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

A Study on

NATURAL CONVECTION CABINET DRYING

Submitted to the
National Energy Administration
Ministry of Science, Technology and Energy

Under the
Renewable Nonconventional Energy Project
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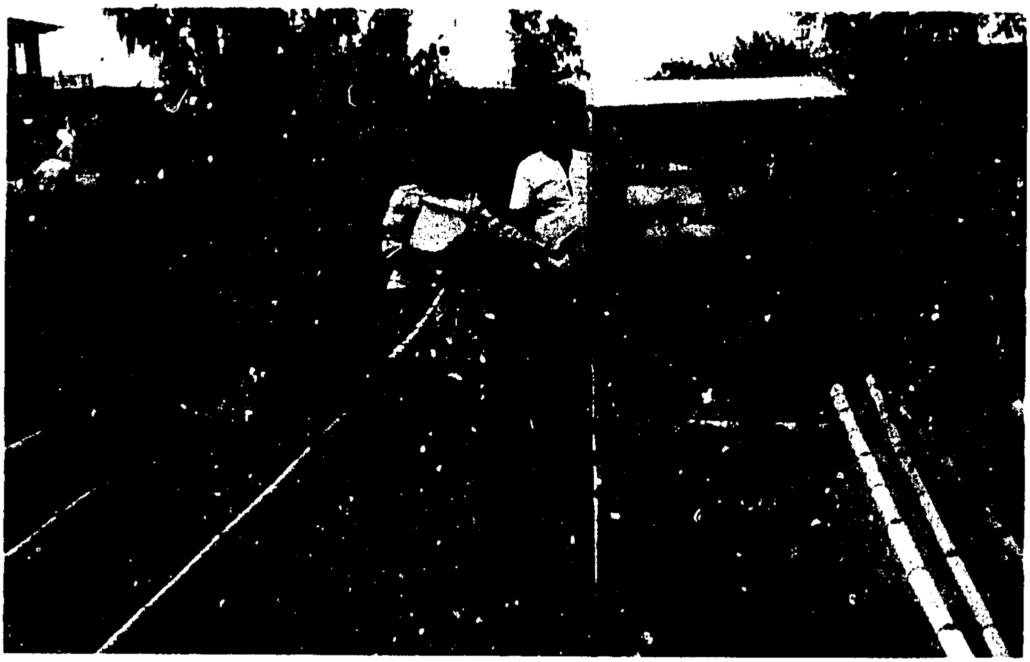

A solar cabinet dryer field tested at Phitsanulok

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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ACKNOWLEDGEMENTS

As author of this report I would like to thank Professor Prida Wibulsawas, the component leader, for his contribution and efforts in developing the solar drying work at KMIT, Thonburi and for his guidance throughout the project.

Mr. Robert Vernstrom, Mrs. Autcharapan Jitmanas, Mr. Jadet Bunyasiri, Mr. Tinnakorn Cleesunthorn and Mr. Watanapong Rakvichien are also acknowledged for their assistance and cooperation in providing sites for field tests. Further thanks are due to the workshop staff at the Faculty of Energy and Materials and lastly, to Miss Varunee Vatabutr, my counterpart, for her assistance and companionship.

Gratitude is also expressed to the U.S. Agency for International Development (USAID) for giving NEA the financial support necessary to initiate the solar drying sub-project.

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EXECUTIVE SUMMARY

The objective of the solar drying project was to introduce the technology of solar drying to Thai villagers by developing a simple, inexpensive solar dryer that could be used for small to medium scale drying of food/agricultural products. A cabinet dryer with a separate air heater was chosen in which air circulation in the cabinet occured by natural convection--no external power was required.

Preliminary tests were conducted to find the most efficient type of air heater and to study the important parameters affecting dryer performance. The results obtained were used to design a dryer for field testing.

Cabinet dryers were field tested at 5 selected sites, namely: Muaglek-Saraburi, Samuthsakorn, Bangkrathum-Pithsanulok, Wat Chant-Pithsanulok and Petchburi. The products dried were bananas, salted fish, salted beef and sweet coconut chips. The procedure was to determine the drying rates and compare the product quality to sun-drying.

For such products as salted beef and coconut chips, for which the drying times are short and the color is not crucial, the application of the dryer was satisfactory. The drying time was reduced approximately 20%. However, a few problems were encountered in the drying of bananas and salted fish. The air circulation in the cabinet was not enough to remove water, even though the temperatures in the dryer were high enough. The characteristics of the solar-dried products were different from the sun-dried products. In addition, unequal drying rates and poor heat distribution caused uneven color, particularly for bananas. And for these two products, the drying time was not shortened significantly. The following conclusions can be drawn from the field test results and from the comments of the users:

1. All users agreed that the dryer provided clean, hygienic products and protected the products from intrusion of animals.

2. The application of the dryer depends upon individual needs and types of products. The users feel that the dryer is not needed when the amount of produce to be dried is small and the drying time is already short.

3. For products like bananas in which color and softness are important, the application of the dryer requires experience and careful operation. For these products the dryer itself needs to be improved.

4. Some of the villagers are interested in using the dryer provided that it is cheap, can be used during the rainy season and the product quality can be maintained --or upgraded.

As a result of the field tests, a number of design changes in the dryer are recommended. It is recommended that the wire-mesh drying trays be replaced by bamboo trays, since wire can become rusty and cause cuts/marks on the products. The temperature on the top tray should be reduced. This can be accomplished by enlarging the outlet port opening which will also enhance air flow. The addition of a chimney or a circulating fan will help distribute heat in the dryer, increase air circulation and, thus, improve dryer performance.

Conclusions

The following conclusions summarize the technical data obtained from the field tests, as well as experiences and comments of the users.

Cleanliness

All users agreed that solar-dried products are cleaner and more hygienic than sun-dried products. The dryer protects the products from intrusion of animals, and prevents spoilage due to wind and rain.

Success of Application

The success of the application of the dryer to various products is dependent upon each product, individual techniques of the drying process, and those characteristics of dried products that are accepted by particular communities since the drying characteristics of products vary from one to another.

Small-Scale, Medium-Scale & Industrial-Scale Drying

The villagers who are involved in a small-scale drying are not interested in adopting the solar-drying technique. Those who dry a medium amount of produce show interest, provided that the quality of the products are better or, at the least, the same as sun-dried products. They also require that besides, the dryer be cheap and efficient. These results imply that the natural convection cabinet dryer would be inappropriate for industrial scale drying.

Dryness and Appearance of Product

If the only purpose of drying is to reduce the moisture of the product, and its color and texture are not significant, the solar-dryer developed for this study will serve the purpose. However, with certain products such as bananas where color, and softness affect the quality and price of the product, careful operation and experience are required to use this dryer effectively.

Dryer Design Characteristics

- Wire mesh trays become rusty and cause cuts on the product surface.
- Ventilation of humid air in the dryer was low and affected the quality of the products.
- Temperatures of the top tray were too high.

Recommendations

Dryer Design Characteristics

1. Wire-mesh trays can become rusty and cause marks and cuts on product surfaces. Trays made from bamboo, nylon nets which are cheaper should replace wire-mesh trays.

2. It was observed that ventilation of humid air in the dryer was low. This affected the quality of the products. Thus, a larger outlet port opening is suggested. The work in progress at King Mongkut's Institute of Technology, Thonburi (Wongsiri,1984)reports that when a ventilation fan ($\sim$ 40 W) was placed at the top-back door of the dryer, the heat distribution in the dryer was improved and this improved the product quality.

3. The temperature of the top tray was too high. The users suggested that the outlet-port be enlarged or the transparent roof (cover) changed into an opaque sheet.

Medium-Scale Drying

The results of the study showed that the most interest was generated by medium-scale users. Thus, further studies in developing a more efficient dryer should concentrate on this group.

Dryness and Appearance of Product

Procedures for ensuring careful operation for the dryer to produce attractive products should be established where appearance is a critical aspect of saleability.

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Chapter 1

Introduction

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INTRODUCTION

This report discusses the development of a simple, inexpensive solar cabinet dryer that can be used for small to medium scale drying of food/agricultural products. Those problems associated with sun drying and convectional drying which have caused so much interest in solar drying are discussed.

A. BACKGROUND

In many developing countries sun-drying is conventionally used to dry and preserve diverse products such as fruits, vegetables, cereal grains, meat and tobacco. Since sun-drying is practiced in Thailand the local population is familiar with both sun-drying techniques and sun-dried products. However, there are several problems with sun-drying:

- It is intermittent, as it is affected by rain and clouds;
- It is affected by dust and atmospheric pollution;
- It is not safe from intrusion by people and animals; and
- The products being dried are subject to infestation by insects.

In developing or industrialized regions throughout the world, artificial drying supplants traditional sun-drying in order to achieve better quality control, reduce spoilage and cut down the losses and inefficiencies introduced by the difficulties mentioned above. However, the advent of higher prices for fossil fuels and the prospect of depletion and scarcity of these fuels has stimulated interest in solar agricultural dryers.

When evaluating technologies that might be suitable for developing areas, one should distinguish between small and large-scale operations. In the case of artificial drying technology, small-scale dryers would be used for individual families or producers when the amount of produce to be dried is small and where space is limited. Especially when the main objective is to introduce the solar-drying technology for crafting and using (and even refining) at the village level, small-scale dryers must be of low-cost and simple designs. This means that the dryers must be able to be easily built with inexpensive materials. The dryer should work without any additional input of energy and be capable of drying a variety of crops to increase its utility to the users throughout the year.

B. OBJECTIVES

The objectives of this study were to:

1. Develop a cabinet type natural convection solar dryer;
2. Test the dryer for optimum design and performance; and
3. Demonstrate the application of the designed dryer for drying of foods/agricultural products at various sites.

C. SIGNIFICANCE

The natural convection cabinet dryer developed in this study was to be appropriate for the small to medium scale drying of some foods/agricultural products and was to ease the problems of sun-drying. Since the design and operation of the dryer was to be simple and its cost low, the dryer would serve the needs of Thai villagers/families.

D. SCOPE

This solar dryer study includes detailed designs for construction of the natural convection cabinet dryer designed and developed under the Solar Thermal Processes Component.

Laboratory tests of the performance of dryers of the same basic design were compared as follows:

- Dryers having glass/plastic cover for the cabinet and the air heater.
- Dryers with and without an air heater; and
- Dryers with 6 different types of air heaters.

Field tests on the drying of bananas, salted fish, salted beef and sweet coconut chips were conducted in order to compare the results on the basis of drying rate and quality of dried products compared to those of sun-drying under the same weather conditions.

Users' attitudes were also to be assessed.

Chapter 2

Review of the Literature

REVIEW OF THE LITERATURE

Solar dryers may be classified according to their heating modes or the manner in which heat, derived from solar radiation, is used. In the "direct" solar dryer, heat is generated by absorption of solar radiation on the product itself as well as on the internal surfaces of the drying chamber. This heat evaporates the moisture from the drying product and serves to expand the air in the enclosure, causing the removal of moisture by the circulation of air. In "indirect" solar dryers, solar radiation is not directly incident on the material to be dried. Air is heated in a solar collector and then ducted to the drying chamber to dehydrate the product. Where the combined action of solar radiation incident directly on the material and preheated in a solar air heater furnishes the heat required to complete the drying, then such a dryer is called a "mixed-mode" dryer.

Various designs of solar dryers have been proposed and employed for the drying of different products. The dryer is called a "forced convection" dryer when a fan or blower provides air circulation. "Natural convection" dryers are those in which heated air circulation is caused by its density gradient. A review of natural convection solar dryers is presented below.

The most simple design for a solar dryer was developed by the Brace Research Institute, Canada, (1975). It is essentially a hot box where fruits, vegetables or other materials can be dehydrated on a small scale (see Figure 2.1).

The construction of such a dryer can take many forms. Nevertheless, certain specifications were recommended. The experimental results at Kampur, India (Chantawanasri, 1978) for the drying of fruits and vegetables showed that solar-drying saved considerable time compared with sun-drying in the open. Also, the product obtained from the solar dryer was found to be superior in taste and odor to sun-dried produce and was not contaminated by dust or infested by insects.

Studies of the design parameters which affect the performance of solar box-dryers were carried out at KMIT, Thonburi (Thaina, 1980) and at Prince of Songkla University (Chantawanasri, 1978). A similar dryer was used for drying bananas (Vatabutr, 1981) and the results showed that, compared with sun drying:

- The drying time was 2 days shorter;
- The product had better appearance; and
- Solar-dried produce lost vitamin C more than sun-dried produce. This was due to the high temperatures (58.5 -75°C) in the dryer.

A solar tent-dryer was developed for fish drying in Bangladesh (United Nations, 1978). The dryer consisted of polyethylene sheeting on a bamboo frame. The dryer proved successful in killing flies. An improvement in drying time was obtained. The Bangladesh authorities proposed to construct this type of dryer for fish-drying communities.

In Columbia, a vertical dryer designed for drying cassava particles was tested (Chantawanasri, 1978). It was made of wooden uprights and two wire-mesh panels. Top and bottom openings made the dryer easy to load and unload. The unit was covered with a wooden roof to protect the produce from rain and to allow drying to continue overnight. This drying method produced a high-quality cassava that was easy to handle and store.

The see-saw dryer was originally developed in the Ivory Coast for drying coffee and cocoa beans (Chantawanasri, 1978). The dryer consisted of a rectangular tray framed in wood and divided length-wise into parallel channels of equal width. Retaining bars were placed crosswise. The tray was covered with a transparent PVC film and all the internal parts of the dryer were painted black. The see-saw operation was achieved by mounting the drying frame on a north-south trestle. The frame was tilted to face east during the morning and west during the afternoon. This increased output led to a more evenly-dried product.

A glass-roof dryer was developed in Brazil (Chantawansri, 1978). Its principle was similar to a greenhouse (see Figure 2.2) except that there was a ridge cap of folded zinc sheeting that allowed moist, heated air to escape and fresh air to enter through side shutters. The drying surface was made of galvanized iron wire-mesh. All internal surfaces were painted black to facilitate the absorption of solar radiation.

