

CHAPTER II

REVIEW OF LITERATURE



2.1 Parboiling Technology

One of the latest well-developed premilling treatments given to paddy to improve its milling, nutritional, cooking, and keeping qualities is parboiling process technology. The rice obtained from parboiling treatment is called "parboiled-rice". Parboiling is a process of antique origin. It originated in the Far East [1], principally India, and in some regions of Equatorial Africa, from where it has spread more recently to other continents [1].

The simplest method, used in ancient times, consisted of merely soaking the rice in water and drying it in the sun. In the classic system, however, there are three different operations, namely: soaking in the water, steaming, and drying. In ancient times the process most probably was invented to make hulling easier and the different modifications parboiling made to the product were considered merely accidental; however, after the introduction of mechanical milling, parboiling not only survived but also began to spread all over the world because of its economical and nutritional advantages. The first studies on parboiled-rice went back to the start of the century when medical opinion began to emphasize that the people who consumed this rice were rarely affected by beriberi, and endemic disease caused by

lack of vitamin B-1, or thiamine. However, it was only after the Second World War that a certain amount of industrial activity, especially in the United States, Italy, and British Guiana, aroused interest in a much wider program of studies and research on parboiled rice and the technique to be used in preparing it [2].

2.1.1 Structure of the Rice Caryopsis

The rice grain consists of the outer covering structures -the hull or hull- and the enclosed edible portion, the rice caryopsis or brown rice. Brown rice constitute 72 to 82 % of rough rice weight. The surface of caryopsis has ridges that correspond to those of the hull. Brown rice varies widely among cultivars in size, shape and weight.

The caryopsis is enveloped by the caryopsis coat composed of pericarp, seed coat and nucellar layers (Figure 2.1).

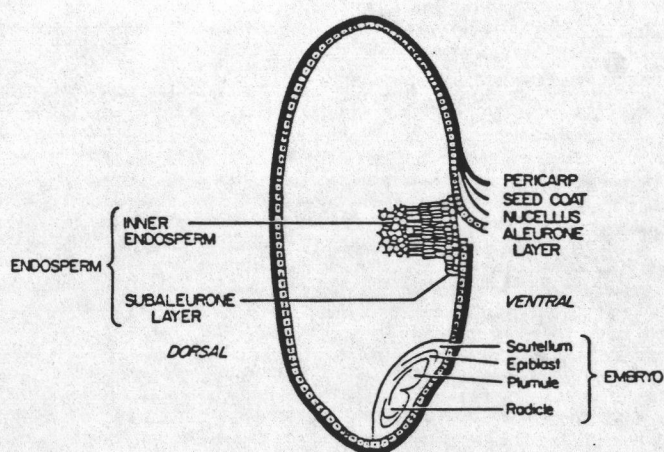


Figure 2.1 Diagrammatic representation of the rice caryopsis.

The next enclosing layer is the aleurone, which completely encloses the endosperm and the embryo [3]. The aleurone layer is

composed of quadrangular or rectangular parenchyma cells with 2 μm walls. The embryo or germ is extremely small and is located on the ventral side of the caryopsis [4]. The starchy endosperm consists of thin-walled parenchyma cells, usually radially elongated and heavily loaded with compound starch granules and some protein bodies (Figure 2.2).

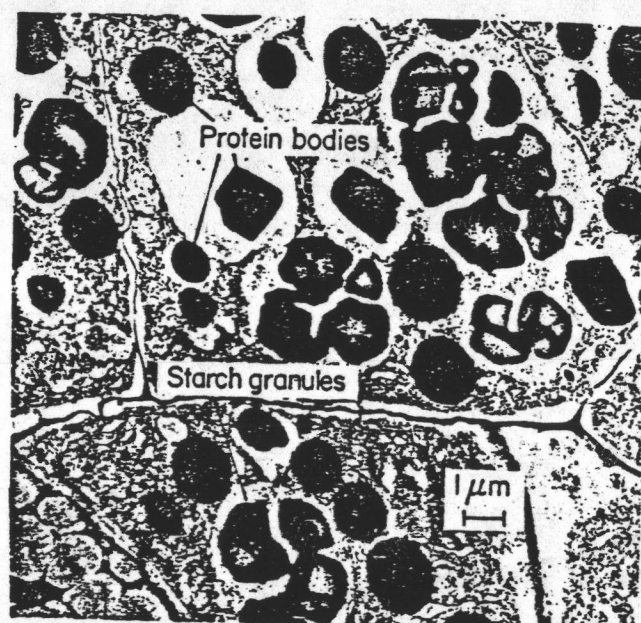


Figure 2.2 Protein bodies and compound starch granules in subaleurone layer of developing IR 26 rice grain.

Cultivars differ in hardness distribution in the endosperm. Hardness distribution is represented by hardness values in kg per mm^2 . Hardness ratio is the ratio of hardness at the middle point of the lateral lines (halfway between the center and the periphery) to that at the central point. Indica cultivars tend to have a hardness ratio of less than 1.0 (Figure 2.3). Japonica cultivars tend to have a hardness ratio more than 1.0. In these grains, hardness is greatest at the middle region and becomes less toward the central core and the peripheral

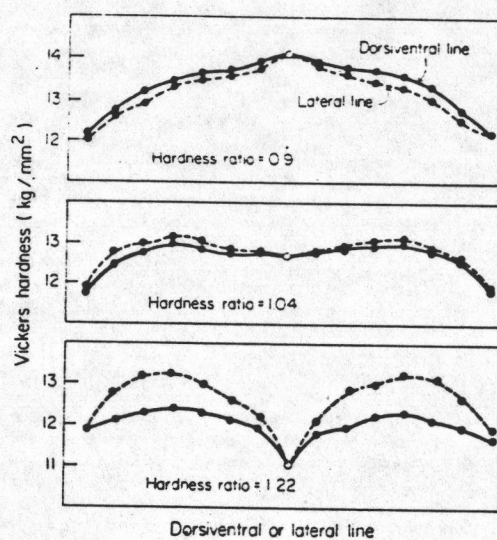


Figure 2.3 Hardness distribution and hardness ratio of brown rice.

region. In addition, the dorsiventral region is softer than the lateral region. Soft-grain cultivars have higher moisture contents than hard-grain cultivars. The moisture content of their grains also changes faster with a change in relative humidity.

2.1.2 The Changes Occuring in the Parboiling Process

Parboiling is a hydrothermal process in which the crystalline form of the starch is changed into an amorphous one, due to the irreversible swelling and fusion of starch. This is accomplished by soaking, steaming, drying and milling the rice. The parboiling process is to produce physical and chemical modifications in the rice with economic and nutritional advantages [1], [5]. The major objectives of parboiling are to [6]:

1. increase the total and head yield of paddy;
2. prevent the loss of nutrients during milling;
3. salvage wet or damaged paddy; and
4. prepare the rice according to the requirements of consumers.

The changes occurring in the parboiling process are as follows:

1. The water-soluble vitamins and mineral salts are spread throughout the grain, thus altering their distribution and concentration among its various parts. The riboflavin and thiamin contents are 4 times higher in parboiled rice than in whole rice. The thiamin is more evenly distributed in the parboiled rice and the niacin level in this rice is 8 times greater [7].

2. The moisture content is reduced to 10-11 % for better storage.

3. The starch grains imbedded in a proteinaceous matrix are gelatinized and expanded until they fill up the surrounding air spaces.

4. The protein substances are separated and sink into the compact mass of gelatinized starch becoming less liable to extraction.

5. The enzymes present in the rice kernel are partially or entirely inactivated. A reduction in the free fatty acid content of parboiled rice that has been stored for 10 months.

