with four layers of PVC. An auxiliary heating system, using butane as fuel, was attached to the dryer so as to facilitate all weather operation. Results using the auxiliary heating system were however not available. The results for tests using solar energy alone, for drying bell peppers and sultana seedless grapes, gave dried products of superior quality compared to open air sun drying.

Another type of solar dryer has been reported by Akyurt et al (5). It consisted of a solar air heater connected to a multistorey array of wooden shelves. The ambient air flowed through an inclined matrix of steel shavings, increased in temperature and then passed through the shelves. The air picked up moisture from the crops and then passed out to the ambient through vents at the top of the cabinet. The movement of the air was achieved by natural convection. Tests were performed using white mulberries, peaches and seedless sultana grapes. It was noticed that the fruits in the bottom and top shelves dried faster than those in the middle ones. The times taken for drying the fruits using the dryer were substantially decreased compared to those for open air drying.

A crop dryer using a two pass solar air heater has been reported by Satcunanathan (6). The design eliminated the need for insulation. Two glass covers and the corrugated absorbing plate were located so that the air passed through the glass plates and then underneath the blackened absorber plate. This collector was located on top of the drying cabinet so that the warm air from the collector flowed from the top to bottom of the drying compartment through the crops. The air was circulated by a blower located at the bottom of the compartment. Crops such as sorrel, cacao, sliced bananas, chilli peppers and sweet potatoes were dried, giving superior quality products compared to open air drying, although the crops on the upper trays dried better than those on the lower trays.

A grain drying and storage house has been described by Buelow (7) which used the roof as the collector. Hot air moved by a fan flowed underneath the roof, through ducting and then through the grain, stacked to a depth of five feet in bins. The author in (7) claimed that drying time could be reduced by as much as 50 to 70 percent.

Rao and Macedo (8) used a solar dryer consisting of a round bin with a perforated floor and a solar air heater. The air was circulated with the aid of a fan. Six hundred kilograms of carioca dry beans were dried in a bed 0.8 m deep. The tests indicated that the drying rate at the top of the bin increased by four times.

Large scale dryers have been developed for grain drying. The grain is usually housed in a bin and the heated air removes moisture from the grain. Two types of collectors are used for heating the air. The first is a flat plate collector system inclined at the appropriate angle for that location, (9), (10), (11). The second type of collector is a part of the vertical wall of the bin. The side predominantly facing the sun is painted black and covered with a transparent medium (12). The air flows between the absorber and the transparent cover and is heated up before it passes through the grain.

1.4 Justification of Work and Methodology

The majority of work on crop drying have been confined to the use of solar energy, electricity, gas and other conventional fuels for producing the heat. Use of these fuels have been made as auxiliary sources of heat due to the cost of the fuels, and the related systems needed for their use make it expensive for the rural farmer to make use of dryers using them.

Solar energy is an attractive source of heat for crop drying in developing rural areas. A substantial amount of work have been done on its use in the drying of various crops. Despite this progress, there are certain technical problems which tend to restrict the use of solar crop dryers. Firstly, the intermittent nature of the available solar radiation restricts the use of solar crop dryers to specific periods of the day and times of the year. There is also the need to circulate the warm air through the crops during drying which is done in many cases by the use of fans or blowers which need electricity for their operation. The air can also be moved in the crop dryer by natural convection, a process needing proper design of the whole dryer compared to that using a fan.

There is obviously a definite need for dryers to be developed which use, natural convection for circulating the air, and auxiliary fuels which are relatively inexpensive. Developments along these lines would improve the capacity of the rural farmer to produce better products for the market.

The literature on solar crop dryers give an adequate basis for further work on the development of systems for rural areas in developing countries. There has however been relatively little work done on the use of auxiliary sources of heat with solar dryers which are appropriate to the needs of the rural farmer. The systems which are presently being used utilize electricity, oil or gas for relatively large drying operations.

Work on the use of waste materials as fuel has been initiated by the author, at the University of Sierra Leone. The use of sawdust as a fuel has been of interest due to its availability in large quantities in many countries, including Sierra Leone. Preliminary work has been done to determine an adequate configuration for burning this fuel and to identify the variables which affect the burner (13), (14). Further work (15) showed the possibility of using the burner configuration in cookers. These studies indicated that detailed work was necessary in order that efficient burners could be designed for various applications.

Considering the above, the project was carried out with two objectives in mind; to investigate the variables which affect the performance of sawdust as a fuel using a simple burner configuration and to use the results to design a crop dryer using solar energy and sawdust as sources of heat.

The first phase of the project consisted of:

(a) estimating the quantity of sawdust available in Sierra Leone.

(b) identifying various trees and to determine the calorific values of their sawdust as a function of moisture content.

(c) carrying out detailed experiments so as to understand the burning process and to quantitatively describe it.

(d) proposing design parameters for burners using sawdust.

The second phase of the project was concerned with designing a crop dryer using solar energy, and sawdust as an auxiliary heat source. The sawdust burner would be designed using the results obtained in the first phase of the study. Tests would be carried out on the dryer, under no load and load conditions using solar energy and the sawdust burner, in order to assess its performance.

The results of this research project will hopefully be a basis for further developments since there has, in the author's knowledge, not been any such work reported in the literature.

Chapter 2

AVAILABILITY AND DISTRIBUTION OF SAWDUST IN SIERRA LEONE

It was of interest to know the quantity of sawdust which would be available in Sierra Leone as a whole. A survey was carried out to obtain an estimate of the quantity of sawdust available and to relate it to areas where crop drying is needed. This chapter discusses the details of the survey.

2.1 Availability of Sawdust in Sierra Leone

A survey was carried out to identify the various areas in which sawdust was produced and in what quantities they existed. Due to the area which had to be covered, it was decided to obtain a list of registered wood workshops in the country and then visit them to collect the information needed.

The survey indicated that sawdust can be obtained from, sawing of trees in the forests, sawing the trees into boards in the sawmills, and in carpenter and furniture workshops. The quantity of sawdust obtained from sawing the trees in the forests is small and difficult to estimate since it falls to the ground and is scattered amongst the leaves, making it difficult to collect.

Estimating the amount of sawdust available in Sierra Leone was not easy since no records are kept by sawmills or workshops. Estimates have therefore been obtained from measuring the sawdust produced over a time period and by interviews.

There are five sawmills which are known to produce sawdust in substantial quantities and they are located in Kenema, Panguma, Zimi, Kasiri and Hanga as shown in figure 2.1. The areas where workshops also produce sawdust are also shown in figure 2.1. It should be noted that there are many small towns where some small scale wood workshop produce sawdust which are not included in the survey.

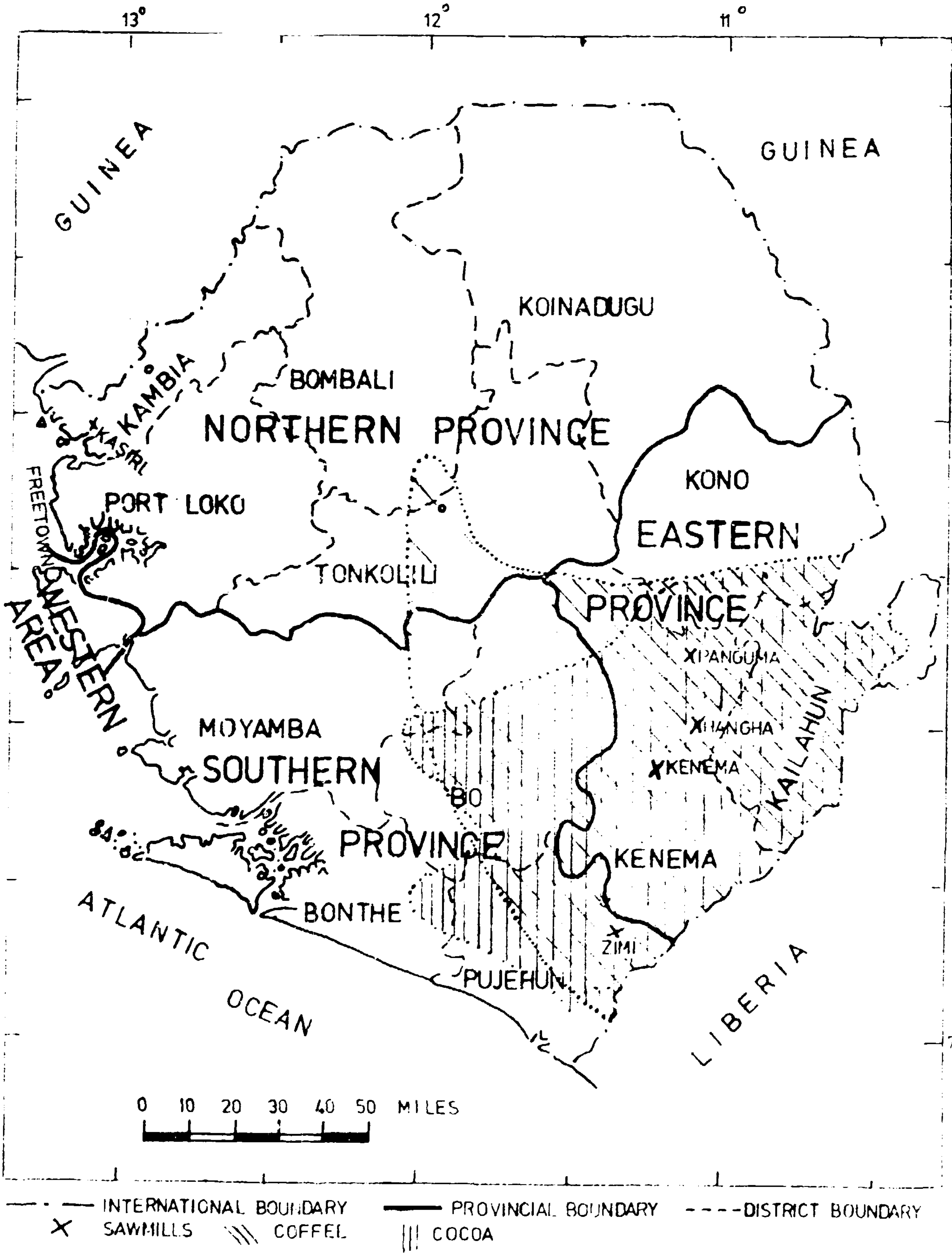

13°
12°
11°
10°
9°
8°
7°
GUINEA
GUINEA
KOINADUGU
KAMBIA
BOMBALI
NORTHERN PROVINCE
KASIRI
FREETOWN
PORT LOKO
TONKOLILI
KONO
EASTERN
PROVINCE
WESTERN AREA
PANGUMA
HANGHA
KENEMA
KAILAHUN
MOYAMBA
SOUTHERN
BO
PROVINCE
KENEMA
BONTHE
ZIMI
PUJEHUN
LIBERIA
ATLANTIC
OCEAN
0 10 20 30 40 50 MILES
INTERNATIONAL BOUNDARY
PROVINCIAL BOUNDARY
DISTRICT BOUNDARY
SAWMILLS
COFFEE
COCOA

Fig. [illegible]

The estimated quantity of sawdust available at the time of the survey in 1978 for various sawmills is shown in table 2.1 and are considered to be on the low side.

Table 2.1 Estimated quantities of sawdust available from various sawmills in 1978.

Location of Sawmill	Quantity of Sawdust m^3/month
Kenema	700
Panguma	400
Zimi	200
Hanga	200
Kasiri	200

The sawmills produced over 1700 m^3/month of sawdust.

The comparison between sawdust produced by the sawmills and other workshops in other towns is shown in figure 2.2. The sawdust from workshops in the towns where the sawmills are located are not shown due to their relatively small quantities compared to the output of the sawmills. The sawmills produce the substantial part of sawdust in the country due to the small scale nature of the activities in other workshops. Since the amount of sawdust in figure 2.2 add up to 1835 m^3/month it is realistic to conclude that considering other areas of the country, the amount of sawdust available in Sierra Leone in 1978 was about 2000 m^3/month.

Discussions with sawmill authorities indicated there were plans to increase production. The sawmill at Kenema for example had plans to double their output of timber which would result in doubling the output of sawdust. It was therefore of interest to estimate the output of sawdust from these sawmills up to 1982.

The quantity of trees cut and processed by the Kenema sawmill from 1973 to 1977 were obtained, but the amount of sawdust produced was not available. It was however estimated from the survey that 700 m^3/month of sawdust was produced in 1977. Noting that this production of

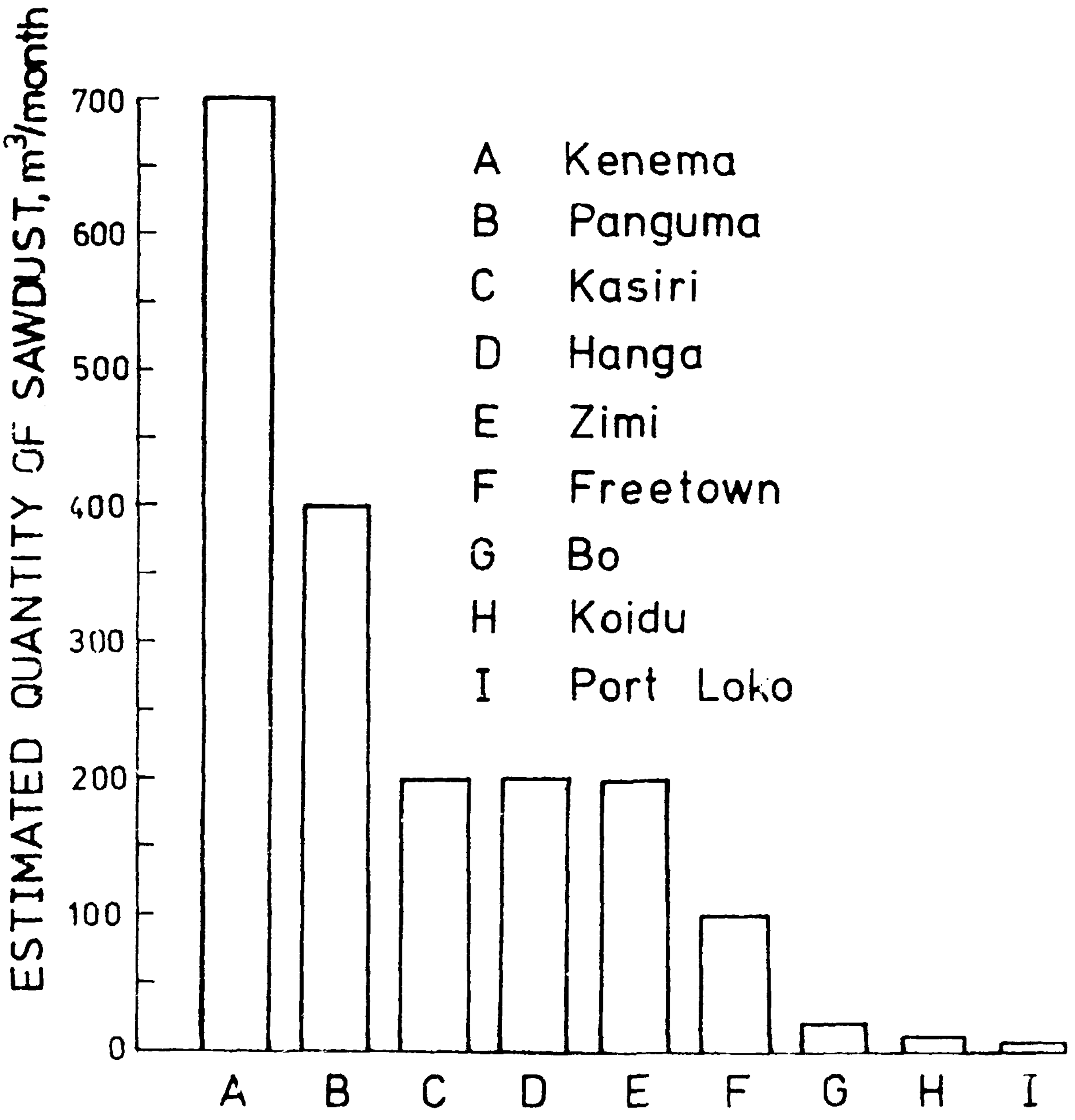


Fig. 2.2 Estimated quantities of sawdust in various locations.

sawdust was not markedly different from 1978 it was assumed that 700 m^3/month of sawdust was produced in this year.

Assuming that the amount of sawdust produced at the Kenema sawmill was directly proportional to the volume of trees cut, and knowing the volume of trees cut in each year from 1973 to 1977, the quantities of sawdust produced in these years were estimated are are shown in figure 2.3. It is seen that there has been a drop in the amount of sawdust produced (or trees processed) from 1974 to 1977. It would appear that the future production would decrease yearly if predictions are made using standard mathematical procedures. However, the sawmills intended to increases production; Kenema sawmill expecting to double its output whereas it is estimated that the others would increase production by at least 5 percent of the 1978 output over the next five years. In view of this information the amount of sawdust expected over the five year period 1978-1982 are shown in table 2.2.

Table 2.2 Estimated quantities of sawdust to be expected in the period 1978-1982.

	Estimated quantity of sawdust m^3/month				
	1978	1979	1980	1981	1982
Kenema	700	1000	1400	1400	1400
Panguma	400	420	440	460	480
Zimi	200	260	220	230	240
Hanga	200	210	220	230	240
Kasiri	200	210	220	230	240

The amount of sawdust produced in small workshops, based on the 1978 survey can be expected to range from about 0.2 m^3/month for small workshops to about 1 m^3/month for large workshops. It is expected that these workshops will not expand their facilities appreciably and will therefore maintain roughly the same output of sawdust over the next few years. Increase in the production of sawdust from workshops will be due to the setting up of new enterprises, such as for making furniture, throughout the country.

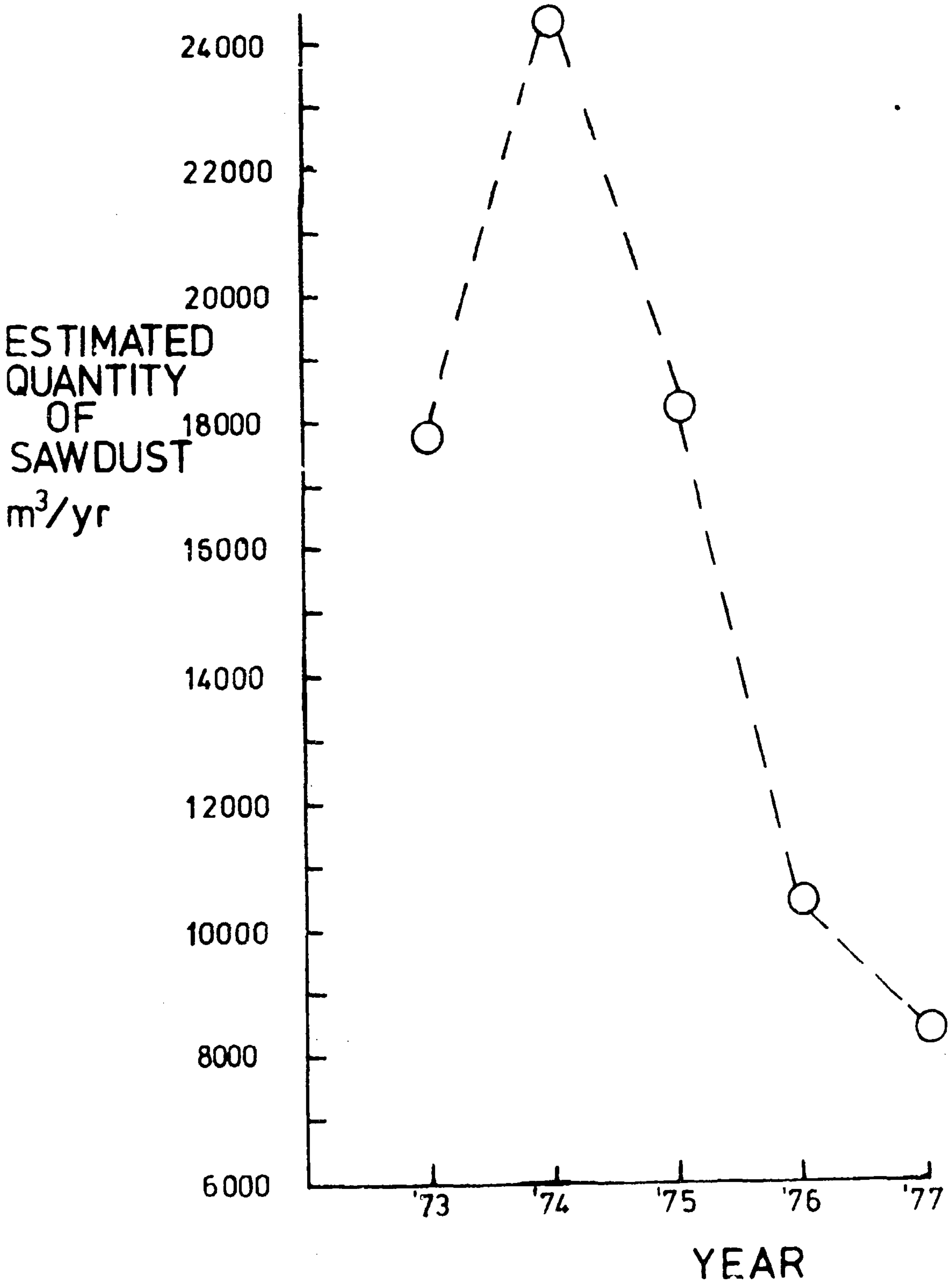


Fig. [illegible] Estimated yearly variation of quantity of sawdust [illegible] at the [illegible] sawmill.

2.2 Collection and Distribution of Sawdust

The preceding section outlined the source and quantities of sawdust produced in Sierra Leone. It is now of interest to work out methods of collection and distribution of sawdust noting the limitations which exist in various parts of the country.

Towns where sawdust are available are surrounded by small farms and villages where this fuel may be used. There are roads linking these towns to the villages and farms, thus facilitating the transportation by vehicles after collection has been done.

The collection in sawmills will not be difficult as workers can be employed to fill up sacks or appropriate containers and then store them. The sawdust can then be collected by the farmers.

It is felt that the sawmills would welcome this arrangement as they now have to dispose of their sawdust daily. They are located in areas of agricultural activities and the sawdust would be in demand.

Small workshops can make arrangements with individuals farmers who would collect the sawdust at weekly or monthly intervals. Transportation to the villages can be done by local transport as is the case for taking agricultural produce to the market.

The price that would have to be paid for sawdust has so far not been discussed due to the uncertainty of such a factor in the use of the sawdust. It is felt that sawmills will charge a small fee to farmers or nothing at all. Small businesses will try to make the maximum profit from the sale of sawdust.

Chapter 3

CALORIFIC VALUE OF SAWDUST

The main parameter which determines the suitability of a material as a fuel is its calorific value, which is the amount of heat liberated by a unit mass of the substance on combustion. It is necessary for the calorific value to be known so that proper design can be effected for systems using the fuel for generating heat.

The calorific value of sawdust depends on factors such as:

a) the type of tree from which the sawdust is obtained,

b) the amount of water present in the sawdust i.e. its moisture content.

Experiments were carried out to determine the effect of conditions (a) and (b), mentioned above, on the calorific values and are reported in this chapter.

3.1 Experimental Determination of Calorific Values

3.1.1 Description of Apparatus

A bomb calorimeter was used to measure the calorific values of the sawdust samples, its basic features are shown in figure 3.1 and 3.2. The bomb shown in figure 3.2 is made of a rust proof material which is resistant to corrosion by acids formed during the tests. The cover of the bomb consists of two sections which make it airtight. The leads to the terminals, used for igniting the platinum wire, were carried by the bottom cover. One of the leads acted as a support for the crucible. Also attached to the bottom cover was the valve which allowed pressurized oxygen to be supplied to the bomb but prevented any from escaping to the atmosphere.

The bomb was immersed in a container, having a known quantity of water, which in turn fitted in an insulated jacket. The temperature of the water was measured with a Beckman thermometer, capable of reading temperature changes from 0 to 6°C and accurate to 1/100th of a degree. A stirrer for mixing the water surrounding the bomb was operated by an electric motor.

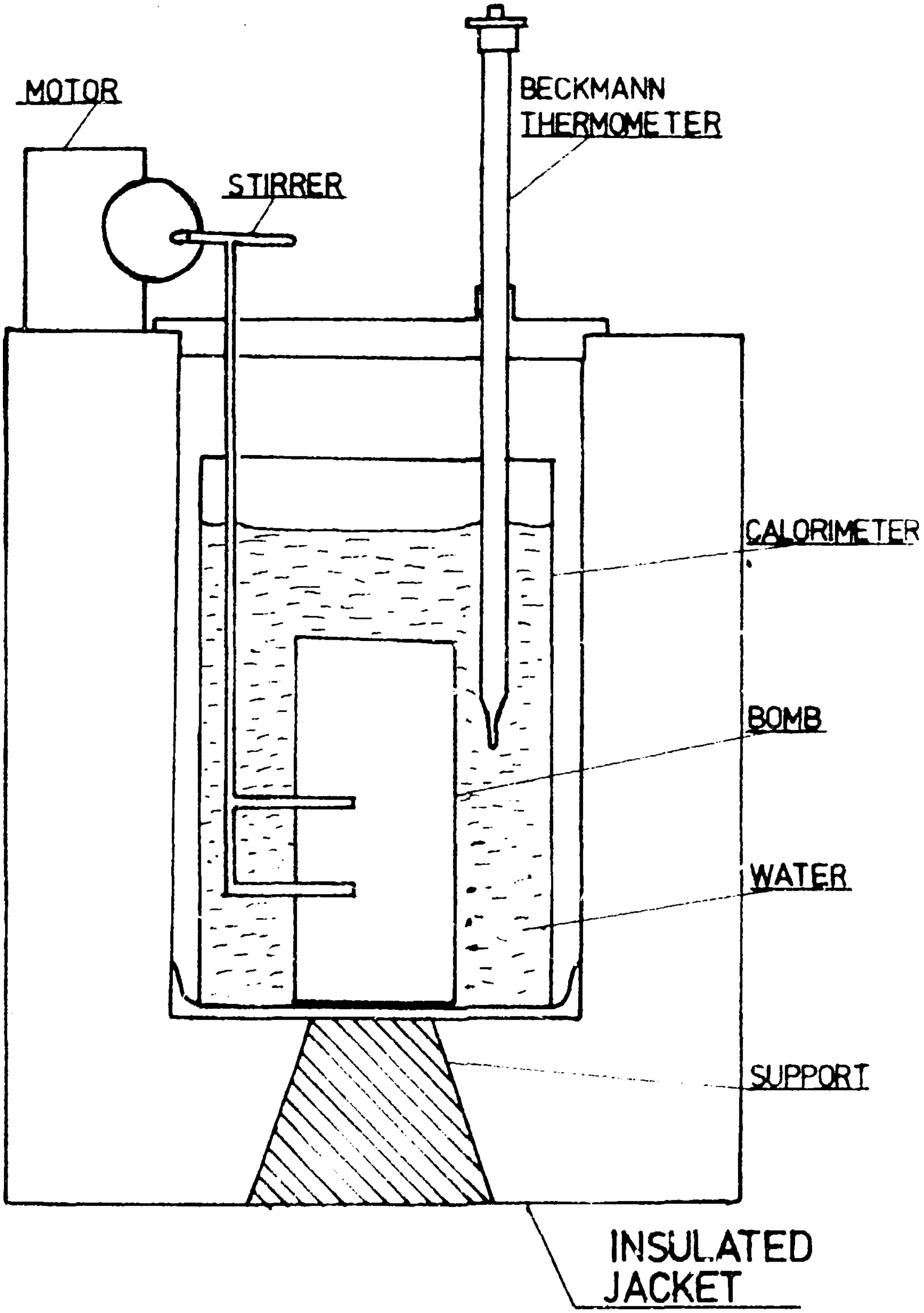


Fig. 3.1 General arrangement of the bomb calorimeter.

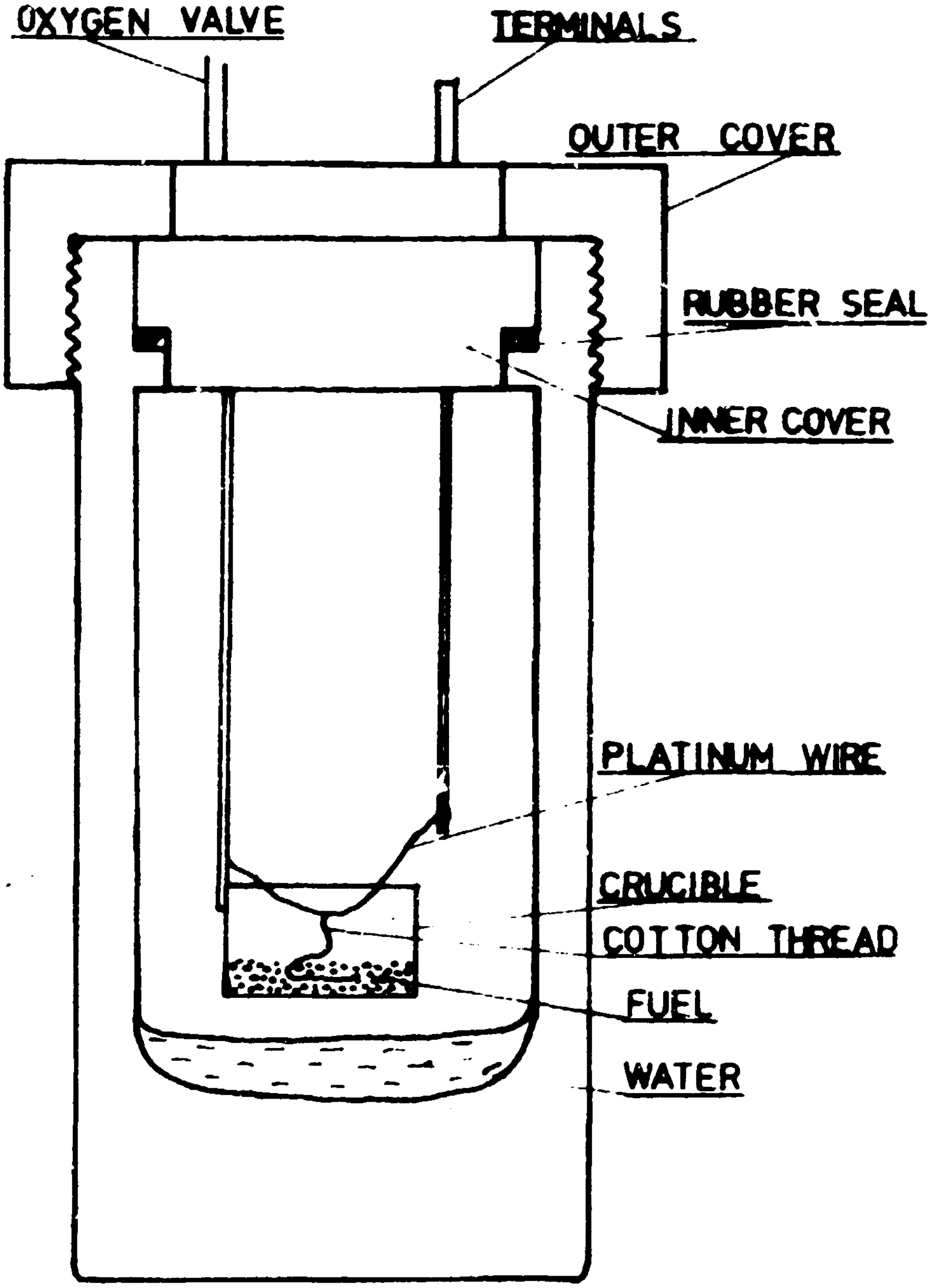


Fig. [illegible] Diagram of the bomb used in the calorimetric experiments.