The simple mixed-mode chamber dryer was designed (Chantawansri, 1978) to dry fruits and vegetables for domestic needs and for small. restaurants. Figure 2.3 shows a section view of this dryer. The dryer worked on the same principles as the natural-convection cabinet dryer reported herein. Air, preheated in a solar air heater, was admitted at the bottom of the dryer. From there it flew through the drying racks, dehydrating the product; it was then exhausted through openings located at the top rear wall of the chamber by natural convection. Drying was also carried out with the help of direct sunlight reaching the product through the transparent side, front and top panels.

A low-cost solar rice dryer was developed at the Asian Institute of Technology (Doe, 1977) (see Figure 2.4). The dryer was made of bamboo poles covered by a transparent plastic sheet. Air was naturally circulated above the absorber (made of burnt rice husk) through the paddy layer(of which optimum thickness was determined to be approximately 10 cm). On sunny days such a dryer could dry 80 kg of paddy per square meter of space available in the dryer. During the rainy season it dried about one ton of paddy per sunny day. When it was overcast, one ton of paddy took three or four days to dry.

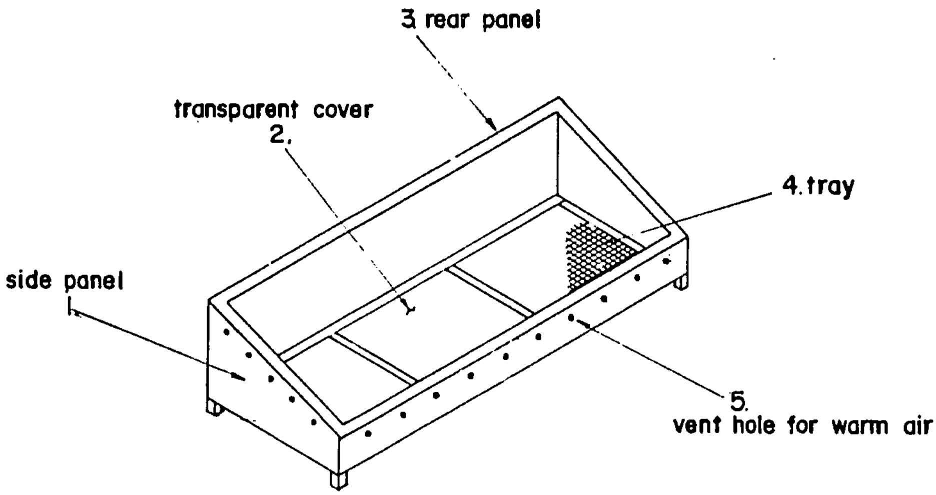


Figure 2.1 Box dryer

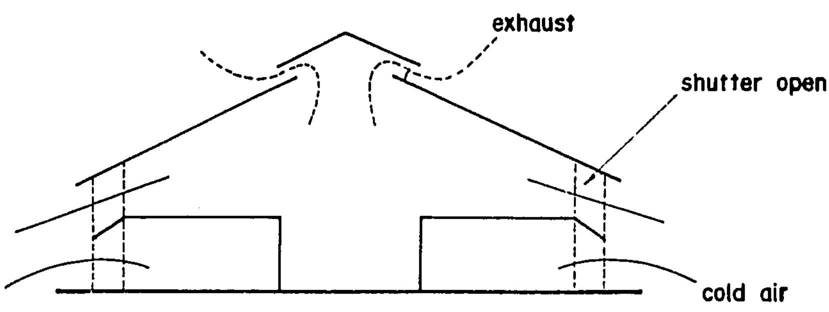


Figure 2.2 Glass-roof dryer

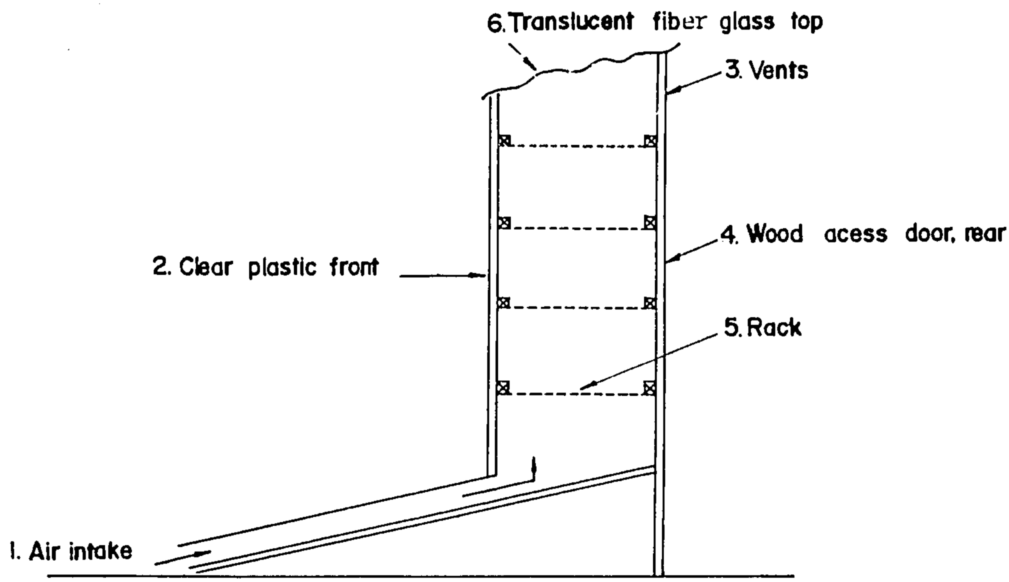


Figure 2.3 Section view of the fruit and vegetable dryer

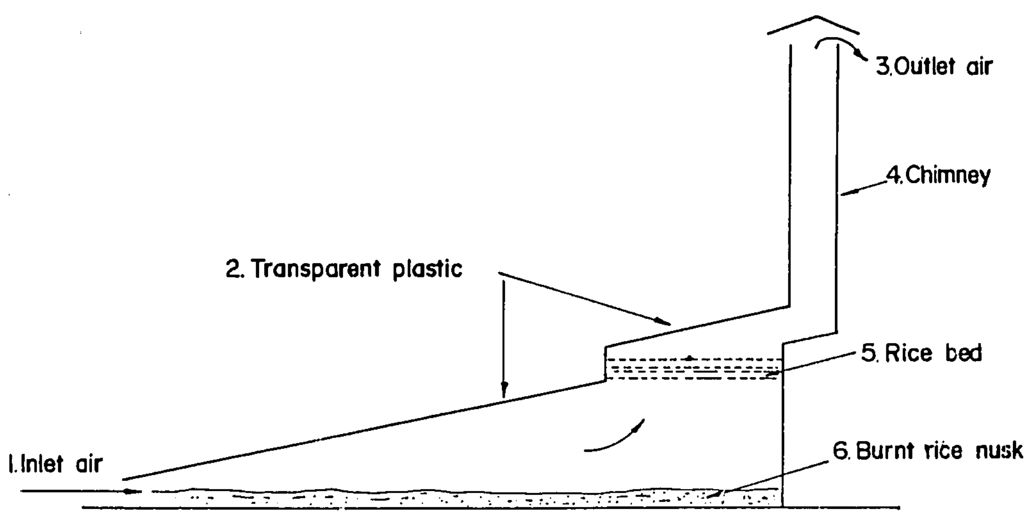


Figure 2.4 AIT rice dryer

Chapter 3

Design of the Project

DESIGN OF THE PROJECT

To introduce solar drying technology to the village, it is important that practical, social and economic considerations are taken into account. Thus, in selecting a solar dryer, the following selection criteria were required. It must:

- Have no external power sources;
- Be easily duplicated by villagers with readily available materials;
- Be on an appropriate scale (in operation and economics) for individual farmer/family or village co-op;
- Have more than one use (year-round utility); and
- Be inexpensive and efficient.

The design adopted for this study, i.e., the natural convection cabinet dryer, was expected to meet the criteria mentioned above.

A. DESIGN OF A NATURAL-CONVECTION CABINET DRYER FOR LABORATORY TESTS

The components which made up the cabinet dryer chosen for this study were the drying cabinet and the air heater. The cabinet (1.0 x 0.8 x 1.1 m.) was able to house drying trays. Its back wall was made of plywood painted black and its top was provided with an adjustable outlet port for moist air. The side, front and top covers were made of either plastic or glass sheeting.

The air heater was approximately 1 m. wide and 1.8 m. long. The inside surface was covered with a thin layer of matt black paint to provide the absorbing surface. A plastic or glass sheet was used as the cover of the air heater.

Since it was expected that the cabinet dryers (with/without air heaters constructed from different materials) would give different drying rates, the cabinet dryers developed for the laboratory tests were designed in 4 different ways:

- The dryer with a glass cabinet and a glass cover for the air heater;
- The dryer with a plastic cabinet and a plastic cover for the air heater;

- The dryer with a glass cabinet with no air heater; and

- The iryer with a plastic cabinet with no air heater.

A glass sheet of 3 mm. thickness and a polythene plastic sheet were used.

The cabinet dryer described above (in which the top, the front and sides of the cabinet were made of 3 mm. glass sheets) was tested to compare the performance of the six different kinds of air heaters listed below. (See Figure I.2 in Annex I).

- Glass cover and black mild steel sheet placed at the center of the air gap;

- Glass cover and black metal lathe placed on the floor of the air heater;

- Acrylic cover and black mild steel sheet placed at the center of the air gap;

- Acrylic cover and black metal lathe placed on the floor of the air heater;

- Fiber-reinforced plastic cover and black mild sheet placed at the center of the air gap; and

- Fiber-reinforced plastic cover and black metal lathe placed on the floor of the air heater.

B. FINAL DESIGNS FOR FIELD USE

The laboratory test results of the cabinet dryers (see Chapter 5) were use to finalize the designs for field use. The field dryer possessed the same general features as the laboratory dryers. The air heater which was found to give the highest drying efficiency was that which had a glass cover and a metal sheet absorbing plate at the center of the air gap. The outlet port opening area was 1.0% of the total absorbing surface. Two changes were made before field testing.

- The overall dimensions were enlarged; and

- Fiber-reinforced plastic sheets were used for the front and sides of the cabinet instead of glass.

These changes were made because glass and plastic sheets are available in standard sizes and, making the dryer larger, we were able to make use of all materials (no cutting wastes). Further, because plastic sheets are not breakable, the staff believed it would be more durable for field testing. The total cost of materials is shown in Table I.1 , Annex I.

C. DESIGN OF EXPERIMENTS

Laboratory Tests

The experiments were so designed that the design parameters affecting the drying rate and the dryer performance were established. Variables were the types of air heaters and the covers and sizes of the outlet ports. For convenience and consistency, pieces of wet cloth were used as a drying material.

Field Tests

The experiments on drying of foods/agricultural products were carried out in parallel, drying in the cabinet dryer and sun drying. With such an arrangement the drying rates and product quality could be compared for the same weather conditions.

Chapter 4

Techniques and Procedures

TECHNIQUES AND PROCEDURES

The techniques and procedures included in this chapter are based on the design of experiments as discussed at the end of the previous chapter for the laboratory to distinguish the parameters affecting dryer performances. During the field tests observations concentrated on drying time and quality of the products. Users' attitudes and comments were also noted.

A. LABORATORY TESTS OF DRYERS WITH & WITHOUT AIR HEATERS WITH PLASTIC OR GLASS COVERS

Tests were carried out on the cabinet dryer with and without air heaters A large number of square pieces of cloths folded into rectangular blocks and saturated with water were used as drying material.

Pieces of wet cloth for each drying tray were weighed in the morning before loading into the dryer. Drying took approximately 8 hours per day. After that the dried sample was weighed. Temperatures at various positions in the dryer were measured at intervals. Daily radiation was also recorded. By these methods the following data were calculated.

By setting the outlet port area at 0.013 m^2 for all dryers we were able to compare the drying rate vs. daily radiation of the 4 different types of dryers as described in the design section of Chapter 3. (See results in Fig. II.1, Annex II.)

Tests were carried out on the cabinet dryers with and without air heaters. A large number of square pieces of cloth folded into rectangular blocks and saturated with water were used as drying materials. Data were recorded on the following variables.

- Drying rate vs. daily radiation for the dryers having the same outlet port areas of 0.013 m^2 for 4 cases;
- Drying rate from five drying trays in the cabinet dryer having glass cover and air heater; outlet port area of 0.013 m^2,
- Drying rate from five drying trays in the cabinet dryer having plastic cover and no air heater; outlet port area of 0.013 m^2,
- Drying rate vs. outlet port area for the cabinet dryer having air heater and glass cover.

B. LABORATORY TESTS OF DRYERS WITH DIFFERENT AIR HEATERS

The outlet port area was set at 1.1% of the horizontal absorbing area. The daily drying rate of wet cloth was to be determined. The measurements were as follows:

Drying Rate vs. Daily Radiation of the Cabinet Dryers

The amount of radiation in three different designs were tested. They were:

- Black absorbing plate at the middle of the air gap;
- Black metal lathe on the floor of the air heater, and
- Black paint on the floor of the air heater.

Drying Rate vs. Daily Radiation of the Cabinet Dryer Where the Air Heater Had Three Different Covers

The effect of three different air heater covers on the amount of radiation was tested. The air heaters were named as follows:

- Air heater with glass cover;
- Air heater with acrylic plastic cover; and
- Air heater with fiber reinforced plastic cover.

C. LABORATORY TESTS OF A CABINET DRYER FOR DRYING OF BANANAS

A cabinet dryer designed for the laboratory tests (see the "Laboratory Test Results" in Chapter 5 and Annex IV) was used to dry bananas. Four batches of drying were carried out. Each batch required approximately 480 bananas. The following data were recorded:

- Daily solar radiation;
- Ambient temperatures;
- Temperatures at various positions in the dryer;
- Daily weight loss of each tray; and
- Initial and final moisture contents of bananas.

During the tests there was no interchange of trays. The bananas were flattened after the second day and were turned over every day.

