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AID/SCI Progress Report No. 4.488

Final Report

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FINAL REPORT

on

HEAT STERILIZATION AND ACCELERATED DRYING OF HIGH MOISTURE ROUGH RICE FOR SAFE STORAGE

Submitted to

United States Agency for International Development (USAID)

Prepared by

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PROJECT PROFILE

Project Title	: Heat Sterilization and Accelerated Drying of High Moisture Rice for Safe Storage
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ABSTRACT

A study was carried out to evaluate the effectiveness of high temperature conduction heating for sterilizing and drying freshly harvested rough rice (RD-23 variety). Experimental prototype heating units were specifically designed and constructed to provide surface temperatures ranging from 75 to 200 °C. The quality effects of heat treatments on rough rice were investigated in terms of moisture removal, head rice yield, milled rice whiteness and cooked rice texture. Safe holding periods of heat-treated rough rice samples were evaluated based on accepted criteria of reduction in head rice yield and an increase in the proportion of discolored kernels. Finally, the performance and economic feasibility of using the proposed prototype heating-cum-drying units were evaluated.

Conduction heat treatments distinctly reduced fungal activity in rough rice as measured by dilution plating and carbon dioxide production. Exposure times for isothermal heating of rough rice were determined for inactivating the fungi to specific levels based on the heating surface temperature. Subsequently, a general procedure which accounted for the heating lags was developed for estimating the heat dosages based on the time-temperature history of the bulk grain in any given heating equipment.

In general, conduction heating prevented the spoilage of high moisture rough rice leading to its safe temporary storage prior to drying. Heat treatment of rough rice corresponding to 90 to 95% fungal mortality increased the safe holding periods of about 10 to 23 days based on an acceptable limit of 1.5% increase in discolored kernels in the milled rice. Heat treatments resulting in fungal mortality levels equal to 90% and higher were found to be satisfactory for general use. A relationship was developed for estimating the safe storage periods of heat-treated rough rice based on its moisture content and fungal mortality achieved with various heat treatments. A comparison of computed and experimental safe storage periods determined with a full-scale prototype heating unit showed a reasonable agreement and thus validated the general applicability of the proposed heat treatment procedure.

Heat-treated rough rice showed an increase in head yields accompanied by a reduction in milled rice whiteness and improvement in cooked-rice texture depending upon the heating surface temperature, exposure time, and initial moisture of rough rice. Heat treatments of rough rice corresponding to fungal inactivation level of 95% led to maximum head rice yields and acceptable level of reduction in the whiteness of milled rice. In general, high temperature conduction heating was found to be suitable for continuous rapid drying of high moisture rough rice down to about 15% w.b. without significant reduction in milling quality.

Finally, a comparison of rice drying costs when using the proposed rotary conduction heating systems and conventional heated-air drying systems clearly showed the rice husk-fired rotary dryer to be highly competitive.

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I. INTRODUCTION

1.1 General

In the tropics, rice is not only a staple food but also a major source of livelihood. Rice supports more human beings per hectare than any other grains. Therefore increased production through direct increase in yield and minimization of losses, will directly contribute to the better well-being of most peoples of Asia.

Rough rice is usually harvested at relatively high moisture levels (22 to 26 % w.b.) to minimize field losses and maximize the quality of milled rice. However at these moisture levels, rough rice may suffer substantial losses both in quality and quantity due to specific physical, physico-chemical, and biological factors, or a combination of them. In freshly harvested rough rice, the losses resulting from the rapid growth of micro-organisms on and within the grains are much more significant (Schroeder and Sorenson, 1961; Mendoza et al., 1981). These losses include reduction in germinability, discoloration of whole or part of the grains, reduced milling yields, unfavorable changes in cooking and eating quality, and potential health hazards from mycotoxins. In tropical and sub-tropical countries, the rate of these losses is further accelerated by unfavorable warmer and more humid climatic conditions.

Quality deterioration in rice following harvest leads to a direct economic loss. A real solution to this problem will consist of either avoiding the drying delays or extending the safe storage period of high moisture rice. Methods of holding high moisture rice prior to drying include the aeration of wet grain (Calderwood, 1966 and 1979), airtight storages (de Padua, 1965) and the use of chemical preservatives (Calderwood and Schroeder, 1975). These methods have been used only with limited success.

Heat sterilization and accelerated drying of high moisture grains as a method of arresting spoilage has not been attempted in the past. Earlier studies carried out at the Asian Institute of Technology clearly showed that high-temperature short-time drying of high moisture rewetted and parboiled rice in a screw conveyor heat exchanger heated by a rice husk-fired furnace could prove to be an innovative and practical approach (Suhargo and Jindal, 1983; Obaldo, 1983). Though these experiments aimed initially at the accelerated drying, they can be used for heat sterilization of high moisture rice to increase its safe storage period prior to final drying. Therefore, this study aimed at evaluating the thermal inactivation of fungi present in freshly harvested high moisture rough rice as a means of extending its safe storage period prior to drying. In addition, the effects of

heat treatments on accelerated drying and associated changes in the physical quality of rice were also investigated.

The results of this study will be particularly useful to the capital-short tropical countries where climate accelerates the deterioration in quality of rough rice following the harvest. The perceived benefits include the preservation of rice quality, increased production through minimization of losses, and improved utilization of dryers through proper scheduling of drying and heat treatment operations.

1.2 Objectives

The overall objective of this study was to evaluate the heat sterilization-cum-accelerated drying of high moisture rice as a means of preserving its physical quality and milling potential. The specific objectives consisted of the following:

i) to evaluate the quality effects of high-temperature short-time (HTST) exposure of high moisture rice,

ii) to investigate heat sterilization and accelerated drying of rice in experimental rotary conduction dryers to prolong its safe storage period, and

iii) to compare conduction and fluidized-bed heating and their economic feasibility.

2. REVIEW OF LITERATURE

2.1 Spoilage of High Moisture Rough rice

In high moisture fresh rough rice and similar grains, the loss in quality and quantity is mainly caused by field and storage fungi (Schroeder and Sorenson, 1961; Mendoza et al., 1981; Naewbanij et al., 1981, Ilag, 1982, Quitco, 1982). Generally, the field fungi are those that invade the grain while the plant is still growing in the field or after the grain is cut but before it is threshed. While the storage fungi are those which develop on and within the seeds in storage. Freshly harvested rough rice if stored at 18% moisture content and above provides a good living environment for field and storage fungi.

In any attempt to prevent microbiological deterioration in high moisture rice, attention should be focused on the control or eradication of both field and storage fungi. As of to date, the control of these microorganisms has been ineffective especially for high moisture food grains.

Many studies have demonstrated the similarities in microflora found in paddy and other grains. Therefore, selected investigations on other food grains were also included in this review.

2.1.1 Field fungi

The reported field fungi that invade the rice grains are species of Alternaria, Cladosporium, Curvularia, Fusarium, Nigrospora and Rhizopus (Panse and Christensen, 1970; Schroeder, 1963; Mendoza et al., 1981). All field fungi require a high moisture content in equilibrium with a relative humidity of 90% or higher (Christensen and Kaufmann, 1969; Ayerst, 1969; Lacey, 1980; Christensen and Sauer, 1982). The equilibrium moisture content of rough rice at this relative humidity and temperature of 30 °C is about 18.0 % (Wassermann and Calderwood, 1972). Therefore during temporary storage of high moisture rough rice, field fungi continue to grow in competition with other storage fungi.

A summary of the major fungi with their growth requirements is presented in Table 2.1.

2.1.2 Storage fungi

Most storage fungi have the ability to grow in food grains whose moisture content are in equilibrium with relative humidities of 70% and above (Table 2.1). The major fungi that invade the rice seeds at 9 to 20% moisture contents are Aspergillus and several species of Penicillum (Schroeder and Sorenson, 1961; Christensen, 1969).

Table 2.1 Growth limits of some common fungi

Some common rice fungi	Physiological classification[4]		Growth limits	
	Temperature	Water activity	°C	Minimum rice[7] moisture(% w.b.)
Penicillum spp.	Psychrotolerant		-10 -35[4] (20-25)[3]	
	Lower mesophilic	Slightly xerophilic	2 - 37[4]	15 - 17[4]
	Upper mesophilic	Slightly xerophilic	5 - 50[4]	15 - 17[4]
Aspergillus flavus	Upper mesophilic	Moderately xerophilic	5 - 50[4] (33)[2]	14 - 15[4] (>24)[2]
A. candidus	same	same	5 - 55[3,4]	14 - 15[4]
A. ochraceus	same	same	5 - 55[4]	14 - 15[4]
A. glaucus	Mesophilic	Extremely xerophilic	2 - 50[4] (30-35)[3]	13 - 14[4]
A. restrictus	Mesophilic	same	2 - 50[4] (30-35)[3]	13 - 14[4]
Helminthosporium	Lower mesophilic	Hydrophilic	2 - 37[4]	>18[4] (24-25)[6]
Fusarium	Lower mesophilic	Hydrophilic	2 - 37[4]	>18[4] (24-25)[6]
Cladosporium	Psych[illegible] tolerant	Slightly xerophilic	-	15 - 17[1]
Alternaria	Lower mesophilic	Hydrophilic	max 37[1]	>18[1]
Mucor		Hydrophilic	2 - 50[4]	>18[4]
Rhizopus		Hydrophilic	5 - 50[4]	>18[4] (24-25)[6]

Note: Items in parenthesis are optimum levels for growth.
Source: (1) Apinis (1972)
(2) Ayerst (1969)
(3) Christensen and Kaufmann (1974)
(4) Lacey et al. (1980)
(5) Quitco (1982)
(6) Ilag (1982)
(7) Wratten and Kendrick in Wassermann and Calderwood (1972)

In freshly harvested rice stored at 18% moisture content and higher, the major storage fungi that grows well with the field fungi are species of Aspergillus flavus (Mendoza, et al., 1981; Ilag, 1982; Quitco, 1982).

2.2 Source of Fungal Inoculum

At the time of harvest, most of the mycelium on and within the rough rice kernels appears to be that of Alternaria, Helminthosporium, Fusarium or other field fungi (Schroeder and Sorenson, 1961; Mendoza et al., 1981; Naewbanij et al., 1981). However, inoculum of storage fungi as dormant spores are present on the outside of most rough rice kernels right after threshing. These dormant spores increase tremendously within a few days under favorable conditions. Most fungi isolated from grains (e.g. Aspergillus, Fusarium, Penicillium, and Rhizopus) occur also in soil (Apinis, 1972). Whereas Alternaria, Cladosporium, and Helminthosporium are found on plant parts such as leaves in the field but rarely in the soil.

2.3 Quality Deterioration due to Microbial Infestation

Fungi growing in stored grains can result in substantial qualitative and quantitative losses. These are discussed in the following sections.

2.3.1 Decrease in germinability

There is considerable evidence in the literature to support that invasion by storage as well as field fungi can result in loss of germinability of the grain. Infections by Fusarium and Helminthosporium usually result in death and discoloration of the grain (Schroeder and Sorenson, 1961; Quitco, 1982). In all rice storage studies, an invasion by storage fungi was accompanied by a reduction in germinability (Papavizas and Christensen, 1960; Fields and King, 1962). But not all decrease in germinability could be attributed to fungi, high temperatures can also be lethal to the seed especially at high moisture content.

2.3.2 Discoloration

In general, both field and storage fungi may cause discoloration of the whole seed or portions of it, particularly the germ. Much of the discoloration caused by field fungi occurs prior to harvest. However, the activities of field fungi may continue if rice is stored at a relatively high moisture. Helminthosporium, Nigrospora, Cladosporium, Curvularia, Fusarium, Rhizopus, and Alternaria produce pigmented materials when growing in rice. Grain discolorations from red to yellow have been associated with Fusarium chlamydosporium (Schroeder, 1964; Quitco, 1982). Dark to brown discoloration is often found in high percentage of rice kernels infected by Helminthosporium oryzal and Curvularia (Fazli et al., 1966 a, b; Schroeder 1967; Quitco, 1982). While Rhizopus sp. infested grains produce

yellowish-brown milled rice (Quitco, 1982).

Storage fungi also have been associated with discoloration in rice. Penicillium puberlum is known to cause orange stain, while P. Islandicum and Aspergillus flavus are recognized to give a yellowish color in rice (Schroeder, 1957; Tatsumo, 1963; Quitco,1982; Christensen and Kaufmann, 1974).

2.3.3 Respiration and heating

All living things respire and as a result of this, water and heat are produced and carbon dioxide evolved. At moisture contents that are suitable for seed germination, fungi and seed respiration contribute to total respiration.

It has been shown by Naewbanij et al., (1981) that rice having greater fungal load respires more than samples having less fungal load during temporary storage at low temperatures.

2.3.4 Biochemical changes

A variety of biochemical changes accompany or follow the invasion of stored seeds by fungi. The major biochemical changes are increase in fatty acids, increase in reducing sugars, decrease in non-reducing sugars, and increased respiration (Pomeranz, 1982).

The changes that occur in rice and other cereal grains are inner changes occurring in grain themselves and other damages caused by fungi. These changes and damages tend to take place simultaneously during the storage and are inseparable from each other.

2.3.5 Mycotoxins

Some metabolites of fungi that grow in rice have been shown to be detrimental, or even toxic to human and other animals (Hiscocks, 1965; Schroeder, 1969; Christensen and Kaufmann, 1969). These metabolites are called mycotoxins.

Species of the Aspergillus flavus group constitute a universal and significant part of the fungal flora of stored rice. Aflatoxins, which are known to have been responsible for the deaths of large number of poultry are toxic metabolites produced by Aspergillus flavus (Christensen and Kaufmann, 1974). Rice has been shown to be an excellent growth supporting substrate for species of the A. flavus group and for the production of aflatoxin (Schroder, 1969; Schroeder and Ashworth, 1966). In 1966, Boller and Schroeder found aflatoxin in 11.25 percent of the 281 samples from the rice-growing areas in the U.S. However, only 0.7% samples contained significant amount of aflatoxin.

Calderwood and Schroeder (1968) found out that high moisture rice stored at low airflow was significantly contaminated with aflatoxin within 2 days.

The problem of aflatoxin contamination in rice is apparently not serious. Schroeder (1969) reported that most of the aflatoxin in contaminated rice was located in the bran and outer layer of the kernel. Therefore, ordinary milling procedure can be expected to remove most of the toxin. However, rice bran containing aflatoxin may have implications for use as an animal feed especially in Asian countries.

2.3.6 Total decay, mustiness and caking

These represent advanced stages of spoilage by fungi and are detectable by the unaided eye and nose. Webbing of fine thread-like mycelium between kernels results in various degree of clumping or caking of the kernels. Caked and decayed grains are not appealing to the consumer thus leading to reduction in market value.

2.4 Control of Quality Deterioration in High Moisture Rice

There are basically two general ways to extend the storage life of high moisture grains. These could be either through the use of chemicals (gas treatments and fungicides) or by the action of physical agents to inhibit or kill the fungi and other microorganisms. The means to prolong the storage life of high moisture grains can be also classified as either control of microorganisms by retarding growth (drying, aeration, refrigeration, controlled atmosphere storage, and the use of fungicides) or control by the destruction of microorganisms (gas treatments, ultraviolet radiation and ionizing radiation).

2.4.1 Drying

Drying to a safe moisture level too low for fungi to grow is the most widely used method of preserving quality in grains intended for human consumption. A low and uniform moisture content is effective in prolonging viability and maintaining quality in most agricultural seeds (Hukill, 1974; Foster, 1982). Aside from the prevention of microbial growth, drying is also used to preserve the product from physical and chemical changes induced or supported by excess moisture; to reduce the packaging, storage and transportation costs; and to bring the product to a desirable moisture level for grading purposes.

2.4.2 Aeration

The primary objective of aeration is cooling to retard mold growth and respiration of grains. Aeration generally results in slight additional drying and uniform temperature throughout the mass of stored grain. This is helpful since

unequal temperatures are known to be a cause of moisture migration (Hukill, 1953).

Though typical airflow rates for aeration range from 1×10^{-6} to 2×10^{-6} $m^3/s\text{-}kg$, aeration of high moisture rice below 1×10^{-6} $m^3/s\text{-}kg$ is still ineffective in controlling the quality deterioration (Shroeder and Sorenson, 1961; Shroeder, 1963; Calderwood, 1966; de Castro et al., 1980). Calderwood and Schroeder (1968) found out that high moisture rice stored at low airflow was significantly contaminated with aflatoxin within 2 days. However, aeration of wet rough rice (20% w.b.) at 1×10^{-6} $m^3/s\text{-}kg$ and above could maintain the quality of stored rice for a very limited period of about 5 days. At these high airflow rates, the increase in storage life of high moisture rice was mainly due to the drying and cooling effects of aeration.

2.4.3 Controlled atmosphere storage

Controlled atmosphere storage of high moisture rice has been found to be ineffective because of the ability of some fungi to grow under such adverse conditions (de Padua, 1965; Hyde, 1969; Teunisson, 1954; Iwasaki and Tani, 1967). Teunisson (1954) reported a continued growth of anaerobic bacteria and yeasts in rice having moisture in the range of 18 to 32% stored under anaerobic conditions. De Padua (1965) observed that controlling the levels of carbon dioxide and oxygen was not effective in inhibiting mold growth in high moisture rice.

2.4.4 Refrigeration

Some fungi, when sufficient moisture is present, will grow at temperatures well below freezing. It has been reported that field fungi may survive in low temperature storage of high moisture grains and may be found growing actively in conjunction with storage fungi (Lagrandeur and Poisson, 1968; Pelhate, 1968).

In general, refrigeration is expensive and drying to safe moisture levels may still be necessary (Kreyger, 1963). Therefore, refrigeration may not be economically feasible under tropical climatic conditions.

2.4.5 Use of fungicides

The application of fungicides such as propionic acid, sodium propionate, calcium propionate, etc. is limited mainly to high moisture grains to be used as animal feeds (Sauer, 1972; Lane, 1972; Sauer and Burroughs, 1974; Perry, 1972; Wilson, 1972). There are various limitations in using these chemicals such as reduced germinability, development of acid taste and odor, toxicity to animals, difficulty of application, and excessive costs.

2.4.6 Gas treatments

Fumigants such as phosphine, ethyl dibromide and methyl bromide are commonly used in stored grains to destroy the microorganisms and insects. However at present, their use is mainly limited to insect disinfestation in relatively dry grains because of high costs, and ineffectiveness in high moisture grains (White, 1977; Wesley et al., 1965; Banwart, 1979).

2.4.7 Ionizing radiation

In food preservation, the use of gamma rays has been preferred for killing microorganisms (Herson and Hulland, 1980). The death or injury of microorganisms is due to either direct or indirect effects.

The use of ionizing radiation proves to be an expensive method of microbial destruction. At higher levels of ionizing radiation, the quality of the food may suffer due to the development of off-flavor. In addition, irradiated food may not be easily accepted by the consumer because of the fear of possible health hazards.

2.4.8 Ultraviolet radiation

The anti-microbial effect of ultraviolet (UV) light has been known for about 100 years. The lethal action of UV light varies with the intensity of light and time of exposure. However, the energy of UV light is much lower than that of ionizing radiation (Fields, 1979). Therefore, low penetrating power of UV light is not very effective in killing the microorganisms in grains.

2.5 High Temperature Heating of Grains

In food industry, the most common method of killing microorganisms is based on the application of heat. Besides killing microorganisms, heating can inactivate enzymes (tissue or microbial) causing deterioration during temporary or long storage periods. However, the use of heat treatment for microbial destruction in high moisture grains for prolonging their safe storage period has not been explored so far.

Heating of agricultural grains for drying is an accepted practice. Recently, fluidized bed heating has been shown to be an effective means of insect disinfestation in low moisture wheat (Dermott and Evans, 1978). Later it was suggested that heat sterilization may be used in a similar manner to reduce the microbial deterioration in high moisture fresh rice (Evans, 1980).

Fluidized bed heating characteristically offers high rates of heat transfer with accurate temperature control. However, high power requirement is a major disadvantage in applying the fluidized bed technique. As an alternative, the use of screw-type

heat exchangers for conduction heating of high moisture paddy to accelerate drying process may prove to be effective (Suhargo, 1982; Obaldo, 1983).

Other studies on the use of elevated temperatures to disinfest stored grains and cereal products with infra-red, microwave and dielectric heating (Boulanger et al., 1971; Nelson, 1972, 1973; Kirkpatrick and Tilton, 1972; Kirkpatrick et al., 1972; Kirkpatrick, 1975 a and b; Watters, 1976) have evaluated the effectiveness of rapidly heating infested grain or flour to temperatures within the range of 48 - 85 °C for various exposure times followed by passive cooling.

It appears that a knowledge of the relationship between microorganisms mortality, exposure temperature and time is essential in planning heating strategies and designing disinfestation systems. In addition, possible deterioration in grain quality due to heating process needs to be taken into consideration along with the economics of operation.

2.5.1 Conducted Heating of Grains for Drying

There are a limited number of studies on the application of conduction heating to grain drying in the reported literature. Basically, two different types of conduction heat transfer systems have been used. In the first system, a solid heat transfer media such as salt or sand is used (Khan et al., 1974; Raghavan and Harper, 1974; Ali and Bhattacharya, 1980; Mittal and Lapp, 1984). This system necessitates the separation of the grain from the heat transfer media following the drying and thus making its mechanical operation cumbersome. In the second system, the grain is rolled over the heated surface by mechanical means (Hall and Hall, 1961; Chancellor, 1968a; Suhargo, 1982; Acasio and Belonio, 1983; Obaldo, 1983). This system appears to be more practical in providing a simple means of applying heat in a direct manner.

2.5.2 Quality Deterioration in Grains Due to Heat Treatment

Heating of grain using high temperature could be beneficial in terms of rapid drying, improved milling quality and possible destruction of microorganisms. However, it may result in excessive development of cracks or fissures (Kunze, 1984), gelatinization of starch (Khan et al., 1974; Juliano 1979; Calderwood 1971; Kunze 1979), and loss of germinability. The gelatinization of starch which is usually termed "parboiling effect" may be appreciated because of more translucent and harder kernels and reduced breakage during milling operations. In addition, there is evidence in literature that heating of high moisture fresh rice may result in artificial aging leading to significant improvements in its eating and cooking qualities (Normand et al., 1964; Juliano, 1979).

2.6 Conduction Heating of High Moisture Grains for Fungal Disinfestation

Aside from drying to safe moisture levels, presently available means of extending the safe storage period of high moisture rice have been used with limited success. Serious limitations including excessive cost, undesirable taste and odor, and ineffectiveness have been encountered.

Heat sterilization of high moisture rough rice could prove to be an innovative approach to extend its safe storage period. The inactivation of microorganisms by the application of heat is common in food processing industry but it has not been applied to preserve the quality of high moisture grains. Though maximum temperatures for fungal growth in grains have been reported to be in the range of 50 to 55 °C, the maximum exposure times which the fungi can tolerate are not known (Ayerst, 1969; Christensen and Kaufmann, 1974). Conduction heating of high moisture rough rice for inactivating the fungi could prove to be an innovative and practical approach for temporarily holding wet grain prior to final drying. However, evaluation of this approach must include detailed investigations of the time-temperature history of the grain during conduction heating, the operational characteristics of the heat application system and the changes in grain quality due to heating. This approach could be practical because conduction heating equipment generally require less capital investment and energy, and such equipment are easy to fabricate (Chancellor, 1968; Root and Cook, 1980).

The time and temperature requirements for killing rice microflora to any desired level would need to be established first. This information could perhaps be expressed in general terms so as to be applicable to a given heat treatment system. From practical point of view, inexpensive conduction heating system would need to be devised and evaluated for their performance. Simple conduction heat application systems reported by Suhargo (1982), Obaldo, (1983), and Acasio and Belonio, (1983) could prove to be practical means of applying heat to high moisture grain for preserving its quality during temporary storage.

It is expected that possible deterioration in grain quality due to the heating process would need to be taken into consideration along with the economics of the operation.

III. MATERIALS AND METHODS

The overall experimental plan included the following: (i) heat sterilization and accelerated drying of freshly harvested rough rice in experimental rotary conduction heating units, (ii) quality effects of heat treatments on high moisture rough rice, and (iii) performance and economic analysis of prototype conduction and fluidized-bed heating units.

The first part of this study included a detailed investigation of the thermal inactivation of fungi in freshly harvested rough rice and subsequent drying during heating operations. In the second part, the quality effects of heat treatments on high moisture rice were investigated in terms of its safe holding periods, head rice yield, milled rice whiteness and cooked-rice texture. The safe holding periods of heat treated rough rice samples were determined based upon accepted criteria of reduction in head rice yield and an increase in the proportion of discolored kernels. Finally, the performance and cost anaysis of the proposed prototype heating units were evaluated in detail.

3.1 Preparation of Samples

Rough rice used for this study was a medium grain variety (RD-23) which was harvested manually from the experimental field of the Division of Agricultural and Food Engineering. Immediately after harvesting, the moisture content of rough rice was about 22 to 24 % wet basis (w.b.). In some tests, the moisture content of freshly harvested rough rice was adjusted to 26% by slight addition of water in order to have an uniform initial moisture content. Lower moisture content of 18% were obtained by exposing the high moisture rough rice to ambient conditions under shade. For 30% initial moisture content samples, rough rice was soaked in water at normal temperature for 24 hours, then spread on a nylon mat under shade and frequently stirred until the desired level of moisture was obtained. Rough rice samples were temporarily stored in a freezer at about -15 °C in order to suppress fungal growth and minimize quality changes. Prior to heating tests, rough rice was removed from the freezer and conditioned to room temperature while in plastic storage bags.

3.2 Heat Application Units

In this study, two small-scale conduction heating units for batch operation, two full-scale prototype conduction heating units for continous operation and a spouted- bed heating unit were used for heat sterilization and rapid drying of freshly harvested rough rice. The small-scale heating units were used for preliminary studies and controlled heating and drying experiments. On the other hand, full-scale prototype heating units were used to simulate on-farm handling of newly harvested high moisture rice. The design details of these heating units are

presented in the following sections.

3.2.1 Small-scale rotary heating unit with axial flights (model I)

This batch type rotary conduction heating unit consisted mainly of a rotary cylinder, 0.35 m in diameter and 0.85 m long, with six equidistant straight axial flights extending 4 cm from the inside surface. The schematic diagram of the heat treatment unit is presented in Fig. 3.1. A heavy duty ball bearing mounted on the steel frame supported the cylinder from one side only during its rotation. The other end of the cylinder served as inlet and outlet for rough rice samples through a removable perforated cover. Samples were discharged by removing the cover and lifting the rear side of the unit. Four 1-kW electric resistance heaters were placed beneath the rotary cylinder to supply the required heat. The heaters and rotary cylinder were encased in an outer cylinder and insulated using 6 cm thick wool fibre packing. The temperature of the cylinder surface could be raised up to 300 °C. The heating surface temperature was regulated with an automatic electric temperature controller equipped with a copper-constantan thermocouple sensor. This sensor was placed 1 cm above the surface of the rotating drum. The average temperature of the rotary drum surface was measured directly using thermocouples connected to a separate temperature recorder. The settings of temperature controller were adjusted subsequently based on the calibration of the drum surface temperature with the sensor temperature. It was possible to maintain the temperature of the drum surface within ± 5 °C. The cylinder rotation speed could be adjusted from 10 to 40 rpm by a variable speed 1-kW electric motor. Other details are given by Reyes (1986).

3.2.2 Small-scale one-pitch rotary heating unit (model II)

A second batch type rotary conduction heating unit consisted mainly of a rotary cylinder, 0.6 m in diameter and 0.2 m long. This heating unit represented a one-pitch section of the prototype rotary dryer with helical flights (see prototype units, section 3.2.4). Fig. 3.2 show the features of this one-pitch rotary heating unit. One side of the cylinder was covered with steel sheet connected to a driving system. The other end which served as an inlet and outlet for rice samples was covered with a perforated plate. Samples were loaded through a 0.1 m diameter center-hole of the perforated cover and unloaded through a removable sector of the perforated cover. Four 1-kW electrical resistance heaters were placed in between the rotary cylinder and an insulated exterior cylinder to supply the required heat. The temperature of the cylinder surface could be raised up to 300 °C and maintained within ± 5 °C by a temperature controller.The cylinder rotation speed could be adjusted from 3 to 35 rpm by a variable speed 1-kW electric motor.

1. Rotary heating chamber
2. Straight flights
3. Inlet / outlet
4. Removable cover
5. Fixed outer casing
6. Electric heater
7. Variable speed motor
8. Paddy outlet guide
9. Chain drive
10. Handle
11. Temperature controller

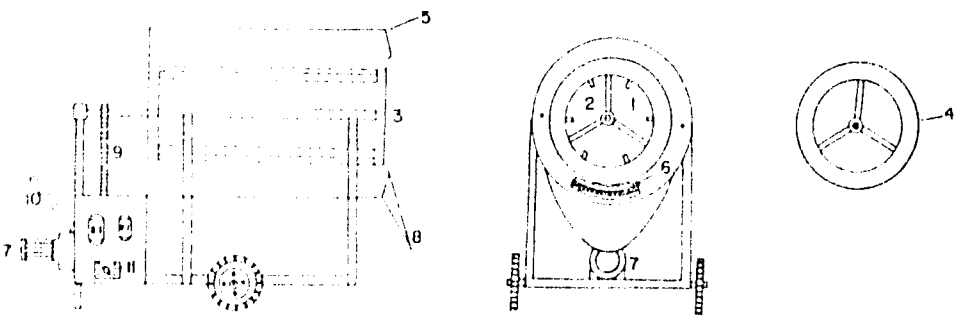
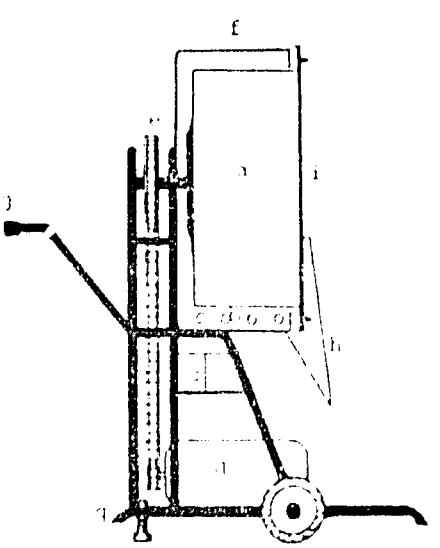


Fig. 3.1 Schematic diagram of the small-scale heating unit with axial flights



a Solid surface heat exchanger
b Electric tube-heater
c Temperature control box
d Electric motor
e Sprocket-chain drive assembly
f Shroud and insulation
g Frame support assembly
h Grain discharge chute
i Heat exchanger cover
j Handle

Fig. 3.2 Schematic diagram of the small-scale one-pitch rotary heating unit

3.2.3 Full-scale prototype rotary heating unit with axial flights (Prototype I)

This electrically-heated prototype heating unit consisted mainly of a heating cylinder, heater housing, inlet feeder, and dryer support frame. Fig. 3.3 shows the schematic diagram of this prototype rotary heating unit.

Heating cylinder. The heating or drying cylinder, constructed from 3 mm thick mild steel sheet was 2.5 m length and 0.6 m in diameter. Eight straight flights 2 m long and 7.5 cm high were equally spaced and welded along the cylinder's inside wall. At the inlet side of the cylinder, four baffles were alternately welded 45-degrees to the end of four axial flights for facilitating the flow of grains. Two guide rings, 0.64 cm thick and 5 cm wide, were placed around the cylinder to facilitate its smooth rotation along the rollers. A 1-kW electric motor with a gear reducer was used to rotate the drying cylinder. A chain and sprocket gear drive was used for power transmission from gear box to the drying cylinder.

Support frame. The dryer support frame was constructed using 5 cm angle bars. The drying cylinder rested on four rollers 10 cm in diameter and 5 cm wide, each fitted with heavy-duty roller bearings 8 cm in diameter. In front of the cylinder was a support made up of two rollers 10 cm diameter for carrying the weight of the cylinder and its contents when tilted. The dryer inclination could be adjusted up to 9-degrees.

Heater housing. The heater housing, which was constructed with 3 mm thick mild steel sheet was 2 m long and 0.8 m in diameter. The cylinder housing was divided into two parts longitudinally for maintenance and repair purposes. The inside housing was insulated with two layers of 0.3 cm thick asbestos board and the outside was insulated with 5 cm thick microfiber insulation. In the lower portion of the housing, 15 1-kW electrical resistance heaters were installed equally spaced and divided into three 5 kW circuits. The electrical installation was designed to provide a cylinder surface temperature of up to 200 °C. A thermocouple probe was placed 1 cm above the surface of the drying cylinder. The probe was connected to a temperature controller with a range of 0 to 300 °C and a 2.5 % full scale indicating accuracy.

Inlet feeder. The feed rate could be controlled by a rotary feed gate attached to the electromagnet. The feed rate could be varied from 1 to 40 kg/min. Other details are given by Molano (1987).

1. Dryer cylinder
2. Heater housing
3. Electric motor
4. Dryer support
5. Paddy inlet hopper
6. Paddy inlet hopper control
7. Electric heater
8. Axial flight
9. Front dryer support
10. Electromagnet vibrator
11. Paddy outlet guide
12. Microfiber insulation
13. Asbestos insulation
14. Heater housing shell
15. Chain drive

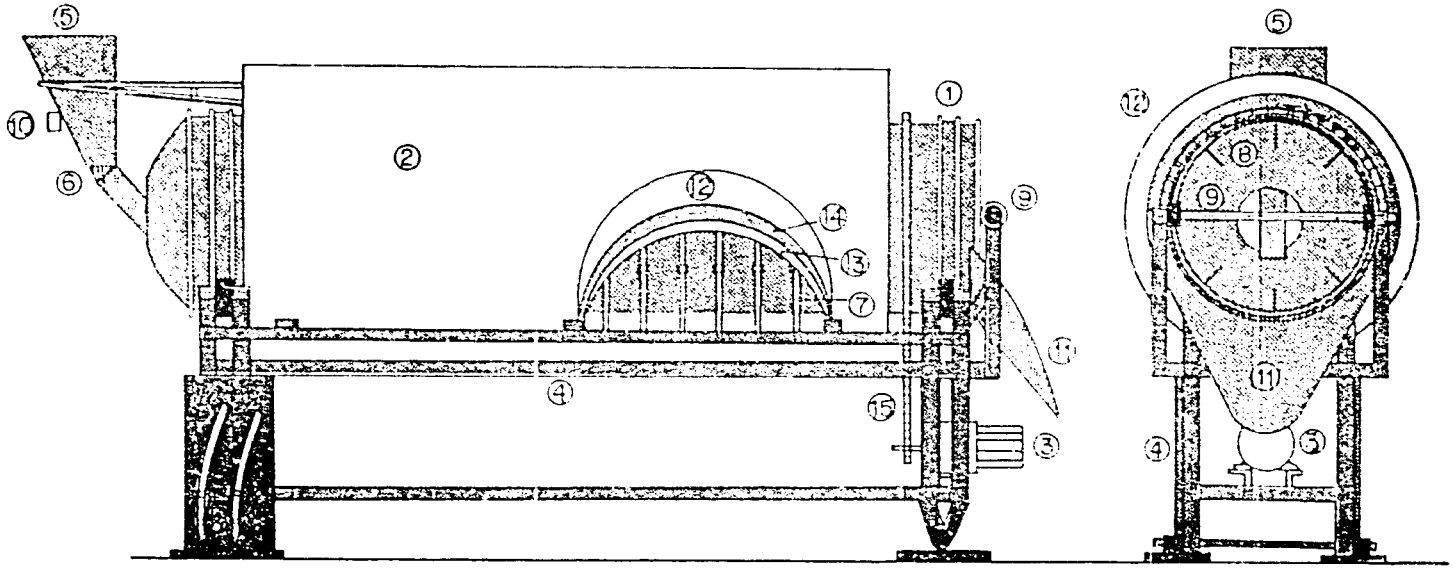


Fig. 3.3 Schematic diagram of prototype rotary heating unit with axial flights

3.2.4 Full-scale prototype rotary heating unit with helical flights (Prototype II)

The prototype rice husk-fired rotary heating unit consisted mainly of an inclined grate-type furnace and a slowly rotating drying cylinder enclosed in the flue gas chamber. A continuous helical spiral was attached to the inside wall of the rotary cylinder for conveying and mixing of rough rice samples during heating. The schematic diagram of this heating unit is presented in Fig. 3.4 and detailed drawings are given in Appendix B. The design details are discussed in the following sections.

Rough rice feeder. The feeder assembly consisted of a hopper for loading, a spout for feeding the grain into the drying cylinder, and an electromagnet serving as a vibrator to regulate and maintain the desired feed rate. The feed rate could be regulated manually by adjusting the rotary feed gate attached to the electromagnet from 1 to 40 kg/min.

Rotary heating cylinder. The rotary heater was basically a cylinder 0.6 m in diameter and 2.2 m in length. This cylinder served as a heat exchanger for conduction heating and drying of high moisture paddy. It had a helical spiral welded to the inside wall of the cylinder, machine girth sprocket ring and chain drive assembly powered by an electric motor, flat bar girth rings riding on ball bearings, a discharge spout and chute for unloading the heated and dried grain.

The horizontal travel of the wet grains in the heat exchanger was affected by the helical flights. As the heating cylinder rotated, the flight pushed and conveyed the grains causing it to slide, roll or tumble along the inner wall of the hot cylinder. The helical flight also served as an additional heating surface aside from providing grain agitation and transport. The rotation speed could be varied from 1 to 45 rpm by regulating the speed of the one kilowatt electric motor.

Rice Husk Furnace. The furnace was the main heat source of the rotary heater. It was fueled by rice husk with a maximum furnace temperature of 800 °C attainable at about 30 kg/hr feed rate. The furnace was made of hollow bricks and consisted of a hopper, hull feeder, husk flow equalizer, inclined fire grate, ash dropper and ash collector. The husk feeder was designed to facilitate uniform feed rate. The hull flow equalizer regulated the even distribution of the husk as it drop down the inclined grate. The inclined grate was made of 110 rows of sloping and horizontal fire bars. The husk feed rate ranging from 5 to 30 kg/hr can be regulated manually by adjusting the rotary feeding gate attached to the electromagnet with an on/off switch mechanism.