6. Proliferation of fungus spores, growth of eggs, larvae or insects, etc., are prevented.

7. The solids leached into the cooking water and the extent of solubilization of the kernels on cooking are considerably reduced.

After parboiling, the milling yield is higher and the quality improved as there are fewer broken grains. The grain structure becomes compact, translucent and shiny. The milled parboiled-rice keep longer and better than in the raw state, as germination is no longer possible. The endosperm has a compact texture making it more resistant to attacks by insects. The grains remain firmer during cooking and are less likely to become sticky. The nutritional value of parboiled-rice is greater because of the higher content of vitamins and mineral salts which have spread into the endosperm. The starch endosperm of parboiled-rice has a greater resistance to milling and therefore the bran and germ are more effectively removed.

The changes parboiling brings about in the rice are closely related to the techniques used. Lack of experience may nullify the advantages described, even reducing the food value of the cereal originally possessed. If the paddy is allowed to ferment during or after steeping, the sensory quality of the rice will be unacceptable for consumption. There are problems hindering the more extensive consumption of parboiled-rice. If improperly dried, milled and prepared, the product may have poor color, odor, taste and texture. Better technical knowledge in processing, packaging and storage is needed to improve the quality of parboiled-rice.

2.1.3 Characteristics of Paddy Rice for Parboiling

Rice varieties preferred for parboiling are those which are the most brittle owing to the chalky structure of their endosperm, or lots which would give a low output after milling because of special conditions associated with cultivation, harvesting, and drying. The reason for this preference is that the process raises the milling yield.

Because of their fragility, varieties with a long and slender grain are usually preferred to the short or medium lengths which stand up better to ordinary processing.

A further advantage of the long, slender grains is that the operations of steeping and heating are quicker and easier, as water and heat rapidly reach the middle of the endosperm. Many markets also show a marked preference for the long-grain varieties, and consequently the price is higher.

Some of the characteristics possessed by the paddy can affect processing results from both the quantitative and qualitative points of view. These include:

1. The presence of partially or entirely shelled grains which may be destroyed or misshapen by the process; this also causes the plant to function irregularly in many ways.

2. The awn and hairiness of the hulls which, by reducing the bulk weight of the rice, also reduce plant output and sometimes make operation difficult because of the tendency of the

grains to float on the surface of the water, producing scum and other waste material.

3. Color or pigmentation of the hulls, which may be dissolved by steeping and heating and thus reach the endosperm and deepen its color.

4. The presence of mildew or bacterial infection, and its extension and depth of penetration, affect chemical substances which spread under the effect of the heat and cause partial or total darkening of the endosperm.

If infection is only superficial and is limited to the outer skin of the hull, it does not cause darkening of the processed product. To decide how far the infection has penetrated and what the consequences may be, the rice to be parboiled must not only be examined in the paddy state, but also after shelling (Figures 2.4 and 2.5). If it is examined after polishing, infection present on the cortical layers, which have been removed by milling, sometimes cannot be noted.

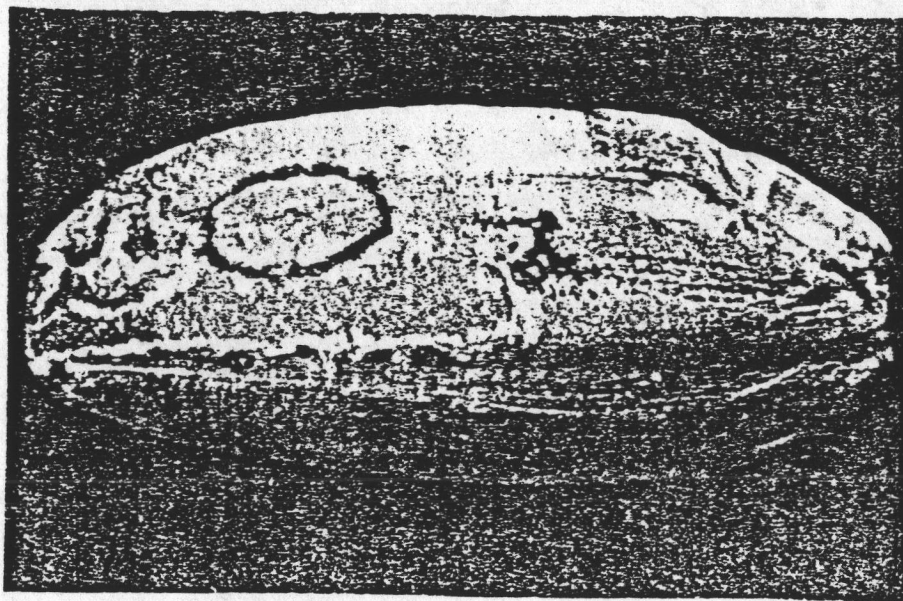


Figure 2.4 Shelled rice grain, showing attack by molds.

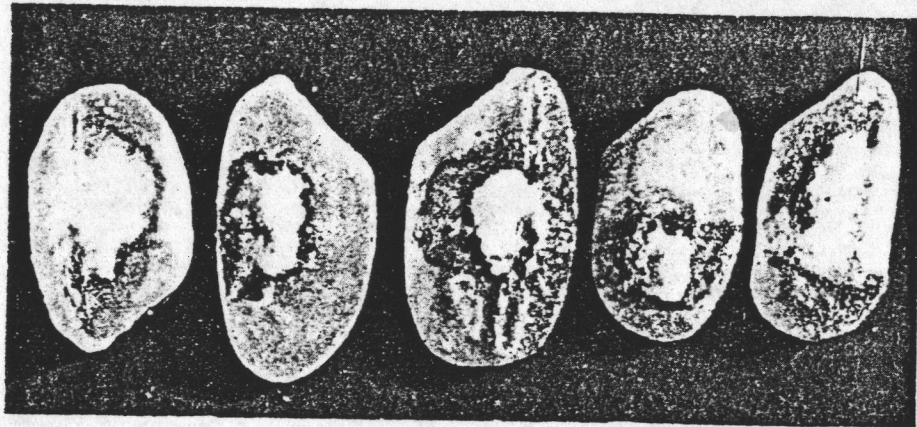


Figure 2.5 Milled nonparboiled rice grain, showing attack by molds.

5. The presence of injuries, sometime minute, on the seed are caused either mechanically or by insects. If these injuries are deep, they may have caused oxidation of the fatty parts of the cortical layers, and may lead to partial discoloration of the processed product.

6. The content of grains which are green, red (either the cuticle or the pericarp), or stained, which processing may affect so that the milled product is more or less deeply colored.

2.2 Parboiling Process

Parboiling process is a hydrothermal process that water or steam is required to gelatinize the starch in the rice grain during parboiling. The water coming in contact with the paddy in washing, floating and steeping must be of potable quality. Parboiling of paddy required four steps: precleaning and grading, soaking, steaming and drying [8]. The parboiling process is shown in Figure 2.6.