D. FIELD TESTS - TECHNIQUES & PROCEDURES

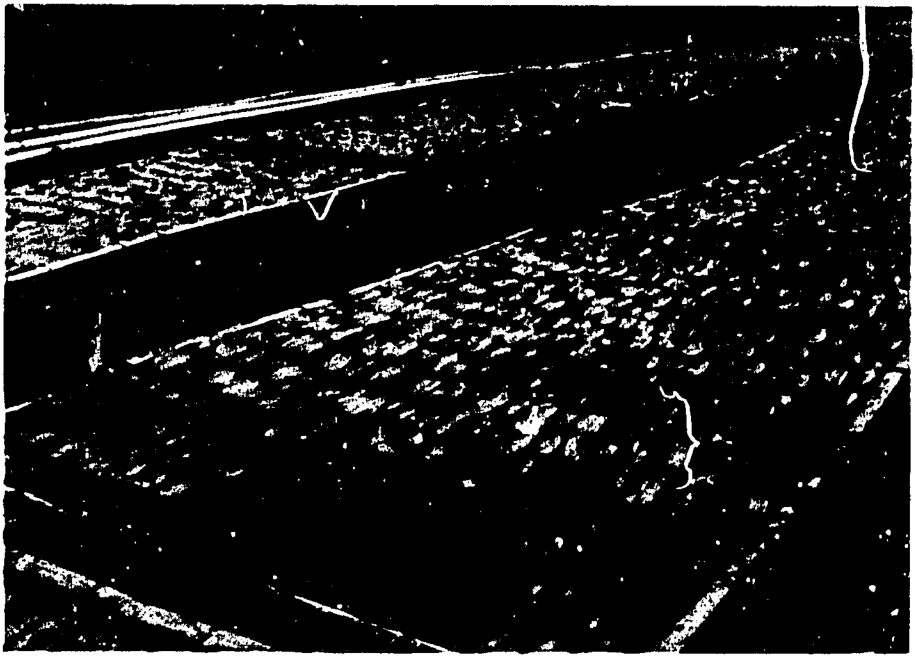
The cabinet dryers designed for field tests were tested at 5 selected sites, namely:

- Muaklek, Saraburi, for drying of beef, bananas and sweet coconut chips;
- Samuthsakorn, for drying of salted fish;
- Bangkrathum, Phitsanulok, for drying of bananas;
- Wat Chanth, Phitsanulok, for drying of salted beef; and
- Phetburi, for drying of bananas.

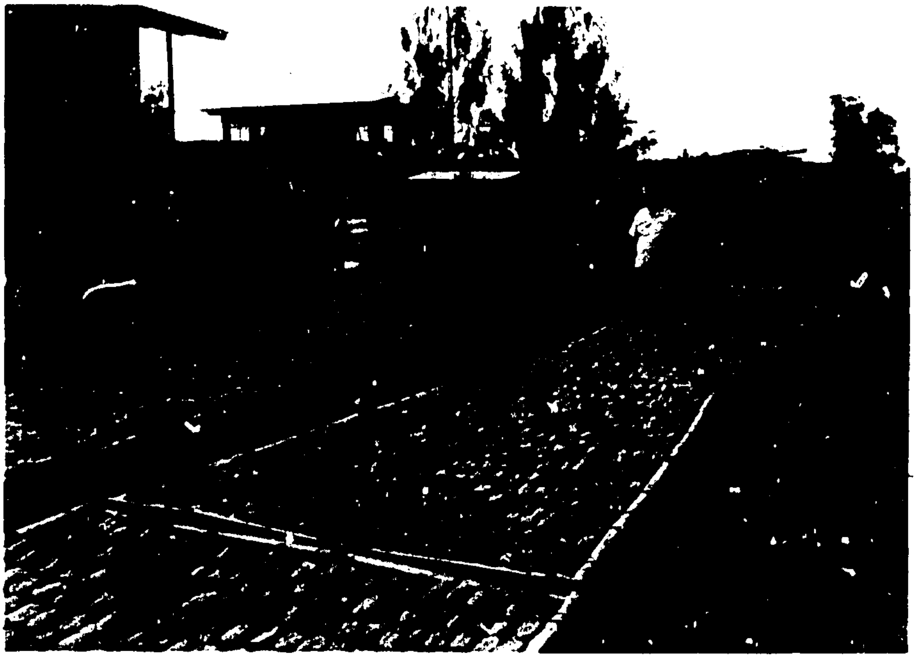
The test procedures for each site/product were the same:

- The dryer was placed outdoors with its air heater facing south;
- The product to be dried (after pretreatment, if necessary) was weighed and was loaded in the morning;
- The temperature of the ambient air and of the air near the outlet port were measured every 2 hours;
- The product might be turned or trays might be interchanged, depending on the products and users' observations;
- The product was weighed after it had been properly dried; and
- A certain amount of the same product was also sun-dried on the same days.

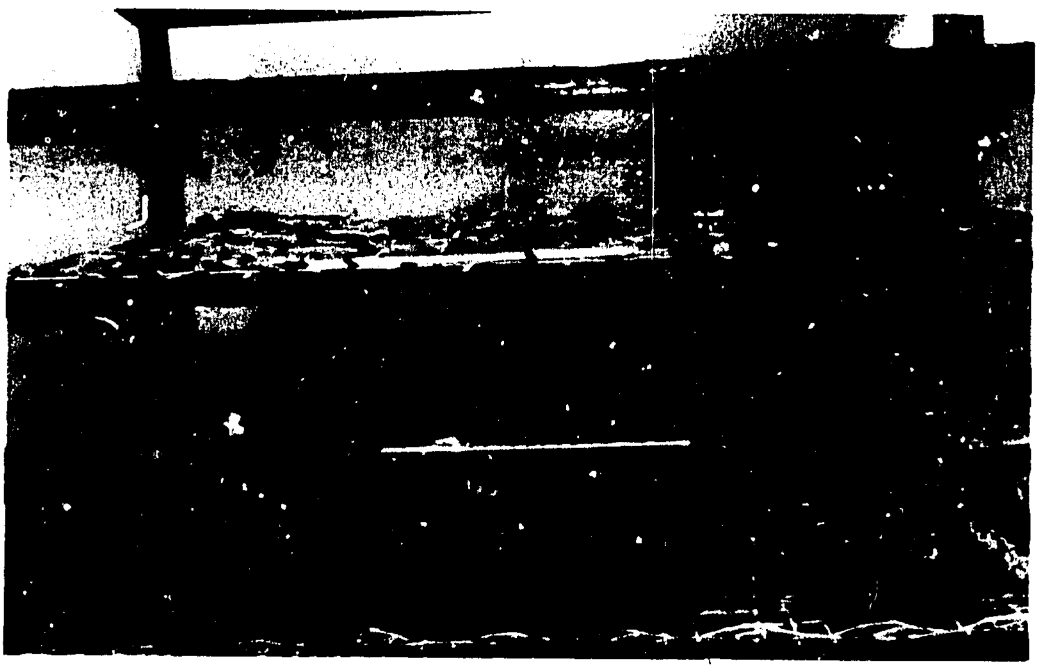
The typical data sheet handed out to users is shown in Annex V.



Sun-drying of Bananas at Bangkrathum, Phitsanulok



Concurrent Sun-drying and Cabinet Drying of Bananas



Bananas drying in a solar cabinet dryer

Chapter 5

Results and Discussion

RESULTS AND DISCUSSION

A. LABORATORY TEST RESULTS

Dryers With and Without Air Heaters With Plastic Cover or Glass Cover

For a full discussion of "comparative performance of cabinet dryers with separate air heaters" see Annex III.

The test results of dryers with and without air heaters with plastic or glass cover were conclusive.

The dryer with a glass cabinet and with an air heater covered with glass was more efficient than the corresponding dryer using a plastic sheet since a glass cover suppresses the infrared radiation loss better than the plastic sheet. The air heater increased the drying rate by 13%.

For the cabinet dryer with an air heater, the drying rate of the top drying tray was highest since the top tray was exposed to more solar radiation than other trays. That of the middle tray was lowest.

The effect of the size of the outlet port on drying rate from the cabinet with a glass cover showed that the maximum drying rate was obtained when the area of the outlet port was about 0.8% of the total horizontal absorbing surface.

Results of the Cabinet Dryers With Different Air Heaters

The test results of the cabinet dryers with different air heaters conclude that the drying rate was highest when the air heater was covered with glass and the black absorbing plate was at the middle of the air gap. The optimum outlet port area was approximately 1.0% of the total absorbing surface area.

The above results were used to finalize the design of a laboratory dryer made up of a drying cabinet and air heater. The cabinet (1.0 x 0.8 x 1.1 m) was able to house drying trays. Its back wall was made of plywood painted black and its top was provided with an adjustable outlet port for moist air. The side, front and top covers were made of either plastic or glass sheeting.

Results of Laboratory Tests on Drying of Bananas

The data recorded were used to calculate drying rate and thermal efficiency. The appearance/quality of the solar-dried bananas were compared to the sun-dried bananas. See Table 5.1

Table 5.1 Laboratory tests on drying of bananas

	Set 1		Set 2	
Day	Total radiation (MJ/m^2)	Drying rate (kg/day)	Total radiation (MJ/m^2)	Drying rate (kg/day)
1	17.64	6.81	18.26	5.80
2	17.86	4.99	20.17	4.00
3	16.80	3.81	19.40	1.85
4	16.86	0.92	17.49	1.66
	12-15 April 1983		16-19 April 1983	
	Total thermal efficiency 22.3%		Total thermal efficiency 16.4%	

	Set 3		Set 4	
Day	Total radiation (MJ/m^2)	Drying rate (kg/day)	Total radiation (MJ/m^2)	Drying rate (kg/day)
1	18.19	5.44	19.83	6.76
2	17.31	4.94	20.50	4.89
3	19.69	2.41	18.58	2.21
4	18.08	1.78	18.24	0.93
	9-12 February 1983		15-18 February 1983	
	Total thermal efficiency 19.0%		Total thermal efficiency 17.8%	

Note Total thermal efficiency (%) =

$$\frac{\text{Latent heat of vaporization} \times \text{drying rate} \times 100}{\text{Total radiation absorbing surface area}}$$

Initial moisture content of bananas 65-70% wet basis
Final moisture content of bananas 25-30% wet basis

During the experiment the temperatures in the cabinet varied with time and positions of measurement; they sometimes reached 55°C. It was found that the drying rate was highest on the first day when the moisture content of the product was still high and decreased with time. The drying rate of the top (5^{th}) tray was higher than that of other trays because the product received heat from direct radiation through the sides and roof of the cabinet. The color of the bananas was uneven and bananas near the glass walls became brown. The sun-dried bananas were yellowish and softer.

To overcome these problems it is expected that the interchange of trays and the rotation of bananas will be necessary. In addition, those who have experience in producing dried bananas will know other practical techniques and important variables that will make the application and acceptance of the solar-cabinet dryer more promising.

B. FIELD TEST RESULTS

Quite a few problems arose when conducting the field tests. It was not easy to get sites where there were products to be dried and users or villagers interested enough to try the dryer with their expensive products without disturbing their routine. Due to the limitations of time and distance it was not possible to collect all the year-round field test data. The users sometimes used the dryer without filling out the data sheets. The dryer was often not fully loaded with the product since users needed to dry a specific amount of produce at certain times. However, from some completed results, interviews and discussions, evaluation of the results, identification of problems, and recommendations for changes were able to be accomplished.

Field Test Results at Muaklek, Saraburi

A dryer was given to a family owning a store selling dried bananas, dried salted beef and sweet coconut chips. The amount of product to be dried varies of is dependent on supply and sale conditions. The data collected are shown in Table 5.2.

Table 5.2 Test results at Muaklek, Saraburi

Product	Bananas	Salted beef*	Sweet coconut chips
Drying period	September '82	October '82	Oct'82 & Feb '83
Initial weight	41 kg	5 kg	10-14 kg
No. of fruit/tray	150-180	-	-
Final weight	17 kg	2.3 kg	5.5-9.8 kg
Drying time	5-6 days	5 hrs	1-1½ days
Interchange of trays	daily, 5th & 3rd	5th & 3rd	5th & 3rd
Turning of products	daily	none	none
Weather conditions	Most data were collected during the rainy season when there were both sunny and cloudy periods. There was some rain in the evening. The ambient temperatures recorded ranged between 28-33.5°C. The temperatures measured near the outlet port were not higher than 50°C, but went up to 55°C in February.		

* Beef marinated with salt, sugar and spices. Sun-drying takes 6-7 hours.

Users' Opinions

The users agreed that the cabinet dryer was convenient to use, but was too high for loading and unloading (especially, the top tray). The products obtained were hygienic since they were protected from dust and flies. When there was rain, there was no need to collect the products into shade. The cabinet dryer saved the drying space.

- Bananas: For drying of bananas the dryer did not shorten the drying time. The users also felt that the product quality was inferior compared to sun-drying. The surface of the bananas was dry and hard and the color was dark and uneven.

- Salted beef: Usually drying of salted beef is easier and takes much less time than bananas. The dryer shortened the drying time approximately 20%. The users were satisfied with the product.

- Sweet coconut chips: The dryer shortened the drying time. The product quality was as good as sun drying. In addition the product was clean and had a longer jelly-life.

Field Test Results at Samuthsakorn

The cabinet dryer was taken to a family at Samuthsakorn. This family sun dries varieties of salted fish except in the rainy season. Fish, after soaking over night in salt water, are laid on rectangular drying trays. The trays are made of old fishing net stretched on wooden frames. Drying, starting from the dipping condition, takes approximately 7 hours on sunny days.

The data that were collected on the cabinet dryer tests carried out during November 1982 are summarized in Table 5.3.

Table 5.3 Test results at Samuthsakorn

	Set 1	Set 2
Initial weight--in a dryer	7.5	8.0
Of fish (kg)--outside	7.5	8.2
Time of loading	9:00 AM	9:20 AM
Time of unloading	5:00 PM	4:20 PM
Final weight--in a dryer	4.3	4.8
Of fish (kg)--outside	5.1	5.7
Interchange of trays	Yes, 5th & 3rd at 12:00	Yes, 5th & 3rd at 11:00 AM
Turning of fish	Yes, 1:00 PM	Yes, 1:00 PM
Temperatures (°C)		
Near outlet port, ambient		
at 10:00 AM	48, 36	48, 37.5
at 12:00 noon	54, 41	54, 41
at 2:00 PM	53, 41	63.5, 41
at 4:00 PM	50, 38.5	51, 40

Users' opinions

The users felt that the use of a cabinet dryer was inconvenient. This was due to the unequal drying rate of each tray. Thus, interchange of trays was needed. The turning of fish was also more convenient when fish were sun dried than cabinet dried.