Flue Gas Chamber. The flue gas chamber was designed for enclosing the rotary heating cylinder and hot gases coming from the rice husk furnace. The walls of the chamber were made of bricks strong enough to hold the dryer and prevent the excessive

1. Rice husk hopper
2. Furnace
3. Paddy inlet hopper
4. Electro magnet vibrator
5. Dryer brick housing
6. Rotary cylinder
7. Electric motor
8. Chain drive
9. Paddy outlet guide
10. Helical baffles
11. Chimney

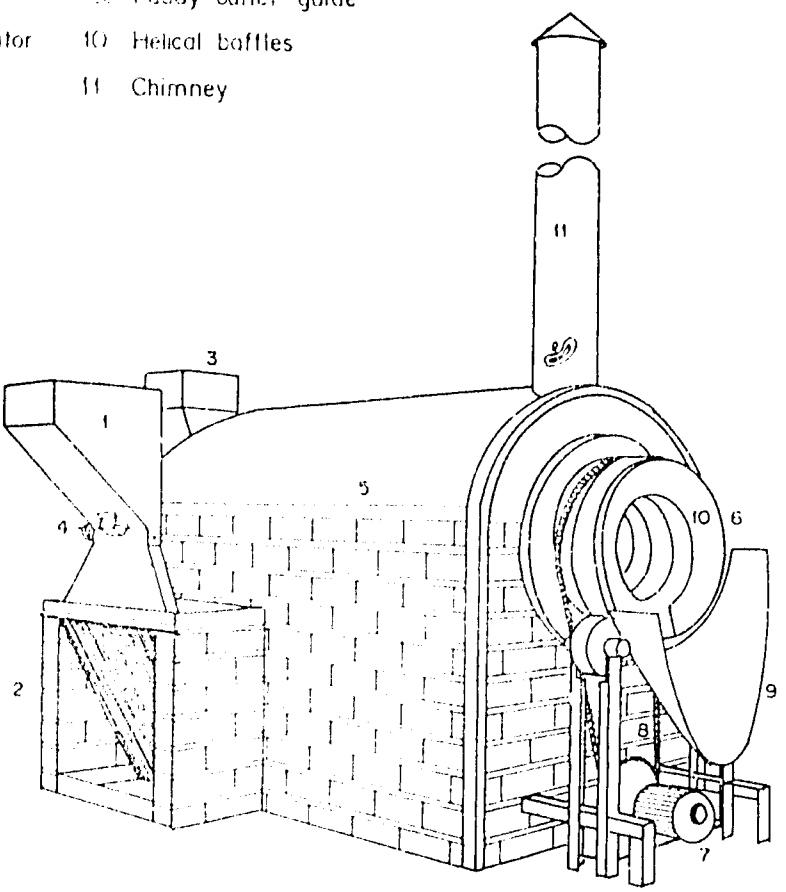


Fig. 3.4 Prototype rice husk-fired rotary dryer with helical flights

heat loss. The frame to support assembly of the bricks was made of 5 x 5 cm mild steel angle bars. The joints were enclosed by 3 mm mild steel sheet.

Rockbed Heat Storage. A rockbed heat storage was incorporated to help minimize temperature fluctuations in the heating cylinder. It consisted of 8 to 10 cm diameter ordinary rocks with a total volume of about 0.5 cubic meter located beneath the rotary heating cylinder. The rockbed heat storage helped stabilize the desired heating surface temperature and maintain it over relatively longer exposure times.

Chimney. The chimney was the exhaust port of the unused heat and products of combustion coming from the furnace. The main function of the chimney was to establish the minimum draft required for complete combustion and to regulate the flow of hot gases by manually adjusting a baffle located at its base. The chimney was made from 1.5 mm thick mild steel and had a diameter and height of 0.20 and 3.6 m, respectively.

3.2.5 Fluidized-Bed Heating Unit

A spouted-bed unit representing a special type of fluidized system was used as an alternate method of accelerating the drying process. The spouted bed dryer consisted mainly of a cylindrical vessal with a conical bottom, a blower and a heater box. Fig. 3.5 shows the features of the spouted bed heating unit. The cylinder was 30 cm in diameter and about 2.4 m in height. The angle of the conical bottom was about 60° from the horizontal. The cylinder wall just above the cone was fitted with a glass window for observation. Copper tubes were also installed for measurements of pressure drop and temperature along the cylinder. An inverted cone-shape head was connected to the top of the column for measuring the airflow rate by a vane anemometer. The dryer was connected to an electric heater box and a centrifugal blower. The blower and heater box were connected by a 15 cm diameter gate valve for airflow regulation. The heating box had twelve 1-kW heating coils with on-off switch control. The heater box was made of double wall from 1.5 mm thick steel sheet and a removable top cover to facilitate the repair of electric heaters. Fire clay was also placed in between the walls to minimize the heat losses. The pipe connecting the heater box and the drying column was also insulated by wool fibre. The centrifugal blower had a capacity of 13 m^3/min of air at 3600 rpm. The blower which was made by Sanco Manufacturin Co., Japan (model TBH-4) had a power requirement of about 3.7 kW or 5 hp. Other details are given by Heng (1987).

Fig. 3.5 Spouted-bed heating unit

3.3 Preliminary studies on high-temperature short-time heating of high moisture rough rice

In order to assess the potential of high-temperature short-time (HTST) heating of high moisture rice in arresting fungal growth, several preliminary tests were conducted using a standard laboratory oven.

In the first set of experiments, newly harvested rice samples having a moisture content of 20% (w.b.) were heated in 5 cm layers fully covered with aluminum foil. Rough rice samples were heated up to 15, 25, 40 and 65 minutes at an oven setting of 200 °C. After heating the grain to desired exposure time, it was taken out and cooled in either rapid or slow mode. In rapid cooling, grain samples were spread on the floor over a nylon mat until its temperature adjusted to the room conditions. In slow cooling, the grain samples were first heated for about 20 minutes in a bucket and later spread on the nylon mat. The heat treated and unheated samples were then placed in plastic buckets covered with perforated aluminum foil for monitoring the microbial activity during subsequent storage.

In second set of experiments, rough rice rewetted from 14 to 22% w.b. was heated to about 70 °C bulk grain temperature for approximately 10 minutes in the same laboratory oven. Heated rough rice sample was then divided into two parts. One part was stored directly in plastic container without cooling, but the second part was cooled for about 10 minutes under room conditions (30 °C, 60-65 % RH) prior to storage. During ten days of storage, rough rice samples weighing about 1 kg were taken at random from the storage tank for quality analyses. The amount of fungal colonies (by dilution plating assay) was also monitored during the test period. The direct plating assay was not used because it was found to be ineffective in assessing the extent of fungal invasion quantitatively.

In the third experiment, two heating trials were performed using the one-pitch experimental heating unit (model II). The method employed in this treatment consisted of exposing 3 kg rewetted rough rice samples for a period of 5 minutes at heating surface temperature levels of 100 and 140 °C and cylinder rotation speed of about 14 rpm. Immediately after heating, the treated grains were transferred into a sterilized aluminum tray and covered with aluminum foil for ambient cooling prior to quality evaluation. Initial and final grain moisture and grain temperature were monitored and recorded for each treatments.

3.4 Heat Sterilization and Accelerated Drying

3.4.1 Heat sterilization of rough rice samples

Rough rice samples with moisture content of about 26% were heated in batches of 3 kg using the experimental rotary unit with axial flights (model I). Four heating surface temperature of 75, 100, 150, 200 °C and exposure times of 3 to 40 minutes were used. The cylinder rotation speed was fixed at 30 rpm to ensure faster heating rates. The time-temperature profiles of the grain were monitored during heating and cooling process.

After heating the grain to a desired exposure time, it was taken out and cooled to room temperature for subsequent microbiological and quality evaluations. Heat-treated rough rice samples were immediately transferred to the aluminum trays in 5 cm layers, completely covered with aluminum foil, and cooled to room temperature in a chamber maintained at -15 °C. Cooling in a fully enclosed container was necessary to avoid any contamination of the samples. This method resulted approximately in a 2 °C/min cooling rate.

Immediately after cooling, the sample was divided into three sub-samples, one for measurement of fungal count and another for carbon dioxide production. The remaining sub-sample was dried under room conditions to about 14% moisture content for subsequent milling tests.

3.4.2 Accelerated drying of high moisture rough rice

Selection of cooling method. Prior to drying tests, the effect of cooling rate on the milling quality of heated rough rice was evaluated first to select an appropriate cooling method. Four methods, designated as very fast, fast, moderate and slow cooling were used for cooling heat treated rough rice samples having initial moisture content of 22% and 30% w.b. For very fast cooling a perforated rotary cylinder similar to the heating unit (model I) was used. An open cylindrical container about 30 cm in diameter and 10 cm in depth with constant agitation was used for fast cooling. A similar cylinder with perforated cover was utilized for moderate cooling. A rectangular aluminum tray covered with aluminum foil was used for slow cooling.

Moisture removal during conduction heating. The accelerated drying behaviour of high moisture rough rice during conduction heating was evaluated first under controlled experimental conditions using the two electrically-heated experimental heating units. The following experimental conditions were used during conduction heating in the first experimental heating unit (model I).

Heating surface temperature	:	75, 100, 150, 175 and 200 °C
Initial moisture content of rough rice	:	18.0, 22.0, 26.0 and 30.0% w.b.
Exposure duration	:	up to 100 minutes
Cooling	:	moderate
Rotation speed	:	20 rpm
Sample size	:	3 kg

The drying behaviour of high moisture rough rice in the second experimental unit (model II) was also evaluated using the above experimental conditions with rough rice samples having moisture contents of 18, 22, and 26% w.b..

3.5 Quality Effects of HTST Heat Treatments

3.5.1 Effects of heat treatments on temporary storage

Rough rice samples were heat-treated using the experimental heating unit with axial flights (model I) and rice husk-fired unit (Prototype II) to study their storability. For the

experimental unit, the test conditions were:

Heating surface temperature	: 100, 150 and 200 °C
Initial moisture content of rough rice	: 22.0 - 26.5 % w.b.
Exposure duration	: depending upon the level of fungal inactivation (75, 90, 95% mortality levels)
Cooling	: moderate
Rotation speed	: 20 rpm
Storage period	: 0, 3, 5, 10 and 15 days
Sample size	: 3 kg

Finally, to validate the results from the above tests, storage tests were also conducted using rice samples heated in the rice husk-fired prototype heating unit. The following were the experimental test conditions:

Heating surface temperature	: 100, 150 and 200 °C
Initial moisture content of rough rice	: 25.0 % b.
Exposure duration	: depending upon the level of fungal inactivation (90 % mortality level)
Cooling	: moderate
Rotation speed	: 10 rpm
Feed rate	: 7.5 kg/min (20 kg per run)
Storage period	: 0, 3, 5, 10 and 15 days

All heating tests were replicated thrice in order to have sufficient quantities available for storage and subsequent quality evaluation tests.

Storage experiments

After each treatment, rough rice samples were allowed to cool to room temperature in plastic buckets covered with perforated aluminum foil to allow the escape of vapor during cooling. Subsequently, the samples were transferred into 2 liter capacity glass bottles with provision for carbon dioxide to escape through the cotton plugs into the atmosphere during storage. The samples were aerated using a simple hand pump every 24 hours to prevent the building of carbon dioxide concentration in the storage chamber. The samples were stored at room temperature (28-30 °C) during the test period.

3.5.2 Effects on milling and cooked-rice quality

The experimental test conditions for milling quality and cooked-rice texture evaluation when using small-scale and prototype heating units were the same as in drying tests.

3.6 Fludized-Bed Drying

Several inlet air temperatures were used for evaluating the drying rate and milling quality of high moisture rice during spouted bed drying. The drying experiments were conducted using the following experimental conditions:

Weight of sample	= 12 kg
Grain moisture	= 26% w.b.
Inlet air temperature	= 50, 68, 80 (±2) °C
Inlet orifice diameter	= 5.0 cm
Airflow rate	= 4.8 m^3/min
	(1.10 m^3/sec.m^2)

For every drying test, a control sample weighing at least 1 kg was taken from the same lot and dried under shade for comparison purposes. Prior to any drying tests, airflow and air temperature were set at desired levels. Rough rice samples 20-30g were taken at 5 min interval during each drying test. At the end of each drying test, the rough rice sample was unloaded into plastic pail for cooling. After 2 h, the sample was spread on a tray for shade drying prior to milling.

3.7 Performance and Economic Evaluation of Prototype Drying Units

In this study, the performance of two proposed heating units were evaluated Finally, the cost of sterilizing and drying high moisture rough rice to specific levels were determined.

3.7.1 Performance evaluation of the prototype rotary unit with axial flights (Prototype I)

The drying parameters considered in the performance evaluation of Prototype I were heating surface temperature, exposure duration, initial moisture content of rough rice, grain feed rate, and rotation speed of the heating cylinder. However, it was found that the rotational speeds in the range of 6 to 30 rpm did not not significantly affect the drying rates. Therefore, The cylinder rotational speed was fixed at 10 rpm for all drying tests.

The following test conditions were used to evaluate the prototype dryer's performance:

Heating surface temperature	: 75, 100, 125 and 150 °C
Initial moisture content	: 22, 26 % w.b.
Exposure duration	: up to final moisture content of about 14% w.b.
Rotation speed	: 10 rpm
Feed rate	: 30 kg/min
Cylider inclination	: 1.5 degree

Initially the cylinder rotation speed and grain feed rate were set as required. Conduction drying was started after attaining the required heating surface temperature. After heating the grain samples for known exposure time or number of passes, they were cooled to room temperature in plastic buckets and dried subsequently to about 14% w.b. by spreading on a nylon mat. Grain moisture contents were determined using a Kett moisture meter and later adjusted to standard oven values. For each heat treatment, rough rice sample weighing 2 kg was also air-dried under shade to serve as control.

3.7.2 Performance evaluation of the prototype rotary unit with helical flights (Prototype II)

Samples of high moisture rough rice, each weighing 30 kg, were heated in the rice husk-fired rotary dryer using the

following experimental conditions:

Heating surface temperature	: 100, 140 and 180 °C
Initial moisture content	: 18, 22 and 26 % w.b.
Exposure duration	: up to final moisture content of about 14% w.b.
Rotation speed	: 10 rpm
Feed rate	. 30 kg/min

A similar procedure as described in the preceding section was also followed in this case.

3.8 Laboratory Methods for Fungal Characterization and Quality Evaluation

3.8.1 Dilution plating assay

The number and proportion of fungi present in the rough rice samples were determined by dilution plating assay. The pour and spread plate methods as described by Flannigan (1977) were used to measure storage fungi in malt salt agar (MSA) medium and field fungi in potato dextrose agar (PDA) medium, respectively. Dilutions were made by blending 50 g of grain in 500 ml of 0.12% sterile agar in water for 2 min. Successive dilutions were made by transferring 10 ml of the suspension medium to 90 ml of 0.12% agar in water. One-ml and 0.2 ml of appropriate dilutions were cultured in sterilized dishes containing malt-salt (6% NaCl) and potato dextrose agar media, respectively. An outline of the dilution plating method is given in Fig. 3.6.

Malt salt agar was composed of the following :

Malt extract (dehydrated)	30 g
Mycological peptone (Difco)	5 g
Sodium chloride	100 g
Agar No. 3	12 g
Distilled water	1 l

Potato dextrose agar was composed of the following :

PDA (Difco)	39 g
Distilled water	1 l

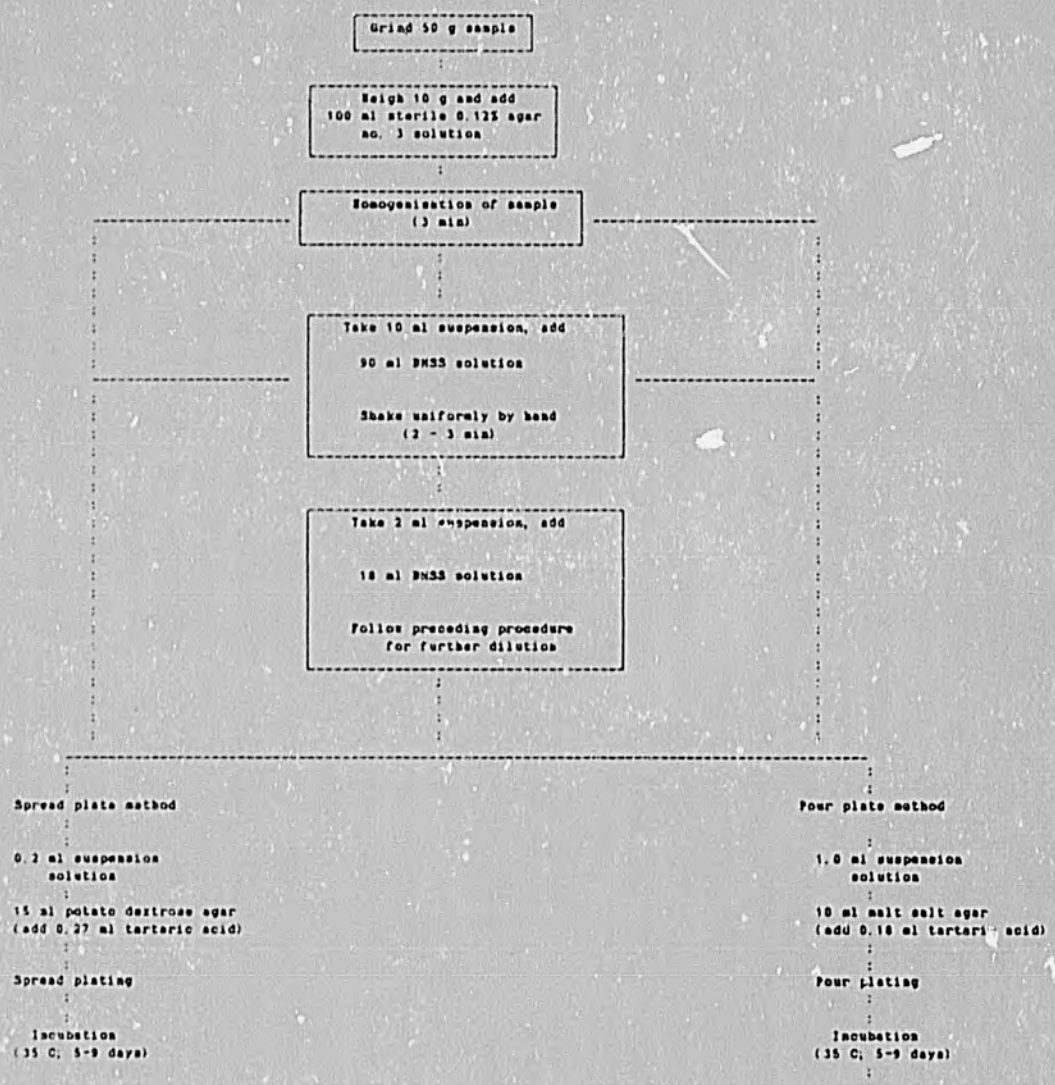


Fig. 3.6 Outline of dilution plating method

The number of required dilutions depended upon the expected number of fungi per plate. Normally a colony count of 5 to 50 colonies per plate was used as the guide. Buffered mineral salt solution (BMSS) was used as the diluting fluid.

BMSS was composed of the following :

Ammonium nitrate (NH_4NO_3)	2.7 g
Potassium dihydrogen orthophosphate (KH_2PO_4)	0.9 g
Dipotassium hydrogen orthosphosphate (K_2HPO_4)	0.7 g
Magnesium sulfate ($MgSO_4 . 7H_2O$)	0.5 g
Potassium nitrate (KNO_3)	0.5 g
Distilled water	1.0 l

The medium and diluting fluids were autoclaved for at least 15 min at 1.1 kg/cm² pressure and 121 °C. All pipettes, petri dishes, glasswares and spatula were sterilized in an air-oven using 160 - 170 °C temperature for 3 to 4 hours.

Petri dishes were incubated at 30 - 35 °C for 5 to 9 days for monitoring the fungal growth. Aspergillus fungi were identified in groups using the guidelines of Raper and Fennel (1977).

3.8.2 Direct plating assay

The percentage of grains invaded by fungi were determined by direct plating (whole grain plating) assay as described by Flannigan (1977). Potato dextrose agar and malt salt agar were used as media for field and storage fungi, respectively. Eight kernels of heat treated rough rice samples were plated equidistantly into each petri dish containing either sterilized malt salt agar or potato dextrose agar and incubated at 25 and 37 °C for 7 and 4 days, respectively. The number of infected kernels in each petri dish was determined at the specified period and expressed on percentage basis.

3.8.3 Fungal identification

The adhesive tape method was used for the examination of fungi microscopically. Self-adhesive tape about 5 to 10 mm in length was used to lift fragments of a fungal colony. The tape was then placed with adhesive side up, on a drop of lactophenol on a slide. Another drop of lactophenol was put on top and the tape was covered by a coverslip and pressed. Magnifications of 20 to 100 times were used for microscopic examination and possible identification of fungal morphology.

3.8.4 Carbon dioxide production

Carbon dioxide production in rough rice samples was measured using a chemical absorption system similar to Steele et al., (1969). A schematic diagram of the set-up is shown in Fig. 3.7. The apparatus mainly consisted of six sections: 1) an air pump for supplying a constant airflow, 2) potassium hydroxide solution and soda lime vessels for carbon dioxide removal from atmospheric air, 3) sulfuric acid solution for controlling the relative humidity, 4) sample storage, 5) silica gel and magnesium perchlorate for moisture removal, and 6) ascarite backed by a small amount of magnesium perchlorate for carbon dioxide absorption.

The operating details of an identical system are given in an earlier study by Tangonan (1980). Rough rice sample weighing about 700 - 800 g was taken from the 3 kg lot and placed inside a the 2 liter capacity glass jar. The system was operated for at least 24 hours per treatment. Three to eight readings were taken during the test period depending on the rate of respiration. The ascarite tube had to be detached each time for recording the gain in weight using an analytic balance accurate up to four decimal places.

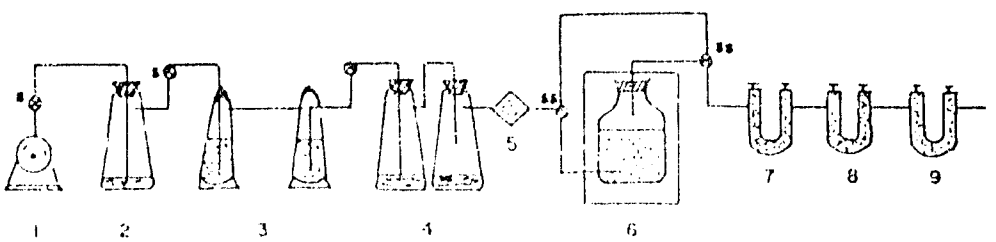
An airflow rate of about 100 ml/min was used to avoid a significant increase in grain temperature due to respiration. After each test, the rough rice sample was removed and the empty system was operated for at least 12 hours per run to determine the gain in weight of the ascarite tube. A correction was then applied to the weight gain of the ascarite tube during the experimental runs. Carbon dioxide measurements were subsequently expressed in mg CO_2/24 h/1000 g dry matter.

3.8.5 Moisture content determination

The moisture content of rough rice was determined using the method specified by Matthews (1962). Three replicates samples of whole grain weighing approximately 15 g were placed in an air oven at 130 °C. After 18 h, the sample container were taken out from the oven and placed in a dessicator to cool to room temperature before weighing. The moisture content was calculated as a percentage on the wet basis. In some cases, the moisture content measurements were made with a Kett moisture tester and adjusted subsequently based on the calibration against the oven procedure.

3.8.6 Grain temperature measurement

The temperature of the bulk grain was measured by transferring the heated grain sample into a vacuum flask. A thermocouple placed inside the flask was used to measure the bulk grain temperature after it attained a steady value.



1.. air pump

2..KOH

3..soda lime

4..H_2SO_4

5..glass wool

6.. storage chamber

7.. silica gel

8.. magnesium perchlorate

9.. ascarite

S.. one way stopcock

SS.. two way stopcock

Fig. 3.7 Schematic diagram of the CO_2 absorption system

3.8.7 Milling test

All rough rice samples (heat-treated and control) were air-dried to 14% moisture content prior to milling. The milling quality of rough rice samples was evaluated in terms of the percentage of the head rice representing 3/4 of whole kernels size or larger and total milled rice. For each test, 125 g of air-dried rough rice sample was passed through a Satake rubber roll husker (Model THU35A), with clearance adjusted to give about 90% brown rice recovery in one pass. The resulting brown rice was whitened for one minute using a McGill type laboratory testing mill. For separating the head rice from the brokens, a laboratory grader was utilized. Percent total milled rice and head rice yields were calculated on the basis of 125 g sample. All head rice yield determinations were replicated thrice. Observations on head rice yields were later expressed as ratios relative to the head yield of control group.

The degree of whiteness of milled rice samples was measured using a Kett whiteness meter (Model C-300). At least three readings were made for each sample.

3.8.8 Germination test

Rough rice samples air-dried to 14% moisture content were surface sterilized using 2% sodium hypochlorite solution for one minute. After surface sterilization, samples were rinsed three times using distilled water. Germination tests were replicated twice by growing 100 rice kernels in petri dishes containing moistened filter paper. Samples were examined for a week and rough rice kernels having both roots and shoots were considered germinated.

3.8.9 Discolored kernels measurement

The discolored kernels in milled rice were separated manually from milled rice samples weighing about 20 to 30 g and expressed later as a percentage by weight.

3.8.10 Evaluation of cooked-rice texture

The texture of cooked rice samples was evaluated in terms of the firmness and stickiness determined with an Instron Universal Food Tester Model 1140, equipped with a 50 kg capacity compression load cell. A back extrusion test cell similar to one reported by Cagampang et al. (1984) was used for firmness measurements. The stickiness was determined using the modified single kernel technique of Okabe (1979). The cooked rice samples were prepared using the adequate water method (Perez and Juliano, 1979).

The back extrusion test cell consisted of a 80 mm long stainless steel cylinder having an internal diameter of 16.3 mm and a spherical plunger with annular gap of 1.8 mm (Fig. 3.8). A removable base could be attached at the lower end of the test cylinder. A 12 g sample of cooked rice was placed into the test cell by gently packing 2-3 g of sample at a time with a wooden rod. This method resulted in about 67.0 mm long packing with its upper level about 7.0 mm below the top of test cylinder. The downward stroke of the plunger ended about 6.4 mm from the bottom of the test cell. The force-distance curve during compression of cooked-rice was recorded using a crosshead speed of 10 cm/min and a strip chart operating at a speed of 20 cm/min. Firmness was defined as the total compression energy or the area under the force-distance curve until the point of extrusion. A digitizer was used for integrating the area under the experimental force-distance curves.

For measurement of stickiness, three kernels of cooked-rice were placed apart with the dorsal and ventral side lying horizontally. The sample was compressed with a 3.6 cm diameter plunger at a speed of 0.5 cm/min to a fixed clearance of 0.2 mm. After 10 seconds, the plunger was pulled up at the same speed. Stickiness was measured as the total energy required to lift the plunger. Stickiness and firmness values were later expressed in terms of stickiness ratio and firmness ratio, respectively to reflect the changes relative to control samples. The reported values of the texture parameters are the average of 5 determinations. Other details of the experimental procedure are given by Reyes (1986).

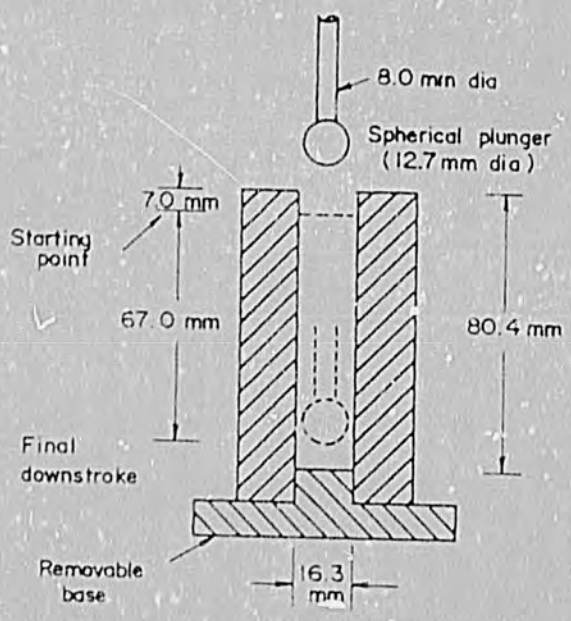


Fig. 3.8 Schematic diagram of back extrusion test cell for measuring the firmness of cooked-rice

RESULTS AND DISCUSSION

4.1 Preliminary Studies

The results of the preliminary tests are presented in Tables 4.1 and 4.2. It appeared that fungal activity was suppressed by heat treatments especially for 40 and 65 min exposure times at 200 °C oven temperature. Slow cooling indicated slight advantage over rapid cooling in arresting fungal growth. This maybe attributed to the extended heat treatment during slow cooling. The percentage of infected kernels showed some inconsistent trends with increased storage time perhaps due to non-uniformity of heat treatment in an air oven (Jindal and Obaido, 1985). Heat treatment of rough rice also resulted in drastic reduction in germinability (Table 4.2). This was obvious for samples heated for at least 40 min which showed no germination at all. Head rice yield (proportion of whole kernels) increased first and then decreased slightly after 15 min exposure. These preliminary results demonstrated the potential of high-temperature short-time heat treatments in arresting fungal growth in high moisture rough rice. However, this mode of heating was not practical and had the drawback of non-uniform heating of rice kernels.

The second set of experiments was specifically aimed at evaluating the influence of heat treatments and the role of cooling in suppressing fungal activity. The results presented in Table 4.3 clearly show the effectiveness of heat treatments and the effects of cooling in suppressing the fungal growth in rough rice having 22 % moisture content. Heat treatment of 10 min at 70 °C bulk grain temperature reduced the fungal load to at least 85% and fungal growth was inhibited throughout the storage period. Without cooling, the fungal growth was retarded up to 7 days but it surpassed the fungal growth in unheated sample on the 9th day. However, heated sample with cooling exhibited the least fungal invasion during the entire period of storage. This clearly showed that cooling prior to storage was necessary to minimize the temperature differences that could lead to excessive moisture redistribution and condensation in some parts of the bulk grain. Thus, proper cooling of samples following heat treatment could be considered an important factor for effective control of the fungal growth during subsequent storage.

Table 4.4 shows the effect of heating high moisture rice in a simple experimetal rotary conducton heating unit. It was obvious that fungal load, respiration rate and percent germination of heat treated rice samples were subsequently reduced. On the other hand, the head rice and milling yields were greatly improved in both treatments. This could be due to slight surface gelatinization of the grains during high-temperature short-time conduction heating of high moisture rice. Observations during the storage of rough rice samples revealed that fungal infestation became visually evident only after 4 and 7 days in samples heated at 100 and 140 °C, respectively. In unheated rough rice samples, fungal invasion was evident on the second day of storage.

Table 4.1 Fungal invasion in rough rice samples having a moisture content of 20% w.b. based on direct plating, percent

Medium	Storage period (day)	Exposure time at 200 °C (min) 0	15 R	15 S	25 R	25 S	40 R	40 S	65 R	65 S
	1	100	100	100	50	62	25	0	0	0
	3	100	100	100	50	100	12	12	12	0
Malt	5	100	100	100	100	100	75	37	25	12
Salt	7	100	100	100	100	100	87	12	12	0
Agar	14	100	100	100	100	100	100	62	12	12
	21	100	100	100	100	100	100	25	12	0
	1	100	100	100	87	100	37	12	0	25
	3	100	100	100	87	100	75	37	25	37
Potato	5	100	100	100	100	100	87	100	75	75
Dextrose	7	100	100	100	100	100	100	75	100	50
Agar	14	100	100	100	100	100	100	100	100	100
	21	100	100	100	100	100	100	100	100	12

R = rapid cooling; S = Slow cooling

Table 4.2 Percentage head rice, brokens and germination of rough rice after heat-treatment (20% w.b.)

Quality criteria	Exposure time at 200 °C (min) 0 control	15 R	15 S	25 R	25 S	40 R	40 S	65 R	65 S
Head rice	48.3	48.6	50.8	46.4	47.8	44.1	45.8	42.0	43.8
Brokens	18.8	17.0	16.9	18.4	17.3	20.1	17.9	22.1	21.2
Germination	85.0	60.0	63.0	27.0	32.0	0.0	0.0	0.0	0.0

Table 4.3 Fungal population in rough rice during storage as affected by initial haeting and cooling interactions, fungal colonies per gram of rough rice (x 10^3)

Treatment	Moisture content (% w.b.)	Storage time, day				
		1	3	5	7	9
Unheated	22.5	21.7	135.0	3000.0	15000.0	35750
Heated & cooled	21.0	1.7	5.5	26.2	2475.0	3850
Heated without cooling	21.0	3.2	9.0	240.0	10000.0	39000

Table 4.4 Preliminary test results on heat sterilization of rough rice using a rotary heating unit (exposure time 5 min)

Heating surface temp. (°C)	Grain temp. (°C)	Moisture content (% w.b.)	Head yield (%)	Respiration rate[1] mg CO_2/g-day	Fungal count[2] colonies/g	Germination (%)
Control	27	29.6	54.1	0.942	38,000	94
100	69	21.6	63.4	0.246	90	7
140	88	17.3	70.8	0.162	50	2

[1] Based on carbon dioxide absorption
[2] Based on dilution plating

The results of these preliminary studies indicated that heat treatment could suppress the fungal activity in high moisture rough rice without adversely affecting its quality. However, the laboratory oven was found to be unsuitable due to uneven heating and the considerable time-lag involved in raising the grain temperature. A simple experimental rotary conduction heating unit could be more practical in heating high moisture rice.

4.2 Heat Sterilization of High Moisture Rough Rice

4.2.1 Fungi present in freshly harvested rough rice

The various fungi detected in freshly harvested high moisture rough rice samples and their respective proportions are summarized in Table 4.5. The fungal count ranged approximately from 1,300 to 5,500 colonies/g. The apparent variability in fungal count was perhaps due to the changes during the holding periods, sampling process, and the test method itself. *Penicillium* species, *Helminthosporium*, and *Aspergillus flavus* made up the bulk of the count in all of the samples. These fungi are usually considered to inflict some damage upon the grain quality during temporary storage at high moisture content (Tatsumo, 1963; Fazli and Schroeder, 1966a, b; Schroeder, 1967; Christensen and Kaufmann, 1974; Quitco, 1982). Also present were *Rhizopus*, *Mucor*, *Aspergillus terreus* and *Aspergillus versicolor* in relatively smaller proportions.

Table 4.6 presents the proportion of fungal species surviving after the heat treatment of fresh rough rice samples. The heat treatment corresponded approximately to 90% fungal mortality level. It was obvious that the storage fungi such as *Aspergillus flavus*, *Aspergillus niger* and *Penicillium* species were most heat resistant. However, most of the field fungi were reduced to a very low level after the heat treatment.

4.2.2 Time-temperature history of rough rice samples during conduction heating

The temperature history of rough rice samples having initial moisture content in the range of 18 to 30% was adequately described by the following relationship:

$$TR = \exp(-c\, t^{d}) \qquad \ldots(4.1)$$

where TR = temperature ratio, $(T_{gi} - T_s)/(T_{go} - T_s)$
T_{gi} = grain temperature, °C
T_s = heating surface temperature, °C
T_{go} = initial grain temperature, °C
t = heating time, min
c,d = regression coefficients

Table 4.5 Fungi present in freshly harvested rough rice of variety RD-23

Fungi	Test Number							
	1	2	3	4	5	6	7	8
Helminthosporium	600	600	600	25	500	0	250	0
Rhizopus	100	20	70	1200	0	600	100	0
Mucor	100	50	100	500	0	0	0	0
Penicillium spp.	250	590	900	3170	2500	1200	1200	400
Aspergillus flavus	65	40	130	500	500	1500	50	1200
Aspergillus niger	50	0	0	0	500	1300	50	300
Aspergillus terreus and *A. versicolor*	0	0	0	100	500	0	0	0
Total fungal count (colonies/g)	1350	1300	1800	5500	4500	5200	1650	2000

Table 4.6 Survival of fungi in newly harvested rough rice following the heat treatment corresponding to about 90 % mortality level

Fungi	Percent of initial count surviving
Helminthosporium spp.	0.2
Rhizopus spp.	0.3
Mucor spp.	0.2
Penicillium spp.	5.2
Aspergillus flavus	2.1
Aspergillus niger	1.6
Aspergillus terreus	0.4

It was not possible to develop general relationships to estimate the coefficients of Eq. 4.1. However, since the computed values of coefficient d showed a narrow range, a mean value of 0.28 was used to modify Eq. 4.1 in the following form:

$$TR = \exp(-c_1 t^{0.28}) \qquad ...(4.2)$$

where c_1 is a regression coefficient.

Finally, a general prediction equation for c_1 was developed as follows:

$$c_1 = 0.4425 - 0.00066182\ T_s + 0.00036068\ N - 0.00011048\ (M_0)^2 \qquad ...(4.3)$$

$$(R^2 = 0.90 \quad ; \quad SEE = 0.014)$$

where N = rotation speed of heating cylinder, revolutions/min
M_0 = initial moisture content of rough rice samples, % (w.b.)

4.2.3 Fungal inactivation during conduction heating

Fig. 4.1 shows the reduction in fungal load ratio with exposure time for various heating surface temperatures. It was obvious that high temperature conduction heating reduced the fungal load in high moisture rough rice in an effective manner. As expected, higher heating surface temperatures resulted in shorter exposure durations in reducing the fungal load to specific levels.

