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King Mongkut's Institute of Technology Thonburi
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SOLAR THERMAL PROCESSES IN THAILAND

A study on

FORCED CONVECTION HUT DRYING

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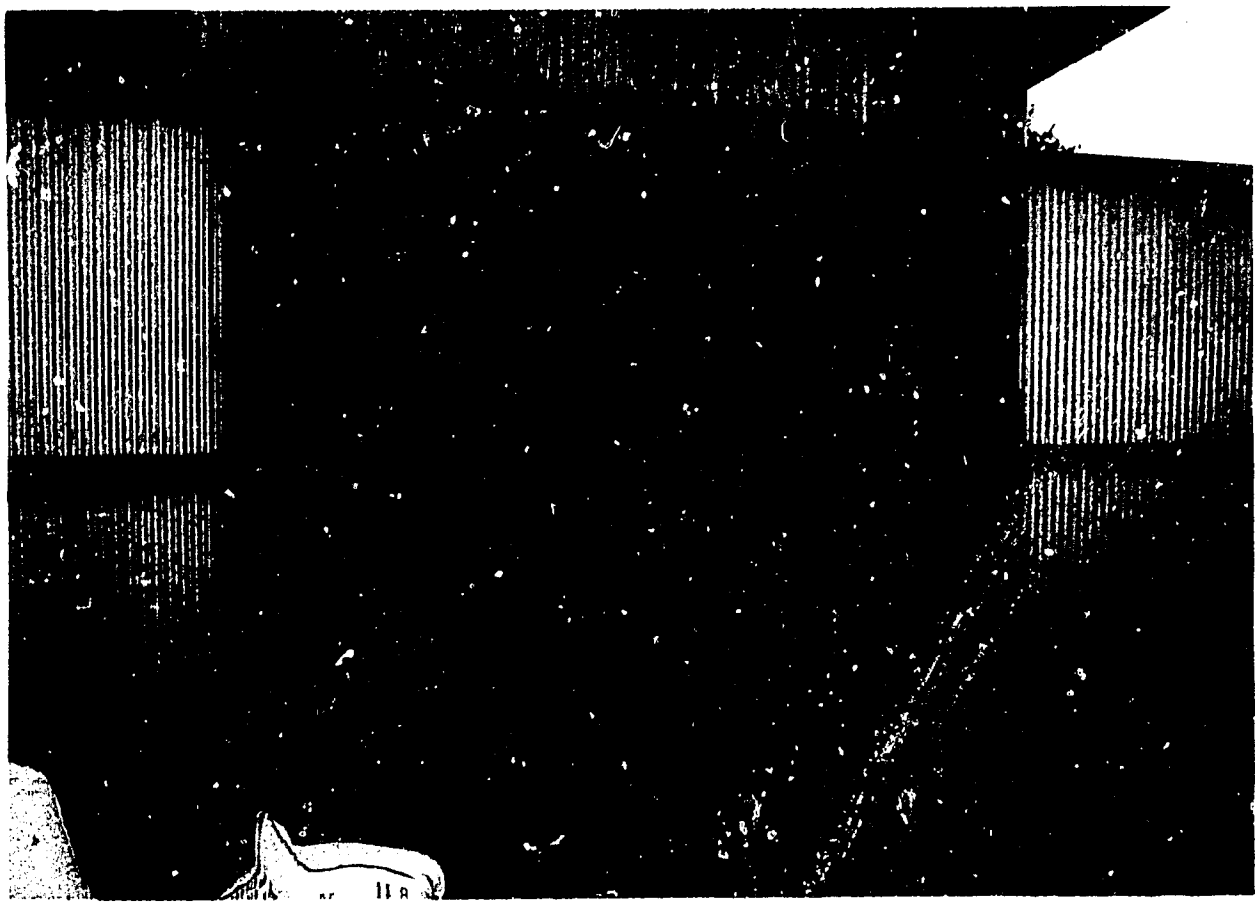

Drying bins inside the Forced Convection Solar Hut Dryer

FOREWORD

Solar thermal energy has been traditionally used in Thailand for many decades for drying crops and salt production. Solar energy applications cover a number of different technologies depending upon the types and places of applications. Some applications have already been commercialized in Thailand, such as solar water heating, photovoltaic generation, etc. Though potentials for solar energy applications are extremely high, a great deal of research and development has to be conducted to make solar energy applications feasible technically, economically and socially.

As a result of the oil crisis in 1973, the 5th National Economic and Social Development Plan identified solar energy as one of the priority areas in the development of alternative energy resources because of its high potential for applications in both rural and urban areas. Solar Thermal Processes has therefore been selected as an area for cooperation between the governments of the United States and Thailand under the Renewable Nonconventional Energy Project (#493-0304).

Solar Thermal Processes is one component of 14 separate components involved in the Renewable Nonconventional Energy Project. Projects carried out include:

Industrial Biogas
Biomass Gasification
Charcoal Improvement
Energy Master Plan Support
Micro-Hydro Project
National Energy Information Center
Pyrolysis of Rice Husks
Regional Energy Centers
Solar Thermal Processes
Solar/Wind Assessment
Stove Improvement
Village Survey
Village Woodlots
Water Lifting Technology

A grant of about US $50,000 was awarded to King Mongkut's Institute of Technology Thonburi (KMITT) by the US Agency for International Development (USAID) Thailand with institutional support from the National Energy Administration, Ministry of Science, Energy and Technology, to conduct research and development on Solar Thermal Processes. The Solar Thermal Processes component is comprised of five sub-components, namely:

Natural Convection Cabinet Drying
Forced Convection Hut Drying
Solar Tobacco Curing
Solar Distillation
Solar Refrigeration

On behalf of the School of Energy and Materials, KMITT, I would like to express my gratitude to USAID for the grant which made the work on Solar Thermal Processes possible. Even with various constraints such as shortages of available time and technical personnel, rigid government regulations, etc., work completed in this component has reached most of its original objectives. In addition to useful results obtained in the component, the Project has stimulated further interest in research and development on solar thermal processes in Thailand far beyond the original scope of the Project.

As leader of the component of Solar Thermal Processes, I would like to thank Mr. John W. Neave and Mr. Mintara S. Watchananai of USAID Thailand, Mr. Prapath Premmani, Mr. Tammachart Sirivadhanakul and Mr. Sompongse Chantavorapap of the National Energy Administration and their colleagues for their tremendous coordinating efforts in spite of a great many tedious government rules and regulations. I am indebted to my co-leader, Dr. Krissanapong Kirtikara and my colleagues, Dr. Surapong Jirarattananon and Dr. Somchart Soponronnarit for their assistance in managing and coordinating the component activities especially during 1983 when I was on leave at the Asian Institute of Technology.

I would also like to thank the sub-component leaders and local experts: namely, Dr. Piyawat Boon-Long of Chiang Mai University, Dr. Sakarindr Bhumiratana, Dr. Ratana (Putranon) Jirarattananon, Dr. Somchart Soponronnarit, and Dr. Suradej Chantranuluck of KMITT and Dr. Sanchai Klinpikul of Prince of Songkla University, for their excellent technical input -- the results of which are reflected in this report. Thanks are due to KMITT Vice Rector Dr. Pibool Hungspreug, to KMITT technical and administrative personnel whose contributions greatly helped facilitate this work.

I finally wish to express my sincere appreciation to Professor M.L. Albertson, Ms. Lana Larsen and their colleagues of the Office of Project Management Support for their coordinating efforts and valuable comments that helped to make the report complete and readable.

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EXECUTIVE SUMMARY

This report describes the research and development of a low-cost solar air heater and grain dryer.

The solar collector is constructed on the roof of a grain storage barn. The structure of the roof is modified so that the quantity of material used is minimized. Material selected is cheap and easily available. The thermal efficiency of the solar collector is also considered. The absorber is made of a corrugated galvanized iron sheet. There is no transparent cover in order to simplify the construction of the collector. Air flows through a gap between the absorber and the insulation placing under the absorber. The average spacing of these two sheets is 20 mm. The insulation is made of styrofoam 20 mm thick and is held in place by bamboo plywood.

From the performance test of the solar collector (following ASHRAE Standard 93-77), it was found that the maximum thermal efficiency of the solar collector was 31% when the air flow rate was 0.34 kg/s for the 18.8 m^2 collector (width 3.7 m and length 5.09 m). In addition, the performance test on a second collector, which differed only in that its absorber was painted dull black, was also conducted. The maximum efficiency of this second collector was 34% at the same air flow rate. Though the efficiency in the latter case was 3% higher, the collector was more expensive to construct. The author feels that the unpainted solar collector is the more attractive prospect, at least for producing hot air used in drying of agricultural products in Thailand.

The experimental performance curve of the solar collector was compared to the simulated result using a mathematical model developed in this report. It was found that a good agreement between the two was obtained, especially for the unpainted solar collector.

A low cost grain dryer was developed. A fixed vertical bed type of dryer was selected because it occupied a smaller area of installation than a flat bed dryer. The dryer was composed of wood, plywood, bamboo matting etc. These materials are cheap and easily available. The capacity of the dryer is about one ton of wet paddy. Two tests of paddy drying were conducted during the dry season (harvesting period of the year crop). During the day, hot air was sucked from the solar collector and delivered to the dryer by a forward curved blade fan driven by a 1.5 kW electric motor. Heat and mass transfer took place in the grain beds before leaving the dryer. At night, ambient air was delivered directly to the dryer by the same blower. Drying was continued until the average moisture content of the grain was reduced to 14-15% wet-basis. From the results of the drying tests, it seems that the drying technique where drying begins in the morning and terminates the following morning is preferred.

Results from the drying of second-crop paddy are not yet available. * The author feels that additional testing is surely needed as the problem of spoiled wet paddy occurs mainly in the case of the second crop. For this reason, the development of a quality solar collector and low-cost grain dryer is most critical.

CONCLUSIONS

1. The maximum efficiency of the unpainted and dull black painted solar collectors are 31% and 34%, respectively. The unpainted solar collector may be a more attractive choice than the dull black painted one if low initial investment is preferred.

2. The mathematical model developed can predict the thermal efficiency of the solar collector accurately at low inlet air temperatures. However, the theoretical efficiency is overestimated at high inlet air temperatures.

3. From the results of the drying tests, it seems that a drying technique like the first drying test (where drying begins in the morning and terminates the following morning, and the ventilation of ambient air is done at night before the end of drying) is preferred to the technique followed in the second test (where drying begins in the evening and terminates the following evening) because there is an advantage of a smaller moisture gradient of paddy in the dryer.

RECOMMENDATIONS

It is recommended that the following work should be continued.

1. The low-cost solar air heater developed in this study is suitable for drying agricultural products on the farm because it is cheap and easily constructed. However, high efficiency solar air heaters may be of more interest to small scale rural industries. The efficiency of the low-cost solar air heater can be significantly improved by adding a transparent cover over the absorber.

2. Drying paddy during the wet season should be investigated.*

3. Mathematical simulation of solar paddy drying is also important because it can be used to aid in the design of similar solar drying systems.

4. An economic evaluation of the solar dryer should be made.*

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* See Annex II for these results.

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NOMENCLATURE

Symbol

A	area, m^2
C_p or C	specific heat at constant pressure, kJ/kg °C
D	dimensionless term of distance
D_h	hydraulic diameter, m
F'	collector efficiency factor
F''	flow factor
F_R	collector heat removal factor
G	solar radiation, W/m^2 or mass flow rate per unit area, $kg/h - m^2$
h	convective heat transfer coefficient, W/m^2 K
h_r	radiative heat transfer coefficient, W/m^2 K
h_{fg}	latent heat of vaporization of free water, kJ/kg
h'_{fg}	latent heat of vaporization of moisture in grain, kJ/kg
H	time required to reduce MR to a half, h
k	thermal conductivity, W/m K or drying constant, h^{-1}
l_i	thickness of insulation, m
L	Length, m
$\dot{m}$	mass flow rate, kg/s
m_w	moisture evaporated, kg
M	moisture content, decimal dry - basis
$\bar{M}$	mean moisture content, decimal dry - basis
M_{eq}	equilibrium moisture content, decimal dry - basis
MR	moisture content ratio
$\bar{MR}$	average moisture content ratio (for the whole grain)
Nu	Nusselt Number

NOMENCLATURE (continued)

P	pressure, Pa
q_u	useful energy per unit time per unit area, W/m^2
Q_u	useful energy per unit time, W
Re	Reynolds number
RH	relative humidity, decimal
S	solar radiation absorbed by absorber, W/m^2
t	time, h
T	temperature, °C or °K
U_b	bottom lost coefficient, W/m^2 K
U_L	total lost coefficient, W/m^2 K
U_t	top lost coefficient, W/m^2 K
V	velocity, m/s or m/h
V_{ref}	reference air velocity
x	bed ordinate, m
X	thickness of grain bed, m
Y	dimensionless term of time
ρ	density, kg/m^3
α	absorptivity
ε	emissivity
ν	kinematic viscosity, m^2/s
η	efficiency, decimal
σ	Stefan - Boltzmann constant

Subscripts

a	ambient, air
c	collector
db	dry bulb

NOMENCLATURE (continued)

dp	dew point
f	fluid, final
i	insulation, inlet, initial
m	mean
o	outlet
p	plate, dry product
pw	wet product
s	sky
T	tilt surface
vs	saturated vapor pressure
w	wind
wb	wet bulb

Chapter 1

Introduction

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INTRODUCTION

Thailand is one of the major rice producing and exporting countries of the world. The production of paddy is approximately 16.2 million tons per year (1980). 14 of the 16.2 million tons is consumed within the country, the remainder is exported.

The present cultivation techniques of Thai farmers consumes a tremendous amount of human labor. Soil tillage, planting, harvesting, handling, threshing, and storage are normally completed manually. Some types of farm machinery have begun to play an important role in rice production. Examples of this include soil preparation by using a tractor as a prime mover, threshing on floor by driving a tractor over the cut plants and/or using a drum thresher driven by an engine.

A. HISTORICAL BACKGROUND

The author wishes to describe briefly the present harvesting, drying, threshing and storage techniques of Thai farmers (see Agricultural Engineering Division report, 1976). The practice of rice production varies from one region to another. Nevertheless, there are common practices among them, for example, harvesting depends mainly on human labor and paddy is field - dried.

Farm Size, Varieties and Yields

The size of farms referred to herein does not mean the amount of land owned by the farmers but it is the farm area in which rice is grown per family. In the Northeast, the farm size is between 10 - 30 rais* while in the North it is less than 20 rais. Farm sizes in the South and Central regions are approximately 10 - 20 and 20 - 30 rais, respectively. Farms over 30 rais are in the minority.

Most rice grown in Thailand is of the non-waxy variety. Waxy rice is grown primarily in the Northeast. There are many varieties of non-waxy rice which may be considered appropriate for the weather and land conditions within each region. Long grain varieties are most preferred because they are well accepted in both local and overseas markets.

The yield of paddy is relatively low compared to that in developed countries. The average yield in 1980 was about 30 tung/rai**. The yield in the Northeast is the lowest.

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* 1 Hectare = 6.25 rais

** 1 tung is about 10 kilogram

Rice may be grown once or twice a year depending upon the available water supply. The year crop is grown during the rainy season and is harvested in the dry season. The second crop is grown during the summer and is harvested in the rainy season (see Annex I). Nowadays, the planting of the second crop has become more popular due to the expansion of irrigation systems. However, farmers have been faced with spoilage of the second crop when moisture can not be reduced fast enough by field drying during the rainy season.

Methods of Harvesting, Drying, Threshing, and Storage

Harvesting depends primarily on human labor and it is often necessary to employ laborers from other areas. The rice is harvested by using a harvesting knife. For a year crop, the plants (with a grain moisture content of 20-22% wet basis) are cut and left in the fields for a few days to reduce the grain moisture content by sun drying. The rice stems are then bundled either in the morning or evening in order to avoid the shaking loss of grain which may be higher if this bundling is done during the strong mid-day sun. The bundles of rice are then transferred, depending upon the available facilities, to the threshing floor by human laborers, carts, two-wheel tractors, four-wheel tractors or boats. In the South a different harvesting method is employed. The harvesting knife, called "Kaire", is able to cut only rice panicles. Paddy is stored as bundles of panicles after they are dried. No threshing is required.

The harvesting method for the second crop is different from that of a year crop as the paddy fields still contain water or are still saturated and humid. Small bundles of cut plants are put on the stubbles above the water level with the panicles directed downward. Using this method the grain will not hold water when there is rain. The bundles are transferred to the threshing floor when they have sufficiently dried.

The harvesting period is normally 2-14 days or more. Most Thai farmers spend more than 14 days for harvesting.

Threshing the paddy by beating the cut plants on logs is quite common in the Northeast of Thailand. Human treading on the panicles, or driving cattle or farm tractors over the cut plants is always done in the Central and the Southern regions. Engine driven drum threshers were rarely used in the past but are relatively popular nowadays.

Cleaning the threshed paddy is carried out by 2 methods. The use of winnowing baskets is usually employed in the North and the Northeast. Winnowing machines have been extensively used in many areas, especially in the Central region. The machines may be driven manually or by engines.

There are 3 main purposes for paddy storage: 1) family consumption, 2) sale, and 3) planting. Most paddy is stored on the farm. The barns may be permanent buildings constructed from wood with the floors elevated above the ground level to avoid flooding. Paddy is loaded and unloaded via the doors. Semi-permanent barns are made of bamboo - matting walls

covered with a mixture of soil and night soil of cattle. There are roofs for protection from the sun and rain. In both barns, there is no ventilation during storage. It was found that some farmers do not store paddy due to either a lack of storage facilities or a need to sell paddy straightaway for financial reasons.

The storage period of paddy depends on its purpose. Those who grow rice for sale store paddy for a few months. For consumption and planting, paddy is stored for one year or even longer. The main problems encountered during storage include the invasion of birds, insects and rodents, the yellowing of grain kernels, moulding and poor germination because of rain. This happens to both the year crop and the second crop but is more sever for the latter.

Need of Grain Dryer and Justification of Heat Source

As mention in the previous section, cut plants are left in the field for sun drying. During the dry season (harvesting period of the year crop) the grain is always safely sun dried in a few days. For the second crop the paddy is harvested during the rainy season and sometimes it can not be quickly dried using this same method due to rain. This leads to the degrading of paddy quality by yellowing or moulding. In addition, the paddy which is left in the field may be partly dried during the day only to reabsorb moisture at night or during a rain. As a result, milling quality is low, i.e. the percentage of head rice decreases. The grain moisture content during harvesting may vary from 20-26% wet basis and it must be quickly reduced to 14%. The safe drying time depends on grain moisture content, grain temperature and the degree of kernel breakage. Arboleda and Manalo (1974) suggested that rice with a moisture content of 24 percent wet basis must be dried in one day and that having a moisture content between 21-23.9 percent must be dried in two days. Rice with a moisture content lower than 20.9 percent must be dried in three days. With the conventional method of sun drying, it is understood that the paddy may not be safely dried during the rainy season. This is, in fact, a great problem which Thai farmers are facing. To ameliorate the problem one must introduce other methods of drying. A mechanical dryer is one attractive solution. It is composed of a bin as a drying chamber, a blower which may be driven by an internal combustion engine or an electric motor, and a heat source which may be electricity, gas, kerosine, fuel oil, agricultural waste, or solar energy, etc.

An electrical heat source is quite simple but operating costs are expensive. Gas and fuel oils are less expensive than electricity but the controls are more complicated. Agricultural wastes, such as rice husk, may be the most practical if it is available on site so that there are no transportation costs involved. Solar energy is freely available, but the solar collector is always expensive. However, a solar collector can be designed, in certain cases at least, for agricultural drying, so that it is inexpensive enough for the farmer. It is the purpose of this study to design a low-cost mechanical dryer using solar energy as a heat source.

B. OBJECTIVES OF THE RESEARCH

The objectives of this research are then:

1. To develop a mathematical model describing the performance of a low-cost solar air heater;

2. To design, construct and test the solar air heater. The test result is then compared to the simulated one obtained from the mathematical model;

3. To design, construct and test a low-cost fixed-bed paddy dryer using hot air produced from the solar air heater and circulated by a blower. Appropriate drying techniques are also investigated.

C. SIGNIFICANCE OF THE RESEARCH

The results of this research on a low-cost solar grain dryer may lead to some benefits for Thai farmers:

1. The problem of spoiled wet grain during the rainy season can be ameliorated;

2. If the grain is safely dried, it can be stored for a few months or even longer. The farmers can then sell it at a better price compared to selling wet grain. As a result, they should have better incomes;

3. An appropriate drying technique can be drawn from the drying tests.

4. In addition, the solar collector mathematical model developed and the grain drying theory reviewed may be useful to the designer for the construction of similar solar drying systems.

D. SCOPE

The work covers the development of a mathematical model describing the performance of a solar air heater. It also includes the design, construction and a technical evaluation of the solar air heater and the fixed-bed dryer. The experiment will be conducted only in the King Mongkut's Institute of Technology, Thonburi campus.

Chapter 2

Review of the Literature

REVIEW OF THE LITERATURE

Some of the previous work concerning grain drying with forced air (unheated air and heated air produced by any kind of energy source) will be reviewed. In addition, parameters required in the analysis of grain drying will be summarized.

A. PREVIOUS WORK OF GRAIN DRYING

Mechanical drying of paddy is still not widely accepted by Thai farmers. However, the need for dryers is increasingly important due to the increased practice of cultivating the second crop. Research in this area has been conducted in Thailand but not very intensively.

Srihavong (1978) reported relatively valuable test results of paddy drying. The experimental dryer had a capacity of approximately 0.085 m^3 and a bed depth of 0.9 meters. The test was done for several air flow rates and drying air temperatures. It was concluded that the drying air temperature should not exceed 48.9°C, otherwise milling quality will be low, i.e., the amount of broken grain increases significantly when drying air temperature is above 48.9°C. Drying paddy from a moisture content of 22-24% wet basis to 14% wet basis may be finished in 4-6 hours if the flow rate is from 20 to 26.7 m^3/min-m^3 of grain. The bed depth should be less than 0.6 m in order to avoid high moisture gradient in the bin after drying. (Remark: There was no conclusion drawn in the paper regarding the effect of drying air temperature on grain germination. It is generally accepted that the drying air temperature should not exceed 43°C).

A farm grain dryer was developed by the Ministry of Agriculture (1977). Grain was dried by hot air at temperatures between 43-48°C. Heat was supplied by fuel oil or by the burning of rice husk. With capacity of 2 tons of paddy and an air flow rate of 30 m^3/min-m^3 of paddy the drying rate was about 2% per hour.

Thongprasert et al. (1983) conducted research on solar paddy drying. The solar collector had a plywood casing 10 mm thick, a corrugated galvanize iron sheet was used as an absorber. There was styrofoam 25 mm thick under the absorber. The transparent cover was made of clear glass. Air flowed in the gap between the transparent cover and the absorber in a perpendicular direction to the corrugation. The dimension of the collector was 1.55 m x 1.12 m x 0.21 m, and it was installed at the inclined angle of 15° facing towards the South. The experimental dryer was also constructed from plywood 10 mm thick. Its dimension

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was 1.0 m x 1.0 m x 0.61 m. There was a perforated iron sheet inside the dryer and approximately 50 kg of paddy was laid on it. Ambient air was forced through the solar collector by a blower and was then heated up to 31-40.9°C. The hot air entered at the bottom of the dryer and left at the top of the dryer after heat and mass transfer processes had taken place in the bed of paddy. The paddy was dried from the moisture content of 17.4-18.7% wet basis to 14% wet basis in 2.75-4.25 hours. An air flow rate of about 55 $m^3/min/m^3$ of grain was measured. The thermal efficiency of the collector was 79%.

A one-ton solar crop dryer was designed and tested under Los Banos, Languna (14°N, 121°E) conditions by Mendoza and Recorba (1978). The system consisted of a 13.4 m^2 polyethylene-covered flat plate collector for directly heating 35.4 m^3/min of air, a batch type drying bin, a dryeration chamber and air delivery accessories. Tests indicated heating effeciency of 4 to 49 percent, and a maximum heating capacity of 49°C. Drying times of 8 to 10 hours were obtained for different commodities. The good point of this solar collector is that the collector is constructed on the roof by using a corrugated galvanized iron sheet as an absorber and then adding materials such as a transparent cover and 13 mm thick plywood as insulation. The weak point of this collector might be the use of plastic which may be torn in a few months if it is not a special plastic designed to resist ultraviolet radiation. This kind of plastic is not available in our local market. In addition, normal plastic is still relatively expensive.

Experiments on corn drying have been done extensively in the U.S.A. Foster and Peart (1976) summarized the results of several experiments in the U.S.A. (most of which were situated in the Corn-Belt, 40°N. Lat), showing that corn harvested at an initial moisture content below 24% wet basis had always been safely dried in bin (drying and storage taking place in the same bin) supplemented by solar energy. It should be noted that this drying technique takes time, usually from 2 weeks to a few months. For a temperate climate, the development of mold on wet grain is so slow that drying time may be prolonged. In Thailand, the weather is always hot and humid and mold development is relatively fast. Thus, grain in Thailand should be dried in a few days, preferably less than one week.