3.1.2 Experimental Procedure

There are many different types of trees which can be used for timber by the sawmills. Due to their large numbers it was decided to use the sawdust from trees which were amongst the most commonly used. Five different types of sawdust were obtained from trees that had just been cut down so that the sawdust was wet.

The aim of the experiment was to obtain the calorific value of each type of sawdust as a function of moisture content.

A small quantity of sawdust was placed in an oven at about 105°C for a predetermined time so as to decrease the moisture content of the sawdust to a particular value. After this time, a small amount (about 1 gm) of sawdust, having a particular moisture content was placed in the crucible of the bomb calorimeter. The remaining sawdust was weighed and then placed in the oven again for 24 hours so that it would get completely dry. The weight of the sawdust was noted at the end of this drying period and its moisture content determined. The moisture content was obtained from the ratio of the mass of water lost from the sawdust sample over the 24 hour period to the mass of the completely dried sawdust.

After the sample had been put in the oven, the small amount of sawdust in the crucible was weighed and used in the bomb calorimeter to determine its calorific value. Standard bomb calorimeter test procedures were followed (see for example (16)). The sawdust in the crucible was ignited electricqlly using the platinum wire and the change in temperature of the water surrounding tne bomb was measured using a Beckman thermometer until the maximum temperature was attained and a gradual fall was noticed. For each sample, at a given moisture content, two tests for the calorific value were carried out and the mean of these values taken.

Calorific value tests were performed using samples of the same sawdust at various moisture contents, the different moisture contents being obtained by heating samples for different time intervals in an oven at 105°C.

Sawdust from five different trees were used in the experiments and calorific values were obtained for each sawdust at six moisture contents. A total of 90 calorific value and moisture contents tests were thus carried out.

3.2 Results for Calorific Values

As already being mentioned, sawdust from five different trees commonly available were used in the experiments to determine the calorific value of sawdust. Their local and botanical names are shown in table 3.1.

Table 3.1 Names of trees from which sawdust was obtained.

Local Name	Botanical Name
Sowuli	Fagara macrophylla
Yawi	Tarrietti utilis
Hendui	Lophira alata
Kondi	Uapaca guineesis
Njilei	Entandrophragma angolense

The calorific values were evaluated from the experimental data as outlined in Appendix A, consisting of a sample data, the possible sources of errors and their estimation.

The results for the variation of calorific value with moisture content are shown tabulated in tables 3.2 to 3.6.

Table 3.2 Calorific Value versus moisture content (dry basis) for sawdust obtained from lophira alata (hendui).

Moisture Content %	Calorific Value kJ/kg
116	9034
87	10972
69	11525
49	13451
24	16272
0	18877

Table 3.3 Calorific value versus moisture content (dry basis) for sawdust obtained from fagara macrophylla (sowuli).

Moisture Content %	Calorific Value kJ/kg
67	11122
51	12314
40	14547
13	15526
6	17038
0	16934

Table 3.4 Calorific value versus moisture content (dry basis) for sawdust obtained from Uapaca guineensis (Kondi),

Moisture Content %	Calorific Value kJ/kg
94	10049
77	11261
65	12206
50	15074
6	17251
0	17448

Table 3.5 Calorific value versus moisture content (dry basis) for sawdust obtained from tarrieti utilis (yawi),

Moisture Content %	Calorific Value kJ/kg
66	11477
55	12457
43	12607
14	15905
3	16082
0	17779

Table 3.6 Calorific value versus moisture content (dry basis) for sawdust obtained from entandrophragma angolense (njilei).

Moisture Content %	Calorific Value kJ/kg
73	10018
62	10382
46	11644
20	13697
3	17565
0	16872

These results are considered to be consistent since comparison between the data obtained for repeated tests showed differences of about 0.2 to 5%, with very few differing by more than 0.5%.

3.3 Discussion of Calorific Value Results

The results show that the moisture content for the sawdust obtained from the sawmill are 116% (hendui), 94% (kondi), 73% (njilei), 67% (sewuli) and 66% (yawi). The initial moisture content of hendui causes the calorific value of its sawdust to be low, about 9000 kJ/kg. The other sawdusts have relatively high calorific values at their initial moisture contents ranging between 10,000 to 11,000 kJ/kg. It is observed that the calorific values of the sawdust increase by 70 to 100%, for a decrease in moisture contents from their original values to zero. This indicates that there is a need to know the calorific value of sawdust at a given moisture content in engineering applications. Such results could therefore be used to determine the value to which the moisture content should be decreased in order that the fuel be used economically.

The variation of the calorific value of the five different types of sawdust used are shown plotted versus their moisture contents in figures 3.3 to 3.7. The distribution of the data points suggest that straight lines can be used to represent their variation. The equations for these lines are shown in table 3.9 together with their correlation coefficients. It is noted that the equations predict the experimental data very well and they can therefore be used to predict the calorific

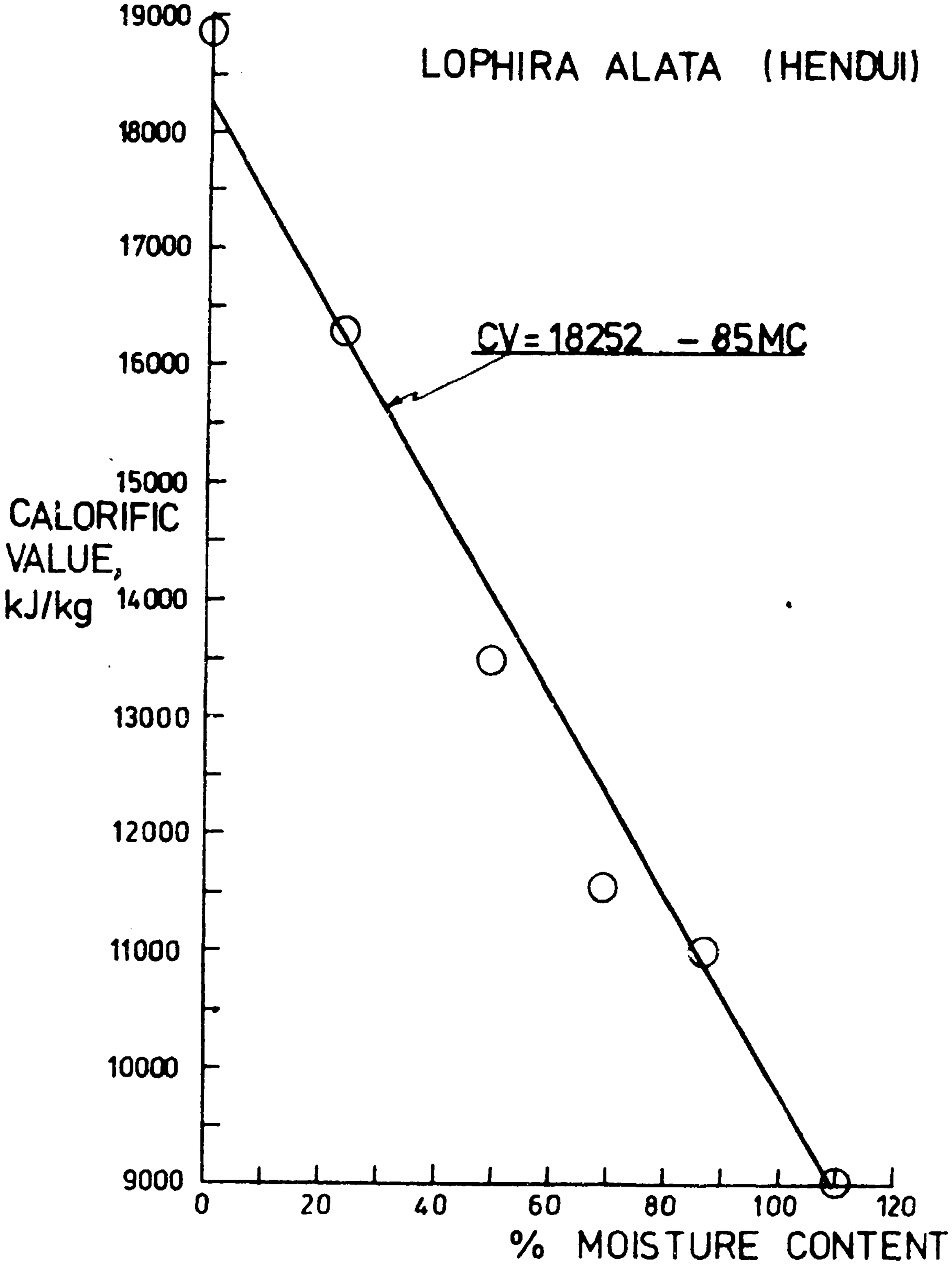


Fig. 3.3 **Variation of calorific value with moisture content of sawdust.**

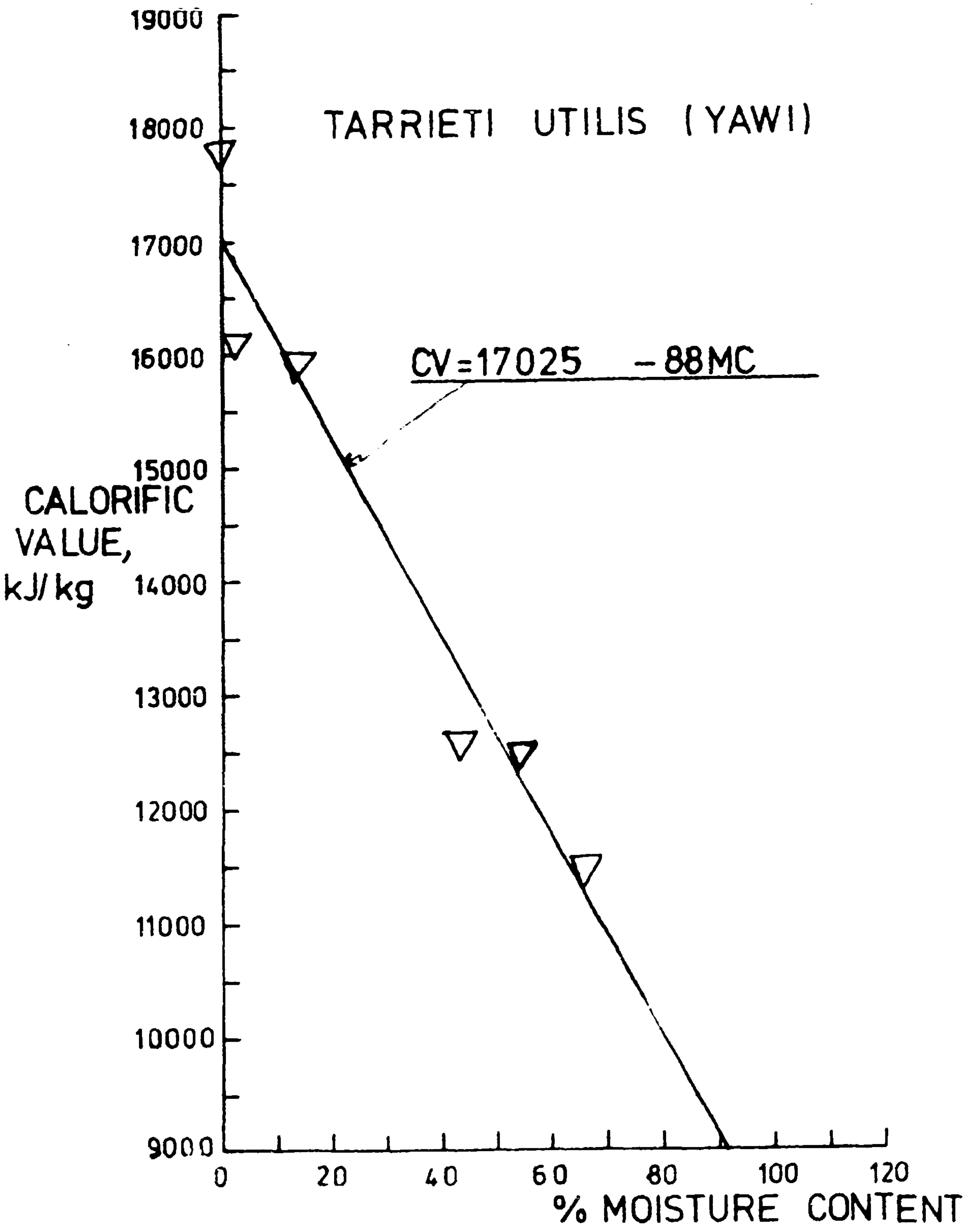


Fig. 3.4 Variation of calorific value with moisture content of sawdust.

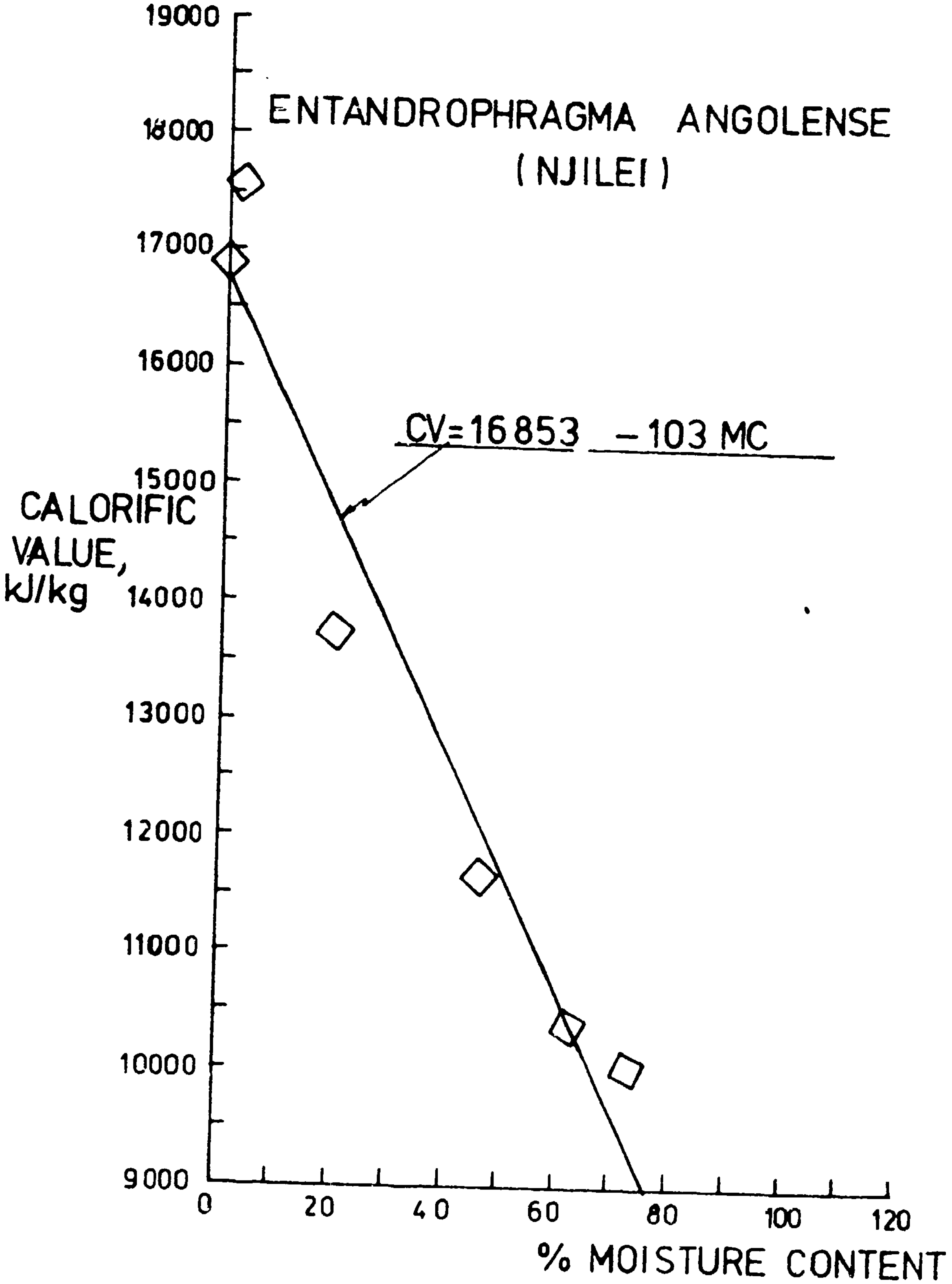


Fig. 3.5 Variation of calorific value with moisture content of sawdust.

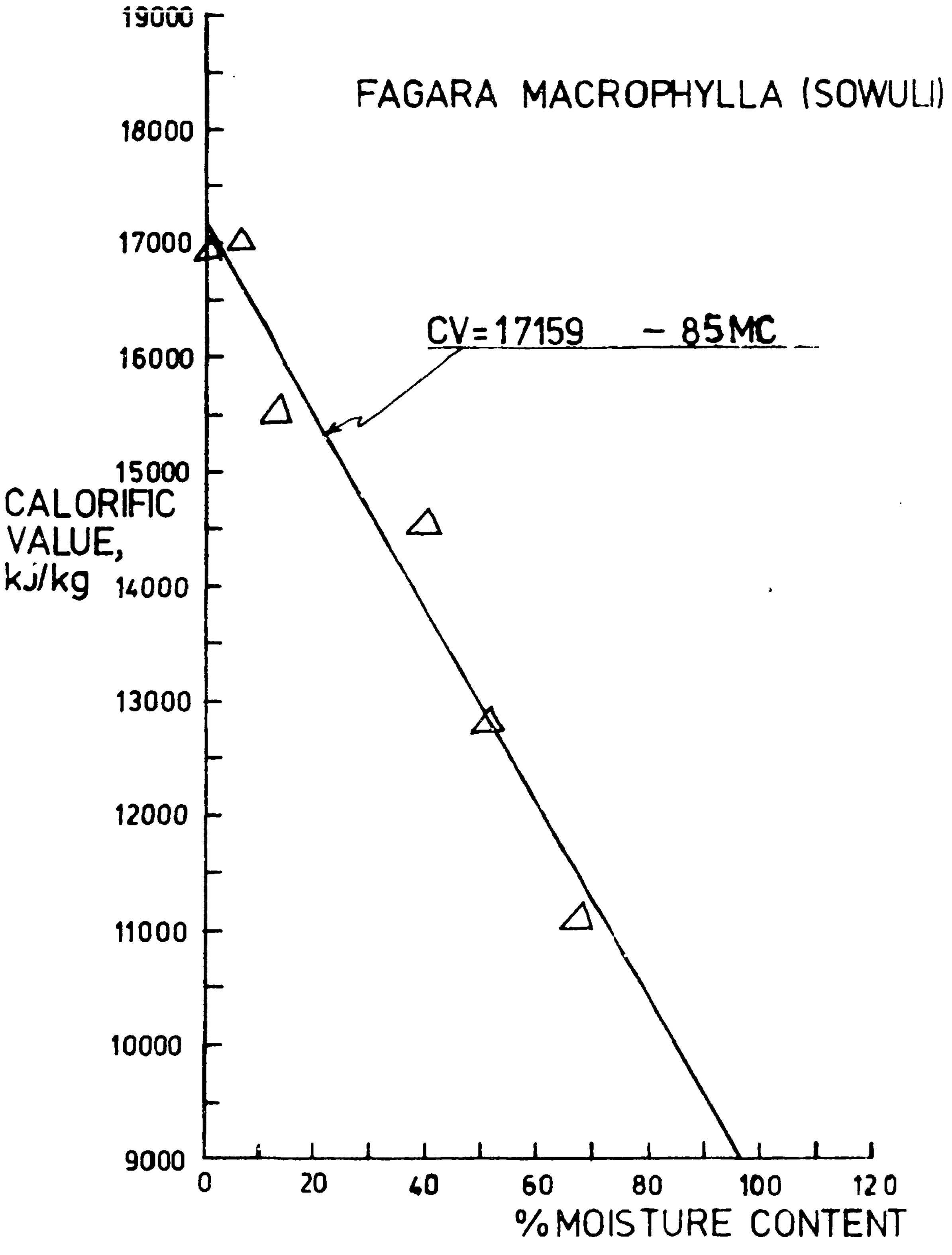


Fig. 3.6 Variation of calorific value with moisture content of sawdust.

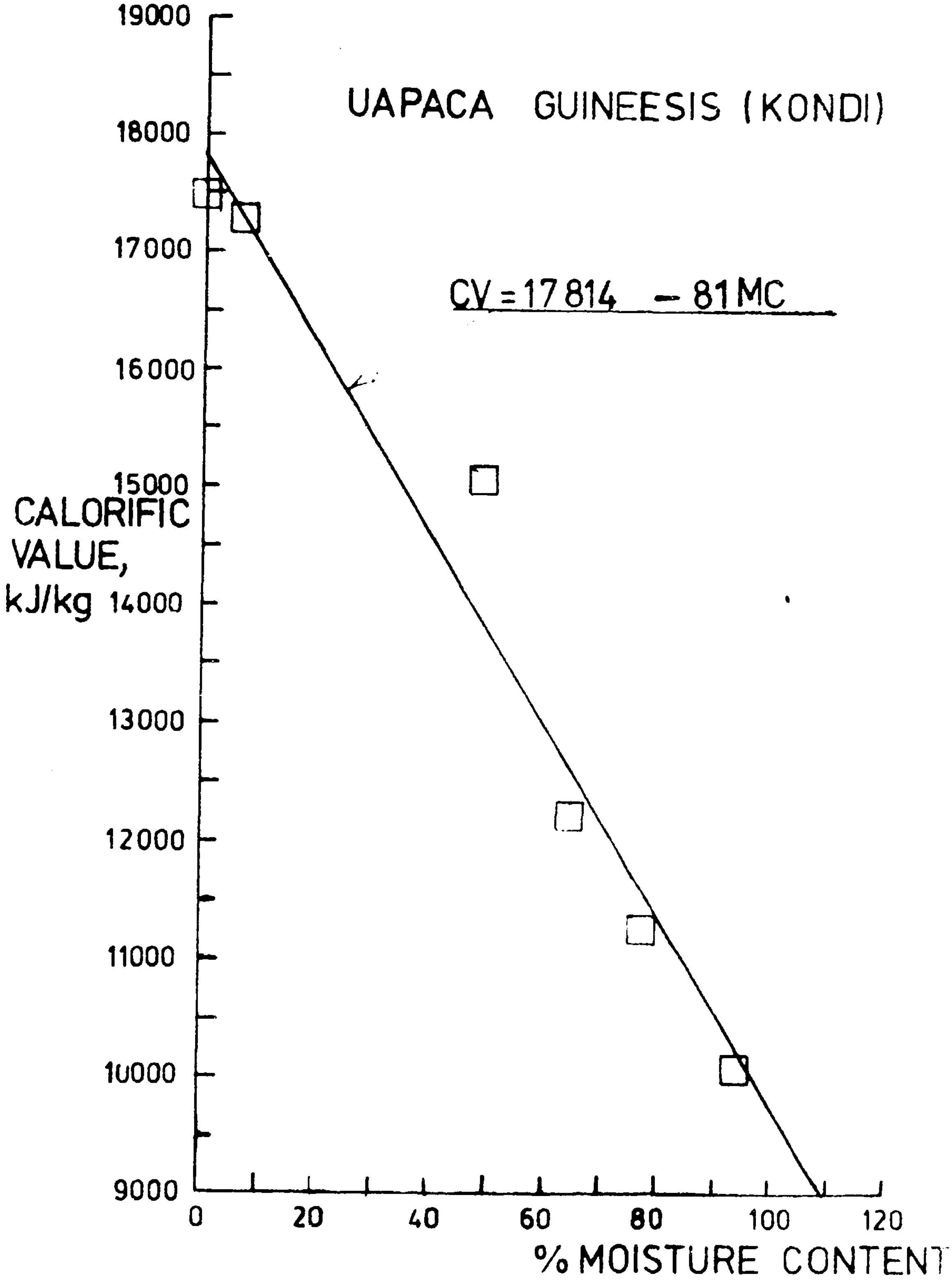


Fig. 3.7 Variation of calorific value with moisture content of sawdust.

Table 3.7 Equations for predicting the calorific values of various types of sawdust for any moisture content (dry basis).

Type of Sawdust	Equation	Correlation coefficient
Hendui	CV = 18252 - 85 MC	- 0.99
Sowuli	CV = 17159 - 85 MC	- 0.98
Kondi	CV = 17814 - 81 MC	- 0.98
Yawi	CV = 17025 - 88 MC	- 0.98
Njilei	CV = 16852 -103 MC	- 0.97

values of the specific types of sawdust if the moisture content is known.

The question is immediately raised as to the validity of these equations when mixtures of sawdust are only available, which is in fact a realistic case. However under such real conditions, it is not easy to determine the various types of sawdust present in a moisture or the proportions in which they exist. It would therefore appear that it is difficult to give a generalized formula for predicting the variation of calorific values with moisture content for different proportions and types of sawdust mixtures without further extensive experimentation.

It is nevertheless helpful to compare all the results as shown in figure 3.8. The straight lines indicate that there are lower and upper limits for the variation of CV with MC. The data points also suggest that there are maximum and minimum differences between these two regression lines of about 38 and 8 percent respectively corresponding to the high and low moisture content regions.

Since the spread in the data shown in figure 3.8 is not great it is possible to represent these results by a single equation which can be used to predict the variation of calorific value with moisture content for mixtures of sawdust. This equation has been obtained and is given by the equation

$$CV = 17155 - 81\ MC \quad \ldots\ldots (3.1)$$

It should be stressed that cases very often exist where the sawdust available from a sawmill or workshop consist only of one

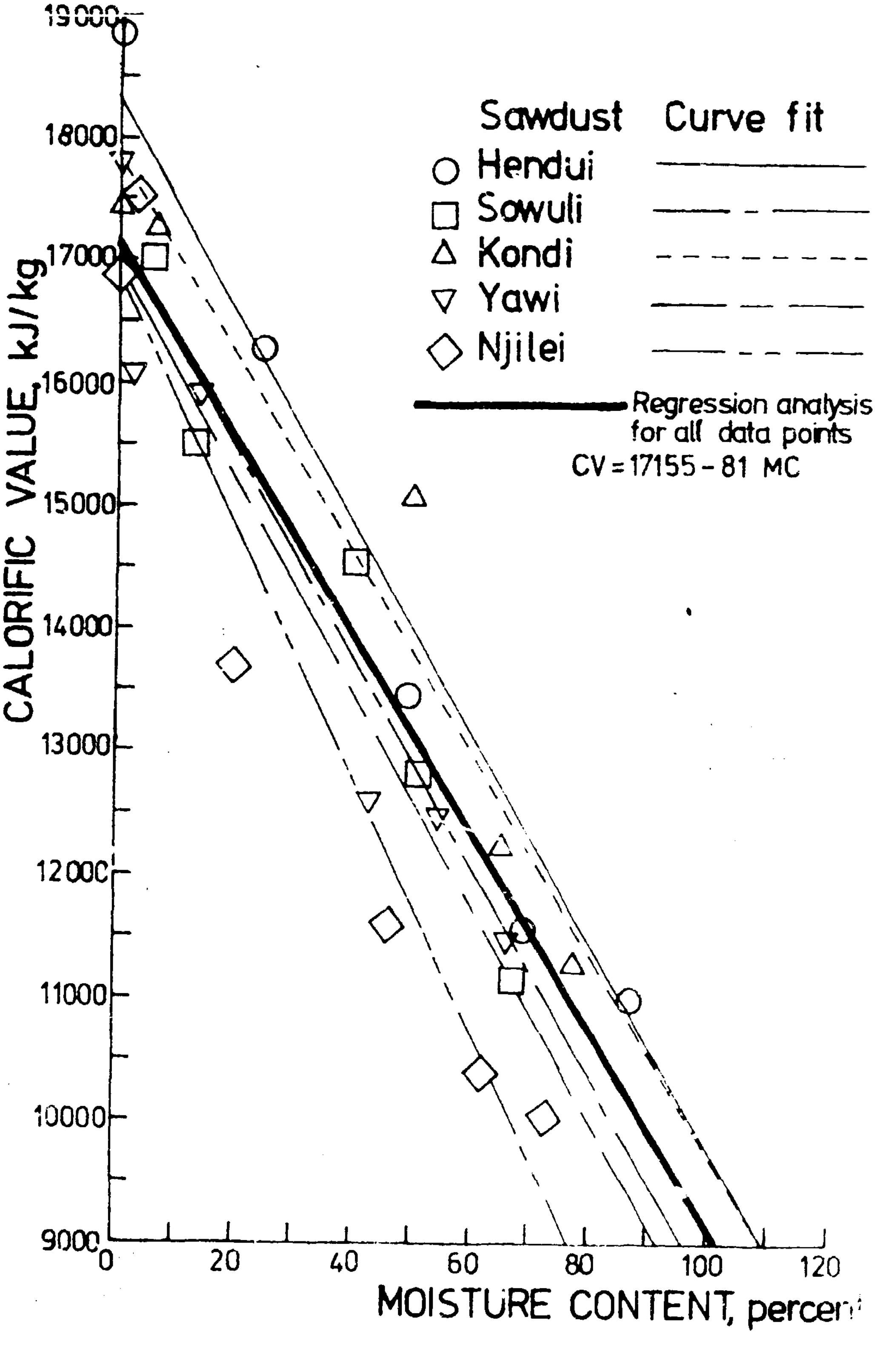


Fig. 3.8 Comparison of calorific value versus moisture content for various types of sawdust.

type, in which case the equations shown in table 3.7 can be used accordingly.

A closer look at figure 3.8 indicates that the difference between the lower and upper correlations decreases at lower moisture contents. Tests in this study have indicated that satisfactory burning of sawdust is achieved using it at a moisture content (dry basis) of about 20%, which can be obtained by open air drying. It is thus seen that for this range of moisture content the maximum difference between the calorific values is less than 10%. There is therefore no need, under practical conditions, to prefer the use of one type of sawdust over the other.

With regards to the use of mixtures of sawdust, mention should be made of calorific values of sawdust mixtures which have been used in experiments outlined in Chapters 4 and 6. The mixtures whose compositions were unknown had a calorific value of about 17000 kJ/kg at a moisture contents of about 15 to 30% (dry basis). There appears to be no adverse effect on the calorific values due to mixing various types of sawdust. More conclusive comments will, of course, depend on further investigations.

