Chapter II

LITERATURE REVIEWS

2.1 Parboiling Technique

Parboiling is one of the latest well-developed premilling treatments given to paddy to improve its milling, nutritional, cooking, and keeping qualities, The rice obtained from parboiling treatment we called it "Parboiled rice". Parboiling is a process of antique origin. It originated in the Far East[2], principally India, and in some regions of Equatorial Africa, from where it has spread more recently to other continents.

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 water, steaming, and drying. The application of water and heat brings about considerable modifications of a physical, chemical, physicochemical, biochemical, aesthetic and organoleptic nature.

In ancient times the process most probably was invented to make hulling easier, and the different modifications parboiling made to the product considered merely accidental; however, after the introduction of mechanical milling, parboiling not only survived but even began to spread all over the world because of its economical and nutritional advantages.

The first studies on parboiled rice go back to the start of the century when medical opinion began to emphasize that the peoples who consumed this rice were rarely affected by beriberi, an endemic disease caused by a 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.

2.1.1 Mechanism of Parboiling[3]

From figure 2-1, it shows the structure of a paddy grain. The endosperm, which constitutes the major volume of the rice grain, is mainly composed of polygonal starch granules. The voids or intergranular spaces are filled with air and moisture. The presence of voids, fissures, and/or cracks, developed during maturity, causes breakage of rice during milling. This breakage may be eliminated by gelatinizing the starch, which fills the voids and cements the fissures and cracks.

The starch granules may be swelled by soaking the paddy in water. During soaking, water penetrates into starch granules, forms hydrates by hydrogen bonding, and causes swelling. Starch granules exhibit only a limited capacity for absorbing water,

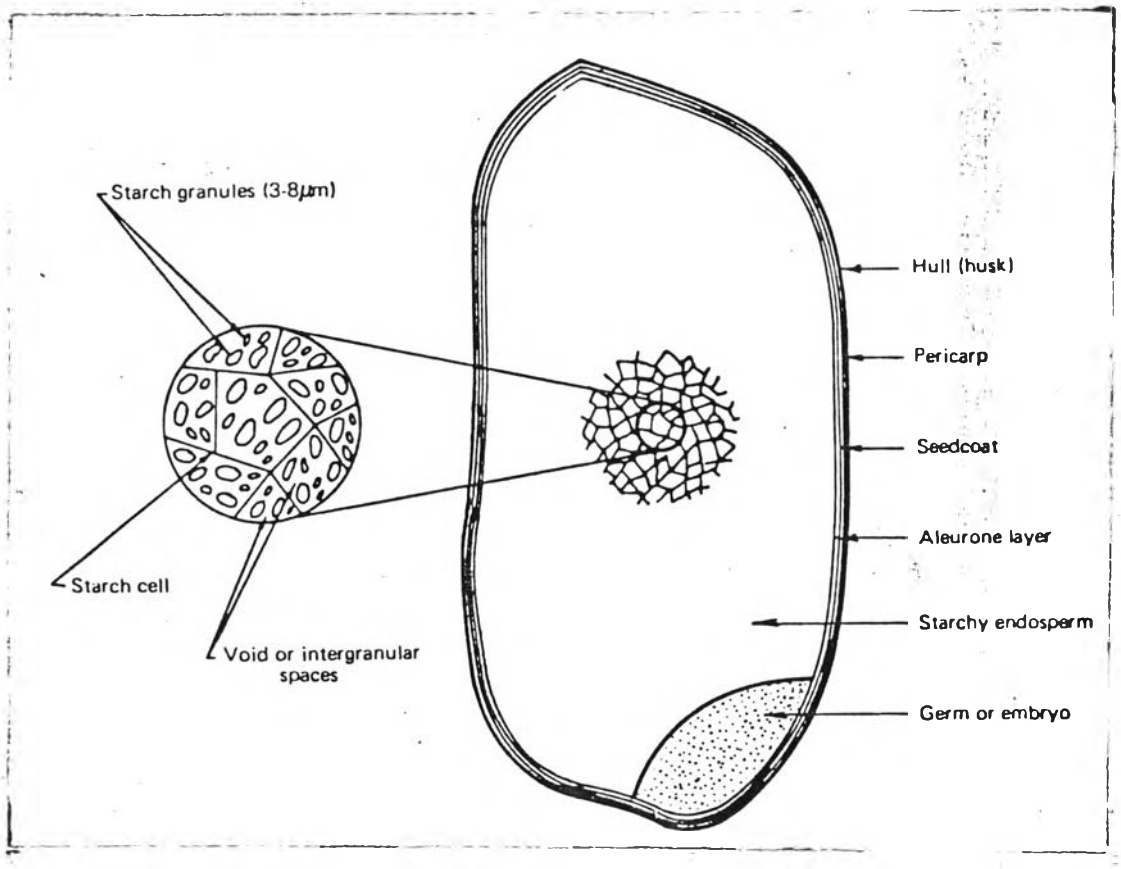

Figure 2-1 Diagrammatic representation of the structure of a paddy grain in longitudinal section