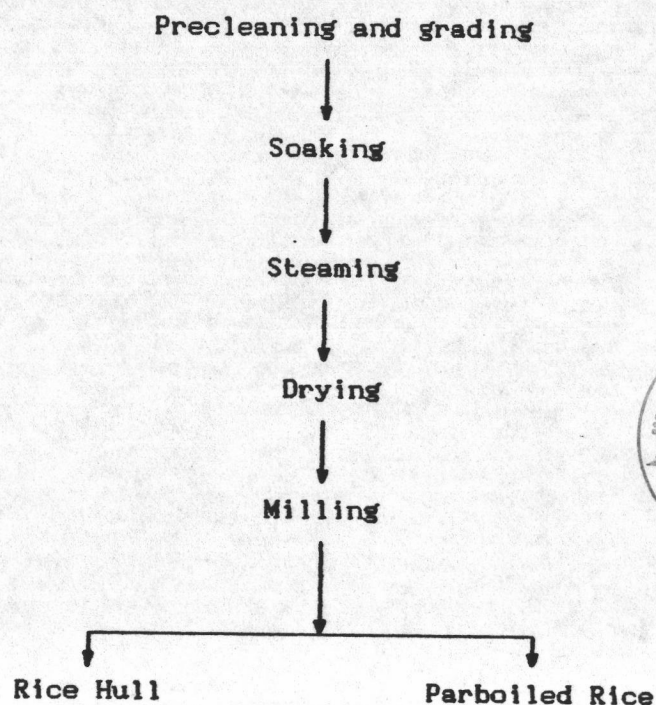


Figure 2.6 Parboiling process diagram

2.2.1 Precleaning and Grading

It is of the importance to ensure that all organic or inorganic impurities are removed from the paddy prior to parboiling. To get an evenly processed and colored product with the starch gelatinized to a uniform degree, dividing the paddy into homogeneous lots may sometime be necessary. As the time required for water and heat to reach the center of the endosperm depends on the thickness of the grain.

2.2.2 Soaking

It is basically a diffusion process of simultaneous water absorption and swelling. The movement of the water into the paddy will continue as long as the vapor pressure inside the

grain is less than that of the soaking water and will stop when equilibrium is reached [1].

Hydration characteristics of the paddy depend on the agronomic variety, on cultivation conditions, and on length of storage. These factors must be considered in deciding how long soaking must be continued. Another factor of great importance in soaking is the temperature of the water. The process can be speeded up by the use of physical and chemical agents such as air vacuum, hydrostatic pressure and wetting agents.

The main objectives to be achieved in the soaking stage are: quick and even water absorption by the grain and the avoidance of hull opening as far as it is possible. Length of steeping time and water temperature have an effect on the solubilization of substances in the rice, and on color, smell, and taste. If the temperature of the water exceeds that at which the starch is gelatinized, hydration takes place more rapidly, and a greater quantity of water is absorbed. This also mean, however, that the hull is opened to an appreciable extent, and part of the caryopsis comes out into the water. From this it may be deduced that the most suitable soaking temperatures lie between 60 and 70 °C [1].

When grain impregnation does not reach the center of the endosperm, the part which has not absorbed water does not gelatinize by the application of heat. Apart from their uneven "white belly" appearance grains not fully gelatinized are more brittle during milling [1].



2.2.3 Steaming

The use of steam for gelatinizing the starch in the paddy grain is preferable to other methods of heating because it does not remove moisture from the soaking paddy, rather it adds moisture by condensation, which increases the total moisture content of the grain [1], [6]. The other advantages of steam are that its high heat content is applied at constant temperature, it is sterile, and it can be used to produce power before it heats the paddy. During steaming, the following points should be considered [1], [6].

1. Whether the steam is saturated or superheated;
2. The pressure of the steam, which determines the temperature at which heat is transmitted; and
3. The steaming time, which determines the total heat supplied to the paddy to cause the gelatinization of the starch.

The total amount of heat applied to the paddy is equal to the heat provided by the soaking and steeping water plus the heat derived from the condensation of steam during the steaming operation.

The temperature of the steam has a considerable effect on the color of the rice although the causes are not yet fully understood. However, by steaming the paddy with nonpressurized steam (at 100 °C) as the traditional oriental methods, only small variations are found in the color and quantity of soluble starch and in the amount of swelling of the milled parboiled-rice [1],

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[6]. Generally, saturated steam at a pressure of 1-5 kg/cm² is used for steaming the soaked paddy in the different methods of parboiling [6], [9]. The duration of steaming is dependent upon the quantity of paddy to be steamed.

2.2.4 Drying

The main aim in the drying process is to reduce the moisture content of steam-parboiled paddy without cracking and creating stress for proper milling and storing, but it is different from drying raw paddy because steamed paddy has a high moisture content (45-60 %) which was to reduce to 18-25 % which may not lead to breakage during milling. The reduction in moisture may take place quickly by use of high temperatures and large quantities of air, and without intervals or stoppages until 16 to 18 % moisture is reached. From this point onwards the drying process must be slowed down and preferable stopped for a few hours (conditioning). When it is resumed in order to reduce moisture to 12 to 14 %, a good plan is to proceed slowly, alternating drying with one or more periods of rest or storage lasting several hours.

A successful experiment has also been carried out in which the parboiled-rice was dried until the moisture content was low enough for milling, after which a further stage of drying was made on the milled product until moisture was reduced below 12 to 14 %, this being the level necessary for ensuring good and long-term storage.

2.3 Principles of Fluidization

Fluid is passed upward through a bed of fine particles as shown in Figure 2.7. At a low flow rate, fluid merely percolates

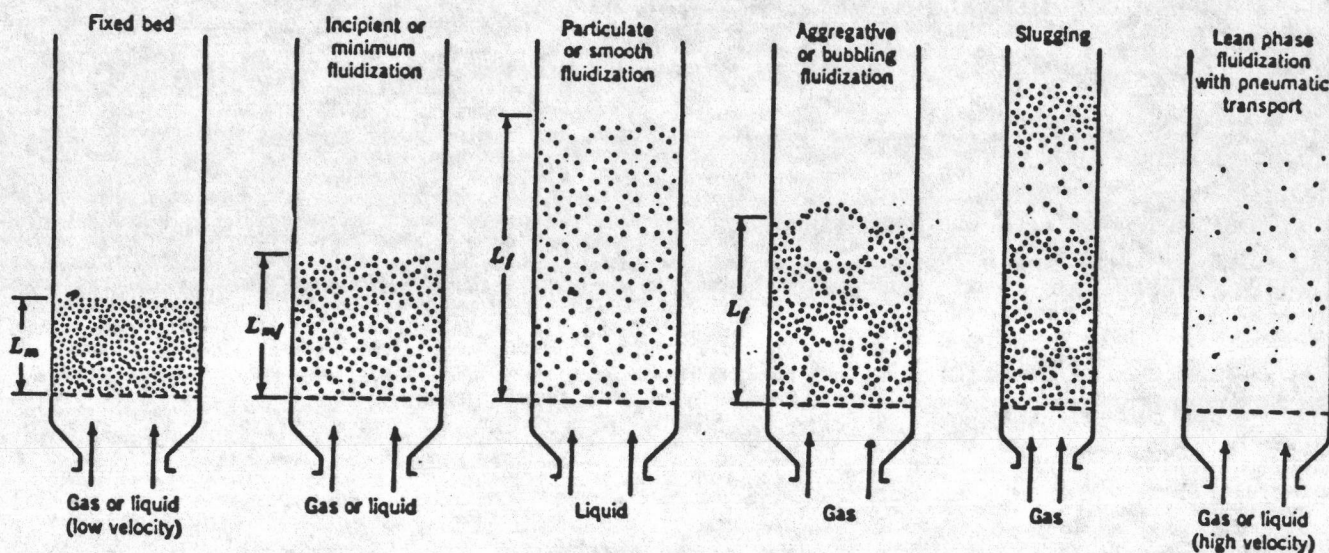


Figure 2.7 Various kinds of contacting of a batch of solids by fluid.

through the void spaces between stationary particles. This is a fixed bed.