It is useful to mention that sawdust does not need any special effort to reduce its moisture content to the range of values necessary for its effective use. It can be adequately dried by leaving it exposed to the atmosphere. Of course, the drying process would be dependent on the environment surrounding the sawdust. It is therefore recommended that it should be stored in a warm place with a lot of ventilation.

Summarizing the results of the calorific value study it can be concluded that:

a) the calorific values of the different sawdust studied vary substantially with changes in moisture content.

b) the magnitude of the calorific values are adequate for low grade heat production,

c) equations are now available to predict the variation of calorific value with moisture content.

d) the calorific value of sawdust can be substantially increased by open air drying.

e) there appears to be no restriction on the use of mixtures of sawdust or a specific sawdust in practical applications.

Chapter 4

CHARACTERISTICS OF SAWDUST BURNER

The availability and the calorific value of sawdust has been reported in the preceding chapters. The results have so far indicated that there is adequate justification to use this waste material as a fuel for producing low grade heat.

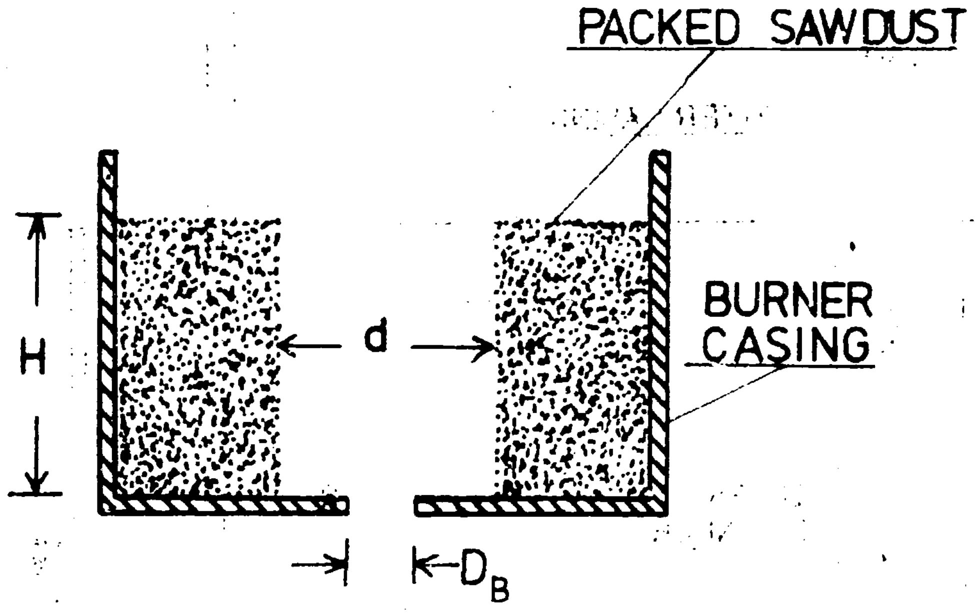
This chapter is concerned with the process of burning the sawdust. A simple method of combustion has been used and is shown in figure 4.1. The burning process has been investigated so as to understand its operation and to also obtain parameters for the design of burners for various applications. The apparatus used, the experimental procedure adopted and the results and discussions are presented below.

4.1 Experimental Apparatus

The basic system studied is shown in figure 4.1. In operation the loose sawdust was packed to a height H around a rod passing through the air inlet hole of diameter approximately equal to D_B. The inner surface of the hole was then lit and combustion took place by the passage of air through the burner hole by natural convection. The burning process was studied using the apparatus described below.

A schematic diagram of the apparatus used to study the characteristics of the sawdust burner is shown in figure 4.2. Two different views of the apparatus are shown in figures 4.3 and 4.4. The outer casing made of 0,16 cm thick galvanized sheet metal was 91 cm high and had a diameter of 61 cm. The inner cylinder, shown in figure 4.2 and 4.4, was 15 cm high. It had enough clearance with the outer cylinder to enable its free movement vertically. It was supported on two stands as shown in figures 4.2 and 4.4. The rods connecting the inner cylinder to the stand were free to move vertically through slots cut on the side of the outer cylinder. Using this arrangement, it was possible to have various heights of packed sawdust and at the same time make provision for a calorimeter to be used to assess the rate of heat generation.

The stands supporting the inner cylinder, and the outer



D_B = air inlet diameter
d = burner hole diameter
H = packed height of sawdust

Fig. 4.1 Basic burner configuration studied.

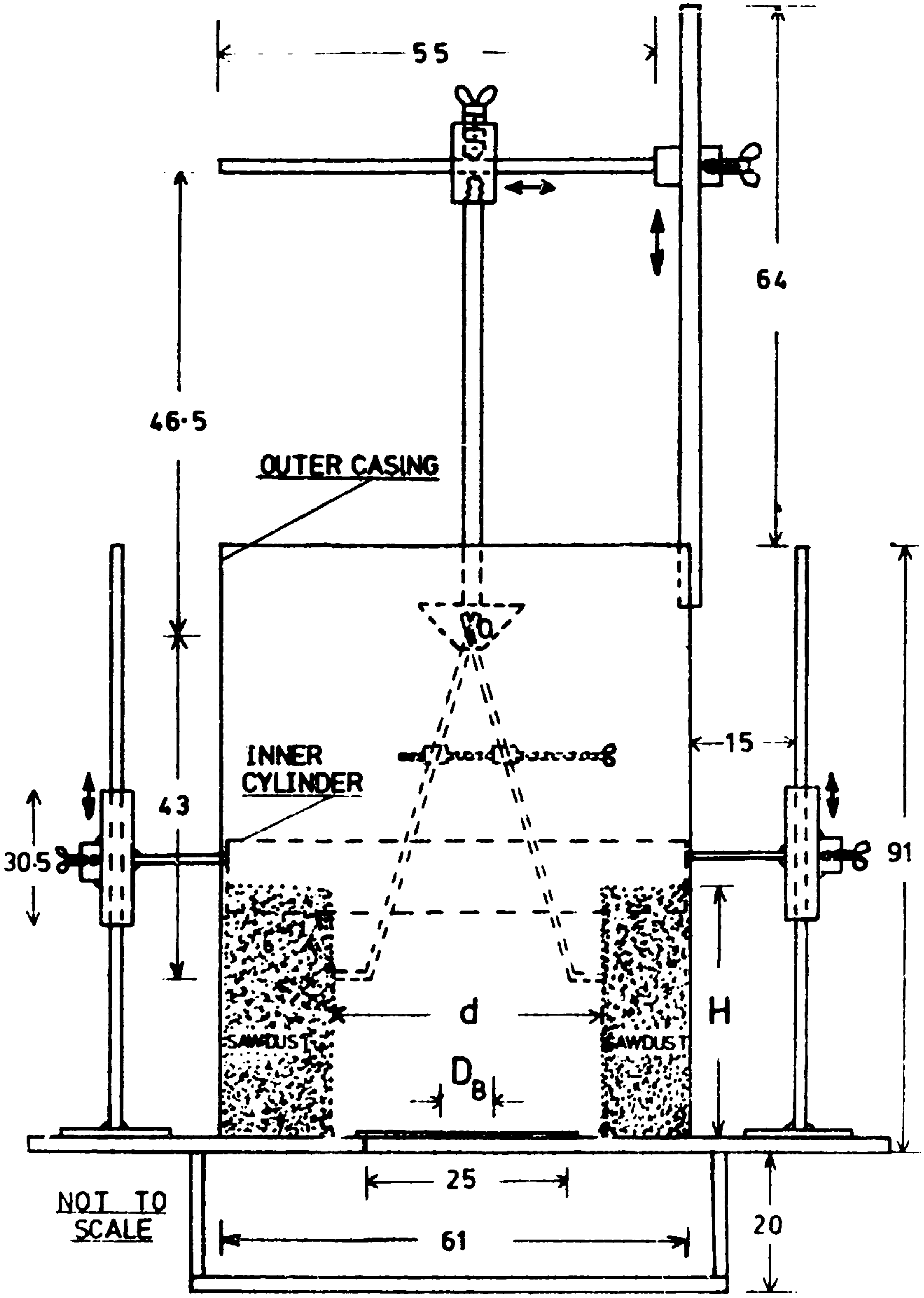
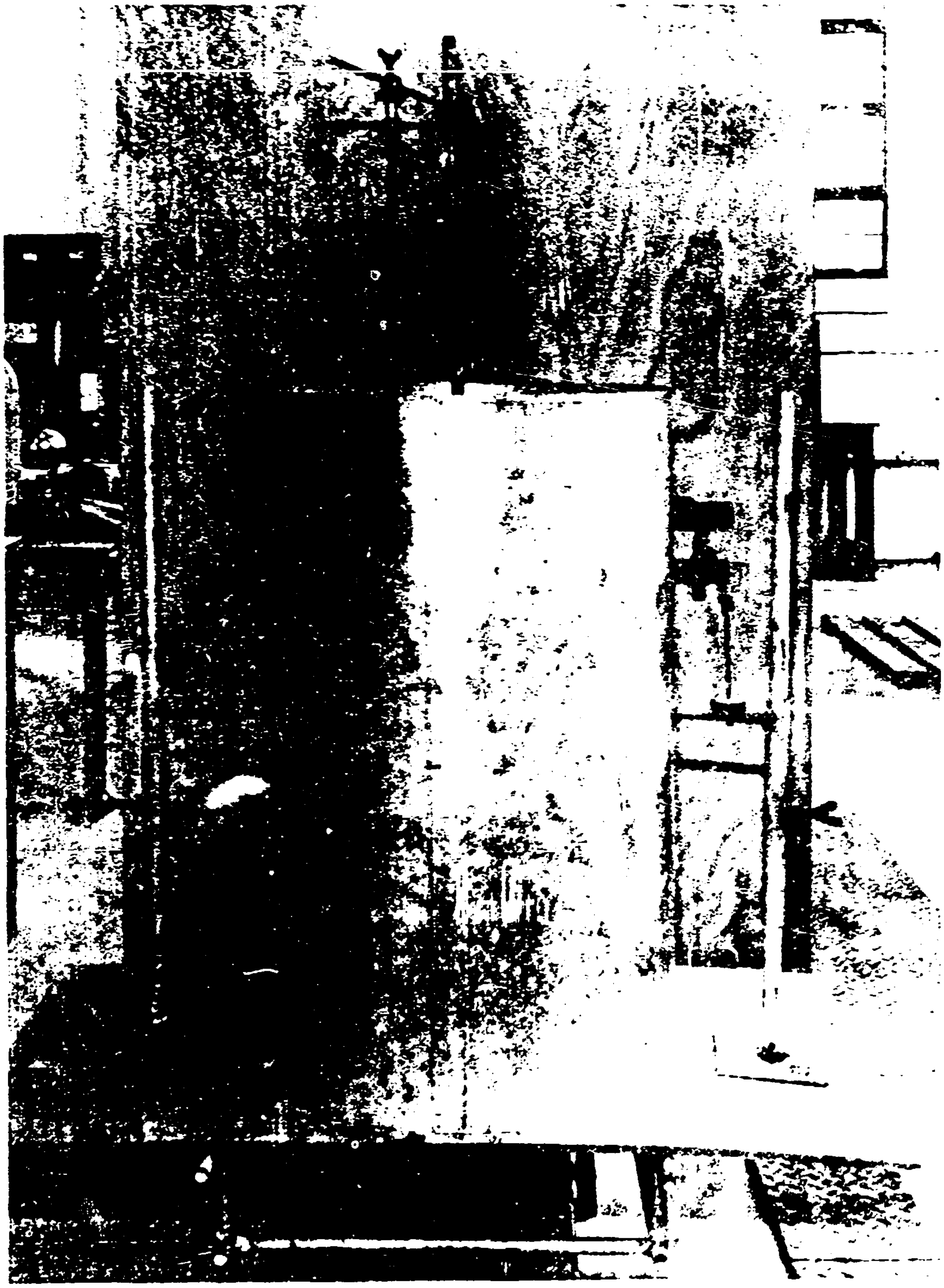


Fig. 4.2 Schematic diagram of apparatus used to study the characteristics of the sawdust burner.



casing rested on a plywood platform which was in turn supported on a metal frame 20 cm high. It should be pointed out that a hole of diameter 25 cm was cut on the plywood platform and various plates having different diameter holes D_B could be mounted as shown in figure 4.2. Scorching of the plywood platform was thus prevented using this arrangement.

The entire apparatus was supported on a scale so that the decrease in mass of the sawdust could be measured during the course of the experiments.

The burner hole diameter, d, was measured using the set-up shown, for example, in figures 4.2 and 4.4. The caliper was free to move vertically, laterally and about a horizontal axis through O as shown in figure 4.2. This arrangement was devised to allow data to be obtained with less strain and discomfort as was the case in previous studies (12) and (13).

4.2 Experimental Procedure

4.2.1 Determination of Variation of, Mass of Fuel Consumed, Burner Hole Diameter and Effect of Air Inlet Diameter.

The sawdust used in the experiments was a mixture of various types. A large quantity was obtained and thoroughly mixed so that the composition was uniform. Samples were occasionally taken to determine their calorific values and moisture content throughout the experiments.

In carrying out the experiments, a rod of diameter equal to the air inlet diameter D_B was passed through the air inlet hole. The sawdust was placed in the casing and compressed, after about every 5cm had been added, till a height H = 15.24 cm was obtained. The rod was carefully withdrawn leaving a hole having a diameter approximately eaual to D_B. A flame was then placed underneath the air inlet hole to ignite the sawdust. The time needed for the whole burner hole to be ignited was about 10 minutes and there was little smoke at this point.

The mass of the whole assembly was then weighed and the diameter of the burner hole measured. Readings of the mass of the assembly and the burner hole diameter were recorded at about 15 minute intervals for at least 3 hours. For a given value of air inlet diameter D_B, the experiments were repeated at least five times giving at least sixty data points for each experiment performed at a given value of D_B. Data were obtained for values of D_B equal to 2.54, 5.08, 7.62 and 10.16 cm which spanned the range of realistic values which may be used in burners.

The density of packing of the sawdust was effectively uniform during all experiments; variation between experiments was not more than 0.9 percent. The moisture content of the sawdust used was about 20 percent.

4.2.2 Determination of effect of height of packing

The same procedure used in the tests outlined in the previous section was adopted for these tests, the difference being that various heights of packing were investigated.

In the experiments sawdust was packed to a height H and for a given value of air inlet hole diameter D_B, the variation of the mass of the whole assembly and the burner hole diameter were measured at about fifteen minute intervals. The experiments were carried out for values of D_B = 2.54, 5.08, 7.62 and 10.16 cm.

The height H was then changed and experiments repeated using all values of D_B mentioned above for H = 15.24, 30.48, 45.72 and 60.96 cm.

Again the moisture content and the density of packing were effectively constant during all tests.

4.3 Result of Experiments on Burner Characteristics

4.3.1 Results for variation of mass of fuel, burner hole diameter and effect of air inlet diameter

The preceding section outlined the experimental procedures adopted to obtain data which was used to determine the characteristics of the sawdust burner. It is recalled that two sets of experiments were carried out. The results of these tests are presented in this section.

The first set of experiments performed (see section 4.2.1) was concerned with determining the characteristics of the burner in terms of the variation of, mass of fuel consumed, burner hole diameter and the effect of the air inlet hole diameter.

The variation of the change in the mass of the sawdust used with time during the experiments was obtained from the experimental data. The results for the mass of sawdust used, m_f, with time are shown in figures 4.5 to 4.8, for D_B = 2.54, 5.08, 7.62 and 10.16 cm respectively.

Figure 4.9 shows the variation of burner hole diameter d, with time t. The data are presented for air inlet diameters D_B equal 2.54, 5.08, 7.62 and 10.16 cm. Many data points are shown since it is recalled that for a particular value of D_B, the experiments were done five times so as to establish their repeatability. It should also be mentioned that only one height of packing, i.e. H = 15.24 cm, was used in these experiments.

4.3.2 Results for the effect of height of packing on variables

It is recalled that these experiments were carried out to determine the effect the height of packing had on the other variables used to characterize the performance of the burner. The variation of burner hole diameter d with time t for values of H = 15.24, 30.48, 45.72 and 60.96 cm at values of D_B = 2.54, 5.08, 7.62 and 10.16 are shown in figure 4.10. Similar results for the variation of mass of fuel consumed m_f with time t for various values of D_B are shown in figures 4.11 to 4.14.

4.4 Discussion of Results for Experiments on Burner

The experimental data have been presented in section 4.3. These data were obtained to firstly determine the variation

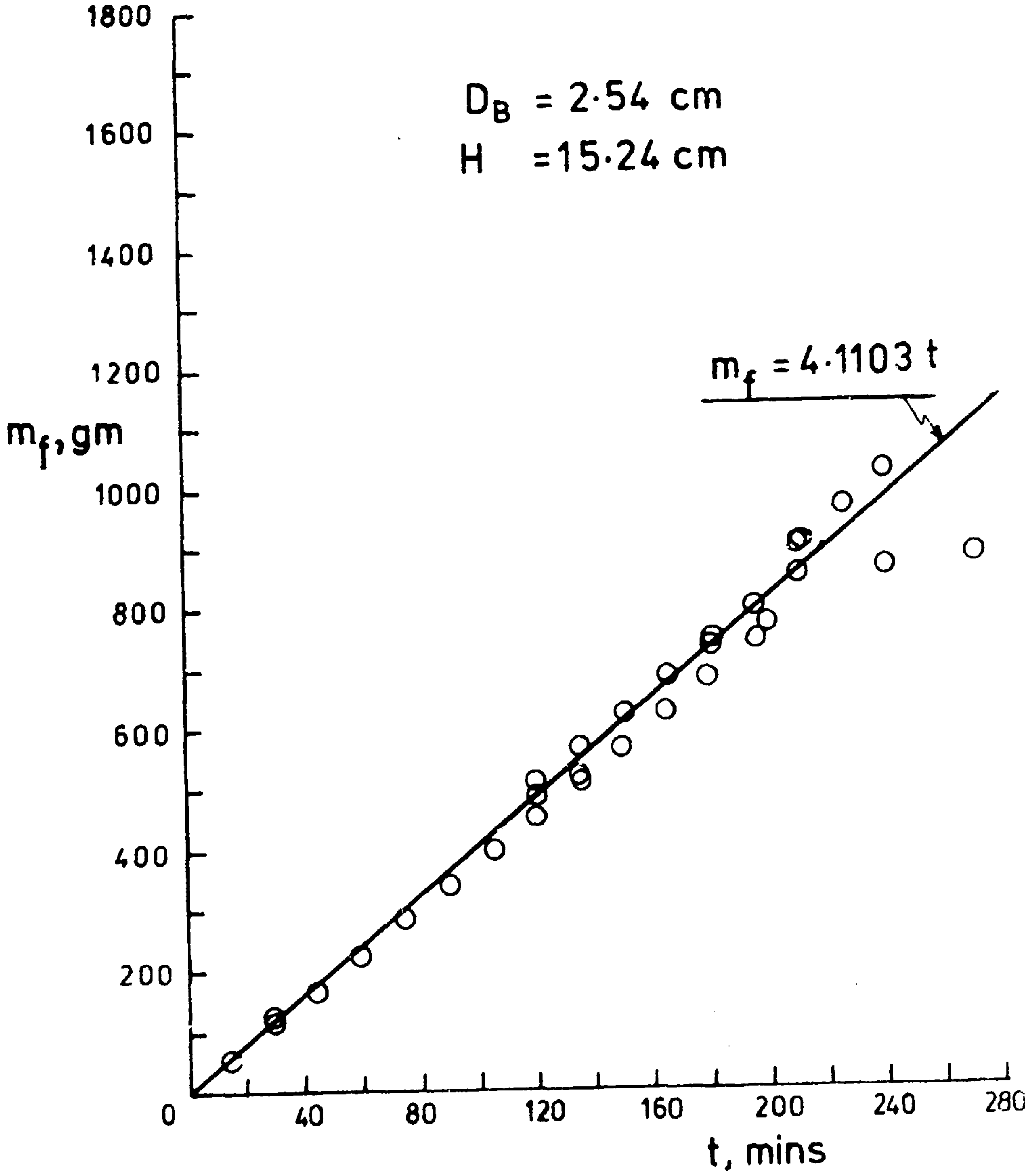


Fig. 4.5 Variation of mass of sawdust used with time for D_B = 2.54 cm.

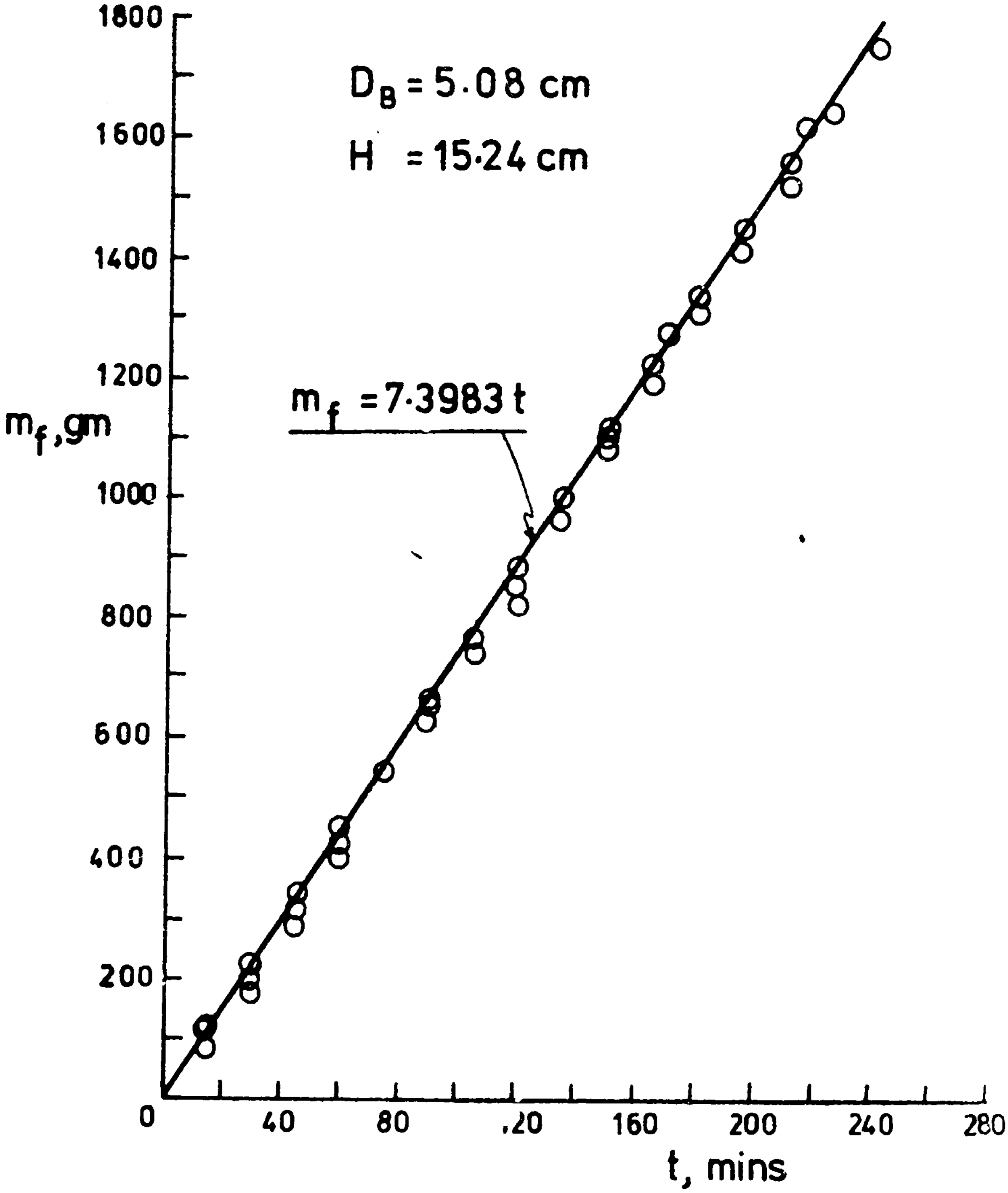


Fig. 4.6 Variation of mass of sawdust used with time for D_B = 5.08 cm.

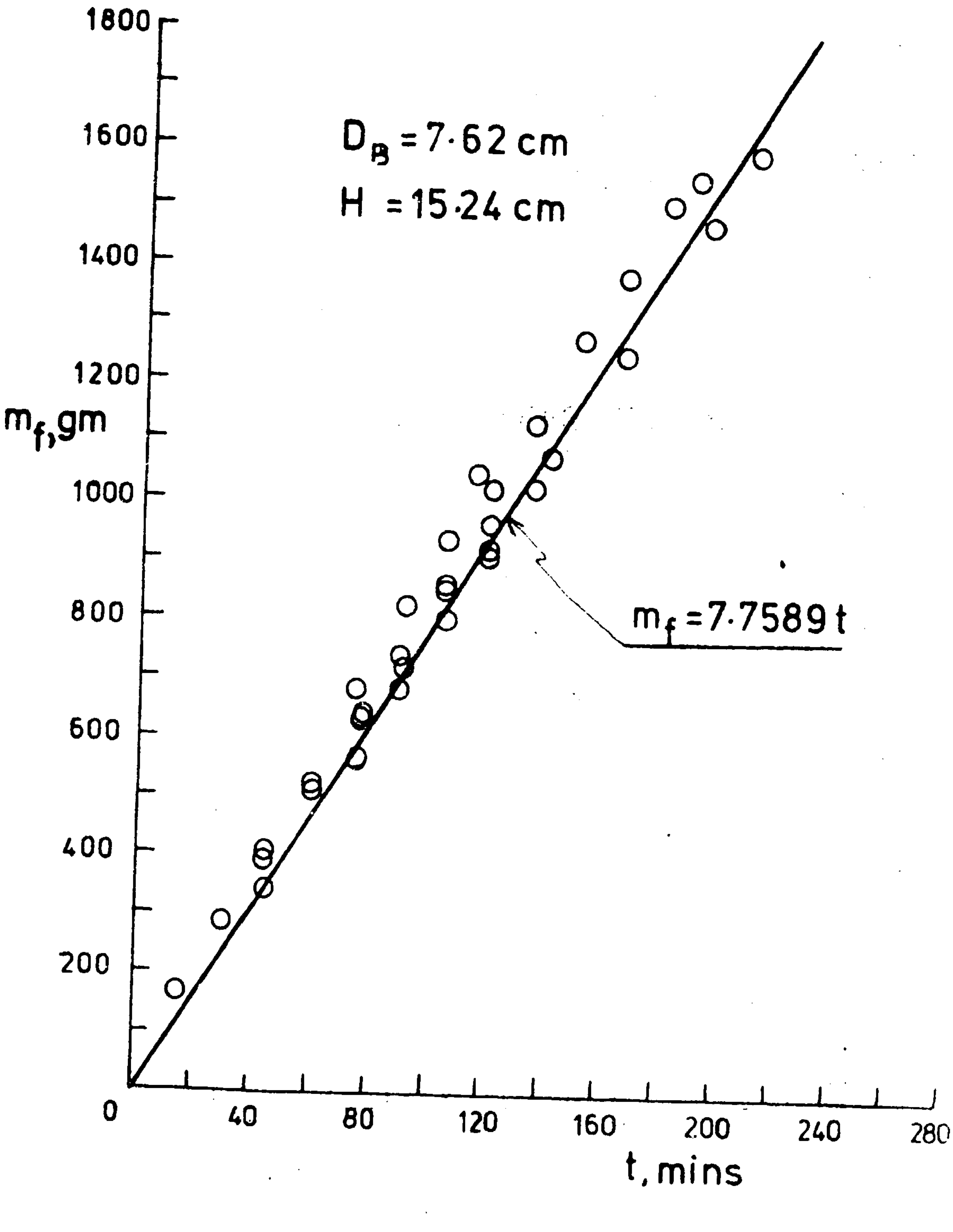


Fig. 4.7 Variation of mass of sawdust used with time for D_B = 7.62 cm.

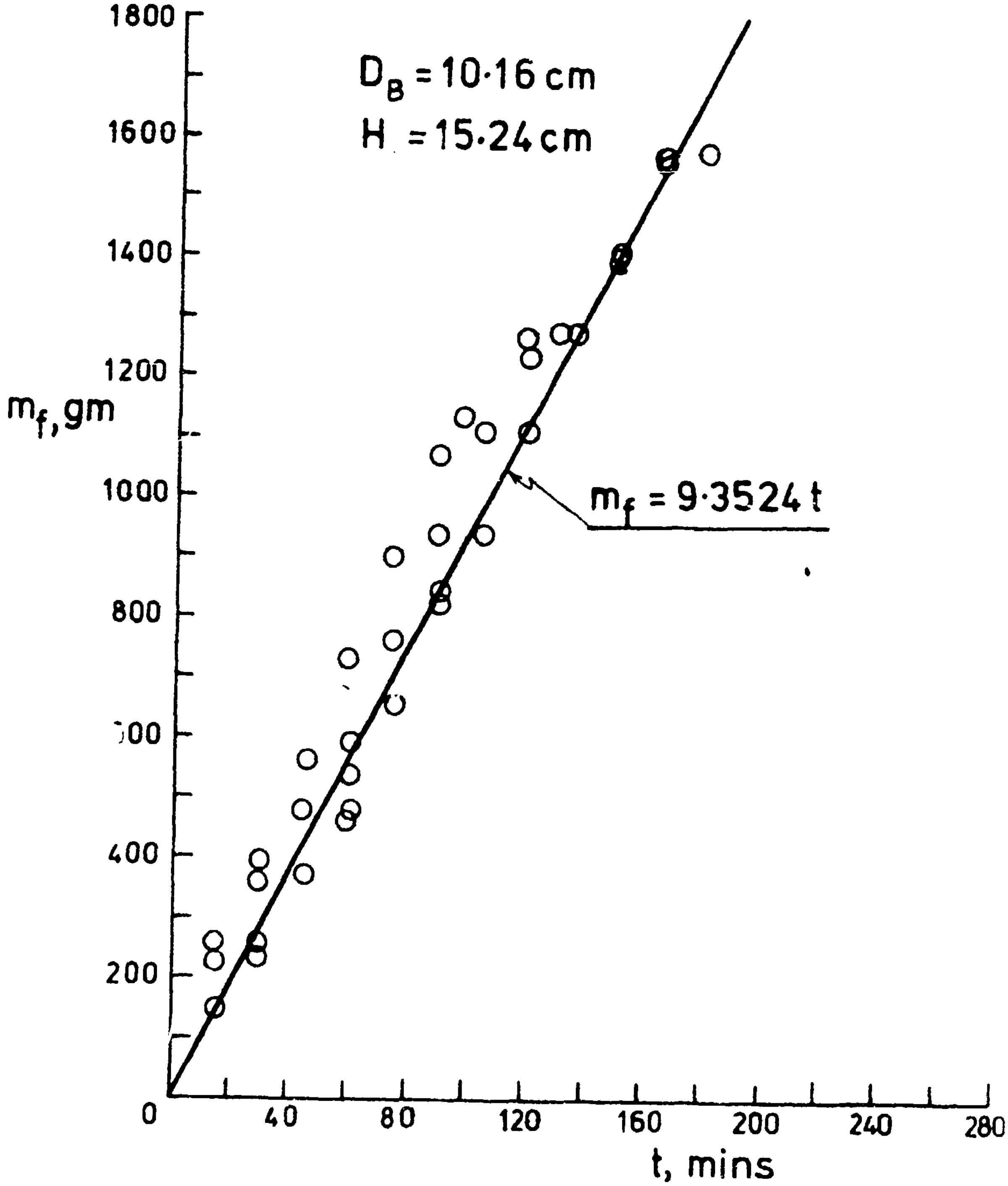


Fig. 4.8 Variation of mass of sawdust used with time for D_B = 10.16 cm.