Fish dried faster in the dryer, and thus the final weight of solar-dried fish was less than sun-dried fish; thus, selling solar-dried fish means selling underweight fish, also, the skin of solar-dried fish was wetter than that of sun-dried fish, while the inside was dryer. When drying was continued outside the dryer in order to dry the skin, the product obtained was overdried and underweight.

Field Test Results at Bangkrathum, Phitsanulok

Bangkrathum is a district where the staple product is sun-dried bananas. Each family dries up to 100,000 hands of bananas per month. A cabinet dryer was given to a family that showed interest and was cooperative. The user commented and gave suggestions on the performance of the dryer and product quality on the basis of his experience.

Tests were carried out during December 1983 - February 1984 when rain was scarce and the weather was fine. The temperatures in the cabinet recorded during the day ranged 33-55°C, while the ambient temperatures were 20-34°C. Approximately 50 kgs of bananas were loaded. Weight loss (after 4 days) was about 20 kgs. It was observed that solar-dried bananas were golden-brown in color, those on the top tray/near the glass wall were brownish and were harder than sun-dried bananas. This corresponds to the results found at Muaklek, Saraburi.

Users' opinions

The user reported that, depending on the ripeness of bananas and the weather conditions, the dryer may not shorten the drying time or, if it does, it will not be more than 20% of the total drying time. Weight loss is not the only critical indicator of properly dried bananas; their appearance and texture are also very important and must be judged by experience. The user agreed that solar-drying saves space and that the products obtained were clean and hygienic. However, the following points were raised:

- The temperatures of the top tray were to high. The user, later, did not put the bananas on that tray;

- The wire mesh can become rusty and cause marks or cuts on banana surfaces. Therefore, bamboo trays were put over existing trays;

- Low air circulation in the dryer did not provide enough heat distribution;

- The dryer was too small for the amount of bananas to be dried;

- If the bananas are slightly over-ripe, the solar-dried products are found to be sweeter and softer than sun-dried products.

- The user was willing to use the cabinet dryer provided that the color of the solar-dried bananas can be improved, the dryer is cheap and the dryer can be used during the rainy season.

Field Test Results at Wat Chant, Phitsanulok

The family in Wat Chant approached to use the cabinet dryer sells dried, salted beef - marinated with salt only. The amount of beef sun-dried each day varies between 7-11 kgs. On sunny days, sun drying takes only 3 hours. It is not desirable to remove too much moisture since dried beef is sold by weight.

Users' opinions

The solar dryer shortens the drying time by only half an hour since sun-drying of beef does not take time, for the small amount of beef dried per day, the dryer was too big for the family's needs. However, the users felt solar-drying had the advantage that the product was clean and safe as it was not necessary to watch out for dogs or cats.

Field Test Results at Petchburi

The family testing the solar dryer at Petchburi dries 500-700 or 900-1000 hands of bananas per batch, depending on the availability of bananas. The data/information was collected on only one batch of bananas in the cabinet dryer. During this test the bananas were loaded on trays 1, 3 and 5 only. However, the user was satisfied with the results. He reported that solar-drying shortend the drying time by one day. The solar product tasted better than the sun-dried product and the golden color looked better. Further, the solar-dried product was not as soft as the sun-dried product and weighed more; i.e., 1 kg of sun-dried bananas contained 33 bananas while 1 kg of solar-dried bananas requires only 30 bananas.

Users' opinions

The wire mesh trays cut or marked the banana surface. The user suggested replacing them with bamboo trays. He was not worried about uneven color. He collected the bananas from the cabinet at the end of the day and piled them together overnight. Using this method, syrup was distributed among the bananas and the color became even.

Chapter 6

Conclusions

CONCLUSIONS

The following conclusions summarize the technical data obtained from the field tests, as well as experiences and comments of the users.

Cleanliness

All users agreed that solar-dried products are cleaner and more hygienic than sun-dried products. The dryer protects the products from intrusion of animals, and prevents spoilage due to wind and rain.

Success of Application

The success of the application of the dryer to varicus products is dependent upon each product, individual techniques of the drying process, and those characteristics of dried products that are accepted by particular communities since the drying characteristics of products vary from one to another.

Small-Scale, Medium-Scale & Industrial-Scale Drying

The villagers who are involved in a small-scale drying are not interested in adopting the solar-drying technique. Those who dry a medium amount of produce show interest, provided that the quality of the products are better or, at the least, the same as sun-dried products. They also require that besides, the dryer be cheap and efficient. These results imply that the natural convection cabinet dryer would be inappropriate for industrial scale drying.

Dryness and Appearance of Product

If the only purpose of drying is to reduce the moisture of the product, and its color and texture are not significant, the solar-dryer developed for this study will serve the purpose. However, with certain products such as bananas where color, and softness affect the quality and price of the product, careful operation and experience are required to use this dryer effectively.

Dryer Design Characteristics

- Wire mesh trays become rusty and cause cuts on the product surface.
- Ventilation of humid air in the dryer was low and affected the quality of the products.
- Temperatures of the top tray were too high.

Chapter 7

Recommendations

RECOMMENDATIONS

Dryer Design Characteristics

1. Wire-mesh trays can become rusty and cause marks and cuts on product surfaces. Trays made from bamboo, nylon nets which are cheaper should replace wire-mesh trays.

2. It was observed that ventilation of humid air in the dryer was low. This affected the quality of the products. Thus, a larger outlet port opening is suggested. The work in progress at King Mongkut's Institute of Technology, Thonburi (Wongsiri,1984)reports that when a ventilation fan ($\sim$ 40 W) was placed at the top-back door of the dryer, the heat distribution in the dryer was improved and this improved the product quality.

3. The temperature of the top tray was too high. The users suggested that the outlet-port be enlarged or the transparent roof (cover) changed into an opaque sheet.

Medium-Scale Drying

The results of the study showed that the most interest was generated by medium-scale users. Thus, further studies in developing a more efficient dryer should concentrate on this group.

Dryness and Appearance of Product

Procedures for ensuring careful operation for the dryer to produce attractive products should be established where appearance is a critical aspect of saleability.

ANNEXES

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ANNEX I

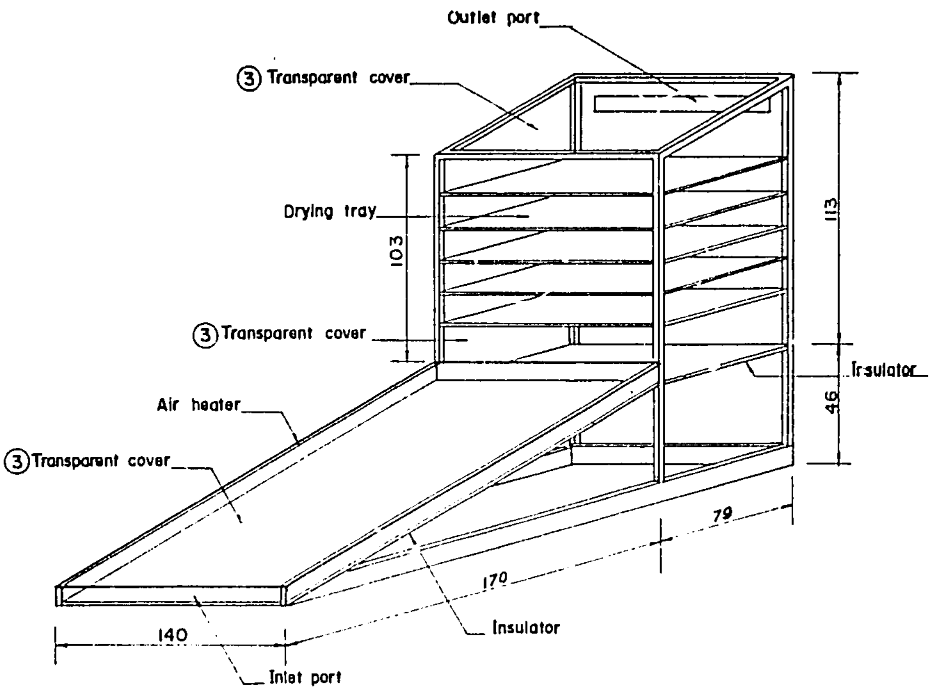

Figure I.1 Solar cabinet dryer with separate air heater

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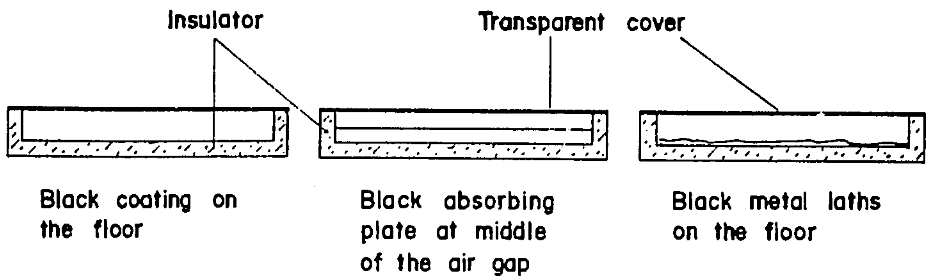

Details of absorbing surfaces

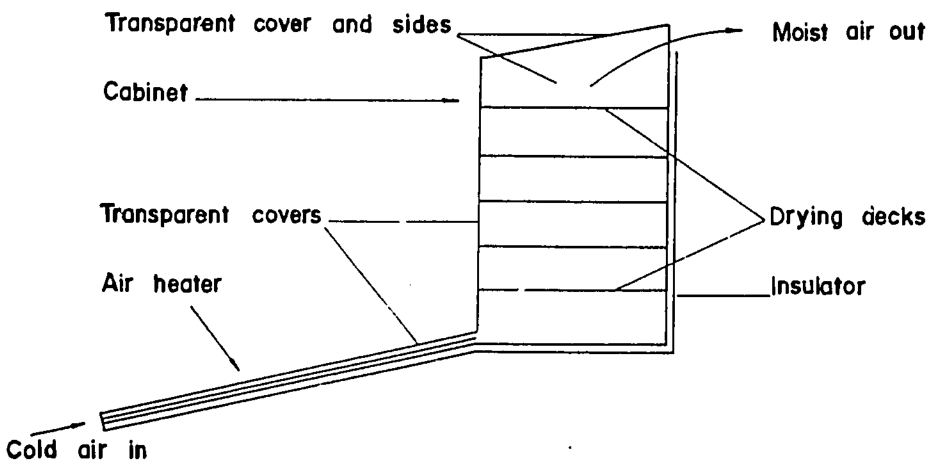

Figure I.2 Section view of a cabinet dryer and details of absorbing surfaces.

Table I.1 Costs of Materials Required for the Field Cabinet Dryer

Material	Cost (Baht)
Steel bars (2" x 1", 1" x 1", $\frac{3}{4}$" x $\frac{3}{4}$")	432.-
Wheels and wheel components	370.-
3 glass sheets	577.-
Wire mesh	700.-
Fiber reinforced plastic (3 pieces)	540.-
Knots	15.-
Epoxy, glue	162.-
Plywood	670.-
Zinc sheet	450.-
Others (paint, screw etc.)	300.-
Total	4,216.- Baht

ANNEX II

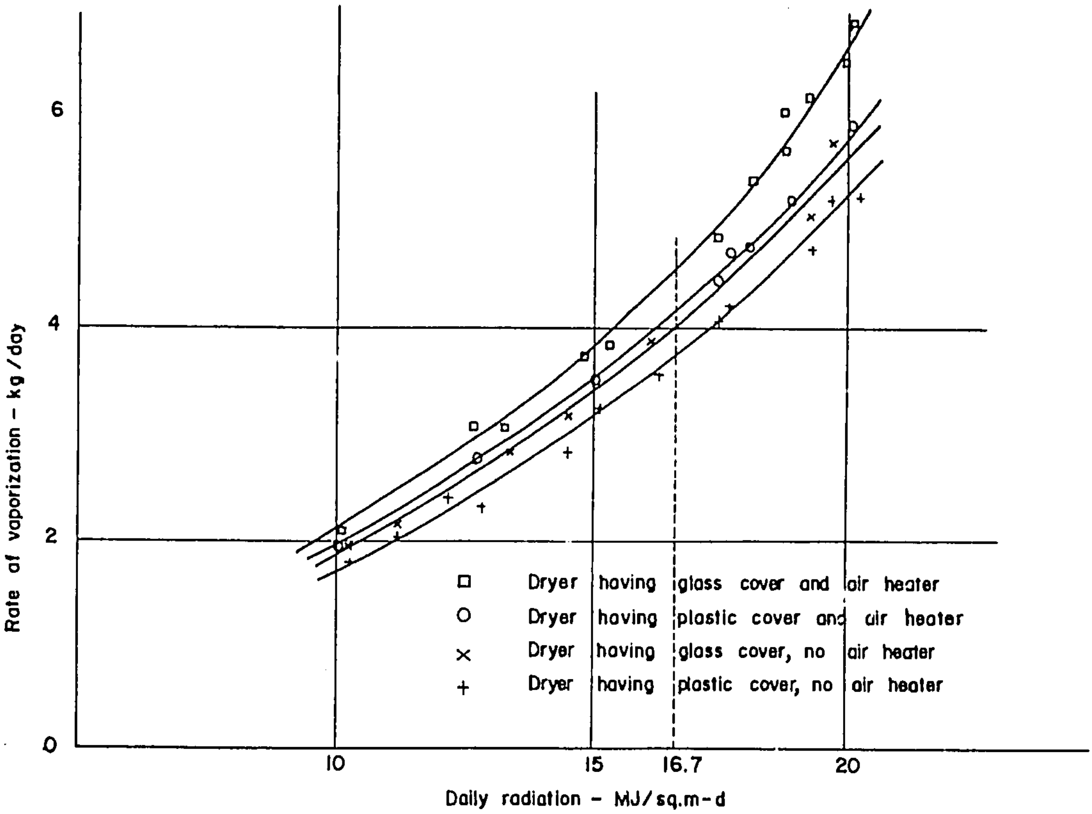

Fig. II.1 Comparison of the Rates of Vaporization in Four Cabinet Dryers Having the Same Outlet Port Areas of 0.013 sq.m.