B. PARAMETERS REQUIRED IN THE ANALYSIS OF GRAIN DRYING

There are many parameters which are required in the analysis of grain drying. However, a simple analysis does not require all of the parameters. It is the purpose of this section to summarize some of the parameters which is necessary for the analysis of grain drying by using simple drying models which will be revised in the next chapter. These parameters are : dry bulb density, latent heat of vaporization of moisture from the grain, equilibrium moisture content of grain and thin layer drying equation. The latter will be discussed in the next chapter.

Steffe and Singh (1980) summarized relatively completed parameters of paddy from several reports.

For bulk density (loose fill and clean),

$$\rho_{pw} = A + B\ (M_w) \qquad (2.1)$$

in which

ρ_{pw} = bulb density of paddy, kg/m^3

M_w = moisture content in percent wet basis

A and B are constants and depend on grain type.

For medium grain,

A = 499.7 ; B = 8.33

For long grain,

A = 519.4 ; B = 5.28

For latent heat of vaporization of moisture in paddy,

$$h'_{fg} = (1740.34 - 2.72\ T)\ M^{-0.308} \qquad (2.2)$$

in which

h'_{fg} = latent heat of vaporization of moisture in paddy, kJ /kg

T = temperature, °C

M = moisture content, decimal dry basis

For equilibrium moisture content of paddy,

$$M_{eq} = 0.325535 - 0.046015\ \ln[-1.987\ (T + 35.703)\ln(RH)] \qquad (2.3)$$

in which M_{eq} = equilibrium moisture content, decimal dry basis

RH = relative humidity, decimal

Dry bulb density of corn and sorghum is not found in the literature. However, dry bulb density at relatively low moisture content of corn and sorghum are known (Brooker, Bakker-Arkema and Hall, 1974).

$$\rho_{pw(corn)} = 752\ kg/m^3$$

at moisture content of 7.3 percent wet basis

$$\rho_{pw(sorghum)} = 752 \text{ kg/m}^3$$

at moisture content of 6.8 percent wet basis.

Latent heat of vaporization of moisture in corn and sorghum can be determined by the following equations.

$$h'_{fg(corn)} = h_{fg} [1 + 4.35 \exp (-28.25 M)] \quad (2.4)$$

and

$$h'_{fg(sorghum)} = h_{fg} [1 + 12.1 \exp (-40.8 M/(1 + M)] \quad (2.5)$$

in which h_{fg} = latent heat of vaporization of free water, kJ/kg

Pfost et al., 1976 reported the equilibrium moisture content equation for corn and sorghum as follows:

$$1 - RH = \exp [-c (T + K) (100 M_{eq})^n] \quad (2.6)$$

for corn; $c = 8.654 \times 10^{-5}$, $n = 1.6834$, $k = 49.81$

for sorghum; $c = 8.532 \times 10^{-6}$, $n = 2.4757$, $k = 113.725$

Chapter 3

Theoretical Considerations

THEORETICAL CONSIDERATIONS

In this chapter the mathematical model describing the thermal performance of a solar collector is developed. Simple existing grain drying models are revised.

A. DEVELOPMENT OF A SOLAR AIR HEATER MATHEMATICAL MODEL

The analysis of a flat plate solar air collector without transparent cover will be presented. Fig. 3.1 shows the detail of a solar collector at any location and its thermal network. At a steady condition, three equations based on energy balance can be formulated.

$$S = h_1 (T_p - T_f) + U_t(T_p - T_a) + h_r(T_p - T_i) \quad (3.1)$$

$$q_u = h_1 (T_p - T_f) - h_2(T_f - T_i) \quad (3.2)$$

$$h_2(T_f - T_i) = U_b(T_i - T_a) + h_r(T_i - T_p) \quad (3.3)$$

in which S = absorbed solar radiation at the absorbing plate, W/m^2

q_u = useful energy, W/m^2

U_t = top lost coefficient, W/m^2 K

U_b = bottom lost coefficient, W/m^2 K

h = convective heat transfer coefficient, W/m^2 K

h_r = radiation heat transfer coefficient, W/m^2 K

T = temperature, in degrees Kelvin

From Eq. 3.3,

$$T_p = \frac{U_b(T_i - T_a) - h_2(T_f - T_i) + h_r T_i}{h_r} \quad (3.4)$$

From Eq. 3.1,

$$T_p = \frac{S + h_1 T_f + U_t T_a + h_r T_i}{(h_1 + U_t + h_r)} \quad (3.5)$$

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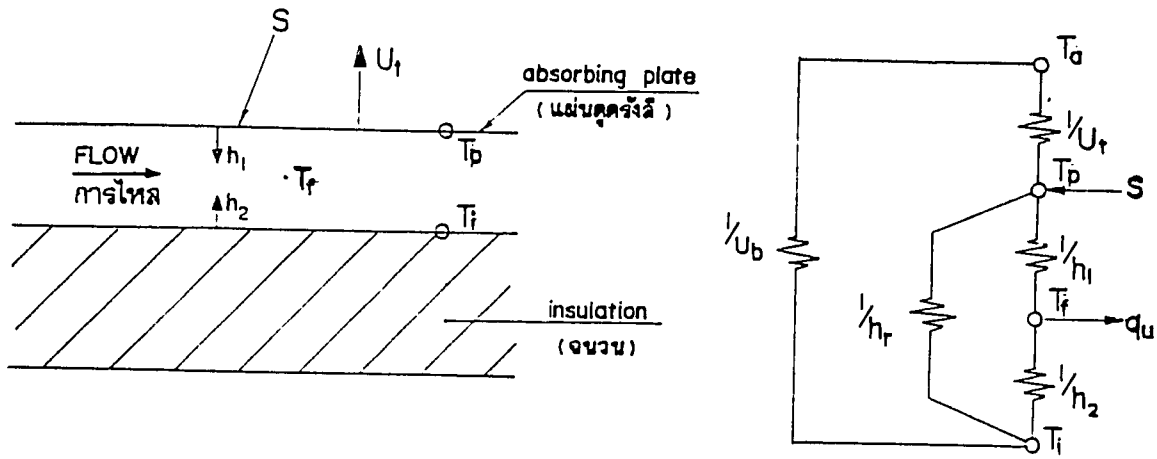

Figure 3.1 Solar air collector and thermal network
(รูปที่ 3.1 ตัวรับรังสีดวงอาทิตย์แบบมีอากาศเป็นตัวถ่ายเทความร้อนและวงจรความร้อน)

From Eqs. 3.4 and 3.5, T_p can be eliminated.

$$T_i = \frac{(S + h_1T_f + U_tT_a)h_r + (U_bT_a + h_2T_f)\ (h_1 + U_t + h_r)}{(h_1 + U_t + h_r)\ (h_r + h_2 + U_b) - h_r^2} \tag{3.6}$$

Subtracting both left and right sides of Eq. 3.6 by T_f and rearranging, then

$$T_i - T_f = \frac{h_rS - (T_f - T_a)(U_bU_t + U_bh_1 + U_bh_r + U_th_r)}{(h_1 + h_r + U_t)(h_r + h_2 + U_b) - h_r^2} \tag{3.7}$$

Subtracting both left and right sides of Eq. 3.5 by T_f and rearranging, then

$$T_p - T_f = \frac{(h_2 + h_r + U_b)S - (T_f - T_a)(U_bU_t + U_bh_r + U_th_2 + U_th_r)}{(h_1 + h_r + U_t)\ (h_r + h_2 + U_b) - h_r^2} \tag{3.8}$$

Substituting $T_i - T_f$ and $T_p - T_f$ from Eqs. 3.7 and 3.8 into equation 3.2, and then rearranging.

$$q_u = F'\ [\ S - U_L\ (T_f - T_a)\ ] \tag{3.9}$$

in which

$$F' = \frac{h_1h_2 + h_1h_r + h_1U_b + h_2h_r}{(h_1 + h_r + U_t)(h_r + h_2 + U_b) - h_r^2} \tag{3.10}$$

$$U_L = \frac{(U_b + U_t)(h_1h_2 + h_1h_r + h_2h_r) + U_bU_t(h_1 + h_2)}{h_1h_2 + h_1h_r + h_1U_b + h_2h_r} \tag{3.11}$$

If $h_1 = h_2 = h$, then Eqs. 3.10 and 3.11 become

$$F' = \frac{h^2 + 2hh_r + hU_b}{(h + h_r + U_t)(h + h_r + U_b) - h_r^2} \tag{3.12}$$

$$U_L = \frac{(U_b + U_t)(h^2 + 2hh_r) + 2U_bU_th}{h^2 + 2h\ h_r + h\ U_b} \tag{3.13}$$

It will be more convenient if the relationship between q_u and $T_{f,i}$ is employed instead of q_u and T_f. $T_{f,i}$ is the fluid temperature at the inlet of the solar collector. The equation can be written as follows:

$$q_u = F_R [S - U_L (T_{f,i} - T_a)] \tag{3.14}$$

Duffie and Beckman (1980) determined F_R by assuming that F' and U_L are independent of the position of a collector, then

$$F_R = \frac{\dot{m} C_p}{A_c U_L} (1 - e^{(A_c U_L F'/\dot{m} C_p)} = F' F'' \tag{3.15}$$

The thermal efficiency of the collector can be determined by dividing the useful energy by the amount of solar radiation incident on the plane of the collector.

$$\eta = \frac{q_u}{G_T} = F_R \alpha - F_R U_L (T_{f,i} - T_a)/G_T \tag{3.16}$$

where $S = G_T \alpha$ (3.17)

and α = absorptivity of the absorbing plate

G_T = solar radiation incident on the plane of the collector, W/m^2

To obtain the value of F' and U_L, it is necessary to know how to determine the values of U_t, U_b, h, and h_r.

$$U_t = h_w + h_{r,p-a} \tag{3.18}$$

h_w is the convective heat transfer coefficient by the wind and depends on the wind velocity. McAdams (1954) as quoted in Duffie and Beckman (1980) gives the relationship between $h_w (W/m^2K)$ and wind velocity (m/s) as follows:

$$h_w = 5.7 + 3.8 V \tag{3.19}$$

$h_{r,p-a}$ is the radiation heat transfer coefficient and can be determined by the following equation:

$$h_{r,p-a} = \frac{\varepsilon_p \sigma (T_p + T_s)(T_p^2 + T_s^2)(T_p - T_s)}{(T_p - T_a)} \tag{3.20}$$

in which ε_p = emittance of the absorbing plate

σ = Stefan - Boltzmann constant = 5.669×10^{-8} $W/m^2 K^4$

T_p = absorbing plate temperature, °K

T_a = ambient temperature, °K

T_s = sky temperature, °K

Swinbank (1963) as quoted in Duffie and Beckman (1980) relates sky temperature to the local air temperature in the simple relationship.

$$T_s = 0.0552\ T_a^{1.5} \tag{3.21}$$

in which T_s and T_a are both in degrees Kelvin.

Bliss (1961) as quoted in Duffie and Beckman (1980) relates the effective sky temperature to ambient temperature and dew point temperature. The result is as following.

$$T_s = T_a \left[0.8 + \frac{T_{dp} - 273}{250} \right]^{1/4} \tag{3.22}$$

It is assumed herein that heat loss by convection and radiation at the back of the collector is so small that U_b is due to conduction only.

$$U_b = \frac{k_i}{l_i} \tag{3.23}$$

In which k_i and l_i are the thermal conductivity and the thickness of insulation, respectively.

The forced convection heat transfer coefficient between two flat plates for the air can be obtained by the correlation derived from Kays' (1966) data (as quoted in Duffie and Beckman, 1980) for fully developed turbulent flow with one side heated and the other side insulated.

$$Nu = 0.0158\ Re^{0.8} \tag{3.24}$$

In which the characteristic length is the hydraulic diameter (twice the plate spacing). For flow situations in which L/D_h is 10, Kays indicates that the average Nusselt number is approximately 16% higher than that given by Eq. 3.24. At L/D_h equal to 30, Eq. 3.24 still underpredicts by 5%. At L/D_h equal to 100, the effect of the entrance region has largely disappeared. (Remarks: $Re = \frac{V\ D_h}{\nu}$ and $Nu = \frac{h\ D_h}{k}$).

The radiation heat transfer coefficient, h_r, between two infinite paralleled plates can be determined by the following equation:

$$h_r = \frac{\sigma\ (T_2^2 + T_1^2)\ (T_2 + T_1)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \tag{3.25}$$

When T_1 and T_2 are close together, then,

$$4\bar{T}^3 = (T_1^2 + T_2^2)\ (T_1 + T_2) \tag{3.26}$$

From the above equations it is possible to predict the performance of the solar air heater described but the process is a little bit tedious. First of all, the mean temperatures of the absorbing plate and of the fluid are assumed in order to be able to calculate U_L, F', and F_R. Then the mean plate temperature and mean fluid temperature are determined by the following equations.

$$T_{p,m} = T_{f,i} + \frac{Q_u/A_c}{U_L F_R}\ (1 - F_R) \tag{3.27}$$

and

$$T_{f,m} = T_{f,i} + \frac{Q_u/A_c}{U_L F_R}\ (1 - F'') \tag{3.28}$$

If the temperatures calculated by Eqs. 3.27 and 3.28 are not much different from the ones assumed, the process is terminated. Otherwise, the process has to be repeated.

B. THEORY OF GRAIN DRYING

The theory of grain drying has been studied extensively. Several drying models have been developed. The difficulty of use varies from one model to another. Some particular models require a computer for aiding in calculation, but other models can be solved by using a pocket calculator or a microcomputer. In this section we will review only some grain drying models which are simple.

The drying of grain may be divided into thin layer (or single kernel) drying and deep bed drying. When a kernel of grain having a sufficiently high moisture content is dried by a stream of air under constant conditions, the drying rate will be constant at the beginning of drying and then it will decrease. The latter is called the falling drying rate period and it depends on grain moisture content, air temperature, relative humidity and air velocity. Grain moisture content from normal harvesting is always low

enough to be dried during the falling drying rate period. However, in thick bed drying the drying rate is always constant, except at the end of drying. Due to the different drying characteristics of the two situations the analysis should be done separately, starting with thin layer drying and then thick bed drying. In fact, thick bed is composed of several thin layers where one is laid on another. Grain drying is usually done using the thick bed method. (Remark: readers who do not have sufficient background in the theory of grain drying should refer to Brooker, Bakker-Arkema and Hall, 1974).

Thin Layer Drying

Several theoretical and empirical thin layer drying equations have been developed. The author will discuss only one model. This is not the best available model but it is a part of the deep bed models which will be reviewed later.

It is assumed that drying rate is proportional to the difference between the moisture content at any given time and the equilibrium moisture content.

$$\frac{d\,\overline{M}}{dt} = -k\,(\overline{M} - M_{eq}) \tag{4.1}$$

The initial condition is,

$$\overline{M}\,(t = 0) = \overline{M}_i \tag{4.2}$$

in which $\overline{M}$ = moisture content, decimal dry basis

M_{eq} = equilibrium moisture content, decimal dry basis

$\overline{M}_i$ = initial moisture content, decimal dry basis

t = time, h

and k is called the drying constant and has the unit of h^{-1}.

The solution of Eq. 4.1 is,

$$MR = \exp\,(-kt) \tag{4.3}$$

in which

$$MR = \frac{\overline{M} - M_{eq}}{\overline{M}_i - M_{eq}} \tag{4.4}$$

The values of k are determined experimentally.

Sabbah et al. (1977) gives the value of k for corn as a function of saturated vapor pressure and air velocity.

$$k = a\, P_{vs}^{b}\, (V/V_{ref})^{n} \qquad (4.5)$$

in which P_{vs} = saturated vapor pressure, Pa

V = apparent air velocity, mh^{-1}

V_{ref} = reference air velocity = 3.092×10^{3} m h^{-1}

a = 4.925×10^{-4}

b = 0.722

n = 0.8

For temperatures from 2-21 °C

Theoretically, k does not depend on air velocity because the rate of moisture evaporation from the surface of the grain is limited by the internal resistance of the grain kernel, i.e., mainly on moisture diffusion. However, it was found experimentally by Troger and Hukill (1971) that drying rate also depends on air velocity.

Soponronnarit and Peyre (1982) give the value of k for sorghum in a similar way.

$$k = a\, P_{vs}^{b}\, (V/V_{ref})^{n}$$

in which V_{ref} = 7.308×10^{2} mh^{-1}

a = 2.018×10^{-3}

b = 0.493

n = 0.8

The equation is valid for drying at low temperatures.

The drying constant of paddy has not yet been presented, but it will be discussed in the next section.

Deep Bed Drying

Deep bed drying can be divided into 2 types: 1) fixed bed drying, and 2) moving bed drying. Deep bed drying models being reviewed herein will be limited to those of fixed bed. The earliest model developed comes from Hukill (1947). He considered a thin layer of grain at any level in a deep bed to be his control volume. He then made an energy balance on

that control volume by supposing that variation in the sensible heat of air flowing in and out of the control volume is equal to the heat required to evaporate water out of the control volume. The equation can be written as follows:

$$\frac{\partial \overline{M}}{\partial t} = \frac{G_a C_a}{\rho_p h'_{fg}} \frac{\partial T}{\partial x} \tag{5.1}$$

in which G_a = mass flow rate per unit area, kg/h-m^2

C_a = specific heat of air, kJ/kg - °C

T = air temperature, °C

ρ_p = dry bulb density, kg/m^3

h'_{fg} = latent heat of vaporization of moisture in grain, kJ/kg

x = bed ordinate, m

The initial and boundary conditions are:

$$t = 0,\ \overline{M} = \overline{M}_i \text{ and } T = (T_i - T_o)e^{-Cx} + T_o$$

$$t = \infty,\ \overline{M} = M_{eq}$$

$$x = 0,\ T = T_i \text{ and } \overline{M} = (\overline{M}_i - M_{eq})e^{-kt} + M_{eq}$$

$$x = \infty,\ T = T_o \tag{5.2}$$

in which T_i = air temperature at the inlet of the dryer, °C

T_o = air temperature at the exit of the dryer, °C, and is determined by assuming: 1) enthalpy of the drying air is unchanged and 2) drying air and grain are in equilibrium at the outermost layer of grain (at the exit or in other words, at the grain layer having initial moisture content). Therefore, T_o can be determined by finding the interception point between the line of constant enthalpy of air and the one of isoequilibrium moisture content plotted on the Psychrometric chart.

By inspection of Hukill's model, the solution can be written as follows:

$$MR = \frac{e^{Cx}}{e^{Cx} + e^{kt} - 1} \tag{5.3}$$

and $$\frac{T - T_o}{T_i - T_o} = \frac{e^{kt}}{e^{Cx} + e^{kt} - 1} \tag{5.4}$$

in which C is written as follows:

$$C = \frac{k\,\rho_p\,h'_{fg}(\overline{M}_i - M_{eq})}{G_a\,C_a(T_i - T_o)} \tag{5.5}$$

Eq. 5.3 can be written in another form:

$$MR = \frac{2^D}{2^D + 2^Y - 1} \tag{5.6}$$

in which D and Y are the dimensionless terms of distance and time, respectively.

$$D = \frac{\rho_p\,h'_{fg}\,(\overline{M}_i - M_{eq})\,x}{H\,G_a\,C_a\,(T_i - T_o)} \tag{5.7}$$

and $$Y = \frac{t}{H} \tag{5.8}$$

in which H is the time required to reduce the moisture content ratio of a thin layer of grain to a half. By the definition of H, we can write,

$$MR = 0.5 = e^{-kH}$$

$$k = \ln 2/H$$

H of paddy may be found by the following thin layer drying equation of paddy. (Wang and Singh, 1978)

$$MR = a \exp(-60\,bt) \tag{5.9}$$

in which $a = 0.96 - 0.00008826\,T + 0.02324\,RH$

$b = 0.002814 + 0.0001267\,T - 0.00362\,RH$

By the definition of H, MR = 0.5, then,

$$0.5 = a \exp(-60\,b\,H)$$

or $$H = \frac{\ln(2\,a)}{60\,b} \tag{5.10}$$

Hukill's model can predict the moisture content of grain at any depth and at any time. But, it is only valid to the drying of grain with uniform initial moisture content and with constant inlet conditions.

The solution of Hukill's model can be integrated to obtain the average moisture content ratio, $\overline{MR}$, which is the average value for the whole grain in the dryer. This model may be called the model of Barre et al. (1971).

$$\overline{MR} = \frac{1}{D'} \ln \frac{(e^{D'} + e^{Y'} - 1)}{e^{Y'}} \tag{5.11}$$

in which $$D' = \frac{k\, \rho_p\, h'_{fg}\, (\overline{M}_i - M_{eq})}{G_a\, C_a\, (T_i - T_o)} . X \tag{5.12}$$

$$Y' = kt \tag{5.13}$$

X = the thickness of grain bed, m

If $e^{(D' - Y')} >> (1 - e^{-Y'})$ Eq. 5.11 can be reduced to,

$$\overline{MR} = 1 - Y'/D' \tag{5.14}$$

or $$h'_{fg}(\overline{M}_i - \overline{M})\ \rho_p\ X = G_a\ C_a\ (T_i - T_o)\ t \tag{5.15}$$

Which can be found by making an energy balance employing the same assumption as used in deriving Hukill's model, but it is done for all the grain in the dryer instead of a thin layer. This equation is valid for general drying practices, but not very accurate and drying time is always underestimated.

Chapter 4

Experimental Investigation

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EXPERIMENTAL INVESTIGATION

In this chapter the simulation results of the solar air heater are presented. The experiments on solar air heaters and solar dryers are then designed.

A. SIMULATION RESULTS OF SOLAR AIR HEATER

The performance of solar air heaters can be determined by simulation using the mathematical model developed in chapter 3, i.e.,

$$\eta = F_R\alpha - F_R U_L (T_{f,i} - T_a)/G_T \qquad (3.16)$$

The procedure of calculation has already been described. If it is assumed that $F_R\alpha$ and $F_R U_L$ are constant, Eq. 3.16 can be expressed graphically as a straight line. In fact, U_L is a function of temperature and wind velocity and F_R is a weak function of U_L. The performance of two solar air heaters is simulated. Neither solar air heater has a transparent cover and their structures are identical to the model described in Fig. 3.1. The absorber is made of corrugated galvanized iron sheet (usually being used as a roof). The only difference is that the absorber of one solar air heater is painted dull black and the other is left unpainted.

Air flows in the gap between the absorber and the insulation parallel to the corrugation. For simplicity in calculation, it is assumed that the absorber is a flat plate. The average spacing between the absorber and the insulation is used to calculate a convective heat transfer coefficient. The first simulation is done by using the optical properties, i.e., absorptivity and emissivity of a galvanized iron sheet and of a dull black paint (quoted in Duffie and Beckman, 1980). The simulated results show that the performances of both solar collectors are nearly the same. The unpainted one is preferred because of its lower cost. A dull black paint has an absorptivity value higher than that of a galvanized iron sheet but the emissivity is also higher. These properties give the two collectors nearly identical performance curves. Details are shown in Fig. 4.1.

The values of the absorptivity and emissivity of both absorbers are also measured by a spectrophotometer. It is found that the emissivity of the galvanized iron sheet is about 0.64 instead of 0.2 as quoted in Duffie and Beckman (1980). So the collector performance is resimulated using the measured optical properties. The result is shown in Fig. 4.2. The dull black painted solar collector has a higher efficiency than that of the unpainted one but the difference is not very significant.