Fig. 4.2 shows the moisture content of rough rice as a function of exposure time for various heat treatments. The moisture content of rough rice samples was markedly reduced due to heat treatments especially for higher heating surface temperatures. The beneficial effects of heat treatments in terms of reduced fungal activity and partial drying of high moisture rough rice thus could contribute directly to safe holding periods of newly harvested rice awaiting drying.

The various time-temperature combinations needed to achieve 75, 90 and 95% fungal mortality levels for the batch heating of 3 kg rough rice samples are shown in Fig. 4.3. As expected, higher heating surface temperatures resulted in shorter exposure durations in reducing the fungal load to a specific level. The exposure of rough rice at 200 °C heating surface temperature for about 3.5 min was enough to reduce the fungal load to about 90%. The same level of fungal inactivation

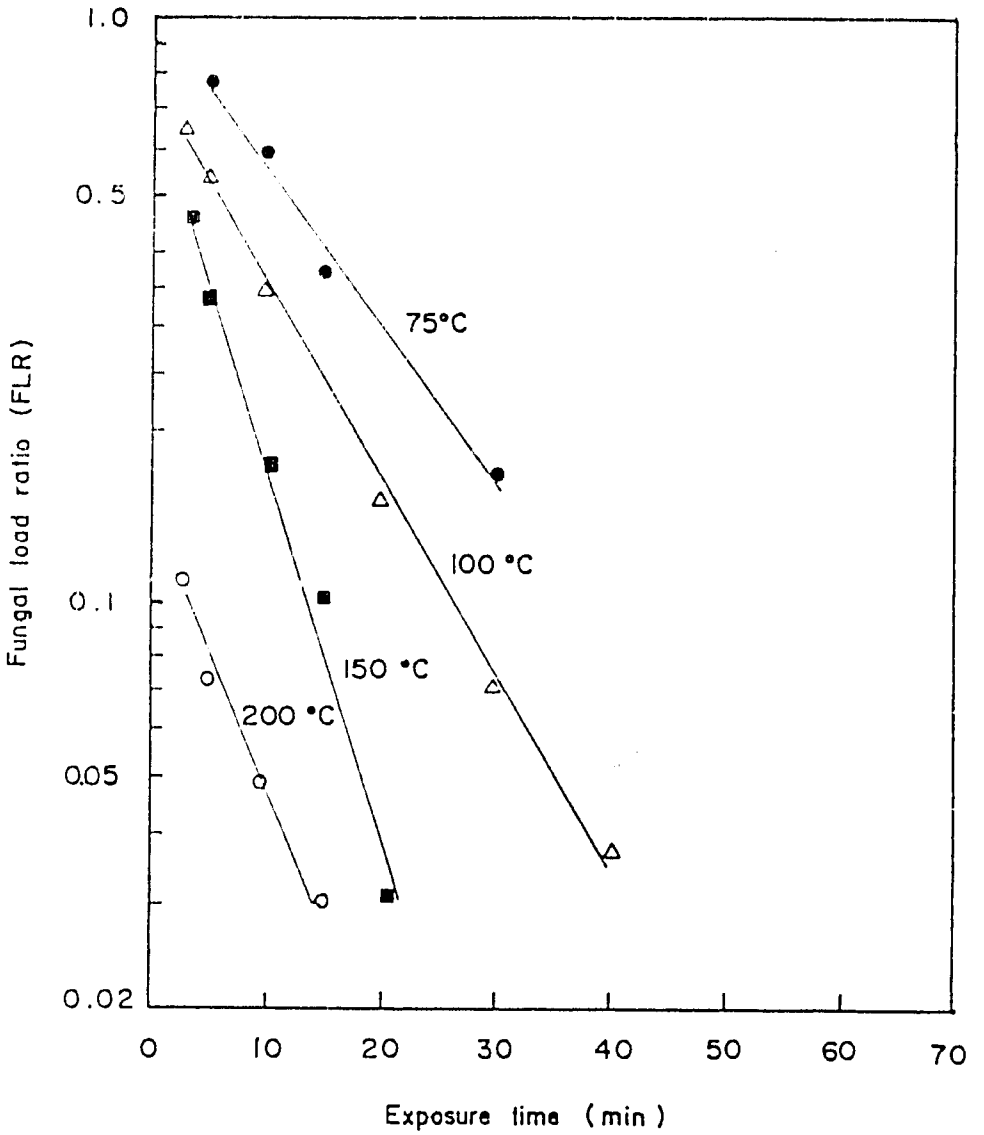


Fig. 4.1 Fungal load ratio as a function of exposure duration for various heating surface temperatures

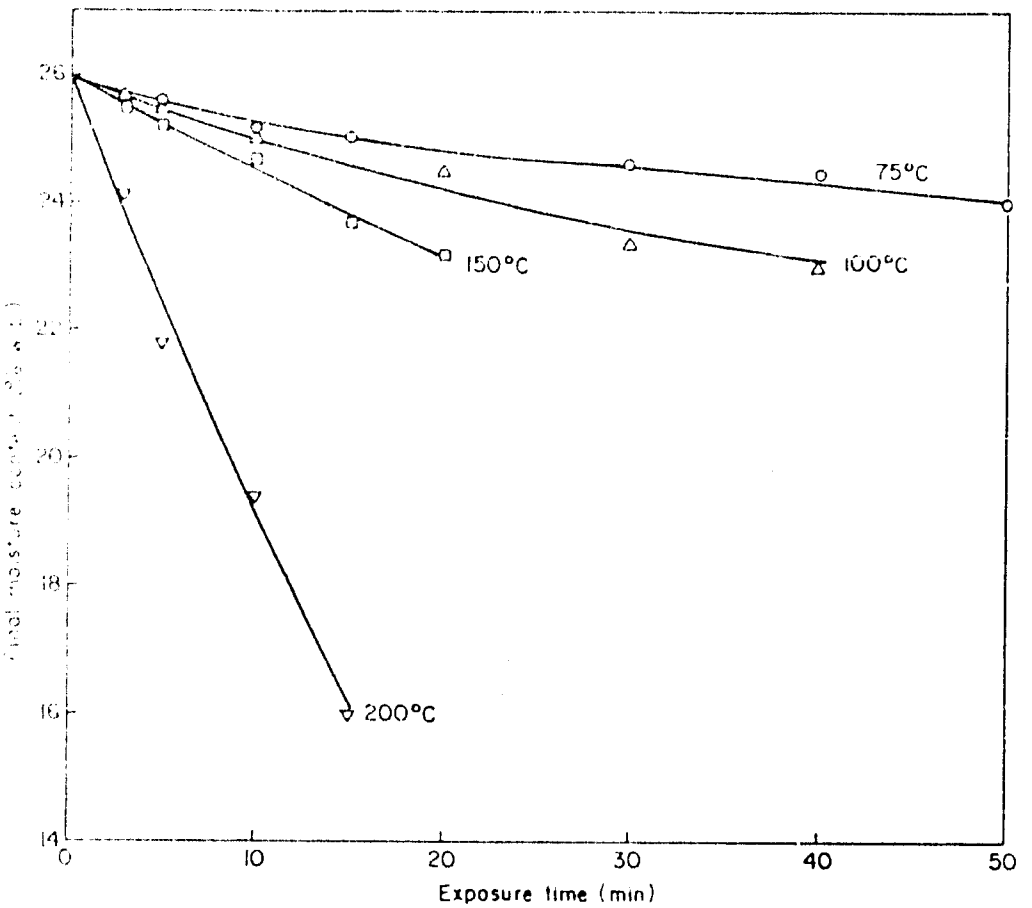


Fig 4.2 Final moisture content as a function of exposure duration for various heat treatment combinations

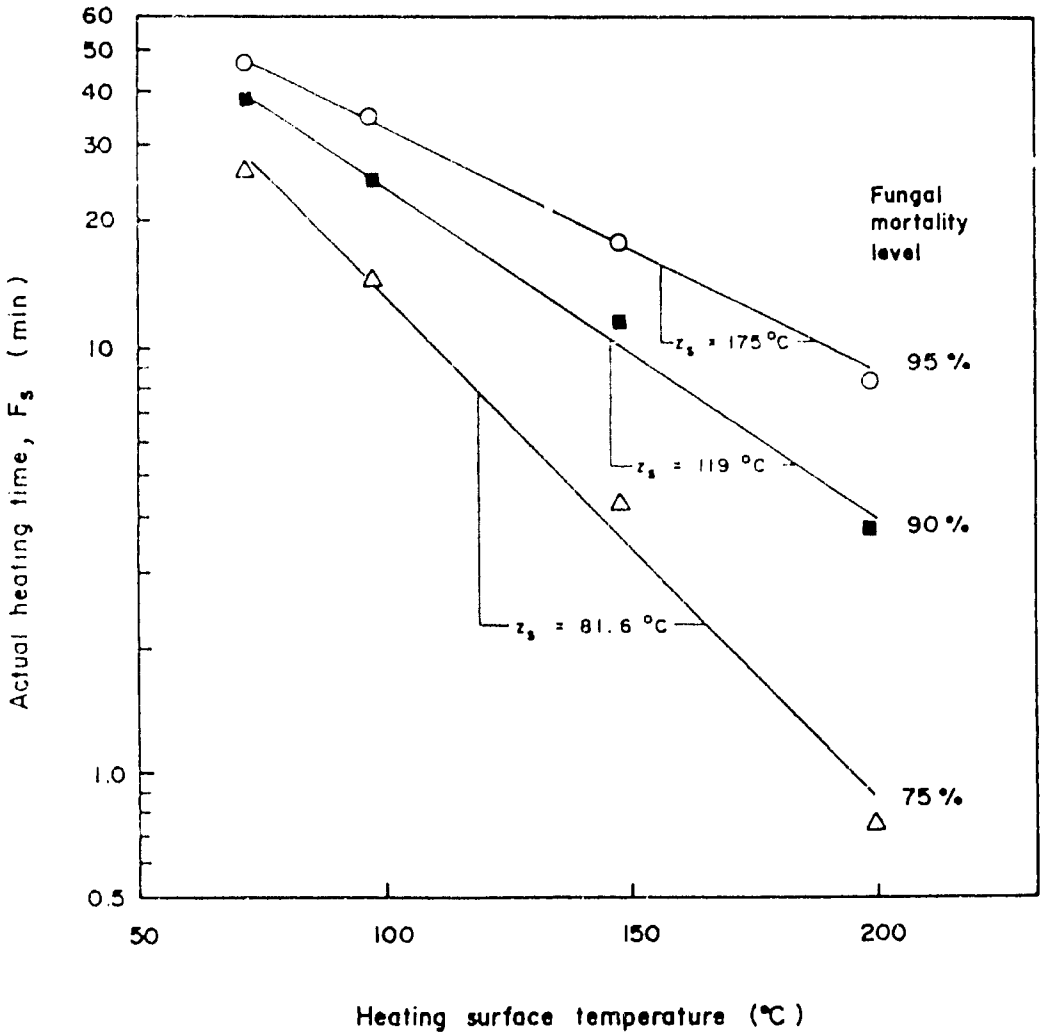


Fig. 4.3 Actual heating time as a function of heating surface temperature for various fungal mortality levels

could be accomplished by heating the grain using 150, 100, and 75 °C heating surface temperatures for 13, 25 and 36 min, respectively. These heat treatments will also reduce the moisture content of rice by approximately 2 to 3 % w.b. which should further increase with an increase in the heating surface temperature. The bulk grain temperature corresponding to heating surface temperature of 75 and 200 °C were 60 and 85 °C, respectively. These experimental results are based on the freshly harvested rough rice having an initial moisture of about 26% w.b. Rough rice with lower moisture would probably heat at a faster rate, and require shorter exposure duration for a given fungal inactivation level. The estimated exposure times and temperatures are only applicable to the experimental heating unit used in this study. A general approach for representing thermal inactivation of fungi in high moisture rice based on the bulk grain temperature history is presented in the following section.

4.2.4 Generalized representation of fungal inactivation

In thermal processing of foods, the lethality of a thermal process to kill the microorganisms is commonly defined by the following equation given by Bigelow et al. (1920):

$$F_{process} = \int_0^t 10^{[\,T(t) - T_{ref}\,]/z} \qquad \ldots (4.4)$$

where $F_{process}$ = the equivalent exposure time for a given reference temperature (T_{ref})
$T(t)$ = product temperature at time t
z = inverse of the slope of the thermal death time (TDT) curve

Using the time-temperature history of bulk grain during the heating process and an iterative procedure proposed by Hayakawa et al. (1977), Eq. 4.4 was solved numerically for equivalent exposure times (F_B) and z_B-values based on bulk grain temperature. The kinetic parameters F_B and z_B were determined for 75, 90, and 95% fungal mortality levels (FML). The solution scheme involved the following steps:

(1) Assume a z_B-value and from the time-temperature curves of bulk grain for known heating durations and fungal load reduction levels, compute the equivalent exposure time in each case by arbitrarily selecting different reference bulk grain temperatures (T_{ref}).

(2) Plot the FLR against the equivalent exposure time and compute the time (F_B-values) corresponding to a desired level of FLR for each reference bulk grain temperature.

(3) Plot the common logarithm of time (F_B-values) determined at Step 2 against reference bulk grain temperature (T_{ref}) and determine the slope of the relationship by regression. Compute the reciprocal of the slope to give a z_B-value (z_{cal}). Compare the computed z_B-value with the assumed z_B-value used at Step 1. Set z_B equal to z_{cal} and repeat Steps 1,2 and 3 until the assumed z_B-value becomes almost equal to the computed z_B-value. The flowchart depicting the solution scheme is presented in Fig. 4.4.

The plot of equivalent exposure time (F_B-value) against reference bulk grain temperature obtained from the iterative procedure is shown in Fig. 4.5. The figure shows the isothermal heating times required to achieve 75, 90 and 95% fungal mortality levels (FML) in an ideal process with no heating and cooling lags. In addition z_B-values are given for each fungal mortality levels. A 90% reduction in fungal load could be achieved by heating the bulk grain to 70 °C for 22 or to 50°C for 82 min. The computed values of F_B and z_B could be used in estimating the actual heating time required for thermal inactivation of fungi in high moisture rice based on its time-temperature history during conduction heating with any given equipment.

Calculation of heating time. The method for calculating the required heating time is basically a trial- and- error procedure requiring the following information : (i) time-temperature profile during heating and cooling processes, and (ii) F_B and z_B-values for desired level of fungal mortality at any arbitrary selected reference bulk grain temperature. The F_B and z_B-values are given by Fig. 4.5. A flowchart of the computation procedure is presented in Fig. 4.6. The main steps consist of the following:

(1) Assume some value of the required heating time, F_{ht}, initially.

(2) From the time-temperature profile of bulk grain in a given heating system, calculate the equivalent exposure time using Eq. 4.4 for a selected reference bulk grain temperature (T_{ref}) during the heating period (F_h) and the cooling period (F_c).

(3) Equivalent exposure times during heating and cooling are combined to give a total equivalent time, F_t, based on T_{ref}.

(4) Compare the computed (F_t) and actual (F_B) values of equivalent exposure times. If the difference between F_t and F_B is insignificant, then F_{ht} is taken as the required heating time for the process. Otherwise adjust the assumed F_{ht} by increasing (if $F_t < F_B$) or decreasing (if $F_t > F_B$) its value and repeat from Step 2.

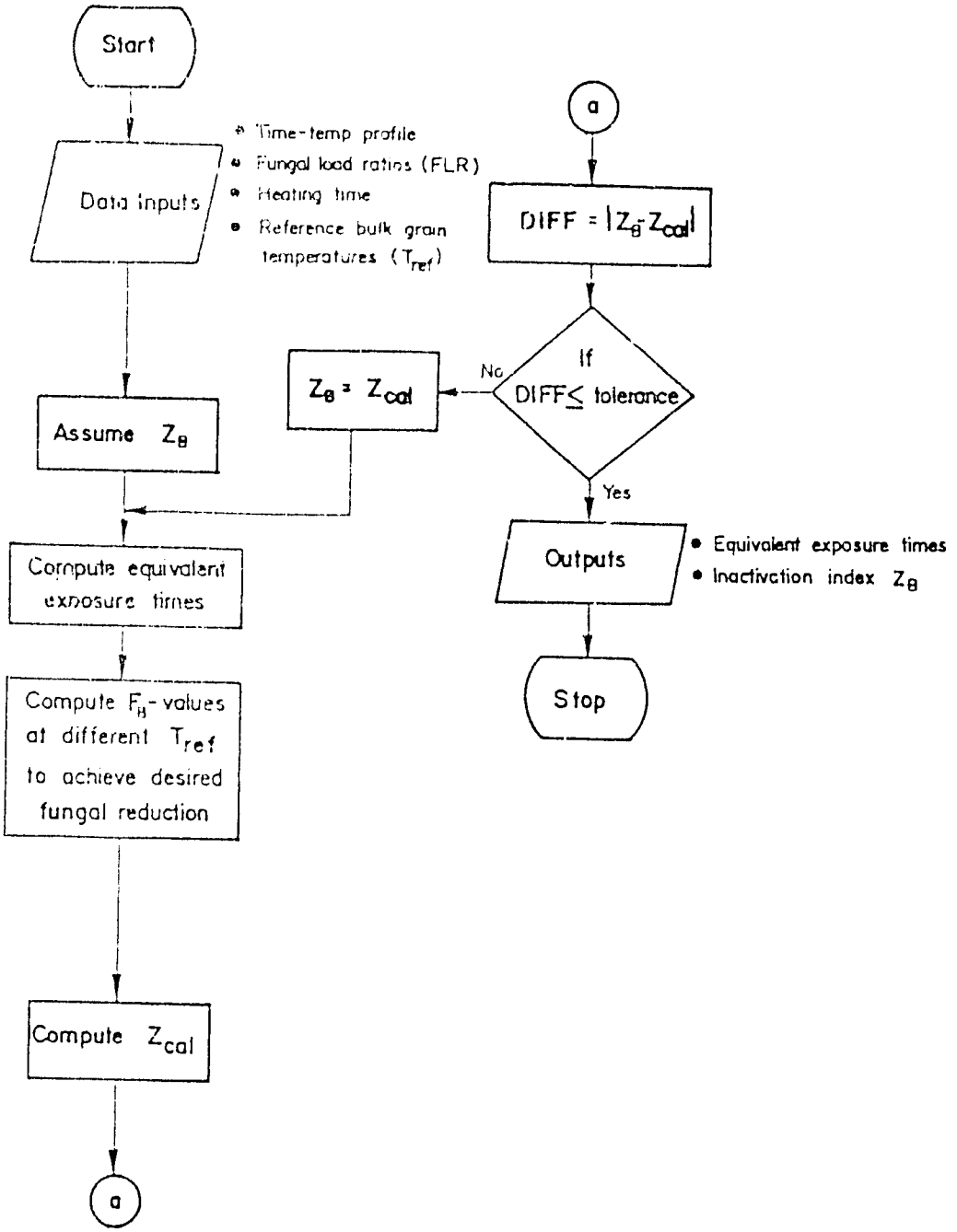


Fig. 4.4 Flowchart for determining z_B-value

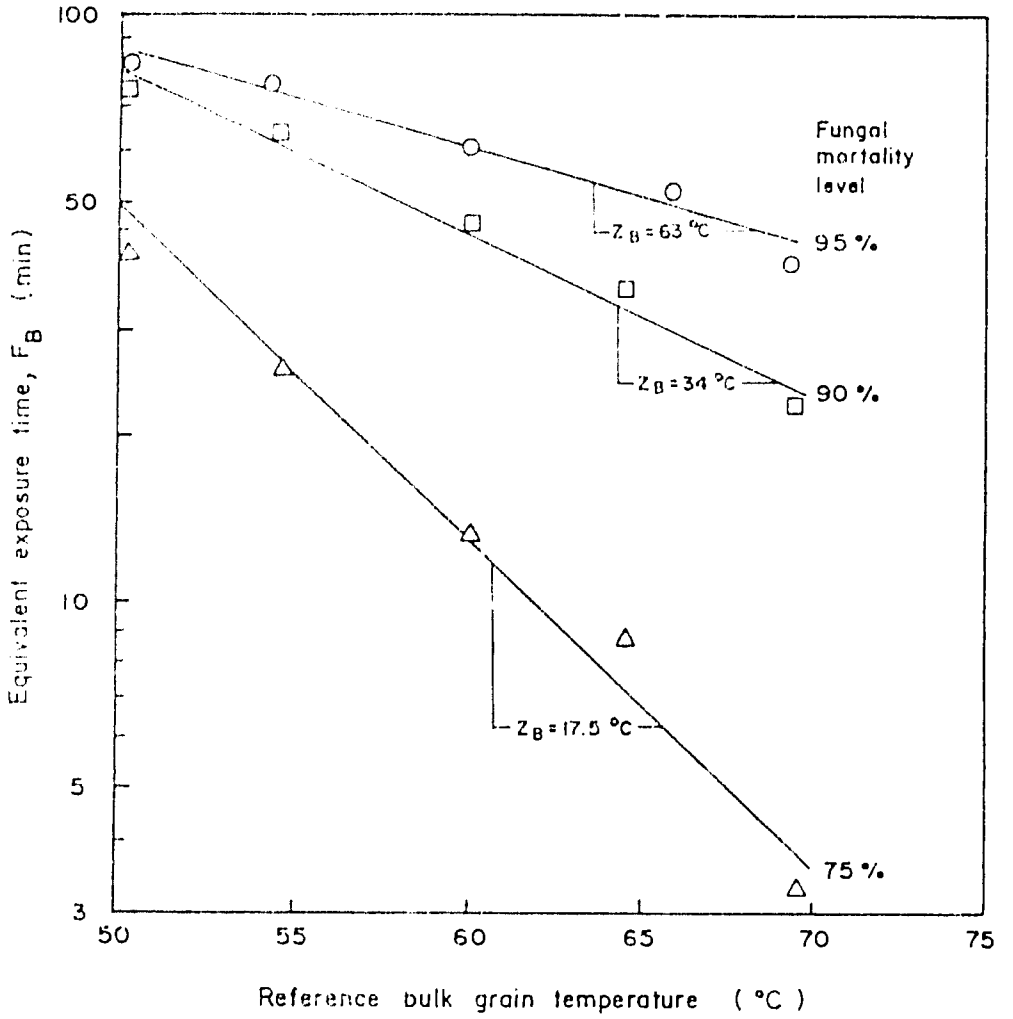


Fig. 4.5 Equivalent exposure time as a function of reference bulk grain temperature for various fungal mortality levels

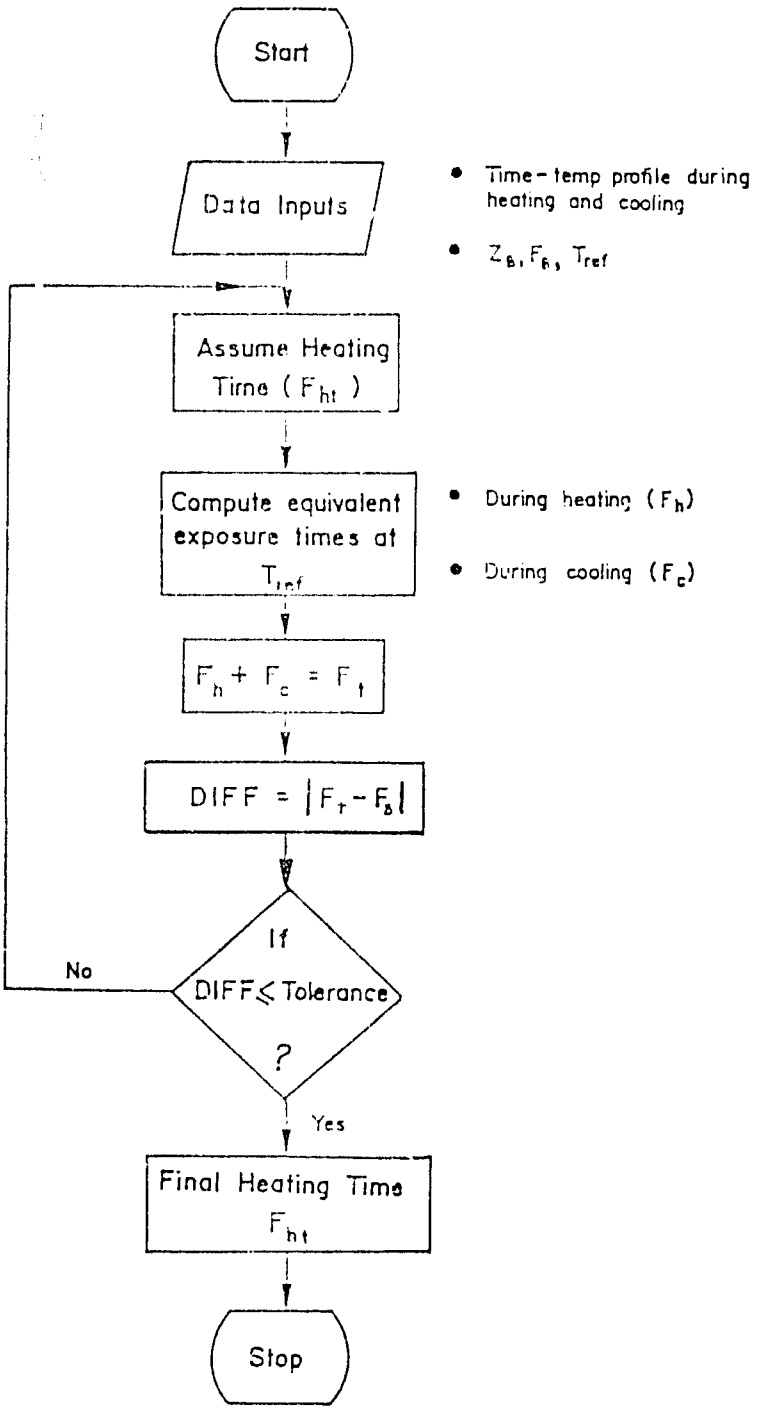


Fig. 4.6 Flowchart for calculatin heating time based on bulk grain temperature analysis

The estimated heating times for 75, 90 and 95% fungal mortality levels based on heating surface temperature analysis and the bulk grain temperature method are presented in Table 4.7 for relative comparison. The differences in heating times calculated from these two methods were not statistically significant based on a chi-square test. Therefore, it was concluded that the two methods were comparable to each other in achieving desired levels of fungal mortality during the heat treatment of high moisture rice.

The above results showed that high-temperature short-time conduction heating of freshly harvested high moisture rough rice could effectively reduce its fungal activity. Time-temperature requirements for killing the fungi in rough rice grains was generalized in terms of the kinetic parameters (F_B and z_B - values) based on the time-temperature history of the bulk grain. This representation accounted for the heating and cooling lags that would be encountered during the actual heat treatment of grains in a given equipment.

Table 4.7 Comparison of estimated heating times based on bulk grain temperature and heating surface temperature analyses

Heating surface temp. (°C)	Fungal mortality level (%)	Exposure duration (min) based on: Heating surface temp.	Exposure duration (min) based on: Bulk grain temp.
75	75	22.8	21.6
100	75	13.8	12.3
150	75	6.6	4.5
200	75	0.6	0.4
75	90	35.4	34.0
100	90	25.7	25.2
150	90	13.5	11.0
200	90	3.6	3.8
100	95	35.4	33.5
150	95	19.4	17.0
200	95	9.0	10.9

Chi-square: Computed = 2.29
Tabulated (0.05) = 19.70

4.2.5 Relationship between fungal count and carbon dioxide production

There appeared to be a direct relationship between the respiration rate of the rough rice samples in terms of carbon dioxide production and the total fungal count determined by the dilution plating. Heat treatment of rough rice samples resulted in a marked reduction in the carbon dioxide production perhaps due to the destruction of fungal cells and reduced grain viability.

The fungal count of rough rice samples was found to be highly correlated with carbon dioxide production in form of the following relationship:

$$Y = a + b X + c X^2 + d X^3 \qquad \ldots(4.5)$$

where Y = log of fungal count in colonies/g
X = log of carbon dioxide production in mg/kg-day
a, b, c, d = regression coefficients

The regression coefficients of Eq. 4.5 representing the experimental data are given in Table 4.8. These results were found to be in agreement with an earlier study made by Lin (1985) which covered a wider range of fungal activity (Fig. 4.7). A second degree polynomial adequately described the combined data shown in Fig. 4.7 (Table 4.8). This suggests that that carbon dioxide production could be used as an alternative method of estimating fungal activity. Since the experimental procedures for measurement of carbon dioxide are simpler than dilution plating assays, monitoring fungal activity indirectly would be more practical especially with large number of rough rice samples.

Table 4.8 Regression coefficients of the relationship between fungal count and carbon dioxide production (Eq. 4.5)

Reference	a	b	c	d	R^2	SEE
Present study	1.5261	0.8520	0.0	0.0	0.810	0.30
Lin (1985)	2.5341	-1.0209	0.8176	-0.0405	0.896	0.79
Present study and Lin (1985)	2.4588	-0.7674	0.5950	0.0	0.860	0.77

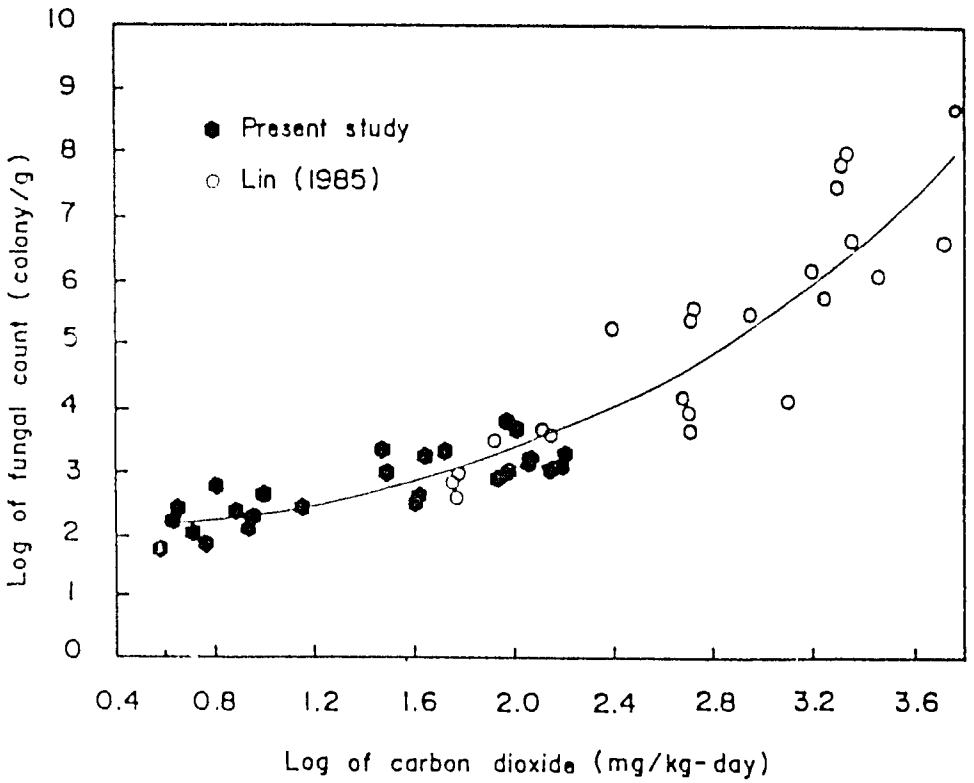


Fig. 4.7 Fungal count as a function of carbon dioxide production in rough rice samples

4.3 Accelerated Drying of High Moisture Rice

4.3.1 Selection of cooling rate

The change in temperature of heated grain samples during very fast, fast, moderate and slow cooling was accurately described by the following equation:

$$CR = \exp(-x\ t^{y}) \qquad \ldots(4.6)$$

where CR = cooling ratio, $(T_{gi} - T_a)/(T_{go} - T_a)$
T_{gi} = grain temperature, °C
T_{go} = grain temperature before cooling, °C
T_a = ambient air temperature, °C
t = cooling duration, min
x, y = regression coefficients

The regression coefficients of Eq. 4.6 for various cooling methods are given in Table 4.9.

Table 4.9 Regression coefficients of the Eq. 4.6 relating cooling rate of rough rice samples with time

Cooling method	x	y	R^2
Very fast	0.85670	0.4147	0.920
Fast	0.03332	1.0790	0.997
Moderate	0.05285	0.8315	0.996
Slow	0.01635	1.0000	0.990

The effect of different cooling rates on head rice yield was evaluated using exposure times corresponding to 75, 90, and 95 % fungal mortality levels. Drastic reduction in head rice yields occurred as a result of longer exposure times during heating followed by fast cooling due to sudden drop of grain temperature. Therefore, rough rice exposed to same heating durations were analysed for cooling rate effects. This helped minimize the effect of heating times on head rice yield. Based on the multiple regression analysis, the head yield ratio (HYR) was expressed as a function of heating surface temperature, cooling rate and time. The developed regression equations for rough rice samples having 22 and 30% initial moisture content were as follows:

$$HYR = 1.344 + 0.0001633\ T_s - 0.002091\ t - 2.0598\ c'$$

(22 % initial moisture content samples)

$$(R^2 = 0.89 \quad ; \quad SEE = 0.065) \qquad ...(4.7)$$

$$HYR = 0.1068 + 0.0060\ T_s + 0.02396\ t - 0.731\ c'$$

(30 % initial moisture content samples)

$$(R^2 = 0.68 \quad ; \quad SEE = 0.100) \qquad ..(4.8)$$

where HYR = head yield ratio, HYS/HYC
HYS = head yield obtained from heated rough rice samples, %
HYC = head yield obtained from control sample, %
c' = slope of log (CR) with t

Eqs. 4.7 and 4.8 clearly showed the dependence of head rice yield on the cooling rates under specific experimental conditions. This result is supported by the study of Acasio and Belonio (1984) which also showed a large increase in cracked kernels due to rapid cooling of heated rice samples. The lower cooling rates, on the other hand, appeared to result in condensation of moisture and its subsequent redistribution. Hence, moderate cooling of rough rice samples was adopted as a compromise for the quality evaluation tests.