With an increase in flow rate, particles move apart and a few are seen to vibrate and move about in restricted regions. This is the expanded bed. At a still higher velocity, a point is reached when the particles are all just suspended in the upward flowing gas or liquid. At this point the frictional force between a particle and fluid counterbalances the weight of the particle, the vertical component of the compressive force between adjacent particles disappears, and the pressure drop through any section of the bed about equals the weight of fluid and particles in that

section. The bed is considered to be just fluidized and is referred to as an incipiently fluidized-bed or a bed at minimum fluidization.

In gas-solid system, with an increase in flow rate beyond minimum fluidization, large instabilities with bubbling and channeling of gas are observed. At higher flow rates agitation becomes more violent and the movement of solids becomes more vigorous. In addition, the bed does not expand much beyond its volume at minimum fluidization. Such a bed is called an aggregative fluidized-bed, a heterogeneously fluidized-bed, a bubbling fluidized-bed, or simply a gas fluidized-bed, in a few rare cases liquid-solid systems will not fluidize smoothly and gas-solid systems will not bubble. At present such beds are only laboratory curiosities of theoretical interest.

A fluidized-bed is considered to be dense-phase fluidized-bed as long as there is a fairly clearly defined upper limit or surface to the bed. However, at a sufficiently high fluid flow rate the terminal velocity of the solids is exceeded, the upper surface of the bed disappears, entrainment becomes appreciable, and solids are carried out of the bed with the fluid stream. In this state we have a disperse-, dilute-, or lean-phase fluidized-bed with pneumatic transport of solids. Consider briefly the quality of fluidization in a bubbling bed. Although the properties of solid and fluid alone will determine whether smooth or bubbling fluidization occurs, many factors influence the rate of solid mixing, the size of bubbles, and the extent of heterogeneity in the bed. These factors include bed geometry, gas

flow rate, type of gas distributor, and vessel internals such as screens, baffles, and heat exchangers. As an example consider slugging, a phenomenon strongly affected by the vessel geometry. Gas bubbles coalesce and grow as they rise, and in a deep enough bed they may eventually become large enough to spread across the vessel. Thereafter the portion of the bed above the bubble is pushed upward, as by a piston. Particles rain down from the slug and it finally disintegrates. At about this time another slug forms and this unstable oscillatory motion is repeated. Slugging is usually undesirable since it increases the problems of entrainment and lowers the performance potential of the bed for both physical and chemical operations. Slugging is especially serious in long, narrow fluidized-beds [10], [11].

2.3.1 Minimum Fluidizing Velocity

Onset of fluidization occurs when

$$\left[\begin{array}{l} \text{drag force by} \\ \text{upward moving gas} \end{array} \right] = \left[\begin{array}{l} \text{weight of} \\ \text{particles} \end{array} \right] \dots\dots\dots(1)$$

or

$$\left[\begin{array}{l} \text{pressure drop} \\ \text{across bed} \end{array} \right] \left[\begin{array}{l} \text{cross-sectional} \\ \text{area of tube} \end{array} \right] = \left[\begin{array}{l} \text{volume} \\ \text{of bed} \end{array} \right] \left[\begin{array}{l} \text{fraction} \\ \text{of solids} \end{array} \right] \left[\begin{array}{l} \text{specific} \\ \text{weight} \end{array} \right] \dots\dots\dots(2)$$

$$\Delta P A_t = W = (A_t L_{mf})(1-E_{mf})[(p_s - p_g)g/g_c] \dots\dots\dots(3)$$

By rearranging, we find for minimum fluidizing condition that:

$$\Delta P/L_{mf} = (1-E_{mf})(p_s - p_g)g/g_c \dots\dots\dots(4)$$

In a bed at onset of fluidization the voidage is a little larger than in a packed bed, and it actually corresponds to the loosest state of a packed bed of hardly any weight. Thus we may estimate E_{mf} from random packing data or, better still, it should be measured experimentally, since this is a relatively simple matter [12].

The pressure drop through fixed beds of uniformly sized solids has been correlated by Ergun [13] using the equation.

$$\begin{aligned} (\Delta P/L)g_s &= [150(1-E_m)^2 \mu U_o] / [E_m^3 (\phi_s d_p)^2] \\ &+ [1.75[(1-E_m) \rho_s U_o^2] / [E_m^3 \phi_s d_p]] \dots\dots(5) \end{aligned}$$

U_{mf} , the superficial velocity at minimum fluidizing conditions, is found by combining Eq.(4) with Eq.(5). In general, this gives a quadratic in U_{mf} :

$$\begin{aligned} [d_p^3 \rho_s (\rho_s - \rho_g) g] / \mu^2 &= [1.75 / (\phi_s E_{mf}^3)] [(d_p U_{mf} \rho_s) / \mu]^2 \\ &+ [150(1-E_{mf}) / (\phi_s^2 E_{mf}^3)] [(d_p U_{mf} \rho_s) / \mu] \dots\dots(6) \end{aligned}$$

However, for small particles of small specific weight Eq.(6) simplifies to eliminate the kinetic energy losses, Eq.(6) becomes

$$U_{mf} = [(\phi_s d_p)^2 (\rho_s - \rho_g) g / 150 \mu] [E_{mf}^3 / (1-E_{mf})] \dots\dots(7)$$

for $Re_p < 20$ [14]

For large particles Eq.(6) simplifies to eliminate the viscous losses. Thus Eq.(6) becomes

$$U_{nr}^2 = [\phi_d (p_s - p_a) g E_{nr}^2] / 1.75 p_s \dots \dots \dots (8)$$

for $Re_p > 1000$ [15]



2.3.2 Heat Transfer in Fluidized-Bed [13]

Drying is essentially a process of simultaneous heat and mass transfer. Heat, necessary for evaporation, is supplied to the particles of the material and moisture vapors are removed from the material into the drying medium (Figure 2.8).

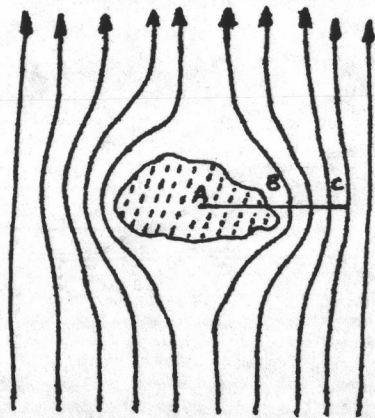


Figure 2.8 Heat and mass transfer in the drying of the particle in a fluidized-bed. The drying medium flows around the particles. Collisions with other particles, occurring incessantly, are not indicated in the figure. A - inside of particle, B - surface of particle, C - drying medium.

Heat is transferred by convection from the surroundings C to the particle surface B, and from there, by conduction, further into the particle, to A. Moisture is transported in the opposite direction: within the particle it moves from A to B as a

liquid or vapor; at the latest on the surface it evaporates and passes on by convection to the surrounding C.

The driving force for heat transfer between the drying medium and the surface of the particle is the difference in temperature at C and B. The driving force for the conduction of heat within the particle is the difference in the temperatures at B and A. The driving force for the overall transport of heat from the surrounding to the central layers of the particle is the difference in temperatures at C and A.

There is an extensive literature on heat transfer in fluidized-beds. Many studies have been reported as correlations of dimensionless numbers in the form:

$$Nu_p = C Re_p^m \dots\dots\dots(9)$$

C and m are empirically determined constants from observational data. The exponent m vary somewhere in the neighborhood of unity.

Some reported correlations from previous studies are given below:

$Nu_p = 0.054 Re_p^{1.28}$	Richardson and Ayers
$Nu_p = 0.0135 Re_p^{1.30}$	Kettering, Manderfield and Smith.
$Nu_p = 0.055 Re_p$	Lemlich and Caldas
$Nu_p = 0.3 Re_p^{1.30}$	Kunii and Levenspiel

The relation proposed by Kunii and Levenspiel is an overall correlation based on the works of Richardson and Ayers,

Kettering et al., Heertjes and McKibbins, Donnadien, and Walton et al. The Kunii and Levenspiel expression treated with gas-solid heat transfer in fluidized beds. Lemlich and Caldas, who report the exponent of the particle Reynolds number as one, dealt with heat transfer from a retaining wall to bed particles in a water fluidized-bed (Figure 2.9).