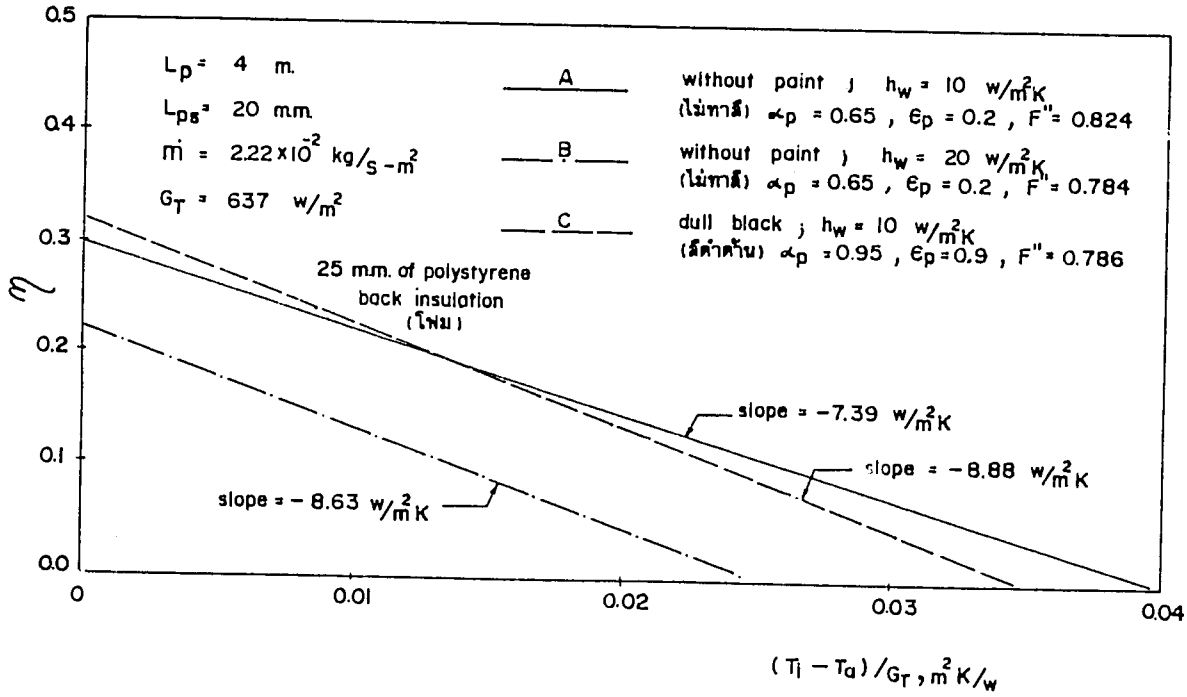


Figure 4.1 Simulated thermal efficiency curves for solar air collectors without transparent covers

(กร๊าฟแสดงประสิทธิภาพเชิงความร้อนจากการจำลองสภาพของตัวรับรังสีทำอากาศร้อนแบบไม่มีแผ่นใส่ปิด)

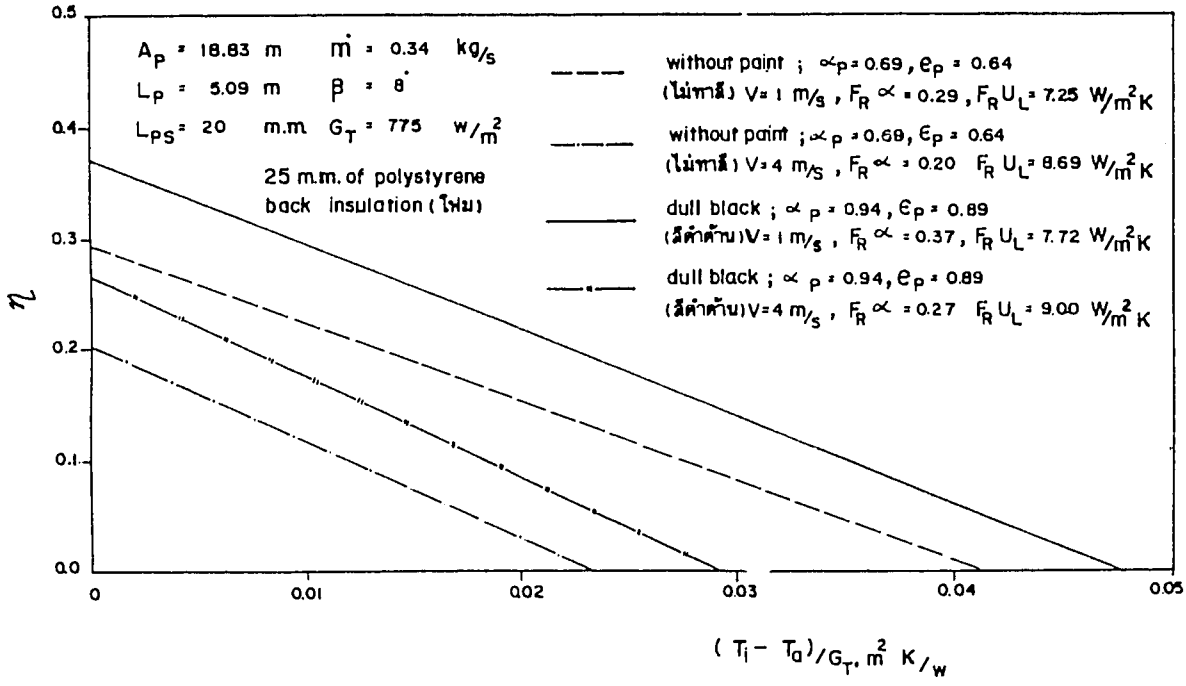


Figure 4.2 Simulated thermal efficiency curves for solar air collectors without transparent covers.

(กร๊าฟแสดงประสิทธิภาพเชิงความร้อนจากการจำลองสภาพของตัวรับรังสีทำอากาศร้อนแบบไม่มีแผ่นใสปิด)

An important parameter which greatly affects the efficiency of both collectors is wind speed. As shown in Fig. 4.2, efficiency decreases rapidly as the wind speed increases from 1 to 4 m/s. However, in the Central Region of Thailand, wind speed at a height of 10 meters is normally less than 4 m/s. This low wind velocity has a positive effect on this type of solar collector. Another advantage comes from the humidity. The sky temperature depends strongly on ambient temperature and partly on dew point temperature as expressed in Eq. 3.22. Dew point temperatur. is a function of ambient temperature and relative humidity. In case of high relative humidity, i.e., high dew point temperature, long wave radiation from the sky may be significant and can be absorbed directly by the absorber as there is no transparent cover as would normally be found in high efficiency collectors.

B. EVALUATION METHOD OF DRYING CAPACITY AND SOLAR COLLECTOR AREA

The majority of farms in the Central region vary from 20-30 rais, and the average yield is about 300 kg of paddy per rai. This means the production of paddy is about 6-9 tons per season per family and harvesting of this paddy will be completed from a minimum of 2 to more than 14 days. If it is assumed that harvesting is done in 14 days, the harvesting rate will be 0.43-0.64 tons per day.

To evaluate the solar collector area required for drying, the thermal efficiency of the solar collector at a given specific air flow rate must be known. In addition, meteorological data such as global solar radiation and the ambient air condition must be given. The increased air temperature is then calculated from the above information.

The air from the outlet of the solar collector is further heated by a fan. (It is generally assumed that it will be heated 1.1°C by the fan.) The air property at the inlet of the dryer is then determined with the aid of the Psychrometric chart.

The next step is to calculate the air flow rate required to dry the paddy. A simple equation describing the global heat balance is used. It is written as follows:

$$h'_{fg}\, m_w = \dot{m}\, C_p\, (T_i - T_o)t \qquad (6.1)$$

in which m_w = moisture evaporated, kg

or, written in another form, as seen in Eq. 5.15

$$h'_{fg}(\overline{M}_{in} - M_f)\rho_p X = G_a\, C_a\, (T_i - T_o)t \qquad (6.2)$$

Once the air flow rate is calculated from the equation, the solar collector area can be determined.

Example of Calculation

To reduce the moisture content of 0.64 ton paddy from 0.22 wb (0.282 db) to 0.15 wb (0.176 db) 53 kg of moisture is evaporated.

Mean global solar radiation during the rainy season in Bangkok is about 15 MJ/m^2 per day. From the simulation result of the unpainted solar air heater, the efficiency for the air flow rate 0.018 $kg/s/m^2$ is 29% (at $T_i = T_a$). If it is assumed that air is heated by solar energy 8 hours a day, the average increasing air temperature will be 8.4°C. The air from the outlet of the solar collector is further heated by the fan. It is generally assumed that it will be heated by 1.1°C by the fan. Therefore, the increase in air temperature during the day is 9.5°C. It is also assumed that ventilation is done at night. Thus, the average increasing air temperature is 3.9°C (day and night).

The average ambient air temperature and relative humidity during rainy season are 28°C and 0.8, respectively. The air temperature at the inlet of the dryer is thus 31.9°C. If the enthalpy of drying air is assumed constant during the drying process and it is also assumed that the grain is humid enough so that air at the exit of the dryer is saturated. Therefore, the exit air temperature (T_o) is the wet bulb temperature.

$$T_o \simeq T_{wb} = 26°C$$

The air flow rate required is then

$$\dot{m} = \frac{h'_{fg}\, m_w}{C_p\,(T_i - T_o)t}$$

$$= \frac{2600 \times 53}{(1)\,(31.9 - 26)(24 \times 3600)} = 0.27 \text{ kg/s}$$

the solar collector area (A_c) required is then

$$A_c = \frac{0.27}{0.018} = 15 \text{ m}^2$$

C. EXPERIMENTAL SOLAR AIR HEATER

The theory of a solar air collector without transparent cover has already been described in the previous chapter. The detailed design of a low cost solar collector will be discussed in this section. The characteristics of a low cost collector may be summarized as follows:

1. It is composed of a minimum amount of materials.

2. Materials are properly selected so that they are cheap and locally available.

3. The construction must not be too complicated in order to allow farmers to build the collector themselves.

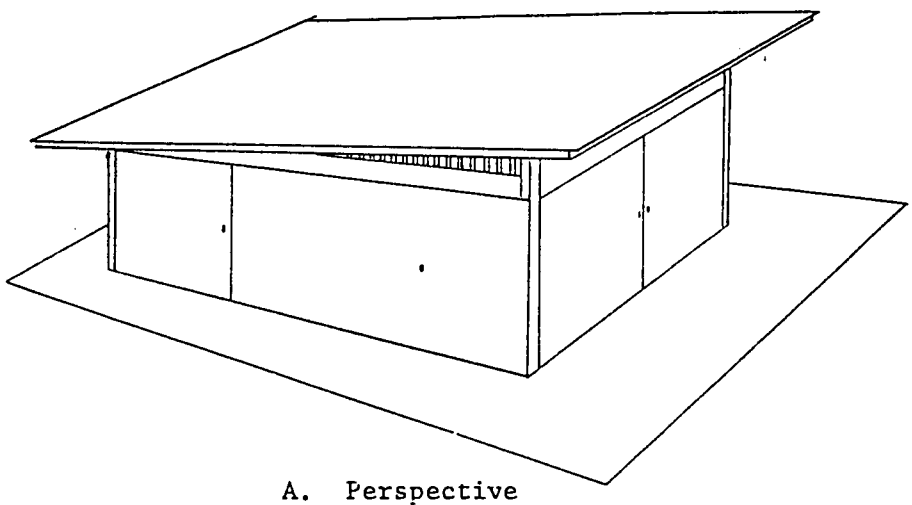
To accommodate the above requirements, a low cost solar collector may be constructed on an existing building and act as the roof as shown in Fig. 4.3. It can be seen that the roof of a barn currently used for the storage of paddy can be modified to act as a solar collector. A batch dryer may be installed inside the barn for drying paddy during harvesting. If storage space is not sufficient, the dryer may be placed outside of the barn.

The 19 m^2 solar collector in Fig. 4.3 does not have a transparent cover even though lower thermal efficiency is obtained in comparison to those which do have transparent covers. However, transparent covers may cause the solar collector to become too complicated for construction by farmers. The absorber, which also acts as a roof, is made of a corrugated galvanized iron sheet. There is approximately a 20 mm gap between the absorber and the 25 mm styrofoam. The styrofoam is held in place either by bamboo plywood 2.5 mm thick or plywood. (Bamboo plywood is used herein because the wood frame can be reduced by half compared to the use of plywood 4 mm thick. Their prices per unit area are nearly the same. However, bamboo plywood is not easily available). Air flows from the highest point of the roof through the gap and is directed downwards by the aid of a blower driven by an electric motor or an internal combustion engine.

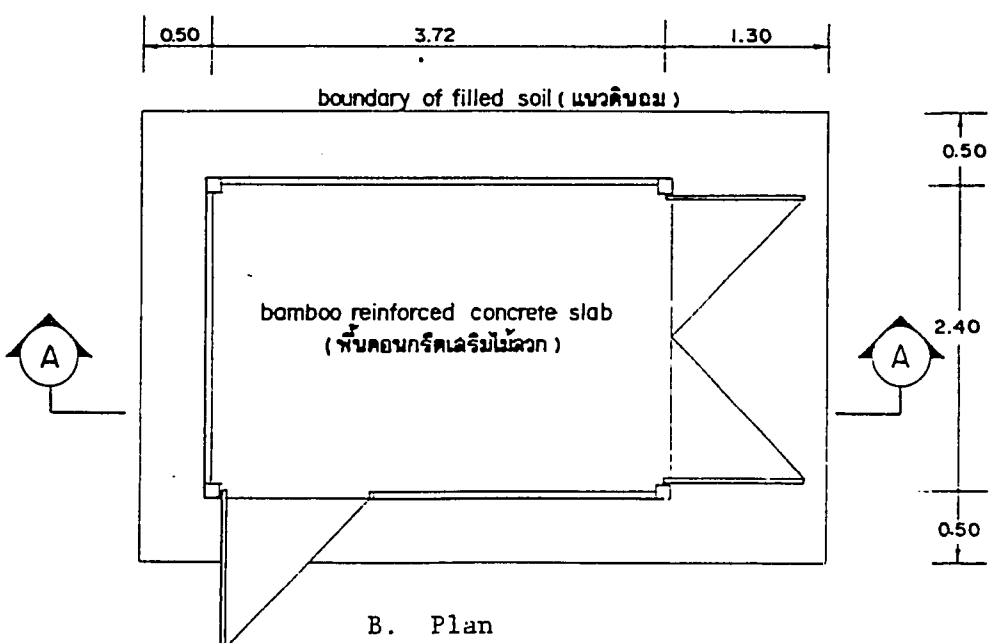
The air flow direction is downward because it is expected that nutural convection of hot air will take place when the blower is not in operation. As a result, air temperature in the gap will not become high enough to damage the styrofoam. At the exit of the solar collector, the direction of air flow is bent 180 degrees. Though the resistance to air flow is significant, the construction is easy and the materials used are minimized.

Most of the roof area is also used for air heating and an air duct can be installed inside the barn. In this case, the insulation of the air duct can be done simply with low cost, i.e, there is no need to have a protective cover for the insulation.

Two branching air ducts 10 mm in diameter are mounted to the two exits in the roof. These two air ducts then join a main air duct 30 mm in diameter. Air is sucked from the collector through its exits into the branching ducts and main duct by a fan and air then delivered to the dryer. A centrifugal fan (forward curved blade type) driven by a 1.5 kw. electric motor is employed for the drying procedure.



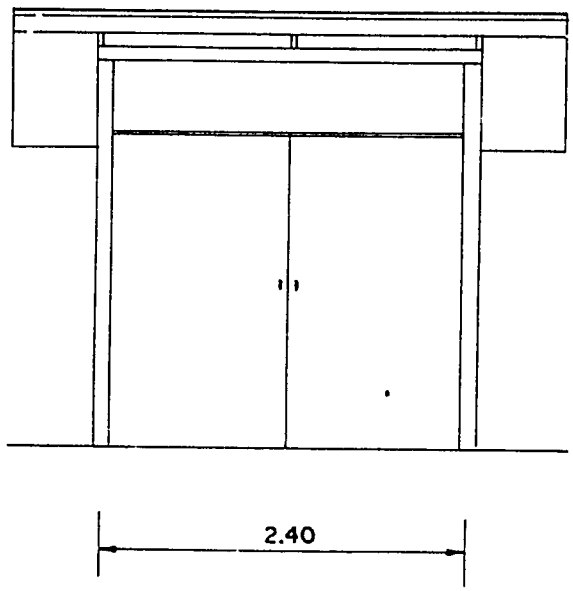
A. Perspective



B. Plan
1:50

Figure 4.3 Low-cost solar collector

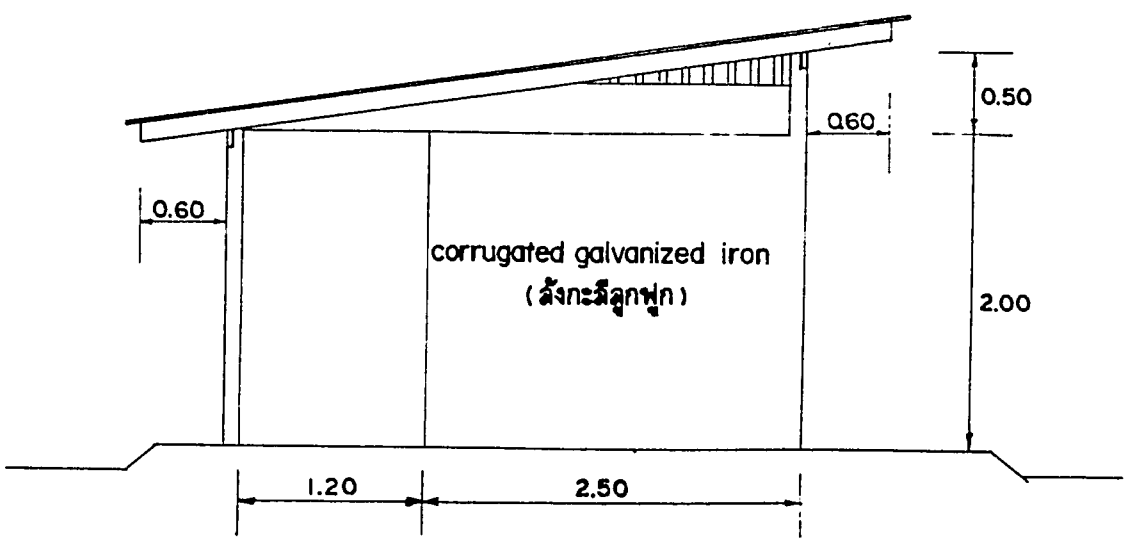
(รูปที่ 4.3 ตัวรับรังสีดวงอาทิตย์แบบประหยัด)



C. FRONT VIEW

C. รูปด้านหน้า

1:50

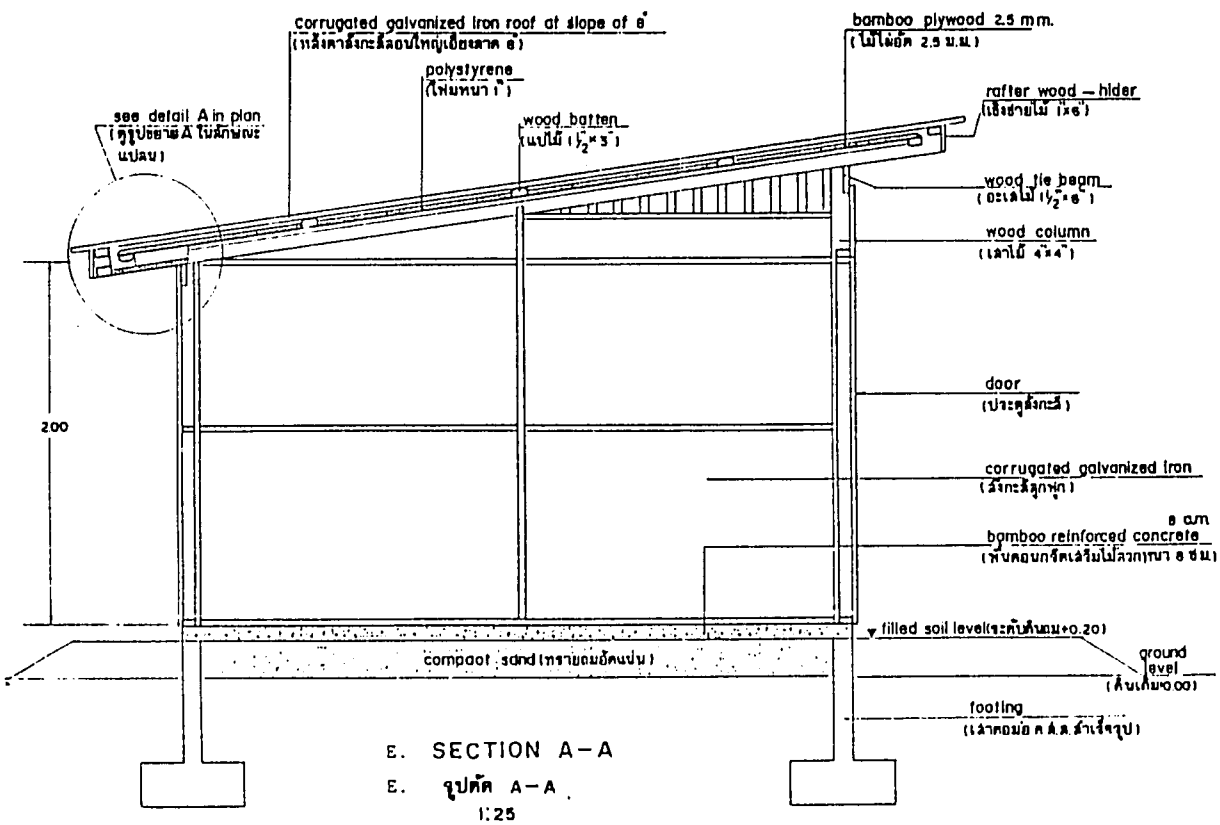


D. SIDE VIEW

D. รูปด้านข้าง

1:50

Figure 4.3 (continued)

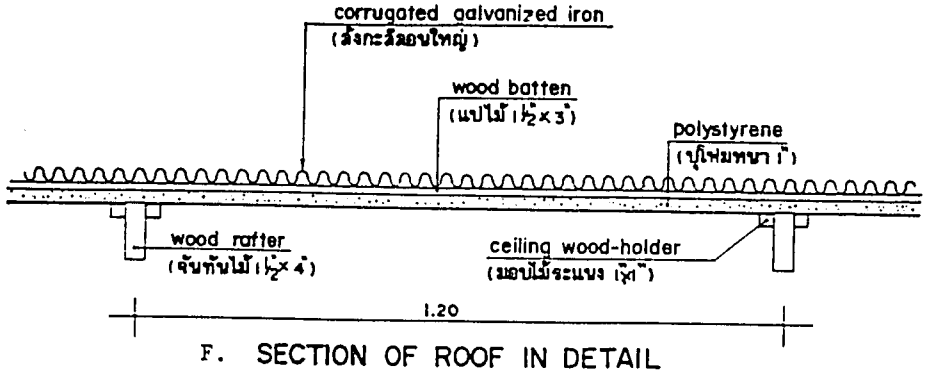


E. SECTION A–A

E. รูปตัด A–A

1:25

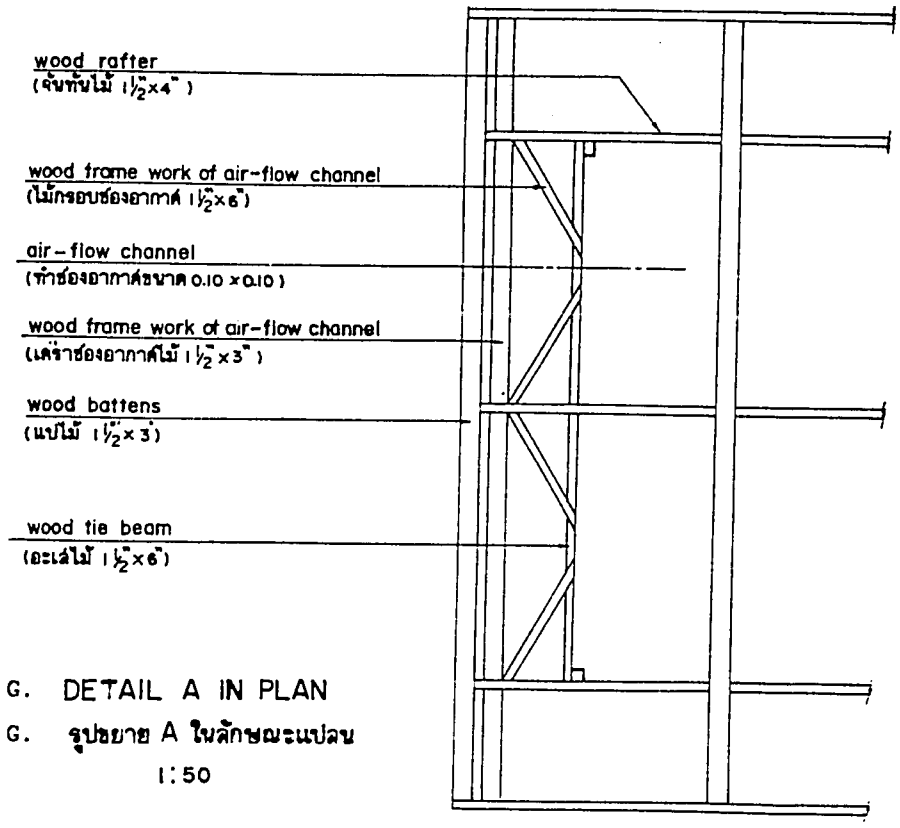
Figure 4.3 (continued)



F. SECTION OF ROOF IN DETAIL

F. รูปขยายภายในหลังคา

1:10

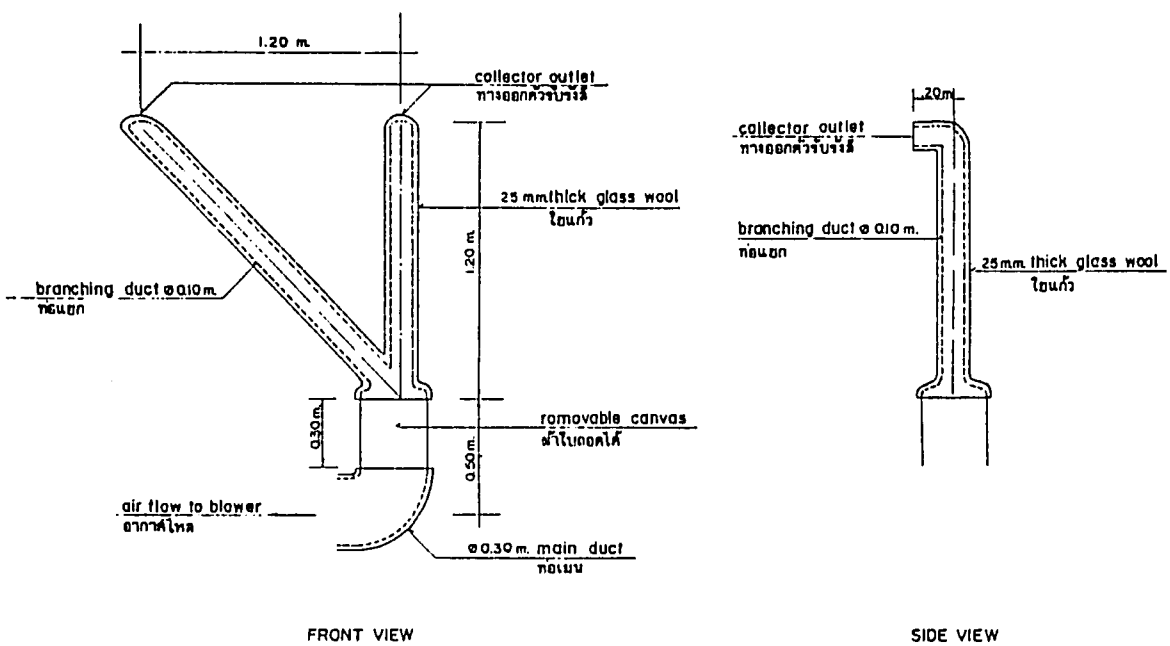


G. DETAIL A IN PLAN

G. รูปขยาย A ในลักษณะแปลน

1:50

Figure 4.3 (continued)



H. Air duct system

ระบบท่อลม

Figure 4.3 (continued)

It was found during the 1st drying test that the resistance to air flow at the exit of the collector and at the branching ducts was significant. Modification of these two parts were done as shown in Figs. 4.4 and 4.5. The cross section area of the solar collector was enlarged from 0.1 m x 0.1 m to 0.15 m x 0.15 m and branching ducts of 150 mm diameter were used. The calculated total pressure drop when the air flow rate is 0.34 kg/s is reduced from 40.4 mm H_2O to 22.8 mm H_2O. Measurement of the air flow rate during drying tests showed that the flow rate significantly increased after modification. The details will be discussed in the next chapter.