and swelling in cold water is due to the presence of hydrogen bonds between the amylose and amylopectin fractions of the starch. During hot soaking, energy supplied in the form of heat weakens the granule structure by disrupting the hydrogen bonds; therefore, more surface area is available for water absorption by the starch granules. This permits further hydration and irreversible granule swelling caused by the increase in the number of dissociated water molecules. This phenomenon is called gelatinization of starch. The temperature at which gelatization takes place is known as the gelatinization temperature and is specific for each variety. At the end of the gelatinization process, the paddy has a acquired a moisture content of about 45-50%* and must be dried before further processing. The starch in the paddy grain may be gelatinized by either of two methods: (1) the paddy may be soaked in water at or above its gelatinization temperature for a time, which depends on the variety; or(2) the paddy may be soaked in water at or below its gelatinization temperature for sometime to facilitate the uniform hydration of the rice kernel, and then heated to produce irreversible expansion and fusion of the starch granules. The heat should be moist, or the soaked paddy will start to dry. The best source of this heat is steam. This method is commonly used in practice.

* all moisture content values are based on dry basis

Chemical analysis of rice showsthat most of the nutrients, which are concentrated in the outer layers (bran and polish) of the rice kernel, are lost during milling. This lost of nutrients may be reduced to a certain extent either by consuming shelled or under-milled rice, or by making some of the nutrients present in the outer layers penetrate the kernel, so that they are not removed during milling. The former is not advisable because of consequent digestion trouble; however, if the paddy is soaked in water and subsequently steamed, the water soluble nutrients may be retained to some extent in the kernel.

2.1.2 Characteristics of the Paddy for Parboiling

The paddy varieties preferred for parboiling are those that are the most brittle because of the soft structure of their endosperm and those that give a low output after milling because of special conditions associated with cultivation, harvesting, and drying. Varieties that are long and slender are usually parboiled because they are fragile compared with short or medium length grains, which stand up better to the ordinary milling process. Scented and fine varieties, which have good milling quality, are generally parboiled.

Some characteristics of the paddy affect the final product both quantitatively and qualitatively[2]: (1) the presence of partially or fully shelled grains, which may be destroyed or misshapen by the process, cause the parboiling plant to function

irregularly; (2) the awn and hairiness of the husk may make the soaking operation difficult because of the tendency of the grains to float on the surface of the water, which produces scum and other waste materials; (3) the pigmentation of the husk and pericarp may be dissolved during the soaking and steaming operations and deepen the color of the endosperm; (4) bacterial infestation may cause a partial or total darkening of the endosperm; and (5) even minute injuries on the seed, caused either mechanically or by insects, may lead to partial discoloration of the parboiled rice.

2.1.3 Parboiling process

It is a hydrothermal process that may be defined as the gelatinization of starch within the rice grain. During the process, an irreversible swelling and fusion of starch granules occurs that changes the starch from a crystalline form to an amorphous one. As a result of this transformation, the orderly polyhedral structure of the compound starch granules changes into a coherent mass. Parboiling of paddy requires four steps: precleaning and grading, soaking, steaming, and drying.

2.1.3.1 Precleaning and Grading: It is of the greatest importance to ensure that all organic or inorganic impurities, which the soaking step would cause to ferment or remain in suspension, 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, all that is needed is to grade the paddy according to grain thickness.

2.1.3.2 Soaking: It is basically a diffusion process of simultaneous water absorption and swelling. The movement of water into the paddy will continue as long as the vapor pressure inside the grain is less than that of the soak water and will stop when equilibrium is reached. 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 avoidance of husk opening as far as is possible. If soaking time is too prolonged, certain substances contained in the rice may become dissolved in the water; and further, the seed may start to germinate if there is sufficient air in the water. This leads to many and complex changes of a biochemical nature, avoidance of which are of great importance in securing a good processing result.

Several modern processes have made practical experiments by adding special solutions to the soaking water to cause the rice to absorb substances which it normally lacks (e.g., calcium or vitamins), plus other solutions to prevent browning.