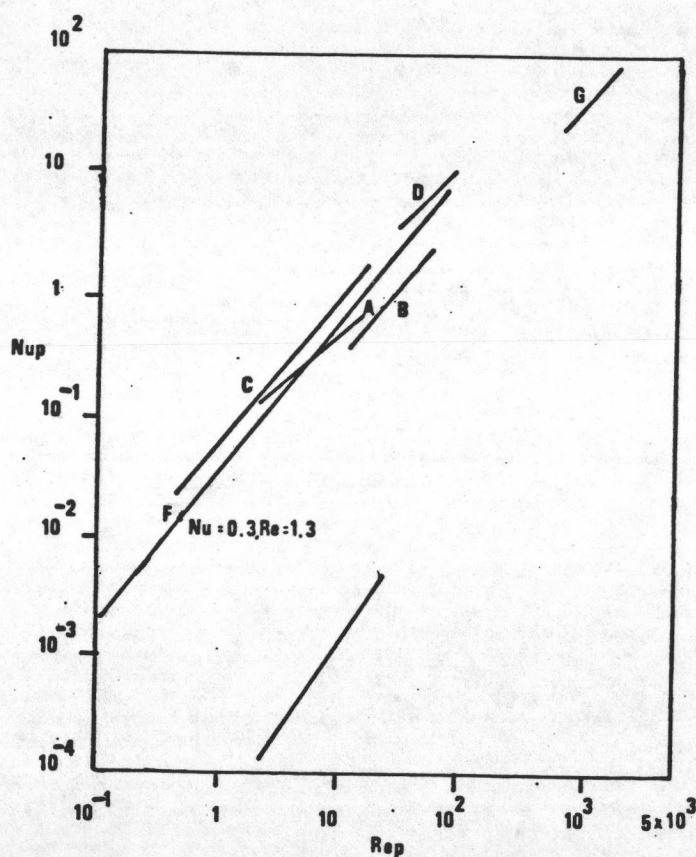


Figure 2.9 Experimental results; (A) Lemlich and Caldas, (B) Kettering, Mansfield and Smith; (C) Richardson and Ayers; (D) Heertjes and McKibbins, (E) Ferron; (F) Kunii and Levenspiel; (G) Pfafflin, Shridhar and Jullier.

A heat balance is struck among the heat entering and leaving the expanded bed, the heat given up to the bed solids, are neglecting heat losses to the walls and in mixing.

The following assumptions are made:

1. The trajectory of temperature change with time of the bed follows closely a first-order response.
2. The bed is at a uniform temperature throughout, except in the small region (1 to 2 cm) near the entering hot gas.
3. No distinction is made between aggregative and particulate fluidization.
4. The temperature of the influent fluid is a constant value and the initial bed temperature is zero.

Setting the balance at steady state:

$$\begin{aligned} (\text{heat in bed by gas}) - (\text{heat out by gas}) \\ = (\text{bed transferred to bed solid}) \end{aligned}$$

or, in symbols,

$$A u_o \rho_s c_{ps} (T_{st} - T_{sb}) dt = h_p A (T_{st} - T_{sb}) dt \dots\dots\dots(10)$$

$$Q_h = Q_o \rho_s c_{ps} (T_{st} - T_{sb}) = h_p A (T_{st} - T_{sb}) \dots\dots\dots(11)$$

where Q_h is the rate of heat transfer (Joules/sec), Q_o is the volumetric flow rate of air (m^3/sec), and h_p is the heat transfer coefficient between hot-air and particles ($\text{Joules}/\text{sec} \cdot m^2 \cdot K$).

The heat transfer coefficient can be solved from Equation (11), and can be simplified to

$$Nu_p = C Re_p^m \dots\dots\dots(9)$$

where, Nu_p = Nusselt number for gas-particle heat transfer, dimensionless.

$$Nu_p = h_p d_p / k_g \dots\dots\dots(12)$$

Re_p = particle Reynolds number, dimensionless

$$Re_p = d_p v_o \rho_g / \mu_g \dots\dots\dots(13)$$

By taking the logarithm of both sides of equation (9),

$$\log Nu_p = \log C + m \log Re_p \dots\dots\dots(14)$$

From Equation (14) the empirical constants C and m of the system can be found by plotting the logarithmic graph of the Nusselt number versus Reynolds number.

2.4 Fluidized-Bed Dryer

Dryers in which the solids are fluidized by the drying gas are called fluidized-bed dryers. The particles are fluidized by air or gas in a boiling-bed unit. Mixing and heat transfer are very rapid. In the dryer, there is a random distribution of residence times; average time a particle stays in the dryer is typically 30 to 120 sec when only surface liquid is vaporized, and up to 15 to 30 min if there is also internal diffusion. The inlet gas may be hot, for it mixes so rapidly that the temperature is virtually uniform, at the exit gas temperature, throughout the bed.

Some rectangular fluidized-bed dryers have separate fluidized compartments through which the solids move in sequence from inlet to outlet. These are known as "plug-flow dryers"; in those, dryers the residence time is almost the same for all particles. Drying conditions can be changed from one compartment to another, and often the last compartment is fluidized with cold gas to cool the solids before discharge.

2.4.1 Definition of Terms Used [13], [26]

Moisture Content is expressed as the amount of moisture contained per unit mass of dry (dry basis) or wet solid (wet basis)

$$W_d(\text{dry basis}) = (M - M_d) / M_d \dots\dots\dots(15)$$

$$W_w(\text{wet basis}) = (M - M_d) / M \dots\dots\dots(16)$$

Unless specified otherwise, dry basis moisture content is assumed throughout.

Free Moisture Content is the moisture content which is removable at a given temperature and humidity.

Critical Moisture Content is the average moisture content at which the constant-rate period ends.

Equilibrium Moisture Content is the lowest moisture content to which a given material can be dried under constant specific conditions of air temperature and humidity.

Relative Humidity is the ratio of the mole fraction (or vapor pressure) of water vapor in the air to the mole fraction (or vapor pressure) of water vapor in saturated air at the same temperature and (atmospheric) pressure.

Humidity is the water vapor contained in moist air per unit mass of dry air.

Dry-bulb Temperature is the temperature of moist air indicated by an ordinary thermometer.

Wet-bulb Temperature is the temperature of moist air indicated by a thermometer whose bulb is covered with a wet wick.

Drying Rate is expressed as the mass of evaporated water per time-mass of dry material

$$R_w = -(dW / d\theta) \dots\dots\dots(17)$$

$$R = R_w (M_d / A) \dots\dots\dots(18)$$

2.4.2 Fundamental Concepts of Drying [26]

One general pattern of behavior which always appears is a wet solid drying with a gas of fixed temperature and humidity. After contact between the sample and the drying medium, immediately the solid temperature adjusts until it reaches a steady-state. The solid temperature and the rate of drying may increase or decrease to reach the steady-state condition. At steady-state, the temperature of the wet-solid surface nearly becomes the wet-bulb temperature of the drying medium.