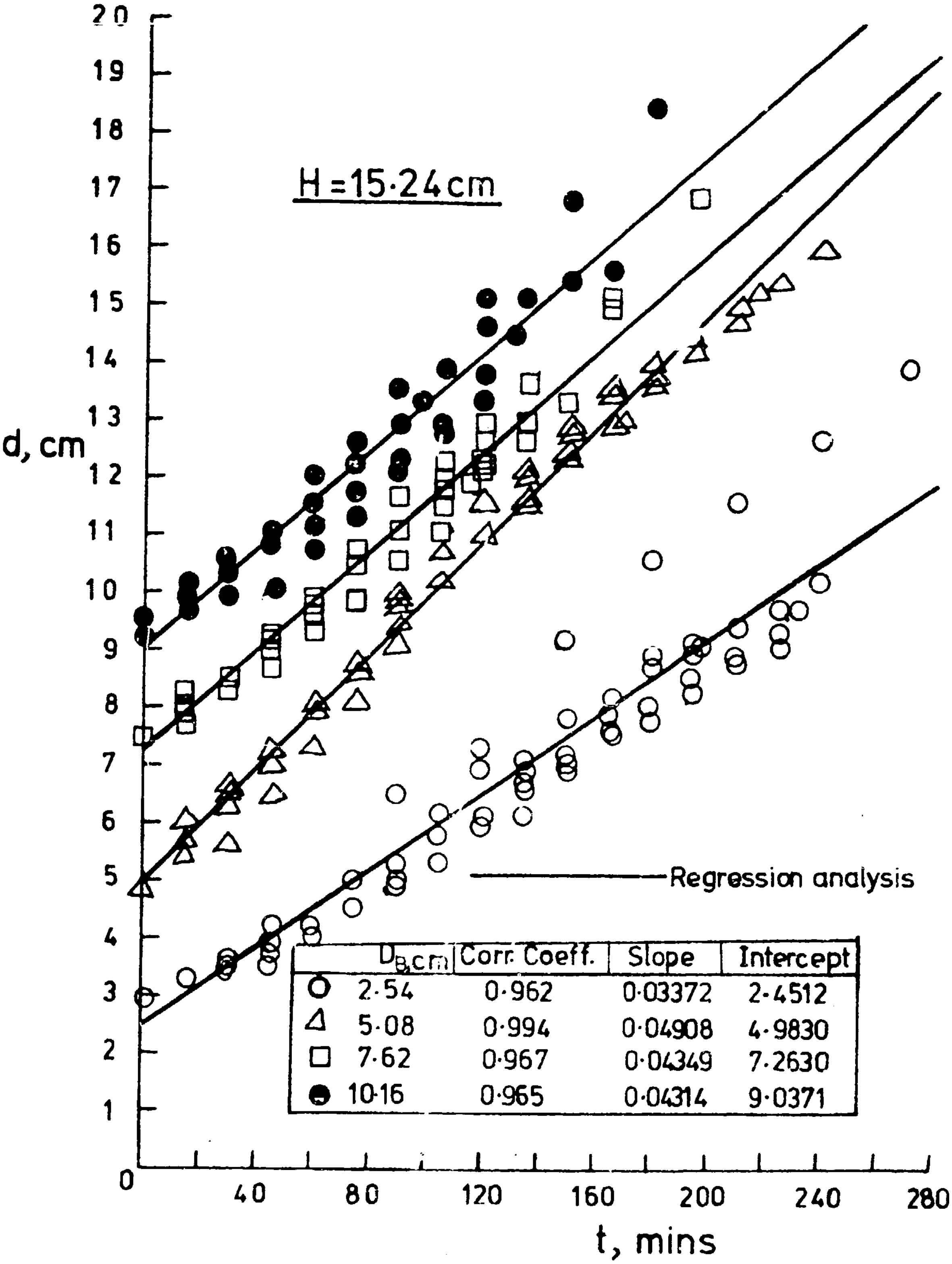


Fig. 4.9 Variation of burner hole diameter with time for various values of D_B.

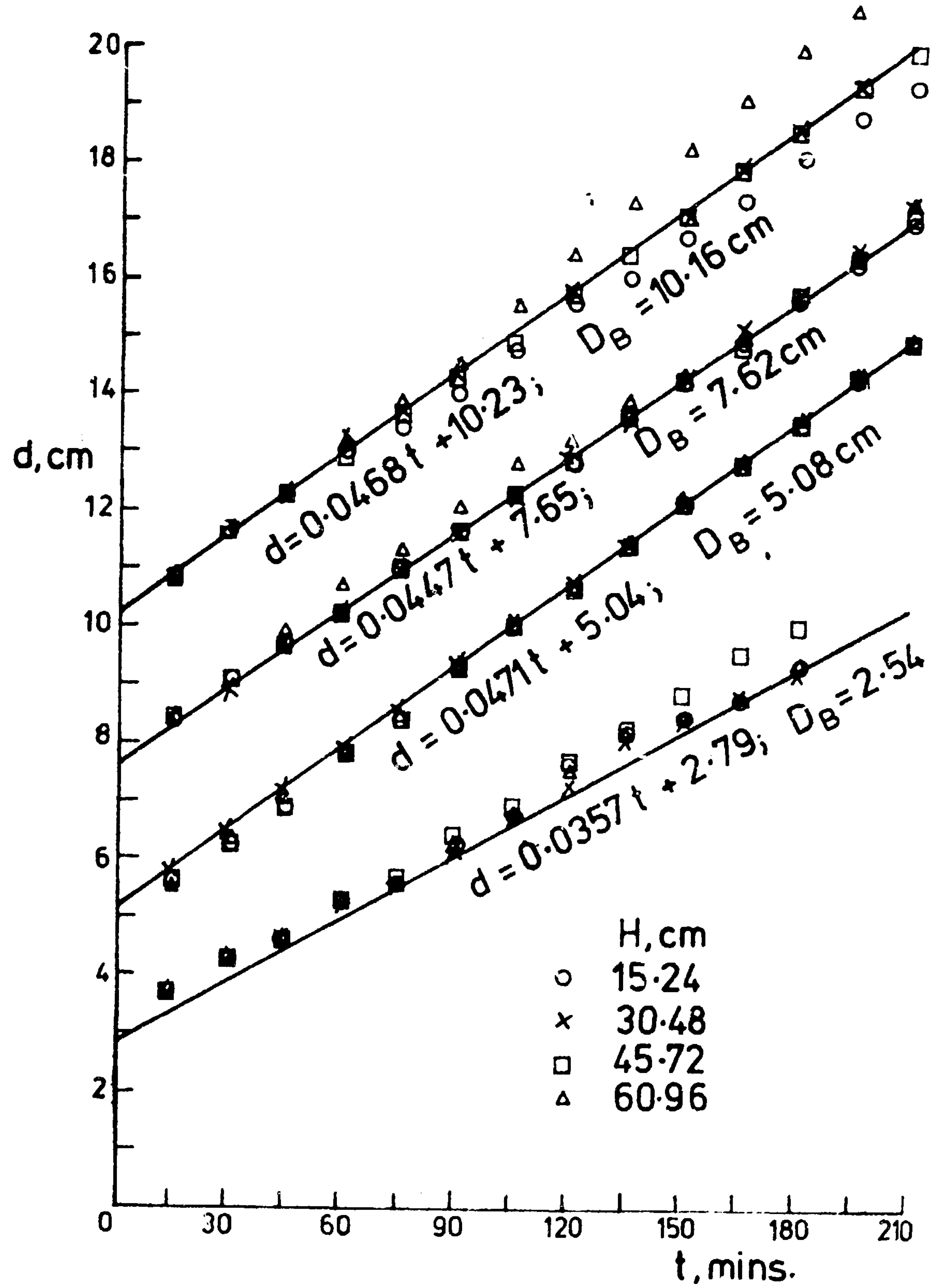


Fig. 4.10 Effect of height of packing on variation of burner hole diameter with time.

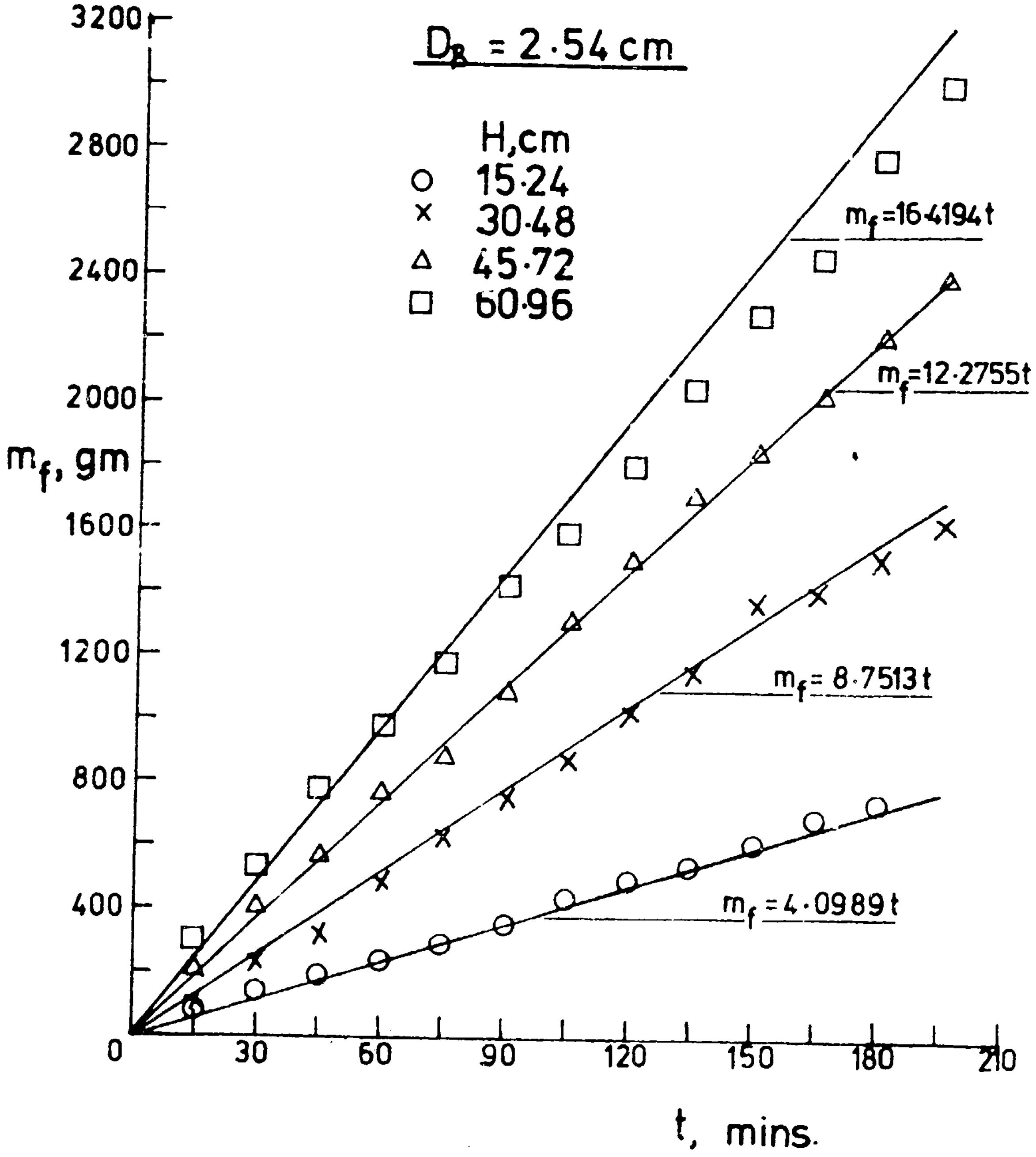


Fig. 4.11 Effect of height of packing on variation of mass of sawdust used with time for D_B =2.54cm.

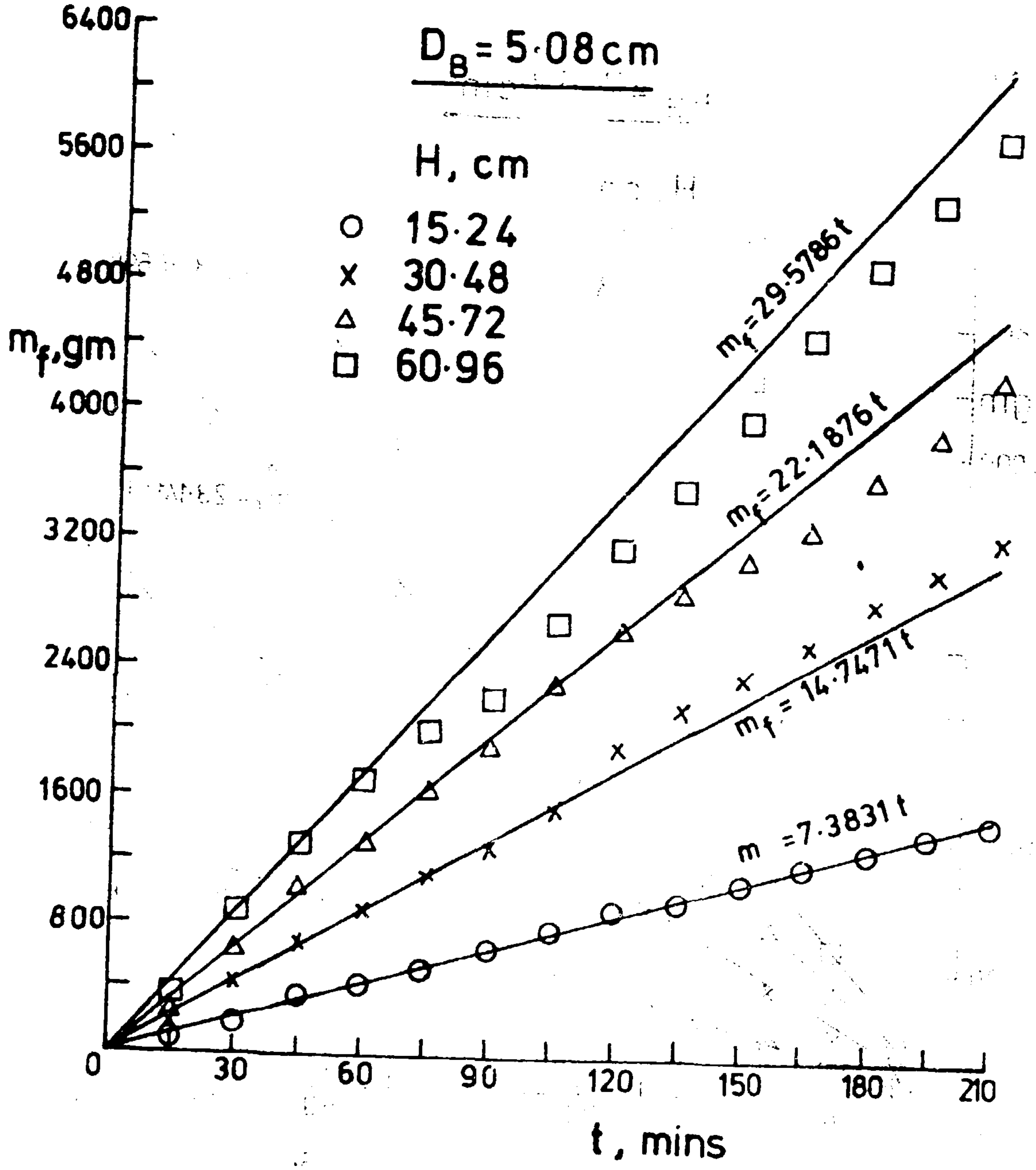


Fig. 4.12 Effect of height of packing on variation of mass of sawdust used with time for D_B = 5.08 cm.

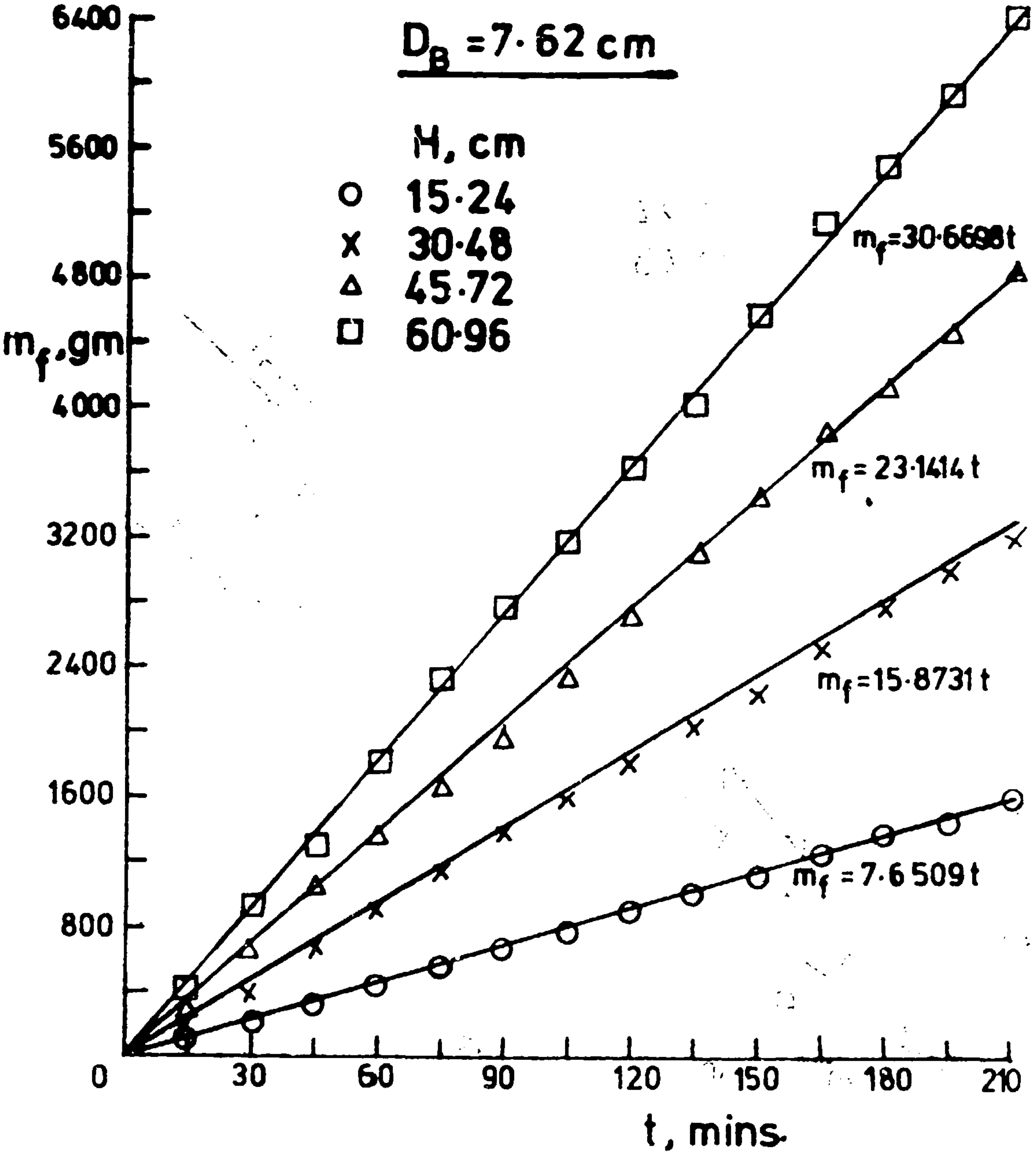


Fig. 4.13 Effect of height of packing on variation of mass of sawdust used with time for D_B = 7.62cm.

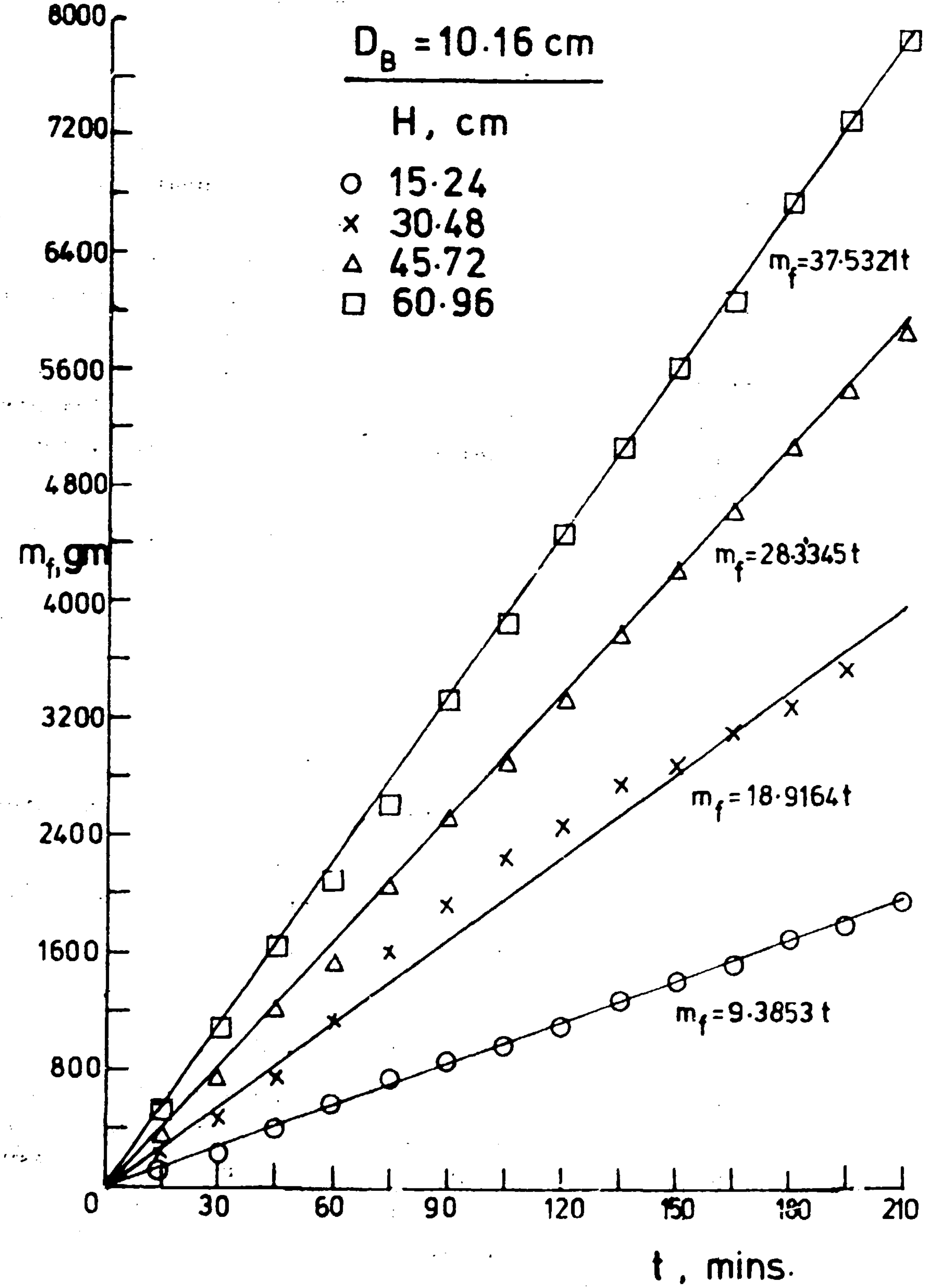


Fig. 4.14 Effect of height of packing on variation of mass of sawdust used with time for D_B = 10.16cm.

of the various parameters during the burning process and secondly to assess the effect of the height of packing of the sawdust on these parameters. It is now intended to explain and analyze the results obtained.

4.4.1 Consumption of Sawdust During Operation of Burner

The results for m_f versus t shown in figures 4.5 to 4.8 indicate close grouping of the data points. Since the data in each figure represent five experiments as already mentioned in section 4.2.1 it can be concluded that the repeatability of the experiments is good and the data are reliable. The distribution of the data points suggest that straight lines can be used to predict the variations of m_f versus t. Linear regression analysis for these results are shown on figures 4.5 to 4.8 for various values of D_B. The correlation coefficients for the linear equations are 0.99 or greater, indicating that they represent the data very well.

The equations for the variation of m_f with t have the form

$$m_f = St \qquad (4.1)$$

where

m_f = mass of fuel in gm

S = slope of straight line

t = time after start of experiments in minutes.

(The equations are shown below).

$$m_f = 4.1103t;\ D_B = 2.54 \text{ cm},\ H = 15.24 \text{ cm} \qquad (4.2)$$

$$m_f = 7.3983t;\ D_B = 5.08 \text{ cm},\ H = 15.24 \text{ cm} \qquad (4.3)$$

$$m_f = 7.7589t;\ D_B = 7.62 \text{ cm},\ H = 15.24 \text{ cm} \qquad (4.4)$$

$$m_f = 9.3524t;\ D_B = 10.16 \text{ cm},\ H = 15.24 \text{ cm} \qquad (4.5)$$

It is noted for this case of constant value of H studied, that the magnitude of the slope depends on the value of the air inlet diameter. The variation of S with D_B can be expressed by a straight line as shown in figure 4.15, i.e.

$$S = 0.6333\ D_B + 3.1333 \qquad (4.6)$$

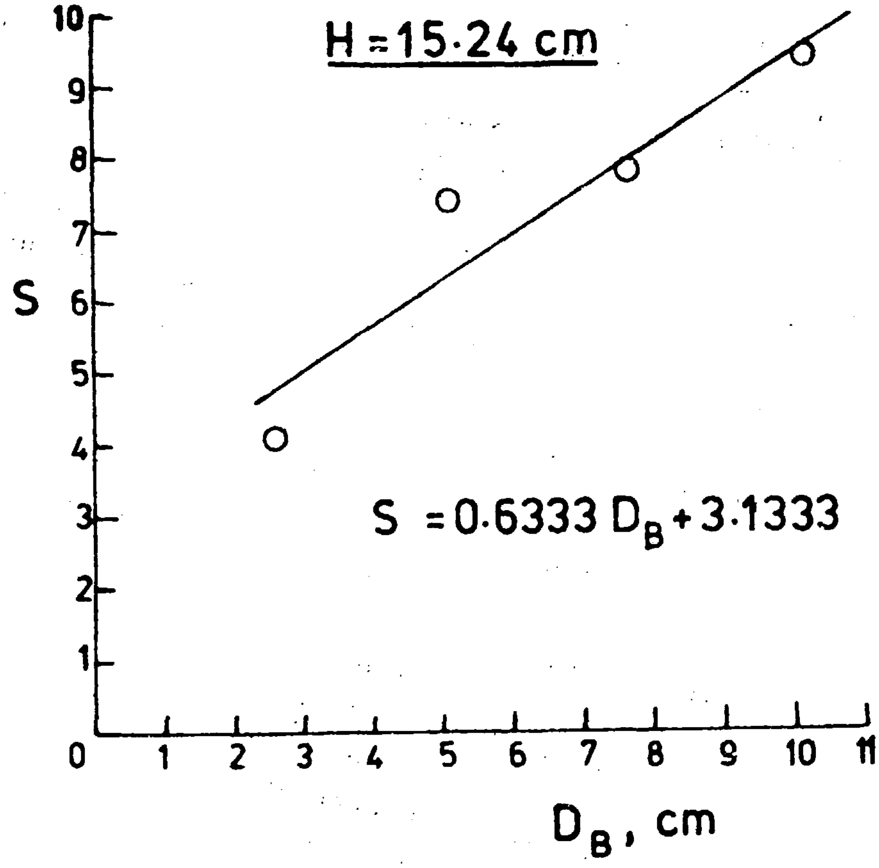


Fig. 4.15 Dependence of slope of line, representing the variation of mass of sawdust used with time, on D_B.

for $2.54 \geqslant D_B \leqslant 10.16$ cm, H = 15.24 cm. Thus equations 4.1 and 4.6 can be used to estimate the amount of fuel which can be used for a particular application, or the size of the air inlet hole which can be used for a known mass of fuel and duration of burning.

It is however to be noted that although the basic characteristics of the variation of m_f with t has been obtained, the application of the generalizations made is restricted to the narrow condition of constant H = 15.24 cm. These initial results nevertheless have indicated the scope of further experiments which should be performed to obtain more useful generalizations. This has been done in this study and results are discussed in later sections of this report.

4.4.2 Variation of Size of Burner Hole

The diameter of the burner hole increased with time during the experiments as shown in figure 4.9. Again the data points for each value of D_B are closely grouped and can be represented by straight lines.

It is immediately noticed that the values of the intercept of the straight lines, i.e. values of d at t = 0, are different from the values of D_B, which should be the case. The explanation for this is that the regression analysis fits the best line through the data points, implying that this line does not have to pass through $d = D_B$ at $t = 0$ even if the data at $t = 0$ corresponds to $d = D_B$. The difference between these values of the intercept of the straight lines and values of D_B are 4, 2, 5 and 11 percent for D_B = 2.54, 5.08, 7.62 and 10.16 cm respectively. These differences are consistent with the scatter of the experimental data. The correlation coefficients for the straight lines range between 0.96 and 0.99 indicating that the equations represent the data well. The slopes of these straight lines are nearly parallel. Further discussions of these results will be presented later.

4.4.3 Effect of Height of Packing

Variation of d with time.

The discussion has so far shown the variation of the burner hole diameter and the mass of fuel consumed with time for H = 15.24 cm, and correlations have been obtained. It was however noted that although these results have shown salient features of the operation of the burner it was necessary to obtain a wider range of data to broaden the scope of the generalizations which would be made.

It is recalled that the effect of H on d and m_f were presented earlier in figures 4.10 to 4.14. The results shown in figure 4.10 indicate that for a given value of D_B all the data points for various values of H are very closely grouped and the conclusion can be made that the variation of d with t, at a given value of D_B, is independent of H. This conclusion is very important considering the experimental data presented in figure 4.9 for H = 15.24 cm. Both independent results, figures 4.9 and 4.10, show the same trends and slopes of the straight lines, at a given value of D_B as indicated by the equations. Close comparison between the two sets of data show that they are effectively the same.