D. EXPERIMENTAL BATCH DRYER

Because of the harvesting capacities as figured earlier in this chapter, a batch dryer having a capacity of 0.64 ton of wet paddy ($\approx$ 1 m^3) is recommended. However, the experimental dryer has a capacity of about 1 ton of wet paddy ($\approx$ 1.5 m^3). This volume of paddy may be dried in one day if weather conditions are favorable or may take two days of drying on cloudy days. A vertical bed dryer was selected because it occupies a smaller area of installation than a flat bed dryer. Locally available and cheap materials such as wood, plywood and bamboo matting were used for constructing the dryer. Details of the dryer are shown in Fig. 4.6.

During operation, approximately one ton of paddy is loaded into paddy chambers at the top of the dryer. Hot air from the solar collector is sucked in by a fan and then delivered to the dryer through a duct hole. Air is distributed through the grain beds where heat and mass transfer between grain and air takes place. The air flows out of the dryer through bamboo matting walls and at the top of the grain beds. Drying may be finished in one or two days depending upon initial grain moisture content and weather conditions. Dried grain is then loaded into sacks via a bagging chute mounted at the sliding gates.

E. TEST PROCEDURE

Solar Collector Performance Test

Test procedures of the solar air collector follows the standard of ASHRAE 93-77 (1977). However, there are some differences between the test procedures and that of ASHRAE. This is due to the limited amount and accuracy of measurement instruments. For example, solar radiation on a horizontal surface is measured instead of radiation on an inclined surface. The accuracy of temperature measurements is lower than the one suggested by ASHRAE.

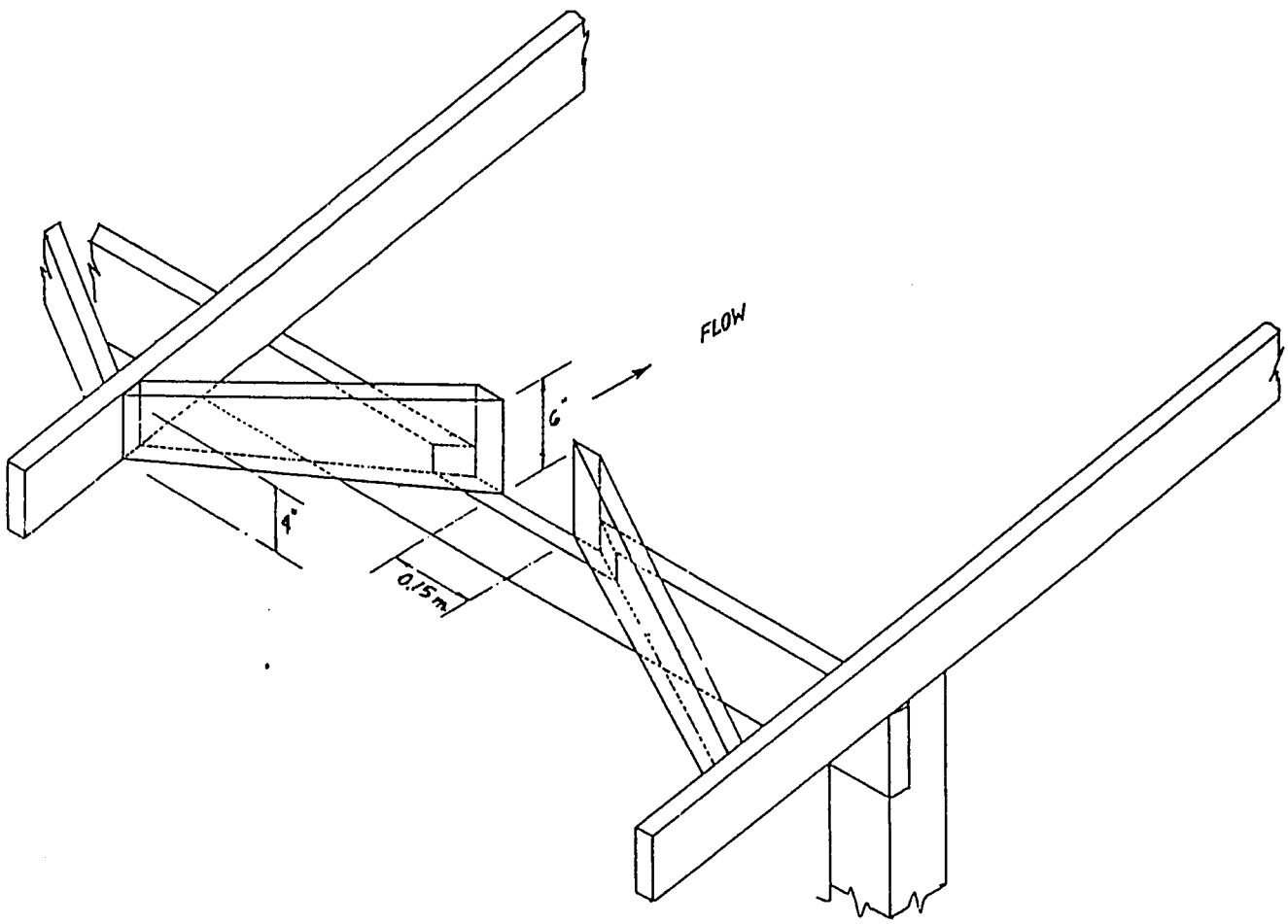


Figure 4.4 MODIFIED AIR EXIT

รูป 4.4 ทางออกของอากาศเมื่อได้รับการดัดแปลง

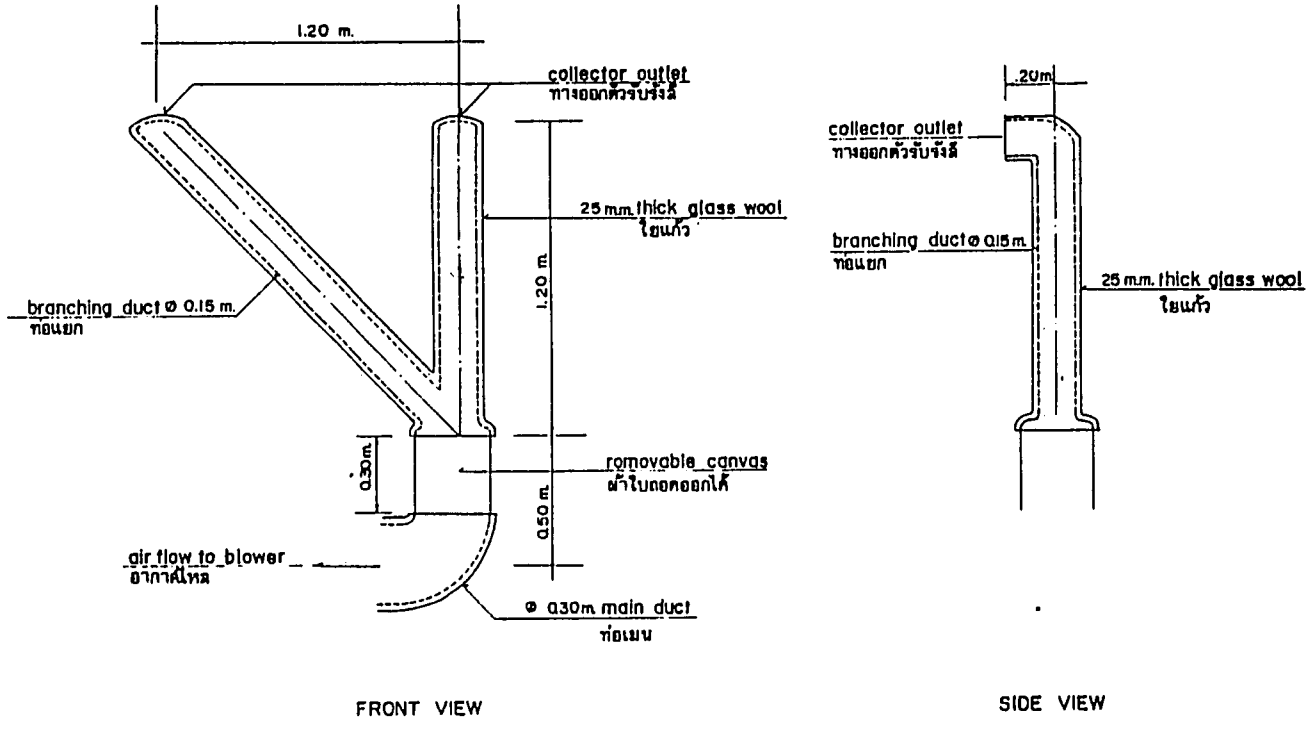
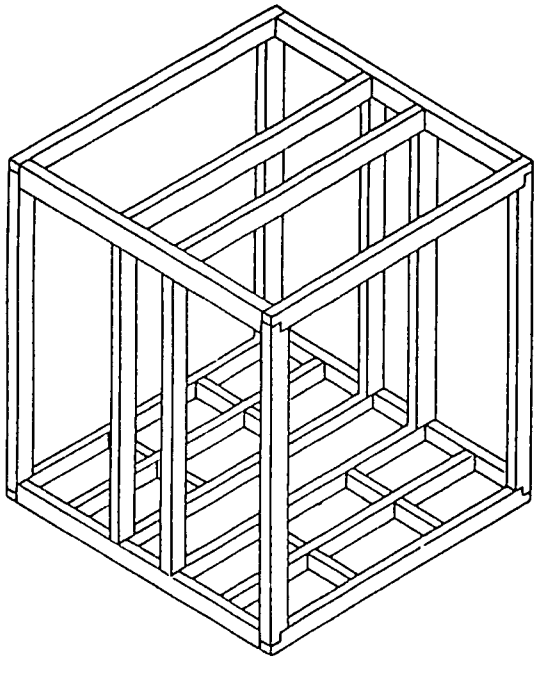
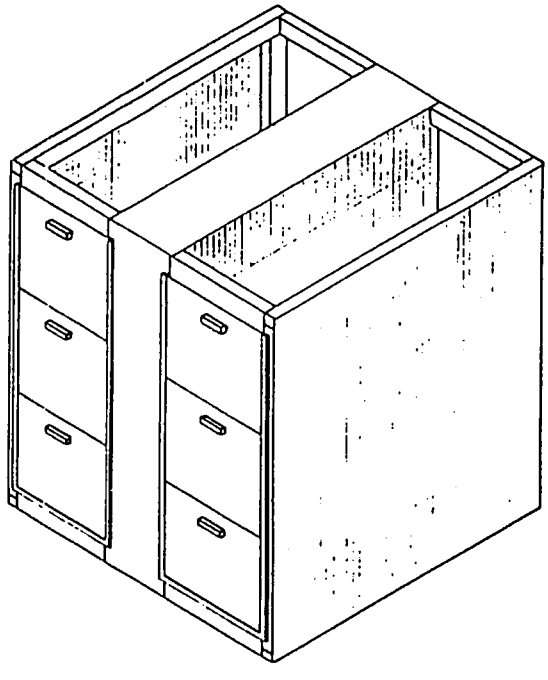


Figure 4.5 Modified air duct system
รูปที่ 4.5 ท่อลมเมื่อดัดแปลงแล้ว

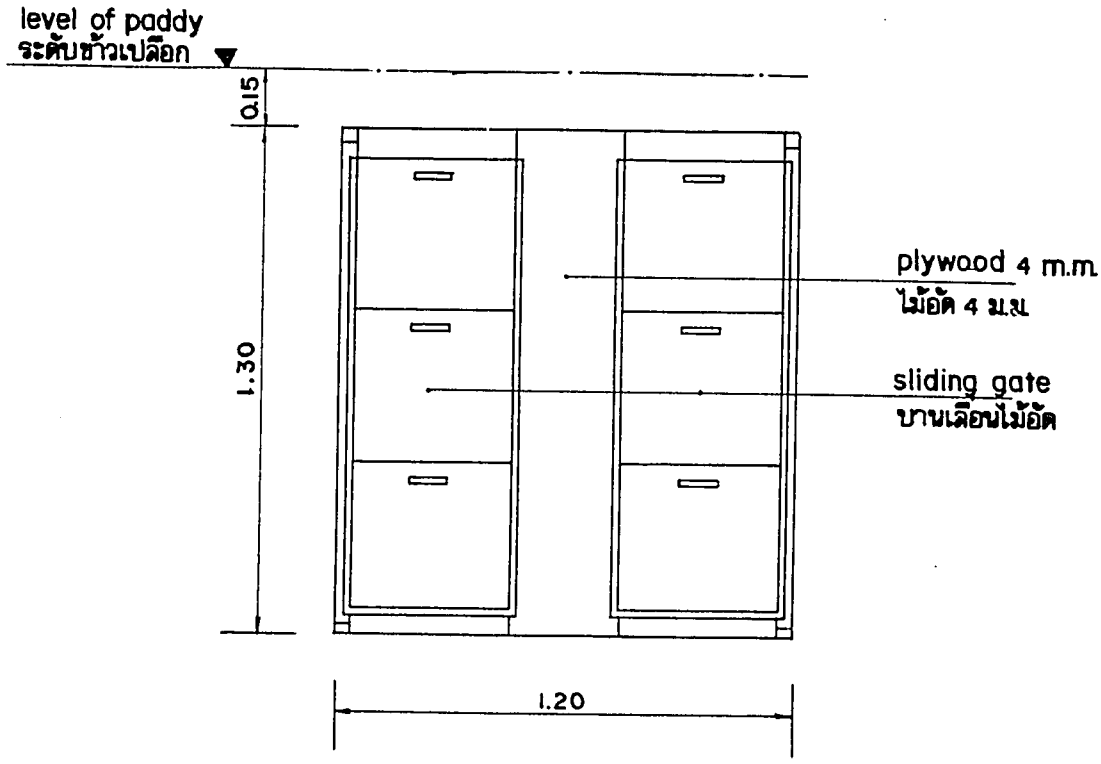


A. WOOD FRAME
รูปแสดงการต่อโครงไม้
(ใช้ไม้ $1\frac{1}{2}" \times 3"$)



B. ISOMETRIC

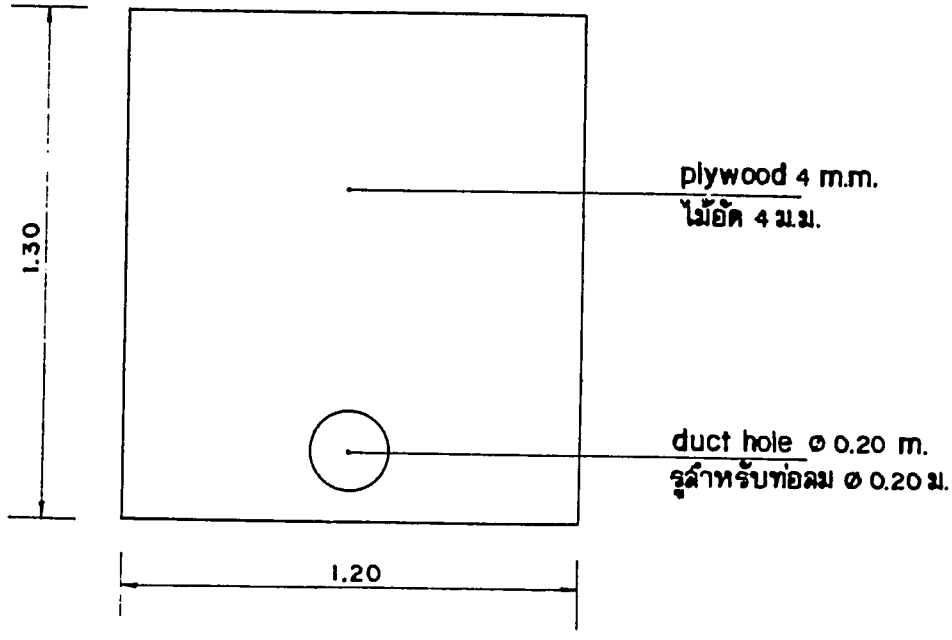
Fig. 4.6 Low-cost paddy dryer
รูป 4.6 เครื่องอบแห้งข้าวเปลือกแบบประหยัด



C. FRONT VIEW

C. ด้านหน้า

1:20

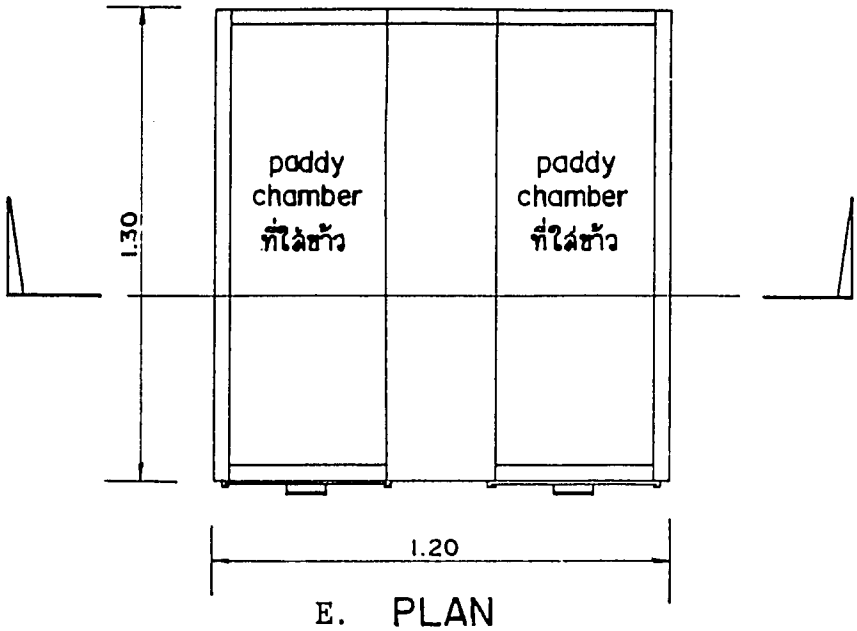


D. REAR VIEW

D. ด้านหลัง

1:20

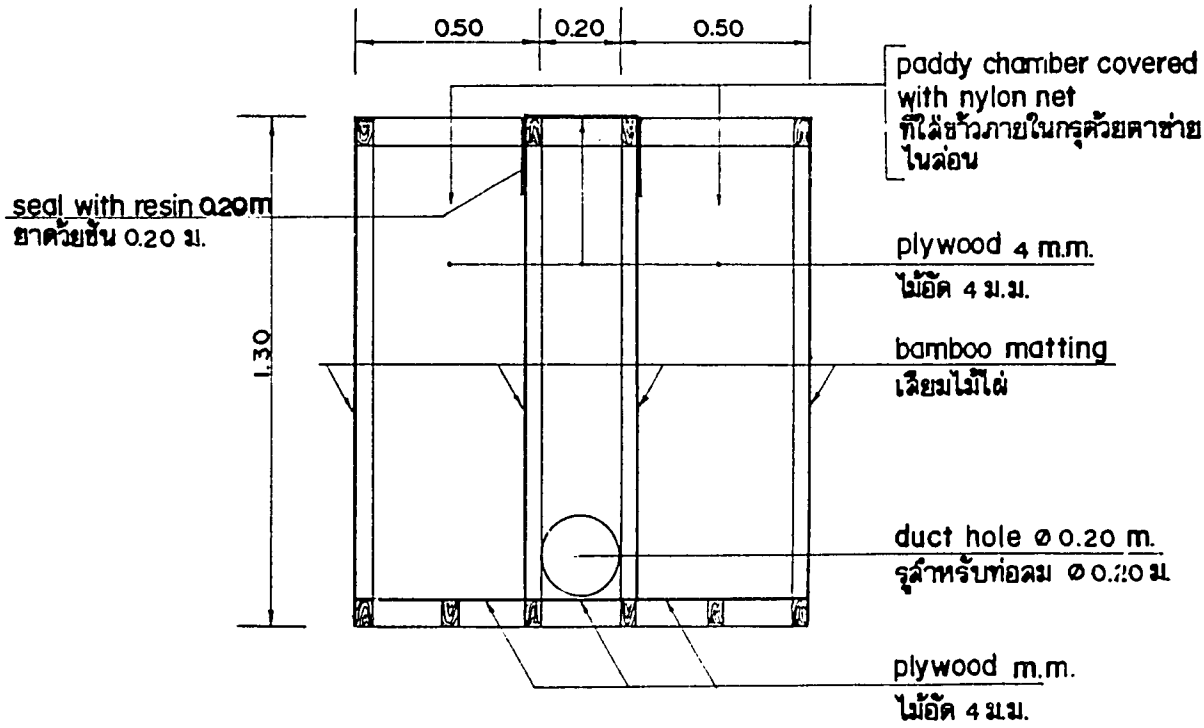
Figure 4.6 (continued)



E. PLAN

E. แปลน

1:20



F. SECTION

F. รูปตัด

1:20

Figure 4.6 (continued)

G. BAGGING CHUTE

G. อุปกรณ์ลำเลียงข้าวเปลือกลงกระสอบ

1:5

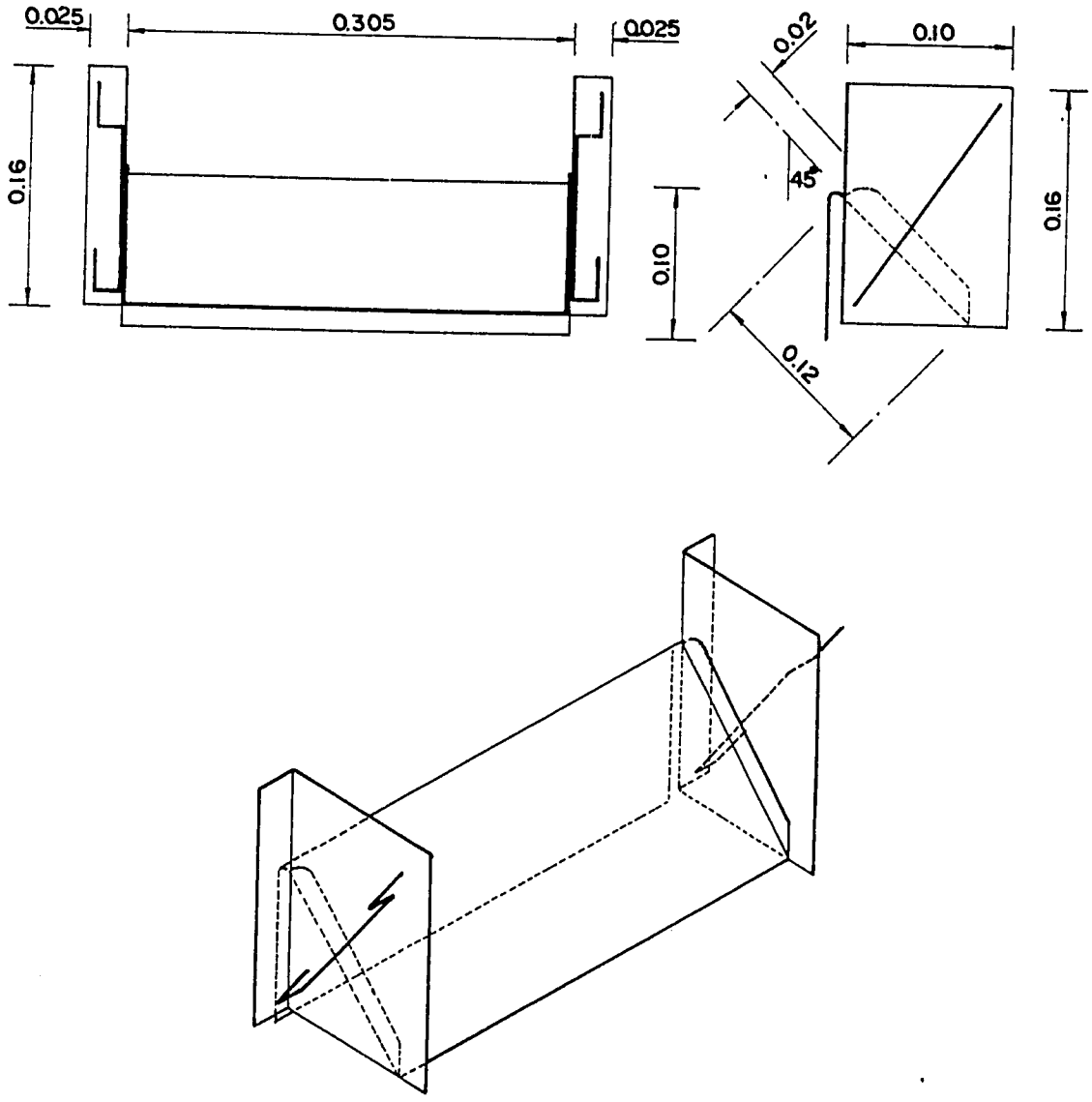


Figure 4.6 (continued)

During the test of the solar collector, air was forced to flow upward in order to facilitate the test. A forward curved blade centrifugal fan driven by a 373 W electric motor was employed to deliver air through the heater, duct system, and solar collector, respectively. Inlet air temperature at the entrance of the collector was controlled by a thermostat. Details of measurements will now be described.