Water temperature and length of soaking time have an effect on the solubilization of substances in the rice, and on color, smell, and taste. The content of minerals or other substances in the soaking must be carefully considered, as they may affect the result of the process. The degree of hardness and the content of sulfides, such as H_2S, must be analyzed so that steps may be taken against any possible formation of sulfide compounds which may affect the smell and taste of the finish product. It has been pointed out that the color of milled rice is affected by the pH of the soaking water and by the possibility of adjusting it. Accurate studies are still necessary, however, to determine the most favorable pH for avoiding or reducing corrections. On the other hand, if the pH is too much reduced, this causes a hydrolyzing effect and the formation of compounds such as sugars and aldehydes which adversely affect the flavor of the finished product.

Apart from fermentation caused by the presence of organic impurities in the rice, the albumins which are solubilized during soaking can decompose, or rather hydrolyze, splitting up into the amino acids of which they are composed. Steam heating causes the sulfur amino acids to split up still further, freeing hydrogen

sulfide and other organic sulfide products of low molecular weights. Combining with alcohols produced by decomposition of lignin, a quantity of which the husks contain, these products form others of an odorous nature such as thio-alcohols and thio-ethers, which give a characteristic flavor and smell to some types of parboiled rice, and which can also be noted in the atmosphere surrounding the plants.

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 means, however, that the husks open to an appreciable extent, and part of the caryopsis comes out into the water, together with a great quantity of hydrosoluble substances contained in the rice. Water temperatures below that of gelatinization proportionately increase hydration times and reduce the quantity of water absorbed, as well as husk splitting and the amount of soluble substances in suspension. From this it may be deduced that the most suitable soaking temperatures lie between 60° and 70°C[2]. Theoretically, soaking of paddy can be done at, or below, its gelatinization temperature. The lower the temperature used, the slower is the process of soaking and vice versa. However, the temperature should not be more than 75°C, or the paddy will be cooked. Soaking time can be reduced by subjecting the paddy to vacuum for a few minutes before soaking and/or by soaking under pressure in hot water.

2.1.3.3 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 soaked paddy, rather it adds moisture by condensation, which increases the total moisture content of the grain. 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[2], (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. Apart from the spread of coloring pigments contained in the husk and bran, it seems that coloring of the endosperm is caused by absorption of reducing sugars that react with the amino acids, and by fusion of the aleurone layers of the endosperm with the starchy core. However, by steaming the paddy with non-pressurized steam (at 100°C), as in 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.

Generally, saturated steam at a pressure of 1-5 kg/cm^2 is used for steaming the soaked paddy in the different methods of parboiling[4]. The duration of steaming is dependent upon the quantity of paddy to be steamed. For small batches steaming takes 2-3 min; whereas, larger batches of about 6-8 t take about 20-30 min. It has been reported that splitting of the husk can be taken as an indication of completion of the steaming process[5],[6], although it is not a necessary condition and the paddy can be properly parboiled without any splitting of the husk. The steam requirement per ton of paddy parboiled in a modern parboiling plant using steam at a pressure of 4-5 kg/cm^2 is about 120 kg for soaking, 60 kg for steaming, and 20 kg in losses.

2.1.3.4 Drying: Steam-parboiled paddy is dried essentially for proper milling and storing, but it is different from drying raw paddy because the steamed paddy has a high moisture content (45-50%) and is hot. The main aim of the drying process is to reduce the moisture content to 14-16% without causing cracks or stresses in the rice caryopsis, which may lead to breakage during milling.

Removing of the excess moisture is so importance. If the moisture is removed at a very slow rate, microorganism will grow and partially or fully spoil the parboiled paddy. On the other hand, if drying is done rapidly and continuously, cracks may

develop and the rice will break during milling. However, if parboiled paddy is uniformly dried by any means (shade, sun, or hot air), practically no breakage will occur. Improper drying conditions may result in as high as 100% breakage; therefore, parboiled paddy should be dried with great care.

When parboiled paddy is dried rapidly, a steep moisture gradient develops between the surface and the centre of the kernel. This sets up a stress, and at a certain stage the kernel relieves the stress by cracking. These cracks are irreversible and set up lines of weakness, along which fractures easily occur under the mechanical stresses of milling. This behavior is also observed in the drying of raw paddy.