Variation of m_f with time.

The variation of mass of fuel consumed with time are shown in figure 4.11 to 4.14. All the results indicate a linear variation of m_f versus t. At a given value of D_B, it is observed that the mass of fuel consumed over a time period is greater the higher the value of H. Thus in the design of burners it may be convenient, for example, to double the height of packing than to use twice as many burner holes of a given height.

The results also show that more sawdust is consumed the larger the value of D_B. It is therefore obvious that the results presented here can be used to design burners depending on, the rate of heat input needed, the duration the heat is needed, the quantity of heat required and the size of burner which would be economical.

4.4.4 Generalizations for the Design of Burners

Two sets of experiments have been presented and discussed in this chapter. The first consisted of the investigation of the characteristics of the burner using only one value of H throughout the experiments. In these experiments tests were repeated five times so as to ascertain the dependability of the results. The second set of experiments were carried out to determine what effect the height of packing had on the data of the first experiments. The results for the experiments have been discussed individually and it is the intention to now present more general equations considering all the experimental data presented so far.

Equation for the variation of d with t.

The results for the variation of d versus t are shown in figure 4.16. The full lines represent the regression analysis for the experiments which used a single value of H and the broken lines represent the straight line equations for experiments to determine the effect of H. These data were all obtained for H = 15.24 cm.

It would ideally be expected that for each value of D_B the full lines and broken lines would coincide. In practice as indicated by results in figure 4.9, for example, some scatter is expected from experiment to experiment for identical conditions. The data in figure 4.9 show a maximum scatter at any D_B of about 10% which is consistent with the differences shown between the curves in figure 4.16. Based on this comparison, it can be concluded that since it has been shown that the variation of d versus t is independent of H (see figure 4.10), the more comprehensive data in figure 4.9 should be used to obtain generalizations for the variation of d with t.

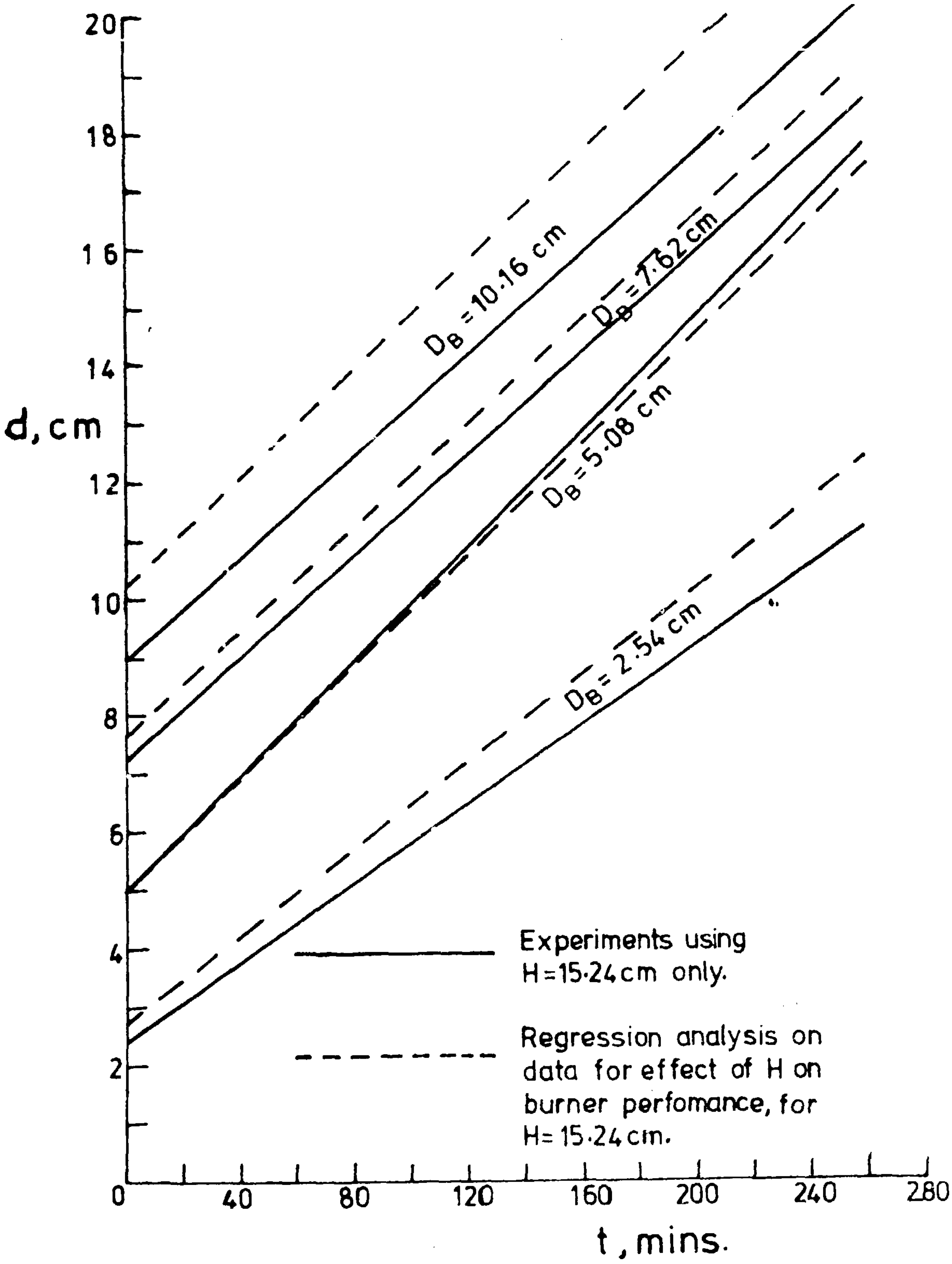


Fig. 4.16 Comparison of equations for variation of m_f versus t, for experiments for characteristics of burner and effect of H.

Now, noting that straight lines which are nearly parallel represent the experimental data well in figure 4.9 it was attempted to reduce the data to a form that could be represented by a single equation. The results in figure 4.9 have been replotted in the form d/D_B versus t and are shown in figure 4.17. There is a closer grouping of the data in this case for all values of D_B, compared to figure 4.9.

An experimental relationship of the form

$$\frac{d}{D_B} = A \exp (Bt) \qquad (4.7)$$

has been fitted to the data, where A, B are constants and are equal to,

$A = 1.04$, $B = 0.0063$. This curve is shown in figure 4.17. It is noted that this equation is independent of H as indicated by experiments and earlier discussions.

The errors involved in practice due to the use of sawdust having different moisture contents, and different mixtures are expected to be within the scatter of the data shown in figure 4.17. Thus the errors involved by using equation 4.6 are considered to be within the limits encountered in realistic cases.

The generalized equation presented above can be used to determine the variation of d with t for a given D_B. It can also be used in the design of burners to specify various sizes which can perform a given task.

Equation for the variation of m_f with t.

In order to check the consistency of the experimental measurements, results for the two sets of experiments performed are shown in figure 4.18 for the variation of m_f versus t. The straight line fits through the data are shown. It is observed that the results for both independent

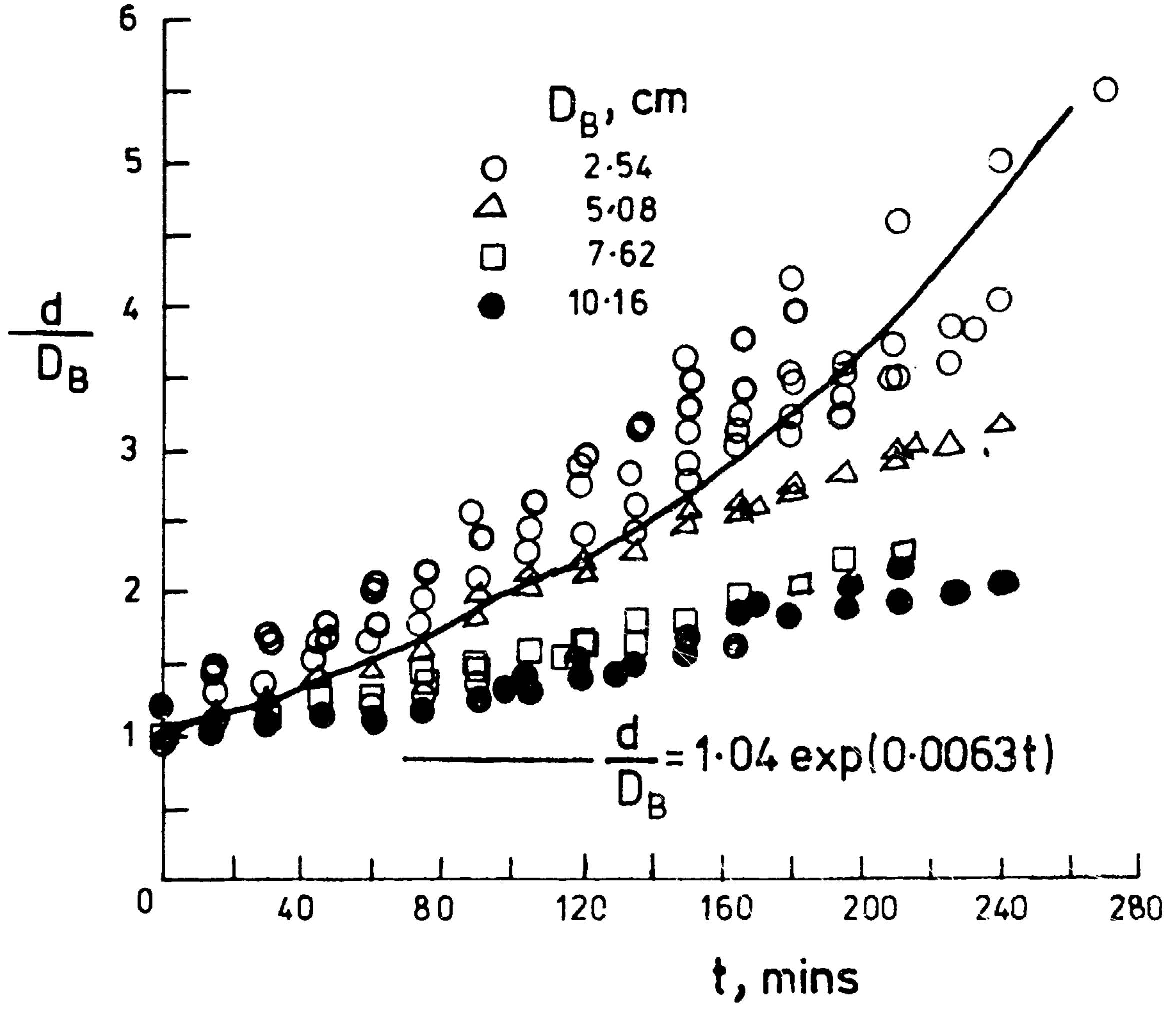


Fig. 4.17 Correlation of data for the variation of the burner hole diameter with time for various values of D_B.

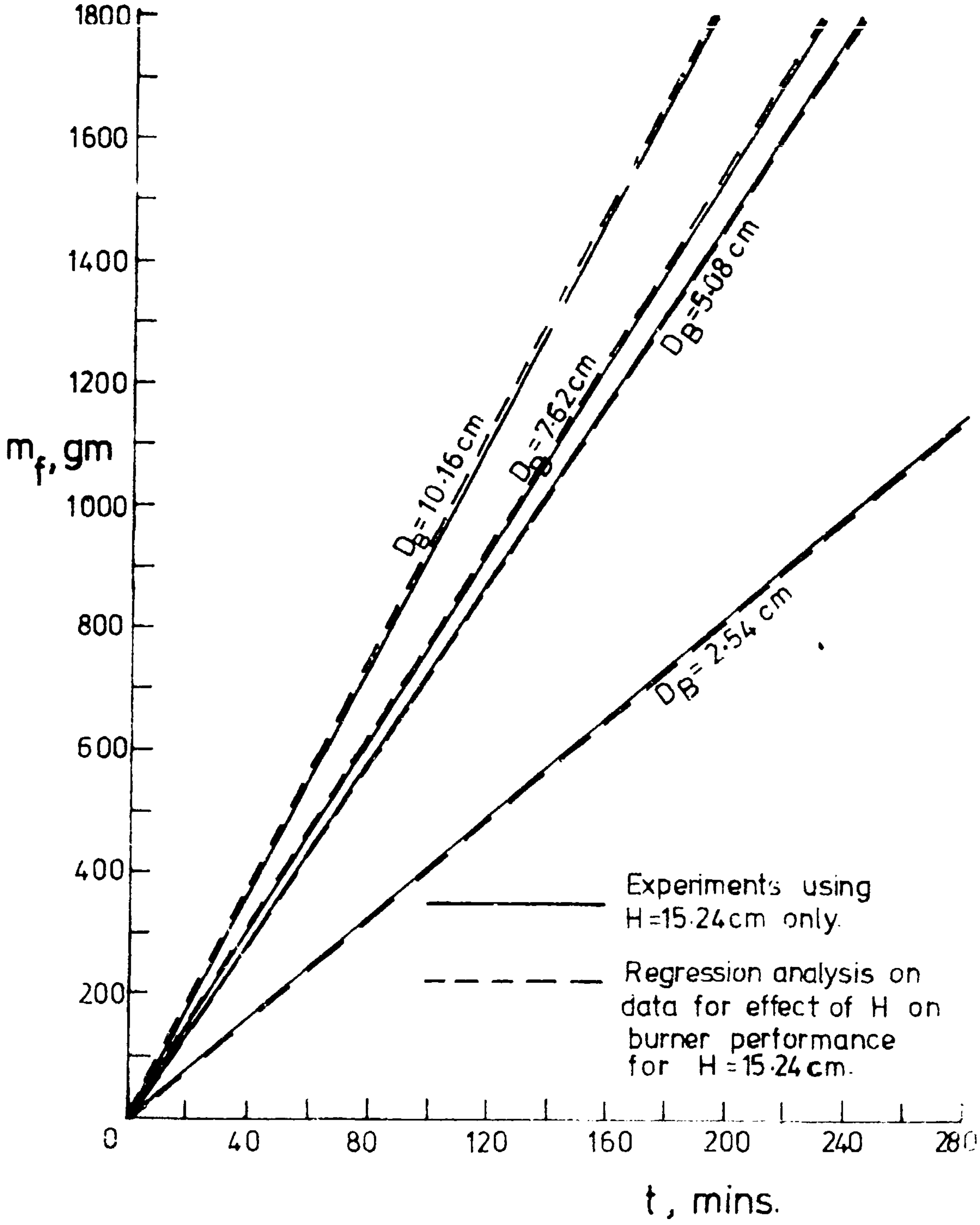


Fig.4.18 Comparison of equations, for variation of m_f versus t, for experiments for characteristics of burner and effect of H.

measurements are virtually identical. In view of these agreements between the straight line fit through the data; it can be concluded that the results presented for the variation between m_f and t for various values of H (shown in figures 4.11 to 4.14) are reliable.

It has been pointed out in the discussion that the variation of m_f versus t is dependent on the value of H and given by $m_f = St$, where S is the slope of the straight line representing the data. Figure 4.15 indicated that at a given value of H, the variation of S with D_B can be predicted by a straight line equation. In view of this, the results in figures 4.11 to 4.14 have been presented in the form shown in figure 4.19 with the corresponding straight line equations having correlation coefficients of about 0.95.

The equations are however restricted to fixed values of H. A closer look at the results show that the data in figure 4.19 can be made into a single curve if replotted in the form $\frac{S}{H}$ versus D_B. Figure 4.20 shows this variation, the data being virtually identical at a given value of D_B. A regression analysis has been done and a curve representing the experimental data is given by

$$\frac{S}{H} = 0.2421 \exp (0.0982\ D_B) \tag{4.8}$$

Where

$S = \frac{m_f}{t}$, $\frac{gm}{min}$

D_B = air inlet diameter, cm

H = height of packing, cm.

Equation 4.8 can therefore be written as

$$\frac{m_f}{Ht} = 0.2421 \exp (0.0982\ D_B) \tag{4.9}$$

Equation 4.9 has now brought together all the parameters of this study.

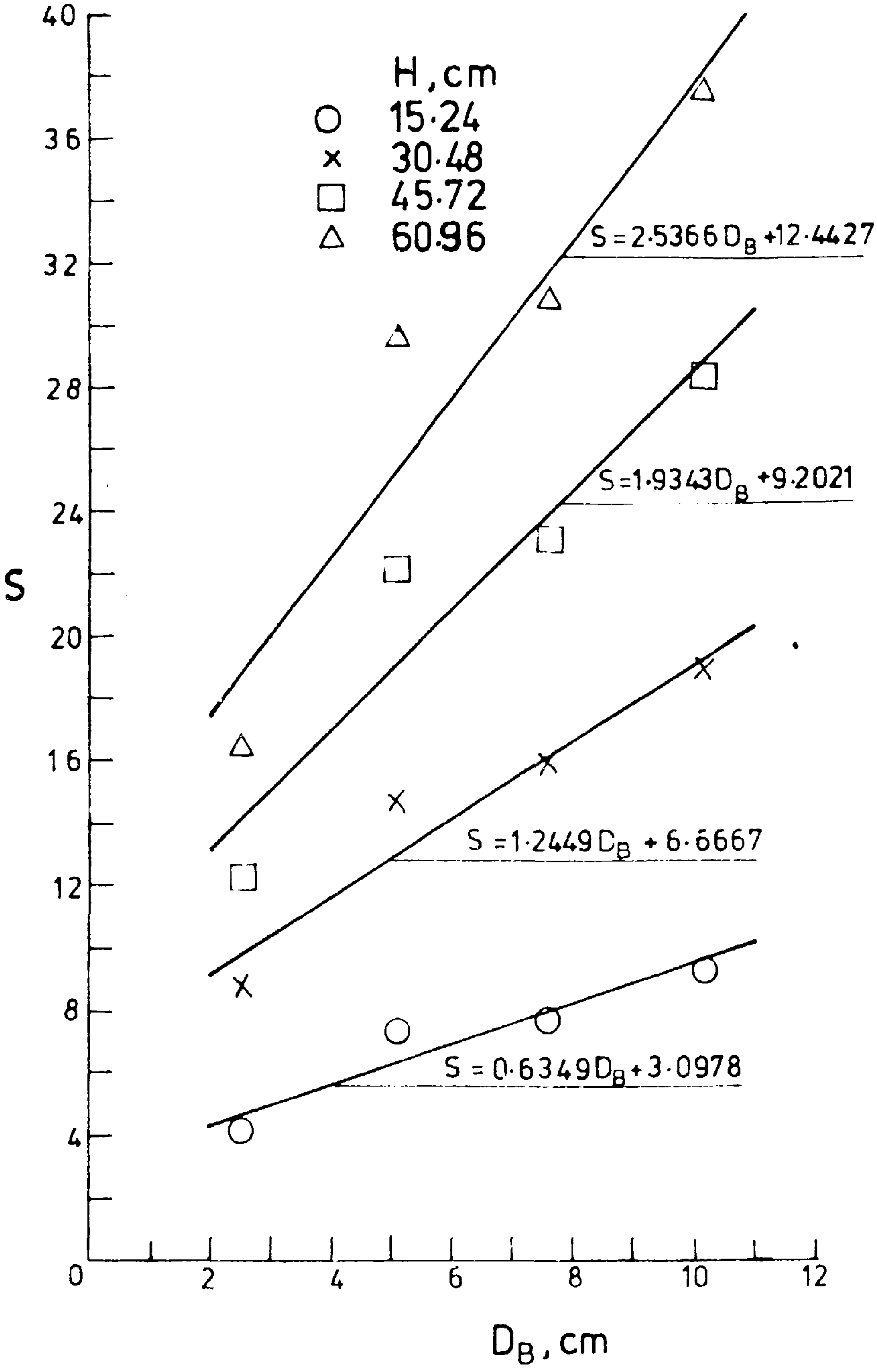


Fig. 4.19 Variation of S with D_B for various values of H.

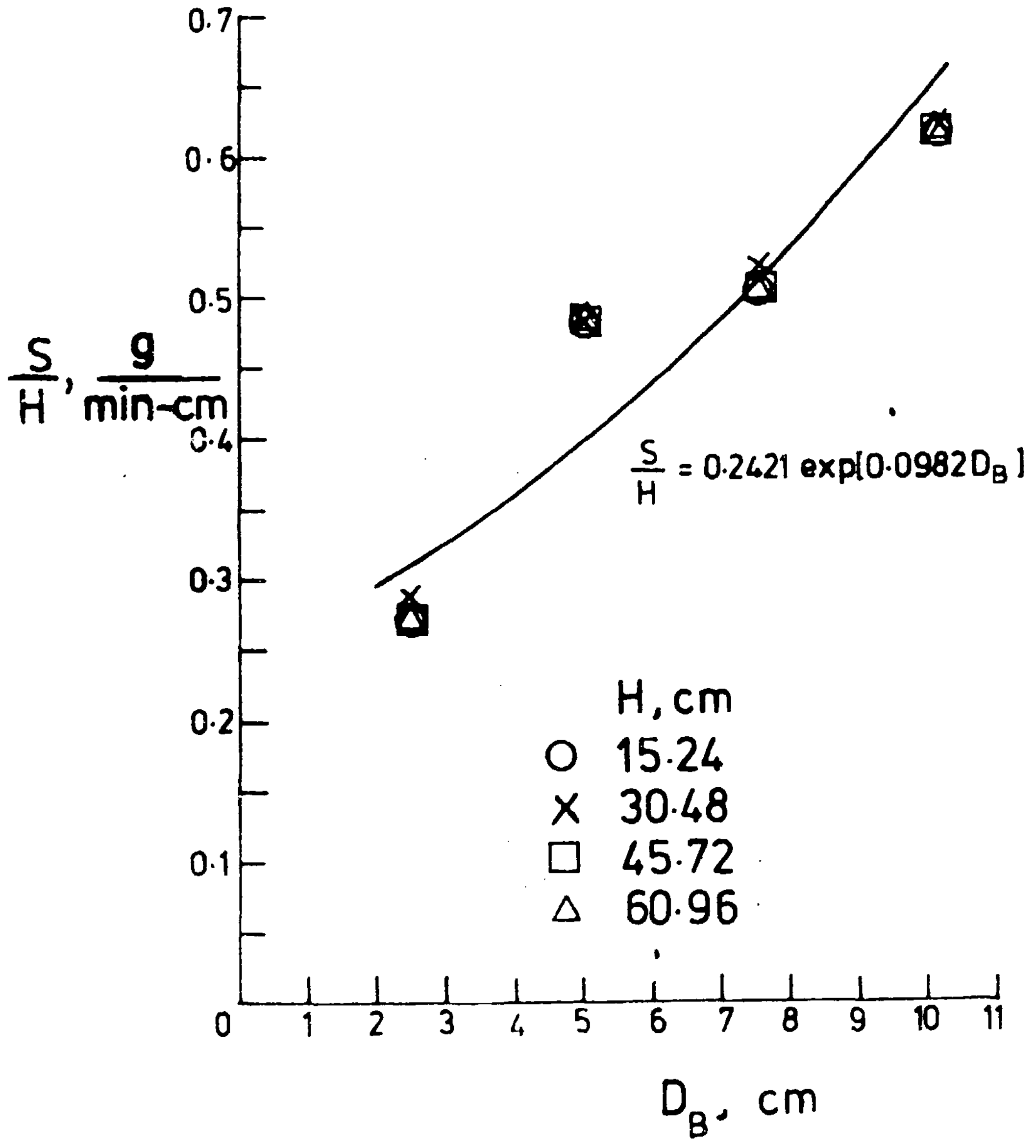


Fig. 4.20 Variation of S/H versus D_B.

Use of equations in the design of burners.

The equations presented above are strictly speaking restricted to the range of values of D_B studied in this work. It is however considered that the minimum value of D_B used in practice will not be much lower than the minimum value of D_B used in this study. It is also expected that in applications using these burners the maximum value of D_B used would not be much greater than that investigated in this study.

In the design of burners the particular application greatly influences the options available. These options may include:

(a) whether the burner should occupy a minimum floor area or minimum height,

(b) whether the heat transfer is by direct contact with the hot gas or by exchange of heat between the hot gas and a surface

(c) whether the conservation of the fuel is of utmost importance

(d) whether the rate at which heat is supplied is of importance.

Once the application has been ascertained, the equations can be utilized.

It is evident that there cannot be a particular procedure in the use of the results presented in this study as there are a variety of starting conditions possible. In the case where the duration of operation of the burner is known in equation 4.7 can be used to obtain the relative final sizes of the burner hole for different air inlet diameters. The choice of the size of D_B would depend on the final size of the burner hole that can be tolerated considering various factors. The value of D_B can then be used in equation 4.9, since t is known, to obtain $\frac{m_f}{H}$. The amount of heat liberated is dependent on the value of m_f used. If this quantity of heat needed has been estimated, then H can be determined.

It may be necessary to do a few trial calculations in order tha an optimum design can be obtained. It is of course obvious that the design should make use of a number of burner holes, the number depending on the amount of heat needed.

4.5 Summary of Results and Discussions

The work which has been discussed in this section was concerned with experimental investigations to characterize the performance of the sawdust burner.

Two different experiments were performed:

(a) To obtain data which will clearly describe the variation of parameters used to characterize the burning of this fuel.

(b) To obtain data which will show the effect the height of packing of the sawdust has on the variables investigated in (a)

The results of these experiments have been presented. It is observed that the experimental data are reliable.

The variation of the mass of fuel consumed with time depends on the values of the height of fuel H and the air inlet diameter D_B, and individual equations have been presented. The variation of the burner hole diameter d with time is on the other hand independent of H for a given value of D_B.

Two generalized formulae have been obtained, from analysis of all the experimental data, which can be used to predict the performance of the sawdust burner investigated in this work. The equations are

$$\frac{d}{D_B} = 1.04 \exp (0.0063t)$$

and

$$\frac{m_f}{tH} = 0.2421 \exp (0.0982\ D_B)$$

where H, d, D_B are in cm, m_f in gm, t in min.

The generalized equations can be used to design burners for various applications.

Chapter 5

DESIGN OF SOLAR/SAWDUST CROP DRYER

It was mentioned earlier that one of the objectives of this study was to design a crop dryer which could use sawdust as a fuel. The design of a dryer which uses both solar energy and sawdust as sources of heat is described in this chapter.

5.1 General Description and Overall Operation of Crop Dryer

The general features of the crop dryer are shown in figure 5.1. The system for producing the heat using the sawdust is shown in figure 5.2 and consisted of two burners, large and small burners having twenty and eight burner holes respectively. Four pipes of diameter 1.27 cm were connected to two headers of diameter 6.5 cm such that they passed directly over the holes on both burners as shown in figure 5.3. Thus, when the burners were in operation the heat generated was supplied to the four parallel pipes which passed directly over the holes. A vent pipe was located on one of the evaporator pipes as shown in figure 5.3. A valve connected to it was used to bleed off excess water in the evaporator pipes. A covering made of galvanized sheet metal was used to protect the burners from rain and also to produce a draft, for the operation of the burners, through a 15 cm diameter tube (see figure 5.1).

The crop dryer is shown in figure 5.1. It was a cabinet type dryer measuring 220 cm long, 100 cm wide and 63 cm high with a top inclined at 20 degrees to the horizontal. The top had a single glass cover. The dryer was insulated with sawdust shavings on all its sides and bottom. Vent holes drilled at its side panels allow air entering at the bottom to flow out at the top (see figure 5.1 and 5.4). The inside of the crop dryer was painted black so as to absorb solar radiation coming in through the transparent cover.