4.3.2 Moisture removal during conduction heating

A typical plot showing the change in the moisture content of rough rice during conduction heating is illustrated in Fig. 4.8. Rapid moisture removal from rough rice was obvious in all experiments especially at higher heating surface temperatures. The results of various drying tests indicated that

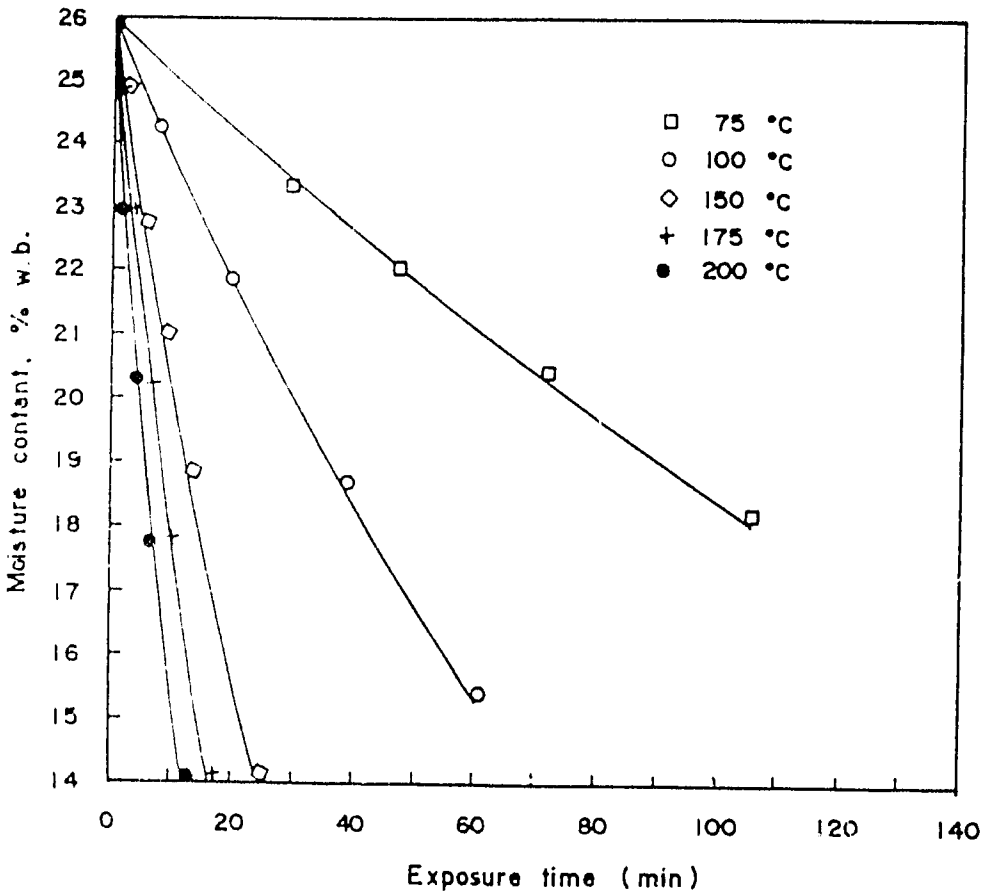


Fig. 4.8 A typical plot of moisture content as a function of exposure duration during conduction heating of rough rice having 26% w.b. moisture content

a simple logarithmic model (Hukill, 1947) and its modified form (Page, 1949) could describe the individual drying tests satisfactorily. The simple and modified logarithmic representations were as follows:

$$MR = \exp(-k\,t) \qquad ...(4.9)$$

$$MR = \exp(-k_1\,t^n) \qquad ...(4.10)$$

where MR = moisture ratio, $(M_t - M_e)/(M_0 - M_e)$, dimensionless
M_t = instantaneous grain moisture content during drying, % w.b.
M_0 = grain initial moisture content, % w.b.
M_e = grain equilibrium moisture content, % w.b.
k = drying constant, (1/min)
k_1 = drying constant, $(1/min)^n$
t = drying time, min
n = an exponent

The applicability of Eqs. 4.9 and 4.10 was examined to describe the drying behaviour of rough rice during conduction heating. There is no information available on the equilibrium moisture content of rough rice in the temperature range of 100 to 200 °C when the air relative humidity is very low. However, the rough rice samples will be bonedried after prolonged heating under such conditions. Therefore, the moisture ratio was approximated simply by droppping the equilibrium moisture content term and thus the ratio of instantaneous moisture content of rough rice to its initial moisture content. The results indicated that both simple and modified logarithmic models described the drying behaviour satisfactorily as indicated by high values of coefficient of determination (Table 4.10). However, the modified logarithmic model appeared to be slightly better in representing the individual drying tests. The dependence of drying constants on the experimental conditions was further studied using stepwise multiple regression analysis resulting in the following equations:

$$\ln k = -7.8623 + 0.02448\,T_s \qquad ...(4.11)$$

$$(R^2 = 0.936\ ;\ SEE = 0.313)$$

$$\ln k_1 = -7.1496 + 0.02132\,T_s \qquad ...(4.12)$$

$$(R^2 = 0.926\ ;\ SEE = 0.295)$$

Table 4.10 Regression coefficients of the equations representing the drying of rough rice samples during conduction heating

Initial moisture content (% w.b.)	Heating surface temp. (°C)	Simple log model		Modified log model				
		Eq. 4.9		Eq. 4.10			Eq. 4.13	
		k	R^2	k_1	n	R^2	k_2	R^2
18	75	0.0022	0.976	0.0025	0.9720	0.952	0.0033	0.963
18	100	0.0073	0.964	0.0073	1.0000	0.993	0.0102	0.942
18	150	0.0270	0.945	0.0138	1.0596	0.872	0.0345	0.924
18	175	0.0389	0.981	0.0393	0.9684	0.987	0.0482	0.969
18	200	0.0483	0.951	0.0466	0.9512	0.952	0.0580	0.935
22	75	0.0018	0.780	0.0035	0.8550	0.888	0.0027	0.783
22	100	0.0036	0.780	0.0080	0.7961	0.899	0.0050	0.813
22	150	0.0162	0.946	0.0242	0.8226	0.947	0.0210	0.932
22	175	0.0254	0.992	0.0360	0.8614	0.999	0.0319	0.997
22	200	0.0353	0.961	0.0324	1.0405	0.978	0.0430	0.952
26	75	0.0015	0.945	0.0032	0.8269	0.995	0.0022	0.977
26	100	0.0041	0.971	0.0049	0.9362	0.954	0.0057	0.954
26	150	0.0203	0.999	0.0194	1.0125	0.998	0.0267	0.994
26	175	0.0244	0.984	0.0297	0.8861	0.924	0.0310	0.973
26	200	0.0365	0.978	0.0661	0.7127	0.939	0.0453	0.973
30	75	0.0022	0.941	0.0048	0.8179	0.910	0.0033	0.935
30	100	0.0061	0.899	0.0078	0.9483	0.970	0.0088	0.926
30	150	0.0202	0.826	0.0348	0.8467	0.908	0.0271	0.864
30	175	0.0328	0.997	0.0470	0.8657	0.992	0.0425	0.998
30	200	0.0393	0.971	0.0375	1.0289	0.994	0.0498	0.977

Eqs. 4.11 and 4.12 revealed the strong dependence of drying constants on heating surface temperature. Figs. 4.9 and 4.10 show the plots of the constants k and k_1, respectively as obtained from regression analysis against the heating surface temperature. The exponent n in the modified logarithmic model (Eq. 4.10) did not show any meaningful relationship with the experimental conditions. Therefore, the modified logarithmic relationship can not be used to predict the drying behaviour. However, the exponent n showed a relatively narrow range with mean 0.91 and standard error 0.09 (Fig. 4.11). This observation led to a simplified drying model in the following form:

$$MR = \exp(-k_2 \; t^{0.91}) \qquad \ldots(4.13)$$

where k_2 = drying constant, $(1/min)^{0.91}$

Eq. 4.13 was also found to represent the drying data reasonably well as shown by the coefficient of determination values given in Table 4.10. A plot of the drying constant k_2 against the heating surface temperature shown in Fig. 4.12 resulted in the following relationship:

$$\ln k_2 = -7.3631 + 0.02298 \; T_s \qquad \ldots(4.14)$$

$$(R^2 = 0.931 \; ; \; SEE = 0.0052)$$

The results of above analysis showed that either the logarithmic model (Eq. 4.9) or the modified logarithmic model (Eq. 4.13) could be used to describe the drying behaviour of rough rice satisfactorily during high-temperature conduction heating. For overall comparison, the values of standard error for both drying models were computed considering the experimental and estimated moisture contents. The overall standard error using the logarithmic and the simplified logarithmic drying models were determined to be 0.87 and 1.18 % moisture content, respectively. Therefore the use of simple logarithmic model (Eq. 4.9) is recommended for general represention of the drying behaviour of rough rice during conduction heating in the experimental conditions considered in this study.

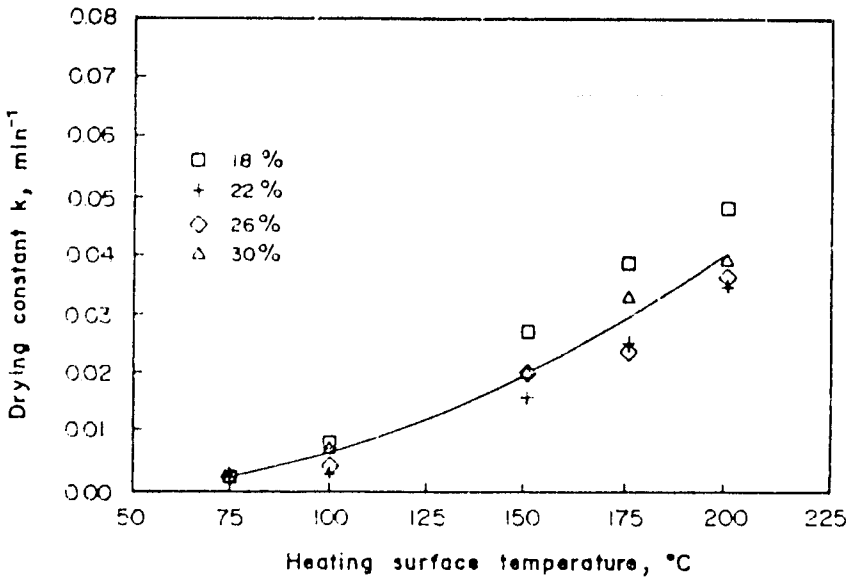


Fig. 4.9 Drying constant k in Eq. 4.9 as a function of heating surface temperature

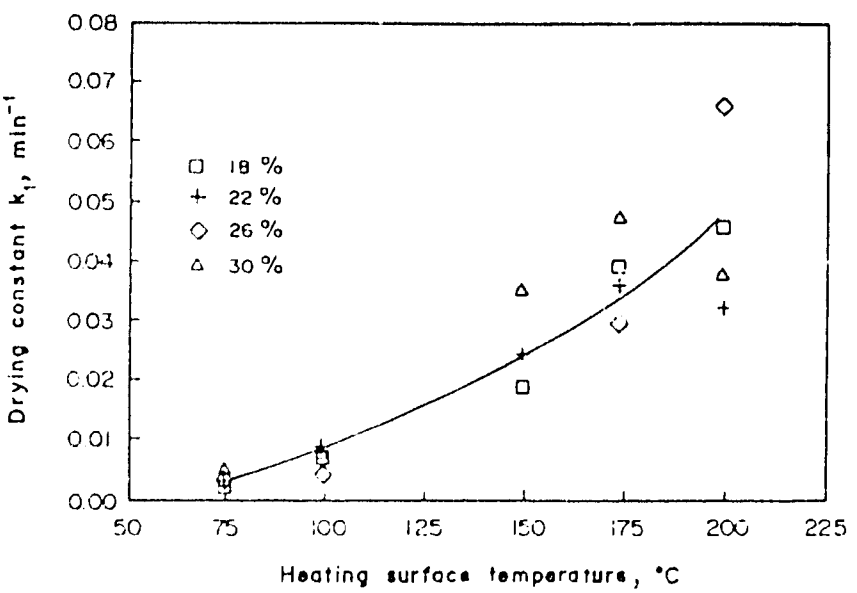


Fig. 4.10 Drying constant k_1 in Eq. 4.10 as a function of heating surface temperature

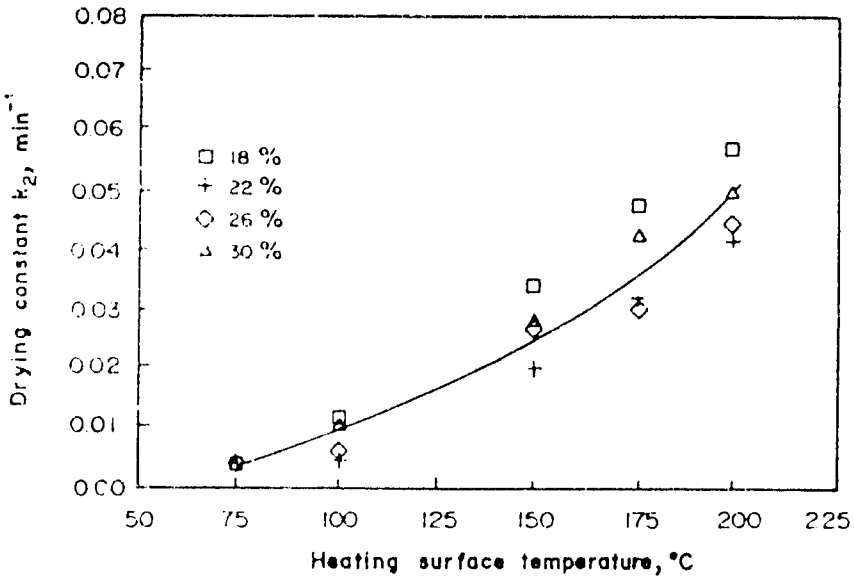


Fig. 4.11 Drying constant n in Eq. 4.10 as a function of heating surface temperature

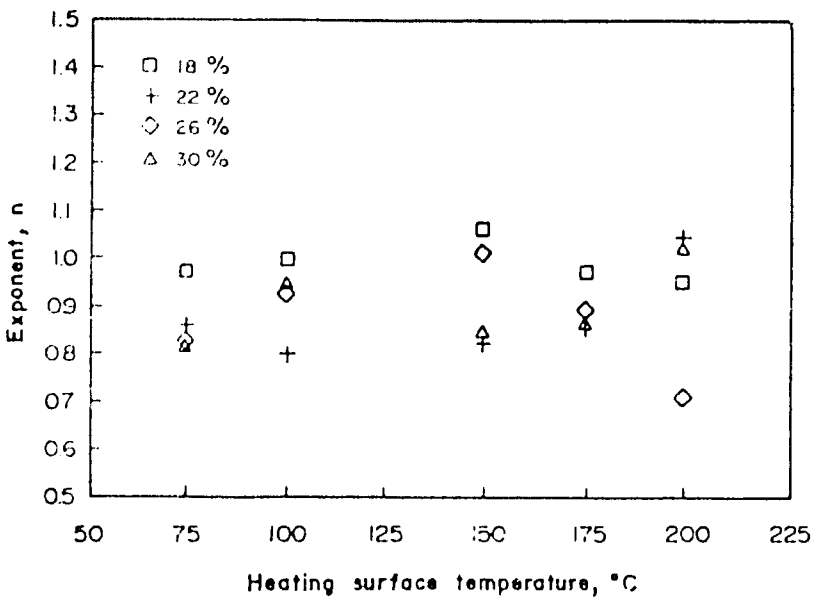


Fig. 4.12 Drying constant k_2 in Eq. 4.13 as a function of heating surface temperature

4.3.3 Analysis of drying based on bulk grain time-temperature history

The empirical drying representations developed in the preceding section are equipment specific and thus have limited application in view of the possible differences in the time-temperature history of rough rice when using different equipment. Therefore an attempt was made to describe the drying behaviour of rough rice in terms of the bulk grain temperature attained during conduction heating. From the time-temperature history of rough rice, the values of mean bulk grain temperatures (T_{mb}) were computed for various drying times as illustrated in Fig. 4.13. The mean bulk temperature values were determined by dividing the area under the grain time-temperature curve by the heating duration. Subsequently the mean bulk grain temperature was considered as an independent variable in the stepwise multiple regression analysis in place of heating surface temperature. The following relationship was developed for estimating the moisture ratio:

$$MR = \exp\{-0.000645\,[\exp(0.06321\,T_B)] * t^{0.47}\} \qquad ...(4.15)$$

$(R^2 = 0.926;\ SEE = 0.730)$

A comparison of experimental and estimated moisture content values based on Eq. 4.15 showed a mean standard error of 0.73 % moisture content which was very close to the mean standard error values of Eqs. 4.9 and 4.13. Therefore Eq. 4.15 could be used in in an alternate but equally satisfactory manner to estimate the change in moisture content of rough rice during conduction heating. Fig. 4.14 shows a typical plot of mean bulk grain temperature against the drying time for various initial moisture contents of rough rice. It should be emphasized here that the calculation of mean bulk grain temperature is based on the assumption of isothermal heating times representing an intermediate step in the estimation procedure.

In order to validate the above procedure, the changes in moisture content of rough rice during conduction heating using the small-scale one-pitch experimental unit (model II) were predicted based on the above procedure. A typical plot of moisture ratio with time in this experimental unit is shown in Fig. 4.15. The plot of drying constant k against heating surface temperature is shown in Fig. 4.16. The drying k was found to be dependent on the heating surface temperature in the following form:

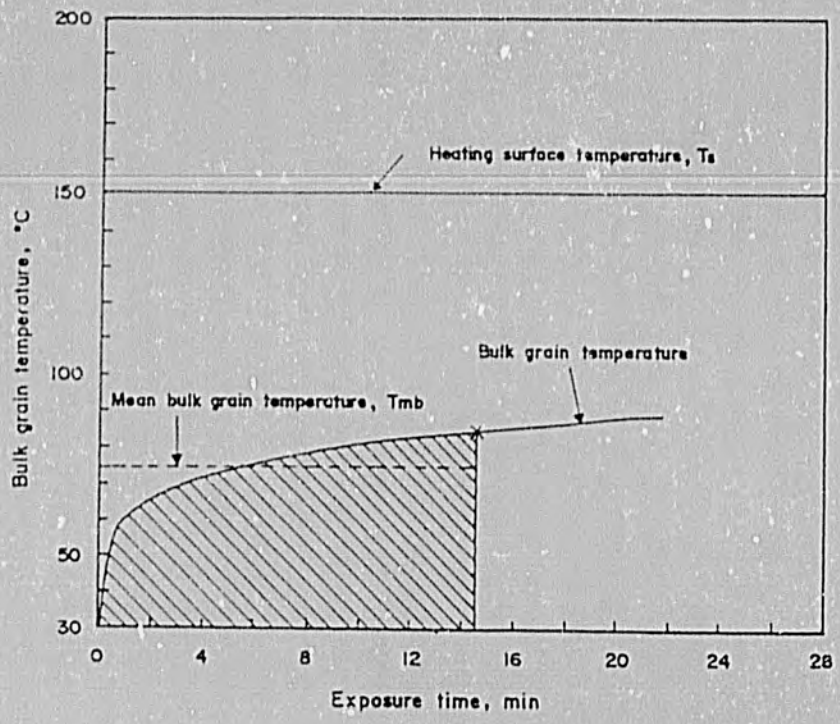


Fig. 4.13 Determination of mean bulk grain temperature for selected heating duration

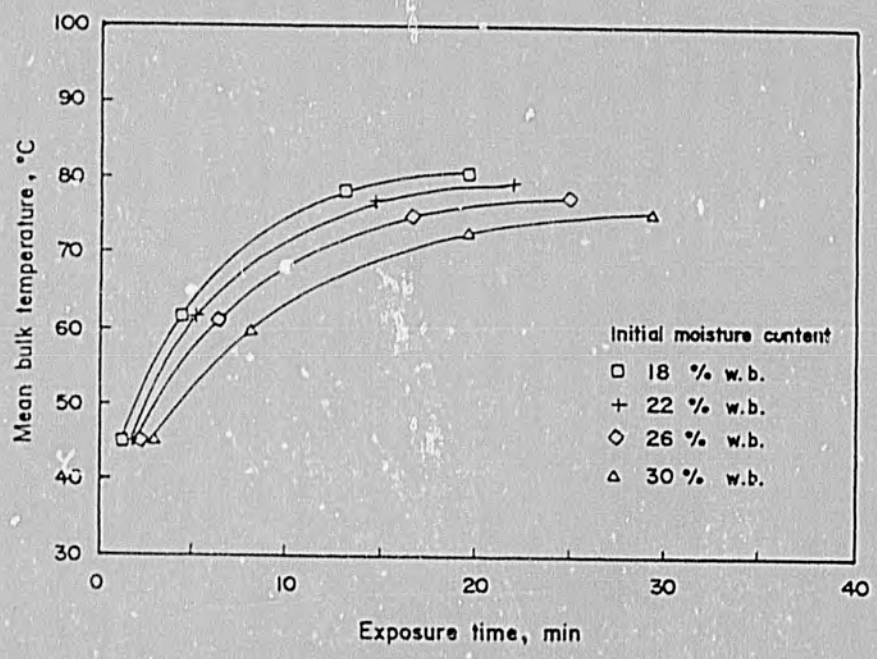


Fig. 4.14 Mean bulk grain temperature as a function of exposure duration

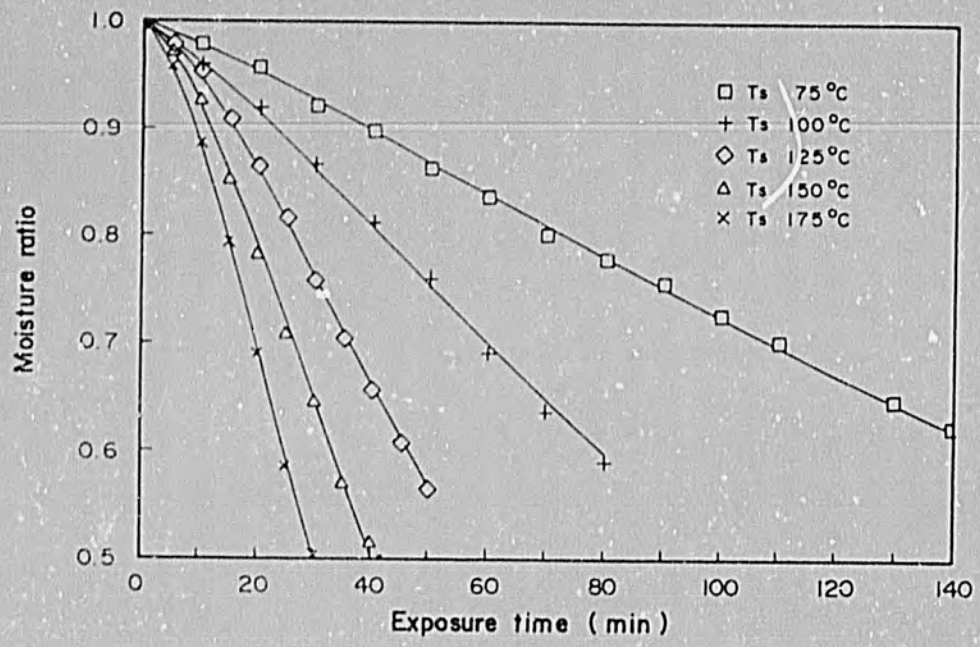


Fig. 4.15 Moisture ratio as a function of exposure time for various heating surface temperatures (M_0 26%)

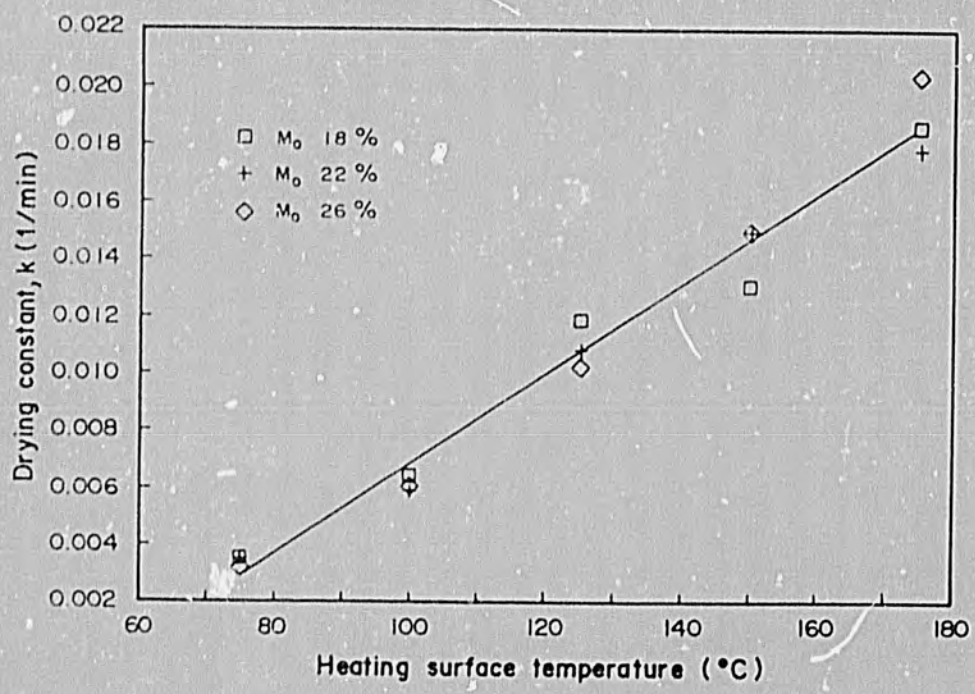


Fig. 4.16 Drying constant k of Eq. 4.9 as a function of heating surface temperature

$$\ln k = -6.8316 + 0.01705\ T_s \qquad ...(4.16)$$

$$(R^2 = 0.957;\ SEE = 0.137)$$

Using time-temperature history of grain in each test, mean bulk grain temperatures for various heating durations could be calculated. A comparison of experimental moisture contents based on Eqs. 4.9 and 4.16 and predicted moisture contents from Eq. 4.15 showed a mean standard error of only 0.95 % moisture content. Therefore, the proposed general procedure based on the mean bulk grain temperature computed from the time-temperature history of the grain could be used to estimate the change in moisture during conduction heating in any given equipment satisfactorily.

4.4 Effects of heat treatment on temporary storage

Table 4.11 presents the test conditions of heat treatments and quality indices such as fungal mortality level, fungal load ratio and head yields of rough rice samples at the start of the storage experiments. The values shown in Table 4.11 are average of three replications. As expected, heating surface temperature and the exposure time played a significant role in reducing the fungal load ratio. On the contrary, the head rice yield ratios were increased in general perhaps due to the partial gelatinization of starch in the grains. The head yield ratio increased in the range of 9 to 11 percent for rough rice with initial moisture of about 26% w.b. due to high-temperature short-time conduction heating. The corresponding increase in head yield ratio was only 2 to 4% for rough rice with initial moisture content of about 22% w.b. The beneficial effects of heat treatments were thus obvious in terms of reduced fungal activity and improved milling quality. It appeared that heat treatments corresponding to a reduction in fungal mortality level of 0.90 to 0.95 (or fungal load ratio of 0.10 to 0.05) resulted in a final moisture of rough rice about 2 to 5% w.b. lower than the initial moisture depending upon the heating surface temperature.

4.4.1 Effects of temporary storage on head rice yield

In general, the head rice yield of heat-treated and control samples decreased progressively with an increase in the storage period in all experiments. However, rough rice samples which were heat treated to at least 90% fungal mortality level showed a marked reduction in the proportions of brokens in the milled rice in comparison with control sample at the start of the storage experiments. In addition, the effect of prolonged storage was found to be less severe for heat-treated rough rice samples in comparison with the control samples. The reduction in head yield appeared to be linearly related with the storage period in all twenty-four experiments by the following equation:

Table 4.11. Experimental conditions and quality indices of rough rice samples after heat treatment

Test number	Initial moisture content (% w.b.)	Heating surface temp. (°C)	Exposure time (min)	Fungal load ratio	Final moisture content (% w.b.)	Head yield (%)	Discolored kernels (%)
1	23.5	200	0.0	1.000	23.5	56.7	0.76
2	23.5	200	0.6	0.855	23.3	57.5	0.76
3	23.5	200	2.2	0.016	22.7	59.8	0.76
4	23.5	200	7.4	0.016	18.2	60.6	0.76
5	22.0	150	0.0	1.000	22.0	47.5	0.75
6	22.0	150	1.6	0.460	21.7	48.0	0.75
7	22.0	150	5.3	0.018	20.4	48.8	0.75
8	22.0	150	14.6	0.010	17.6	48.1	0.75
9	22.2	100	0.0	1.000	22.2	47.8	0.68
10	22.2	100	8.	0.326	21.7	48.5	0.68
11	22.2	100	19.8	0.038	20.6	49.7	0.68
12	22.2	100	33.2	0.008	19.3	49.3	0.68
13	26.4	200	0.0	1.000	26.4	50.7	0.20
14	26.4	200	0.8	0.553	25.2	54.8	0.20
15	26.4	200	3.0	0.162	24.1	59.3	0.20
16	26.4	200	9.1	0.084	19.5	60.0	0.20
17	27.3	150	0.0	1.000	27.3	50.1	0.42
18	27.3	150	2.1	0.475	26.4	55.1	0.42
19	27.3	150	6.5	0.190	25.2	60.8	0.42
20	27.3	150	16.6	0.031	21.5	60.6	0.42
21	26.3	100	0.0	1.000	26.3	51.6	0.48
22	26.3	100	9.8	0.281	25.1	55.5	0.48
23	26.3	100	22.0	0.187	24.8	58.6	0.48
24	26.3	100	40.0	0.074	22.7	60.3	0.48

$$HYS = HYC [1 + b (SD)] \quad ...(4.17)$$

where HYS = head rice yield of rough rice samples, %
HYC = head rice yield of control sample at the start of storage experiments, %
SD = storage period, day
b = regression coefficient

The values of regression coefficient b in Eq. 4.17 represented the reduction in head rice yield ratio per day during the storage and are presented in Table 4.12. A similar relationship was reported by Dardo (1986) during temporary storage of rough rice heated in a microwave oven.

Unheated rough rice samples with initial moisture contents in the ranges of 22-23% and 26-27% showed a reduction in head rice yield of about 0.45% and 1.31%, respectively for each day of storage. However, similar rough rice samples when subjected to heat treatments corresponding to at least 95% fungal mortality level showed about 0.14% and 0.32% reduction in head rice yield per day for low and high moisture content samples, respectively. The higher rate of reduction in head rice yield of control or unheated rough rice samples could be attributed to an increase in the damaged kernels because of higher fungal activity during the temporary storage. Heat-treated rough rice samples produced higher head yields indicating low levels of damage incurred under similar storage conditions.

4.4.2 Effect of temporary storage on discoloration of milled rice

The effect of heat treatments in suppressing the fungal growth was more pronounced in terms of reduction in discolored milled rice kernels appearing during the storage period. It was observed that the discoloration in high moisture rice increased exponentially with the length of storage period and could be represented by the following equation:

$$DS = DC + \{ 1 - \exp [(-a_1 SD)^{b_1}] \} \quad ...(4.18)$$

where DS = weight fraction of discolored kernels in rough rice during storage, decimal
DC = weight fraction of discolored kernels in control sample initially, decimal
a_1, b_1 = regression coefficients

Typical plots of such relationships are shown in Figs. 4.17 and 4.18. The values of regression coefficients a_i and b_i appearing in Eq. 4.18 are presented in Table 4.12.

During the temporary storage of high moisture rough rice samples, it was observed that the rate of appearance of discolored milled rice kernels was relatively faster in comparison with the rate of reduction in head rice yield. Therefore it was obvious that the proportion of discolored kernels will be the limiting factor affecting the safe storage period of rough rice and its market grade subsequently.

4.4.3 Safe holding period for high moisture rice

In order to relate the reduction in head rice yield and an increase in the percentage of discolored kernels with the safe holding period of high moisture rough rice, the acceptable limits of these quality indices were selected based on one-step reduction in U.S. market grade (USDA, 1977). Accordingly the time required for a 3% reduction in the head rice yield or a 1.5% increase in discolored kernels was defined as the safe storage period. The safe storage periods were estimated from Eqs. 4.17 and 4.18 based on the reduction in head yield and an increase in discolored kernels, respectively. Table 4.13 shows that the limiting factor affecting the market grade of milled rice would be the percentage of discolored kernels because of its greater sensitivity to loss in quality during temporary storage of high moisture rice.

Unheated rough rice samples with initial moisture content of approximately 22 to 23.5% were lowered one-step in market grade within 3 to 5 days. Whereas rough rice with moisture content of about 26% had a safe holding period of about one day. These observations are in line with the findings of McNeal (1960) who reported storage damage in rough rice having 24% moisture content at the end of the first day and for rough rice having 21 to 23.9% moisture content between third and fourth day.

In general heat treatments corresponding to 90% fungal mortality in rice samples having moisture in the range of 22 to 23.5% resulted in an increase of about 10 to 23 days in the safe holding periods. For example, heating of rice using 200 °C surface temperature for 2.2 minutes resulted in safe storage period of about 12 days. On the other hand, rough rice with an initial moisture content of 26% when heated corresponding to 90 to 95% fungal mortality level (for about 3 to 9 min using 200 °C surface temperature) showed an increase of about 10 to 12 days in safe storage period. This safe storage period should enable effective utilization of dryer capacity through proper scheduling of heat treatment and drying operations.

Table 4.12. Parameters of the equations relating head rice yield and percent discolored kernels with storage time

Test number	Eq. 4.17		Eq. 4.18		
	b	R*	a_1	b_1	R*
1	0.00272	0.950	0.0035550	1.4225	0.900
2	0.00243	0.900	0.0000041	4.0200	0.980
3	0.00162	0.910	0.0001507	1.8800	0.953
4	0.00080	0.950	0.0005258	0.8989	0.978
5	0.00648	0.930	0.0009878	1.8600	0.971
6	0.00592	0.900	0.0022790	1.1000	0.880
7	0.00219	0.890	0.0000390	2.0656	0.982
8	0.00106	0.900	0.0000863	1.2159	0.998
9	0.00425	0.910	0.0004351	2.1600	0.996
10	0.00408	0.860	0.0001610	1.9600	0.998
11	0.00241	0.940	0.0007016	0.9117	0.850
12	0.00720	0.920	0.0001458	1.3161	0.900
13	0.01595	0.930	0.0482190	0.5315	0.920
14	0.01114	0.950	0.0009663	2.0015	0.996
15	0.01082	0.890	0.0000023	3.9000	0.998
16	0.00199	0.950	0.0000008	4.0600	0.994
17	0.01389	0.920	0.0581920	0.3840	0.943
18	0.01345	0.960	0.0042281	1.2850	0.923
19	0.01697	0.950	0.0002913	2.0600	0.968
20	0.00085	0.930	0.0000338	2.3120	0.900
21	0.00937	0.900	0.0095140	1.1960	0.900
22	0.00746	0.910	0.0016850	1.6200	0.939
23	0.01262	0.930	0.0004949	2.0100	0.979
24	0.00678	0.900	0.0000124	3.2000	0.965

* Correlation coefficient

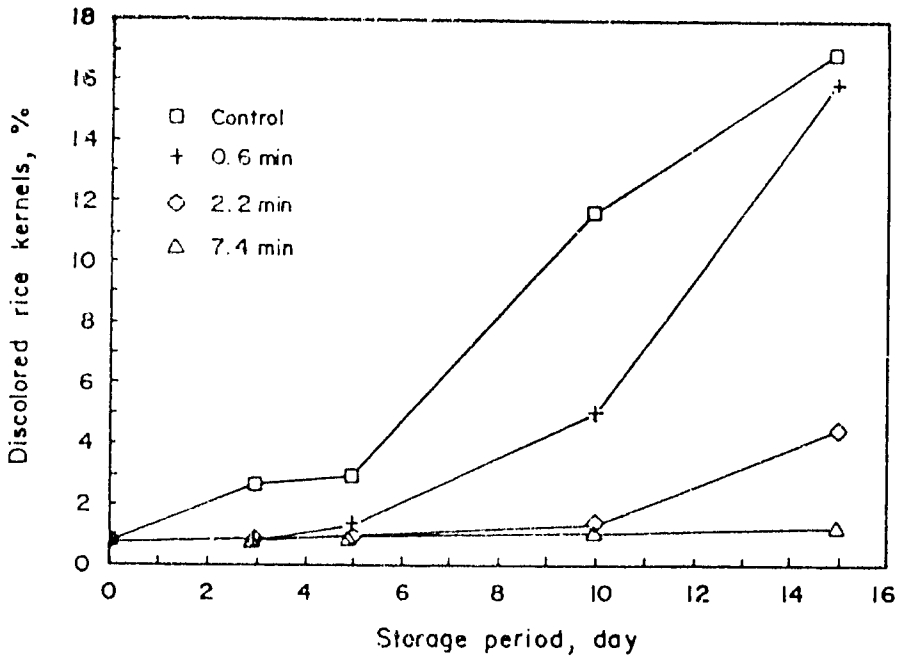


Fig. 4.17 Discoloration of milled rice as a function of storage period of rough rice having 22% initial moisture when heated for different duration using 200°C surface temperature

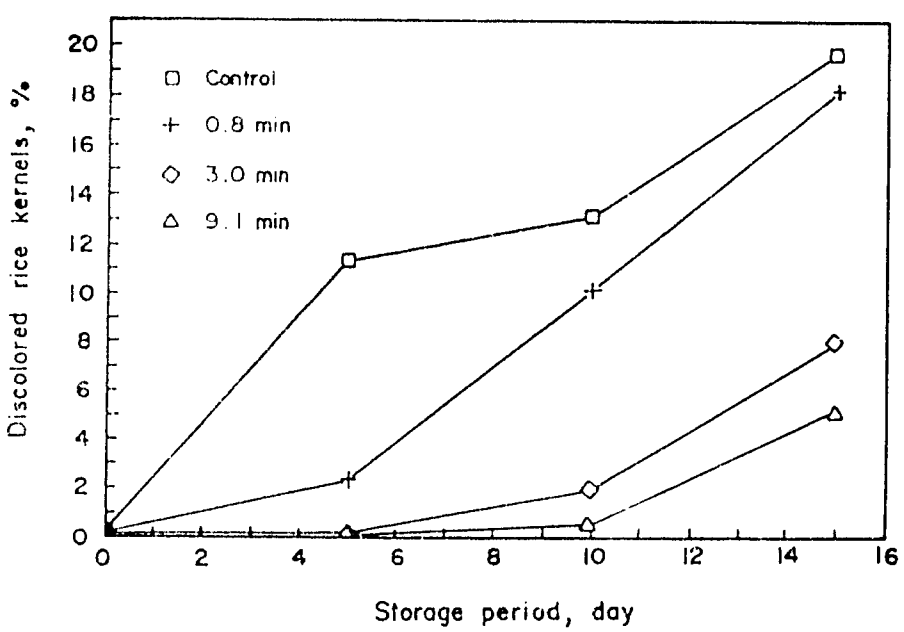


Fig. 4.18 Discoloration of milled rice as a function of storage period of rough rice having 26% initial moisture when heated for different duration using 200°C surface temperature

Table 4.13. Safe storage periods for high moisture rough rice

Test number	Safe storage period (days) based on	
	Head rice yield	Discolored kernels
1	19.5	2.7
2	27.3	7.7
3	53.5	11.6
4	142.5	26.0
5	9.7	4.3
6	12.2	5.6
7	40.2	17.9
8	71.3	70.0
9	14.7	5.2
10	18.7	10.2
11	40.0	29.0
12	41.6	34.0
13	3.7	0.1
14	11.7	4.0
15	18.1	9.5
16	103.5	11.4
17	4.3	0.0
18	10.9	2.7
19	13.3	6.8
20	262.4	14.0
21	6.2	1.5
22	16.7	3.9
23	13.6	5.5
24	28.7	9.2

Using multiple regression analysis, a relationship was developed for estimating the safe storage period based on the fungal load ratio and final moisture content attained as a result of various heat treatments as follows:

$$\ln SSD = 7.1223 - 0.7731 \exp(FLR) - 5.466 \times 10^{-12} \exp(FMC) - 0.1616 (FMC) \quad ...(4.19)$$

where SSD = safe storage period, day
FLR = fungal load ratio (FC_1/FC_0), decimal
FC_1 = fungal count of heat-treated rough rice sample, colonies/g
FC_0 = fungal count of unheated rough rice sample, colonies/g
FMC = final moisture content of rough rice after heat treatment, % w.b.

The coefficient of determination and standard error of estimate for Eq. 4.19 were found to be 0.90 and 0.58, respectively and considered satisfactory based on the experimental limitations. Eq. 4.19 clearly shows the strong dependence of safe storage period of rough rice on its moisture content and fungal load following the heat treatment. Further analysis showed that the coefficient of determination was about 0.50 without moisture content as a parameter, thus indicating a high correlation of safe storability of rough rice with the fungal activity.

4.4.4 Heat sterilization of high moisture rice in prototype unit

The prototype rice husk-fired rotary heating unit (prototype II) was tested to further check the validity of proposed heat treatment procedure for extending the safe storage period of high moisture rough rice. It was not possible to control the heating surface temperature within a narrow range due to fluctuations in the operation of the rice-husk-fired furnace. In addition, the grain temperature could not be monitored during the actual heating operation. Therefore, average time-temperature profiles estimated on the basis of extensive experimentation were used in the general prediction procedure.