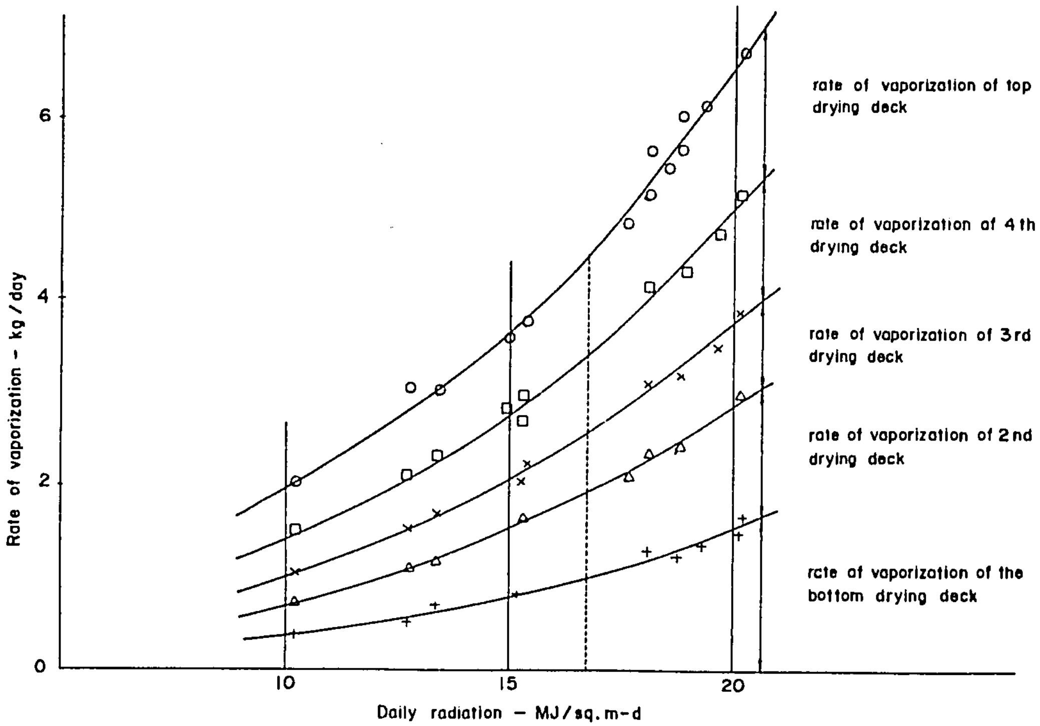

Fig. II.2 Rates of Vaporization from Five Drying Decks in the Cabinet Dryer Having Glass Cover and Air Heater; Outlet Port Area of 0.013 sq.m.

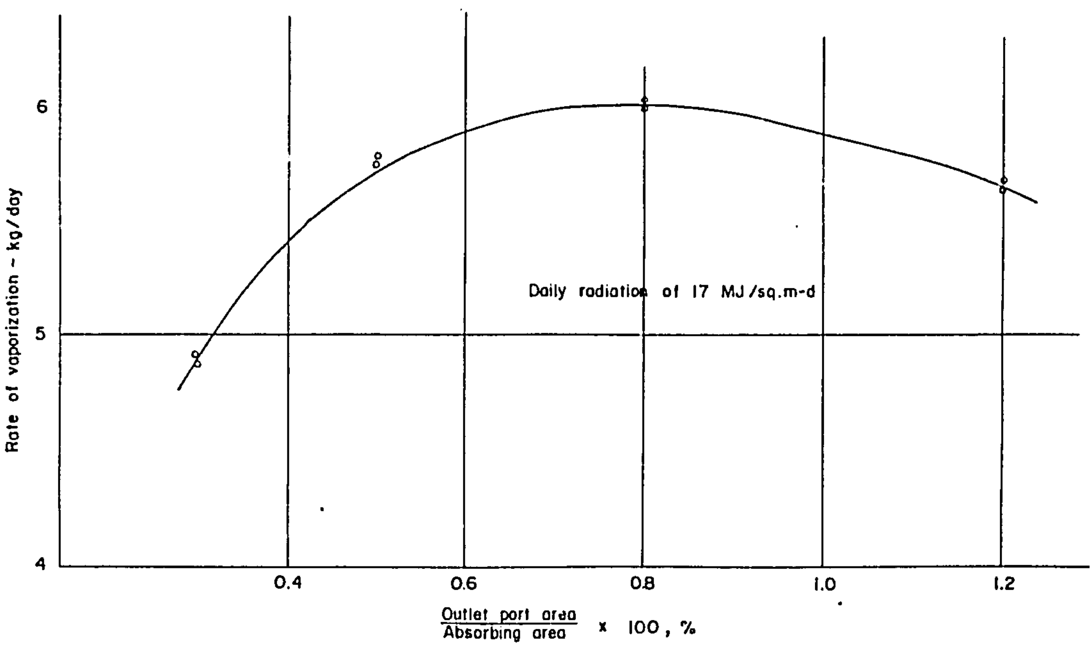

Fig. II.3 Effect of the Outlet Port Area on the Rate of Vaporization for the Cabinet Dryer Having Air Heater and Glass Cover.

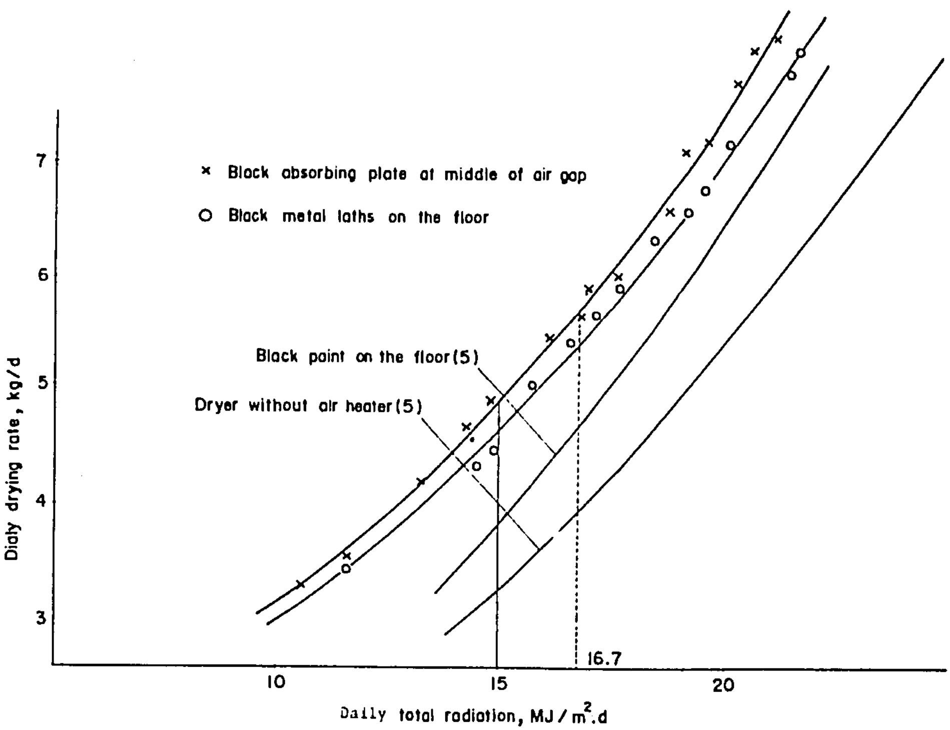

Fig. II.4 Comparison of Dryers and Air Heaters, All Having Glass Covers but Different Absorbing Surfaces.

ANNEX III

Comparative performance of cabinet dryers with separate air heaters

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SUMMARY

Comparative performances of two cabinet dryers having separate air heaters were studied. Both dryers were identical in dimensions but had different cover-materials namely glass and polyethylene sheets.

Test results show that the dryer having glass covers is more efficient and economical than the dryer using plastic covers. The air heater increased the drying rate by about 13 %. A more efficient air heater is still needed to make it more economical than the dryer without air heater.

RÉSUMÉ

Résultats comparés de deux séchoirs solaires à chambres de chauffage séparées.

On a étudié les résultats comparés de deux séchoirs solaires équipés de deux chambres de chauffage de l'air séparées. Les deux séchoirs étaient de dimensions identiques mais avec des capteurs différents en verre et en feuilles de polyéthylène.

Les résultats du test ont montré que le séchoir avec le capteur en verre est plus efficace et économique que celui dont le capteur est en plastique. La chambre de chauffage à capteur en verre a augmenté le taux de séchage d'environ 13 %. On a encore besoin d'une chambre de chauffage plus efficace pour le rendre encore plus rentable que le séchoir dépourvu de chambre de chauffage.

1. INTRODUCTION

Various types of solar dryers have been developed in many countries [1] mainly for agricultural products in order to increase their qualities and save conventional fuels. In Thailand, simple and low-cost box dryers have been already been developed [2-3] for cashcrop drying. However, if the amount of product to be dried is fairly large, the box dryer may not be suitable since the area occupied by the dryer will be too large. Free-convection cabinet dryers having separate air heaters seem to be more superior and were thus developed.

In this work, the effects of separate air heaters on the performances of the cabinet dryers were studied. The effects of glass and polyethylene plastic, used as transparent covers, were also investigated.

2. General Feature

Two cabinet dryers, each of 1.1 m. high, 1.0 m wide and 0.8 m. deep., were constructed for testing (fig. 1). The transparent top covers of the two cabinet dryers were made of 3 mm. glass pane and thin polyethylene plastic sheet. Both top covers inclined at angles of 14 degrees at which the lattitude of Bangkok is. Front and side walls of both dryers were made of the same transparent materials as the top covers. The back walls and floors were made of wood of about 7 mm. thick. The inside surfaces of the back walls and floors were covered with thin layers of a matt black paint to provide the absorbing surfaces while their outside surfaces were insulated with styrofoam of 20 mm. thick. The top parts of the back walls were provided with adjustable outlet ports for moist air. The back walls were removable in order that materials to be dried might be easily moved into and out off the cabinets. Five drying decks were available in each cabinet.

Air heaters for both cabinet dryers were 1.75 m. long and 1 m. wide. Like the covers of th eir corresponding cabinets, the transparent top covers of the air heaters were made of 3 mm. glass pane and polyethylene plastic sheet. Each cover was about 30 mm. above the floor whose inside surface was covered with a matt black paint to provide the absorbing surface. A styrofoam sheet of 20 mm. thick vas used as an insulator underneath the floor of each air heather. Both air heaters were also inclined at the angles of 14 degrees.

3. Drying mechanism

Moisture vaporises from the moist objects inside a cabinet dryer in two ways. First, solar radiation passes through the transparent cover, front and side walls of the cabinet and then absorbed by the moist objects. The moisture is thus transferred by free convection. Secondly, solar radiation is also absorbed by the black surfaces inside the air heater and the back wall of the cabinet. Air above these black surfaces is heated and flows upwards. As the hot air passes around the moist objects, the moisture is transferred into the hot air current, by forced convection in this case.

Convective mass transfer theory, developed by D.B. Spalding[4] may be conveniently applied to the drying process inside the solar dryer as fellows:

Rate of vaporization per unit surface area

— $i = g^* \ln (1 + B)$ [1]

where,

— driving force, $B = \dfrac{m_{H_2O,S} - m_{H_2O,G}}{1 - m_{H_2O,S}}$ [2]

and

— m_{H_2} = mass fraction of water vapour in the air,

and subscripts 'G' and 'S' indicates the bulk and interface states.

The mass transfer conductance, g^*, is usually computed from heat transfer data. In the case of forced convection,

— $g^* = f(Re, Sc_{H_2O})$ [3]

where

— Re = Reynolds number of the hot air,

and

— Sc_{H_2O} = Schmidt number of water vapour in the air,

Equation [1] indicates that the rate of vaporization will be high if the driving force, B and conductance, g^* are large. Equation [2] implies that B will be large if the mass fraction, $m_{H_2O,G}$ is low and hence a high temperature of the bulk air inside the dryer. The air heater and the cabinet must therefore be placed at the optimum position for solar radiation. The top covers of the air heater and cabinet are thus inclined at lattitude angles and face the equator. From equation [3], the conductance, g^* will be large if the Reynolds number of the hot air is large. A high flow rate of hot air through the cabinet is therefore required, and may be induced by a wide outlet port at the back walk of the cabinet. However, if the outlet port is too wide, the large amount of air passing through the dryer may lower the temperature of the air in the cabinet so much that the driving force, B will decrease more rapidly than the increasing, g^*.

4. Test and results

Tests were carried out on the cabinet dryers without and with air heaters. Objects to be dried were a large number of square pieces of cloths which were folded into rectangular blocks and initially saturated with water. The daily rate of vaporization from each drying deck in the cabinet dryer was measured. The optimum size of the outlet port for moist air was also determined.

Fig. 2 shows that the daily rates of vaporization of moisture from the four types of cabinet dryers increase with the daily radiation. The dryers having glass covers with and without air heaters yield higher rates of vaporization than their corresponding dryers having plastic covers since the glass covers suppress the infrared radiation losses from the dryers better than the plastic sheets. Additions of air heaters increase the rates of vaporization by about 13 % as the air heaters raise the temperatures of air inside the cabinets and hence higher values of the driving forces, B.

The daily rate of vaporization from each drying deck of the dryer having glass covers and air heater may be seen in fig. 3. The top and bottom decks give highest rates of vaporization since the top deck is exposed to more solar radiation than other decks and the hot air flowing through the bottom deck has the lowest $^{m}H_2O$, G and hence the highest B. The middle deck yields the lowest rate of vaporization as the value of $^{m}H_2O$, G of the air around the deck is lower than those around the lower two decks and the middle deck also receives less solar radiation than the upper two decks.

Fig. 4 shows the daily rate of vaporization from each deck of the dryer having plastic cover and no air heater. The rate of vaporization from the top deck is highest since the deck receives more radiation than other decks. The bottom deck yields the lowest rate of vaporization as it receives least radiation and has no air heater to provide extra hot air.

The effect of the size of the outlet port for moist air on the rate of vaporization from the dryer having glass covers and air heater is shown in fig. 5. The maximum rate of vaporization is obtained when the area of the outlet port is about 0.8 % of the total horizontal absorbing surface. With a smaller area of the port, less air passes through the dryer and hence a lower conductance, g^*. If the area of the port is too large, the temperature of the air inside the dryer will be too high for an efficient driving force, B.