Ambient temperature, air temperature at the inlet (4 points) and at the outlet (4 points) were measured by an iron - constantan thermocouple and recorded by a data logger (model : Doric 205). Accuracy was approximately ± 0.1°C. Recording was done every six minutes and the average value over a 30 minutes interval was used in calculation.

The air velocity profile in the duct was measured by a Pitot tube. The air flow rate was the product of the average velocity and the duct cross sectional area.

Wind velocity above the solar collector was measured by a cup anemometer. Readings were done instantaneously. Wind velocity was normally less than 1 m/s.

Global solar radiation was measured by a solar integrator (Kip and Zonnen, model : CC 12). It had an accuracy of ± 0.1%. This measured value was employed for calculating the thermal efficiency of the solar collector. It was numerically found that solar radiation on a horizontal surface and on the surface of the solar collector were not much different.

Testing was done between 10:30 A.M. and 14:30 P.M. for clear sky conditions. Inlet air temperature varied at least four or five values. At each temperature, the solar collector was heated about 30 minutes, in order to obtain a nearly steady condition, before taking data.

Paddy Drying Test

Drying rate, moisture and temperature gradients of grain in the bin, and daily thermal efficiency of the solar collector were studied. To obtain these results, the following measurements were made:

Ambient air temperature, wet bulb temperature, inlet (2 points) and outlet (2 points) air temperature of the solar collector, inlet air temperature of the dryer, and temperature gradient in the bin were measured by iron - constantan thermocouple and recorded every hour by a Data Logger (model : Doric 205). The accuracy of measurement was approximately ± 0.1 °C.

Air flow rate, wind velocity, and global solar radiation were measured by the same method employed in the solar collector performance test.

Samples of grain inside the bin were taken from 20 locations (see Fig. 4.7). Each sample weighed about 30 grams. Moisture content of paddy was determined by the oven method. The sample was dried in an oven at 100°C for 3-4 days. A moisture meter of "Kett" (riceter model D), was also used because moisture content determination by oven method is so labor intensive and the space in the oven was limited. Differences in results between these two methods were observed so a calibration curve could be constructed to facilitate the analysis of grain drying.

× location of paddy sampling (ตำแหน่งเก็บตัวอย่างข้าวเปลือก)

o temperature sensor (ตำแหน่งตัววัดอุณหภูมิ)

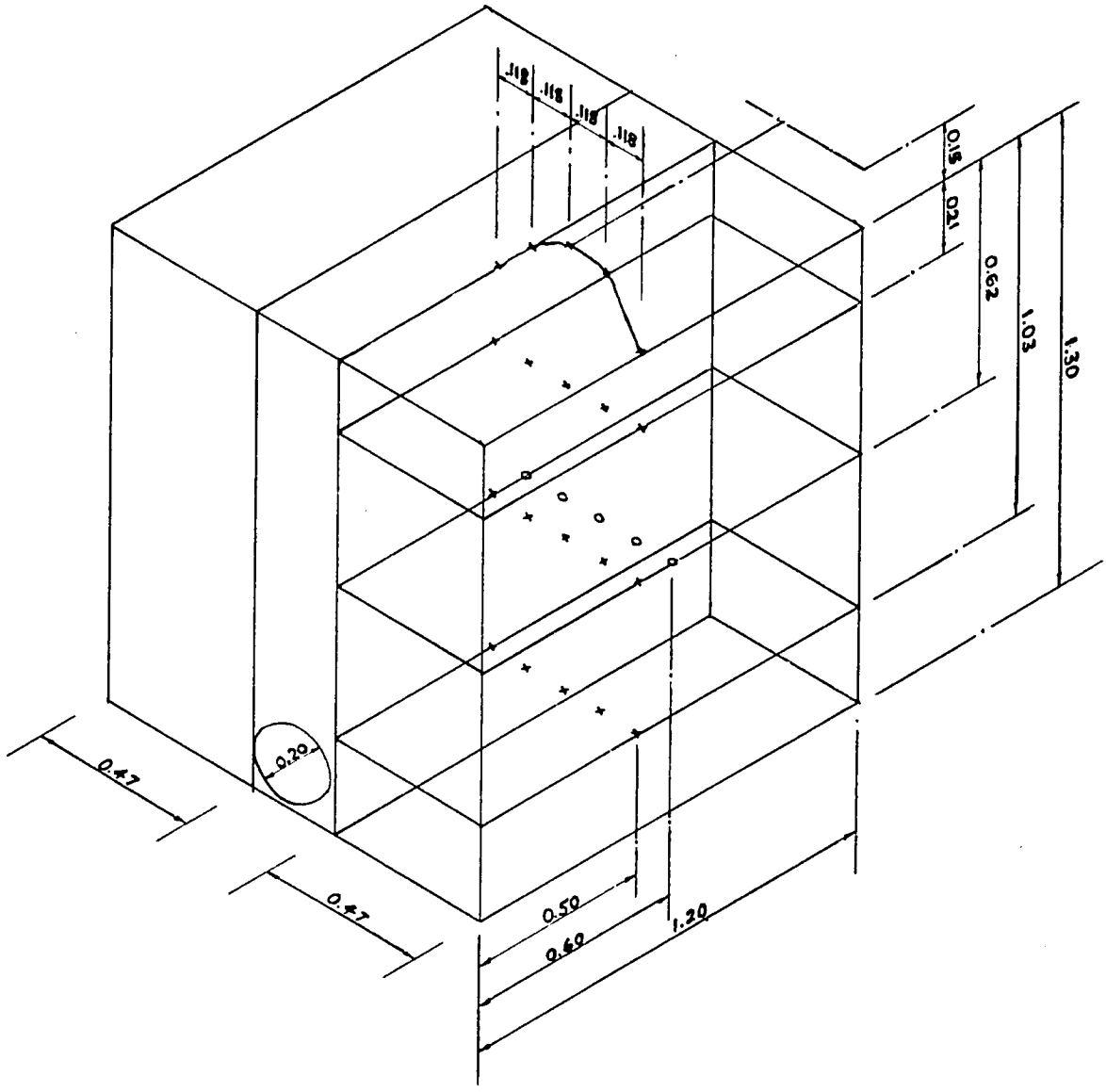


Figure 4.7 Locations of paddy sampling and temperature sensors
(ตำแหน่งเก็บตัวอย่างข้าวเปลือกและตัววัดอุณหภูมิ)

Chapter 5

Results and Discussion

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RESULTS AND DISCUSSION

Results and discussion of the work is divided into two sections: solar collector test and solar paddy drying test, respectively.

A. SOLAR COLLECTOR TEST

The experimental and simulated thermal efficiencies of the solar collector are presented in Figs. 5.1 and 5.2. The points on the graphs obtained from the test results before and after solar noon are scattered. This may be due mainly to the instantaneous change of wind speed and the heat capacity effect of the solar collector. However, straight lines are fit into the points by using the least square method.

The efficiency curves of the unpainted solar collector are presented in Fig. 5.1. There is a good agreement between the simulated and experimental results, especially at the region where inlet air temperature approaches ambient temperature. However, the simulated efficiency is progressively overestimated when inlet air temperature increases. This is partly due to the assumption that theoretical F_R and F_RU_L are constant and is found from the condition of $T_{f,i} = T_a$. At higher temperatures, the radiation heat loss increases ($\propto T^4$), so the simulated heat loss is underestimated at high inlet temperatures. Another reason may lie with the optical and thermal properties which vary with operating temperature. In the simulation tests it was assumed that these properties were constant.

Fig. 5.2 shows the comparison between the experimental and simulated efficiency of the dull black painted solar collector. Because the flow rate obtained during the test was smaller than the one obtained in the test of the unpainted solar collector, the thermal test data is converted for the flow rate of 0.34 kg/s (the same as the previous test) by using the technique quoted in Duffie and Beckman (1980). The converted efficiency curve is then compared with the simulated one. It is found that the simulated efficiency is always overestimated and the difference increases progressively at higher inlet air temperatures. However, it can be accepted at low inlet temperatures.

The experimental efficiency of the unpainted solar collector is about 3% lower than the dull black painted one (31% v.s. 34%). However, the former costs less. The extra material cost of the unpainted solar collector is 1,375 Baht (US $60). This is equal to 12% of the total material cost of the building and the solar collector (US $497). This does not include the air duct, fan, motor and the dryer. The extra material cost of the dull black painted collector is 2,475 Baht (US $108). If low initial investment is considered important, the unpainted solar collector would be the more attractive choice. [Remarks: The total cost of the completed system including labor cost is equal to 26,220 Baht (US$ 1,140)]

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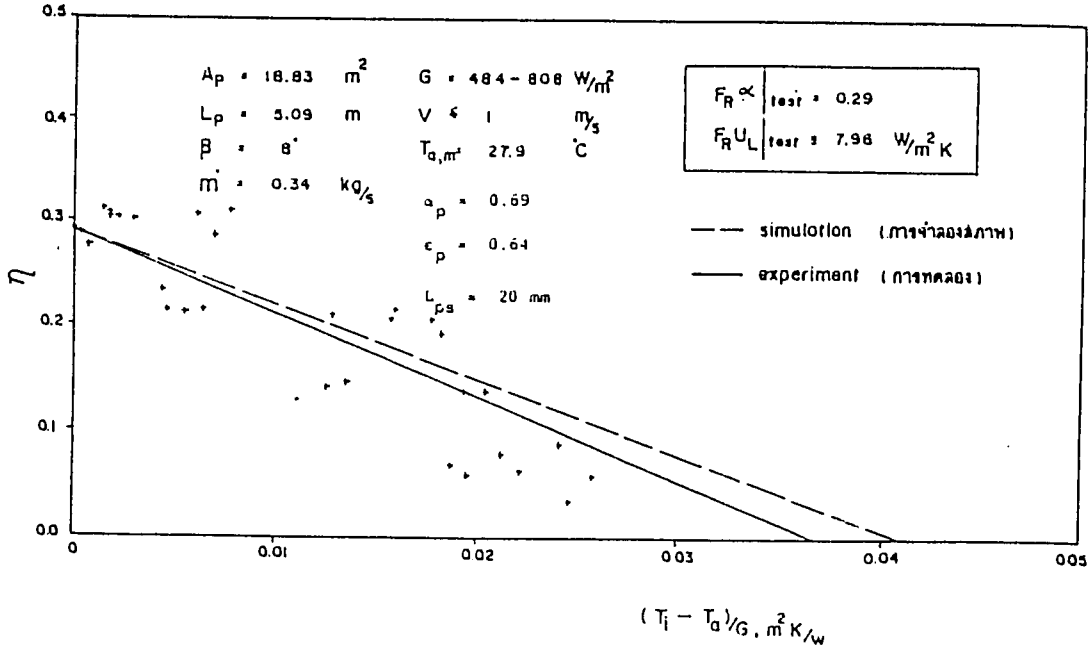

Figure 5.1 Comparison between experimental and simulated efficiencies for unpainted solar air collector, Nov - Dec 1983

(การเปรียบเทียบประสิทธิภาพจากการทดลองและการจำลองสภาพของตัวรับรังสีแบบไม่ทาสี, พ.ย.-ธ.ค. 2526)

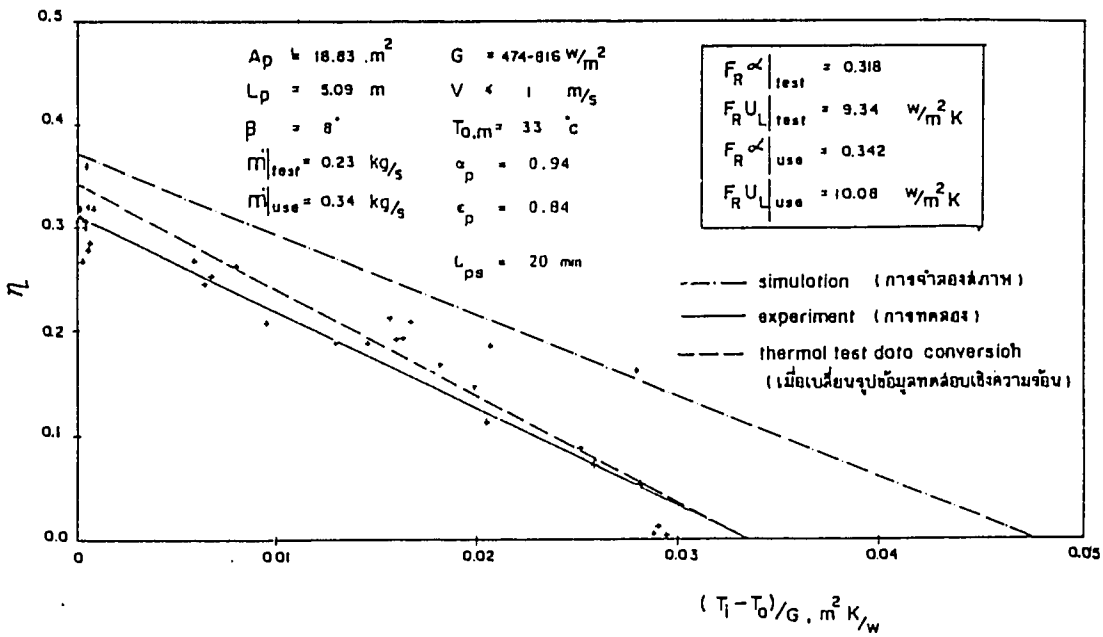

Figure 5.2 Comparison between experimental and simulated efficiencies for dull back painted solar air collector, Dec 1983

(การเปรียบเทียบประสิทธิภาพจากการทดลองและการจำลองสภาพของตัวรับรังสีแบบทาสีดำด้าน, ธ.ค. 2526)

B. SOLAR PADDY DRYING TEST *

Daily Efficiency of the Solar Collector

Daily performance of the solar collector during the drying tests were investigated. The results are summarized in Table 5.1.

Table 5.1 Daily efficiency of the solar collector.

Date	Global solar radiation (MJ/m^2)	Air flow rate (kg/s)	Efficiency (%)
4 Jan 1984	16.2	0.34	20.4
5 Jan 1984	17.1	0.34	27.4
7 Feb 1984	18.2	0.50	30.8

The efficiency of the solar collector obtained from the test on 5 Jan 1984 following ASHRAE standard 93-77 is higher than daily efficiency at the same air flow rate (0.34 kg/s). However, the standard test was conducted under better conditions (around the solar noon).

Experimental Drying Results

Two paddy drying tests were conducted during the dry season. The first test was in January. The drying of approximately one ton of paddy with an initial moisture content of 21.2% db, was started in the morning and the moisture was reduced to 16.3% by the following morning. It took 21.5 hours of ventilation. The evolution of measured moisture content of paddy and of the relevent weather conditions are presented in Figs. 5.3 and 5.4, respectively.

The second drying test was conducted in February. Drying of the same amount of paddy, with an initial moisture content of 22.2% db was started in the evening and the moisture was reduced to 16.3% by the following evening. It took 22.8 hours of ventilation. The results are shown in Figs. 5.5 and 5.6.

Though both tests were performed at different periods of time, the results can be roughly compared because the weather conditions during drying were not much different. Table 5.2 shows the comparative energy used per kilogram of water evaporated. They are 4.45 MJ/kg and 4.67 MJ/kg, respectively. These two figures are not significantly different.

*See Annex II for a technological and economic evaluation of drying paddy in the wet season.

Table 5.2 Energy used to evaporate water

Test No.	water evaporated (kg)	solar energy (MJ)	electrical* energy (MJ)	total energy (MJ)	energy used to evaporate water (MJ/kg)
1	40	62	116	178	4.45
2	49	106	123	229	4.67

* power estimated from the name plate.

In both tests, moisture condensation took place in the grain layer nearest the exit of drying air. This happened mainly during the afternoon when drying air was relatively hot compared to the grain temperature. This effect tends to make the moisture gradient larger. Unfortunately, it can not be avoided.

Even though the drying rate is slow, ventilation of ambient air at night reduces the average moisture content of paddy for both drying tests. However, in the second test the effect of reduced moisture gradient at night is lost as the condition is reversed the following afternoon. At the paddy layer near the inlet of drying air, grain moisture content which had been overdried absorbed moisture from the air and the one near the outlet of drying air which was still humid was dried.

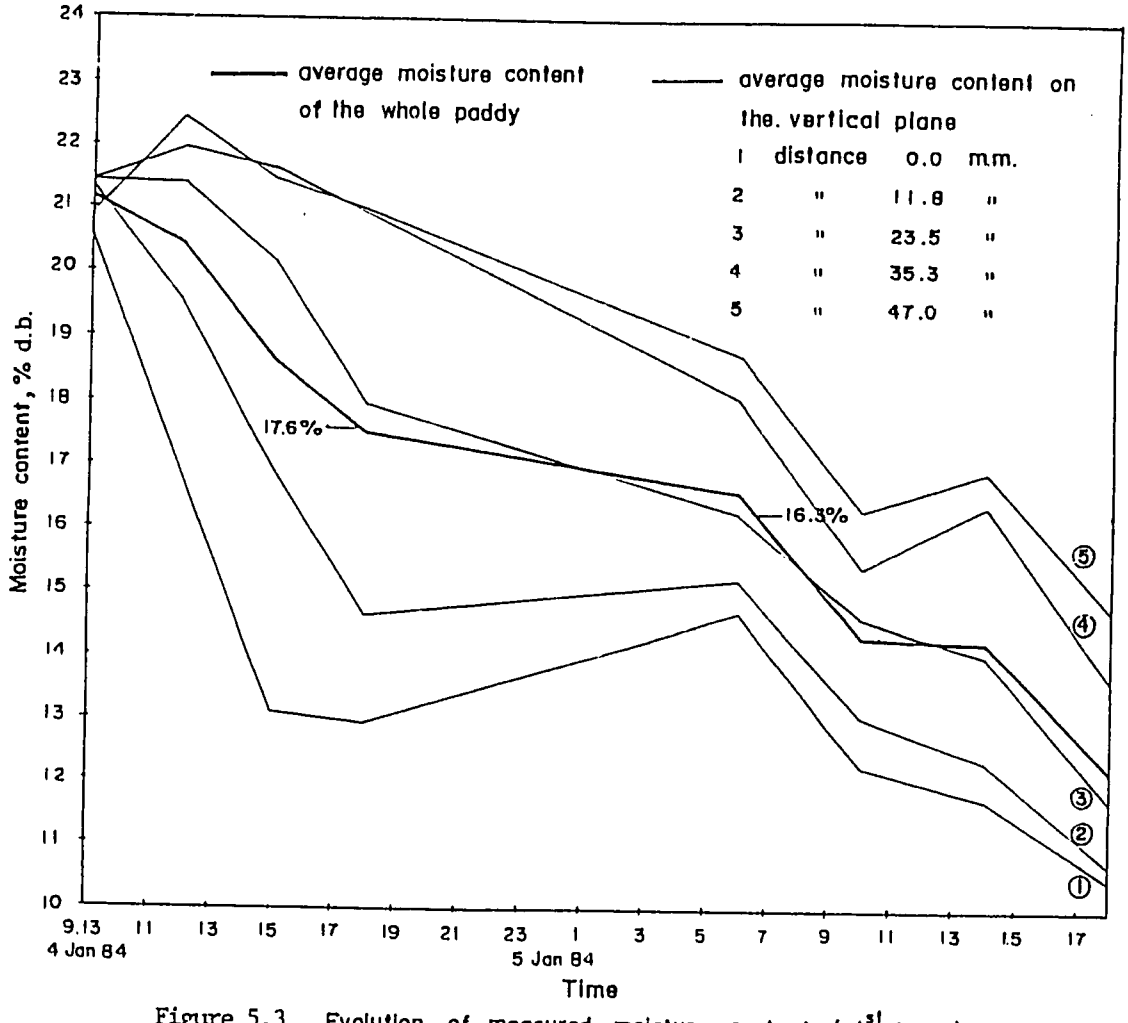

Figure 5.3 Evolution of measured moisture content (1st test)

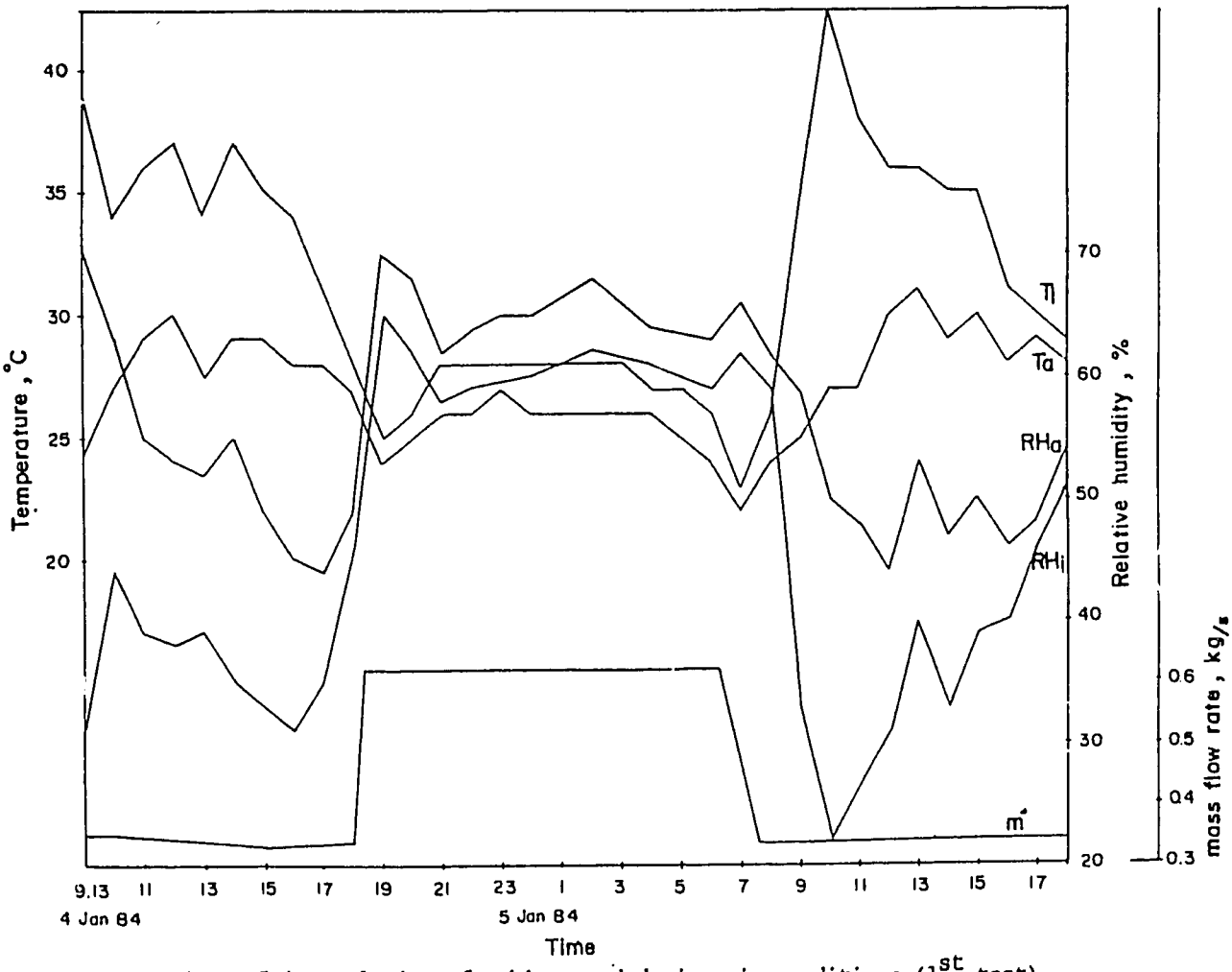

Figure 5.4 Evolution of ambient and drying air conditions (1st test)