Inside the crop dryer were six parallel pipes which were laid near the base of the dryer and connected to headers as shown in figure 5.4. One of the header pipes was connected to the evaporator by simple pipework and the whole piping between the evaporator and the header pipe was insulated. The other header was connected to an outlet pipe which was placed in a small tank containing water. The base of this drum was

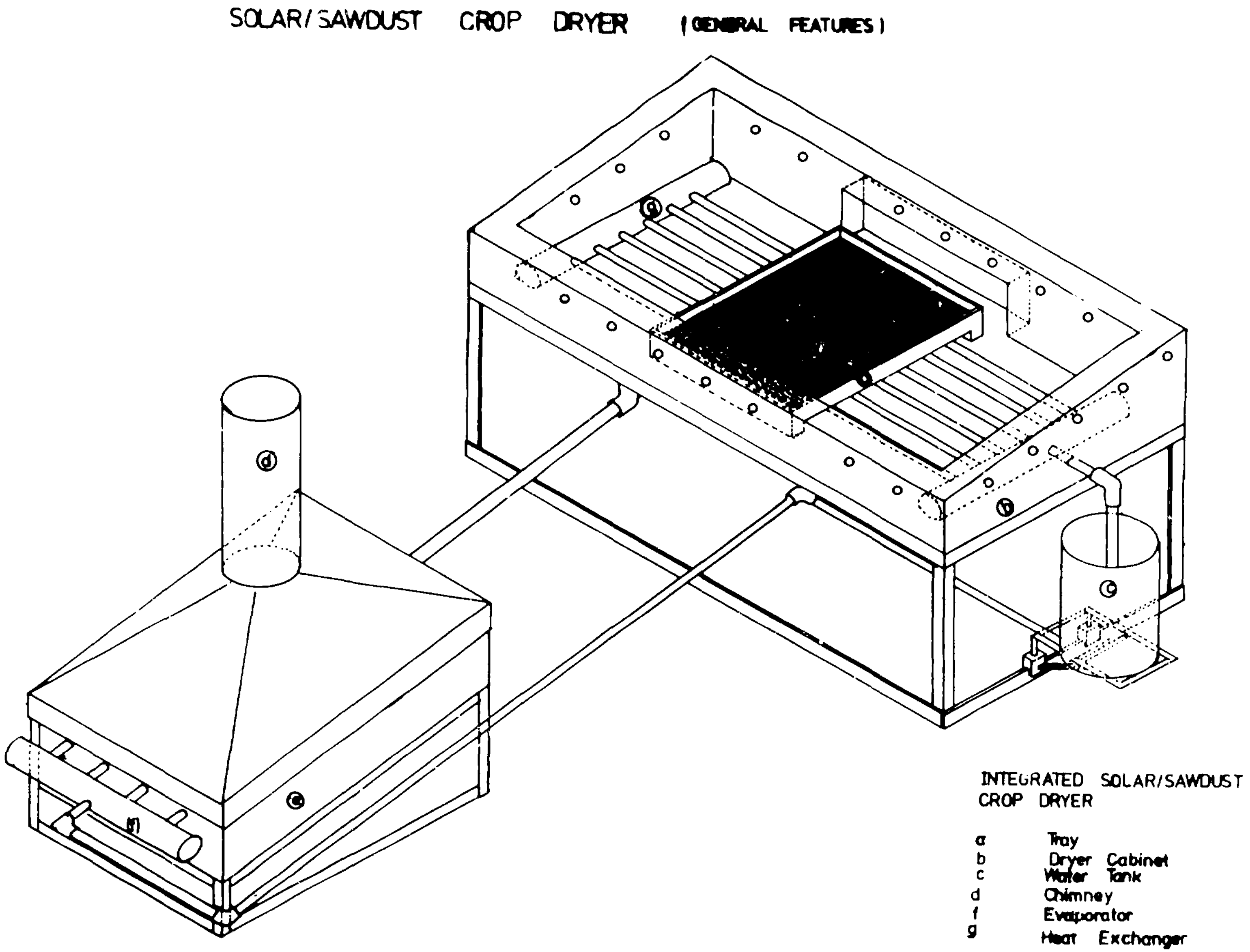


Fig 5.1 General features of crop dryer

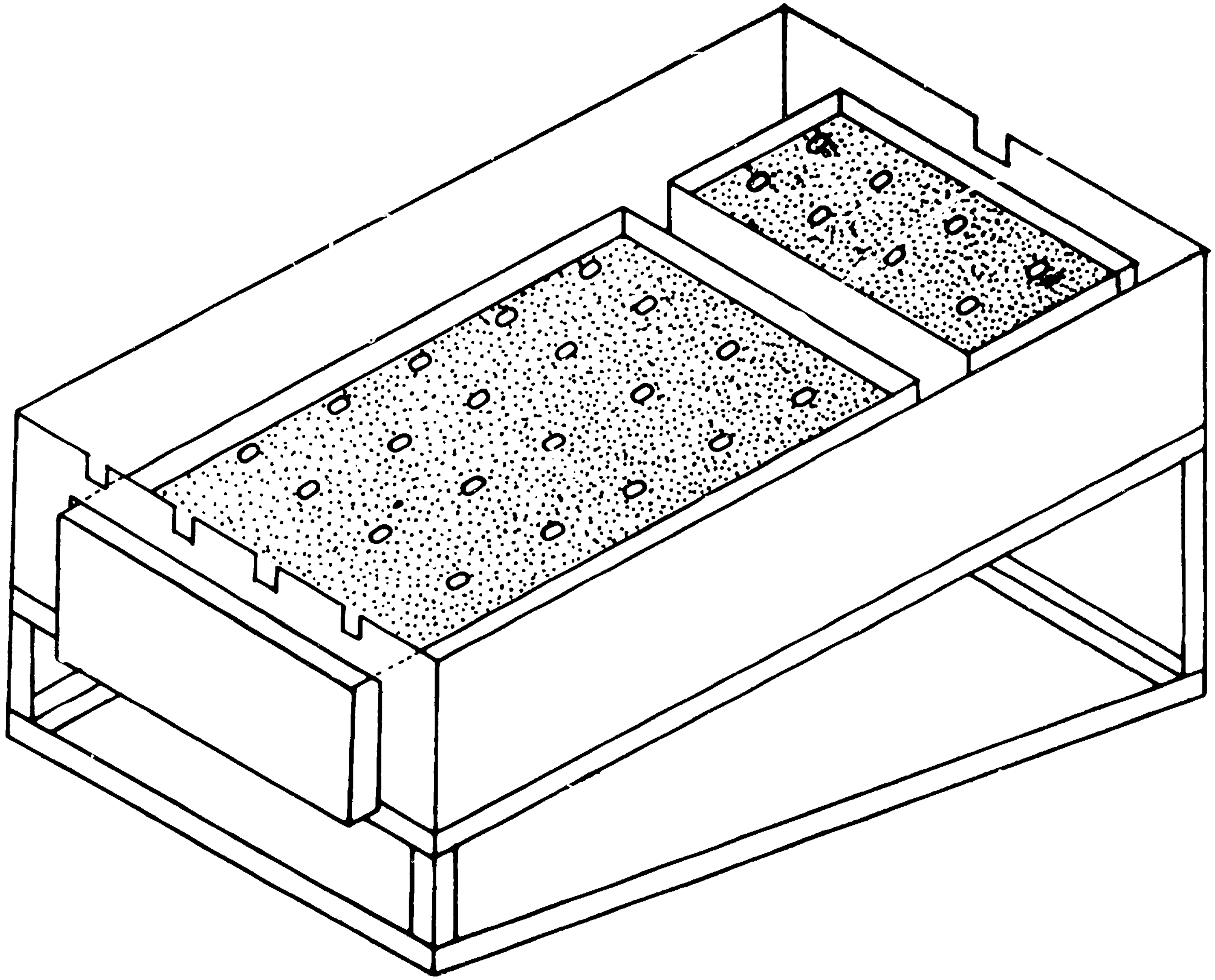


Fig 5.2 Diagram of burner assembly

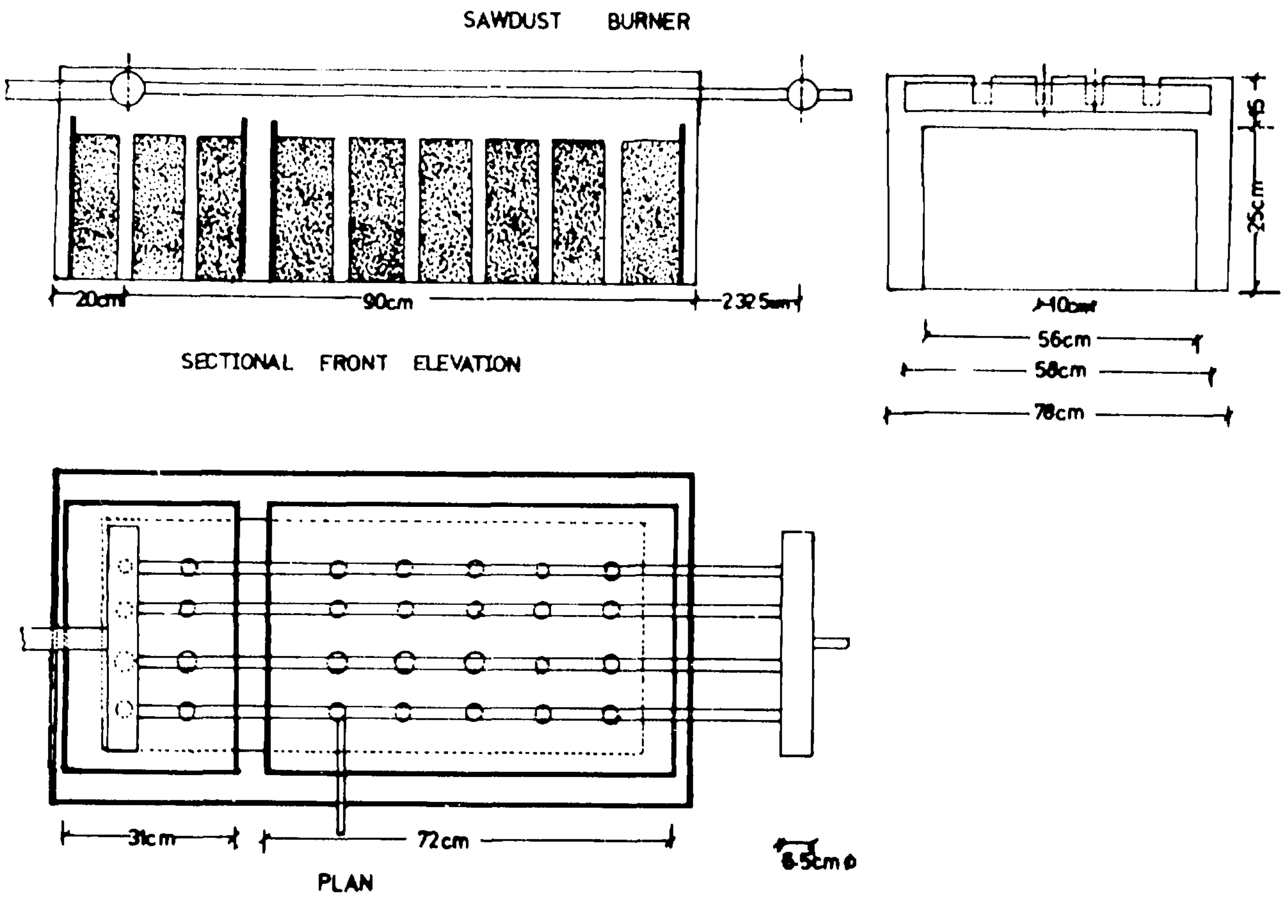


Fig 5.3 Design details of burner

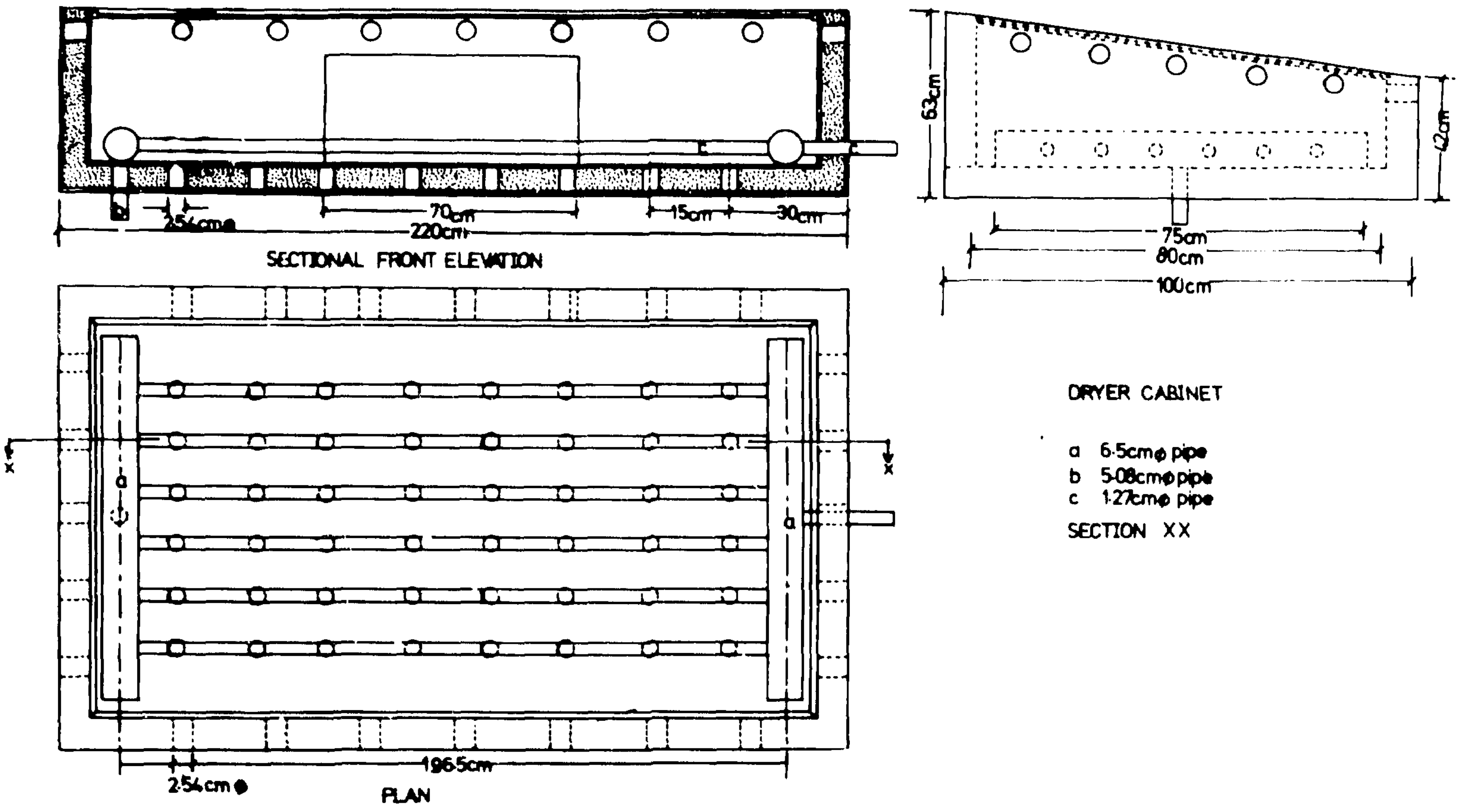


Fig 5.4 Details of crop dryer cabinet

connected to a .27 cm pipe which was in turn connected to the evaporator i.e. to the header outside the burner.

In operation, it was ensured that the connections from the evaporator to the heat exchanger and from the small tank to the evaporator were well sealed. Water was then poured into the tank until its level in the evaporator was such that it started to escape through the vent pipe shown in figure 5.3. The secondary and primary burners were lit using the same method outlined in section 4.2. Twenty-eight burner holes were thus lighted to produce the heat needed to operate the dryer.

After a short period of time the water in the evaporator pipes was heated by the primary burner and steam was produced. The secondary burner heated the steam to a superheated condition and it then flowed through the insulated pipe into the heat exchanger in the dryer cabinet. Heat was transfered to the air in the cabinet by free convection and the warm air was allowed to escape through the vent holes at the top. (In the case where solar energy was utilized the heat was accumulated in the dryer by the greenhouse effect). As a result of the escape of the warm air, ambient air at a lower temperature entered the dryer through the many holes drilled at the base of the cabinet. Thus a continuous flow of warm air took place from inside the cabinet to the ambient.

The steam flowing through the heat exchanger experienced a drop in temperature and flowed out as wet steam through the exit pipe which was made to hang into the small tank without touching the water. The steam continued to flow until the sawdust no longer gave appreciable heat to the heat exchanger.

The dryer had three trays on which the crops were placed during drying. They were loaded into the dryer through an insulated door at the back of the dryer. The control of the temperature in the dryer was achieved by opening or closing the vent holes on the cabinet.

5.2 Design of Crop Dryer Cabinet

The details of the crop dryer cabinet are shown in figure 5.4. It consisted of two frames made of plywood 1.25 cm thick with a gap of 10 cm for insulating material between them all around. In order to utilize locally available materials sawdust shavings were used as the thermal insulating material.

Forty-eight holes of diameter 2.54 cm were drilled through both walls of the cabinet, at the base, to allow inflow of air. Similar sized holes were drilled, totalling twenty-four, at the top of the vertical sides of the cabinet for the outlet air. Plastic hose pieces were passed through the holes to prevent wetting of the insulation. For purposes of temperature control, the holes for the outlet air were provided with simple facilities for opening and covering them.

The top of the cabinet was sloped at an angle of 20 degrees to the horizontal, which allowed for optimum solar radiation collection without tracking. Two pieces of glass were used to cover the top of the cabinet since the sizes available were about a meter square. This arrangement of two panels also helped to strengthen the top surface and to thus avoid easy breakage of the glass. Single glass covering was used so as to minimize the cost of the system. The glass was held in place by wood putty which also prevented rain from entering through the top.

The heat exchanger in the cabinet was constructed from pipes 1.27 cm and 6.5 cm in outer diameter. The 1.27 cm pipes were welded on to the 6.5 cm pipes as shown in figure 5.4. The six pipes 195 cm long and the headers supplied heat from the steam flowing through them to the air in the dryer. The pipes were located directly over the air inlet holes at the base of the cabinet, 3 cm above the holes, so that the colder air entering was immediately heated up, before getting in contact with the air in the cabinet.

The trays were made from wire mesh and plywood. The plywood was used as the stand, and the wire mesh, painted black, carried the crop (see figure 5.1). The dimensions of the top surface of each tray was 60 cm x 60 cm. Thus the three trays effectively had a total surface area equal to that of the base of the dryer, thus preventing wasted space.

The dryer cabinet was mounted on a stand 120 cm high made of 5 cm angle iron. This material was only used since the equipment was moved often. A less expensive material such as wood could have been used if the dryer was permanently located.

The whole interior of the cabinet including the heat exchanger pipes was painted with black paint.

5.3 Design of Burner and Evaporator

Work on crop dryers indicate that it is desirable to have working temperatures suited to the properties of the crop being dried. It is not easy to control the amount of solar energy being used for an application such as crop drying. The use of sawdust in the production of steam for the dryer has an advantage in that the rate of steam production could be controlled. The production of steam is however determined by the burner design.

Results discussed in chapter 4 showed that the design of the burner can be carried out if certain parameters are known or are predicted. In this case, the main purpose of the burner was to produce steam in the evaporator. Considering an air inlet diameter of about 2.5 cm and a height of packing of 15 cm the rate at which the fuel was consumed, m_f/t, was estimated using equation 4.7. Then assuming that about 10% of the heat would be transfered from the fuel to the evaporator and that about 0.1 kg/min of steam would be generated it was estimated that twenty burner holes were necessary. Eight more burner holes were added in a secondary burner to superheat the steam.

The burners were made from 0.3 cm thick galvanized iron sheets. They were rectangular in shape measuring 72 x 56 x 25 cm^3 and 31 x 56 x 25 cm^3 for the primary and secondary burners respectively. The holes at the base of the burners, i.e. the air inlet holes, were drilled 10 cm between centres so that the burning could take place for about two hours before a new batch of fuel could be loaded. The covering over the burner was made of sheet metal so as to withstand the high temperatures. Draught was created by the short chimney 50 cm high and 15 cm in diameter.

The stand for the burners was sloped at an angle of 20° so that when the evaporator was mounted over the burner holes the water level in the small tank coincided with that in the evaporator. The stand was made of angle iron due to the high temperatures involved in the burners.

Chapter 6

PERFORMANCE OF SOLAR/SAWDUST CROP DRYER

The crop dryer which has been described in Chapter 5 was specially designed to make use of available solar energy and waste sawdust. The design was restricted to the use of only locally available materials.

Tests were carried out on the dryer under load and no-load conditions using solar energy and sawdust as fuels. The procedure adopted and the results obtained are discussed in this chapter with reference to the effectiveness of the dryer.

6.1 Tests for No-Load Condition

6.1.1 No-Load Tests Using Solar Energy

These tests were carried out using only solar energy to heat up the crop dryer while it was empty, i.e. there were no crops in it.

Since only solar energy was used it was not not necessary to consider the sawdust burner. The dryer was located so that the sloped top faced south. The glass covers were cleaned, the trays put into the cabinet and the insulated door closed. The temperatures in the dryer were measured at three points above the trays using thermocouples and a temperature indicator. Drybulb and wetbulb temperatures were also taken outside and inside the dryer cabinet.

The experiments started at about 0900 hours and lasted till about 1600 hours and readings of all temperatures were recorded at 30 minute intervals. The tests were carried out during months in the dry season when the incident solar radiation was generally high. The vent holes on the cabinet were closed during the experiments.

6.1.2 No-Load Tests Using Sawdust

The primary and secondary sawdust burners were loaded with sawdust and the burner holes for as explained in section 4.2. The sawdust was packed in both burners to a height of 35 cm and its weight was obtained. The burners were then set on their stand and the connections between the evaporator and the dryer were made. The dryer cabinet was placed in a shaded spot, away from any solar radiation.

Water was added to the tank C, shown in figure 5.1 till excess water flowed out of the small vent pipe attached to one of the evaporator pipes as shown in figure 5.3. The sawdust burners were lit with a match and kerozene; by sprinkling very little kerozene around each hole and lighting it with the match. The chimney cover was put over the burners and the draught caused the holes to glow after a few minutes. The steam generated was allowed to flow through the heat exchanger pipes and into the water tank.

Temperatures were recorded at half hour intervals at the inlet and outlet of the heat exchanger in the cabinet dryer, immediately before and after the header pipes respectively. Temperatures were also recorded at four positions along the outside of one of the heat exchanger pipes, and at three positions directly above the trays in the dryer. The pressure in the evaporator, directly after steam has been superheated was also monitored. Tests were carried out using one and two batches of sawdust. As in the case for the tests using solar energy alone, all the vent holes on the side walls of the cabinet were closed.

6.1.3 No-Load Tests Using Sawdust and Solar Energy

These tests were a combination of the procedures outlined in sections 6.1.1 and 6.1.2. The whole dryer assembly was put out in the sun with the sloped surface facing south. The burner was set up as outlined in section 6.1.2 and the same measurements made as already explained.

6.2 Crop Drying Tests

The effectiveness of the crop dryer was determined using okra, a crop which has a very high moisture content and which can easily get spoilt if not properly processed before storage. This crop is used extensively in Sierra Leone in the raw state or, in the powdery form after it has been dried and pounded. It is used in the preparation of sauces. In view of the lack of time to dry various other crops, okra was used for these tests since it presented many of the problems which will be encountered with other crops. The tests carried out using solar energy and sawdust as the sources of heat are described below.

6.2.1 Crop Drying Tests Using Sawdust

The okra was cut across its diameter into pieces of about 1 cm thick. They were then weighed and placed onto the trays; about 2.8 kg on each of the three trays, giving a total mass of 8.4 kg. About 5.0 kg of okra was set aside for open air drying under the sun and indoors. Small quantities of okra were taken, from each of the trays and from the control sample for open air drying, weighed and put in an oven for 24 hours at about 105°C in order to determine their moisture contents.

The procedure outlined in section 6.1.2 for setting up the sawdust burners was adopted. The crops were put in the dryer cabinet and the sawdust lit. The cabinet was kept from receiving any solar radiation by being placed in the shade. The temperatures in the dryer above the crops, and temperatures on the heat exchanger pipes were recorded at 30 minute intervals. Samples were taken from the three trays every hour, weighed and then put in the oven for 24 hours to obtain the variation of moisture content during drying. The tests lasted from about 0900 hours to 1600 hours.

Air drying under the sun, and indoors were also done simultaneously. The indoor drying simulated the case where there was no sun available. Moisture content tests were also done with these control samples at hourly intervals.

6.2.2 Crop Drying Tests Using Solar Energy and Sawdust

The arrangement of the dryer was similar to that for the no-load tests outlined in section 6.1.3. The okra was weighed and placed on the three trays, giving a total mass of about 10.5 kg. The burner was set up as explained earlier and the temperatures in the dryer measured at intervals of 30 minutes from 0900 hours to about 1600 hours. The burner was kept in operation by reloading it when steam production ceased. A control sample was dried by open air sun drying. Moisture content tests were also performed during the experiments at 1 hour intervals for all samples in the dryer and under the sun.

6.3 Results of Experiments on Dryer

It is recalled that tests were done on the integrated solar/sawdust crop dryer to investigate its performance. Results obtained for loaded and no-load conditions using solar energy and sawdust, separately or simultaneously, are presented in this section.

6.3.1 Results for No-Load Tests

Temperatures measured in the crop dryer during the tests, using only solar energy, included the air temperatures directly above the trays. These temperatures were nearly equal to each other at any given time during the experiments. The mean of these temperatures have been taken and are shown in figure 6.1 for six days in March 1980. Similar temperatures are also shown in figure 6.2 for tests using only sawdust as fuel. Results

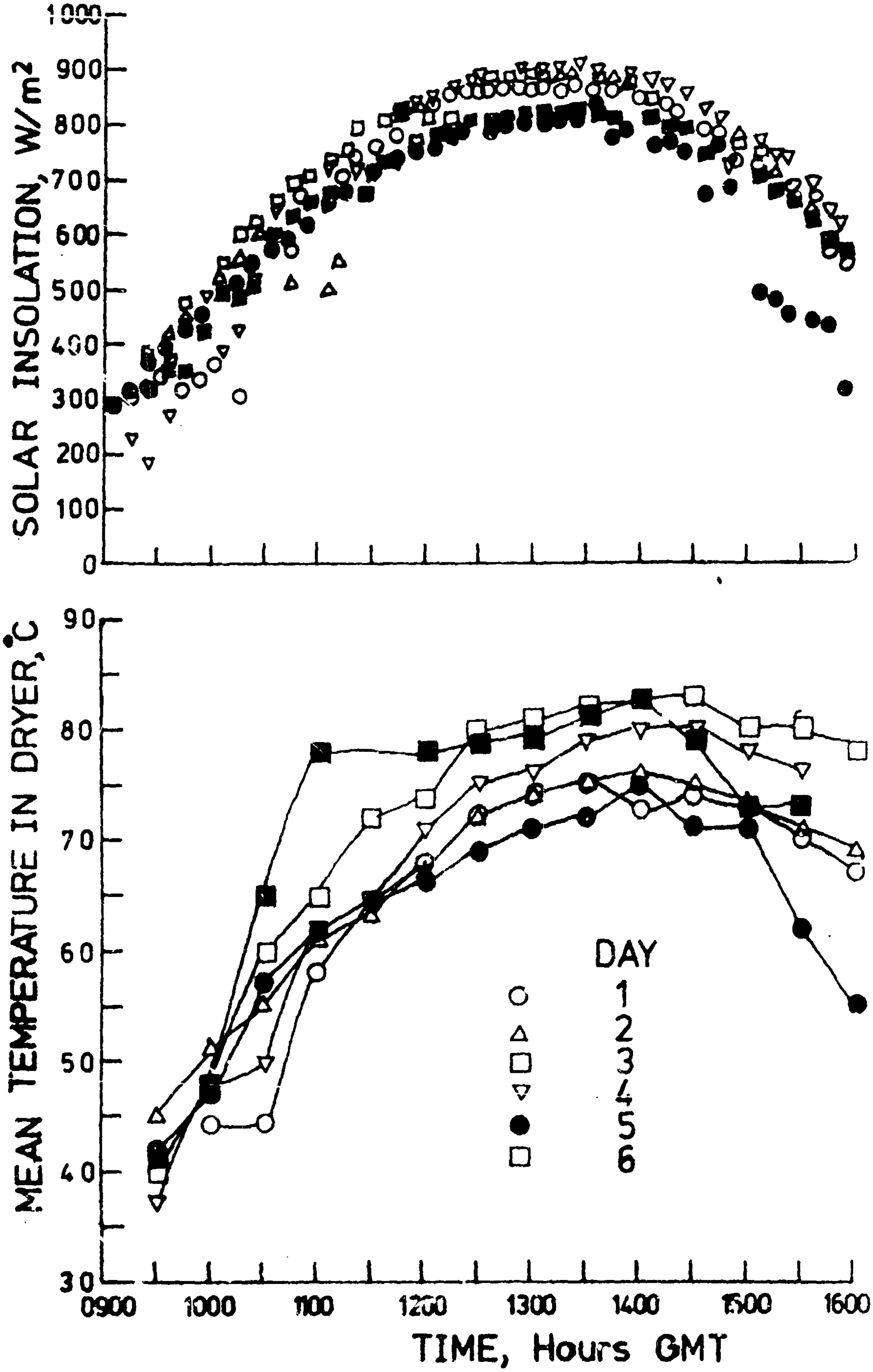


Fig. 6.1 Mean temperature in dryer under no-load condition using solar energy as fuel.

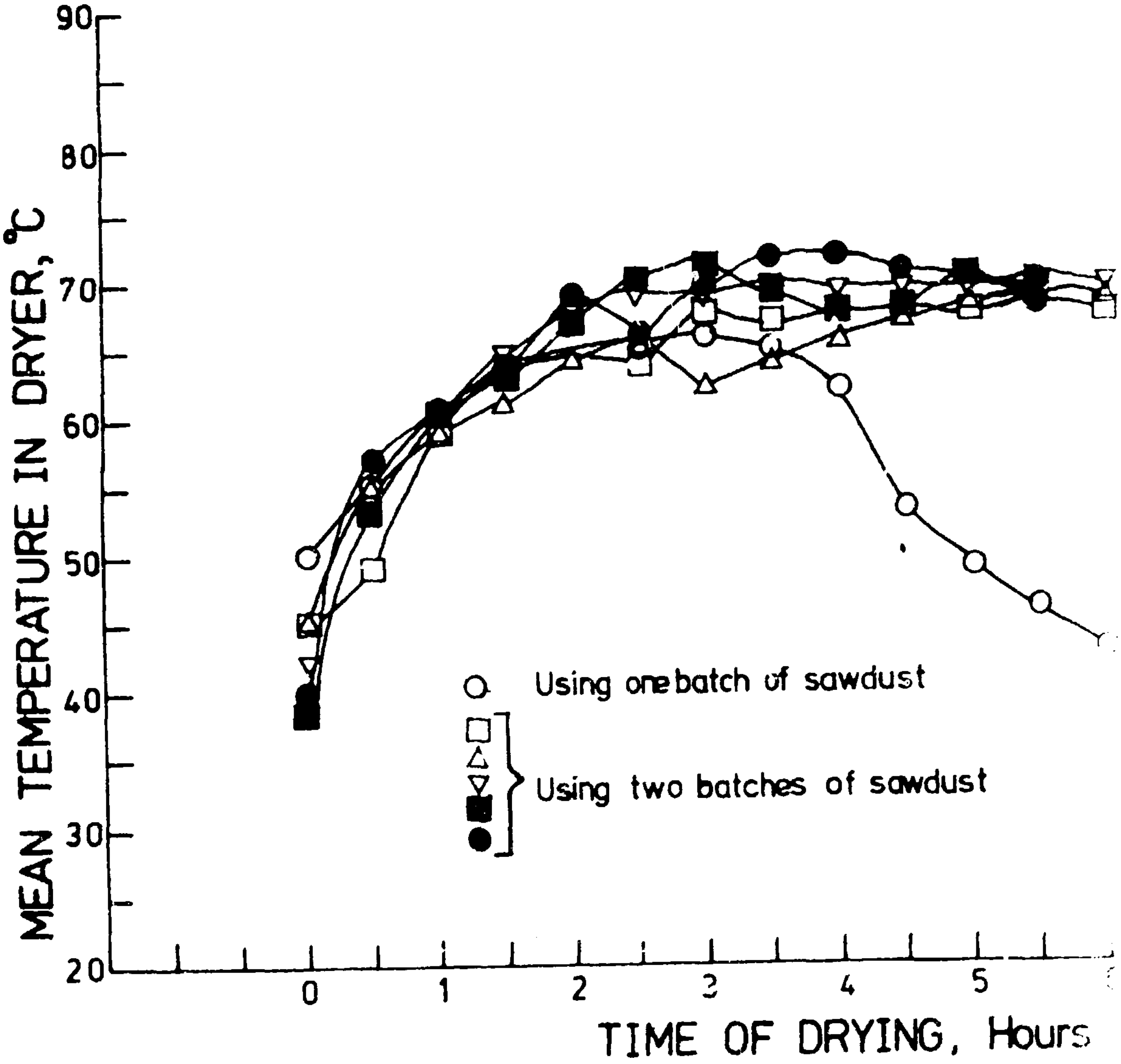


Fig. 6.2 Mean temperature in dryer under no-load condition using sawdust as fuel.

are shown for a test using only one loading and tests using two loadings of the burner. Also shown in figure 6.3 are results of the average temperatures in the dryer for tests using both solar energy and sawdust simultaneously. The solar insolation for the days during which the tests were carried out are also shown in figures 6.1 and 6.3.

6.3.2 Results for Crop Drying Tests

Tests on the dryer under load were carried out and temperatures in the dryer and the moisture content of the crop at certain time intervals were obtained. The results of these tests are presented below.

Figure 6.4 shows the variation of mean temperatures in the dryer with time of drying, for tests using sawdust as a fuel. The experiments lasted for about 24 hours over a period of about four days.