5. Cost analysis

A cost analysis by the annual cost method is employed to determine the cost of useful energy gain in each dryer.

5.1. Annual Cost Method

If P = first cost
n = useful life; years
i = rate of interest per year
CRF = capital recovery factor
$= i(I + 1)^n/[(i+1)^n - 1]$
Annual first cost = (CRF) P
And if S = salvage value
SFF sinking fund factor
$= i/[(i+1)]^n - 1]$
Annual salvage value = (SFF) S
Annual cost = annual first cost + maintenance cost
— annual salvage value

5.2. Useful Energy Gain

If m = rate of vaporization of moisture, kg/day
h_{fg} = latent heat of vaporization, MJ/kg
Useful energy gain from solar radiation
$q_u = m.h_{fg}$ MJ/day
And if I = total radiation, MJ/sq.m-d
A = total effective area of the absorbing surfaces

$$\text{Thermal efficiency of the dryer, } = \frac{m.h_{fg}}{A.I}$$

5.3. Rates of Vaporization of Moisture

From fig. 2, at the total radiation of 16.7 MJ/sq.m-d which is the annual average value for Bangkok, the annual average rates of vaporization of moisture from the four dryers are obtained as follows:

- — Dryer having air heater and glass covers .... 4.62 kg/d
- — Dryer having air heater and plastic covers .... 4.22 kg/d
- — Dryer having glass cover, no air heater .... 4.07 kg/d
- — Dryer having plastic cover, no air heater .... 3.80 kg/d

The horizontal absorber areas of the cabinets and the air heaters were 0.82 and 1.77 sq.m respectively.

5.4. Initial Costs of the Cabinets and Air heaters in US $

Cost	Cabinet with glass cover	Cabinet with plastic cover
Steel and aluminium structures	12.50	7.50
Drying trays	27.50	27.50
Transparent sheets	22.50	7.50
Plywood board	5.00	5.00
Paint, foam, etc.	5.75	5.25
Labour	7.00	6.50
Total cost of cabinet, US$	80.25	59.25

	Air heater with glass cover	Air heater with plastic cover
Steel structure	5.00	5.00
Plywood board	5.00	5.00
Transparent sheet	15.00	2.50
Paint, foam, etc.	4.25	4.00
Labour	4.00	3.50
Total cost of air heater, US $	33.25	US $ 20.00

5.5. Maintenance Costs

US $

Dryer having glass covers and air heater:
cost of re-painting once a year .... [illegible].00

Dryer having glass cover but no air heater:
cost of re-painting once a year 2.25

Dryer having plastic covers and air heater:
cost of re-painting once a year and replacing plastic twice a year 15.00

Dryer having plastic cover but no air heater:
cost of re-painting once a year and replacing plastic twice a year 10.00

5.6. Salvage Values

After the useful lives of the dryers, the usable materials are structures, drying trays and glass panes. The salvage value is estimated at a half of the initial cost.

	Glass cover type	Plastic cover type
Salvage value of cabinet, US $	31.25	17.50
Salvage value of air heater, US $	10.00	3.75

5.7. Other Data

Useful lives of all dryers are assumed at .... 7 year
Interest rate .... 12 % per annum

5.8. Annual Costs of Useful Energy

As an example the cost analysis by the annual cost method for the dryer having glass covers and air heater may be shown as follows.

Annual first cost	= (CRF) P
	(12 %, 7 years)
	= 0.2404 (20.25 + 33.25)
	= US $ 27.30
Annual salvage value	= (SFF)
	(12 %, 7 years)
	= 0.0904 (31.25 + 10)
	= US $ 3,75
Annual maintenance cost	US $ 4.00
∴ Annual cost	= 27.3 − 3.25 + 4.00
	= US $ 27.55
Annual average rate of vaporization	= 4.62 kg/day
Latent heat of vaporization	= 2.37, MJ/kg
Useful energy gain per year	= 4.62 × 2.37 × 3.65
	= 3,998 MJ
	= llll kWh
∴ Cost of useful energy	= 27.55/llll
	US $ 0.0247/kWh

The costs of useful energy in the other dryers are similarly estimated as follows:

	US $/kWh
— Dryer having glass cover but no air heater	0.0194
— Dryer having plastic cover and air heater	0.0315
— Dryer having plastic cover but no air heater	0.0251

As a comparison, the cost of electricity in Thailand is US $ 0.075/kWh

6. Conclusions

The test results show that the rate of vaporization of moisture from the dryer having glass covers and air heater was higher than that from the dryer without air heater by about 13 % and than that from the dryer having plastic cover and air heater by about 10 %.

The approximate cost analysis indicates that the cost of useful energy of the dryer having glass covers and air heater was just under US $ 0.025 which was cheaper than the useful energy of the dryer having plastic cover and air heater by about 28 % but still more expensive than that of the dryer having glass cover but no air heater by about 21 %. As the efficiencies of the air heaters were very low, high cost of useful energy resulted.

It may also be concluded that the dryers using glass covers are more efficient and economical than the corresponding dryers using plastic covers if the glass covers do not break during their useful lives.

A solar dryer will be more attractive if an effective thermal storage is provided. The air heater will be suitable for such purpose if its cost-effectiveness can be justified. At present, a number of more efficient air heaters are being developed in Thailand for the cabinet dryer, and their test results will be soon made available.

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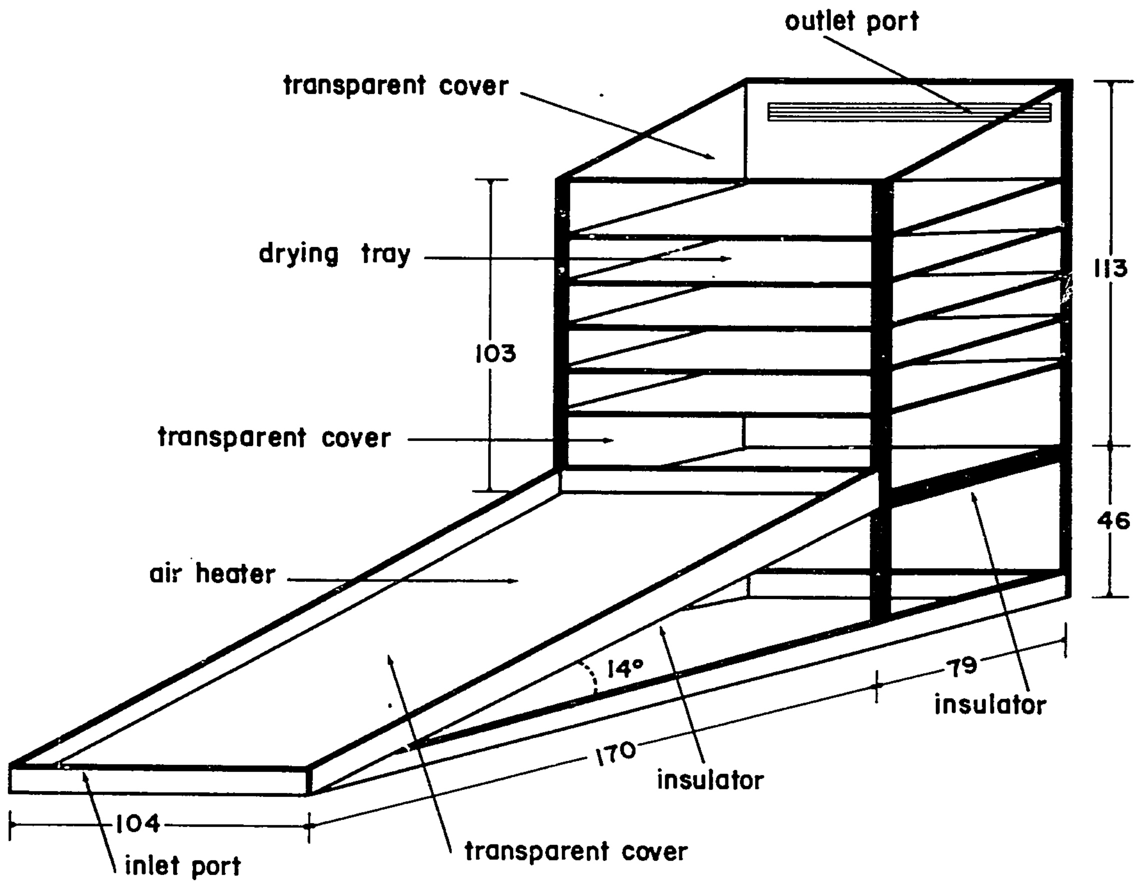

Fig. 1.– Cabinet dryer with separate air heater

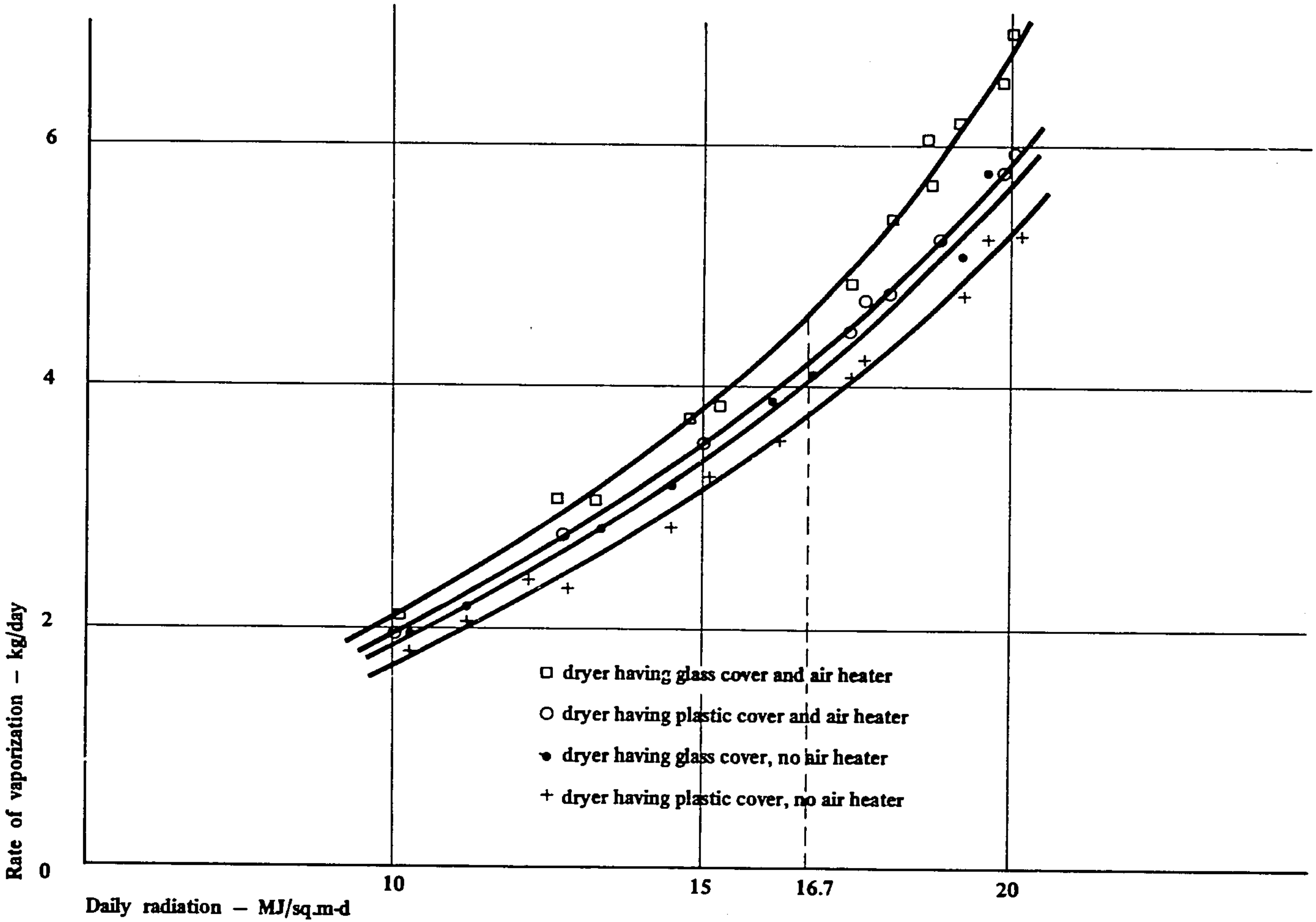

Fig. 2.– Comparison of the rates of vaporization in four cabinet dryers having the same outlet port areas of 0.013 sq.m.