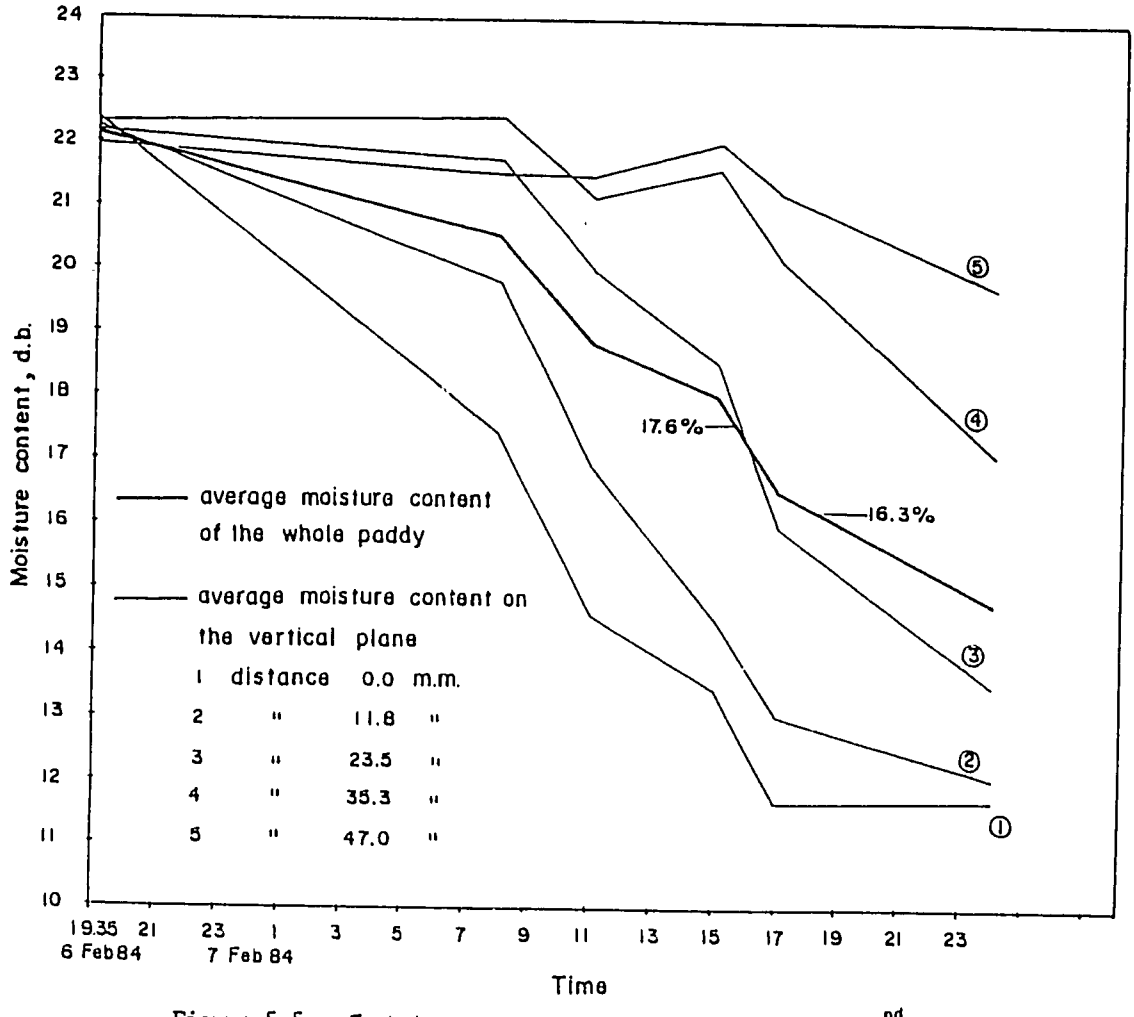

Figure 5.5. Evolution of measured moisture content (2nd test)

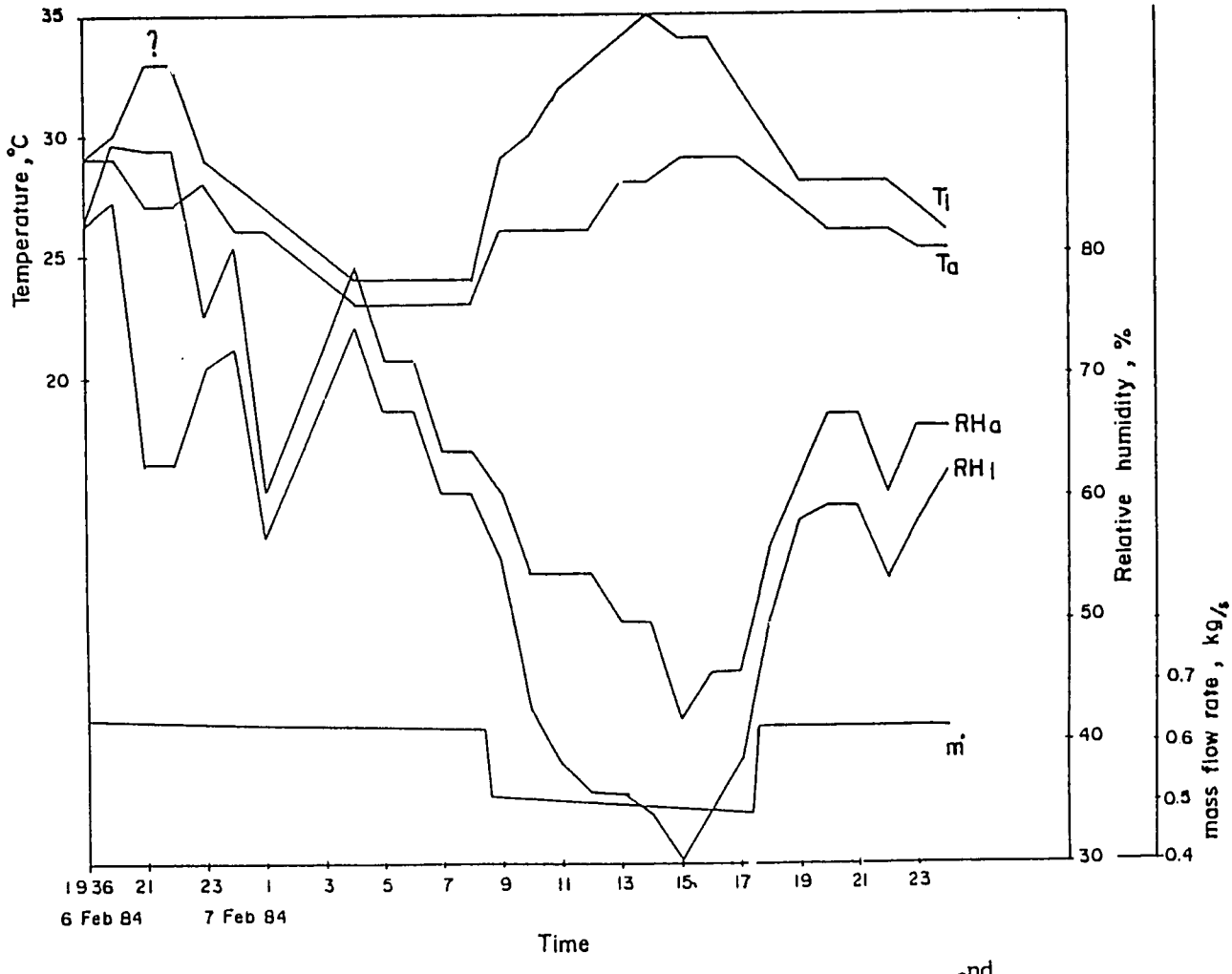

Figure 5.6 Evolution of ambient and drying air conditions (2nd test)

Chapter 6

Conclusions

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CONCLUSIONS

1. The maximum efficiency of the unpainted and dull black painted solar collectors are 31% and 34%, respectively. The unpainted solar collector may be a more attractive choice than the dull black painted one if low initial investment is preferred.

2. The mathematical model developed can predict the thermal efficiency of the solar collector accurately at low inlet air temperatures. However, the theoretical efficiency is overestimated at high inlet air temperatures.

3. From the results of the drying tests, it seems that a drying technique like the first drying test (where drying begins in the morning and terminates the following morning, and the ventilation of ambient air is done at night before the end of drying) is preferred to the technique followed in the second test (where drying begins in the evening and terminates the following evening) because there is an advantage of a smaller moisture gradient of paddy in the dryer.

4. For conclusions involving a technical evaluation of drying paddy during the wet season and an economic evaluation of the solar dryer, see Annex II.

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Chapter 7

Recommendations

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RECOMMENDATIONS

It is recommended that the following work should be continued.

1. The low-cost solar air heater developed in this study is suitable for drying agricultural products on the farm because it is cheap and easily constructed. However, high efficiency solar air heaters may be of more interest to small-scale rural industries. The efficiency of the low-cost solar air heater can be significantly improved by adding a transparent cover over the absorber.

2. Drying paddy during the wet season should be investigated.*

3. Mathematical simulation of solar paddy drying is also important because it can be used to aid in the design of similar solar drying systems.

4. An economic evaluation of the solar dryer should be made.*

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*See Annex II for these results.

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Annexes

d. 6

ANNEX I

METEOROLOGICAL DATA

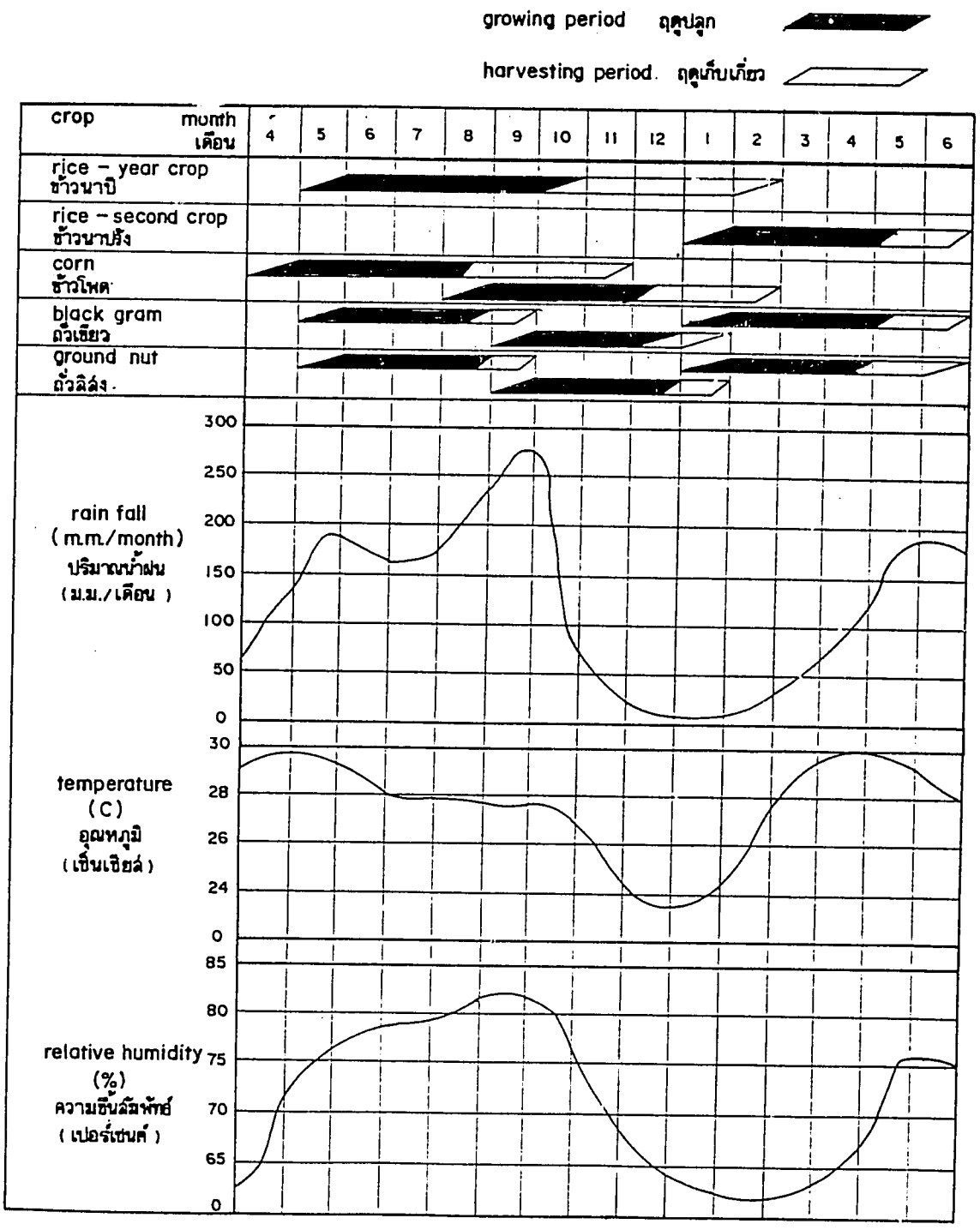
Weather records which record the monthly average temperature, relative humidity and rainfall of the four regions in Thailand are shown in Tables. I.1 - I.4. The monthly average wind velocity at a height of 10 meters is normally lower than 4 m/s in most regions except the areas which are close to the sea.

Table I.5 shows mean daily global solar radiation averaged over 1½ increments at various locations. The differences in solar radiation at different periods of time or locations are not appreciable. The probabilities of solar radiation in Bangkok being at three magnitudes are shown in Table I.6.

TABLE I.1

Growing and harvesting periods of some crops and climatic conditions of the North-Eastern region

ฤดูการปลูกและเก็บเกี่ยวของพืชบางอย่างและสภาวะของอากาศทางภาคตะวันออกเฉียงเหนือ

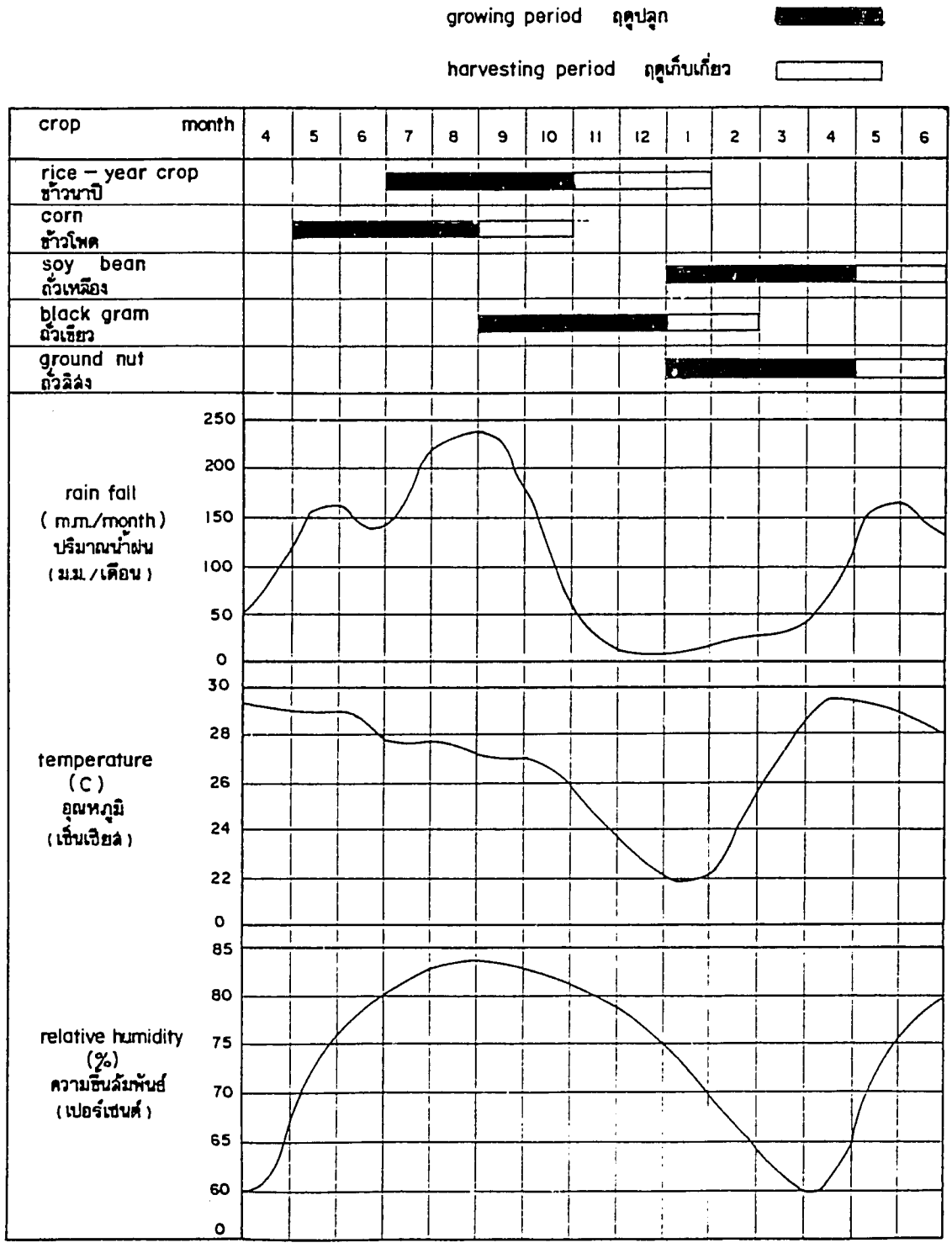


Adapted from a Ministry of Agriculture Report (1976)

TABLE I.2

Growing and harvesting periods of some crops and climatic conditions of the Northern region

ฤดูการปลูกและเก็บเกี่ยวของพืชบางอย่างและสภาวะของอากาศทางภาคเหนือ

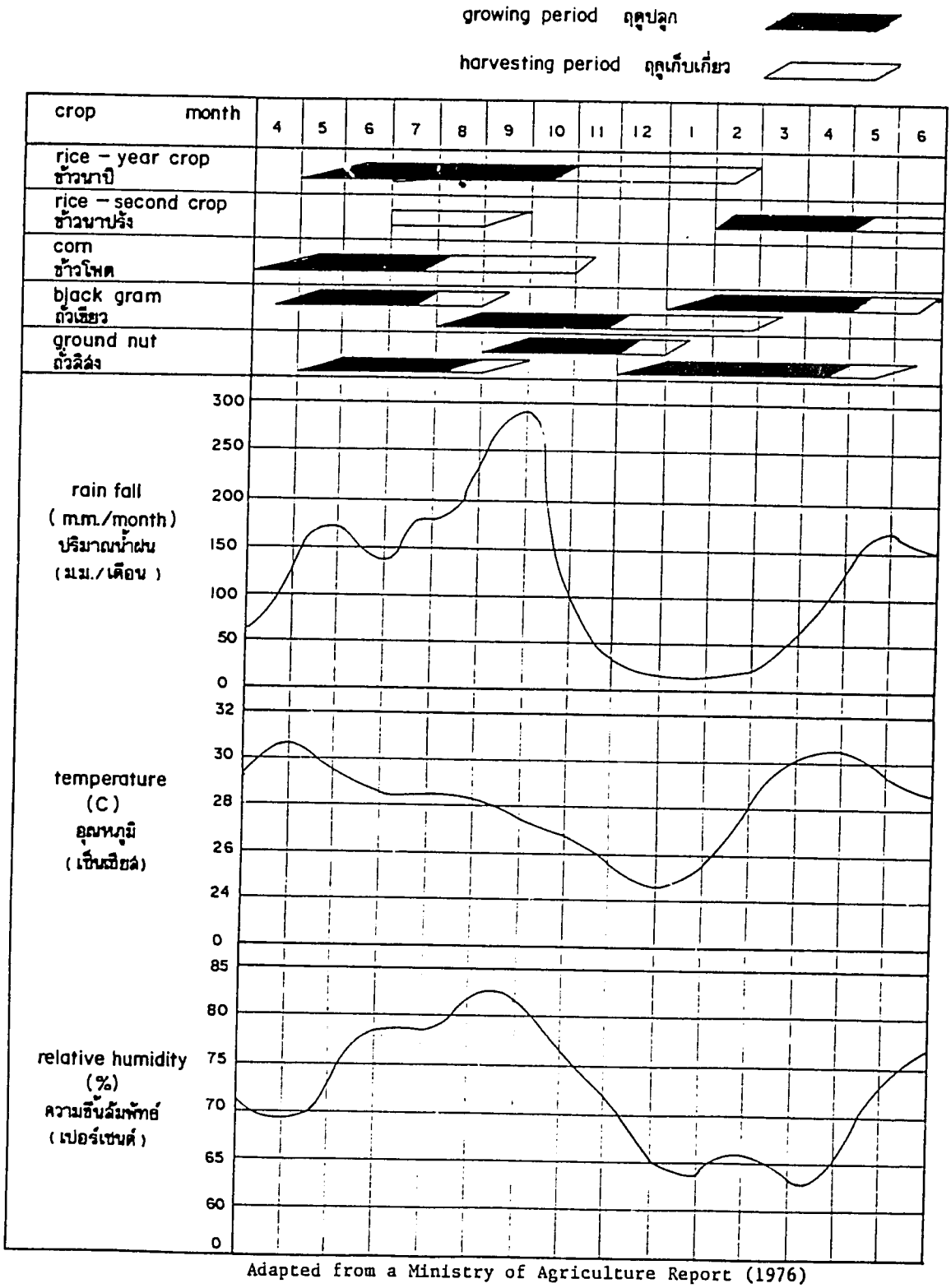


Adapted from a Ministry of Agriculture Report (1976)

TABLE I.3

Growing and harvesting periods of some crops and climatic conditions of the Central region

ฤดูการปลูกและเก็บเกี่ยวของพืชบางอย่างและสภาวะของอากาศทางภาคกลาง



Adapted from a Ministry of Agriculture Report (1976)

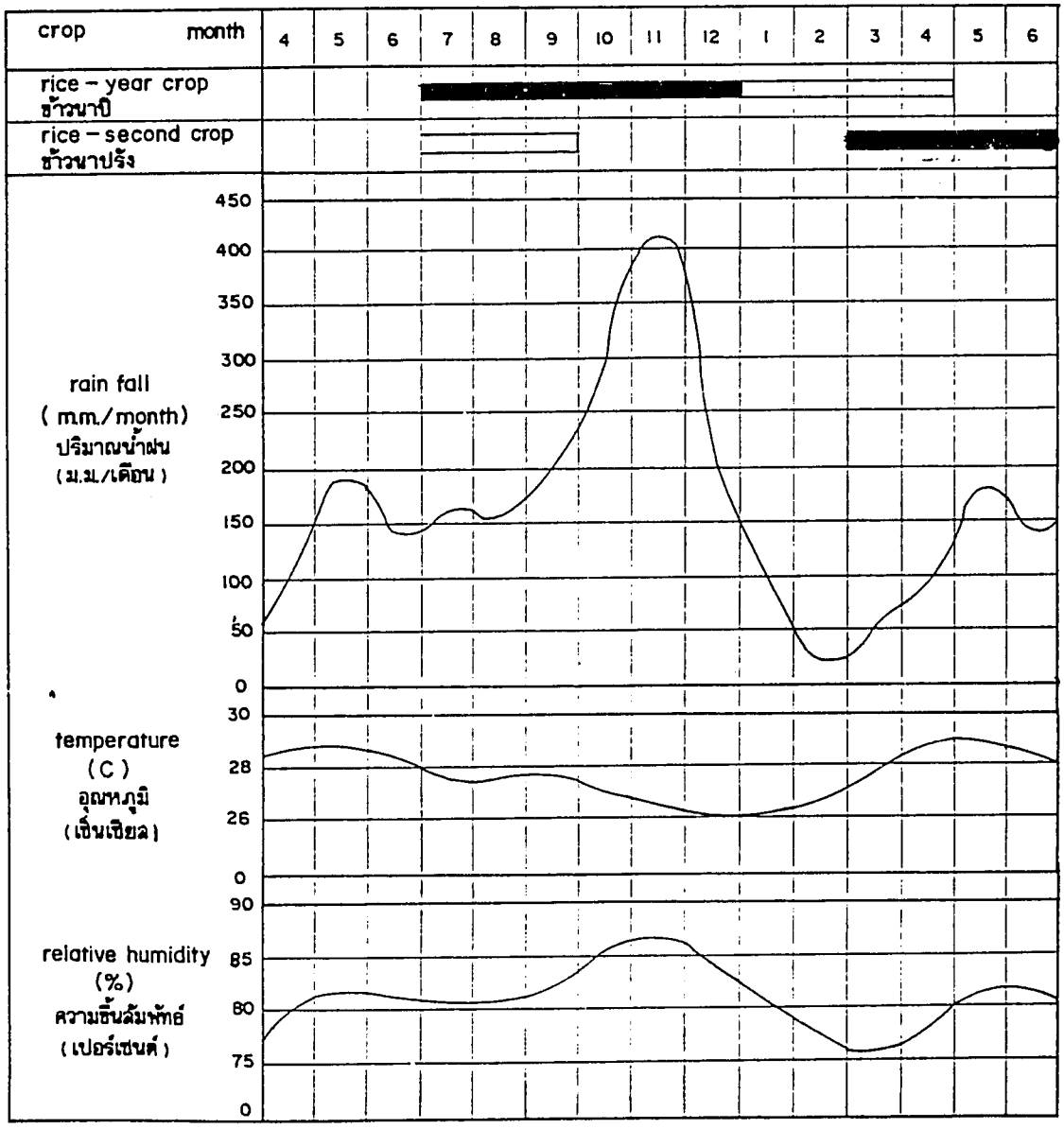
TABLE I.4

Growing and harvesting periods of some crops and climatic conditions of the Southern region

ฤดูการปลูกและเก็บเกี่ยวของพืชบางอย่างและสภาวะของอากาศทางภาคใต้

growing period ฤดูปลูก

harvesting period ฤดูเก็บเกี่ยว



Adapted from a Ministry of Agriculture Report (1976)

Table I.5 Mean daily totals of global solar radiation (MJ/m^2 day) estimated from mean daily durations of sunshine.