During drying, two points are of great importance. First, breakage does not occur throughout the drying process. Its occurs only when the moisture content reaches and then crosses 18%, no matter how fast the drying (Figure 2-2)[7]. After that, breakage

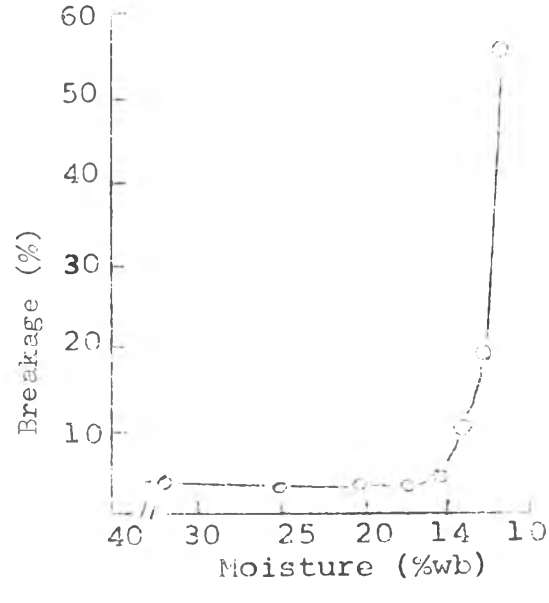

Figure 2-2 Change in milling quality of parboiled paddy during continuous drying in an LSU drier.

increased sharply. Second, the cracks do not develop during, but over a period of 2 h. after the drying has been terminated. Drying of parboiled paddy should be done in two passes to avoid the breakage of rice during milling, although some successful experiments have been carried out in which the parboiled rice was dried until the moisture content was low enough for milling. Presently, the drying of parboiled paddy is done in two passes that are separated by a tempering period. During the first stage of drying, the moisture content is reduced from about 50 to 25%. This is followed by tempering to equalize the moisture within the kernels. The tempered paddy is then dried to 14-16% moisture during the second pass. In actural practice the two methods that are commonly used are sun drying and mechanical drying.

Figure 2-3 and 2-4[4]. show the general nature of moisture removal from the grain during sun drying.

Mechanical drying of parboiled paddy is of quite recent origin. Hot air is forced through the grain, which evaporates and carries away the moisture. Most of the moisture in freshly parboiled paddy is surface moisture. The rate of removal of surface moisture from the grain is dependent upon the evaporating capacity of the drying air, which increases with temperature. However, after removal of the surface moisture, the rate of moisture removal is considerably reduced and depends upon the rate of moisture migration from the center of the grain to its surface, which depends on the characteristics of the grain.

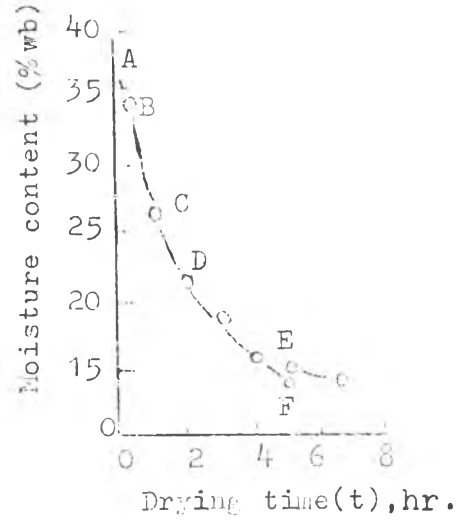

Figure 2-3 Variation of moisture content of paddy with drying time (sun drying) AB=heating period; BC=constant rate period;CD=first falling rate period;DE=second falling rate period; and EF=tempering for 2.5 hr.

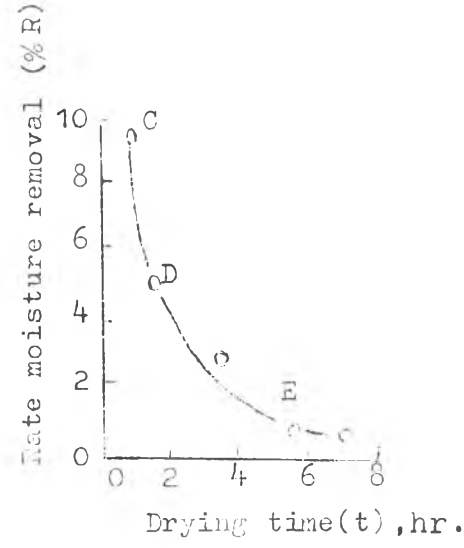

Figure 2-4 Variation of drying rate with drying time (sun drying):CD=first falling rate period;and DE=second falling rate period.

Therefore,[3] an increase in the temperature of drying air at this stage does not increase the drying rate. Unlike drying raw paddy, it is possible to use very high temperatures to dry parboiled paddy because of its increased hardness. To achieve faster moisture removal, drying air at a temperature as high as 120°C[4] is being used in commercial parboiling and drying plants. From the results of field experiments conducted by the Rice Process

Engineering Center, a combination of drying air temperatures has been determined to ensure optimum performance of mechanical drier. To remove the bulk of the surface moisture during the first drying pass, the temperature of the drying air is kept at 95-100°C. However, during the second drying pass, when moisture from the inner part of the grain is to be removed, the temperature of the drying air should be kept at 75°C because a higher temperature will not increase the drying rate but will only result in an increased heat loss in the exhaust air.