Temperatures within the drying solid would also tend to equal the wet-bulb temperature of the gas but it would be imperfect because of lag in movement of mass and heat. Figures 2.10 and 2.11 respectively show typical drying curves, one on the basis of moisture content versus time and the other on the basis of rate

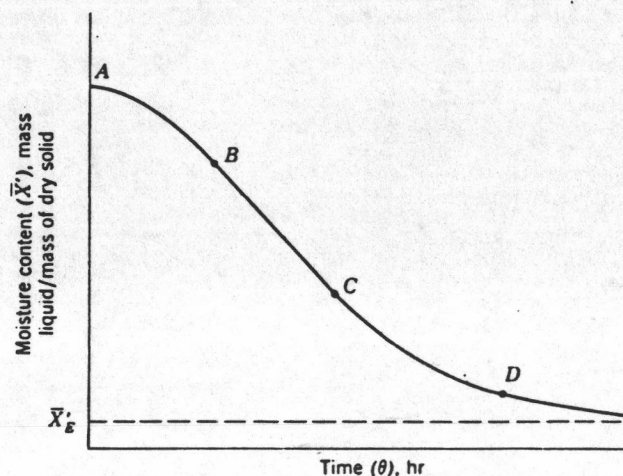


Figure 2.10 Typical drying curve for constant drying conditions, moisture content as a function of time.

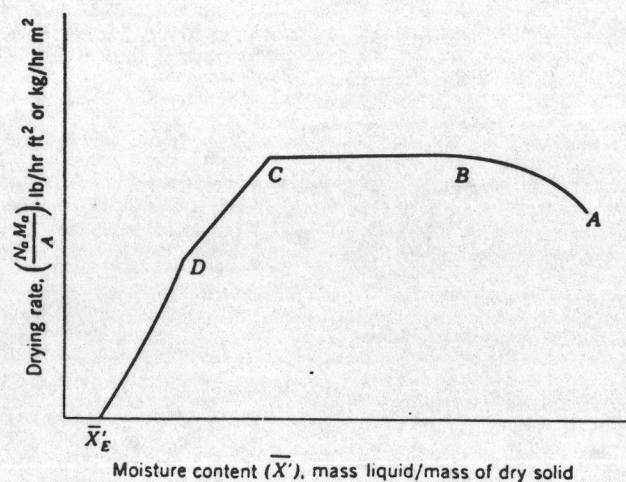


Figure 2.11 Typical drying rate curve for constant drying conditions, drying rate as a function of moisture content.

of drying versus moisture content. The drying rate curve can be roughly divided into two sections; namely constant-rate drying period and falling rate period.

Constant-rate drying period is the temperature within the drying solid would also tend to reach the wet-bulb temperature of the gas. They are found to be quite stable, and the drying rate also remains constant, which is represented by segment BC of the drying curves in Figures 2.10 and 2.11. The constant-rate drying regime continues with the mass that is transferred from the surface continuously replaced by movement of liquid from the interior of the stock. The mechanism of liquid movement and consequently the rate of this movement vary markedly with the structure of the solid itself. This period ends when the solid reaches the critical moisture content. If the initial moisture content of the solid is below the critical moisture content, the constant-rate period does not occur.

The falling-rate drying in which the surface temperature rises and the drying rate falls off rapidly may take a far longer time than the constant-rate drying period, even though the moisture removal may be much less. The drying rate approaches zero at some equilibrium moisture content which is the lowest moisture content obtainable with this solid under the drying conditions used and represented by the curves from C to D in Figures 2.10 and 2.11, called the "first falling-rate drying period". The surface becomes more and more depleted in liquid because the rate of liquid movement to the surface is slower than the rate of mass transfer from the surface, until the point D where there is no significant area of liquid-saturated surface.



The part of the surface that is saturated dries by convective transfer of heat from and mass to the drying gas stream. The diffusion mechanism is very slow compared to the convective transfer from the saturated surface. At moisture contents lower than that at point D of Figure 2.11, called "second falling-rate drying period", in which the moisture content continues to fall, the path for diffusion of heat and mass grows longer, and the concentration potential eventually decreases until equilibrium moisture content is reached when the vapor pressure over the solid is equal to the partial pressure of vapor in the incoming dry gas.

2.4.3 Applications of Fluidized-Bed Drying

The techniques of fluidized-bed has been successfully supplied in drying many types of products. During the past decade, fluidized-bed techniques have been playing more and more important roles in drying systems. The techniques have been studied, improved, and scaled up for industrial processes. Santiyanont [8] has summarized the work done on fluidized-bed drying.

Santiyanont [8] showed that a fluidized-bed dryer was used in drying of parboiled-rice with high efficiency. The system used should be a continuous type operation with a screw feeder since it gives a convenient, fast operation, and yields high quality products at any quantity required. The optimum conditions selected were 183 °C for the air inlet temperature at an air flow rate of 0.65 kg/sec m² for a production rate of 31.59 kg/hr of parboiled rice.

2.4.4 Advantages and Limitations of Fluidized-Bed Drying

Fluidized-bed drying has the following advantages over other methods of drying: [27], [28]

1. High intensity of drying. Drying rates in fluidized-bed dryers may be as high as several hundred kilograms of water per hour in 1 m^3 of dryer volume.
2. A uniform and closely controllable temperature throughout the charge. This is so, even when the temperature of the drying medium is higher than the highest permissible temperature of the material. In other types of dryers a low-temperature drying medium must be employed for the drying of heat-sensitive materials.
3. High thermal efficiencies, when the drop in moisture content is high and the drying temperature is not excessive, or when a multistage dryer is employed and attainable because of the low surface to volume ratio of the dryer, the heat losses are very small.
4. The residence time of the material in the dryer may be chosen arbitrarily. This is an advantage over pneumatic dryers in which the residence time is of the order of seconds.
5. The time of drying is usually less than in other types of dryer, owing to the high rates of heat and mass transfer. In fluidized-bed dryers the time of drying is of the order of minutes, while in tray dryers the time of drying may be several hours.
6. The operation and maintenance of the dryer is relatively simple, as it is of very simple design and contains no moving parts.

7. The process can be automated without difficulty.
8. Fluidized-bed dryers are compact and of relatively small size. The capital costs are lower than for other types of dryers. (e.g. rotary dryers). Heavy buildings and foundations are not needed; the dryer can be situated under the light roofing.
9. Several processes may be combined in a fluidized-bed dryer. Thus, in addition to being dried, the material may also be transported in a fluidized state, mixed, and classified. The dry material may be cooled in a fluidized state, and both operations can be carried out in a single piece of equipment consisting of several stages.

However, fluidized-bed drying has the following disadvantages:

1. A higher pressure drop for the dryer and dust separator. The pressure drop amounts to at least 300-500 mm H₂O. Under favourable circumstances the higher pressure drop is outweighed by the lower consumption of heat.
2. Part of the product is obtained in the form of very fine particles; These have approximately the same moisture content as the coarse product.
3. The residence times of individual particles vary considerably. This is so in a single-stage process.
4. For solutions, the heat consumption is higher than in a multiple-effect evaporation. This may be outweighed by the simplicity of the fluidizing equipment and by the fact that in place of the multiple-effect evaporator and granulator only one piece of equipment is needed.

2.5 Fluidized-Bed Combustion

Fluidized-bed technology for non-energy applications has been on the scene for many decades. However, its use as an energy technology is of much more recent vintage; indeed, on a commercial scale, this use is still in the future. But now this future to be overdue arriving rapidly. Very few people outside the specialist field, however, have even heard of fluidized-bed combustion. Fluidized-bed combustion is on the threshold of becoming a major energy technology because this technology moved rapidly from the laboratory into industrial applications. New combustion technologies are required to meet the twofold challenge of utilizing increasingly low-grade fuels and simultaneously reducing emissions harmful to the environment [16].