Location	Jan 14 to Feb 26	Feb 27 to Apr 12	Apr 13 to May 28	May 29 to Jul 15	Jul 16 to Aug 31	Sept 1 to Oct 15	Oct 16 to Nov 29	Nov 30 to Jan 13
Chiang Mai	16.7	19.2	20.1	17.2	15.7	16.8	17.0	15.6
Khon Kaen	16.9	18.0	19.4	17.5	16.4	15.9	17.5	16.5
Bangkok	16.8	19.5	17.8	16.6	15.5	14.9	16.4	16.7
Songkhla	17.9	19.3	17.4	16.7	17.0	15.9	14.6	14.8

From Exell and Saricali (1975)

Table I.6 Probabilities of solar radiation classes in Bangkok

Radiation Class kJ/m^2/ day	Jan 14 to Feb 26	Feb 27 to Apr 12	Apr 13 to May 28	May 29 to Jul 15	Jul 16 to Aug 31	Sept 1 to Oct 15	Oct 16 to Nov 29	Nov 30 to Jan 13
A (over 20.95)	.12	.36	.41	.16	.09	.11	.13	.01
B (12.57 to 20.95)	.76	.52	.46	.62	.65	.54	.66	.82
C (under 12.57)	.12	.12	.13	.22	.26	.35	.21	.17

From Exell and Saricali (1975)

ANNEX II

Technical and Economic Evaluation of a Forced Convection Solar Hut Dryer*

Somchart Soponronnarit** and Jirawan Tiansuwan***

ABSTRACT

The roof of a hut of 19 m^2 was transformed into a low - cost solar air heater. The absorber was made of corrugated galvanized iron sheet and air flowed through the space between the absorber and insulation. No transparent cover was used. The maximum thermal efficiency according to ASHEAE Standard Test 93-77 was 29 % at the air flow rate of 0.018 kg/s-m^2.

About one ton of paddy was dried in a vertical fixed - bed dryer by using hot air produced from the solar air heater. The air was sucked from the solar air heater through a blower driven by an electric motor of 1.5 kW and then dilivered to the dryer. The moisture content of paddy was reduced from 22 to 16 % dry - basis in about one day.

The materials used for both solar air heater and dryer were easily available in the local market. Total cost of the solar hut dryer was 26,200 ฿ (US $ 1,139). According to the comparison between the cost of the solar hut dryer and the benefit gained from the dryer by making the losses during the chain of rice production reduced idicated that it was economical for the farmers who had the cultivation area more than 25 rais (6.25 rais = 1 hectare) and practiced two crops per year. If the hut was also used as a paddy storage for the first crop, the minimum cultivation area is reduced to 17 rais.

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1. INTRODUCTION

Thailand is one of the major rice producing and exporting countries. The production of paddy is approximately 17.77 million tons per year. (1981) However, the amount of 14.97 out of 17.77 million tons is consumed in the country. The rest is exported.

Most of rice grown in Thailand is non-waxy varieties. It may be grown once or twice a year depending mainly on water supply. The year crop is grown during the rainy season and is harvested in the dry season. The second crop is grown during the summer and is harvested in the rainy season. Nowadays, growing of the second crop becomes more popular due to the expansion of the irrigation system. However, the farmers have been facing with the spoilage of the wet paddy which the moisture can not be reduced fast enough by field drying during the rainy season.

The moisture content of paddy during harvesting may vary from 20 - 24 % wet-basis and it must be reduced fast enough to 14 % The time for safe drying depends on grain moisture content, grain temperature and degree of kernel breakage. Arboleda and Manalo [1] suggested that paddy with moisture content of 24 % , between 21 - 23.9 % and lower than 20.9 % wet-bais should be dried in one, two, and three days, respectively. With the conventional method of field drying, it is understood that the paddy may not be safely dried during the rainy season. To ameliorate this problem, one may introduce other methods of drying. A mechanical dryer may be interesting. It composes of a bin as a drying chamber, a blower which may be driven by an engine or an electric motor, and a heat source which may be electricity, gas, kerosine, fuel oil, agricultural waste, solar energy etc.

An electrical heat source is quite simple but the operating cost is expensive. Gas and fuel oil are less expensive than electricity but the control is more complicated. Agricultural waste such as rice husk may be the most interesting if it is available on site so that there is no cost of transportation. Solar energy is freely available but the solar collector is always expensive. However, it can be designed, in certain case at least for drying agricultural product, so that it is cheap enough for some Thai farmers.

The purpose of this work is then

- To design, construct, and test a low-cost solar air heater.
- To design, construct and test a low-cost fixed-bed paddy dryer using hot air produced from the solar air heater and circulated by a blower.
- To evaluate the economics of the solar hut dryer.

2. PROCEDURES

2.1 Experimental Design

The 18.9 m^2 solar collector was constructed on the roof of a

hut as shown in figure 1. The design was based on the results obtained from the mathematical model developed by Soponronnarit and Tiansuwan [2]. It has an inclination angle of 8 degree and facing toward the South. The detail of it's structure is shown in figures 1b and 1c. The performance test following the ASHRAE Standard Test 93 - 77 [3] was done. During the test air was forced to flow upward in order to facilitate the work. A forward curved blade centrifugal fan was employed to diliver air through a heater, duct system, and the solar collector, respectively. The air temperature at the entrance of the solar collector was controlled by a thermostat. The detail of measurement is described as following.

Ambient temperature, air temperature at the inlet (4 points) and at the outlet (4 points) of the solar collector were measured by Iron - Constantan thermocouple and recorded by a data logger, model : Doric 205. The accuracy was about $\pm$ 1 ^{o}C. Recording was done every six minutes and the average value during 30 minutes was used in calculation.

Air velocity profile in duct was measured by a pitot tube and air flow rate was the product of the average velocity and the duct cross - sectional area.

Wind velocity above the solar collector was measured by a cup anemometer. Reading was done instantaneousely. It is always less than 1 m/s.

Global solar radiation was measured by a solar integrator of Kip and Zonnen, model : CC12. The accuracy was $\pm$ 0.1 %. Global solar radiation was employed for the calculation of the thermal efficiency of the solar collector. It was numerically found that global solar radiation and the solar radiation on the plane of the solar collector were not much different.

Test was done during 10.30 a.m. and 2.30 p.m. for clear sky condition. Inlet air temperature was varied at least four of five values. At each temperature, the solar collector was heated about 30 minutes, in order to obtain neary steady condition, before taking data.

The thermal efficiency of the solar collector is then

$$\eta = \frac{\dot{m} \; C_p \; (T_{f,o} - T_{f,i})}{A_c \; G} \qquad (1)$$

The above solar collector was used to produce hot air to dry paddy of about 1 ton in the dryer installed inside the hut. The dryer looks like the one of IRRI's design [4] but the materials used for construction are defferent. The detail of the dryer is shown in figure 2.

During the day time, ambient air was drawn into the solar collector and then dilivered to the dryer. At night, ambient air went to the fan directly in order to avoid infrared radiation to the sky. In addition, air flow rate increased because the pressure loss of the system decreased.

Drying rate, moisture and temperature gradient of grain in the bin, and daily thermal efficiency of the solar collector were studied. To obtain these results, the following measurement was done.

Ambient air temperature, wet bulb temperature, inlet (2 points) and outlet (2 points) air temperature of the solar collector, inlet air temperature of the dryer, and temperature gradient in the bin (figure 3) were measured by Iron - Constantan thermocouple and recorded by a data logger, model : Doric 205.

Air flow rate, wind velocity, and global solar radiation were measured by the same method employed in the solar collector performance test.

Grain inside the bin was taken at times at 20 locations (figure 3). Each sample weighs about 30 grams. Moisture content was determined by oven method. The sample was dried in an oven at 100 ^{o}C for 3 - 4 days. A moisture meter of "Kett" , riceter model D was also used. The calibration curve for these two methods has been established.

2.2 Evalation Method of Drying Capacity and Solar Collector Area

The majority of farm size in the Central region varies from 20 - 30 rais (1 hectare = 6.25 rais), and the average yield is about 300 kg of paddy per rai. So the production of paddy is about 6 - 9 tons per season per family and all of this paddy is harvested from 2 to more than 14 days. [5] If it is assumed that harvesting is done in 14 days, the harvesting rate will be 0.43 - 0.64 tons per day.

To evaluate the solar collector area required for drying, the thermal efficiency of the solar collector at a given specific air flow rate must be known. In addition, the meteorological data such as global solar radiation, ambient air condition must be given. The increased air temperature is then calculated from the above information. The air from the outlet of the solar collector is further heated by the fan. It is often assumed that it will be heated by 1.1 ^{o}C by the fan. Then the air property at the inlet of the dryer is determined by the aid of the Psychrometric chart.

The further step is to calculate the air flow rate required to dry the paddy. A simple equation describing the global heat balace is used. It is written as following :

$$h'_{fg}\, m_w = \dot{m}\, C_p\, (T_i - T_o)\, t \qquad (2)$$

Once the air flow rate is calculated from the equation (2), the solar collector area can be determined by dividing $\dot{m}$ obtained from the equation (2) by the specific air flow rate of the solar collector.

3. RESULTS AND DISCUSSION

3.1 Solar Collector Test

The experimental thermal efficiency of the solar collector

is presented in figure 4 . The points on the graphs obtained from the test results before and after solar noon are scattered. This may be mainly due to the instantaneouse change of wind speed and the heat capacity effect of the solar collector. However, a straight line was fit into the points by using the least square method. The intercept ($F_R \alpha$) and the slope ($-F_R U_L$) are 0.29 and -7.96, respectively.

3.2 Solar Paddy Drying Test

3.2.1 Daily efficiency of the solar collector

Daily performance of the solar collector during drying test was investigated. The results are summarized in table 1.

Table 1 Daily efficiency of the solar collector

Date	Global solar radiation (MJ/m^2)	Air flow rate (kg/s)	Efficiency (%)
4 Jan 1984	16.2	0.34	20.4
5 Jan 1984	17.1	0.34	27.4
7 Feb 1984	18.2	0.50	30.8
5 Jul 1984	11.4	0.49	31.4

The efficiency of the solar collector obtained from the test following ASHRAE standard 93-77 was higher than daily efficiency at the same air flow rate (0.34 kg/s). However, the standard test was done at better condition (around the solar noon and clear sky condition). At higher air flow rate (0.49-5 kg/s) the daily efficiency tends to increase.

3.2.2 Experimental drying results

Two paddy drying tests were done in the dry season. The first test was in January. The paddy of about one tone, with initial moisture content of 21.2 % d.b., was started to be dried in the morning and the moisture was reduced to 16.3 % in the following morning. It took 21.5 hours of ventilation. The evoluation of measured moisture content of paddy and of air condition are presented in figures 5 and 6 respectively.

The second drying test was done in Febuary, The same amount of paddy with initial moisture content of 22.2 % d.b. was started to be dried in the evening and the moisture was reduced to 16.3 % in the following evening. It took 22.8 hours of ventilation. The results are shown in figures 7 and 8.

Though both tests were performed at different period of time, the results can be roughly compared because the weather conditions during drying are not much different. Table 2 shows the comparative energy used per kilogram of water evaporated. They are 4.45 MJ/kg and 4.67 MJ/kg, respectively. These two figures are not significantly different.

Table 2 Energy used to evaporate water

test no.	range of moisture content (% d.b.)	water evaporated (kg)	solar energy (MJ)	electrical energy* (MJ)	total energy (MJ)	energy used to evaporate water (MJ/kg)
1	21.2-16.3	40	62	116	178	4.45
2	22.2-16.3	49	106	123	229	4.67
3	24.9-18.3	53	67	119	186	3.54

*power estimated from the name plate

Drying test was also done in the rainy season. The experimental results are shown in figures 9 -10. Drying was started in the evening and the moisture content was reduced from 24.9 to 18.3 % d.b. in 22 hours. The specific energy consumption for moisture evaporation shown in table 2 is 3.54 MJ/kg comparing to 4.45 and 4.67 MJ/kg obtained from the 1st and 2nd tests. It was observed that the initial moisture content of the 3rd test was higher and drying rate at night was thus faster though the drying air condition was worse. If the ventilation during the 2nd night was included in the caculation, the specific energy consumption would be 4.4 MJ/kg instead of 3.54 MJ/kg. It can be seen in figure 9 that the moisture content of paddy during the 2nd night was already partly reduced and its value approched the equilibrium moisture content.

From the results of all drying tests, it can be concluded that ventilation at night can reduce the moisture content but not so effectively especially in the case of low moisture content of paddy and high relative humidity of drying air. If drying was done only during the day time, the specific energy consumption would be much lower. However, ventiation at night made the moisture gradient of paddy in the dryer reduced (see figure 5). To compromise both advantages ventiation at night may be partly done.

Milling quality test showed that the head rice yield varied from 49-53 % which was relatively good. Germination was about 92 % for the average.

3.3 Economic Analysis

3.3.1 Cost of the solar hut dryer

The cost of the solar hut dryer is 26,2[illegible] Baht (1US $ = 23 ฿). It is assumed that the service life of the wood structure is 24 years which is the minimum value that we can expect. It is thus assumed that maintenance cost is negligible. However, the corrugated galvanized iron sheet has to be changed every 8 years and it costs 2160 ฿ each time. For making the calculation possible more assumptions were made as following.

- Labour cost for drying is negligible.
- Drying capacity is 1000 kg/24 hours.
- Cost of electricity is 2.2 ฿/kW-h.
- Salvage value of the solar hut dryer is zero.
- Loan interest rate is 18 %/year.

- Deposit interest rate is 13 %/year.
- In case of using the solar hut dryer as a paddy storage the maximum capacity of storage is assumed to be 10 tons.

From the basic economic calculation it was found that aunual fixed cost of the solar hut dryer was 4954 ฿.

Variable cost of the dryer is the electricity consumed by the electric motor of 1.5 kW. According to the assumptions made it was found that variable cost for drying each ton of paddy was 79 ฿.

3.3.2 Benefit gained from the reduction in losses

Losses during the conventional chain of rice production can be summarized as following.

a. Shatter loss before harvesting: It was estimated that this loss was about 5 % of the yield [6].

b. Harvesting loss : From the survey in the Central region of Thailand [7], it was found that harvesting loss varied from 4.98-11.8 % of the yield or 7.8 % as the average.

c. Threshing loss : The average threshing loss was 4.6 % of the yield [7] (Remark : If the paddy is threshed at low moisture content, loss may be less).

d. Shatter loss during transportation : Transportation of paddy from the field to the threshing floor and then to the storage caused an average loss of 4.6 % of the yield [7]

e. Loss during field drying : This loss is mainly due to birds and rodents and it was estimated that the average loss was about 5 % of the yield [6].

f. Loss during storage : If the wet grain is stored in bulk, grain temperature will increase rapidly and leads to the degrading in grain quality such as yellowing, mould, low milling quality etc. In addition, insect may cause an important loss.

If the farmer has a dryer, harvesting may be done three or four days earlier than the usual practice. Reduction in losses of shattering and harvesting is thus expected. Wet paddy is then transported to the threshing floor and field drying will not be practiced any more or in case of labour shortage wet paddy may be laid in the field for one day. It was estimated by the authors that total reduction in losses during shattering before harvesting, harvesting, transportation, and field drying was 6.8% of the yield.

Paddy havested in the rainy season may not be dried fast enough in the field. Thai farmers are sometimes obliged to sell the wet paddy though the price is 100-300 Baht/ton less than the one they expect. In case of poor quality of paddy this number may be as high as 1000 Baht/ton. It is assumed here in that the farmer who has a dryer will dry the paddy before selling it and 200 Baht/ton is the benefit.

The benefit gained from the dryer can be then calculated as following.

For the year crop

$$\text{benefit} = (\text{cultivation area}).(\text{yield/area}).(\text{unit price}).(0.068)$$

For the second crop

benefit = (cultivation area).(yield/area).(unit price).(0.068) + (cultivation area).(yield/area).(200)

The price of paddy varies through out the year. The minimum is normally in December and the maximum is in August. The information from Center for Agricultural Statistics, Office of Agricultural Economics, Ministry of Agriculture and Co-operatives indicated that the price difference of mixed-type paddy between December and April in 1981 was 400 Baht/ton (2800 ฿ ton V.S. 3200 ฿/ton). If the farmer stores the paddy obtained from the year crop, he will get the benefit as shown below.

interest = (unit price).(deposit interest rate).(storage time)
= (2800) (0.13) (4/12) = 122 ฿/ton

The benefit from the storage is then

benefit = 400 - 122 = 278 ฿/ton

The yields of the year crop and the second crop in the Central region are about 0.34 and 0.54 ton/rai, respectively [8]. If the average unit price of 3,000฿/ton is used for calculation, the following results are obtained.

Table 3 Cost and benefit from drying

cultivation area (rai)	1 crop/year		2 crops/year	
	annual cost ฿	benefit ฿	annual cost ฿	benefit ฿
10 - 19	5,269-5,505	704-1,338	5,663- 6,293	2,882- 5,476
20 - 49	5,505-6,293	1,408-3,449	6,372- 8,420	5,764-14,119
50 - 100	6,372-7,711	3,519-7,038	8,499-11,965	14,407-28,814

Table 4 Cost and benefit from drying and storage

cultivation area (rai)	1 crop/year		2 crops/year	
	annual cost ฿	benefit ฿	annual cost ฿	benefit ฿
10 - 19	5,269-5,505	1,538- 3,006	5,663- 6,293	3,716- 7,144
20 - 49	5,505-6,293	3,076- 6,229	6,372- 8,420	7,432-16,836
50 - 100	6,372-7,711	6,299-10,491	8,499-11,965	17,187-31,594

From table 3 it can be seen that the solar hut dryer used for drying alone is economical when the cultivation area is more than 100 rais for 1 crop/year and about 25 rais for 2 crops/year. If the hut is also used as a paddy storage, the cultivation area is reduced to 55 rais for 1 crop/year and 17 rais for 2 crops/year (Table 4). The minimum cultivation area will be further reduced if the yield per unit area increases

4. Conclusion

The maximum efficiency of the solar collector according to the ASHRAE Standard Test 93-77 is 29 % at the air flow rate of 0.018 kg/s-m^2.

Drying rate is about 6-7 % dry-basis per 24 hours depending on both drying air and paddy conditions. Ventilation at night can reduce the moisture content but it makes the specific energy consumption for moisture evaporation increased. However, the moisture gradient of paddy in the dryer decreases. To compromise both advantages ventiation at night may be partly done.

The economic analysis indicates that the solar hut dryer used for drying alone is economical when the cultivation area is about 25 rais and two crops per year is practiced. If the solar hut dryer is also used as a paddy storage, the minimum cultivation area is reduced to 17 rais.

5. Recommendation

It was observed during the test that loading paddy in and out of the dryer was a hard work even for farmers. Therefore, the solar hut dryer should be modified so that it requires the labour as minimum as possible .

Introduction of the solar hut dryer may cause the chain of rice production changed. Thus the farmers may not accept it. In addition, the poverty of the farmers is also an important problem. It is thus valuable to do a study on socio-economic aspect.

Symbols

A	area, m^2
C_p	specific heat at constant pressure, J/kg K
F_R	collector heat removal factor
G	global solar radiation, W/m^2
h'_{fg}	latent heat of vaporization of moisture in grain, J/kg
L_p	length of the solar collector, m
L_{ps}	spacing between the absorber and insulation, m
$\dot{m}$	mass flow rate, kg/s
m_w	mass of water evaporated, kg
RH	relative humidity, %
t	time, s
T	temperature, K

U_L	total lost coefficient, W/m^2K
V	wind velocity, m/s
α	absorptivity
ε	emissivity
η	efficiency
β	tilt angle, degree