The increase in grain temperature during conduction heating in the prototype unit depended upon the initial moisture content of rice, heating surface temperature and exposure time at any selected cylinder rotation speed. Eq. 4.2 described this relationship satisfactorily for a feed rate of 7.5 kg/min and cylinder rotation speed of 10 rpm. The value of constant c_1 in Eq. 4.2 could be estimated by the following relationship:

$$c_1 = -0.88218 - 0.000471\ T_s + 0.1157\ M_0 - 0.002587(M_0)^2 \quad ..(4.20)$$

$(R^2 = 0.90;\ SEE = 0.023)$

Eqs. 4.2 and 4.20 were used for estimating the exposure duration corresponding to 90% reduction in fungal load by following a similar procedure outlined in Section 4.2.4 (Fig. 4.6). For average heating surface temperatures of 115, 165, and 215 °C, feed rate of 7.5 kg/min and grain initial moisture content of 25%, the values of exposure durations were determined to be 18, 5.2, and 4.0 min, respectively.

In case of the prototype rotary heater, a relationship between the discoloration ratio and storage time was developed similar to Eq. 4.18. The corresponding values of regression coefficients a_1 and b_1 are presented in Table 4.14.

Based on the acceptable limit of 1.5% increase in discolored rice kernels, safe storage periods were estimated for various heat treatments. The results presented in Table 4.14 clearly show that heat-treated rough rice could be safely stored for an additional period of 2 to 3 weeks in comparison with the control. The safe storage periods for rough rice samples having initial moisture content of 25% w.b. were estimated using the general prediction equation (Eq. 4.19) for 90% fungal mortality level (or fungal load ratio of 0.10). The experimental and predicted safe storage periods compared reasonably well as shown in Table 4.14 despite the experimental limitations. For rough rice samples which were heat-treated using surface temperatures in the range of 200-230 °C, the predicted safe storage time was considerably shorter perhaps due to a discrepancy in the measurement of either fungal load ratio or final moisture content. Therefore the proposed general procedure based on the time-temperature history of grain in a given heating system could be successfully used for estimating the safe storage period of high moisture rough rice.

4.4.5 Carbon dioxide production by heat-treated rough rice samples

An attempt was made to study the possible relationship between carbon dioxide production by heat-treated samples during storage with their safe holding periods. The production of carbon dioxide by rough rice samples could be attributed to the fungal respiration since the viability of the grains was reduced almost to zero level due to high temperature conduction heating. The carbon dioxide production was expressed in terms of equivalent dry matter loss (EDML) using a conversion factor of 1.46 g CO_2 per g of EDML as recommended by Seib et al. (1980), and was related with the storage period by the following equation:

$$EDML = a_2 + b_2\ (SD) + c_2\ (SD)^2 \quad ...(4.21)$$

Table 4.14 Safe storage period of rough rice samples heated in the prototype rice husk-fired dryer

Heating surface temp. (°C)	Exposure time (min)	Fungal load ratio	Final moisture content (% w.b.)	Initial discolored kernels (%)	Regression coefficients		Safe storage period (days)	
					a_o	b_o	Experimental (prototype)	Predicted (Eq. 4.19)
Control	0.0	1.000	25.0	2.0	0.2252	1.1071	2.3	1.6
100 - 130	18.2	0.014	18.0	2.0	0.1540	0.4074	23.8	28.4
150 - 180	5.2	0.035	21.5	2.0	0.1476	0.4772	16.3	19.1
200 - 230	4.0	0.019	21.2	2.0	0.0258	0.8276	41.1	20.1

where EDML = equivalent dry matter loss,%
SD = storage period, day
a_2, b_2, c_2 = regression coefficients

The typical effects of heat treatment on EDML are illustrated in Figs. 4.19 and 4.20. The values of regression coefficients of Eq. 4.21 are given in Table 4.15. Very low and stable rates of respiration were observed with high moisture rough rice samples heat-treated for about 2 to 3 minutes using heating surface temperature of 200 °C. The results showed that rough rice having initial moisture content in the range of 18 to 22.5% fell in market grade during storage when EDML was about 0.12% or higher. The corresponding value of EDML in higher moisture content range of 22.5 to 27% was found to be 0.20%. These results are supported by Seib et al. (1980) who reported that a dry matter loss of more than 0.25% reduced the market grade of rough rice at 22% moisture content. The limits for EDML obtained in this study during the maximum safe storage period appear to be somewhat stringent. This was perhaps due to a drastic reduction in respiration rate of rough rice samples after the heat treatment and the shorter duration of the maximum safe storage period itself based on a relatively more sensitive criterion of the discoloration of milled rice used in this study.

4.4.6 The role of fungi in discoloration of rice

The results from the separate sub-experiment showed that the fungi Helminthosporium, Penicillium, Aspergillus flavus, and Aspergillus niger produced pronounced discoloration of the milled rice. The discoloration was probably due to the action of fungus metabolites on the pigments within the rice bran and/or by pigments synthesized by molds themselves (Schroeder and Sorenson, 1961). It was revealed that the growth of specific microorganisms in the mass of grain if left unchecked could cause discoloration in the following forms:

a. yellowish brown to black - by Helminthosporium, Penicillium and Aspergillus niger.

b. light yellow to yellowish green color - by Aspergillus flavus.

In addition, the invasion of these specific fungi in rough rice resulted in reduced head rice yields (Table 4.16). The rough rice samples inoculated with Helminthosporium, Penicillium, and Aspergillus niger showed a drastic reduction in head rice yields.

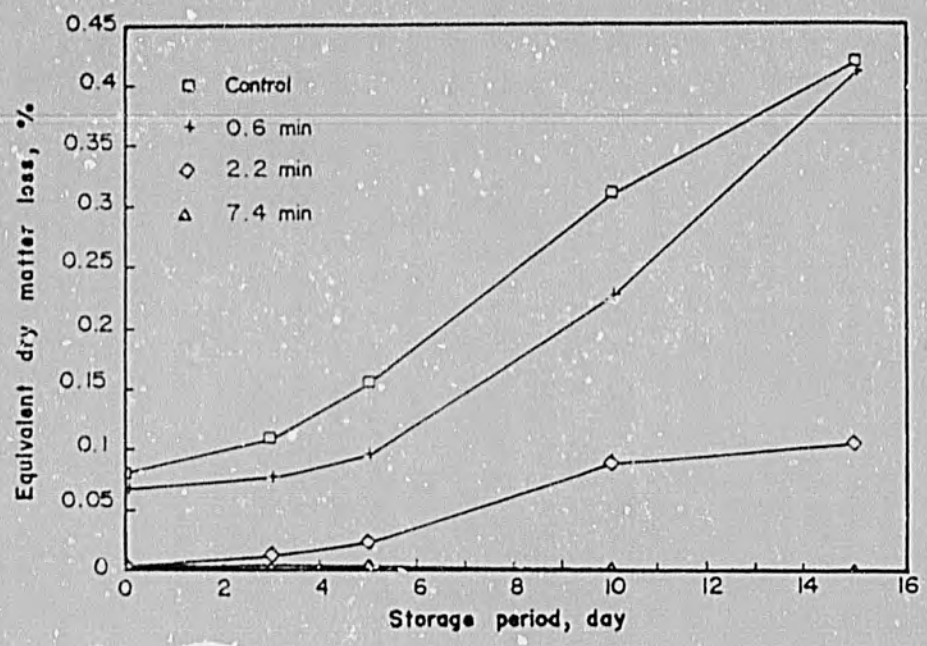


Fig. 4.19 Equivalent dry matter loss as a function of storage period of rough rice having 22% initial moisture when heated for different duration using 200 °C surface temperature

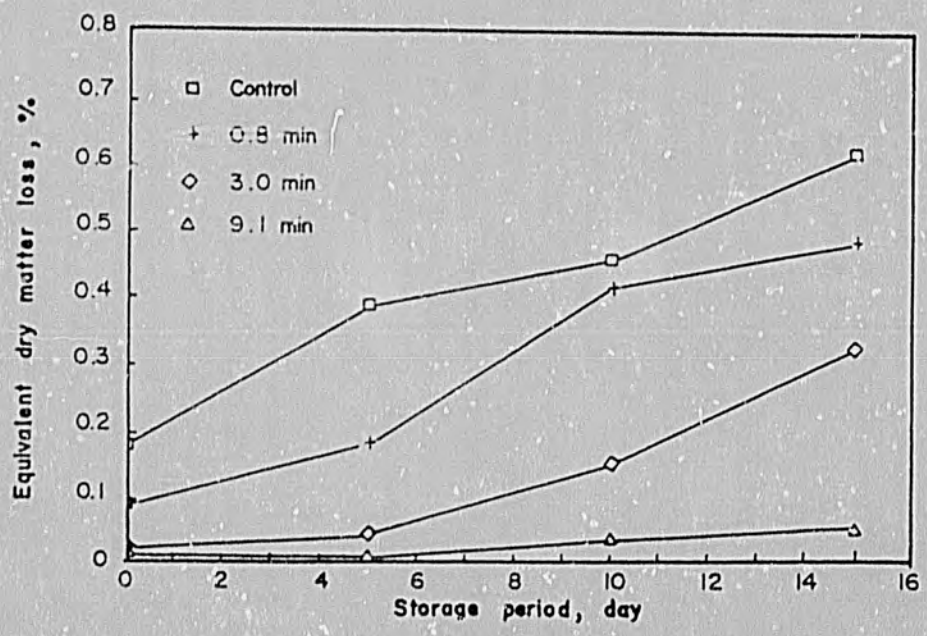


Fig. 4.20 Equivalent dry matter loss as a function of storage period of rough rice having 26% initial moisture when heated for different duration using 200 °C surface temperature

Table 4.15 Parameters of Equation 4.21 relating equivalent dry matter loss in rough rice samples and storage time

Test number	a_2	b_2	c_2	R*
1	0.0639	0.0186	0.0004	0.993
2	0.0607	0.0003	0.0015	0.999
3	0.0000	0.0057	0.0001	0.969
4	0.0006	0.0000	0.0000	0.996
5	0.0748	0.0102	0.0003	0.998
6	0.0183	0.0072	0.0013	0.991
7	0.0000	0.0029	0.0002	0.944
8	0.0020	-0.0011	0.0002	0.992
9	0.0754	0.0295	-0.0009	0.977
10	0.0000	0.0205	-0.0003	0.913
11	0.0003	0.0009	0.0002	0.990
12	0.0000	0.0015	0.0001	0.996
13	0.1859	0.0348	-0.0005	0.924
14	0.0722	0.0314	-0.0002	0.988
15	0.0193	-0.0018	0.0015	0.979
16	0.0077	0.0004	0.0002	0.999
17	0.2131	0.0366	-0.0007	0.982
18	0.0334	0.0745	-0.0020	0.981
19	0.0000	0.0356	0.0005	0.971
20	0.0000	0.0078	0.0001	0.935
21	0.1893	0.0423	-0.0009	0.964
22	0.0237	0.0854	-0.0028	0.955
23	0.0000	0.0631	-0.0003	0.981
24	0.0000	0.0030	0.0016	0.971

* Correlation coefficient

Helminthosporium (a field fungi), together with *Penicillium* are the most common fungi in newly harvested rough rice. During heat treatment, these fungi were either eliminated or reduced to a very low level (Table 4.16). Therefore heat treatment of rough rice samples using proper exposure time and temperature combinations reduced the chances of fungal growth and subsequent occurrence of damaged kernels during the temporary storage.

Table 4.16 Milled rice appearance and head yields obtained from rough rice samples inoculated with specific fungi

Fungi	Appearance	Head rice yield (%)
Control	none	56.40
Helminthosporium	brown to black	30.13
Penicillium	brown to black	29.98
As. flavus	light yellow to yellow green	42.18
As. niger	brown to black	39.86

4.5 Effects of heat treatment on head rice yield

The effects of various heat treatments on head rice yields are illustrated in Figs. 4.21 to 25. Heat-treated rough rice samples showed an increase in head rice yield initially and a subsequent reduction depending upon the exposure time, heating surface temperature and the sample initial moisture. Similar observations have been reported in the past during the high temperature conduction heating of high moisture rough rice (Khan et al., 1974; Acasio and Belonio, 1983; Jindal and Obaldo, 1986). A marked improvement in head rice yield was observed in rough rice samples having initial moisture content of 30% due to conduction heating in all experiments. These results indicated the strong dependence of head rice yield on grain initial moisture and heating surface temperature. The increase in head rice yield may be contributed to the gelatinization of the starch granules and cementing of fissures present in kernels thus preventing the breakage during milling operation (Juliano, 1979). For low moisture rough rice samples, a drastic reduction in head yield ratio was noticed when exposure duration exceeded 5 min, especially in higher heating surface temperatures.

The dependence of head rice yields on the exposure duration was adequately represented by a quadratic equation as follows:

$$HYR = 1 + A\,t - B\,t^2 \qquad ...(4.22)$$

where HYR = head yield ratio (HYS/HYC), decimal
HYS = head yield obtained from heated rough rice sample, %
HYC = head yield obtained from the control sample, %
t = exposure duration, min
A,B = regression coefficients

The dependence of the regression coefficients in Eq. 4.22 on the experimental conditions was described by the following relationships based on multiple regression analysis:

$$\ln A = -17.8816 + 0.079694\,T_s + 0.35658\,M_o - 0.001961\,(T_s * M_o) \qquad ...(4.23)$$

$$(R^2 = 0.927 \;;\quad SEE = 0.73)$$

$$\ln B = -7.7149 + 0.11835\,T_s - 1.03754\,M_o + 0.02849\,M_o^2 - 0.002699\,M_o * T_s \qquad ...(4.24)$$

$$(R^2 = 0.942;\quad SEE = 1.00)$$

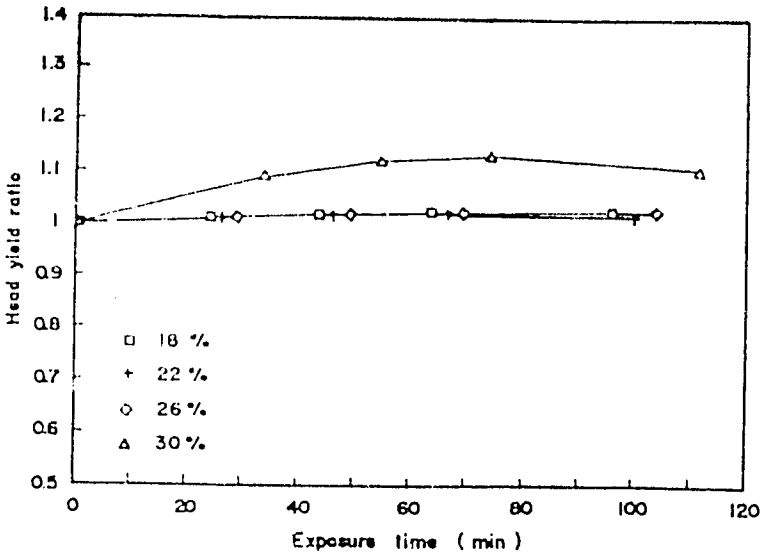


Fig. 4.21 Head yield ratio as a function of exposure duration for various moisture contents of rough rice (heating surface temperature 75°C)

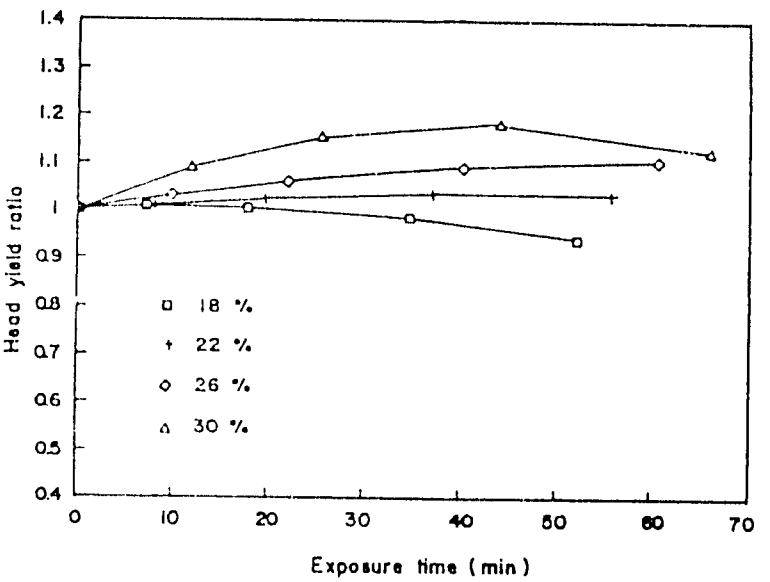


Fig. 4.22 Head yield ratio as a function of exposure duration for various moisture contents of rough rice (heating surface temperature 100°C)

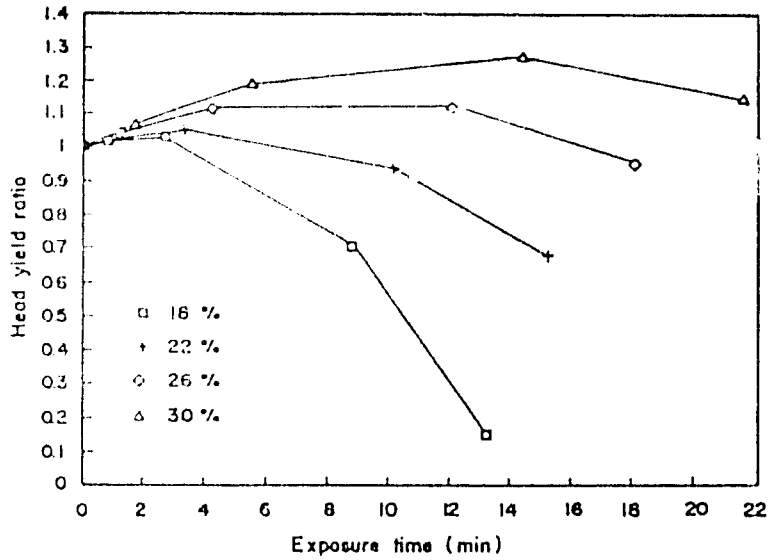


Fig. 4.23 Head yield ratio as a function of exposure duration for various moisture contents of rough rice (heating surface temperature 150°C)

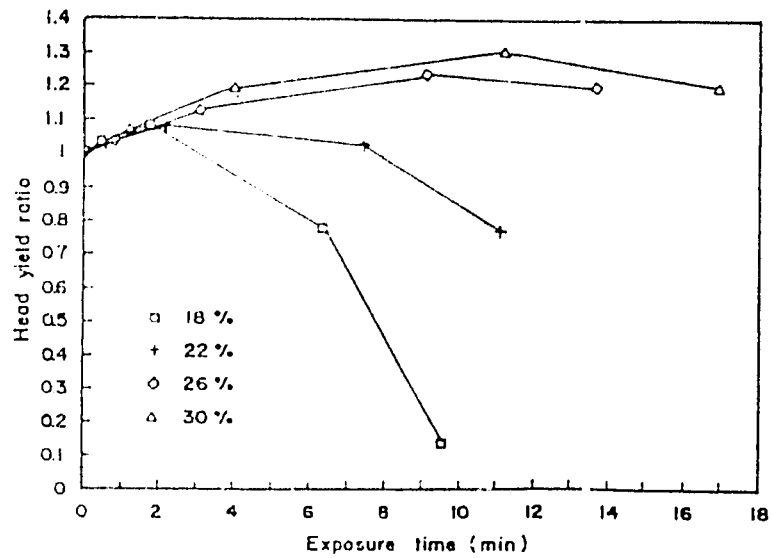


Fig. 4.24 Head yield ratio as a function of exposure duration for various moisture contents of rough rice (heating surface temperature 175°C)

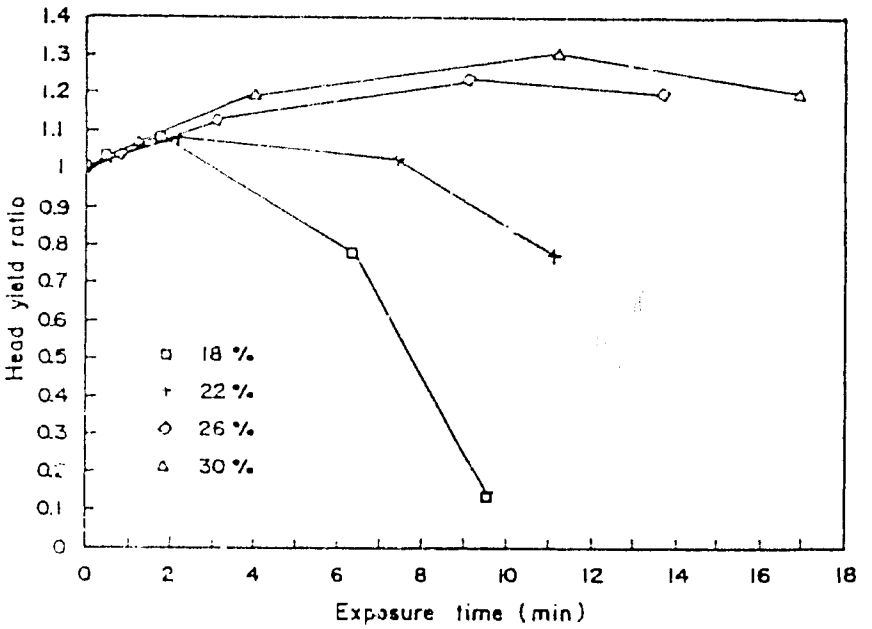


Fig. 4.25 Head yield ratio as a function of exposure duration for various moisture contents of rough rice (heating surface tempearture 200°C)

4.5.1 Optimum heating time for maximum head rice recovery

From the experimental results it was evident that there existed optimum conditions for highest value of head rice yield for various heat treatment combinations. The heating time corresponding to the highest value of head rice yield was estimated by taking the first derivative of Eq. 4.22 and equating it to zero to give the following relationship:

$$t_{(HYR = max)} = A / 2B \qquad \ldots (4.25)$$

where $t_{(HYR=max)}$ = heating time for highest value of HYR, min
A,B = constants of Eq. 4.22

The optimum heating times were computed using Eq. 4.25 in conjunction with Eqs. 4.23 and 4.24 giving the values of constants A and B, respectively for selected experimental conditions. Table 4.17 shows the various combinations of exposure time, heating surface temperature, and initial moisture contents which could be used to attain the highest head rice yields. However, the use of high-temperature short-time heating could be more desirable for maximum utilization of the dryer. This is supported by the attainable head yield ratios of the

rough rice samples presented in Fig. 4.26 which were calculated using Eqs. 4.22 to 4.24 and optimum heating times. At 200 °C heating surface temperature, an optimum heating time of 3 to 6 min would result in about 26 percent increase in head rice yield for rough rice samples having 22 to 26% initial moisture content.

The heat treatment of rough rice samples would result in a net reduction in their moisture content as depicted by Eqs. 4.9 and 4.11. Table 4.18 shows the final moisture content of rough rice samples following the heat treatment for optimum exposure duration. In general, high-temperature short-time heating of rough rice samples could result in rapid drying and as well as higher head rice yields.

The heating times corresponding to maximum head rice yields were compared with fungal inactivation times required for 90 and 95% mortality levels as shown in Fig. 4.27. It was obvious that heating times for achieving 90% FML were not sufficient to attain the highest value of head yield ratios. However, heating times corresponding to 95% FML and maximum head yield ratio appeared to match on average. These results indicated that thermal inactivation of fungi in high moisture rough rice using heating surface temperatures ranging from 75 to 200 °C could be carried out with a distinct improvement in its milling quality.

In view of the complexity of Eqs. 4.23 and 4.24, an alternate simplified relationship was developed to estimate the optimum heating time directly in the following form:

$$\log t_{(HYR=max)} = -2.3919 + 0.3785\, M_o - 0.01527\, T_s - 0.007451\, (M_o^2) + 0.0002497\, (M_o * T_s) \quad ...(4.26)$$

$$(R^2 = 0.999 \; ; \; SEE = 0.001)$$

The estimated values of optimum heating times using Eq. 4.26 and Eqs. 4.22 to 4.23 were almost identical, thus validating the use of Eq. 4.26.

4.5.2 Relationship between head rice yields and drying considerations

Assuming head yield ratio of 1.0 as the acceptable limit for the quality of dried rough rice, the required heating times are given by Eq. 4.27 as follows:

$$t_{(HYR = 1.0)} = A / B \quad ...(4.27)$$

Table 4.17 Optimum heating times for obtaining maximum head rice yields

Initial moisture content (%, w.b.)	Heating surface temperature (°C)				
	75	100	150	175	200
18.0	22.5	12.1	3.5	1.9	1.0
22.0	56.0	31.9	10.3	5.9	3.3
26.0	80.6	48.6	17.7	10.7	6.4
30.0	67.1	42.8	17.5	11.2	7.1

Table 4.18 Final moisture content of rough rice samples corresponding to optimum heating time

Initial moisture content (%, w.b.)	Heating surface temperature (°C)				
	75	100	150	175	200
18.0	17.1	16.6	16.8	17.0	17.3
22.0	19.5	19.0	17.9	18.5	19.2
26.0	22.1	19.3	18.5	19.2	20.3
30.0	26.4	23.4	21.7	22.2	23.0

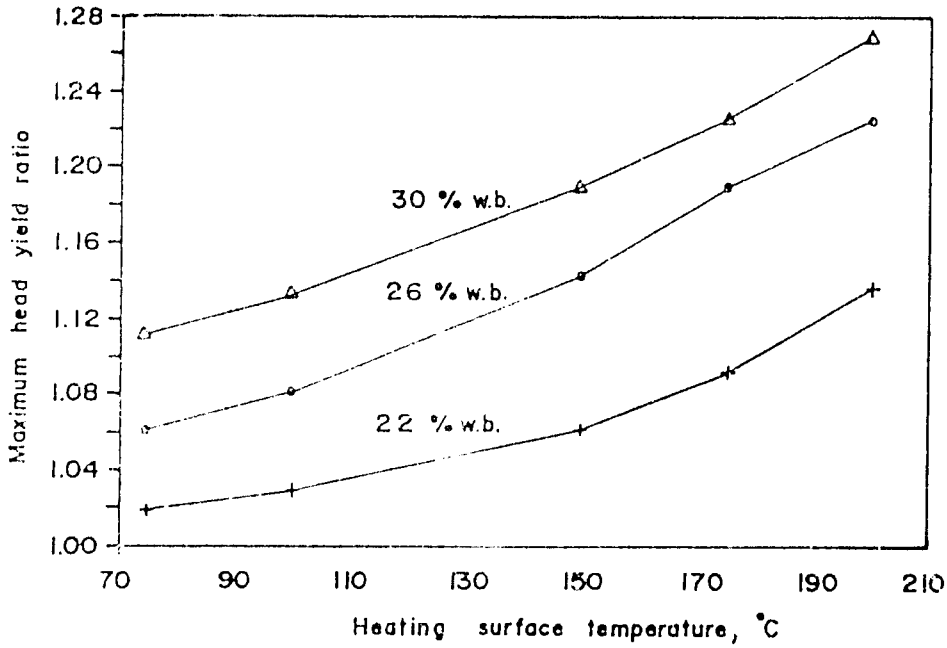


Fig. 4.26 Maximum head yield ratio as a function of heating surface temperature for rough rice having different initial moisture contents

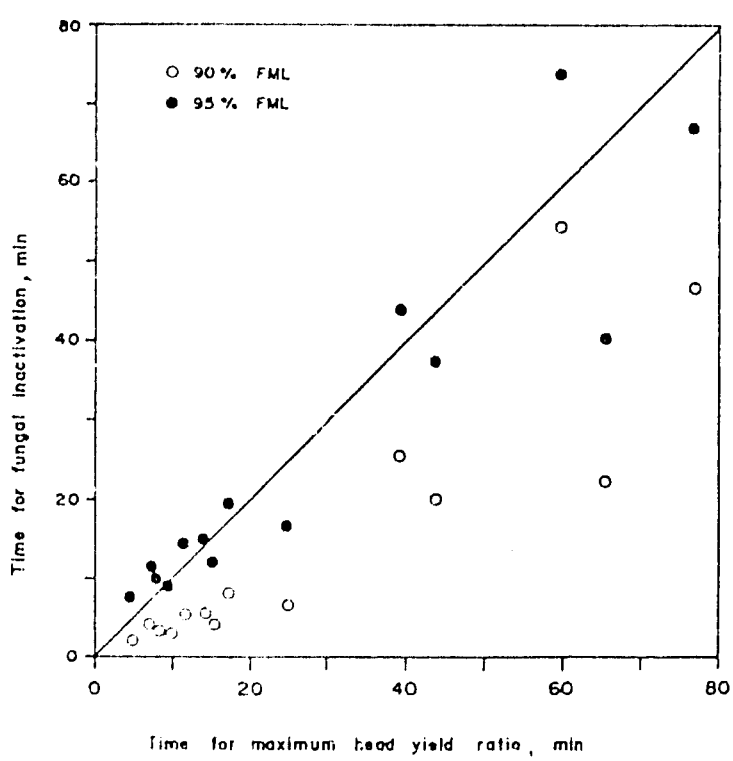


Fig. 4.27 Heating times required for 90 and 95% fungal mortality levels versus heating times corresponding to maximum value of head yield ratio

where $t_{(HYR=1.0)}$ = heating time to obtain unit head yield ratio, min

From Eq. 4.25 it follows that the heating time required to obtain unit head yield ratio would be twice the heating times for the highest head yield ratio. With this HYR limit, all rough rice samples with an initial moisture content of 22-26% could be safely dried to 15-16% using heating surface temperatures of 100 - 200 °C. Table 4.19 shows the final moisture contents of rough rice samples when heated over a period corresponding to the head yield ratio limit of unity. It is obvious that rough rice samples should be subjected to additional heating times in order to dry from 22-26% to 14% moisture content continuously. However, increased heating duration will cause a possible reduction in head yield ratio of about 5%. Therefore, the exposure durations and final moisture contents of rough rice samples corresponding to head yield ratio of 0.95 are shown in Tables 4.20 and 4.21, respectively. Rough rice with an initial moisture content of 18% could be dried to 14 % with a 5 % reduction in HYR using heating surface temperatures in the range of 75 to 150 °C (Table 4.21). A 5% reduction in head yield ratio is equivalent to about 2% reduction in head yield since the average head yield of the control samples in most cases was about 45%.

The results presented in Tables 4.19 and 4.21 clearly indicate that continuous drying of rough rice samples down to safe storage moisture level of about 14% w.b. during the conduction heating process would be accompanied by a slight reduction in head rice yields. Therefore a multi-stage drying operation with provision of tempering would be a desirable option.

4.5.3 Kinetics representation of changes in head rice yields

The quality degradation in foods has been represented by a lethality-like function by several researchers in terms of attributes like degree of cookedness, enzyme inactivation (Mansfield, 1962; Hayakawa et al., 1977; Bradshaw et al., 1982). The lethality function is similar to the calculation of mass sterilizing value (Eq. 4.4). Following a similar procedure outlined in Section 4.24 (Fig. 4.6), the F_c and z_c-values were determined for selected head yield ratios. Based on practical considerations, the heat-treated rough rice samples should result in head rice yields at least equal to that of control sample or higher. Therefore, a value of head yield ratio equal to 0.95 was selected as the minimum acceptable limit for quality deterioration in rough rice.

The developed relationships between the head yield ratio and equivalent exposure time were quadratic in form similar to Eq. 4.22 for any arbitrarily selected reference bulk grain temperature as folows:

Table 4.19 Final moisture content of rough rice samples (% w.b.) corresponding to unit head yield ratio

Initial moisture content (% w.b.)	Heating surface temperature (°C)				
	75	100	150	175	200
18.0	16.3	15.4	15.6	16.1	16.5
22.0	17.4	14.6	14.5	15.5	16.7
26.0	18.7	14.1	12.7	13.9	15.5
30.0	23.1	17.9	15.3	15.9	17.3

Table 4.20 Heating time of rough rice samples (min) corresponding to unit head yield ratio of 0.95

Initial moisture content (% w.b.)	Heating surface temperature (°C)				
	75	100	150	175	200
18.0	109.9	49.5	10.6	5.1	2.5
22.0	162.0	84.7	24.2	13.2	7.3
26.0	189.4	110.4	38.2	22.6	13.5
30.0	147.8	93.1	37.1	23.5	14.9

Table 4.21 Final moisture content of rough rice samples (% w.b.) corresponding to unit head yield ratio of 0.95

Initial moisture content (% w.b.)	Heating surface temperature (°C)				
	75	100	150	175	200
18.0	14.1	13.0	14.4	15.4	16.2
22.0	15.5	12.7	13.4	14.8	16.4
26.0	17.6	12.9	12.0	13.3	15.1
30.0	22.5	17.1	14.6	15.4	16.8

$$HYR = 1 + A_o * F_c - B_o * F_c^2 \qquad ...(4.28)$$

where HYR = head yield ratio, decimal
F_c = equivalent exposure time, min
A_o, B_o = regression coefficients

The regression coefficients A_o and B_o were related with the reference bulk grain temperature (T_{ref}) and initial moisture content of rough rice sample (M_o) by the following equations :

$$\ln A_o = 21.8777 - 0.09909\ T_{ref} - 2.0548\ M_o - 0.008808\ (T_{ref} * M_o) + 0.02548\ M_o^2 \qquad ...(4.29)$$

(R^2 = 0.937 ; SEE = 0.40)

$$\ln B_o = 12.6751 + 0.3334\ T_{ref} - 2.8583\ M_o + 0.03280\ M_o^2 - 0.004479\ T_{ref}^2 + 0.01541\ (M_o * T_{ref}) \qquad ...(4.30)$$

(R^2 = 0.940 ; SEE = 0.50)

Eqs. 4.29 and 4.30 clearly showed that the changes in head yield ratio were highly correlated with the equivalent exposure times estimated from the trial and error procedure. The relationship between equivalent exposure time and reference bulk grain temperature for obtaining 0.95, 1.0 and maximum values of head yield ratio are shown in Figs. 4.28 to 4.31 for various initial moisture contents of rough rice. This method of estimating F_c value is similar to that of Bradshaw et al. (1982), where the inactivation rate of a toxin was also represented by a quadratic relationship. From Fig. 4.28 it is evident that high temperature heat-treatment of rough rice with an initial moisture content equal to or below 13% will not result in head rice yield equal or higher than the control sample. Obviously the initial moisture content of rough rice influenced the relationship between F_c-value and bulk grain temperature and hence the determination of z_c-values. To investigate the dependence of z_c-values on the moisture content, the relationships of Figs. 4.28 to 4.31 were represented in the following equation form:

$$\log F_{c\ (HYR)} = A_1 + B_1\ T_{ref} \qquad ....(4.31)$$

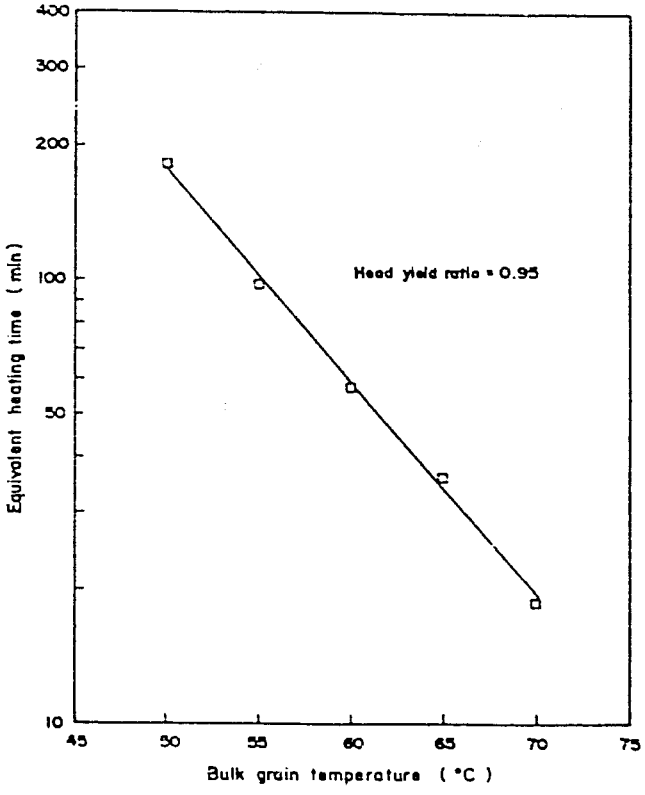


Fig. 4.28 Relationship between equivalent heating time and reference bulk grain temperature for determination of z_c-values at 18% initial moisture content

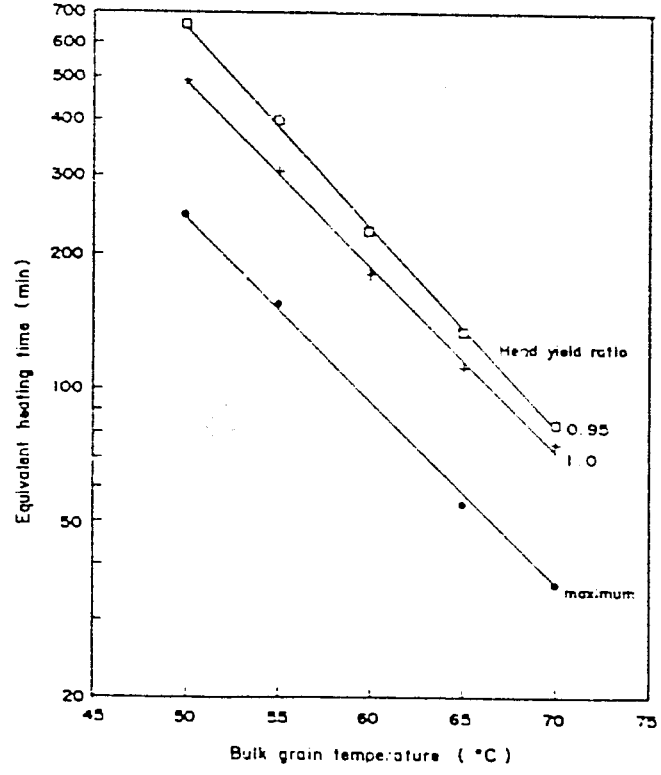


Fig. 4.29 Relationship between equivalent heating time and reference bulk grain temperature for determination of z_c-values at 22% initial moisture content

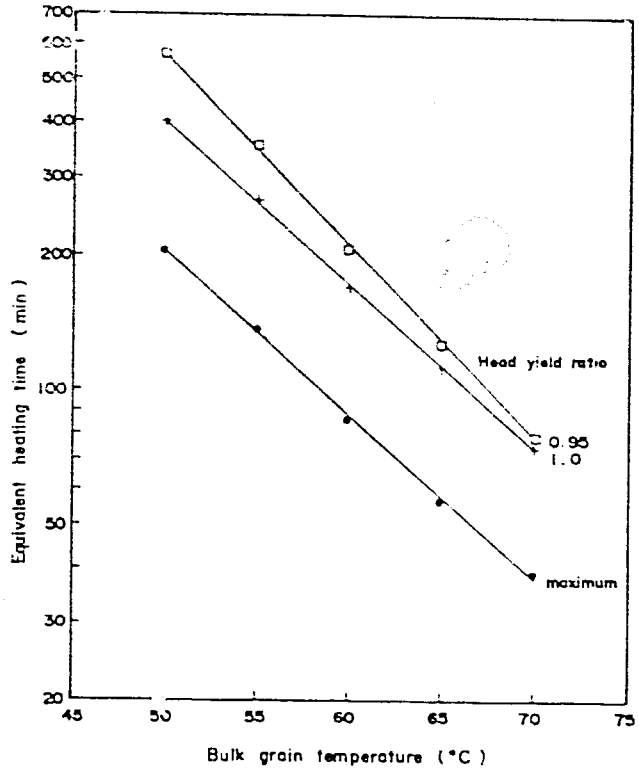


Fig. 4.30 Relationship between equivalent heating time and reference bulk grain temperature for determination of z_c-values at 26% initial moisture content

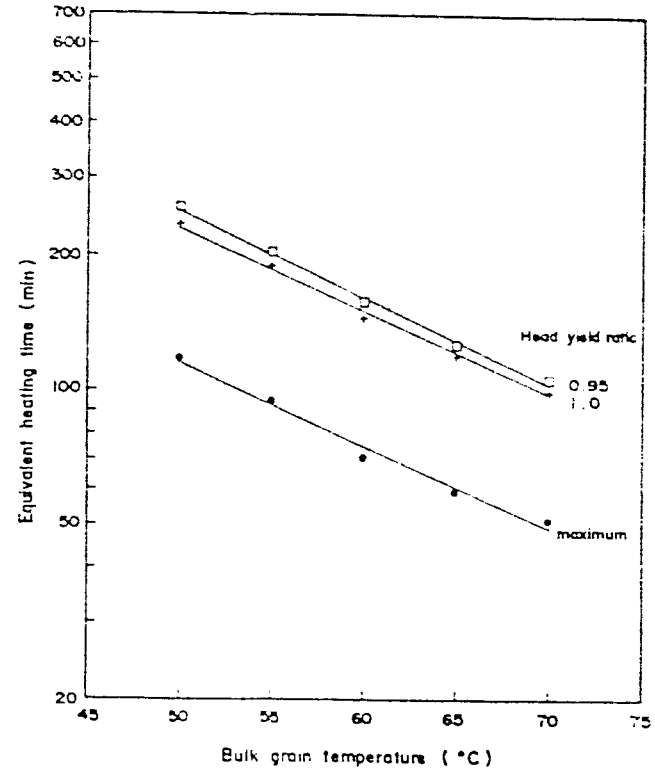


Fig. 4.31 Relationship between equivalent heating time and reference bulk grain temperature for determination of z_c-values at 30% initial moisture content

where $F_{c\,(HYR)}$ = equivalent exposure time required to attain a desired head yield ratio, min
T_{ref} = reference bulk grain temperature, °C
A_1, B_1 = regression coefficients

The regression coefficients of Eq. 4.31 are given in Table 4.22 for selected values of head yield ratio. The inverse of regression coefficient B_1 led to the determination of z_c-value applicable to the heat treatment of high moisture rough rice (Table 4.22).