2.5.1 Fundamental Concepts of Fluidized-Bed Combustor

The fluidized-bed is simple in concept, as shown in Figure 2.12. If a vertical cylinder of any cross section is closed off at the bottom with a perforated plate, the cylinder partly filled with a granular solid material, and sufficient air or gas blown up through the perforated plate, then the bed of granular material is vigorously tumbled by the rising bubbles and is said to be fluidized. A fluidized-bed combines the physical characteristics of a solid and fluid. The application which is of particular interest is the use of fluidized-bed as a medium in which to burn fuels: fluidized-bed combustion. In its simplest form, a fluidized-bed combustor (FBC) consists of a refractory cylinder and the perforated plate commonly called the grid or distributor plate designed to withstand high temperatures. Air is

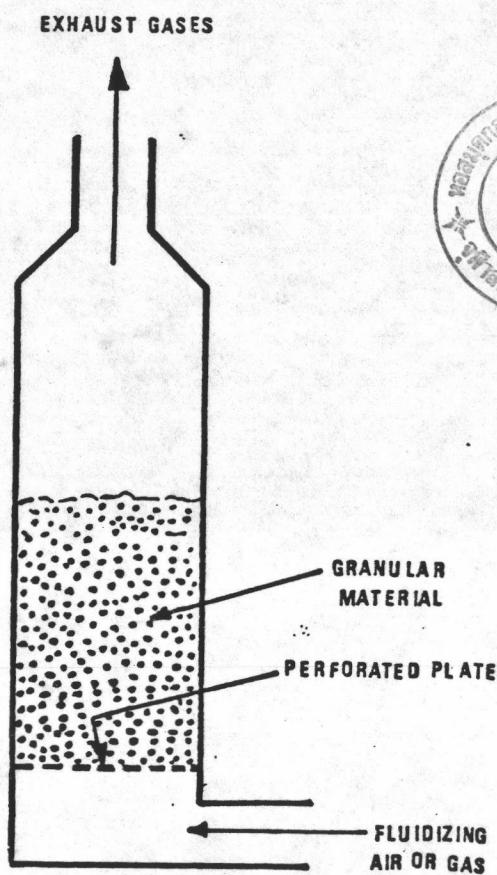
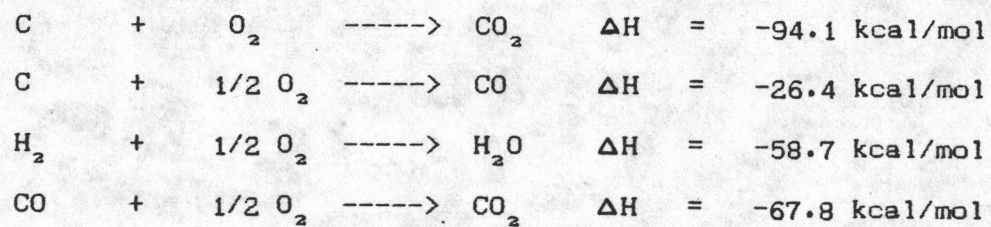


Figure 2.12 An elementary fluidized-bed.

usually used as the fluidizing medium because it can also serve as the oxidant. The granular bed material must have adequate refractory properties, silica frequently being used.

If such a bed is fluidized and heated to the ignition temperature of the fuel by some means as preheating of the fluidizing air, then all the conditions required for combustion are met: air and fuel are present, the temperature is high enough for ignition, and mixing is very good. Thus, the chemical reaction between carbon, hydrogen, other elements and oxygen will occur as shown the following equations:



Any fuel introduced into the combustion chamber will burn, eventhough it may be very dilute relative to the bed material.

The combustion of solid, the heterogeneous reaction is of importance. The combustion will be started at the surface and continue to the inside surface. Because of the limited contacted areas between solid surface and oxygen, eventhough there is an excess of oxygen, the reaction will occur only on the surface. Combustion efficiency may be improved by

1. increasing the surface area of the fuel by grinding; or
2. increasing the mixing efficiency between fuel and oxygen.

Thus, the fluidized-bed combustor is very suitable for improving the mixing performance and appropriately extracting heat from the bed at high temperatures.

Pirstprayvong [17] made runs on continuous combustion of lignite of size 1.5 mm in a combustor of diameter 200 mm. The results indicate that the best operating conditions in continuous combustion are at a temperature of 900 °C with an air velocity of 58.92 m/min and a lignite feed rate of 0.675 gm/cm²

min where a highest combustion efficiency of 89.57 percent was obtained.

Soongswang [18] did some work on combustion of rice hull in a 150 mm diameter column. The results show that the best operating conditions in combustion are at a temperature of 700 °C with an air feed rate of 32.77 m/min and rice hull feed rate of 50.83 gm/min. High combustion efficiency of 96.00 percent was obtained.

2.5.2 Advantages and Disadvantages of Fluidized-Bed Combustor

The ability of a fluidized-bed combustor to operate at relatively low temperatures is advantageous from an operational as well as an environmental viewpoint. First, all the problems associated with slagging and sintering of ash are avoided. Second, the emissions of nitrogen oxides and heavy metals are low compared with conventional combustion systems because the formation of these pollutants is temperature dependent.

Although a fluidized-bed combustor is capable of burning solid, liquid or gaseous fuels, its advantages are most apparent with "difficult" solid fuels that are relatively unreactive or have a high proportion of ash and moisture. The circulating action of the bed provides such fuels with all the residence time necessary to dry and burn, provided the fuel particles are heavy enough not to be elutriated from the bed.

There are still further advantages to FBC. Heat transfer rates to water-cooled tubes immersed in the bed are very

high, making FBC boilers competitive in capital cost with other equipment. Finally, fluidized-beds are amenable to pressurized combustion, making possible compact equipment, substantial cost saving on large scale equipment, and a variety of more efficient fuel-to-electricity cycles.

FBC still has the following disadvantages:

1. Substantial elutriation of particles from the bed, which can lead to high carbon loss and requires high-performance dust collectors, and ;
2. Inability to operate at low loads as well as full load, unless special provisions are incorporated into the design, at additional expense.

2.6 Rice Hull

2.6.1 Structure of Rice Hull

In 1911, the structure of rice hulls was apparently first studied in detail by Van Breda de Maan [1]. After that many studies have been made and published extensively elsewhere. The gross and microscopic structure of a rice hull are shown in Figures 2.13, and 2.14 respectively.

The silicon in rice hulls apparently occurs as a hydrated amorphous form of silica and forms a network. This silicon is taken up and transported in the plant as monosilicic acid. This moves to outer surfaces of rice hull where it becomes concentrated by evaporation and polymerized to form a

cellulose-silica membrane. Figure 2.15 shows details of the structure of rice hull and the ash formed from it.