The moisture content obtained from the various samples are shown in figure 6.5. It is defined as the ratio of the mass of water present in a given sample to the mass obtained after oven drying at about 105 C for 24 hours. The variation of this moisture content over the period of the experiment, using sawdust is shown in figure 6.5.

The results for drying of the okra using both solar energy and sawdust simultaneously are shown are shown in figures 6.6 and 6.7. Figure 6.6 shows the mean temperature in the dryer while figure 6.7 shows the variation of moisture content over the period of drying.

The mean temperatures in the dryer and the variation of the moisture content of the okra for tests using only solar energy as the source

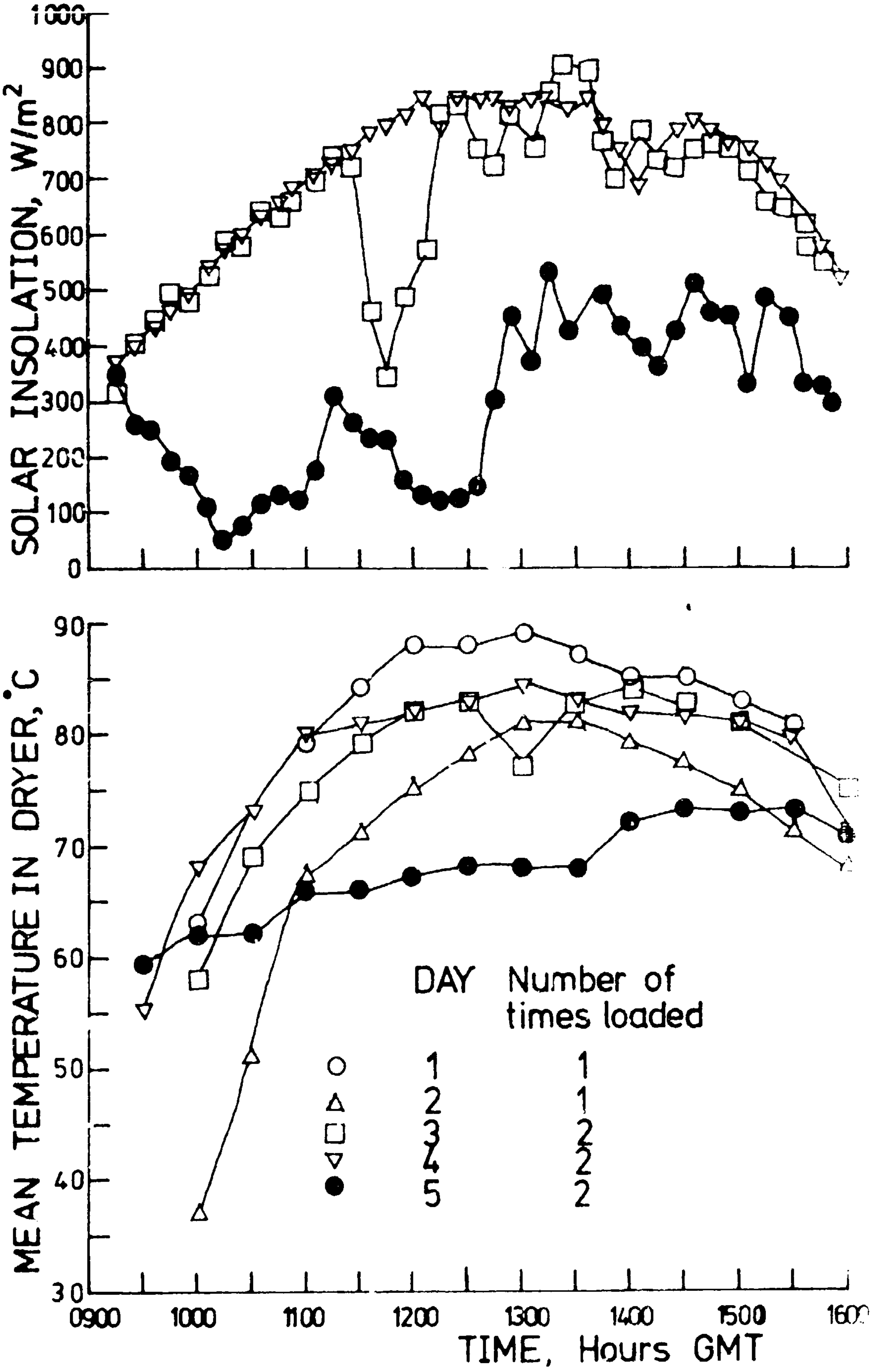


Fig. 6.3 Mean temperature in dryer under no-load condition using solar energy and sawdust as fuel.

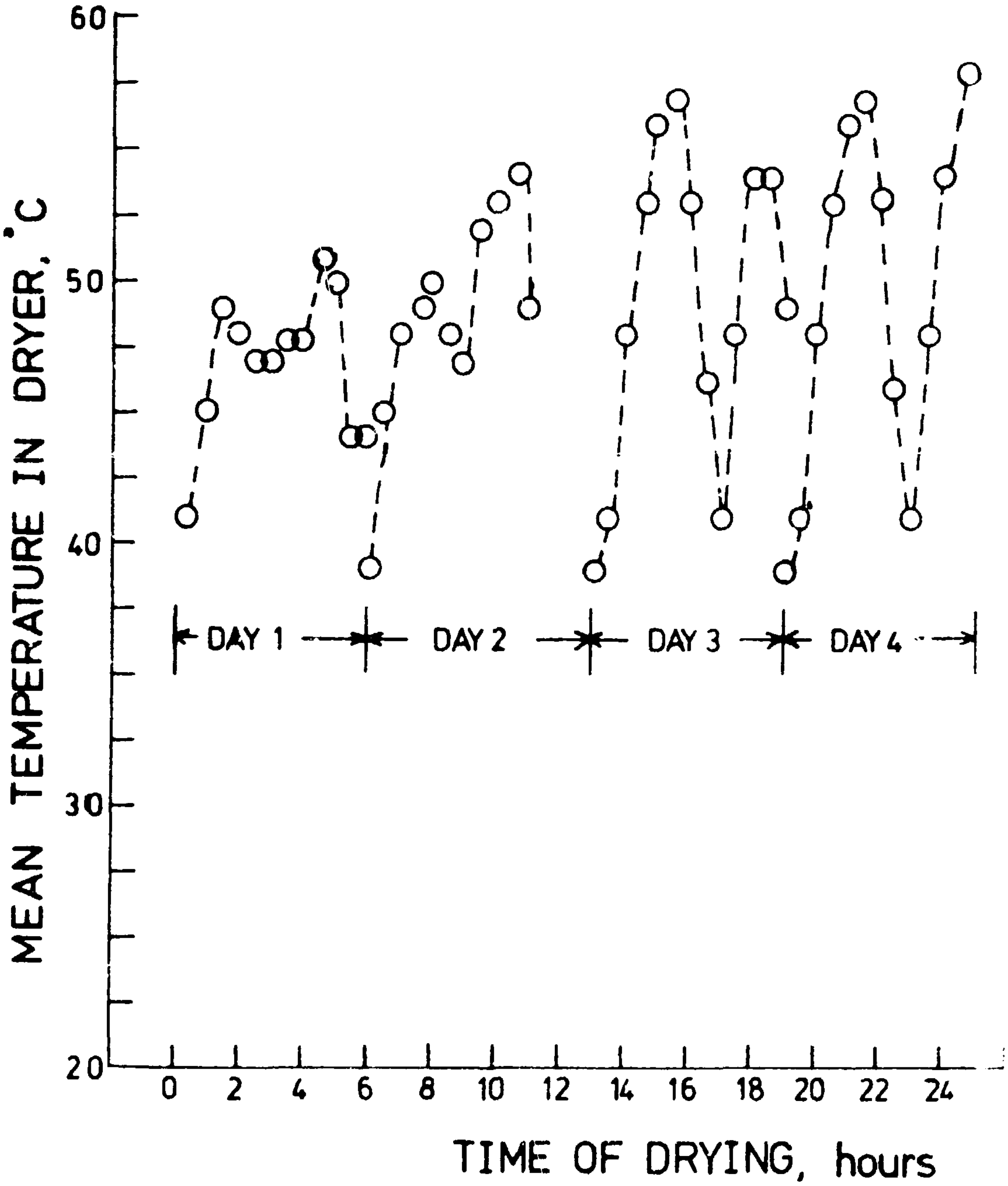


Fig. 6.4 Mean temperature in dryer during drying of okra using sawdust as fuel.

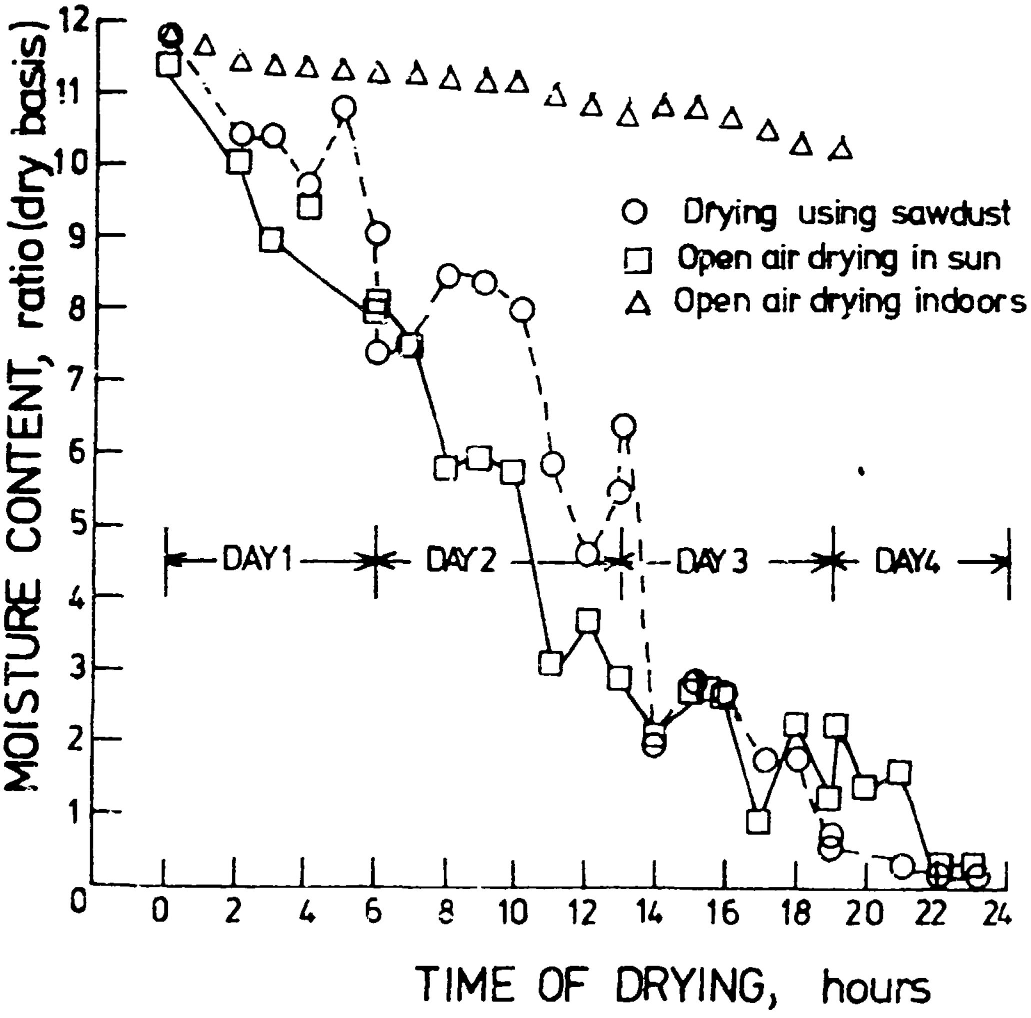


Fig. 6.5 Variation of moisture content of okra during drying using sawdust.

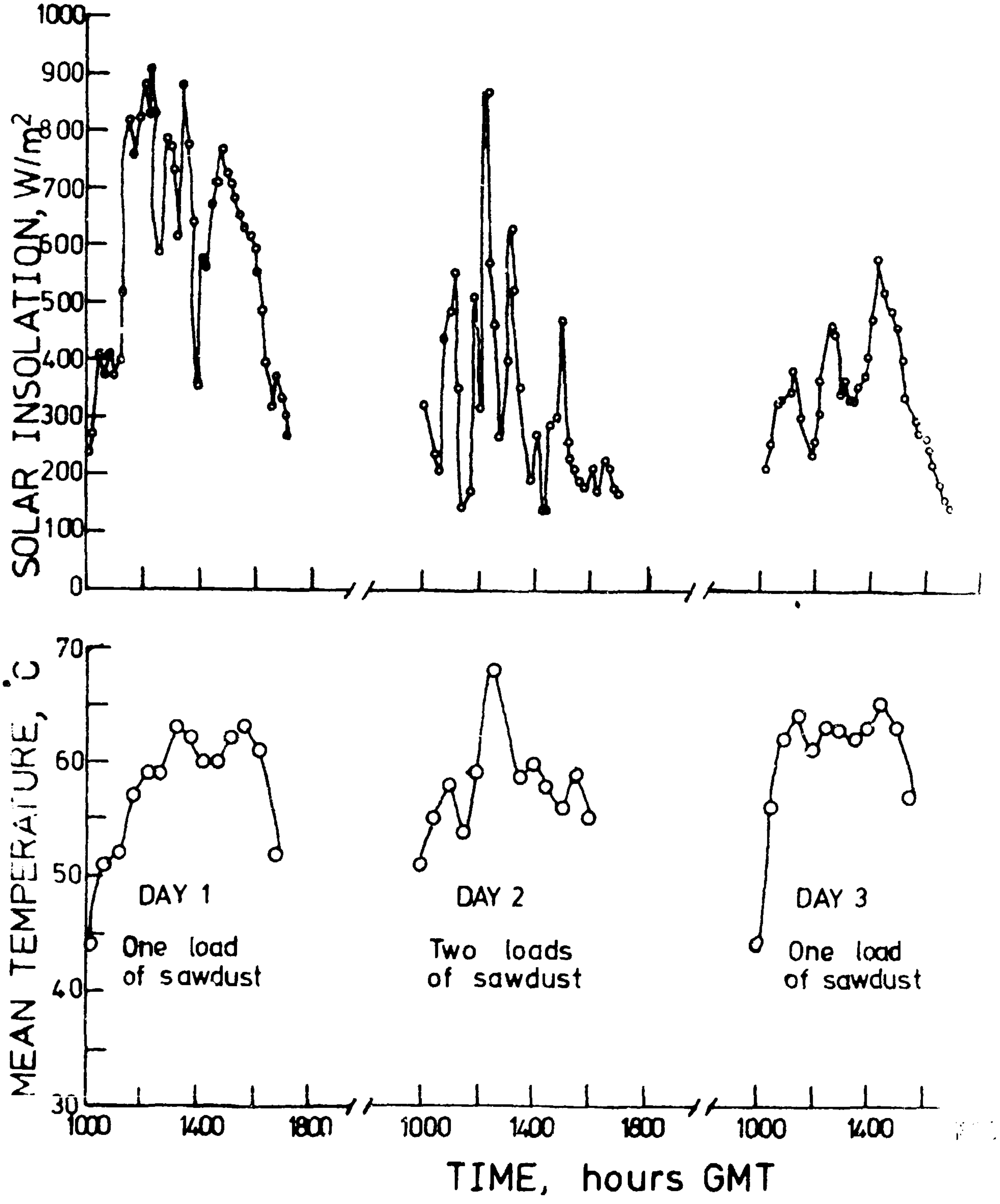


Fig. 6.6 Mean temperature in dryer during drying of okra using solar energy and sawdust as fuel.

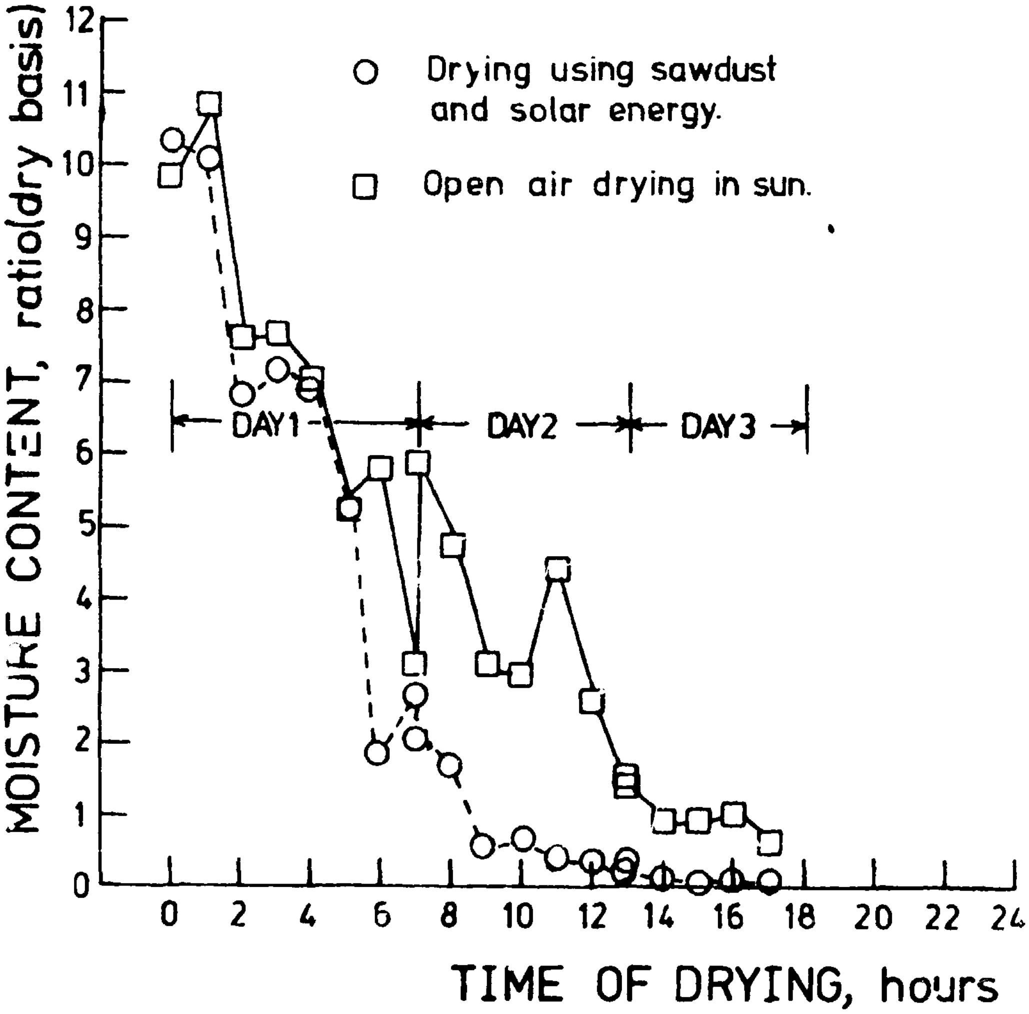


Fig. 6.7 Variation of moisture content of okra during drying using sawdust and solar energy.

of heat are shown in figures 6.8 and 6.9 respectively.

6.4 Discussion of Results for Tests on Dryer

6.4.1 Temperature in Dryer under No-Load Condition

The variation of the temperature in the dryer with time in figure 6.1 shows that using solar energy as the heat source, the temperatures rise, attain a maximum value and then fall. The change in the temperature in the dryer depends on the day being considered, i.e. the solar radiation. It is noted that temperatures can be expected to range from about 70°C to about 80°C over a substantial period of the day depending on the solar radiation. Although the amount of solar radiation for the six days are close in magnitude, the temperatures are definitely different. The effect of cloud cover does not manifest itself on the temperature distributions provided the movement occurs over a few minutes. Generally, higher temperatures are to be expected in the dryer for higher solar radiation availability.

The temperatures shown in figure 6.2 for the no-load condition using only sawdust as the fuel indicates that for only one batch of sawdust, the temperature in the dryer rises to about 70°C and then falls rapidly as the steam generation stops. This shows that the burner will in practice have to be reloaded after about every two and a half hours. The results for the cases where the burners were reloaded indicate that the dryer temperature can be maintained at about 70°C continuously under no-load conditions if the burner is kept in operation. Each experiment indicates a drop in temperature after about two and a half hours and then an increase; this corresponds to the reloading of the burners.

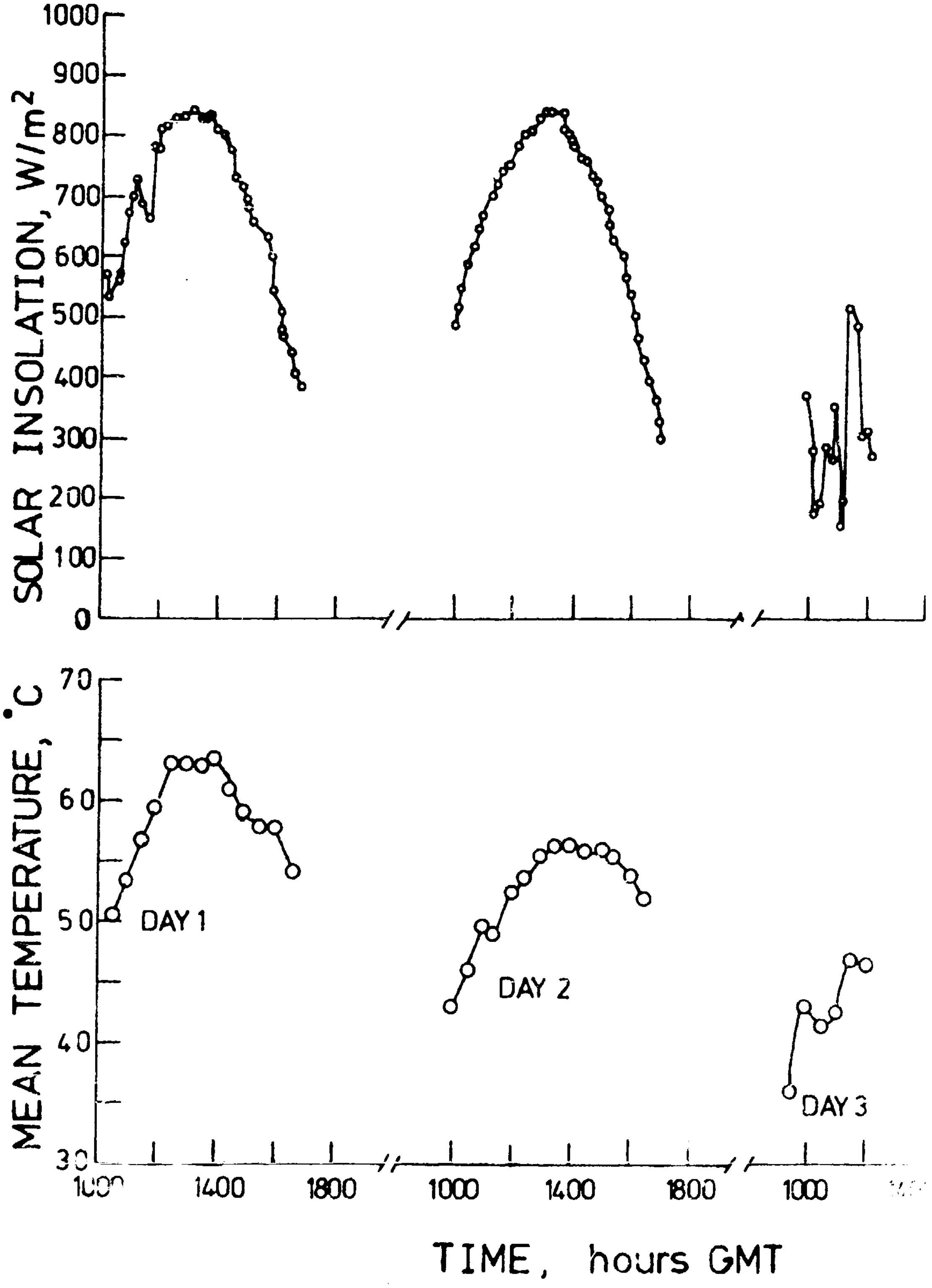
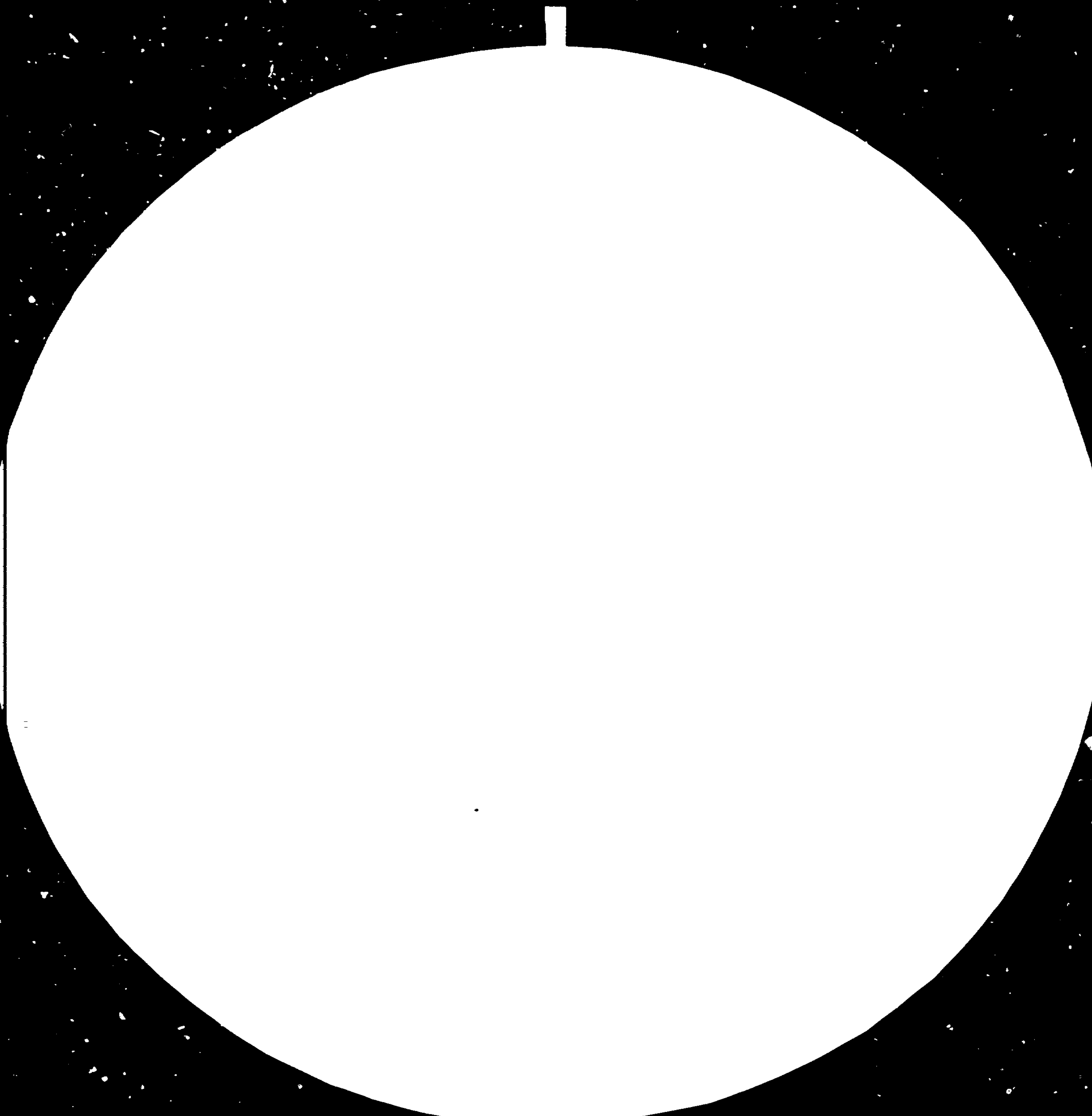
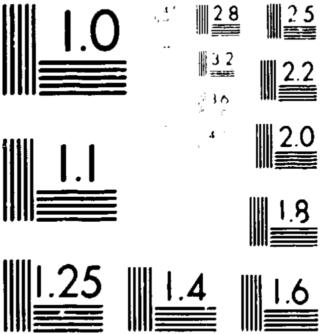


Fig. 6.8 Mean temperature in dryer during drying of okra using solar energy as fuel.





MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

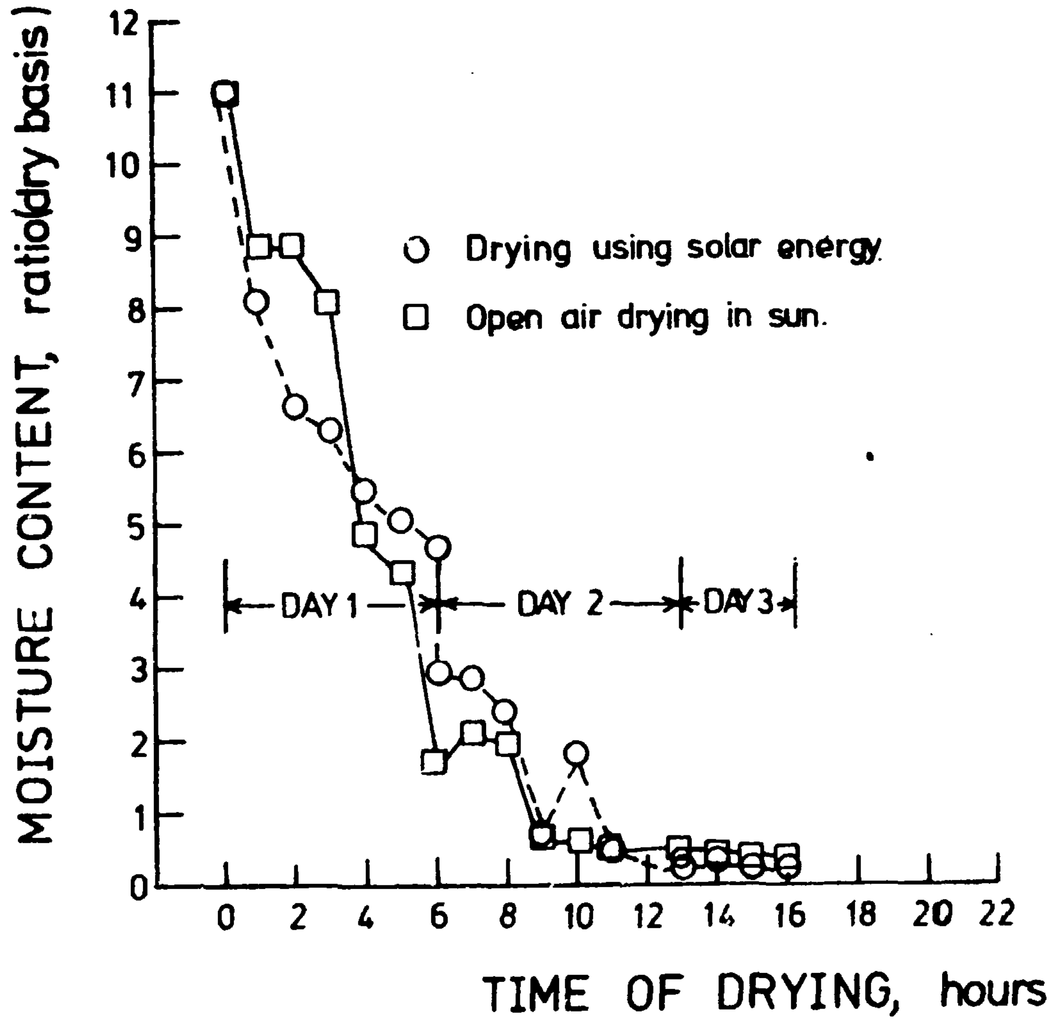


Fig. 5.9 Variation of moisture content of okra during drying using solar energy.