Subscripts

a	ambient air
c	collector
f	fluid
i	inlet
m	mean
o	outlet
p	absorbing plate

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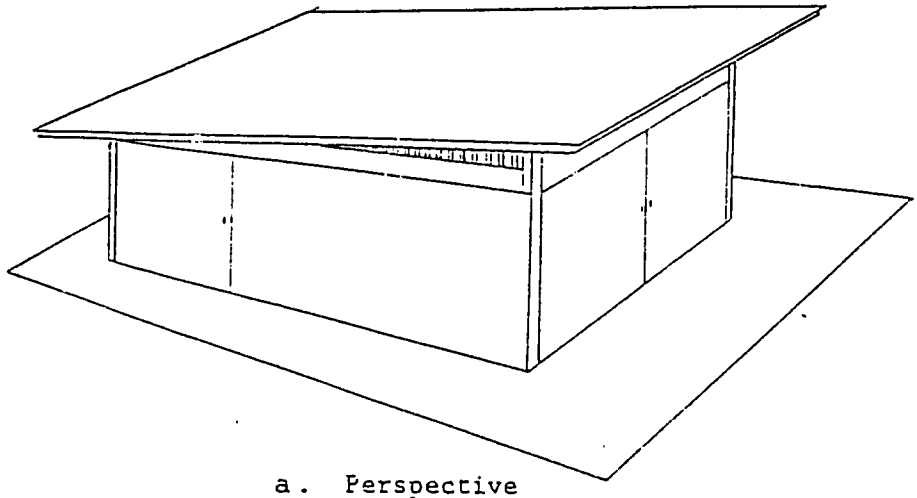
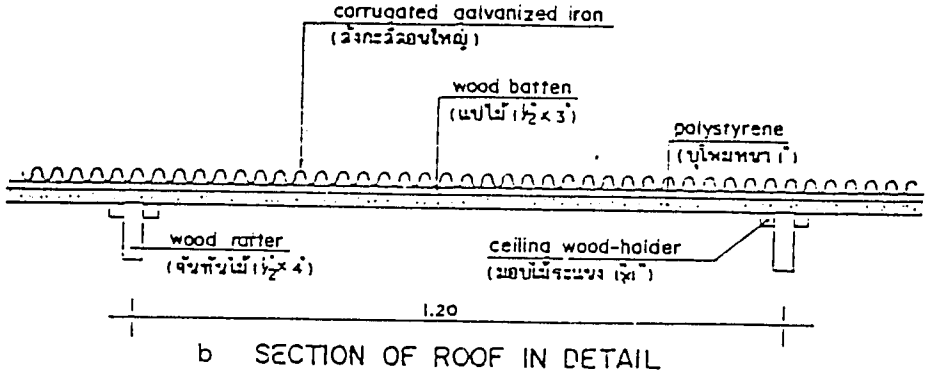
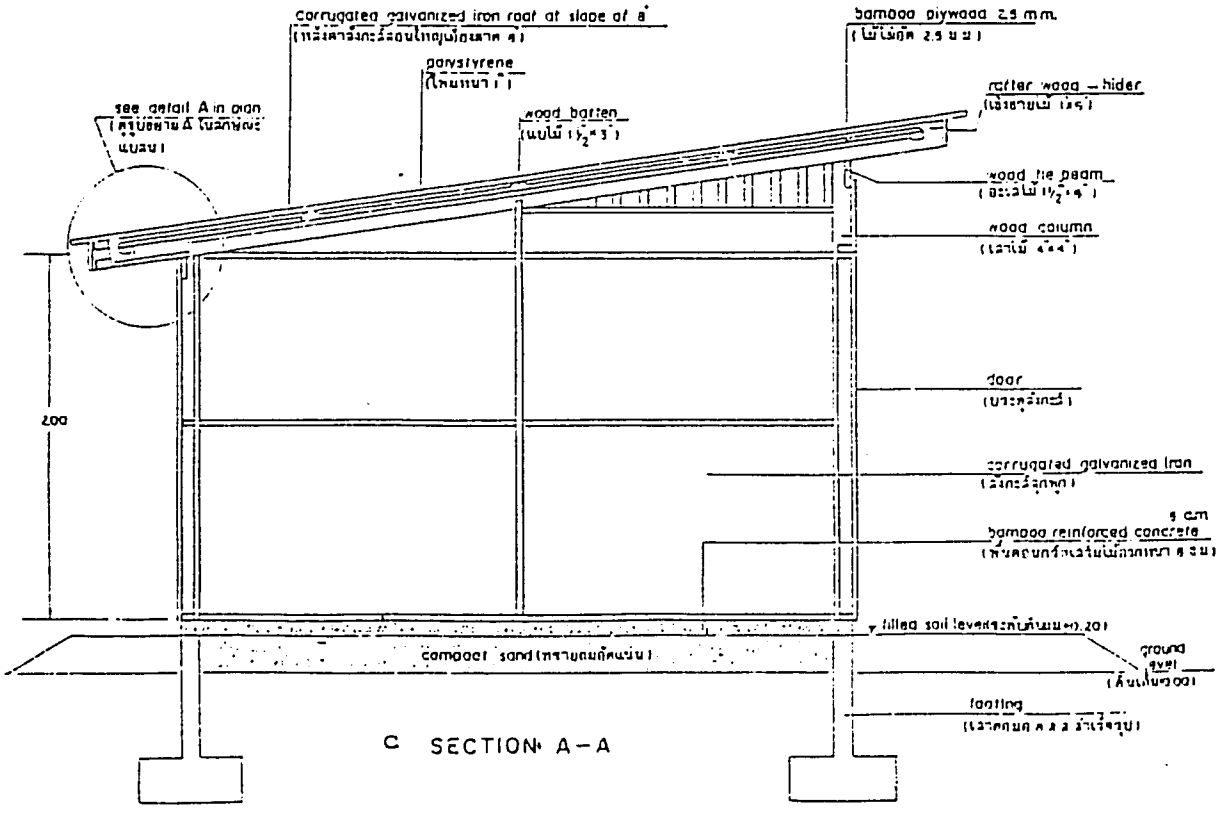


a. Perspective



b SECTION OF ROOF IN DETAIL



C SECTION A-A

Figure 1 Solar hut dryer

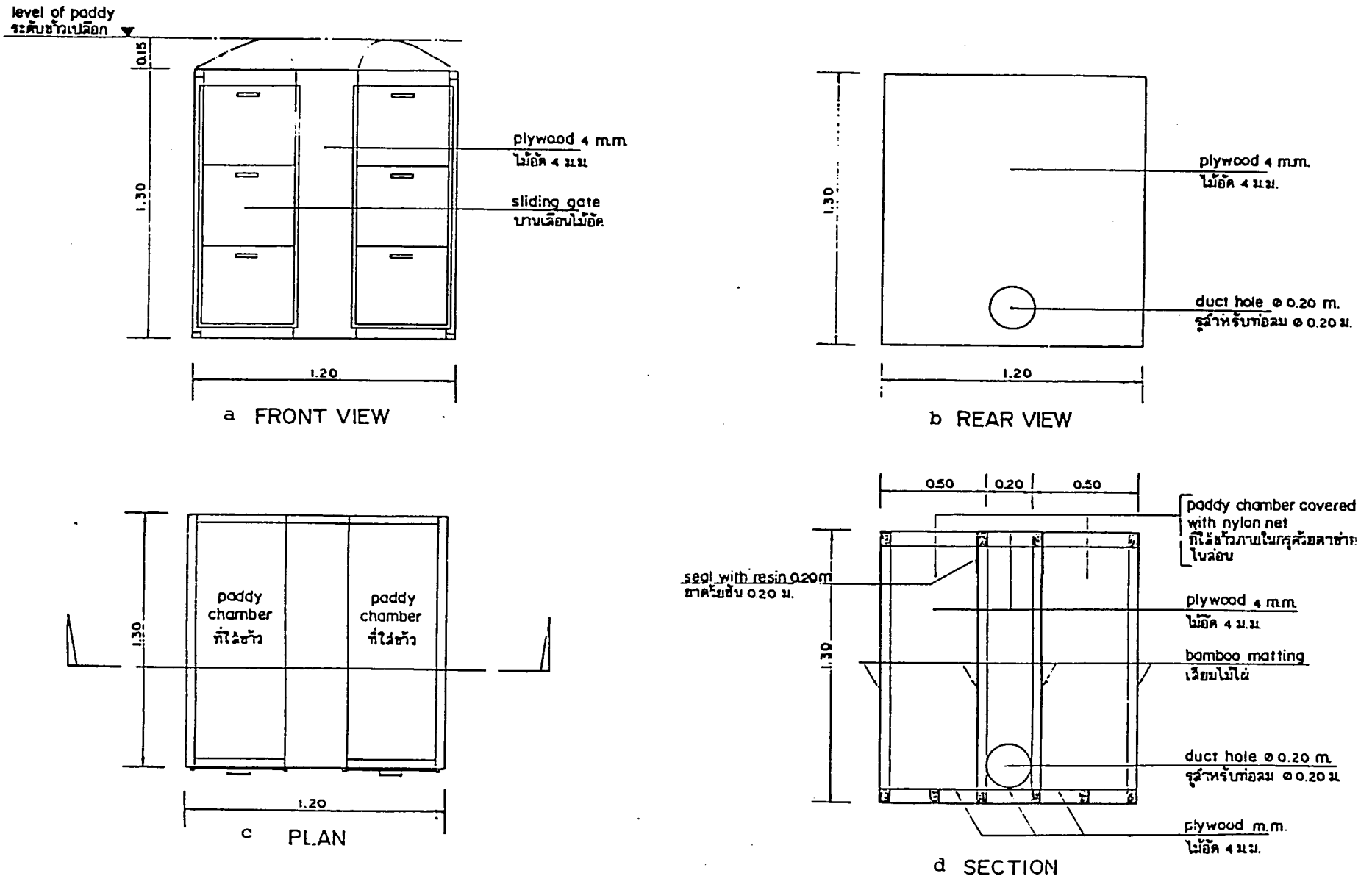


Figure 2 Vertical fixed-bed dryer

× location of paddy sampling (ตำแหน่งเก็บตัวอย่างข้าวเปลือก)

o temperature sensor (ตำแหน่งตัววัดอุณหภูมิ)

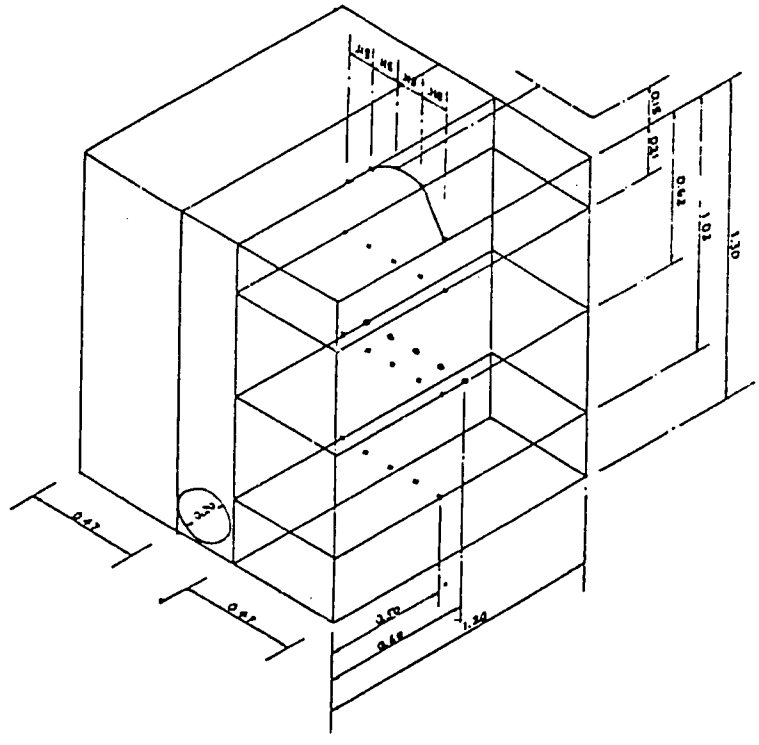


Figure 3 Locations of paddy sampling and temperature sensors

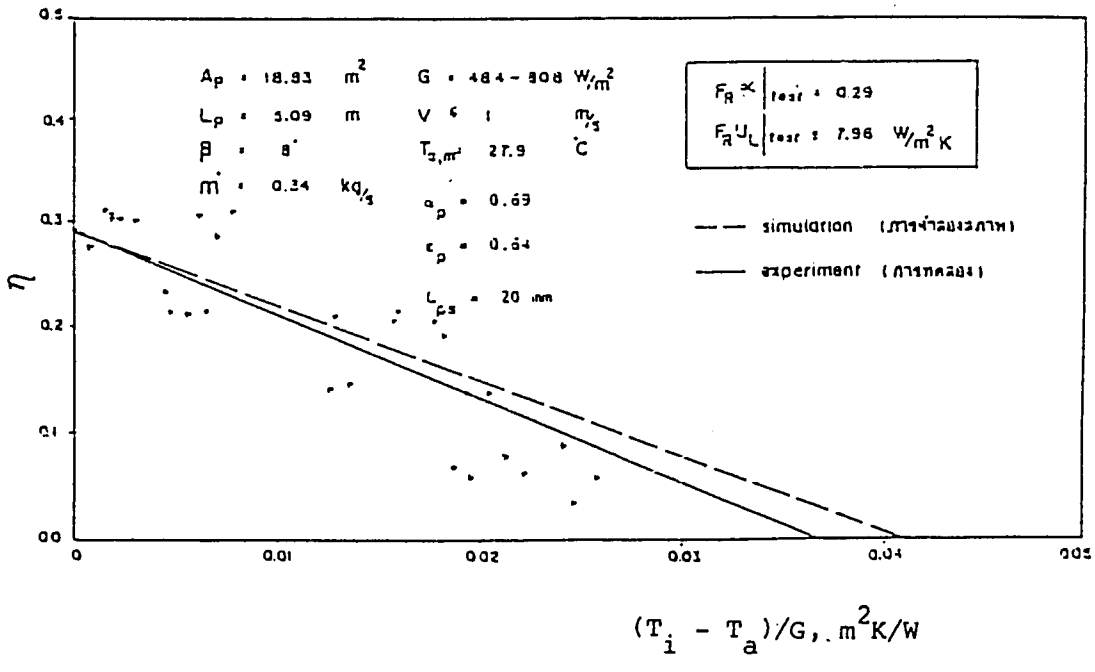


Figure 4 Comparison between experimental and simulated efficiencies for unglazed solar air collector, Nov - Dec 1983

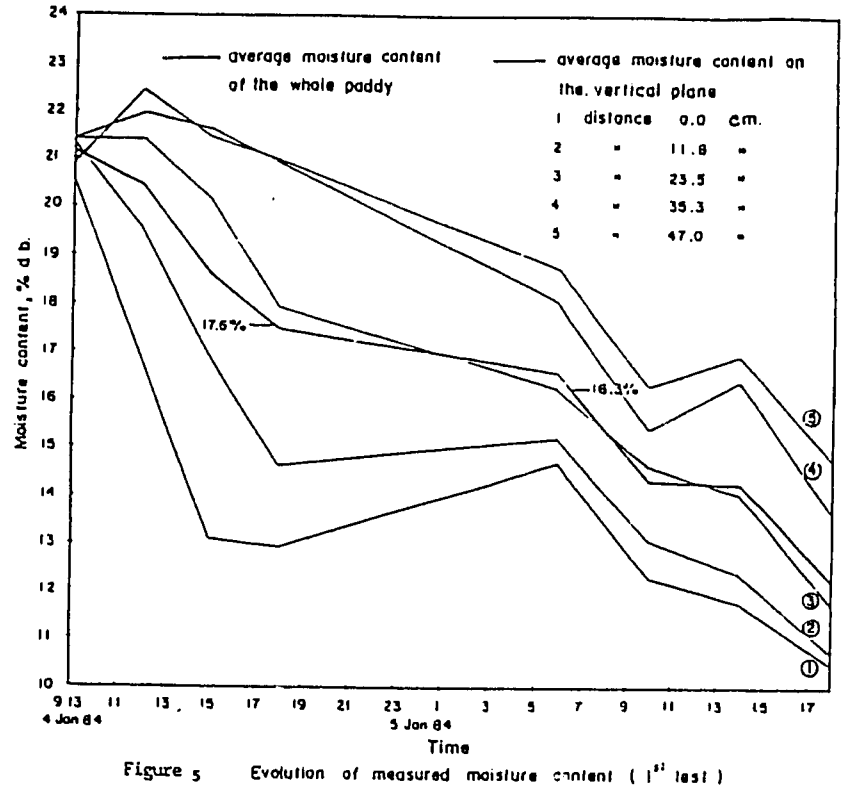


Figure 5 Evolution of measured moisture content (1st test)

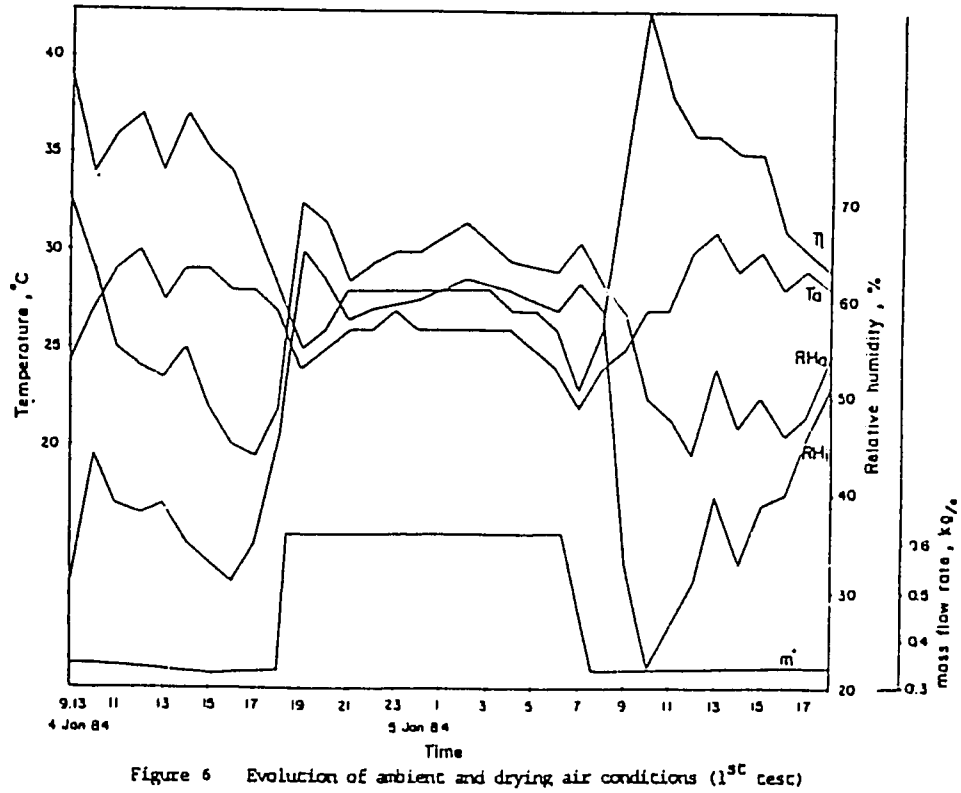


Figure 6 Evolution of ambient and drying air conditions (1st test)

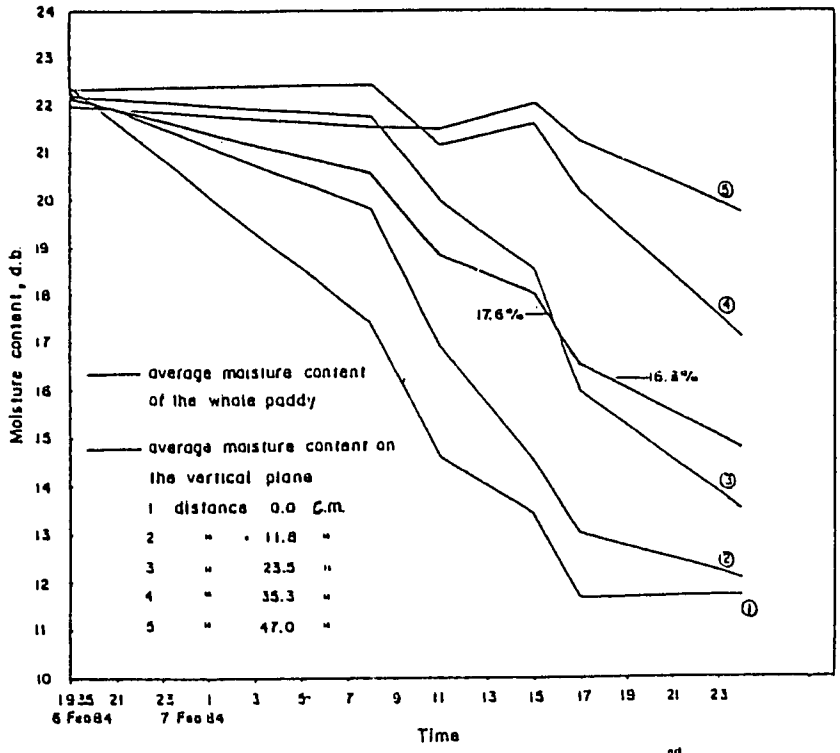


Figure 7 Evolution of measured moisture content (2nd test)

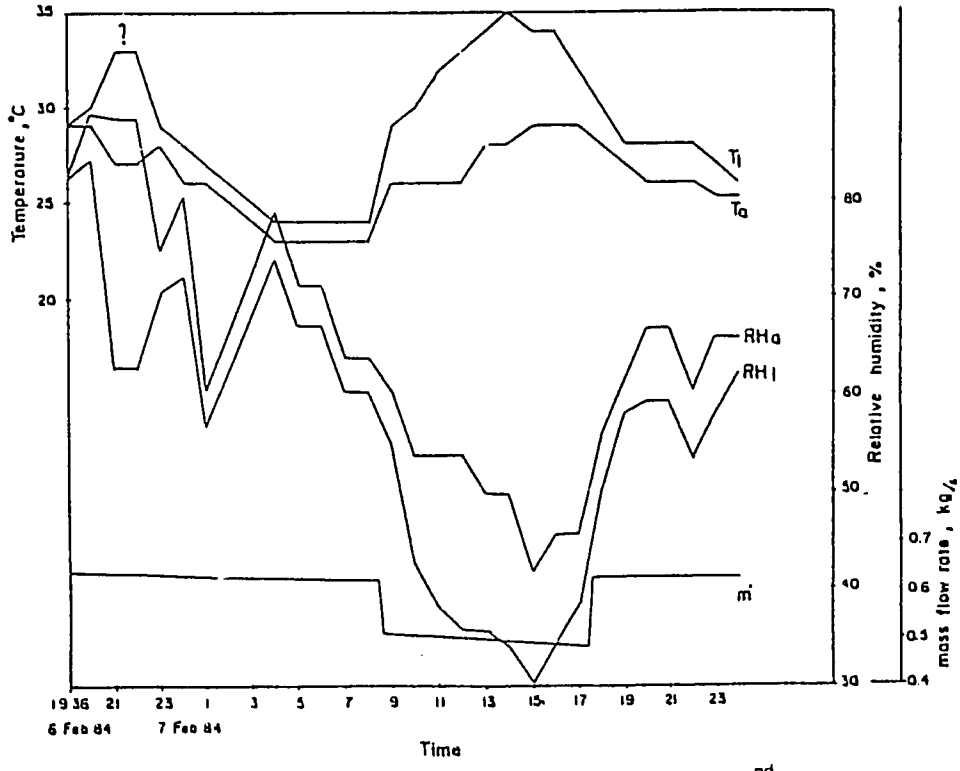


Figure 8 Evolution of ambient and drying air conditions (2nd test)

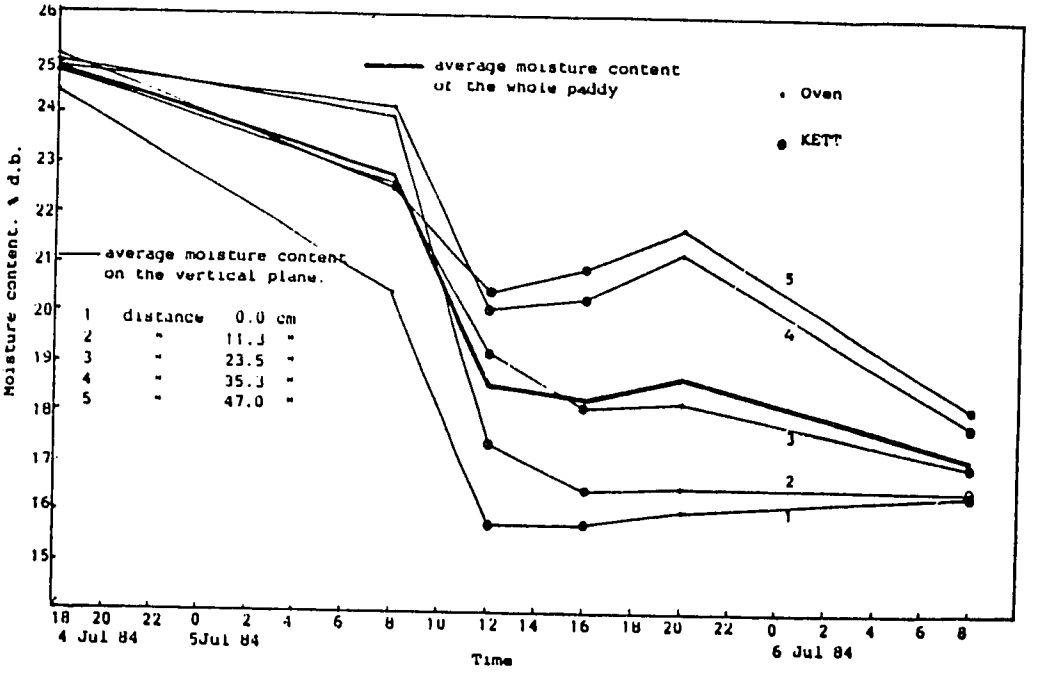


Fig 9 Evolution of measured moisture content (3rd test)

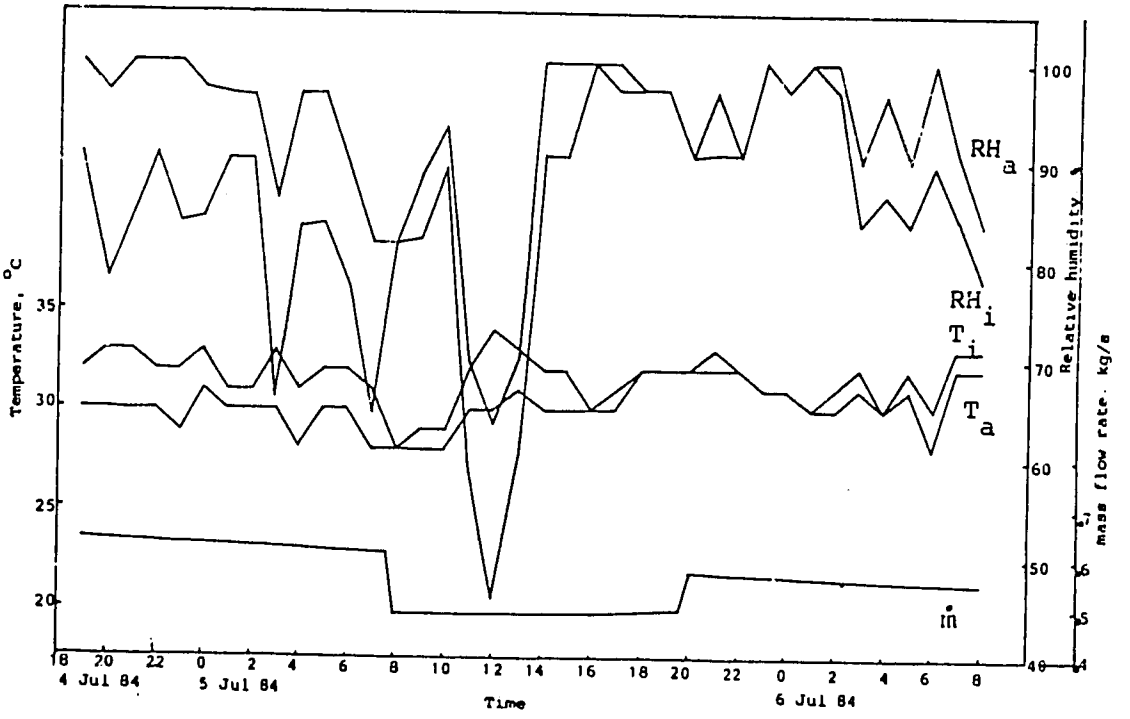


Fig 10 Evolution of ambient and drying air condition (3rd test)

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