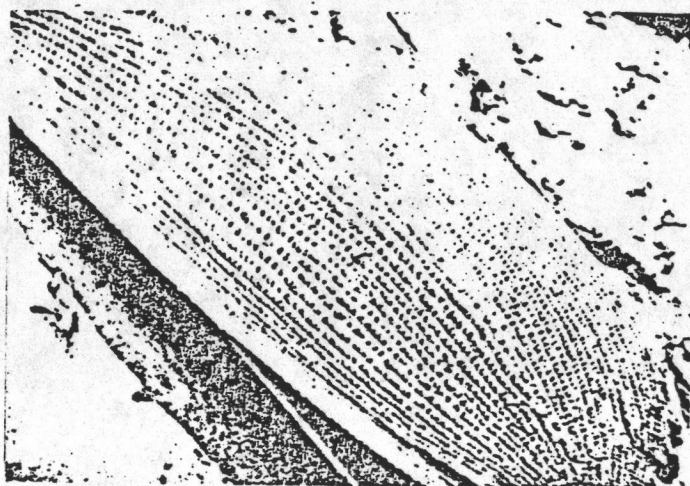
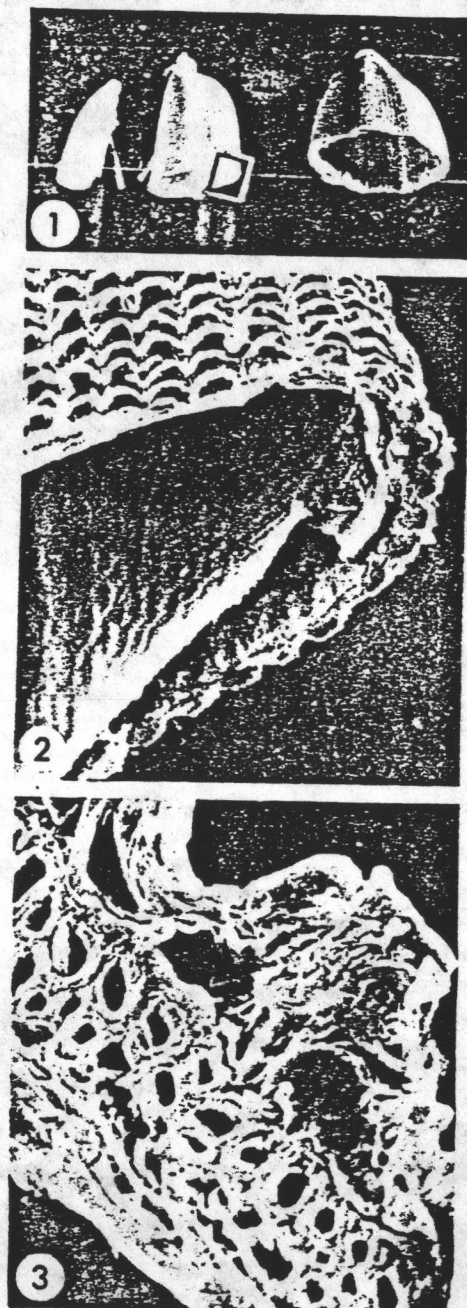


Figure 2.13 Single rice hull.



Figure 2.14 Cross section of rice hull.



- 1 = rice hull cut in half (right) and two fragments of similar half after ashing
- 2 = ashed hull
- 3 = unashed hull

Figure 2.15 Structure of rice hull and rice-hull ash.

2.6.2 Properties of Rice Hull

The properties of rice hull in Thailand was reported in Table 2.1.

Table 2.1 Properties of Rice Hull

Properties	Values		
	Sagetong[19]	Pitakarnnop[20]	Sansupa[21]
Void fraction	0.85	-	0.84
Spherical	0.24	-	0.25
Mean diameter (cm)	0.214	-	0.218
Density (kg/m ³)	850 [*]	105-107 ^{**}	805 [*]
Moisture (%)	10.06	8.1-11.5	10.05
Ash (%)	16.57	16.4-18.3	19.78
Volatile matter (%)	-	61.1-64.5	49.085
Fixed carbon (%)	-	19.2-20.7	21.09
Heating value (%)	3115	3790-4000	3370

* Particle density

** Bulk density

2.6.3 Ash and Slagging Behavior of Rice Hulls

Ash includes all the non-combustible minerals in the feed material. Its composition is shown in Table 2.2 [22]. The predominant component of rice hull ash, about 16.4-20.9 percent of rice hull, is silica in the form of SiO₂. The range of SiO₂

Table 2.2 Rice Hull Ash Compositions [22]

Species	Weight Percent
SiO_2	86.9-97.3
CaO	0.2-1.5
MgO	0.1-2
K_2O	0.6-1.6
Na_2O	Traces-1.75
P_2O_5	0.3
SO_3	0.1-1.13
Cl	0.15-0.4
Fe_2O_3	Traces-0.4
MnO_2	Traces

content in rice hull ash is 86.9-97.3 percent. SiO_2 in rice hull ash exists in three forms: quartz, cristobalite and trypolomite. The last two forms are high-temperature forms of silica, whereas quartz is the low-temperature form. At high temperatures some of the low temperature mineral oxides such as K_2O (350 °C) and Na_2O (1,275 °C) will reach a transition state. In this state the minerals soften before becoming completely liquefied. The softening and melting points of rice hull are strongly dependent on the mass fractions of K_2O and Na_2O [22]. This is shown in the phase diagrams for the $\text{Na}_2\text{O} - \text{SiO}_2$ and $\text{K}_2\text{O} - \text{SiO}_2$ system (Figures 2.16 and 2.17). Because low melting point minerals affect softening point temperatures, at the high temperature, no carbon will be burned off since the atmosphere is inert. The final result is therefore a molten mass of minerals and coaglomerates

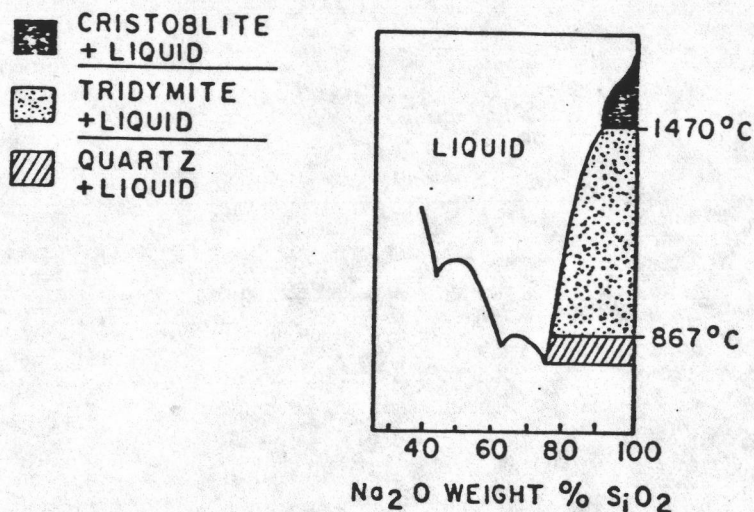


Figure 2.16 Na₂O - SiO₂ system (Levin, 1964).

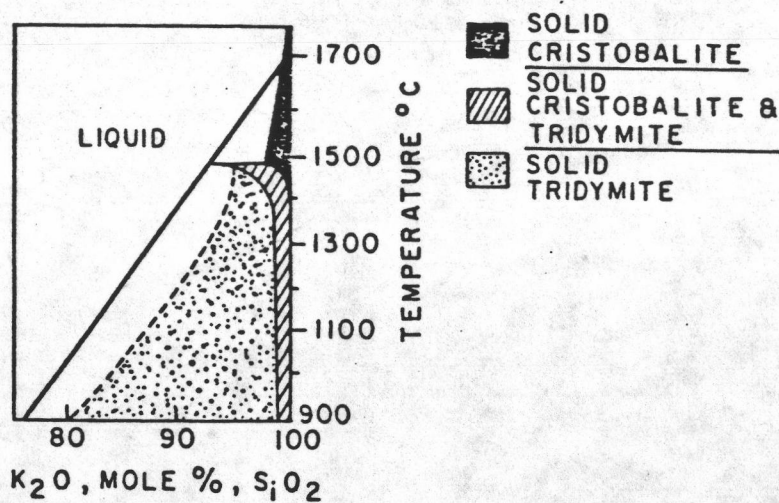


Figure 2.17 K₂O - SiO₂ system (Levin, 1964).

solid carbon and high temperature mineral oxides such as SiO₂, MgO and CaO. These rock-like structures are made up of melted minerals and entrained carbon (slagging).