The possibility of using various heat treatment combinations to achieve specific levels of head rice ratio is evident in Figs. 4.30 to 4.31. For example, at 70 °C reference bulk grain temperature, maximum head rice could be obtained if a rough rice sample with an initial moisture content of 26% w.b. was heated for about 40 min. The same result could be accomplished at 65 °C bulk grain temperature and an equivalent exposure time of about 60 min. Using step-wise multiple regression analysis, the relationships of Figs. 4.30 to 4.31 were expressed in equation form for 0.95, 1.0 and maximum values of head yield ratio, respectively for general estimation purposes as follows:

$$\log F_{c\,(HYR\,=\,0.95)} = 0.5247 - 0.04360\,T_{ref} + 0.3145\,M_o - 0.005544\,M_o^2 \qquad ..(4.32)$$

$$(R^2 = 0.994;\ SEE = 0.032)$$

$$\log F_{c\,(HYR\,=\,1.0)} = -1.5225 + 0.04258\,T_{ref} + 0.2539\,M_o - 0.001353\,M_o^2 - 0.002867\,(M_o * T_{ref}) \qquad ..(4.33)$$

$$(R^2 = 0.992;\ SEE = 0.026)$$

$$\log F_{c\,(HYR\,=\,max)} = -1.82353 + 0.042585\,T_{ref} + 0.2539\,M_o - 0.001353\,M_o^2 - 0.002867\,(M_o * T_{ref}) \qquad ..(4.34)$$

$$(R^2 = 0.992\ ;\ SEE = 0.026)$$

The results presented in Figs. 4.28 to 4.31 further indicate a decrease in the magnitude of z_c-values with decreasing concentration of rough rice moisture. The dependence of z_c-values on initial moisture of rough rice (Fig. 4.32) was described by the following relationship:

Table 4.22 Regression coefficients of Eq. 4.31 relating equivalent exposure time and bulk grain temperature for various levels of head yield ratio

Head yield ratio	Initial moisture (% w.b.)	A_1	B_1	R^2	z_c *
0.95	18.0	4.6155	-0.04748	0.956	21.1
1.0	18.0	-	-	-	-
Optimum	18.0	-	-	-	-
0.95	22.0	5.0557	-0.04490	0.860	22.3
1.0	22.0	4.7488	-0.04130	0.865	24.2
Optimum	22.0	4.4480	-0.04130	0.840	24.3
0.95	26.0	4.9609	-0.04408	0.980	22.7
1.0	26.0	4.4335	-0.03644	0.976	27.4
Optimum	26.0	4.1206	-0.03625	0.970	27.6
0.95	30.0	3.3497	-0.01908	0.950	52.4
1.0	30.0	3.2687	-0.01820	0.950	55.0
Optimum	30.0	2.9795	-0.01836	0.955	54.5

* z_c-values applicable to various head yield ratios ($z_c = 1/B_1$)

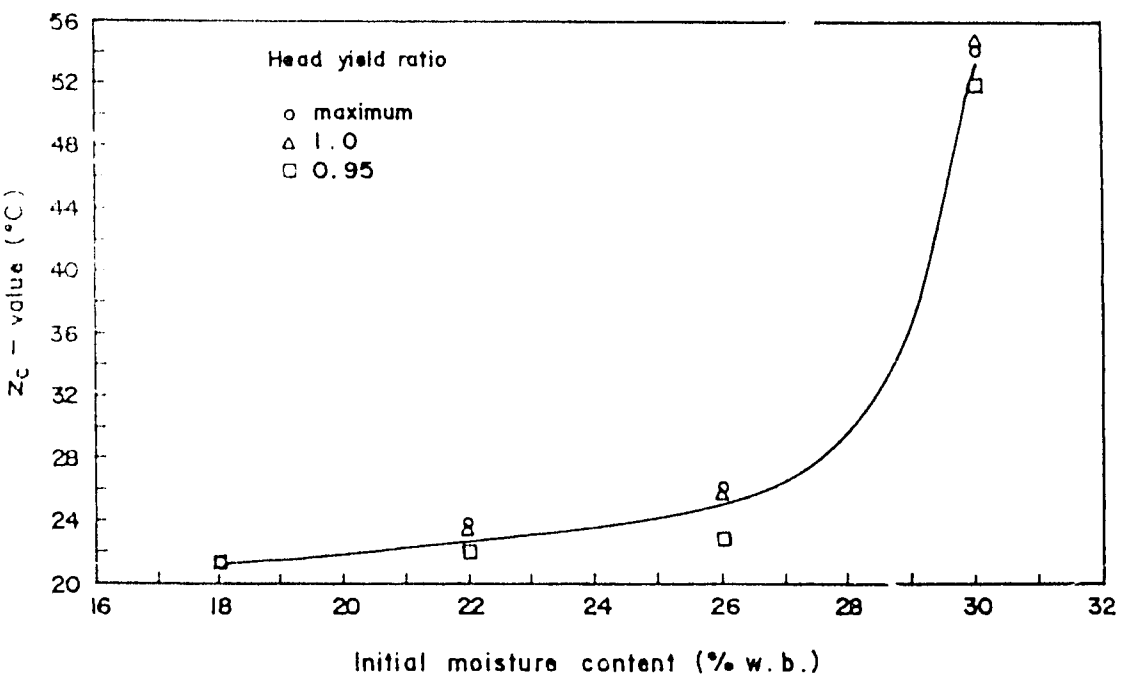


Fig. 4.32 Relationship between z_c-value and initial moisture content of rough rice

$$z_c = 13.5255 + 0.4322\ M_0 + 2.5225 \times 10^{-12} \exp(M_0) \quad ...(4.35)$$

$(R^2 = 0.99;\ SEE = 2.01)$

The multiple regression analysis also showed that the influence of various levels of head yield ratio on z_c-values was not statistically significant.

The F_c and z_c-values determined in this study should be applicable in general to any conduction heating system provided the time-temperature history of rough rice in the system under consideration is known.

4.5.4 Effects of heat treatment on milled rice whiteness

Heat treated rough rice samples yielded milled rice which was slightly yellowish-brown in appearance in comparison with the unheated control sample. This change in color could be due to the non-enzymatic browning and/or the diffusion of coloring pigments of the hull and bran to the endosperm caused by the exposure of the grain to very high temperatures. Generally, the change in color was less severe for milled rice produced from rough rice samples having lower initial moisture content and as well as from samples exposed to lower heating surface temperatures. Whiteness ratio (WR) of milled rice and heating duration appeared to be related in the following equation form:

$$WR = \exp(-a' * t^{b'}) \quad ..(4.36)$$

where WR = whiteness ratio, W_s/W_c
W_s = whiteness units of milled rice obtained from heated rough rice sample
W_c = whiteness units of milled rice obtained from the control sample
t = heating duration, min
a', b' = regression coefficients

The above relationship was considered satisfactory since the average value of coefficient of determination for all experimental tests was found to be 0.84 with a standard deviation of 0.073. The dependence of regression coefficients a' and b' on the moisture content of rough rice and heating surface temperature was given by the following equations:

$$\ln a' = -43.4066 + 0.2177\ T_s + 1.2208\ M_o - 0.006737\ (T_s * M_o) \quad ...(4.37)$$

(R^2 = 0. 900; SEE = 1.250)

$$b' = 8.3793 - 0.03905\ T_s - 0.2593\ M_o + 0.001357\ (M_o * T_s) \quad ...(4.38)$$

(R^2 = 0.800; SEE = 0.310)

The average whiteness value of milled rice samples produced from unheated rough rice was about 31.8 units. Since the change in the whiteness of milled rice detectable to human eye yielded whiteness meter readings between 25 and 26 units, a minimum acceptable level of whiteness ratio was selected to be 0.8. Based on this consideration, allowable heating times were computed using Eqs. 4.36, 4.37, and 4.38 for each combination of heating surface temperature and initial moisture content of rough rice and compared with heating times required for maximum head rice yields (Fig. 4.33). These results showed that high moisture rough rice could be heated up to 95% FML for obtaining maximum head yield without significant reduction in the whiteness of milled rice.

4.5.5 Effects of heat treatment on cooked-rice texture

An improvement in both cooked-rice firmness and stickiness was observed following conduction heating of fresh rough rice samples using heating surface temperatures ranging from 75 to 200 °C. Unheated control samples exhibited characteristic soft and sticky texture of freshly harvested rice. In comparison, the heat-treated samples produced firm and less sticky cooked-rice grains. The firmness of cooked-rice as measured by the total energy in back extrusion test increased approximately from 3 to 9% depending upon the duration of heating (Figs. 4.34 and 4.35). Stickiness, on the other hand, was reduced in the 6 to 18 % range in heat-treated samples. This improvement in cooked-rice texture may be viewed as an added feature of heat treatment aside from a definite increase in head rice yields since most people prefer less sticky and moderately firm cooked-rice. The changes in cooked-rice texture observed in this study are apparently similar to those occuring in the artificial aging process reported by Normand et al. (1964).

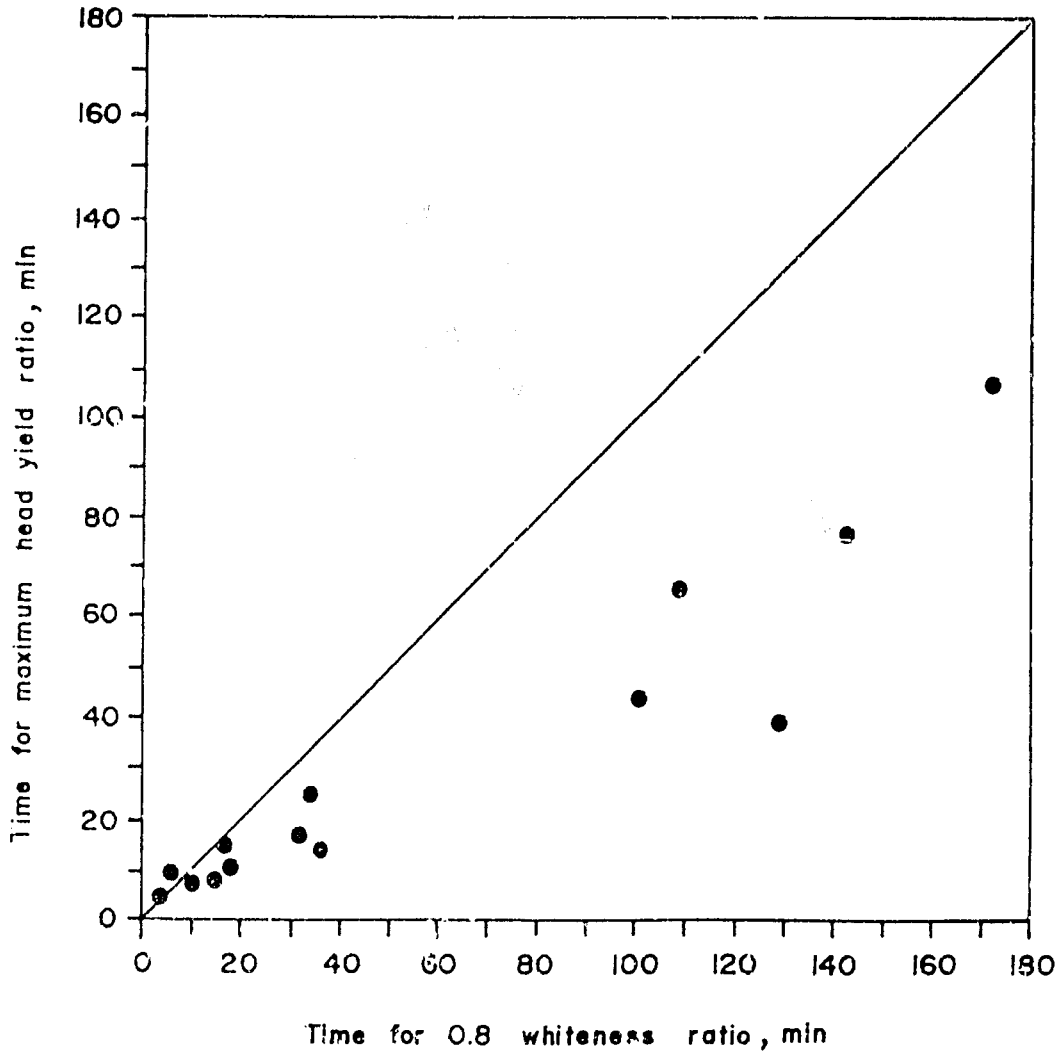


Fig. 4.33 Heating times corresponding to the highest value of head yield ratio versus heating times required for minimum acceptable whiteness

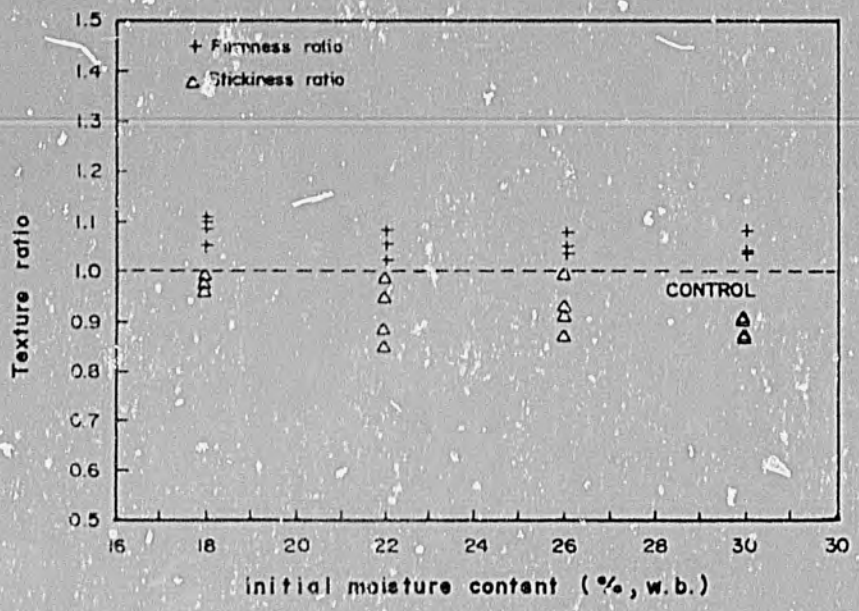


Fig. 4.34 Texture of cooked-rice samples as a function of initial moisture content of rough rice for heat treatments resulting in 90% fungal inactivation

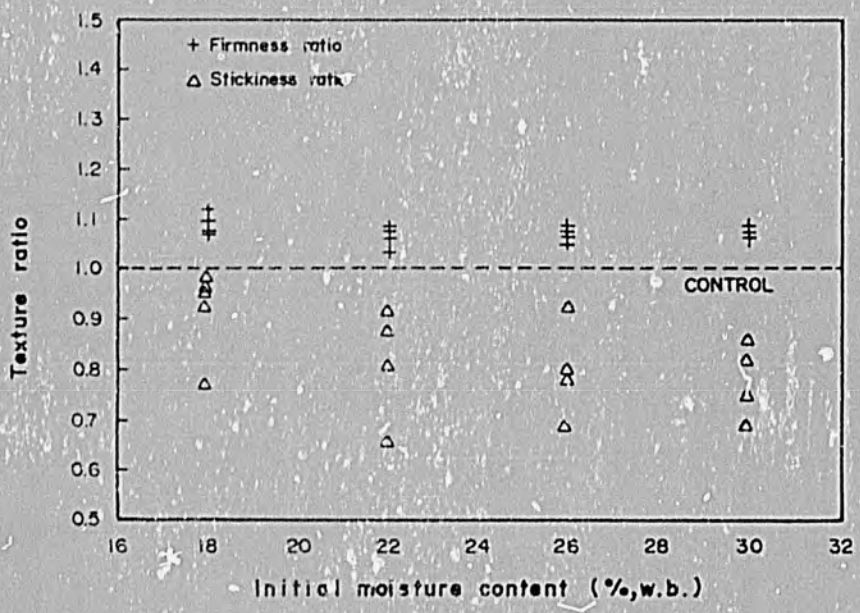


Fig. 4.35 Texture of cooked-rice samples as a function of initial moisture content of rough rice for heat treatments resulting in 95% fungal inactivation

4.6 Perfomance of Full-Scale Prototype Units

4.6.1 Prototype dryer with axial flights (Prototype I)

The operation of each protoytpe dryers was carefully checked and analyzed before actual heating and drying tests. Several adjustments were required before achieving a smooth mechanical operation. Based on calibration results, it was possible to regulate the cylinder surface temperature in a close range by monitoring the air temperature near the surface of the cylinder.

Residence time of rough rice in the cylinder. The residence time and hold-up of the rough rice in the rotary cylinder are related as follows:

$$t_R = W / F \qquad ...(4.39)$$

t_R = residence time, min
W = hold-up in the cylinder, kg
F = feed rate, kg/min

The residence time of rough rice in the cylinder depended upon the experimental conditions in the following equation form:

$$t_R = 10.375 - 1.310 \ln(F) - 1.567 \ln(N) - 0.657 S + 0.0013 F*N + 0.0079 M_o*S + 0.0051 F*S \qquad ...(4.40)$$

(R^2 = 0.953; SEE = 0.124)

where N = cylinder rotation speed, rpm
S = cylinder inclination, degree
M_o = moisture content of rough rice, % w.b.

The residence time and hold-up of rough rice in the rotary dryer could range from 1 to 3 min and 30 to 70 kg, respectively depending upon the experimental conditions.

Moisture removal. Figs. 4.36 and 4.37 illustrate the change in moisture content and head yield of rough rice during conduction heating, respectively. The drying experiments clearly showed the rapid moisture removal especially at higher heating

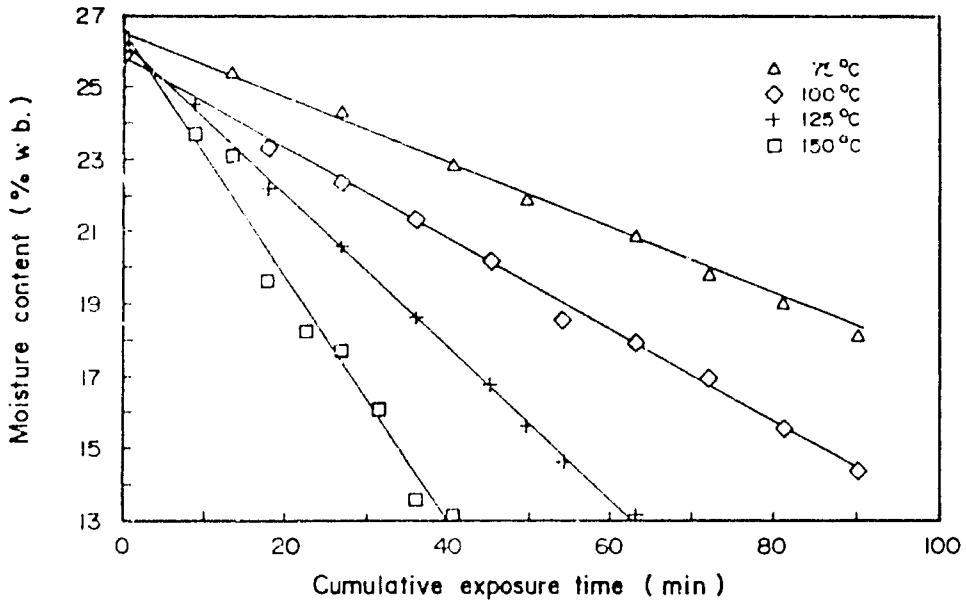


Fig. 4.36 Moisture content of broken rice as a function of exposure time (M_0 26% w.b., 30 kg/min feed rate)

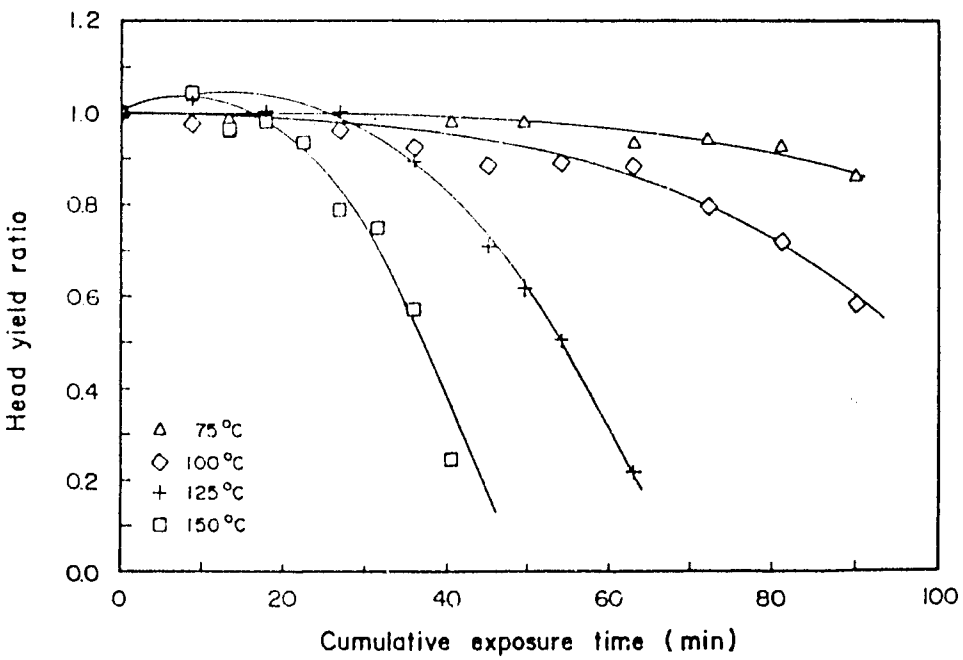


Fig. 4.37 Head yield ratio as a function of exposure duration for various heating surface temperatures (M_0 26%, 30 kg/min feed rate)

surface temperatures. These results also indicated that a simple logarithmic model described the accelerated drying behaviour of high moisture rough rice satisfactorily. The dependence of the drying constant k on the experimental conditions was adequately described by the following equation:

$$\ln k = -7.0253 + 0.01893\ T_s \qquad \ldots(4.41)$$

$$(R^2 = 0.981\ ;\ SEE = 0.085)$$

Eq. 4.41 revealed the strong dependence of drying constant upon the heating surface temperature. These results were similar to those observed in the small-scale experimental heating units.

Head rice yield. Fig. 4.37 is a typical plot showing the effect of various heat treatments on head rice yields. As observed during heating of rough rice in the small-scale experimental heating units, heated high moisture rough rice generally showed an increase in the head rice yields initially with increasing exposure time followed by a subsequent reduction for longer exposure times. The dependence of head rice yields on the exposure duration was represented by a quadratic equation (Eq. 4.22). Only a small increase in head yields was observed in this prototype unit mainly because of the lifting action of its flights causing some cooling action during the heating process. It appeared that rough rice could be dried continuously in this unit without appreciable loss in head rice yield up to 18 to 19% w.b. The corresponding exposure times corresponding to this final moisture content for 75, 100, 125 and 150 °C were approximately 65, 35, 30 and 20 minutes, respectively for rice samples having an inital moisture of 26% w.b. These results showed that the rapid drying of rough rice without significant gelatinization was feasible under controlled experimental conditions. The partially dried rough rice could be safely stored for a few weeks prior to final drying to 14 % w.b..

4.6.2 Prototype dryer with spiral flights (Prototype II)

Rotary Dryer Operation. A relationship between the heating surface temperature and the flue gas temperature was developed in the following form:

$$T_s = 31.12 + 0.005017\ T_f + 0.002367\ T_f^2 \qquad \ldots(4.42)$$

where T_s = surface temperature of the rotary cylinder, °C
T_f = flue gas temperature, °C

Eq. 4.42 was used to monitor the heating surface temperature and to maintain it within a narrow range as far as practically possible. It was observed that the heating surface temperature fluctuated up to ± 30 °C during the dryer operation.

The rice husk feed rates required to maintain heating surface temperatures in the range of 100 to 180 °C are shown in Fig. 4.38. The temperature increase was observed to be linear with husk feed rate. During the drying tests, the sorrounding air temperature varied from 28 to 32 °C.

The relationship between the residence time of grain inside the cylinder and its rotational speed was adequately described by the following equation:

$$t_R = 2.4340 - 0.1377\ N + 0.002428\ N^2 \qquad ...(4.43)$$

where t_R = residence time of rough rice in heating cylinder, min
N = rotation speed of the heating cylinder, revolutions/min

Moisture Removal. Fig. 4.39 shows the changes in the moisture content during conduction heating in the rice husk-fired dryer with helical flights. The dependence of the drying constant k (Fig. 4.40) on the experimental conditions was described by the following equation:

$$\ln\ k = -5.9692 + 0.011296\ T_s \qquad ...(4.44)$$

$$(R^2 = 0.860\ ;\ SEE = 0.160)$$

Head rice yields. Fig. 4.41 is a typical plot showing the effect of various heat treatments on head rice yields. The average head rice yield of the unheated control sample was about 42%. The heat-treated rough rice samples clearly showed an increase in their head rice yields with increasing exposure time initially followed by a subsequent reduction in milling quality for longer heating periods. The dependence of head rice yields on the exposure duration was also represented by a quadratic equation (Eq. 4.22).

The regression coefficients A and B were related with the experimental conditions by the following equations:

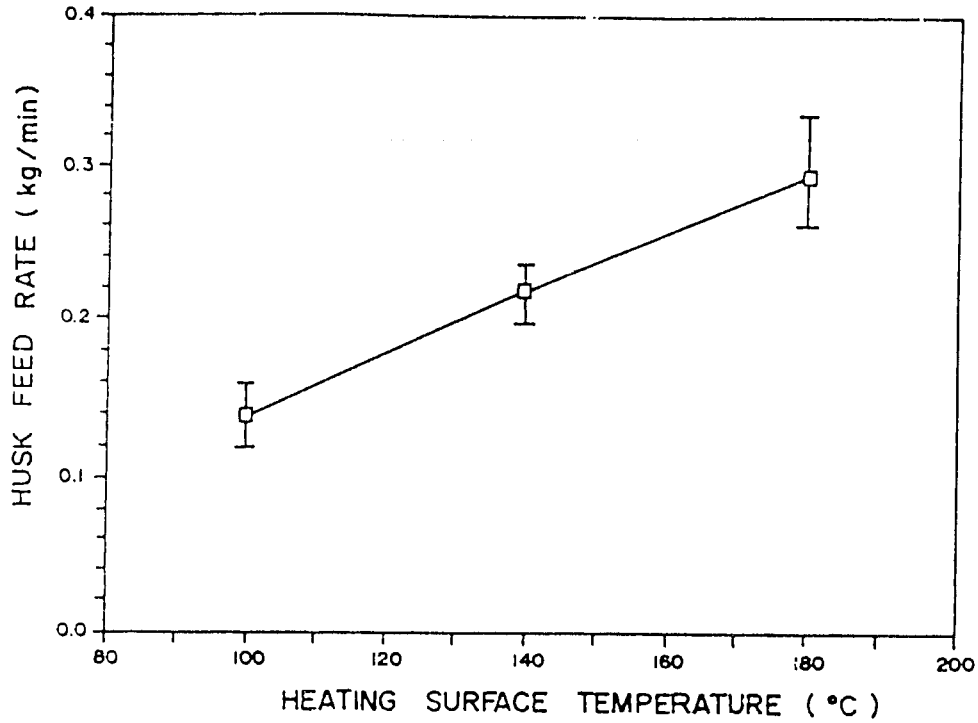


Fig. 4.38 Rice husk feed rate as a function of heating surface temperature

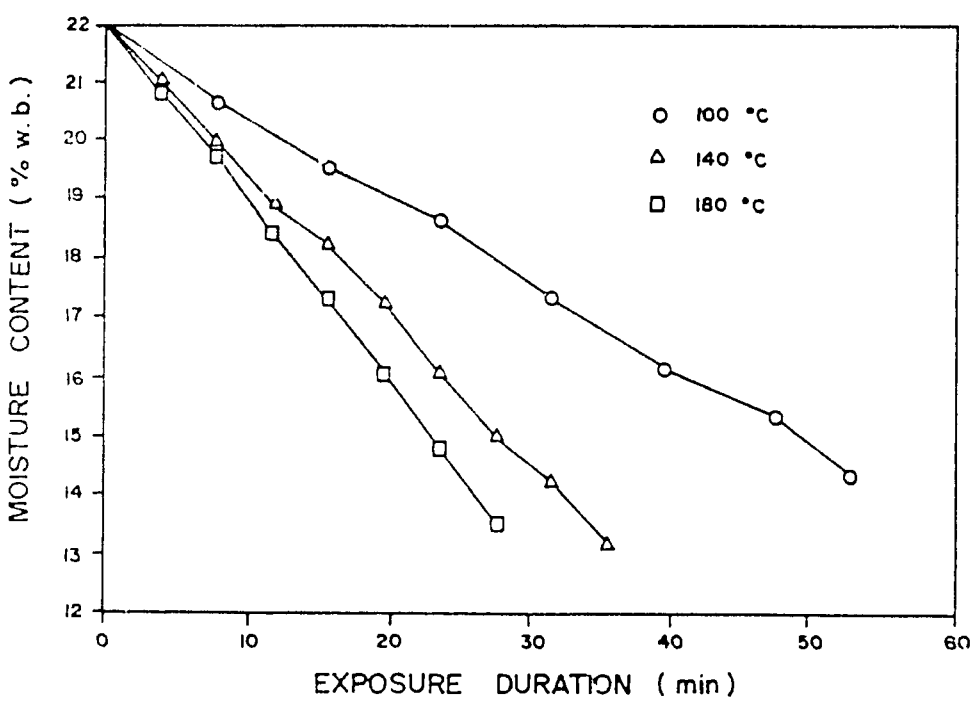


Fig. 4.39 A typical plot of moisture content vs. exposure duration (feed rate 30 kg/min, initial moisture content 22% w.b.)

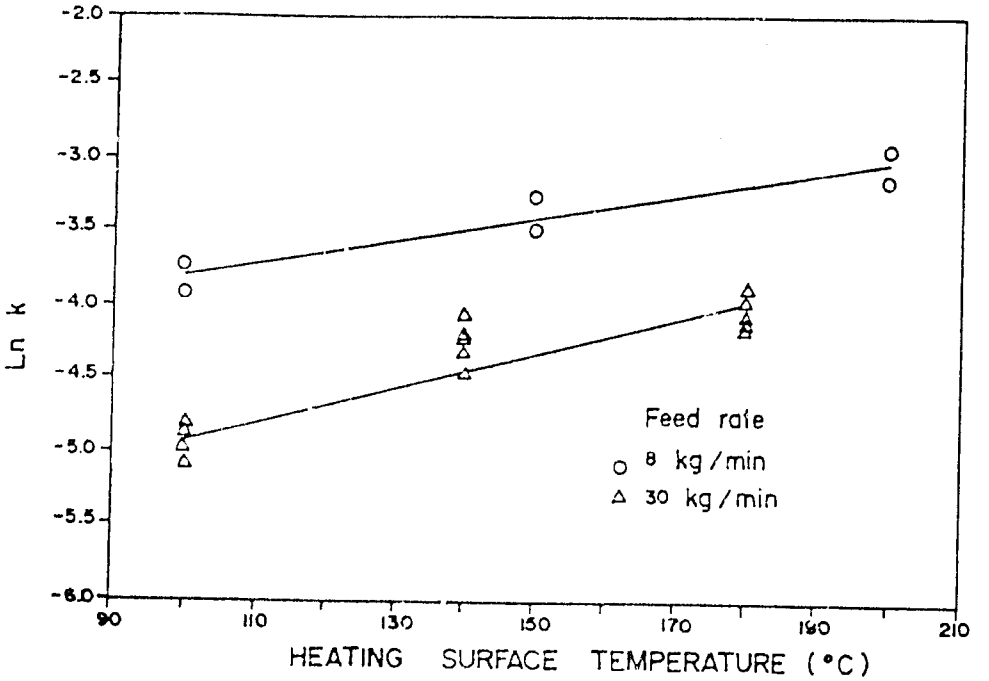


Fig. 4.40 Drying constant k as a function of heating surface temperature

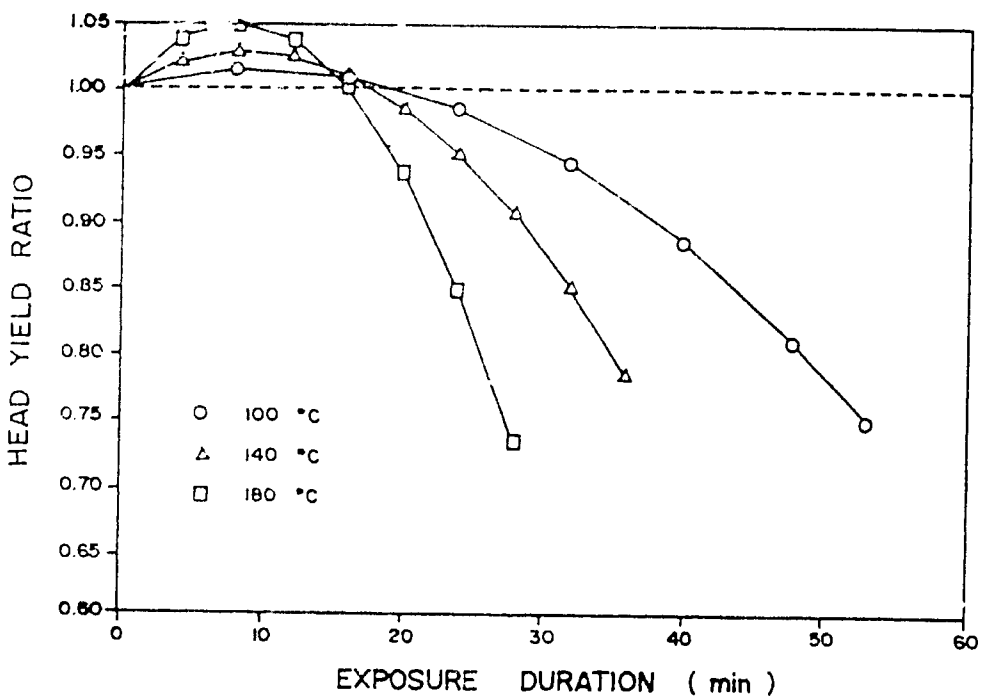


Fig. 4.41 A typical plot of head yield ratio vs. exposure duration for various heating surface temperatures (feed rate 30 kg/min, M_o 22% w.b.)

$$\ln A = 5.0957 - 1.6699\ M_o + 0.04920\ M_o^2 + 0.09411\ T_s - 0.003408\ (M_o * T_s) \quad ...(4.45)$$

(R^2 = 0.982 ; SEE = 0.17)

$$\ln B = 2.63769 - 1.7264\ M_o + 0.05020\ M_o^2 + 0.1215\ T_s - 0.00[illegible]\ (M_o * T_s) \quad ...(4.46)$$

(R^2 = 0.960 ; SEE = 0.320)

<u>Effect of Conduction Heating on Milled Rice Whiteness</u>. The reduction in whiteness was minimal in rough rice exposed to 100 °C heating surface temperature. The dependence of whiteness ratio (WR) on exposure duration for various heating surface temperatures was described by the following equation:

$$WR = \exp\ (-a_o\ t^{b_o}) \quad ...(4.47)$$

where WR = whiteness ratio
t = heating duration, min
a_o, b_o = regression coefficients

Eq. 4.47 was considered satisfactory since the coefficient of determination for all cases was about 0.85 or higher. The whiteness value of the milled rice from the unheated control sample was about 33 whiteness units.