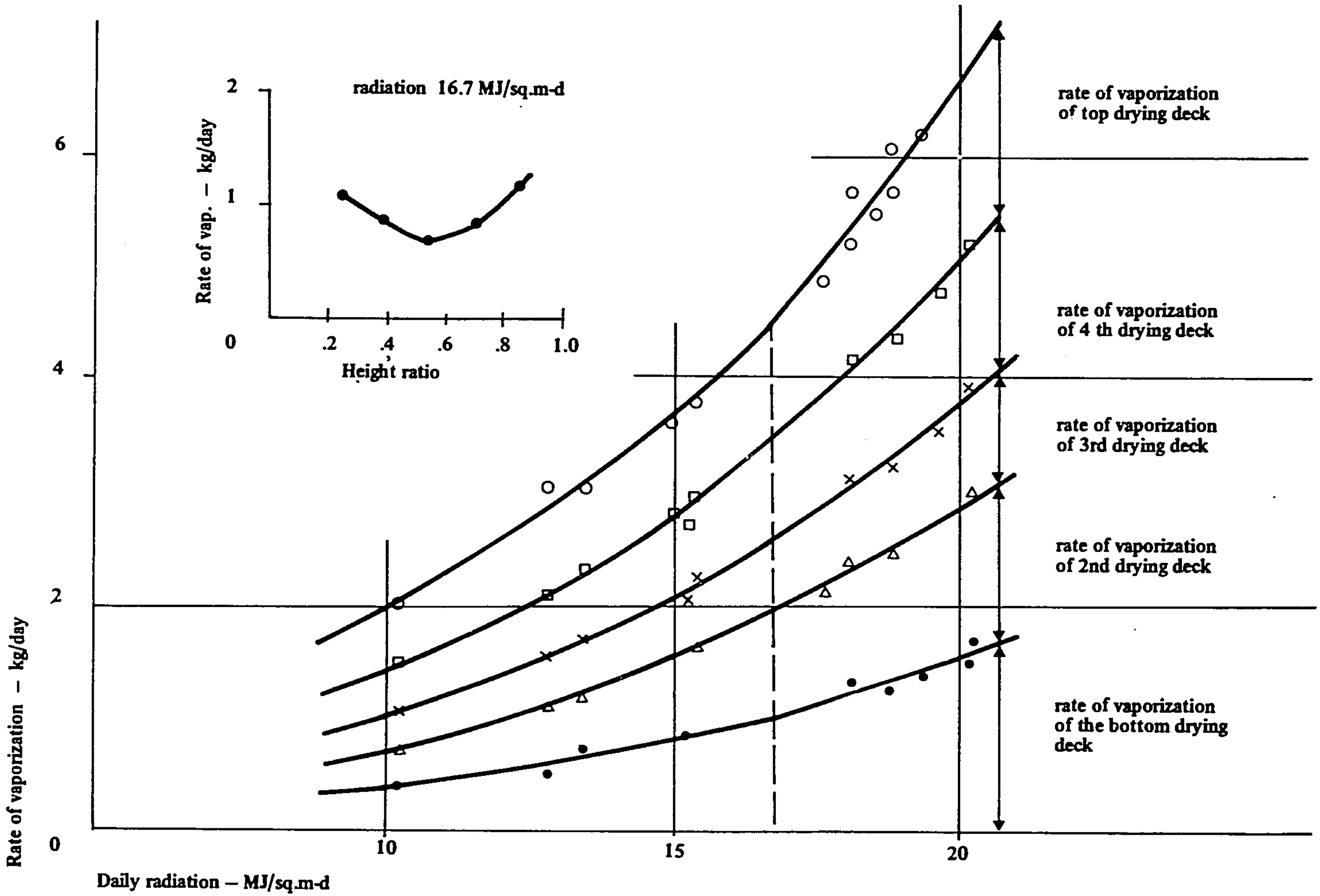

Fig. 3.– Rates of vaporization from five drying decks in the cabinet dryer having glass cover and air heater ; outlet port area of 0.013 sq.m.

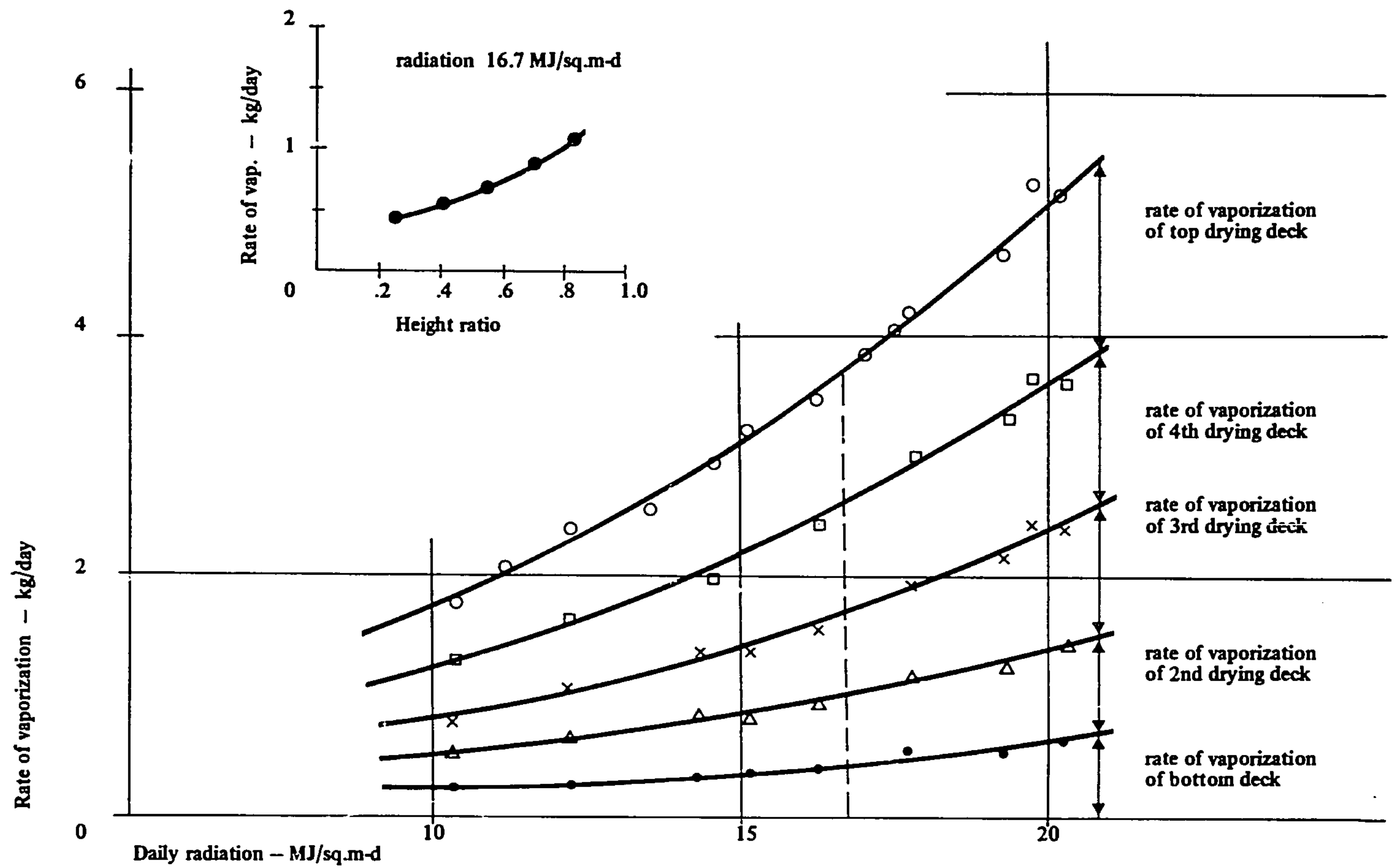

Fig. 4.– Rates of vaporization from five drying decks in the cabinet dryer having plastic cover and no air heater ; outlet port area of 0.013 sq.m.

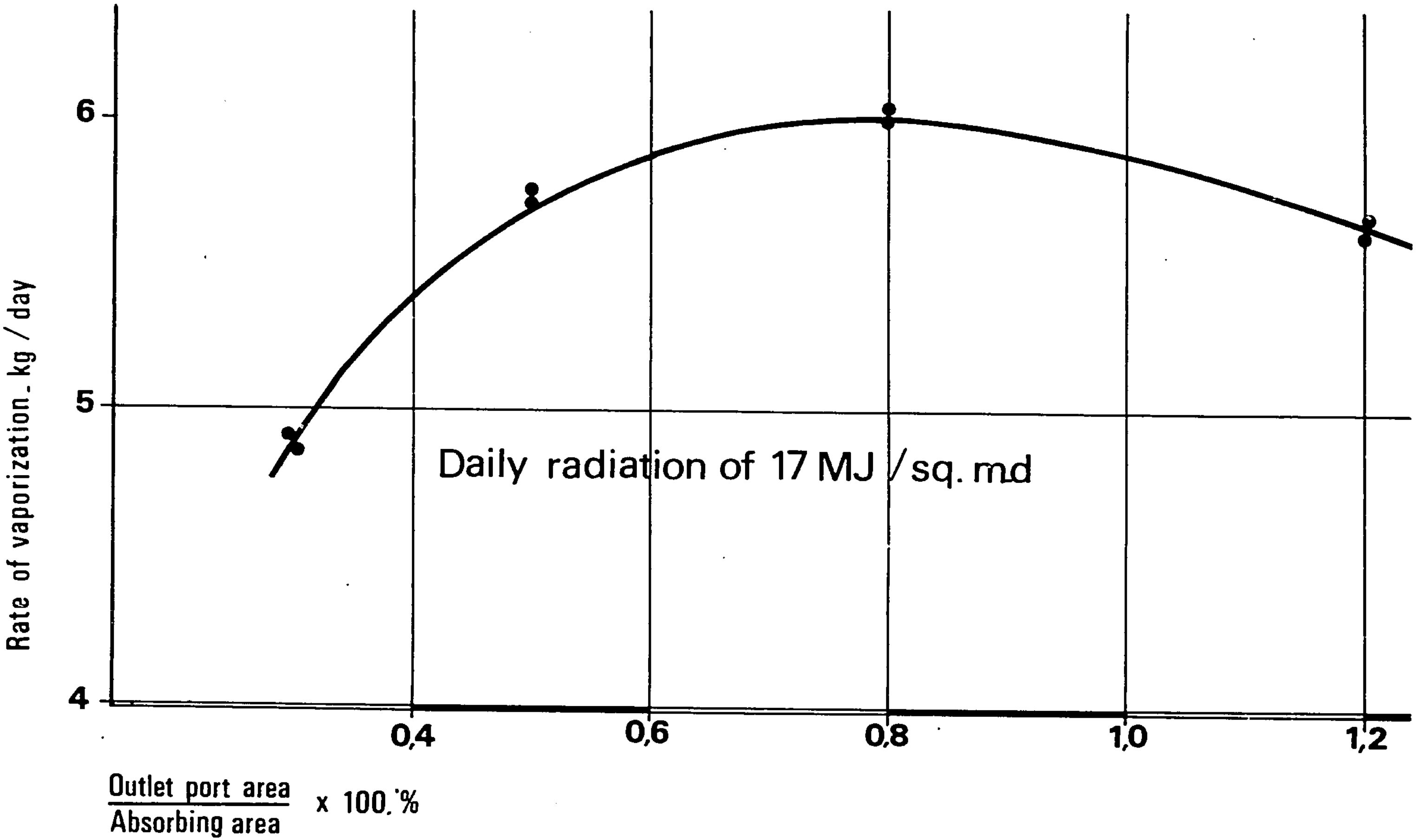

Fig. 5.– Effect of the outlet port area on the rate of vaporization for the cabinet dryer having air heater and glass cover

DISCUSSION

Prof. W. B. MORGAN. To doctor Wibulswas: There is a problem of wet season and damp fuelwood. Can the solar drier work well in the short sunny periods of the rainy season and can it be adapted for drying wood?

To Mr. Théry: The work of an Australian, Mr. Stephen Joseph of the Intermediate Technology Development Group, researching at the University of Reading and with extensive experience fo south-east Asia, bears out many of your criticisms of stove technology. Mr. Joseph found that many home-built ("do-it-yourself") stoves failed — some cracked due to poor clay or use of unsuitable concrete — and many when tested by his methods exhibited less efficiency than the open fire.

Prof. J. O. ADEJUWON. I welcome the emphasis which many participants at this conference have placed on the need to take cognisance of culture and societal values in designing a new technology for tropical and third world countries. I would like to warn however that this can be overdone. It seems to me that some of us unnecessarily dwell on the curiosities of these areas as if they were the essence of community life. I am submitting that this may again lead to another wrong view of the Third World. I hope that we are not unwittingly leading ourselves to the belief that these societies are changeless and impervious to innovation. The fact of the matter is that people in these areas do accept and adopt new ideas. They even seek change in their way of life, hence they migrate. It should be realised that as people's attitudes are affected by tradition, so they are affected by the ever-present influence of the West.

What I believe should be emphasised more is experimentation. True, there is no way of avoiding theory and conceptualisation. There is however always the need to ensure that the concepts we propose can where necessary be shown to be false. Also the empirical substantiation of concepts needs to be undertaken before they are peddled as outputs of specialist efforts. It seems to me that we cannot avoid the age-old process of trial and error in arriving at the desired goal. To me our duty as specialists is to reduce the numbers of both trials and errors.

Dr P. WIBULSWAS (in reply to professor Morgan).

1. One of the main advantages of a solar drier is that the object to be dried will not be spoiled by rain. However, while it is raining, the drying rate will be reduced.

2. A solar drier for firewood is quite practical and not difficult to design. Nevertheless, solar drying of timber for construction may be more difficult, as a higher quality of wood is expected. Perhaps temperature and humidity have to be better controlled. More research and development may be required.

ANNEX IV

DEVELOPMENT OF SOLAR AIR HEATERS FOR A CABINET-TYPE SOLAR DRYER*

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ABSTRACT

Six types of solar air heaters for a cabinet-type solar dryers were constructed, tested and evaluated. The cover, front and sides of the cabinet were made of transparent glass sheets of 3 mm. thick. Inside surfaces of the back and floor of the cabinet were coated with a black paint. Three types of transparent covers, viz. glass, acrylic plastic and fibre-reinforced plastic, were employed on the air heaters. Two types of absorbing surfaces namely black metal lathe and a black mild steel sheet at the middle of the air gap were evaluated. Pieces of wet cloths folded in rectangular blocks were used as the test materials. The exit area for the moist air from the dryer was set at the optimum value.

Test results show that the air heater having glass cover and an absorbing plate at the middle of the air gap giv the highest drying efficiency. Economic analysis by the annual cost method indicates that the cost of useful energy gain, from the dryer and air heater having glass cover and an absorbing plate at the middle of the air gap, is about US ¢ 3/kWh if the useful life of 5 years is assumed.

*Presented at Regional Workshop on Solar Drying, Centre for Non - conventional Energy Development - UNESCO, Manila, December 1980.

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1. INTRODUCTION

In the last few years, there has been a number of research and development on solar drying in Thailand. A study on a solar-assisted tobacco dryer[1] has indicated that as much as 13 % of heat for the drying process can be supplied by solar energy and the cost of useful energy gain is about US ¢ 1/kWh. A low-cost grain dryer[2] has been specially developed for paddy drying. The air circulated naturally through the drying bed up a chimney. Experiments showed that the optimum depth of the drying bed should be about 0.1 m. A forced-convection grain dryer[3] is also being developed. The initial study has indicated that the efficiency of the collector for the dryer is about 45 % at the average hot air temperature of 43 C. The moisture content of paddy grains is reduced from 23 % to 13 % within one day, and a collector area of about 40 sq.m is required for 1 ton of paddy.