The close grouping of the data shows the consistent operation of the burner and dryer.

An advantage of using the sawdust is indicated by the constant temperatures which can be maintained as long as the burners are being charged continuously. The use of solar energy on the other hand gives temperatures which decreases as the available solar radiation diminishes.

When solar energy and sawdust are used, the dependence of the temperatures on the availability of solar energy is shown in figure 6.3 by the differences in the data for the five days. The results for Day 5 indicates that the heat to the dryer is effectively being supplied by the sawdust due to the low availability of solar energy, 1975 Wh/m^2 over the period of the test. The highest temperatures of about 90°C occurred on Day 1, due to the high intensity of solar radiation. The actual values were not however available. The results for Days 1 and 2 were obtained for only one load of sawdust in the burners. The extent to which the dryer would use sawdust would depend on the available solar radiation and the range of temperatures desired.

Comparing the results in figures 6.1, 6.2 and 6.3, it is seen that the highest temperatures are obtained when solar energy and sawdust are used simultaneously. Temperatures in the dryer for solar energy and sawdust being used separately are relatively lower but a more constant variation is obtained.

The results for the no-load conditions clearly show that the temperatures in the dryer are high enough for crop drying.

6.4.2 Temperature and Moisture Content During Crop Drying Sawdust as Fuel

The variation of temperature with time in the crop dryer when okra was dried, using sawdust alone, is shown in figure 6.4. The temperatures are observed to increase and decrease very often during the experiment. During the first day the temperature increases to about 40 C then drops, increases to about 52°C and then decreases. The decrease is explained by the fact that when the fuel in the burner is exhausted, no more steam is produced and the dryer loses heat causing its temperature to fall. The temperature increases again after the burner has been reloaded. This pattern is repeated for all the four drying periods. The fast drop in temperature noticed in figure 6.4 is partly due to loss of heat from the glass surface due to the condensing film and the fast rate at which the water from the crops absorb the heat.

The moisture content results in figure 6.5 show some interesting aspects of the performance of the dryer. (The moisture content is the ratio of mass of water in crops to mass of dried crop). In this case where the dryer is heated by sawdust alone, the variation of moisture content for three drying methods are shown; drying in the crop dryer, drying in open air under the sun and drying in open air in a shaded place. It is noted that the moisture content of 0.5 is achieved in about 22 hours of drying in the dryer and in open air drying in the sun. The moisture content of the okra initially at a value of 12 decreased at a slower rate in the dryer compared to open air drying for the first 14 hours. The reason for this is the high relative humidity in the dryer caused by the water vapour present during the initial period of drying. As soon as the temperature in the dryer drops the crop absorbs water and its moisture content increases. The large amount of water present was noticed by the condensation on the sloped glass. After the first 14 hours the crop in the dryer dried at a faster rate.

The large amount of moisture present during the first two days of drying and the subsequent lower values during the other days are responsible for the temperatures shown in figure 6.5. It is noted that the mean temperature in the dryer during the first day of drying is lower than the other three days. This is because the heat in the dryer is used to evaporate the water from the crop. The temperatures during the last two days are higher since there is relatively little water left in the crop. The results in figure 6.5 therefore shows the regions of increasing moisture content during drying due to the reabsorption of water as outlined above.

Comparing the results in figure 6.5 for open air sun drying and for the dryer, the question immediately arises concerning the effectiveness of the dryer when sawdust alone was used as fuel compared to sun drying. It was observed that the okra from the dryer had a better quality than the open air sun-dried batch; the sun-dried okra was soft and mouldy whereas that from the dryer was crisp and greener. Thus the crop dryer, when operated by sawdust, gave a better quality product compared to open air sun drying.

Considering the case where there is no available solar energy, the crop dryer will be operated by sawdust. In this case, if any drying is done it will be achieved by open air drying in the shade. The result for shade drying are shown in figure

6.5 compared to the crop being dried in the dryer using sawdust. The indoor drying gives effectively constant moisture content over about 19 hours. It was noticed that the okra went bad after about the second day of drying. This comparison is in fact very useful as it shows the usefulness of the crop dryer if there is no available radiation to do open air drying due to prolonged rains, for example,

Sawdust and Solar Energy as Fuel

Figure 6.6 shows the results of temperatures in the dryer during the drying of okra using both solar energy and sawdust as fuel. The variation in temperature for the three periods of drying are similar to those shown in figure 6.4. The drop in temperatures are however due to the cloud cover as manifested by the solar insolation and the burning out of the sawdust in the burners.

The crop dryer, under load, responds to the fluctuations in solar radiation intensities as indicated, for example, by results for Day 2 at about 1230 hours.

The moisture content results using solar energy and sawdust simultaneously are shown in figure 6.7. The results for open air sun drying are shown compared to those obtained using the dryer. It is observed that a moisture content of 0.5 is obtained in 9 and over 17 hours using the dryer and open air sun drying respectively. The moisture content of the crop in the dryer decreased quite rapidly with relatively less reabsorption of water compared to open air drying. It should be pointed out the average ambient air temperature of about 30°C and relative humidity of over 85 contributed to the slower decrease in moisture content for open air drying.

After the period of the experiments, the okra dried in the open air was observed to be soft and moldy due to the water content whilst the product in the dryer was well dried and easy to pound.

Solar Energy as Fuel

The variation of the temperatures in the crop dryer are presented in figure 6.8. Again, the temperatures have a close relation to the available solar energy. The mean temperatures in the dryer over each period of drying decrease over the three days. Since the solar radiation for the first and second days are similar and the mean temperature for Day 2 is less than that for Day 1, there are more losses from the dryer during the second day. This is mainly due to the presence of wind during the second day compared to the calmer condition which existed for Day 1. It is thus noted that the performance of the dryer is influenced by factors other than intensity of solar radiation.

The time required to reduce the moisture content of okra to its equilibrium value is effectively the same for open air drying and for the use of the dryer as shown in figure 6.9. The decrease in the moisture content of the crop in the dryer is generally slower compared to open air drying, although in the first four hours of drying the dryer dried the crop much faster. The reabsorption of water by the crop in the dryer is mainly responsible for the performance of the dryer. The final product for open air drying was again noticed to be poorer in quality compared to the okra in the dryer.

6.4.3 Comparison Between Results Using Different Fuels

Under no-load conditions, the temperatures in the dryer are highest when solar energy and sawdust are used simultaneously. The lowest temperatures would occur at low solar intensities when solar energy alone is utilized. Of course for poor solar availability sawdust would be used to increase the dryer temperatures.

The main differences of the results for no-load shown in figures 6.1 to 6.3 are in the magnitudes and form of the temperature variations. For the use of solar energy alone the temperatures in the dryer increase to a maximum value, and then decrease. The variation of the temperature is closely related to the variation of the solar intensity and an average day would give temperatures up to 80°C.

When sawdust alone is used the temperature in the dryer rises rapidly to a value of about 70°C and can be maintained at this value if the burner is reloaded when the fuel is exhausted.

In the case where solar energy and sawdust are used simultaneously, high temperatures wre obtained and are maintained above about 70°C till the evening.

When the dryer is loaded, (see results in figures 6.5, 6.7 and 6.9) the moisture content is reduced to 0.5 in 19, 9 and 11 hours using sawdust, sawdust and solar energy and solar energy respectively. The quality of crops for all the three cases are effectively the same. It would be expected that it would take substantially less time to dry crops using solar energy and sawdust simultaneously compared to using solar energy alone. But the results in figures 6.7 and 6.9 show that the solar energy gives slightly lower drying rates. These results can be supported by noting that tests using solar energy and sawdust were carried out in April and tests using solar energy were performed in February. In April the

the humidity is high causing less moisture to be given up by the crop. On the other hand the weather in February is dry and windy which aids the faster evaporation of moisture from the okra. This explanation is further supported if the drying rates for open air under the sun in figures 6.7 and 6.9 are compared. The faster rate of drying in the open air shown in figure 6.9 is partly due to the low relative humidity of the air at that time of the year (February) whereqs the lower drying rate shown in figure 6.7 is for the month of April when the relative humidity is very high.

6.5 Efficiency of Solar/Sawdust Crop Dryer

The preceding discussion on the operation of the dryer indicate that the temperatures developed are adequate for drying various crops. These temperatures can also within limits be regulated by the rate of consumption of the sawdust, for example. It is however of interest to know the amount of useful energy from the sun and sawdust which is used during the drying of the crop.

There are several efficiencies which can be determined for the crop dryer. The overall efficiency can be defined as

$$\eta_o = \frac{m_w L}{m_f . CV + G} \qquad (6.1)$$

where

m_w = mass of water evaporated from crops in a given time interval, kg
L = latent heat of water J/kg
m_f = mass of sawdust used in a given time interval, kg
CV = calorific value of sawdust, J/kg
G = total solar radiation incident on dryer in a given time interval, J.

Another efficiency can be defined for the operation of the dryer taking to account the amount of steam generated. This intermediate efficiency is written in the form

$$\eta_I = \frac{m_w L}{m_s L + G} \qquad (6.2)$$

where

m_s = mass of steam generated in a given time interval.

The performance of the burner can be determined by a burner efficiency

$$\eta_B = \frac{m_s L}{m_f . CV} \qquad (6.3)$$

It is, of course, obvious that when sawdust alone is used as fuel G = 0, and when solar energy is used only equation 6.1 can be used to define the efficiency of the dryer with $m_f = 0$.

Preliminary results have been obtained for various efficiencies of the dryer under various operating conditions during the drying of okra. The quantity of water evaporated from the crop, the amount of steam generated by the sawdust and the mass of sawdust used are shown in table 6.1 together with the efficiencies.

Table 6.1

Estimated efficiencies for the dryer under load

Heat source	m_w, kg	m_s, kg	m_F, kg	η_C	η_I	η_B
Solar	7.5	-	-	29	-	-
Sawdust	7.8	36.8	171	0.7	21	3
Solar/Sawdust	9.6	17.2	95	1.4	26	2.6

The overall efficiency of the dryer when only solar energy is used is 29 percent noting that this applies to the conditions under which the tests were carried out. The losses from the dryer are predominantly due to convection heat transfer from the top surface and the sides. The overall efficiencies are 0.7 and 1.4 percent when sawdust and solar/sawdust are used as the sources of heat. These values are low and indicate that there are large amounts of heat losses from the burner. The values of η_B show that large heat losses occur from the sawdust burner.

These preliminary results for the efficiency of the dryer indicate that further tests have to be performed using different crops and improved measuring equipment in order to get more conclusive results. There are substantial heat losses from the sawdust burner which cause the efficiencies to be low. An improvement in the design to minimize these losses will conserve the sawdust used. It may however be argued that the sawdust and solar energy are effectively free and it is not necessary to improve on the design which may increase cost. It is felt that further improvements in the design will be mainly concerned with the burner so as to reduce sawdust consumption.

Chapter 7

ECONOMIC ASPECTS OF CROP DRYERS

The discussion on the solar/sawdust crop dryer so far indicates that it can be used to adequately dry some crops. It is however of interest to evaluate the dryer's effectiveness in terms of cost which is a good indicator of the potential use of such an equipment. The following sections will therefore look at the direct and indirect costs of the dryer together with some of the benefits which will be derived from the use of the dryer. It should be pointed out that the analysis is not exhaustive since, for example, only one crop has been dried and more drying tests need to be carried out using various crops.

7.1 Direct Costs of Dryer

Capital Costs

The prototype solar/sawdust crop dryer which is under discussion was made from plywood, angle iron, galvanized iron sheets, galvanized iron pipes, glass, wire mesh, putty, plastic hose and sawdust shavings. Some of these materials were chosen because of the conditions under which the work was carried out. For example, under laboratory conditions, it was necessary to move the dryer indoors and outdoors every day. The frames had to therefore be made of iron and wheels were attached for easier transportation. Thick plywood also had to be used for the inner and outer walls of the dryer so that it could withstand the rough treatment arising out of having to move the dryer around.

The breakdown of the cost of the materials used in the final prototype as shown in figure 5.1 is given in Table 7.1.

In the table here-below the total cost to produce the prototype taking into account preliminary designs of various parts of the system and labor costs for manufacturing and installation, have not been included since these would make the total value unrealistically high. However in real life, it is estimated that labor costs for manufacturing the dryer as shown would be about U.S.A. $150 if a workshop were requested to produce a single unit.

Table 7.1

Cost of materials used to manufacture prototype

Material	Quantity	Use	Cost in Leones
¼" plywood, 8ft x 4ft	3	Outer and inner side walls	135.00
3/4" plywood, 8ft x 4ft	1	Outer base	70.00
½" plywood, 8ft x 4ft	1	Inner base	29.00
2" angle iron, 20ft	2	Stands	70.00
1/16" galvanized metal sheet, 8ft x 4ft	2	Outer burner casing, Burners	130.00
1/32" galvanized metal sheet, 8ft x 4ft	1	Cover for burner and chimney	53.00
½" galvanized metal pipe, 20ft	4	heat exchanger pipes	40.00
1" galvanized metal pipe, 20ft	1	steam supply to dryer	16.00
2" galvanized metal pipe, 20ft	1	Headers for heat exchangers	24.00
Glass, 3ft x 3ft	.2	Transparent covers	16.00
Wire mesh, 3ft x 3 ft	3	Tray for crops	4.50
Putty	2 tins	Sealant	3.50
Plastic hose, 12 ft	1	air inlet and outlet holes	2.60
Black paint	3 tins	painting of inner walls of dryer and trays	12.50
Welding rod	1 pkt	welding stand	5.00
Rivets	1 pkt	sheet metal work	1.40
Screws	2 pkts	woodwork	1.60
Nails	3 pkts	woodwork	1.50
	TOTAL		616.50

The author should point out that all the materials used are locally available, but are imported which makes them quite expensive. Also, it is possible for prices to double in a few months which makes it difficult to predict costs.

Under normal use the walls of the dryer can be made from ½" inch plywood sheets and wooden poles or bamboo poles used for the stand. The sawdust burner assembly could be made from both galvanized iron (for the burners and pipes) and heat resistant bricks which would appreciably reduce the material cost. Further development work is therefore required to ascertain this but it is felt that such efforts could reduce the material cost of the prototype to about one third of the cost shown in Table 7.1. The labor costs for manufacturing it would then drop to about $ 75 for the prototype.

The costs can be substantially reduced if the manufacturer has the market for many units. Also the client should have the option of ordering a dryer made from durable or less durable materials, e.g. glass compared to transparent plastic. In this way individuals having different income levels can make use of the technology.

Operating Costs

It is at this stage difficult to predict the operating cost of the dryer since many crops have not yet been dried and the future cost of sawdust, which is now free, is unknown. Estimates are however presented in Table 7.2 for the dryer.

Table 7.2

Estimated Operating Cost of Dryer per Month

Item	Cost Leones
Sawdust 1800 kg a month at 50¢ for 60 kg	30.00
Labor for operating unit at $1 daily	30.00
Maintenance cost; 4% of capital cost	2.10
Cost of igniting sawdust, matches	0.50

The cost of the crops have not been included in Table 7.2 since results are not yet available to determine this. For okra it is possible to dry about 10 kg daily with the size of crop dryer being discussed.

It is estimated from results of interviews that sawdust may be sold at about 50 cents for 60 kg which would be the fuel consumption if the burner were loaded thrice daily. The labor costs for operating the dryer is estimated at $ 30 a month since it is envisaged that the job is relatively simple and would be carried out by one person.

7.2 Indirect Costs of Dryer

There are certain factors which have an overall effect of cost in the use of the solar/sawdust crop dryer. Some of these are related to:

a) the use of sawdust in the crop dryer limiting use of sawdust in other applications

b) management problems

c) inconvenience of preparing the sawdust.

Sawdust is presently not used on a large scale for any application; nearly all of this material is discarded as waste. It is therefore felt that since its use in other applications is small, the indirect cost would be low. There is however the possibility that, in the future, there will be some industry set up to manufacture building materials out of sawdust. Also, the work which has been carried out by the author on other applications using sawdust may create a demand for this fuel in the rural and urban areas. In these cases the indirect cost would be substantially increased.

The contribution to the indirect cost due to management problems will depend on the scale of the application, i.e. the size of dryer, the different types of crops which will be dried, the proximity of the source of fuel to the dryer, experience of the operator etc. No attempt is made in this report to quantify these costs due to management problems.

The preparation of the sawdust before ignitition is very simple and can be managed by a six year old child. It is therefore expected that this factor will not appreciably affect the indirect cost of the dryer.

7.3 Benefits of the System

Some of the benefits of the crop dryer are:

a) Improvement in the quality of crops dried compared to open air sun drying

b) Reduction in the drying time compared to open air sun drying

c) The use of sawdust as a fuel which would limit the inconveniences caused by
   i) its accumulation in certain areas
   ii) fire, which burns children playing on it, and produces smoke
   iii) pollution of water in certain areas where it is dumped.

d) Reduction of energy produced by wood to perform some drying activities.

e) The use of a renewable source of energy

f) Employment of local manpower

g) Increase in income of owner

7.4 Comparative Costs of Using Various Sources of Energy

The two sources of energy used by the crop dryer are solar energy and sawdust. The operation of the dryer using these fuels individually or simultaneously has been investigated for okra in this study. Although further tests are needed using different crops before definite conclusions can be made, the present results can give a good indication of the relative costs using various fuels. Table 7.3 shows comparison between various quantities which can be used to assess the relative costs of using different heat sources.

Table 7.3

Comparison of Use of Various Sources of Heat for Drying of Okra

Fuel	Time of Year	Quantity of Crop Okra	Quantity of Sawdust kg	Drying Time hrs
Sawdust	Early May	8.4	272	19
Solar	Mid-February	8.4	-	--
Solar/ Sawdust	April, May	10.5	95	[illegible]

It is seen from the table above that the sawdust dries the crop in about 19 hours whereas solar and solar/sawdust perform the same amount of drying in 11 and 9 hours respectively. This would indicate that the solar/sawdust combination could dry about 11kg of okra during a working day. The sawdust on the other hand would produce heat to dry about 6 kg of okra in two working days. Thus from the point of production the solar/sawdust combination produces more dried crops than the use of solar energy or sawdust alone. Since the solar energy is free it is useful to note that the use of solar energy and sawdust simultaneously will be more economical than the use of sawdust alone. In this regard it is observed that the sawdust consumed when both fuels are used simultaneously is much less than that consumed when only sawdust is used. It is therefore more economical to use the solar/sawdust combination when solar energy is available.

During days when the solar energy is quite high, it may be desirable to conserve the sawdust for less favorable days. It is possible that during the dry season, during periods with relatively low relative humidities, the use of solar energy alone would provide speedy drying. Operation of the dryer using sawdust will be economical during periods of low solar availability since the crops would otherwise go bad without adequate drying.

Another variable which affects the economic justification of the crop dryer is the number of different types of crops which can be dried. The continuous operation [illegible] the dryer would make it more profitable to use. Future [illegible] should concentrate on the drying of various crops and assessing the economics of the applications.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

A programme of research has been carried out to use sawdust, which would otherwise be considered a waste material, as a fuel in rural applications.

The work consisted of four main parts:

a) To estimate the quantity of sawdust which is available in Sierra Leone,

b) To experimentally study the calorific values of sawdust and determine the effect of variables such as moisture content and tree species on the values,

c) To study the operating characteristics of a burner which can be used for burning sawdust and to analyze the data with the view of recommending parameters for designing such burners,

d) To design a crop dryer using both solar energy and sawdust as sources of heat and to investigate its performance under no-load and loaded conditions using solar energy and sawdust simultaneously and individually.

The survey of the availability of sawdust indicates that the greater portion of this fuel is obtained in sawmills. It is estimated that about 2000 m^3/month of sawdust is available.

The effects of moisture content and tree species on calorific values have been determined for sawdust. It was observed that the calorific values of the sawdust were affected substantially by the magnitude of its moisture content; the relationship between them being a straight line variation of the form

Calorific Value = Constant - Slope X Moisture Content

the slope and constant depending on the tree from which the sawdust was obtained. An equation has been recommended for determining the calorific value of mixtures of different sawdust at various moisture contents.

The results of the study on the burner indicated that the variations of the mass of fuel consumed and the diameter of the burner hole, with time, depended on the air inlet diameter and the variations were linear. The mass of fuel consumed depended on the height of packing whereas the change in diameter of the burner hole with time was independent of this variable. Equations have been presented for the variation with time of these parameters individually, for various values of air inlet diameter. An analysis of the data shows that two equations presented in this study can be used to design burners for any application. These equations are: $d/D_B = 1.04 \exp (0.0063t)$ and $m_f/Ht = 0.2421 \exp (0.0982 D_B)$.

An integrated crop dryer using solar energy and sawdust as fuel has been designed and tested. The dryer uses steam generated by the sawdust burner to heat the dryer cabinet and may also use solar energy for direct heating. Results of tests under loaded and no-load conditions show that temperatures, up to 90°C under no-load and up to 80°C when loaded, can be expected. Tests using okra indicated that the dryer when operated using solar energy and sawdust, simultaneously or individually, gave a better dried product. The drying time using open air sun drying can be reduced by 50 percent by using solar energy and sawdust in the crop dryer. The dryer can be used throughout the year, during periods of no sunshine and in the evening depending on the need.

8.2 Recommendations

The results of this study are encouraging and show a definite potential for the exploitation of sawdust for rural production of energy. The following recommendations are presented for future work.

1. Sawdust must not be regarded as a waste material which has no use. Strategies should therefore be devised to collect, store and distribute it on an economical basis.

2. More studies should be carried out of many more types of sawdust so that more comprehensive information on the variation of calorific value with moisture content can be obtained.
3. Further studies are needed to determine the applicability of the design equations presented in this work for ranges of values of D_3 larger than that considered in this work.
4. The crop dryer should be modified with the aim of using it at the village level. The size should be based on the needs of the people. The modification should involve minimizing costs, decreasing heat losses and improving performance.
5. Production of several dryers should then be carried out for experimentation at village level with various types of crops using both solar energy and sawdust.
6. The crop dryer should then be modified, based on the results of the village level tests, so that full scale application can be possible.
7. A cost benefit analysis should be carried out during the village level tests in order to assess the economic viability of the crop dryer.

REFERENCES

1 Brace Research Institute: A Survey of Solar Agricultural Dryers. Brace Research Institute Technical Report T99, December 1975.

2 Kapoor, S.G. and Agrawal, H.G.: Solar Dryers for Indian Conditions. Proceedings of the International Congress. The Sun in the Service of Mankind. Paris, July 2-6, 1973.

3 Headley, O. St. C. and Springer, B.G.F.: A Natural Convection Crop Dryer. Proceedings of the International Congress. The Sun in the Service of Mankind. Paris, July 2-6, 1973.

4 Akyurt, M. and Selçuk, M.K.: A Solar Dryer Supplemented with Auxiliary Heating Systems for Continuous Operation. Journal of Solar Energy, vol. 14, pp 313-320, 1973.

5 Akyurt, M., Ozdaylar, I., Selçuk, M.K.: A Solar Dehydrator for Orchards. Complos Conference, Istanbul, Turkey, September 11-16, 1972.

6 Satcunanathan, S.: A Crop Dryer Utilizing a Two Pass Solar Air Heater. Proceedings of the International Congress: The Sun in the Service of Mankind. Paris, July 2-6, 1973.

7 Buelow, F.H.: Drying Crops with Solar Heated Air. Proceedings of UN Conference on New Sources of Energy, Rome, August 21-31, vol. 5, 1961.

8 Rao, G. and Macedo, I.C.: Grain Drying in Stationary Bins with Solar Heated Air. Journal of Solar Energy, Vol. 18, pp 445-449, 1976.

9 Kranzler, G.A., Bern, C.J. and Kline, G.L.: Grain Drying with Supplemental Solar Heat. American Society of Agricultural Engineers, Paper N° 75-3001.

10 Forster, G.H. and Peart, R.M.: Solar Grain Drying Progress and Potential. Agricultural Information Bulletin N° 401. United States Department of Agricultural, November 1976.

11 Heid, W.G.: The Performance and Economic Feasibility of Solar Grain Drying Systems. U.S. Department of Agriculture, Agricultural Economic Report N° 396.

12 Peterson, J.H. and Hellickson, M.A.: Solar Drying Progress Report. Cooperative Extension Service, South Dakota State University, U.S. Department of Agriculture, EMC 657, July 1977.

13 Bassey, M.W.: The Effects of Air Inlet Hole Diameter on the Performance of a Sawdust Burner. *Engineering Research Publications*, Report N° AT77/1, Faculty of Engineering, University of Sierra Leone.

14 Bassey, M.W.: Variables Affecting the Performance of a Sawdust Burner. Proceedings of the 11th Biennial W.A.S.A. Conference, March 13-16, 1978, Lome, Togo.

15 Bassey, M.W.: Influence of Pot Size on Performance of Cookers Using Single Hole Sawdust Burners. *Proceedings of the International Conference on Appropriate Technology*, July 5-7, 1978, Freetown, Sierra Leone.

16 Joel, Rayner: Basic Engineering Thermodynamics in SI Units, Longman 3rd Edition.

APPENDIX A

DETAILS OF CALORIFIC VALUE EXPERIMENTS AND DATA REDUCTION

Results for the calorific values of sawdust have been presented in Chapter 4. The experimental apparatus used has also been described in that chapter and it was mentioned that the procedure adopted was a standard one similar to than described in 16 . A measured quantity of water was put in the calorimeter so that the bomb was completely covered. The electrical connections were made, the Beckmann thermometer put in the calorimeter to measure the water temperature and stirring of water was started. The temperature of the water was read at one minute intervals for about 5 minutes. This period was the "preliminary" period. At the end of this time, which marked the start of the "chief" period, the switch was closed and the platinum wire burnt to ignite the sawdust in the crucible. The temperature of the water rose rapidly and the thermometer read at 1 minute intervals till the maximum temperature was reached which marked the end of the "chief period", and the beginning of the "after period". Readings were then made for at least 5 minutes in the after period. A sample of the readings made during the experiments is shown in Table A.1.

In calculating the calorific value from the measurements made, it should be noted that there are various sources of errors which could make the calorific value obtained substantially different from the actual value. There are errors due to the energy dissipated by the stirrer causing slightly higher temperatures to be measured. The platinum wire also dissipated heat to the surroundings during its ignition. The oxygen in the bomb received heat from the combustion of the fuel which would reduce the temperature rise of the water. Acids which are formed, e.g. by the combination of the oxygen with any sulphur present in the fuel to form sulphuric acid, and with nitrogen to form nitric acid, produce heat which should be accounted for. These errors mentioned above are however, when

Table A.1 Sample of experimental data obtained for calorific value tests

Name of Tree: Fagara macrophylla (Sowuli)
Moisture Content: 13.24 Percent
Mass of Bomb: 3.115 kg
Mass of Water: 2.5 kg
Mass of Fuel: 0.99×10^{-3} kg

Time (minutes)	Temperature (°C)
0	2.25
1	2.26
2	2.29
3	2.30
4	2.32
$5 = t_c$	2.32
6	3.04
7	3.41
8	3.56
9	3.62
10	3.64
11	3.65
12	3.65
13	3.65
14	3.65
15	3.64
16	3.64
17	3.635
18	3.63
19	3.626
20	3.62

added, turn out to be quite small compared to the errors caused by cooling of the calorimeter by the atmosphere. It was therefore assumed that the main correction which had to be made to the results was that for cooling.

The cooling correction was calculated using the Regnault Pfaundler formula as recommended by B.S. 1016: Part 5: 1967.

The correction is given by

$$\Delta T_{corr} = nv' + \frac{v'' - v'}{t'' - t'} \left\{ \sum_{1}^{n-1} (t) + \frac{1}{2} (t_o + t_n) - nt' \right\} \quad (A.1)$$

or

$$\Delta T_{corr} = nv' + kS$$

where n = number of minutes within chief period

v' = rate of fall of temperature/minute within the preliminary period.
v' is negative if the temperature rises in this period.

v'' = rate of fall of temperature/minute in the after period.

t' and t'' = average temperature during the preliminary and after periods respectively.

$\sum_{1}^{n-1} (t)$ = sum of temperature readings during the chief period.

$\frac{1}{2} (t_o + t_n)$ = mean of the firing temperature t_o and the maximum temperature t_n.

$k = \frac{v'' - v'}{t'' - t'}$, cooling constant of the calorimeter.

Using the data in table A.1 the following values were calculated

$t_c = 2.32$

$v' = - 0.024$

$t' = 2.290$

$nv' = - 0.084$

$\frac{1}{2} (t_o + t_n) = 2.985$

$\sum_{1}^{n-1} (t) = 17.27$

$nt' = 13.74$

$S = 6.515$

$k = \frac{v'' - v'}{t'' - t'} = 0.01$[illegible]

$v'' = 0.0033$

$t'' = 3.64$

Then $\Delta T_{corr} = - 0.084 + 0.00834 = - 0.0006$ °C

The measured temperature rise $T_{meas} = t_n - t_c = 1.33$°C

Therefore the actual temperature rise is given by

$$T_{actual} = T_{meas} + T_{corr} = 1.33 - 0.0006 = 1.3294°C.$$

The calorific value was then evaluated by writing the energy balance for the system.

$$m_{fuel} \cdot CV = m_{bomb}\, c_{p_{steel}}\, \Delta T_{actual} + m_{w}\, c_{p_{water}}\, \Delta T_{actual} \qquad (..2)$$

or

$$m_{fuel}\, CV = \left[m_{bomb} \frac{c_{p_{steel}}}{c_{p_{water}}} + m_{water} \right] c_{p_{water}}\, \Delta T_{actual} \qquad (..3)$$

Noting that $c_{p_{steel}} = 0.4608$, $c_{p_{water}} = 4.1868$ kJ/kg - °K

and $m_{bomb} = 3.115$ kg

the calorific value is given by -

$$CV = 11.9024 \frac{T_{actual}}{m_{fuel}} \text{ kJ/kg}$$

For this example

$$CV = 11.9024 \times \frac{1.3294}{0.99 \times 10^{-3}} = 15983 \text{ kJ/kg}$$

All other calorific values were evaluated in this manner from the data obtained in the experiments.