The regression coefficients a and b were related with the experimental conditions by the following equations:

$$\ln a_o = -17.8829 + 0.5905\ M_o - 0.01187\ T_s \quad ...(4.48)$$

(R^2 = 0.80; SEE = 1.10)

$$b_o = 0.5747 - 0.1576\ M_o + 0.04856\ T_s - 0.0001266\ T_s^2 \quad ...(4.49)$$

(R^2 = 0.800; SEE = 0.310)

Eqs. 4.48 and 4.49 revealed the strong dependence of constants a and b upon the initial moisture content of rough rice and the heating surface temperature.

Interrelationship of Head Rice Yield, Milled Rice Whiteness and Drying Conditions. Figs. 4.42 to 4.44 show the head yield ratio of rough rice samples when heated to various final moisture contents in the proposed rotary dryer. It was obvious that high temperature conduction heating of high moisture rough rice for short durations resulted in better head rice yield and accelerated drying. The increase in head yield was possibly due to the parboiling effect which gelatinized the rice grain partially during high temperature conduction heating. One potential application of conducting heating thus could be in first-stage or partial drying of high moisture rice. This will not only reduce the drying time but also maximize the head rice yields. The maximum attainable head yield ratios were related with the initial moisture content of rough rice and heating surface temperature in the following form:

$$HYR_{max} = 2.1929 - 0.1236\ M_o + 0.003009\ M_o^2 + 0.0004544\ T_s \qquad ...(4.50)$$

$$(R^2 = 0.97;\ SEE = 0.011)$$

It was also possible to develop a relationship for estimating the final moisture content (FMC_{max}) of rough rice samples corresponding to the optimum head rice yield in the following form:

$$FMC_{max} = -31.3799 + 3.5528\ M_o - 0.04809\ M_o^2 + 0.1256\ T_s - 0.006952\ (T_s * M_o) \qquad ...(4.51)$$

$$(R^2 = 0.987;\ SEE = 0.380)$$

In this prototype unit, the heating times for maximum head rice yield appeared to be ranging from 8 to 10 and 16 to 18 min for rough rice having an initial moisture content of 22 and 26% w.b., respectively. The final moisture contents corresponding to these heating times were about 23, 21 and 18% for heating surface temperature of 100, 140 and 180 °C, respectively for rough rice having an initial moisture content of 26%. In rough rice having about 22% initial moisture content, the final moisture content for maximum head yield ranged from 19 to 20% w.b.. The reduction in whiteness ratio was about 5% or less for rough rice samples having initial moisture content of 22% and lower (Figs. 4.45 and 4.47). However, rough rice with moisture content of 26% when exposed to optimum heating times at 100, 140,

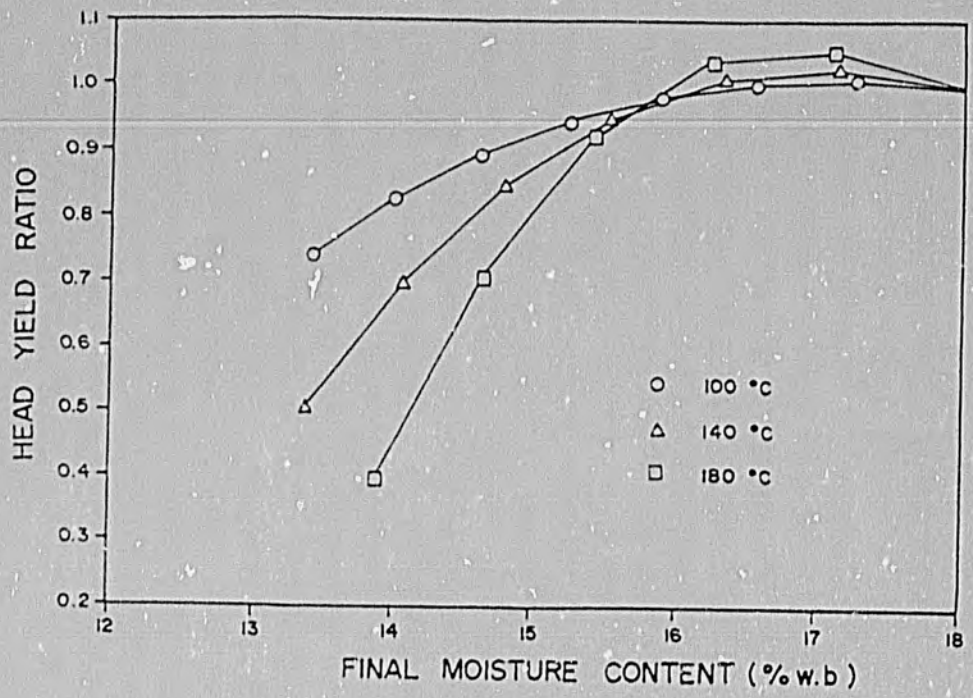


Fig. 4.42 Head yield ratio as a function of final moisture content of rice (feed rate 30 kg/min, M_o 18% w.b.)

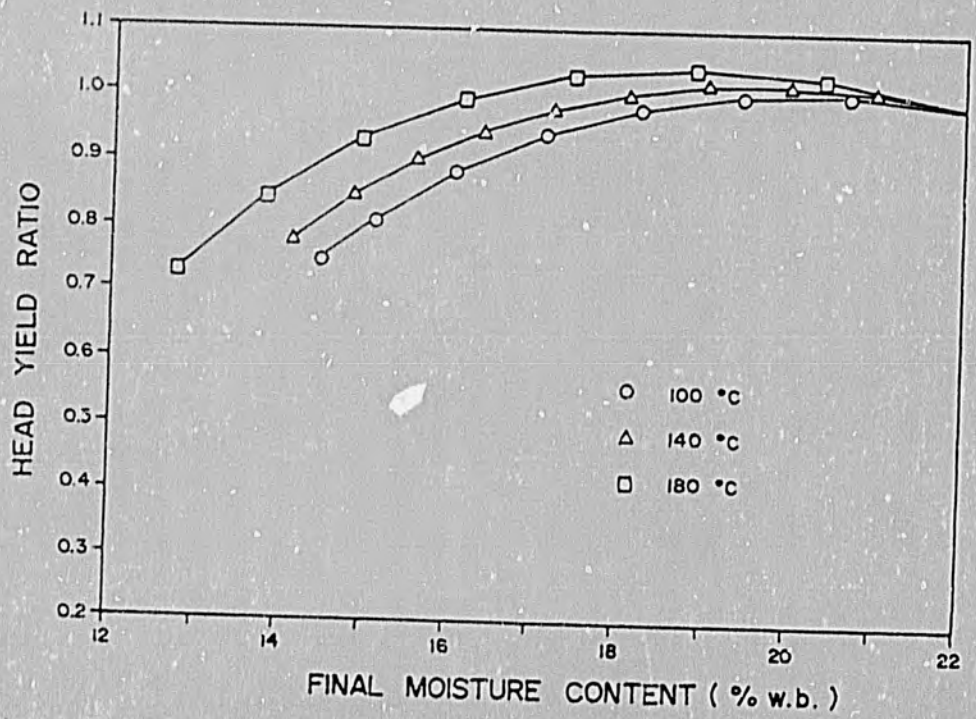


Fig. 4.43 Head yield ratio as a function of final moisture content of rice (feed rate 30 kg/min, M_o 22% w.b.)

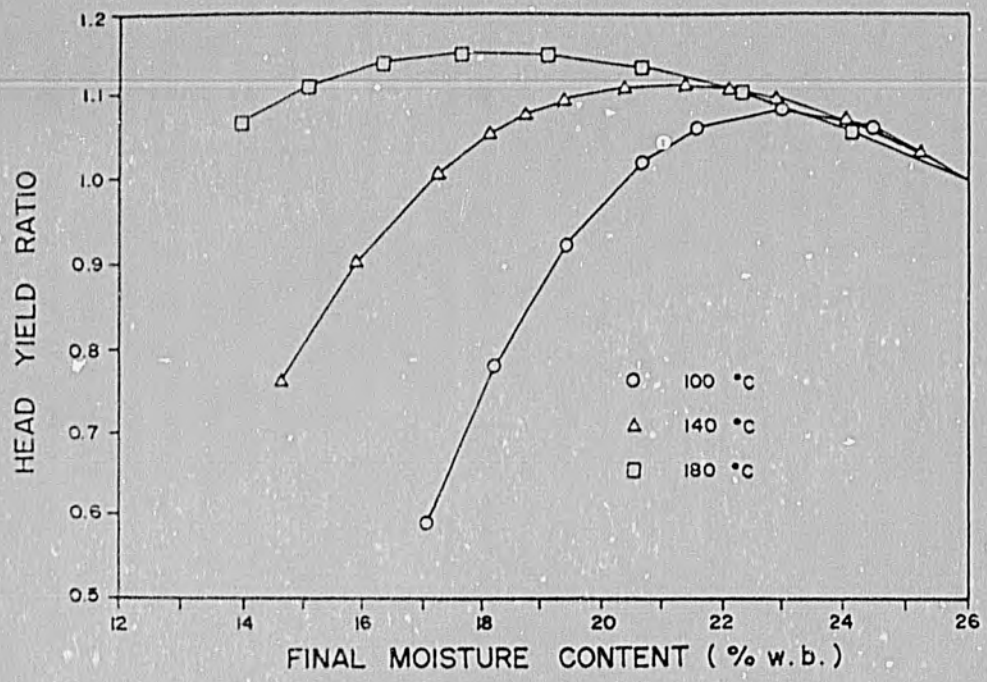


Fig. 4.44 Head yield ratio as a function of final moisture content of rice (feed rate 30 kg/min, M_o 26% w.b.)

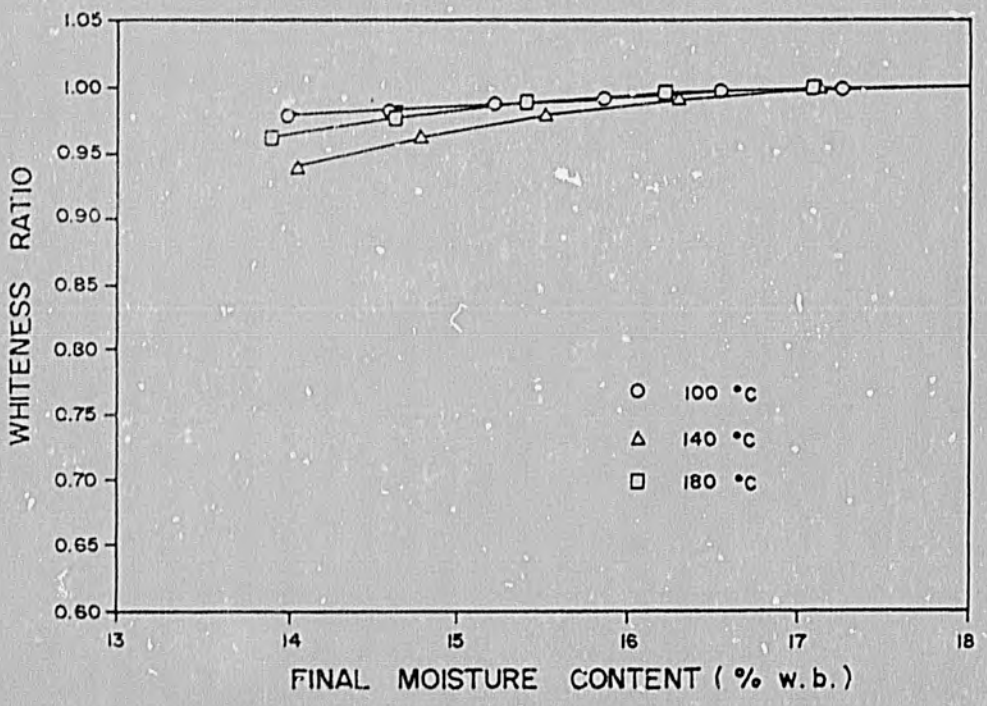


Fig. 4.45 Whiteness ratio as a function of final moisture content (feed rate 30 kg/min, M_o 18% w.b.)

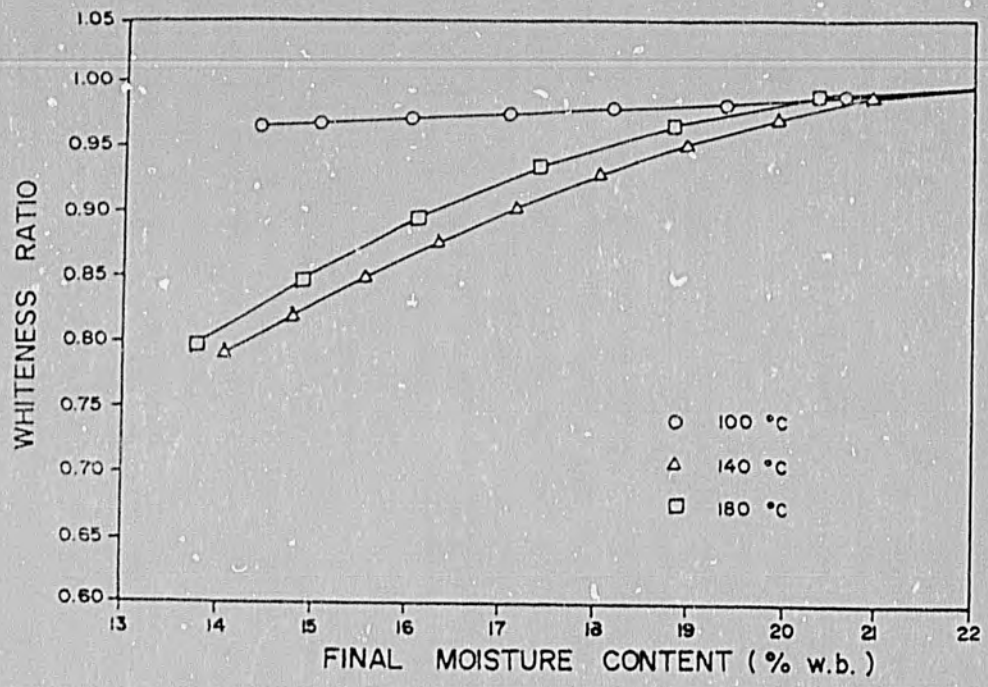


Fig. 4.46 Whiteness ratio as a function of final moisture content (feed rate 30 kg/min, M_o 22% w.b.)

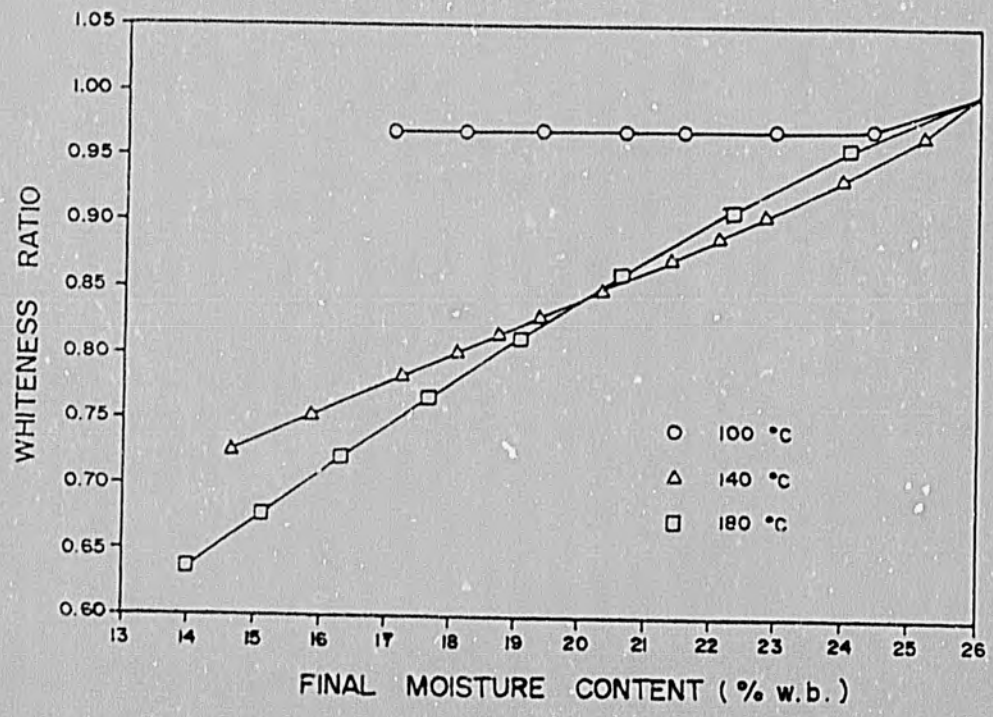


Fig. 4.47 Whiteness ratio as a function of final moisture content (feed rate 30 kg/min, M_o 26% w.b.)

and 180 °C surface temperature resulted in milled rice whiteness ratios of 0.97, 0.85 and 0.76, respectively (Fig. 4.47). Therefore, heating surface temperature below 180°C should be used for rough rice having initial moisture content above 22% in order to have milled rice whiteness comparable with the control sample. It seems that in high temperature conduction drying of high moisture rough rice, the limiting factor would be the whiteness of the milled rice aside from the head yield.

Drying with mechanical recirculation. Since manual recirculation of the grain might be cumbersome for the dryer operator, a mechanical recirculating system could be incorporated in the proposed dryer. The grain lifting device could be a screw conveyor or a bucket elevator which are readily available locally. Fig. 4.48 shows the final dryer's arrangement used in this study. Aside from the inclusion of a screw conveyor, a bin was also installed to serve as a tempering and storage bin. The bin could accomodate up to 0.5 ton of rough rice. Three final drying tests were conducted with this set-up using about 0.3 ton sample in each test. This allowed a tempering time of about 10 minutes between successive passes which is common in large scale drying operation. Rough rice samples in these tets were dried in two-stages. In the first-stage, samples having an inital moisture content of 24% were dried down to a final moisture content of 18% using 180 °C heating surface temperature. Prior to second stage drying, partially-dried samples were tempered for at least 2 hours in the bin. After tempering, samples were proceeded for final drying using a heating surface temperature of 100 °C. However, the first set of samples was dried only using the first stage operation.

The results of the final drying tests with mechanical recirculation are presented in Table 4.23. It was found that continuous drying (with 10 minutes tempering between successive passes) of high moisture rough rice down to 18% gave milled rice product that was comparable to the control unheated sample. On the other hand, rough rice samples dried down to 14-15% gave milled rice products with slightly lower head rice in comparison with the control sample. A reduction in head rice yield of about 2 - 3 % was observed in the final two sets of tests. This drawback could be offset by various advatages offered by the proposed rotary dryer. The milled rice samples from this set of experiments were comparable with those obtained from the control samples, indicating the absence of any parboiling effect.

1. Rice husk hopper
2. Furnace
3. Tempering bin
4. Electro-magnet
5. Dryer brick housing
6. Rotary cylinder
7. Electric motor
8. Chain drive
9. Paddy outlet guide
10. Helical baffles
11. Chimney
12. Screw conveyor

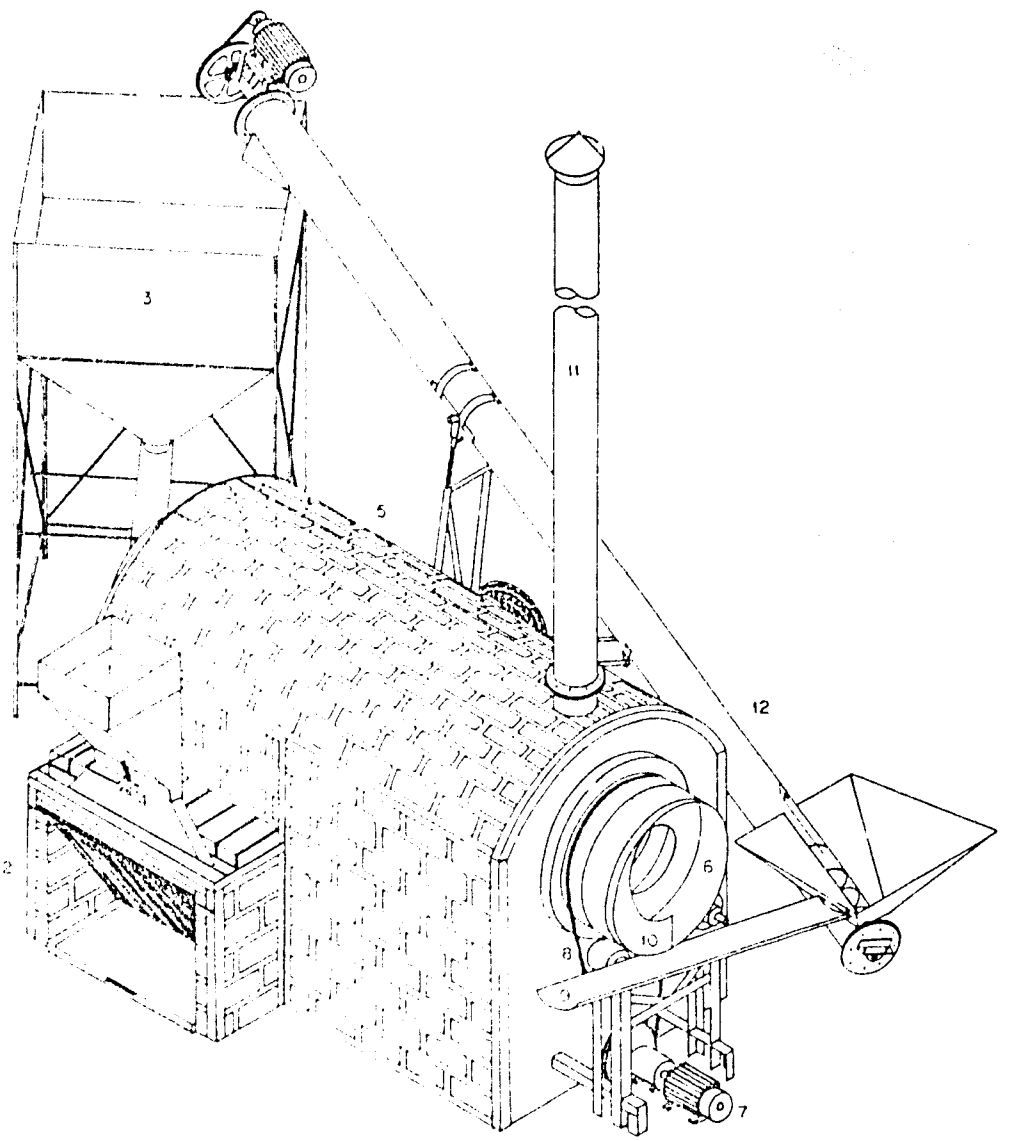


Fig. 4.48 Rice husk-fired rotary dryer with screw conveyor

Table 4.23 Results on two-stage drying of rough rice in rice husk-fired rotary dryer with mechanical recirculation

Drying operation	Initial moisture content (% w.b.)	Final moisture content (% w.b.)	Head rice yield (%)	Whiteness reading (meter units)
	24.0	Control	44.8	28.0
First-stage	24.0	17.0	43.9	27.3
	24.0	Control	45.3	29.6
First-stage	24.0	18.0	46.0	29.5
Second-stage	18.0	14.0	43.5	29.3
	21.0	Control	44.2	28.0
First-stage	21.0	18.0	42.5	29.0
Second-stage	18.0	15.0	41.4	29.0

4.6.3 Spouted-bed drying of rough rice

Mechanism of spouted-bed. Fig. 4.49 shows the variation of pressure drop with increasing superficial air velocity for rough rice at different depths. Three significant regions are indicated as quiscent bed, spouting bed and expanded bed with different mechanisms. Dashed curve illustrate the reverse process - the collapse of spouted bed on decreasing air velocity.

At low velocities (less than 2 m^3/min), the air simply passed through the bed without disturbing the particles and the pressure drop increased with an increase in the flow rate. This region is called quiescent bed region.

At higher air flow rates, a small internal cavity was formed and a noticeable adjustment of particles was evident by the lifting of the particles. This region which is characterized by a less packing arrangement and less resistance to fluid flow through the packing is called the expansion bed region. Futher increase in flow rate transformed the cavity into an internal spout. However, rough rice had no significant internal spout prior to spouting. Due to the unsteady state in the transition zone, it was difficult to observe the region between peak pressure drop and the onset of spouting. At the start of

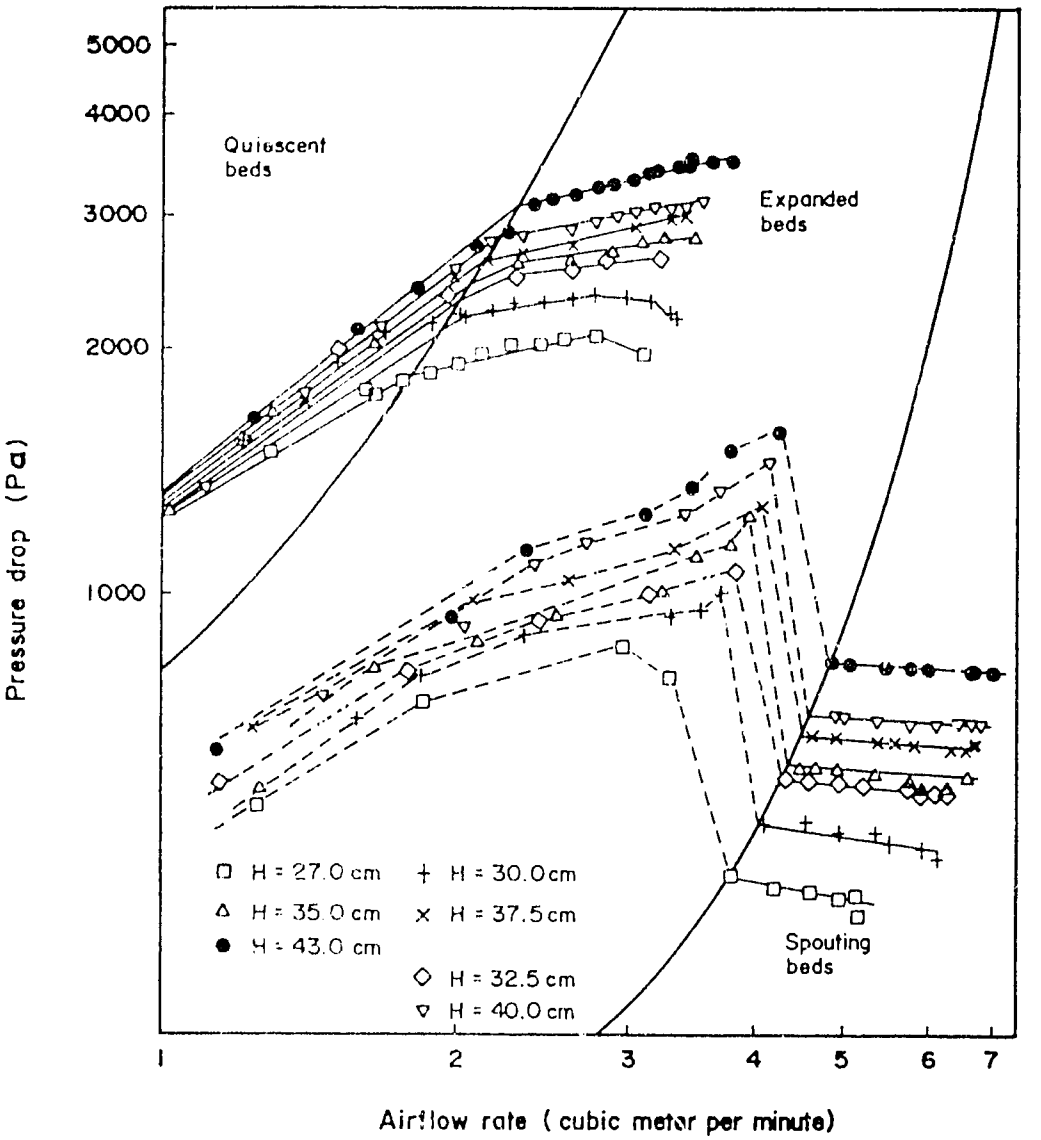


Fig. 4.49 Typical pressure drop- flow rate curve of rough rice in spouted-bed

intercirculatory motion of the particles, the internal spout broke through the bed surface with slight increase in flow rate. This could be the cause of the sharp reduction in pressure drop to a point where the entire bed became mobile and steady spouting set in signalling the onset of spouting. With further increase in air flow, the additional air simply passed through the spout region causing the fountain to shoot up higher without significant effect on total pressure drop. The spouting pressure drop remained constant in this region. In the reverse process, a slight reduction in air velocity (less than the minimum spouting velocity) could cause the collapse of the spout and the increase in pressure drop. In spouted bed, the minimum flowrate, peak pressure drop and spouting pressure drop are vital information.

Minimum spouting velocity. The minimum spouting velocity is the point at which the spout would collapse when reducing the airflow rate from a fully developed spout to a quiescent bed. In this study, the minimum spouting velocity (U_{ms}) was determined in terms of the minimum spouting flowrate (Q_s) which is the product of U_{ms} and the cross-sectional area of the column. Inlet orifice diameter and the bed depth were the main parameters affecting the minimum spouting flow rate. The minimum spouting flow rate gradually increased with an increase in the bed depth and inlet orifice diameter (Heng, 1987). The relationship between minimum spouting flowrate, orifice diameter and bed depth was found to be adequately represented by the following equation:

$$Q_s = 0.3985\ D_i^{1/3}\ H^{1/2} \qquad \ldots (4.52)$$

$$(R^2 = 0.964;\ SEE = 0.094)$$

where: Q_s = minimum spouting flowrate, m^3/min
D_i = orifice diameter, cm
H = bed depth, cm

Peak pressure drop. The high peak in pressure drop which occurs just before spouting sets in is not a unique feature of a spouted bed. It is generally associated with the entry of a high velocity gas jet into a bed of solids. The resulting equation for estimating peak pressure drop of rough rice was:

$$-P_H = 1.42\ H * \rho * g \qquad \ldots (4.53)$$

where $-P_H$ = peak pressure drop, Pa
H = bed depth, m
ρ = bulk density of rough rice, kg/m^3
g = acceleration due to gravity, m/s^2

Spouting pressure drop. The pressure drop remains substantially constant during spouting. The experimental tests of Heng (1987) showed that the spouting pressure drop gradually increased with increasing bed depth for a given inlet aperture. The following relationship appeared to represent the spouting pressure drop satisfactorily:

$$-P_s = a_0 + a_1 + (a_2/H) \qquad ...(4.54)$$

where $-P_s$ = spouting pressure drop, Pa
a_0, a_1, a_2 = regression coefficients

The regression coefficients of Eq. 4.54 are given in Table 4.24.

Table 4.24 Regression coefficients of Eq. 4.54 relating spouting pressure drop with bed depth

Orifice diameter (cm)	Regression coefficient a_0	a_1	a_2	R^2
5.00	-824.6	29.8	9334.3	0.994
5.80	-691.9	29.7	6905.0	0.994
6.40	-426.1	26.8	3784.2	0.976

Drying rough rice in spouted-bed. The changes in moisture content and head rice yield during spouted bed drying are illustrated by Figs. 4.50 and 4.51. Since the trends exhibited by rough rice were similar to those observed in the conduction heating experiments, these results were represented by Eqs. 4.9 and 4.22. The computed values of drying constant k are given in Table 4.25 and those of A and B in Table 4.26. These results indicated that high moisture rough rice could only be dried to certain limits without quality deterioration depending on the

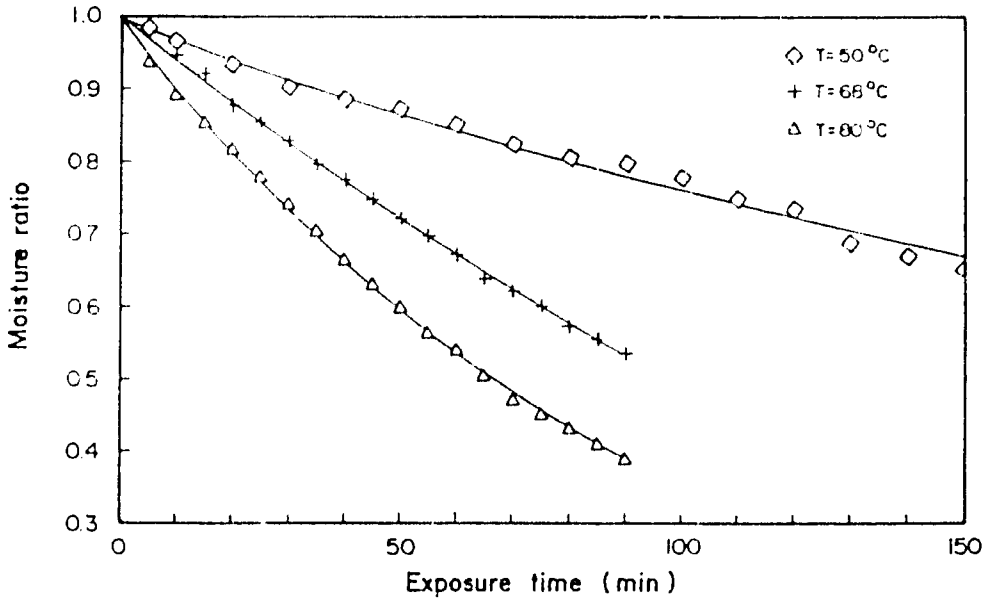


Fig. 4.50 Moisture ratio as a function of exposure time during continuous drying in spouted-bed

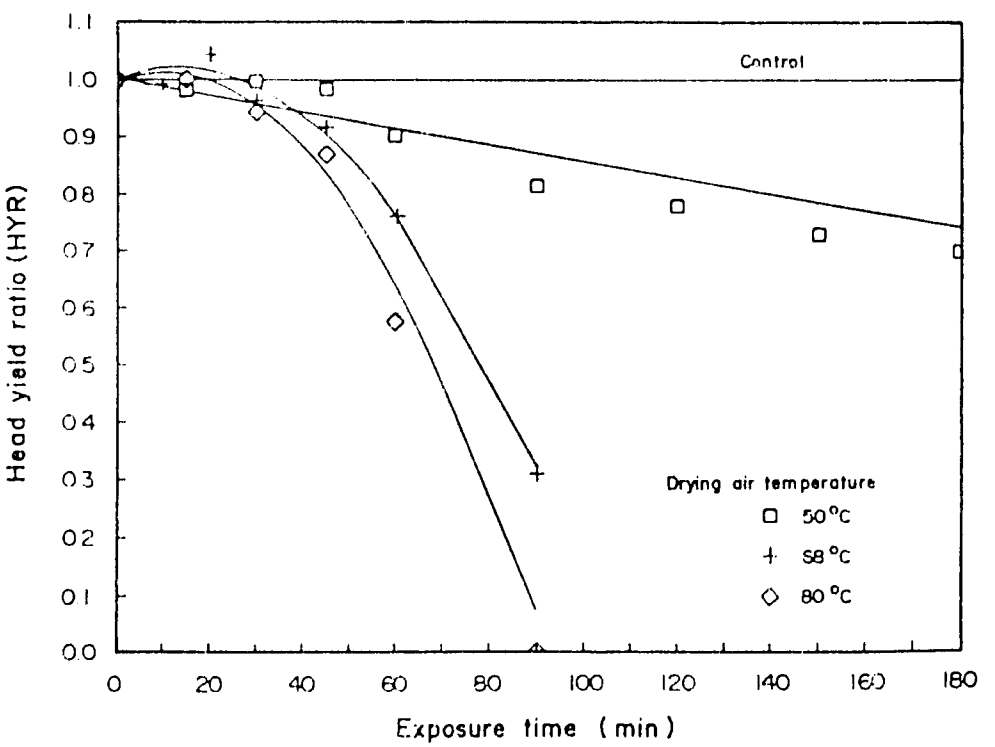


Fig. 4.51 Head yield ratio as a function of exposure time during continuous drying in spouted-bed

Table 4.25 Drying constant k in Eq. 4.9 fitted to rough rice drying in a spouted-bed

Drying air temp (°C)	Continous drying			Batch drying		
	k	R^2	SEE	k	R^2	SEE
50	0.00271	0.989	0.0142	0.00348	0.989	0.0475
68	0.00671	0.996	0.0122	0.00701	0.985	0.0254
80	0.01030	0.999	0.0109	0.01003	0.995	0.0242

Table 4.26 Regression coefficients of Eq. 4.22 relating head yield ratio and exposure time in spouted-drying of rough rice

Drying air temp (°C)	Regression constant		R^2	SEE
	A	B		
50	-0.00142	0.00000	0.940	0.0318
68	0.00329	0.00012	0.994	0.0218
80	0.00319	0.00015	0.994	0.0339

temperature of the heated air. Therefore the final moisture contents for exposure duration corresponding to 1.0 and 0.95 HYR were computed (Table 4.27). Milling quality evaluation indicated that rough rice with an initial moisture content of 26% could only be dried using the spouted bed dryer to a final moisture content of about 18 - 19% without significant reduction in head yield. The rice samples could be dried down to this level using an air temperature of 80 °C and exposure time of about 32 minutes.