With regard to cash-crop drying, a study on a box-type dryer[4] has shown that the maximum efficiency is obtained when the exit area for the moist air is about 12 % of the horizontal absorbing area of the dryer and the cost of useful heat gain is about US $ 1.5/kWh. Another work on a cabinet-type dryer having a separate air heater[5] has indicated that the maximum drying efficiency is achieved when the exit area for the moist air is about 1.1 % of the total horizontal absorbing area of the cabinet and the air heater. It has also been pointed out that a separate air heater is worth while only when it is efficient, other wise, it is more economical to use the cabinet dryer alone. This paper presents technical and economic assessment of various designs of air heaters locally developed in Thailand for the cabinet-type dryer and efficient designs are identified.

2. THEORY

2.1 Mass Transfer Theory

To systematically improve the efficiency of a dryer, it is most helpful to apply the following mass transfer theory developed by D.B. Spalding (6,7)

Mass transfer flux, $\dot{m}'' = g_i^* \ln (1 + B)$ (1)

where g_i^* = mass transfer conductance,

and B = driving force

The mass transfer conductance is usually deduced from an appropriate heat transfer formula, since it can be theoretically shown[6] that

$$\frac{g_i^*}{G} \equiv St = f(Re, Sc_i) \quad (2)$$

and

$$\frac{g_i^* l}{\mu / Sc_i} \equiv Nu = f(Re, Sc_i) \quad (3)$$

where St = Stanton number,

Nu = Nusselt number,

Re = Reynolds number $= \frac{\rho v l}{\mu}$,

Sc_i = Schmidt number,

G = mass velocity,

l = characteristic length,

v = air velocity,

ρ = air density,

and μ = air viscosity

In a drying process, Schmidt number for the moisture in the air is approximately constant at 0.61. The conductance therefore depends mainly upon Reynolds number. A high velocity of the air flowing through the dryer is required to yield a large Reynolds number and thus a high conductance.

The driving force in a drying process may be computed from the following equation:

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2.2 Economic Analysis

The merit of a solar dryer rather depends upon its cost of useful energy gain than its thermal efficiency. The annual cost of the useful energy gain may be estimated as

$$(CRF)P - (SFF)S + \text{annual maintenance cost}$$

where P = first cost of the dryer

S = salvage value of the dryer

CRF = capital recovery factor,

$= i(1 + i)^n / [(1 + i)^n - 1]$

SFF = sinking fund factor,

$= i/[(1 + i)^n - 1]$

i = annual rate of interest,

n = useful life of the dryer, in years.

The useful heat gain per annum

$$= \dot{m} \times h_{fg} \times 365$$

where $\dot{m}$ = drying rate at the annual average daily radiation,

and h_{fg} = latent heat of vaporization

3. TEST EQUIPMENT

A cabinet-type solar dryer having the horizontal absorbing area of 0.82 sq.m. was constructed. The cover, front and sides of the cabinet were made of transparent glass of 2 mm. thick. The height of the cabinet was approximately 1 m. The floor and back panel of the cabinet were made of wood and their inner surfaces were coated with a matt black paint. The cabinet of the dryer contained five drying trays. On each tray, wet pieces of cloths folded into rectangular blocks were placed as the test material.

Six designs of air heaters having the following details were employed in the test program.

(1) glass cover and black mild steel sheet placed at the centre of the air gap,

(2) glass cover and black metal lathe placed on the floor of the air heater,

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Fig.4 also shows relative performances of three air heaters, all having black metal lathe on the floors, but incorporating different cover materials as in the preceding figure. Again, the glass cover exhibited the highest drying rate, and the fibre-reinforced plastic cover showed the poorest drying rate.

It is worth mentioning that the manufacturer of the fibre - reinforced plastic cover has claimed that the material has about the same transmittance as the glass. The presented results prove otherwise.

4.2 Economic Assessment

An economic analysis is carried out for two air heaters, both having glass covers, but different absorbing surfaces. The basic data of the dryers including air heaters are as follows.

	Dryer I	Dryer II
Absorbing surface	Absorbing plate at the centre of air gap	Black metal laths
Material cost, US $	154	147
Labour cost, US $	23	22
Total first cost, US $	177	169
Annual maintenance cost,US$	5	5
Salvage value, US $	63	60
Rate of interest per annum	12 %	12 %
Annual useful heat gain,kWh	1380	1310

In the above table, the salvage values are contributed mainly by the aluminium and steel frames and aluminium drying decks, while the annual maintenance costs arise mainly from re-painting.

The costs of useful energy gain presented in fig.5, appear to be about the same for both types of collectors. If the useful life

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of 5 years is assumed, the cost of useful heat gain is about US$ 0.032 /KWh. It is worth mentioning that the present cost of electricity in Thailand is about US$ 0.07/kWh. If the efficiency of electrical drying is assumed at 80%, the cost of solar drying is only about one third of that of electrical drying. A few dryers having separate air heaters are now being tested in the field for fruit and vegetable drying.

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APPENDIX

An example of the cost analysis of the dryer and its separate air heater having glass covers and a black absorbing plate at the middle of the air gap is shown below:

From fig.2, the daily drying rate at the annual average daily radiation of 16.7 MJ/sq.m-d is 5.74 kg/d.

Latent heat of vaporization of water = 2.371 MJ/kg

Annual useful heat gain = 5.74 x 365 x 2.371/ 3.6 = 1380 kWh

If the useful life of the dryer = 5 years,

Annual first cost	= P(CRF)	= 177 x 0.2774
		= US $ 49.1
Annual salvage value	= S(SFF)	= 63 x 0.1574
		= US $ 9.9
Annual cost of the system		= 49.1 - 9.9 + 5
		= US $ 44.2
Cost of useful energy gain/kWh		= 44.2/1380
		= US $ 0.032

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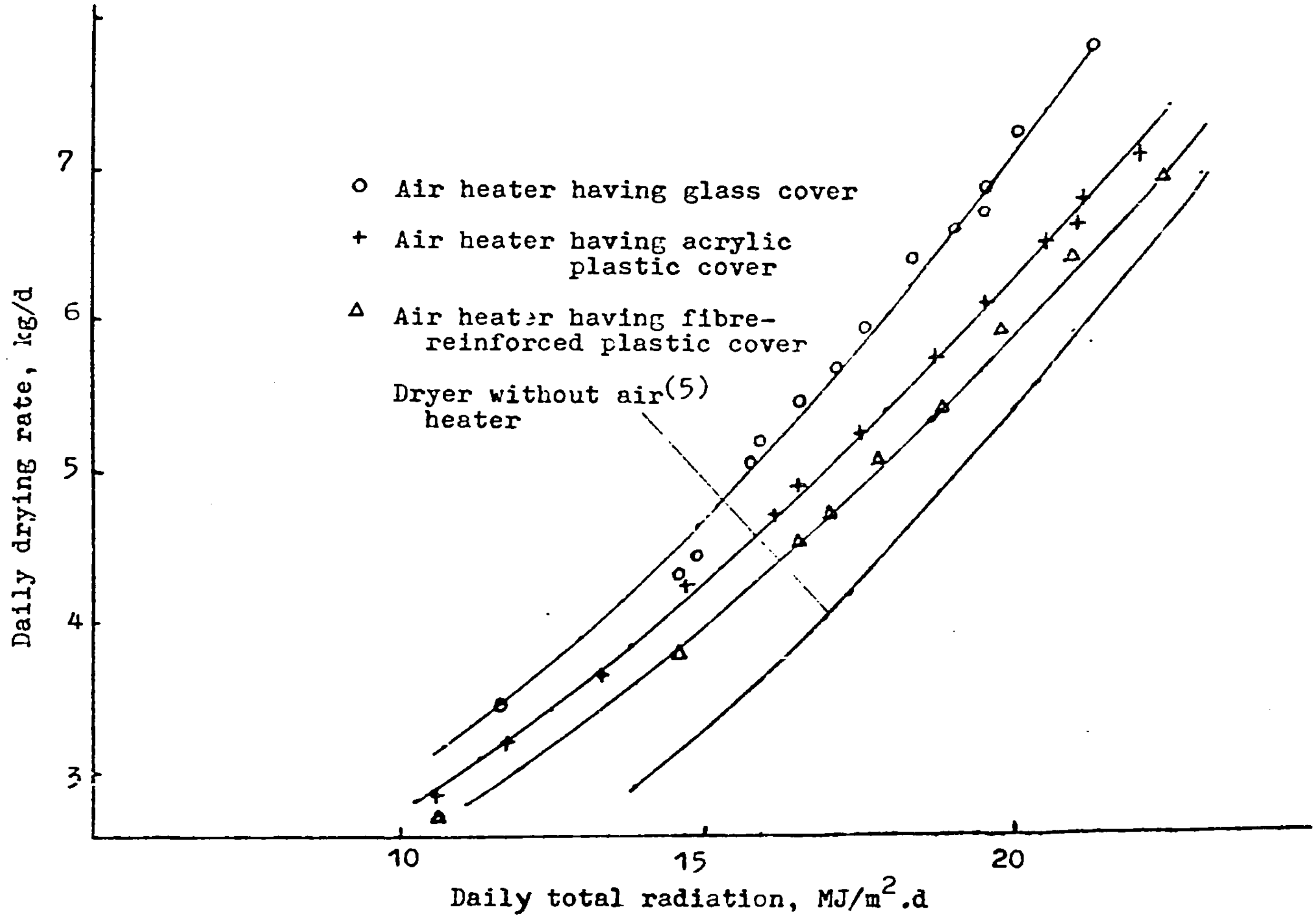

Fig.4 Daily drying rates of dryers and air heaters, all having black metal lathe on the floors, but different cover materials.

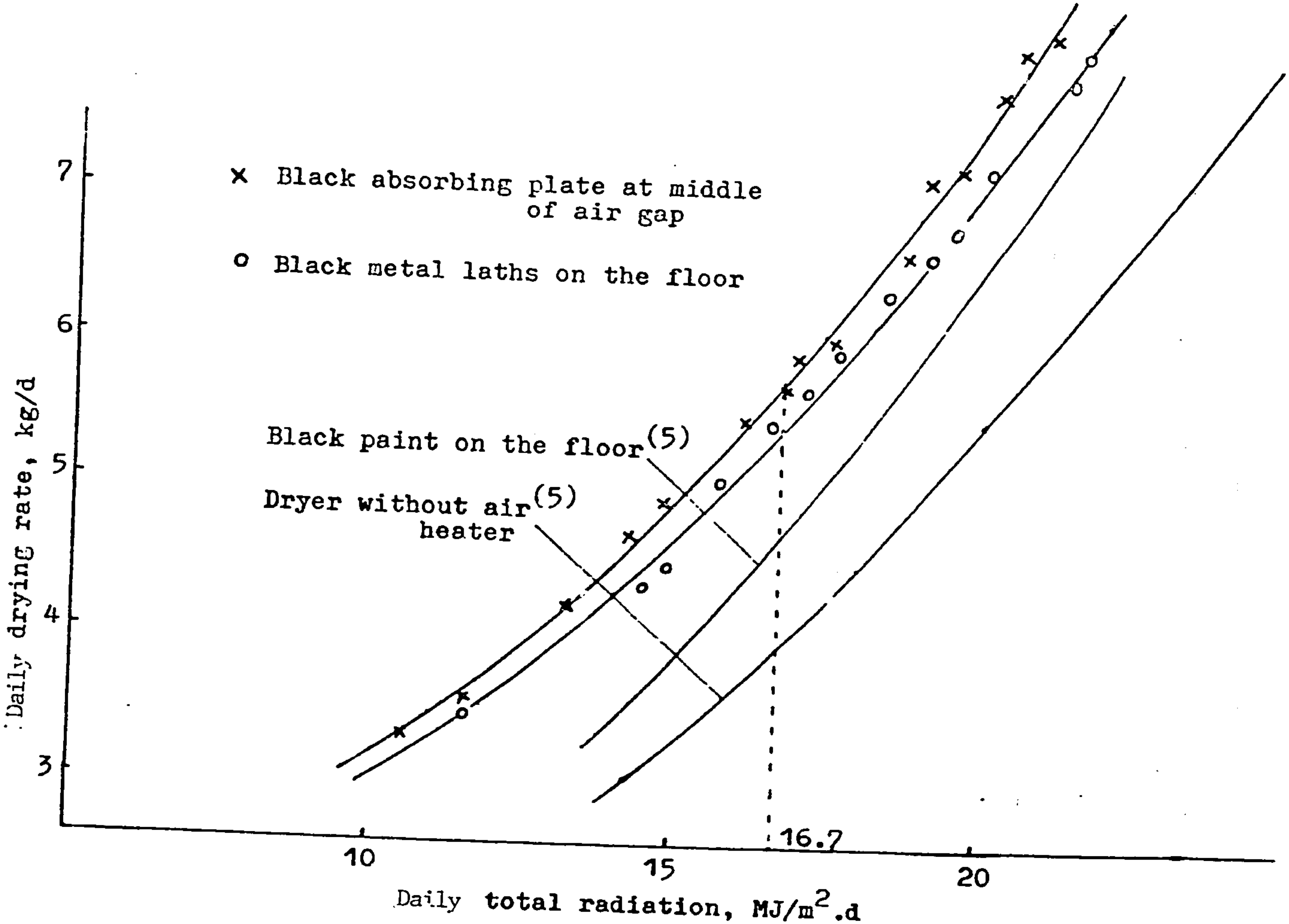

Fig.2 Dryers and air heaters, all having glass covers but different absorbing surfaces.

ANNEX V

Data Sheet for Field Tests

"Solar Drying"

Date .... Product ....

Initial weight of product .... Time of Loading ....

Temperatures in the dryer (near the outlet port) measured every 2 hours.

Ambient temperatures measured every 2 hours.

Any interchange of drying trays.* If yes, what time and which trays?

....

....

Weather conditions ....

....

Users' opinions

1) Is the cabinet dryer convenient to use?

   a) very convenient b) reasonably convenient c) inconvenient

2) Drying rate compared with sun-drying.

   a) faster b) the same c) slower

3) Product appearance and quality compared with sun drying.

   a) better b) the same c) worse

4) Other/recommendations

....

....

....

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* Trays are numbered 1, 2, 3, 4 and 5 starting from the bottom to the top of a cabinet.

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