Table 4.27. Exposure times and final moisture contents of rough rice in spouted-bed drying corresponding to selected values of head yield ratio

Air temp.	Head yield ratio 1.0		Head yield ratio 0.95	
(°C)	time (min)	FMC (% w.b.)	time (min)	FMC (% w.b.)
Control	-	26.0	-	26.0
50	-	-	35.2	23.4
68	13.7	24.0	38.3	20.4
80	10.6	23.1	31.8	18.6

4.7 Thermal Efficiency and Drying Costs

4.7.1 Thermal Efficiency

In order to evaluate the overall performance of the prototype dryers, thermal efficiencies were determined from actual drying tests.

In case of the electrically heated rotary dryer, the thermal efficiency was close to drying efficiency since heat losses and the energy required for running the motor were minimal because of its design. The thermal efficiency was calculated using the following relationship:

$$E_T = (W_w * h_{fg} / Q) * 100\% \qquad ...(4.55)$$

where E_T = thermal efficiency, %
W_w = water evaporated, kg
h_{fg} = latent heat of evaporation of water, kJ/kg
Q = total power consumption, kJ

The latent heat of water vaporization was taken to be 2456 kJ/kg as an average value. Table 4.28 presents the the experimental data used in the calculation of thermal efficiency.

Table 4.28 Performance data of the electrically-heated rotary dryer for thermal efficiency calculation

Feed rate (kg/min)	Hold up (kg)	Water removed (kg)	Energy used in evaporation (kJ)	Input* energy kW h	Input* energy kJ	Efficiency (%)	Energy required (MJ/kg)
			Drying from 26 to 18%				
20	44	4.30	10,561	6.73	24,222	43.6	5.63
30	57	5.56	13,655	8.39	30,210	45.2	5.43
40	68	6.63	16,283	10.35	37,261	43.7	5.61
50	84	8.20	20,139	12.66	45,563	44.2	5.55
			Drying from 26 to 14%				
20	44	6.14	15,078	12.34	44,441	34.0	7.2
30	57	7.93	19,477	13.27	47,785	40.7	6.0
40	68	9.49	23,302	17.70	63,713	36.6	6.7
50	84	11.72	28,785	22.14	73,702	36.1	6.8

* including energy consumed by the motor

It was assumed that rough rice having initial moisture of 26% w.b. was dried down to either 18% w.b. or a safe storage level of 14% w.b. In the first case, the dryer performed as a pre-dryer. As a pre-dryer, the average thermal efficiency was determined to be 44%, requiring about 5.56 MJ of heat energy for removing 1 kg of water from rough rice when drying from 26 to 18% w.b. On the other hand, the average thermal efficiency was about 37% when drying rice from 26 to 14% w.b.

Table 4.29 presents the thermal efficiency values computed from the performance test of the rice husk-fired rotary dryer. The thermal efficiency of the rice husk-fired rotary dryer was calculated to be about 18 % when drying rice from 26 to 18% w.b. and about 11% for drying from 26 to 14% w.b., respectively. The low values of thermal efficiency were mainly due to the heat losses common in rice husk-fired furnaces and partly due to incomplete combustion of rice husk itself. The low efficiencies of rice husk-fired dryers have also been reported in the range of 7 to 19% by Demegillo et al. (1985). Therefore the thermal efficiencies of the experimental rotary dryer should be considered satisfactory for general use. The experimental data also indicated that 1 kg of rice husk could dry 9 to 10 kg of rough rice from an initial moisture of 26% w.b. to about 18% w.b. If the rice moisture was to be lowered to 14% w.b., the required amount of rice husk would be doubled. The husk requirement for rice drying purposes can be easily met by the farmers since husk comprises about 25% of rough rice by weight.

Table 4.29 Performance data of the rice husk-fired rotary dryer for thermal efficiency calculation*

Initial moisture content (% w.b.)	Final moisture content (% w.b.)	Water removed (kg)	Energy used in evaporation (kJ)	Rice husk used		Efficiency (%)	Rice dried to husk ratio
				kg	kJ		
26	18	3.90	9578.4	4.3	52199.4	18.3	9.3
22	18	2.00	4912.0	3.8	46129.7	11.0	10.5
26	14	5.58	13707.9	9.3	112896.4	12.1	4.3
22	14	3.72	9138.6	6.8	82547.9	11.1	5.9

*Assumptions: a) Hold-up - 40 kg, feed rate 30 kg/min
c) Heat value of rice husk - 2,900 kcal/kg (12,139 kJ/kg)

4.7.2 Drying Costs

The following drying systems were considered for cost comparisons:

1) Electrically heated rotary dryer
2) Rice husk-fired rotary dryer with manual recirculation
3) Rice husk-fired rotary dryer with mechanical recirculation
4) Spouted-bed dryer

The costs of using the above heating/drying units for sterilization and drying high moisture rough rice were evaluated based on the experimental drying tests. Also the cost of using these equipment as first-stage dryer for drying rice down to 18% w.b. was evaluated. The heating surface temperature for heat sterilization and first stage drying was selected to be 170 - 180 °C. Final drying of rice to 14% w.b. could be carried out using 100 °C heating surface temperature to avoid any possible changes in milled rice quality. The assumptions used in the cost analysis and other details are given in Appendix A. The summary of cost estimates are given in Tables 4.30, 4.31 and 4.32 for heat sterilization, partial drying to 18% w.b., and complete drying to 14% w.b. moisture content, respectively.

From the results, it was obvious that high moisture rough rice could be sterilized for holding it temporarily or dried most economically using the rice husk-fired dryer with mechanical recirculation (Tables 4.30 to 4.32). The electrically heated rotary dryer operation showed considerable drying costs primarily due to the high cost of electricity, which amouted to 52% of the drying cost. The use of a rice husk-fired furnace eliminated this major component of the operating costs. However, additional man-power was needed to regulate the burning of rice husk in order to maintain the smooth operation of the furnace. Switching from electrically heated dryer to a rice husk-fired dryer resulted in a 30% savings in the drying cost. The installation of a conveyor for recirculating the grain entailed additional capital investment, but the labor cost was reduced to one-half. This arrangement helped reduce the drying cost by 50% in comparison with the use of an electrically-heated rotary dryer. The cost for drying rice from 26 to 14% w.b. using the rice husk-fired dryer with mechanical recirculation was only about US$ 14.0/t. The cost of spouted-bed heating and/or drying was very much higher when compared with the use of the proposed conduction-type rotary dryers. The cost of energy consumption in spouted-bed was about 45% of the total drying cost. In addition, the spouted-bed could be used only as a first-stage dryer or sterilizer because of a marked reduction in head rice yields with the lowering of moisture close to 14%.

In 1982, the Philippines' National Food Authority (NFA) reported on the costs of heated-air drying when using various mechanical dryers (Table 4.33). The results showed the drying cost of a kerosene-fed and rice husk-fed flat bed dryer to be US$ 18.94/t and US$ 20.28/t (US$ 1.00 = PHP 10.00), respectively. This was slightly less than the drying cost for a batch-type Kongskilde dryer (US$ 21.16/t). On the other hand, continuous flow dryers like Satake, Woodland, and Cimbria had an estimated drying cost of US$ 16.5/t, US$ 31.0/t, and US$ 53/t, respectively. It is difficult to project the drying costs under present conditions due to substantial currency fluctuations. However, it can be concluded that the drying costs of the proposed rotary dryers will be highly competetive with the existing drying systems.

Table 4.30 Cost of heat sterilization of rough rice having initial moisture content of about 26 % w.b.

Drying system	Cost (US$/t)
1) Electrically heated rotary dryer	3.0
2) Rice husk-fired rotary dryer with manual recirculation	1.9
3) Rice husk-fired rotary dryer with mechanical recirculation	1.4
4) Spouted-bed dryer	17.3

Table 4.31 Costs of drying rough rice of different initail moisture contents down to a final moisture of about 18% w.b.

Drying system	Cost (US$/t)		
	Initial moisture content (% w.b.)		
	26	24	22
1) Electrically heated rotary dryer	11.2	8.8	6.1
2) Rice husk-fired rotary dryer with manual recirculation	7.3	6.0	4.3
3) Rice husk fired rotary dryer with mechanical recirculation	5.3	4.2	3.1
4) Spouted-bed dryer	64.0	50.4	35.1

Table 4.32 Costs of drying rough rice of different initial moisture contents down to a final moisture of about 14% w.b.

Drying system	Cost (US$/t)		
	Initial moisture content (% w.b.)		
	26	24	22
1) Electrically heated rotary dryer	29.2	25.4	21.3
2) Rice husk-fired rotary dryer with manual recirculation	18.9	18.0	17.3
3) Rice husk-fired rotary dryer with mechanical recirculation	14.0	13.5	12.3
4) Spouted bed dryer	(technically not feasible at present)		

Table 4.33 Rough rice drying costs (NFA, 1982)

Dryer type	Make	Heating	Drying cost (US$ / t*)
Flat-bed batch	-	Rice-husk	20.28
	-	Kerosene	18.94
Batch	Kongskilde		21.16
Continuous flow	Satake		16.52
	Woodland		31.00
	Cimbria		52.70

* (1982: US$ 1.0 = PHP 10.0)

SUMMARY AND CONCLUSIONS

This study showed that high-temperature short-time conduction heating of freshly harvested high moisture rough rice could effectively inactivate the fungi and extend the safe temporary storage prior to final drying.

The prototype rice husk-fired rotary heating unit developed specifically for heat sterilization of rough rice showed good mechanical and thermal performance. Such rotary heaters could prove to be a low cost and practical option for sterilizing and accelerated drying of high moisture rice.

Thermal inactivation of fungi in freshly harvested rough rice (RD-23 variety) with an initial moisture content of approximately 26% w.b. was evaluated using a batch-type experimental heating unit using surface temperatures ranging from 75 to 200 °C and exposure times up to 100 minutes. The heat-treated rough rice samples exhibited reduced fungal population as measured by the dilution plating and carbon dioxide production. The reduction in fungal activity depended directly upon the heating surface temperature and exposure time. Subsequently, fungal mortality was expressed in terms of the bulk grain temperature and equivalent exposure times for general application. A procedure was developed for estimating the heating times required for reducing the fungal activity to a desired level based on the time-temperature history of grain in a given system.

Heat treatments resulted in rapid moisture removal, an improvement in head rice yield and cooked rice texture, and a reduction in milled rice whiteness depending upon the heating surface temperature, exposure time, and initial moisture of rough rice. It was possible to establish optimum time-temperature combinations for obtaining maximum head yields with rough rice samples at different initial moisture contents. A slight decrease in the whiteness of milled rice was offset by improved head yields and cooked rice texture. These results were generalized subsequently in terms of bulk grain temperature and equivalent exposure times for application to other heating systems.

Heat-treated rough rice samples showed an increase in their safe holding periods based upon an acceptable level of reduction in head rice yield and an increase in the proportion of discolored kernels. A relationship was developed for estimating the safe storage period of high moisture rice in terms of reduction in fungal activity and the moisture content after heat treatment. The proposed procedure was validated by comparing the computed and experimental values of safe storage periods of rice samples using a prototype rice husk-fired rotary heating unit.

Finally, the performance aspects of the proposed prototype heating units were compared with a spouted-bed heating for general application. A comparison of rough rice drying costs when using the proposed rotary conduction heating systems and conven-

tional heated-air drying systems clearly showed the rice husk-fired rotary dryer to be highly competitive.

The following conclusions were drawn based on the results of this study:

1. Heat treatments reduced the fungal growth and hence the spoilage in freshly harvested high moisture rough rice leading to its safe temporary storage. The fungal mortality levels close to 90% or slightly higher were found to be satisfactory for general use.

2. It was possible to generalize the time-temperature requirements for arresting the fungal growth in rough rice in terms of the kinetic parameters analogous to those commonly used in thermal processing calculations based on the time-temprature history of bulk grain. Such procedure accounted for the heating and cooling lags usually encountered during the actual heating process in a given equipment. For 90% fungal mortality level, the equivalent exposure times (F-values) were determined to be 22, 43 and 84 minutes for bulk grain temperatures of 70, 60 and 50 °C, respectively.

3. The measurement of carbon dioxide which was produced predominatly due to the respiration of fungi provided a simple alternative for monitoring the fungal growth in rough rice in comparison with the dilution plating method.

4. A simple logarithmic relationship adequately described the accelerated drying of high moisture rough rice in the range of 18 to 30% w.b. during conduction heating. The drying constant in the logarithmic model depended upon the heating surface temperature.

5. A generalized procedure developed in this study can be used for estimating the moisture removal from rough rice during high temperature conduction heating in terms of the mean bulk grain temperature determined from the time-temperature history of grain in a given heating equipment.

6. The thermal effects of conduction heat treatments on head rice yield of high moisture rough rice were expressed in terms of the kinetic parameters (F_c- and z_c- values). The equivalent exposure times (F_c-values) for obtaining 0.95, 1.0 and optimum values of head yield ratio were established for general application.

7. The head rice yield of high moisture rough rice increased during conduction heating first and then decreased with prolonged heating time. High moisture rough rice with moisture content in the range of 22 to 26% w.b. should be dried in a two-stage operation with tempering of grain using heating surface temperature of 100 to 200 °C for gaining maximum benefits from high temperature conduction heating since heat treatments corresponding to mortality level of about 95% lead to a maximum

increase in head yield ranging from 14 to 25% and to a final moisture content of about 13 to 19% w.b.

8. The whiteness of the milled rice obtained from the heat-treated rough rice appeared to be the most limiting factor in its acceptability. However, the changes in milled rice whiteness could be within acceptable limits if the the heating conditions were controlled.

9. Milled rice obtained from heat-treated rough rice showed a definite improvement in its cooking quality in comparison with fresh rice. There was a desirable characteristic increase in the firmness of cooked-rice kernels and a decrease in their stickiness resembling the artificial aging process.

10. Heat treatment of rough rice having initial moisture contents in the range of 22 to 26% w.b. using exposure times corresponding to 90% and higher fungal mortality levels resulted in increased safe holding periods of about 10 to 23 days.

11. The limiting factor affecting the safe holding period of high moisture rice and thus its market grade was the percentage of discolored kernels. It was possible to estimate the safe storage period from the fungal load ratio and final moisture content of rice after the heat treatment.

12. Selected experiments carried out with a full-scale prototype rotary heater validated the applicability of proposed heat treatment procedure and the use of developed relationships for estimating the safe storage periods of high moisture rough rice.

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APPENDIX A

Drying Cost Calculations

APPENDIX A

Table A.1 Assumptions in drying cost calculation

A. Total Investment Cost (TIC) - Cost of dryer and accessories

B. Fixed Costs

1) Depreciation	- Straight line method (10% salvage value, 7 years life span)
2) Repair and maintenance	- 5 % TIC
3) Insurance	- 1.5% TIC
4) Local taxes & licences	- 2% TIC
5) Interest	- 15% per annum

C. Variable Costs

1) Casual labor	- US$ 2.75 / 8 man-h
2) Electricity	- US$ 0.068 / kW-h

D. Other Assumptions

1) Operating hours	- 1440 h per year (2 months harvesting period, 2 harvesting periods per year 12 hours per day operation)
2) Exchange rate	- US$ 1.0 - B 25.5

Table A.2 Cost of the electrically-heated rotary dryer

Drying cylinder	----------		B 8,000
Material cost	--- 6,400		
Labor	--- 1,600		
Dryer heating system			
Material cost	----------		B 13,355
Copper wire, 3.6 mm dia	---------	130	
Porcelain insulation	---------	500	
Square terminal	---------	900	
Electrical heaters	---------	3,200	
Temperature controller	---------	3,700	
Thermocouple	---------	100	
Vibrator	---------	100	
Cable, 10 mm dia	---------	500	
Push buttons	---------	150	
Magnetic starter	---------	1,660	
Overload (45 to 67 A)	---------	765	
Circuit breaker (100 A)	---------	1,650	
Insulation	----------		B 5,000
Asbestos board	---------	3,000	
Microfiber	---------	2,000	
Electric motor	----------		1,700
	Total		B 28,055
			US$ 1,100

Table A.3 Cost of the rice husk-fired rotary dryer with manual recirculation

Drying cylinder	B 6,500
Motor (1 hp)	1,700
Brick housing/insulation	1,500
Ball bearing (4 pcs)	900
Electro-magnet (2 pcs)	800
Sprockets	60
Mild steel	570
Steel rod	2,000
Construction cost	1,200
Total investment cost (TIC)	B 15,230
	US$ 615

Total investment cost (TIC) with mechanical recirculation

= TIC dryer w/ manual recirculation + cost of conveyor etc.

= US$ 615 + 392

= US$ 1,007

Table A.4 Cost of the spouted bed dryer

Blower (3.7 kW / 5 hp; 13 m^3/min; 3600 rpm)	B 30,000
Heater box	300
Spouted bed column	500
Insulation wood	200
Pipings	400
Gate valve	200
Heaters	1,000
Total investment cost (TIC)	B 32,600
	US$ 1,278

Table A.5 Drying cost using the electrically heated rotary dryer

A. Total investment cost	-	US$ 1,100
B. Fixed cost		
1) Depreciation	-	US$ 141
2) Repair & maintenance	-	55
3) Insurance	-	17
4) Local taxes & licences	-	22
5) Interest	-	165
C. Variable cost		
1) Labor (1 casual labor)	-	495
2) Electricity	-	1,046
Total annual cost (TAC)	-	1,941
D. Drying cost per ton of rough rice		
1) Drying from 26 to 14% w.b.	-	29.2
2) Drying from 26 to 18% w.b.	-	US$ 11.2
3) Heat sterilization (90 % FML)	-	3.0

Table A.6 Drying cost using the rice husk-fired rotary dryer with manual recirculation

A. Total investment cost	-	US$ 615
A. Fixed cost		
1) Depreciation	-	US$ 79
2) Repair & maintenance	-	31
3) Insurance	-	9
4) Local taxes & licences	-	12
5) Interest	-	92
B. Variable cost		
1) Labor (2 casual labor)	-	990
2) Electricity (motor: 0.2 kW-h/h	-	20
3) Rice husk ($0.039/30kg)	-	23
C. Total annual cost (TAC)	-	1,256
D. Capacity		
1) Drying from 26 to 14% w.b. (1st stage, 26 to 18% - 180 °C; 2nd stage, 18 to 14% - 100 °C)	-	66.5/yr
2) Drying from 26 to 18% w.b. (180 °C heating surface temp.)	-	173 t/yr
3) Heat sterilization (90% FML, 180 °C)	-	648 t/yr
E. Drying cost per ton of rough rice		
1) Drying from 26 to 14% w.b.	-	18.9
2) Drying from 26 to 18% w.b.	-	US$ 7.3
3) Heat sterilization	-	1.9

Table A.7 Drying cost using the rice husk-fired rotary dryer with mechanical recirculation

A. Total investment cost	-	US$ 1,007
A. Fixed cost		
1) Depreciation	-	US$ 129
2) Repair & maintenance	-	50
3) Insurance	-	15
4) Local taxes & licences	-	20
5) Interest	-	151
B. Variable cost		
1) Labor (1 casual labor)	-	495
2) Electricity (2 motors: 0.2 kW-h/h	-	40
3) Rice husk ($0.039/30kg)	-	23
C. Total annual cost (TAC)	-	923
D. Capacity		
1) Drying from 26 to 14% w.b. (1st stage, 26 to 18% - 180 °C; 2nd stage, 18 to 14% - 100 °C)	-	66.5/yr
2) Drying from 26 to 18% w.b. (180 °C heating surface temp.)	-	173 t/yr
3) Heat sterilization (90% FML, 180 °C)	-	648 t/yr
E. Drying cost per ton of rough rice		
1) Drying from 26 to 14% w.b.	-	13.9
2) Drying from 26 to 18% w.b.	-	US$ 5.3
3) Heat sterilization	-	1.4

Table A.8 Drying cost using the spouted bed dryer

A. Total investment cost	-	US$ 1,278
A. Fixed cost		
1) Depreciation	-	US$ 164
2) Repair & maintenance	-	64
3) Insurance	-	19
4) Local taxes & licences	-	26
5) Interest	-	192
B. Variable cost		
1) Labor (1 casual labor)	-	495
2) Electricity	-	840
C. Total annual cost (TAC)	-	1800
D. Capacity		
1) Drying from 26 to 14% w.b.	-	not possible without significant reduction in head rice yield
2) Drying from 26 to 18% w.b. (180 °C heating surface temp.)	-	28 t/yr
3) Heat sterilization (90% FML, 180 °C)	-	104 t/yr
E. Drying cost per ton of rough rice		
1) Drying from 26 to 14% w.b.	-	not possible without significant reduction in head rice yield
2) Drying from 26 to 18% w.b.	-	US$ 64.0
3) Heat sterilization	-	US$ 17.3

APPENDIX B

Detailed Drawings of the Rice Husk-Fired Rotary Dryer

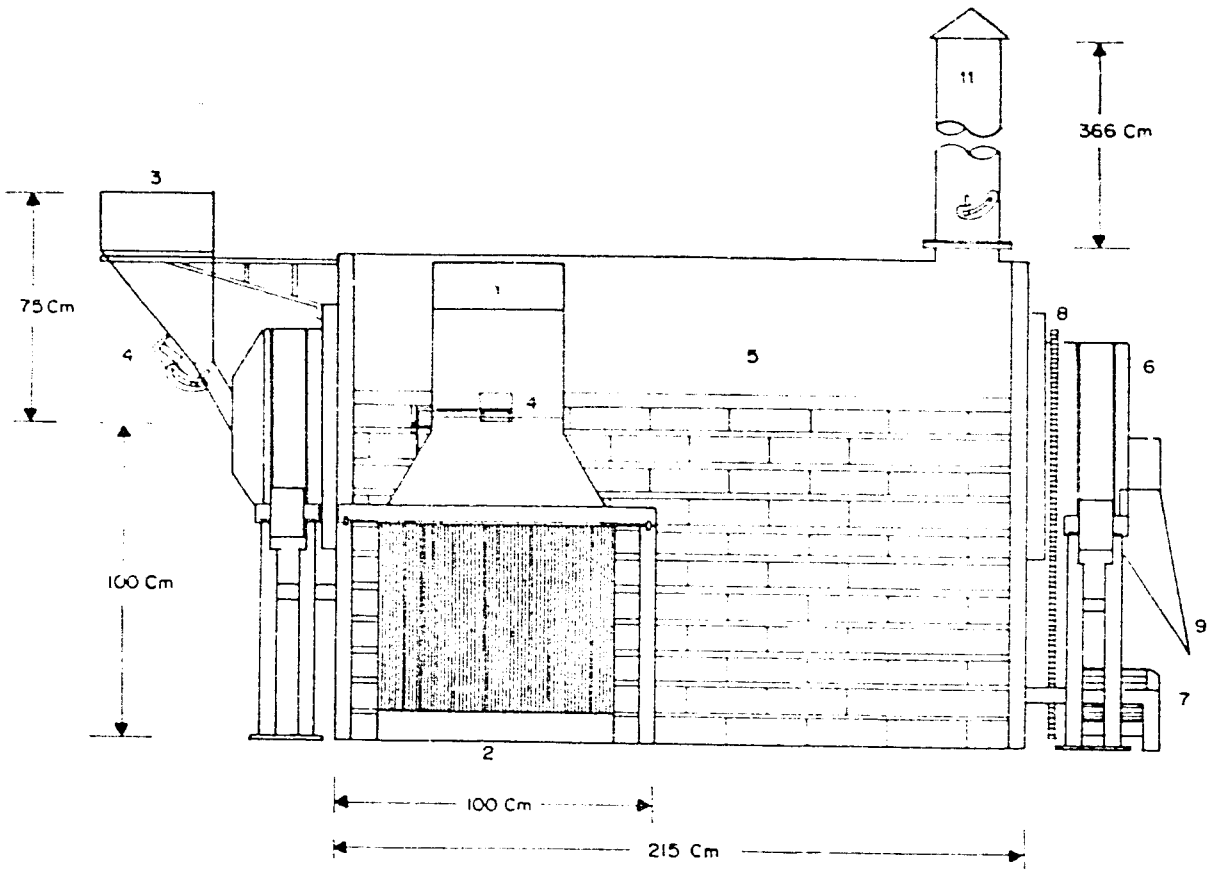

Fig. B.1 Rice husk fired rotary dryer (Side view)

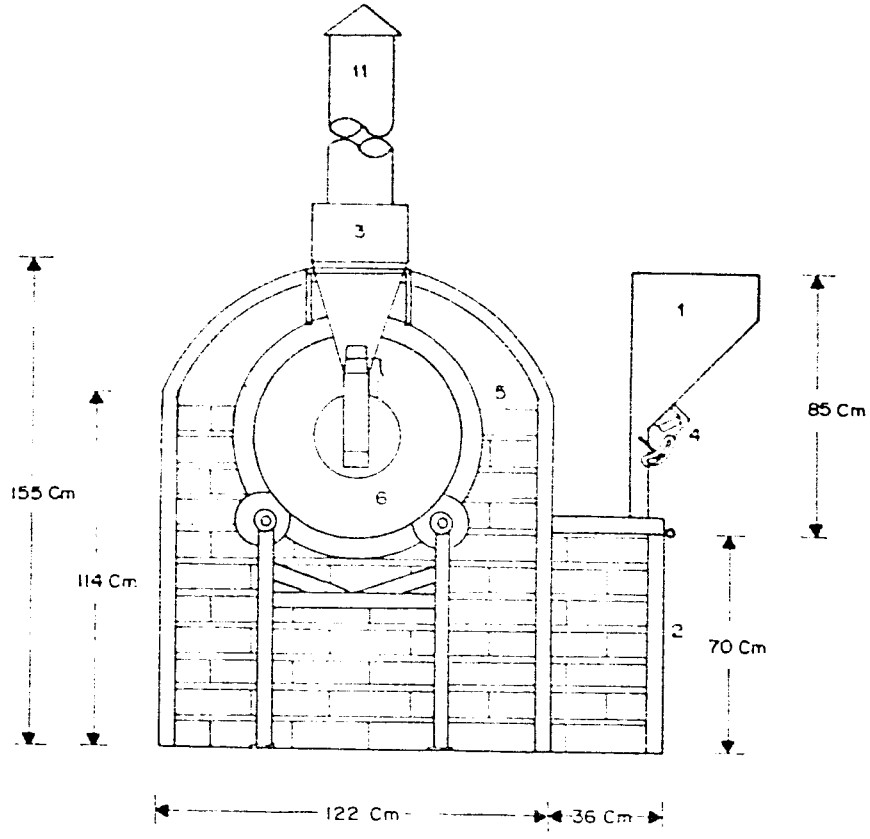

Fig. B.2 Rice husk fired rotary dryer (Rear view)

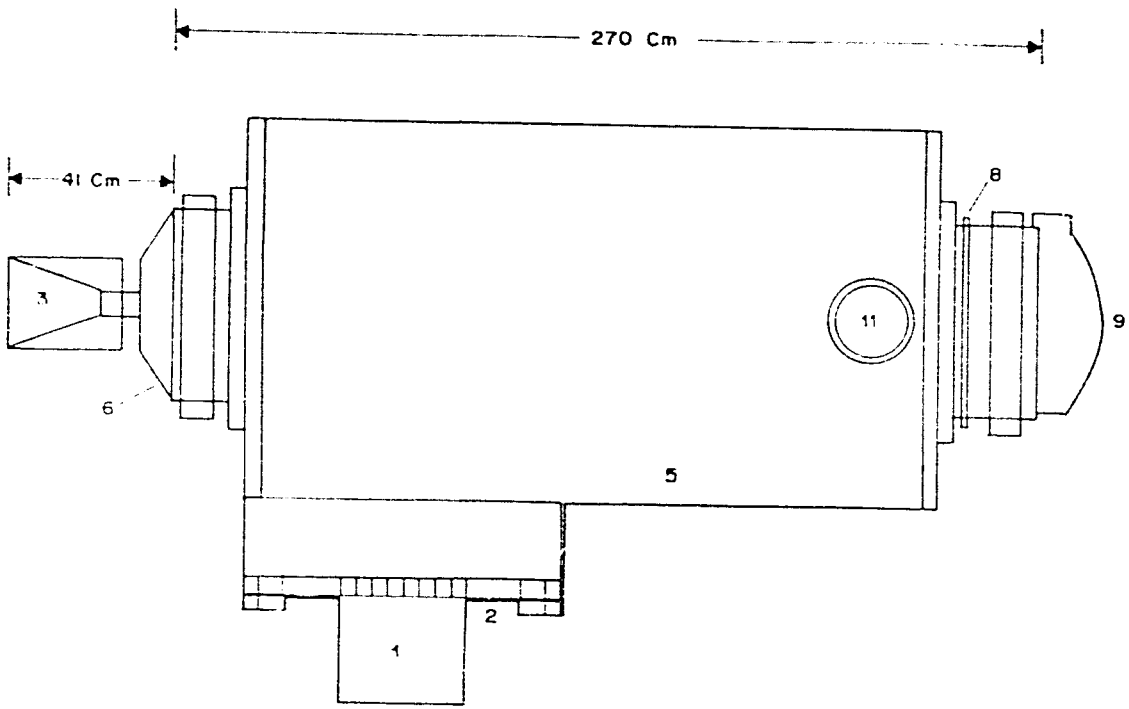

Fig. B.3 Rice husk fired rotary dryer (Top view)

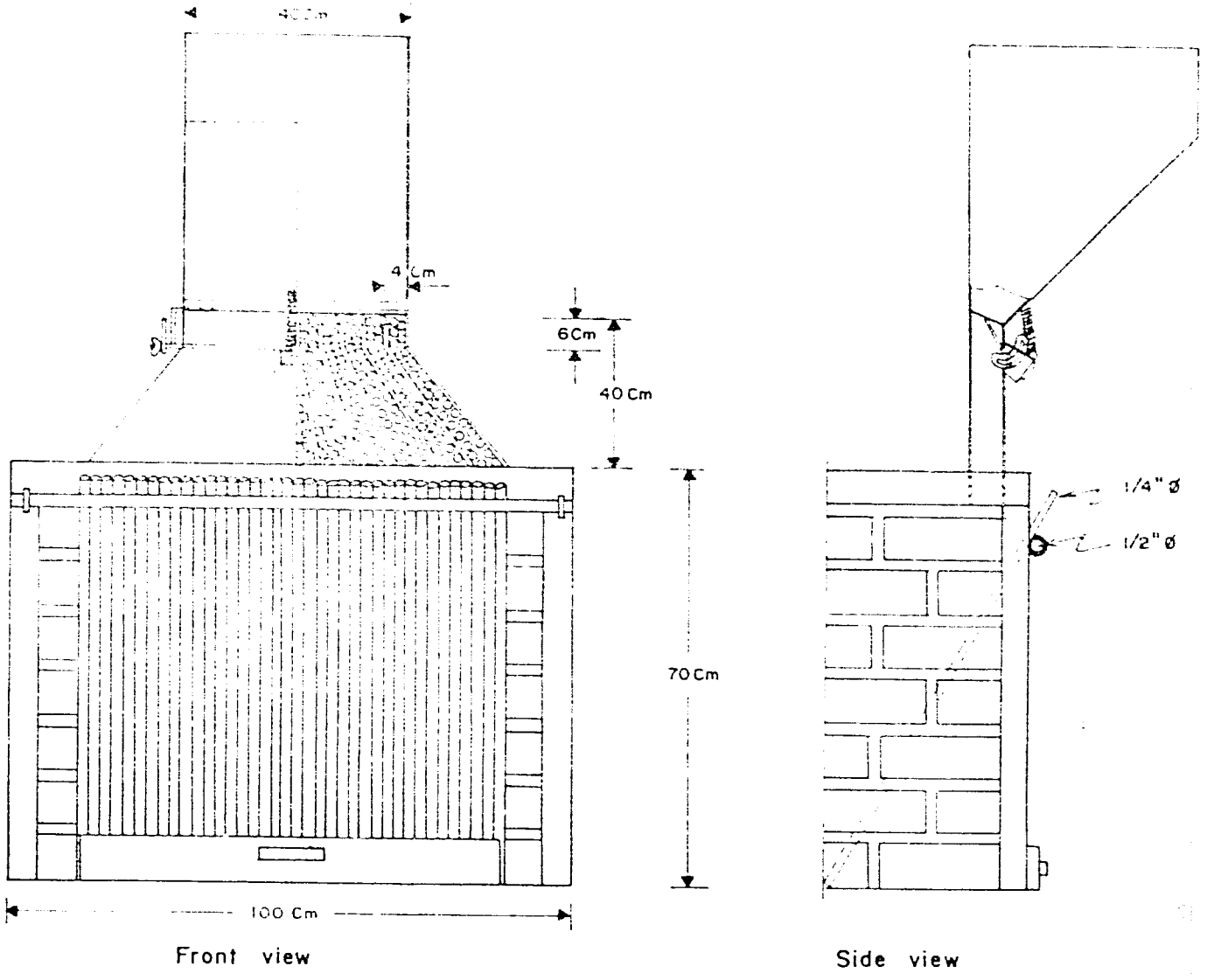

Fig. 8 : Rice husk furnace

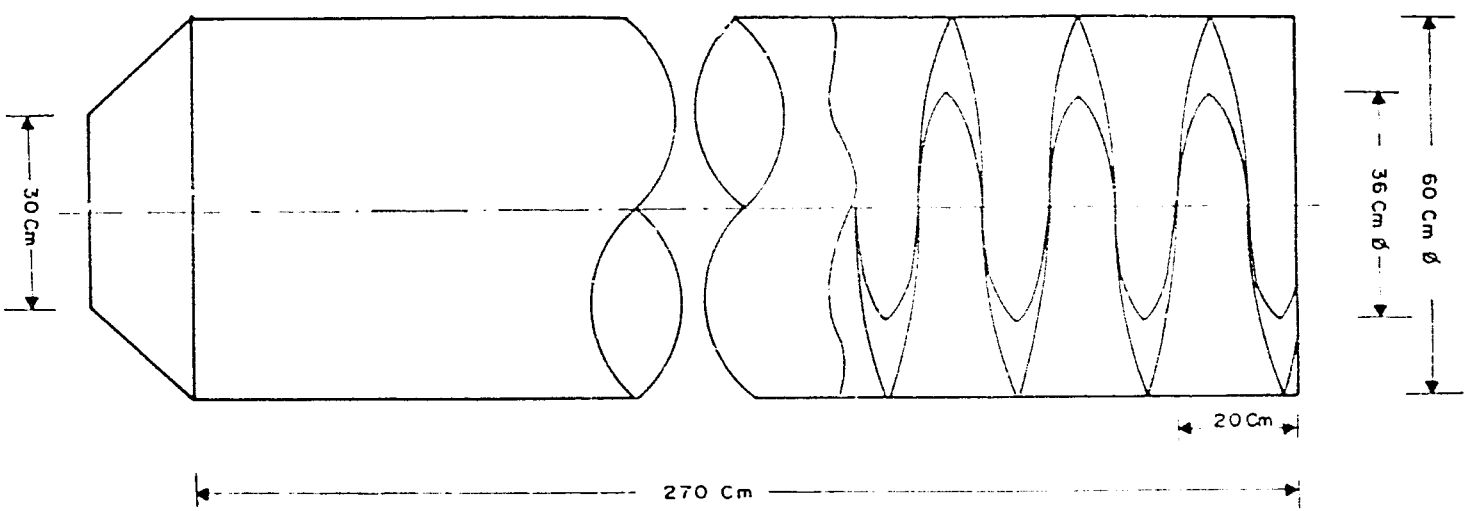

Fig. B.5 Details of the rotary cylinder

APPENDIX C

Presented and Published Papers

1. JINDAL, V.K. and L.G. OBALDO. 1985. Quality effects of heat treatments on high moisture rice. Paper No. 85-3010, American Society of Agricultural Engineers, St. Joseph, MI.

2. JINDAL, V.K. and L.G. OBALDO. 1986. Rice husk-fired rotary dryer for disinfestation and rapid drying. Paper No. 86202 presented at the 9th Annual ASEAN Regional Seminar on Food and Feed Grains Post Harvest Technology, 26-29 August, Singapore.

3. JINDAL, V.K. and V.G. REYES, JR. 1987. Conduction heating of rough rice for accelerated drying. Paper No. 87-6043, American Society of Agricultural Engineers, St. Joseph, MI.

4. JINDAL, V.K. and V.G. REYES, JR. 1987. Heat sterilization and accelerated drying of high moisture rice for safe storage. Proceedings of the USAID Science Research Award Grantees Conference (24-26 July, Nakhon Pathom), USAID, Bangkok, pp. 59-64.

5. REYES, JR. V.G. and V.K. JINDAL. 1987. Heat sterilization of high moisture paddy for safe temporary storage. Paper presented at the 10th ASEAN Regional Seminar on Grains Post-Harvest Technology, 19-21 August, Bangkok.

6. JINDAL, V.K. and B.T. MOLANO. 1987. Design and development of an axial flow rotary dryer for paddy. Paper presented at the Consultative Workshop on Grain Drying and Rice Milling in ASEAN, 24-27 November, Bangkok.

7. REYES, JR. V.G. and V.K. JINDAL. 1988. Effects of heat treatments on the head yields of high moisture rough rice. J. Food Science 53 (2): 482-487.

8. REYES, JR. V.G. and V.K. JINDAL. 1988. Conduction heating of high moisture rice I. Thermal inactivation of fungi. J. Food Process Engineering (in press).

9. REYES, JR. V.G. and V.K. JINDAL. 1988. Conduction heating of high moisture rice II. Safe temporary storage. J. Food Process Engineering (in press).

10. REYES, JR. V.G. and V.K. JINDAL. 1988. Conduction heating of high moisture rice III. Changes in milling and cooking qualities. J. Food Process Engineering (in press).