Many types of mechanical driers are used in drying of parboiled rice such as circulation continuous belt drier, fluidized bed drier, vibrating conveyor drier, rotary drier, air vacuum drier, and flat-bed drier. In modern parboiling methods, rice is heated in an air vacuum or by contact with hot surfaces instead of in driers through which currents of hot air pass.

When drying is finished and before milling is started, the rice must be stored for several hours, or better still for 2 or 3 days, to allow the moisture inside the grain to spread evenly throughout so as to avoid the creation of stresses between layers with different moisture contents.

2.1.4 Advantages and Disadvantages of Parboiling[3]

In general, the parboiling process has the following advantages:

1. shelling of parboiled paddy is easier because the

husk is split during parboiling;

2. the extra strength acquired by the rice kernel during parboiling helps reduce the number of brokens;

3. parboiled rice retains more proteins, vitamins, and minerals than raw milled rice of the same variety;

4. parboiled rice, because it is harder, is more resistant to insect infestation during storage compared to raw rice;

5. the loss of solids into the gruel during cooking is less in parboiled rice compared to raw rice;

6. parboiled rice withstands overcooking without becoming pasty; and

7. the bran from parboiled rice contains about 25-30% oil; whereas, raw rice bran contains about 15-20% oil. The heat treatment of paddy during parboiling destroys, to a certain extent, the lipase enzyme that is responsible for the hydrolysis of oil (development of free fatty acids); therefore, the oil is of a superior quality because it has a lower concentration of free fatty acids (FFA).

Parboiling has the following disadvantages:

1. heat treatment during parboiling destroys some natural antioxidants; therefore, parboiled rice develops more rancidity than raw rice during storage;

2. parboiled rice takes more time to cook to the same degree of softness than raw rice, and may develop a taste, texture, and characteristic flavor and color not liked by many raw rice eaters;

3. because the parboiled paddy has a high moisture content for a long time, mycotoxins that are hazardous to human health may develop;

4. parboiled paddy must be dried from 45-50% to 14-16% moisture for proper milling and storing, which adds an extra drying cost to the total processing cost;

5. shelled parboiled rice is more difficult to polish because it is harder, and consequently the mill throughput capacity is lowered and the milling power requirement is increased;

6. parboiled paddy may choke the polisher because of the higher oil content of the bran; and

7. the parboiling process needs an extra investment of capital.

In spite of these disadvantages, the higher outturn of total rice (about 1-2%) as well as head rice brings in additional profit to the miller and at the same time ensures a lower price to the consumer.

Table 2-1[8] shows the comparison of some properties between raw and parboiled rice.

Table 2-1

Property	Raw Rice	Parboiled Rice
Brown rice		
Hardness (Kiya tester)		
Breaking, kg.	5.40	9.60
Crushing, kg.	8.90	15.40
Moisture, % wet basis	11.67	11.63
Protein, % dry basis	9.99	9.86
Milled rice		
Head rice, % of milled rice	75.30	99.80
Amylose, % dry basis	17.00	16.40
Thiamine (γ/g)	0.50	2.50
Riboflavin (γ/g)	0.19	0.38
Niacin (γ/g)	16.40	32.17

2.2 Solid-Drying Fundamentals[9]

When a solid dries, two fundamental and simultanous processes occur: (1) heat is transferred to evaporate liquid; (2) mass is transferred as a liquid or vapor within the solid and as a vapor from the surface. The factors governing the rates of these processes determine the drying rate.

A study of how a solid dries may be based on the "internal mechanism" of liquid flow or on the effect of the "external conditions" of the temperature, humidity, air flow, state of subdivision, etc., on the drying rate of the solid.

When a solid is dried experimentally, data are usually obtained relating moisture content to time. These data are then plotted as moisture content (dry basis) M vs. time t, as shown in Figure 2-5a. This curve represents the general case when a wet solid loses moisture first by evaporation from a saturated surface on the solid, followed in turn by a period of evaporation from a saturated surface of gradually decreasing area, and finally when the water evaporates in the interior of the solid.

Although Figure 2-5a indicates that the drying rate is subject to variation with time or moisture content, this variation can be better illustrated by graphically or numerically differentiating the curve and plotting dM/dt vs. M, as shown in Figure 2-5b., or as dM/dt vs. t, as shown in Figure 2-5c. These "rate curves" show that the drying process is not a smooth, continuous one in which a single mechanism controls throughout.

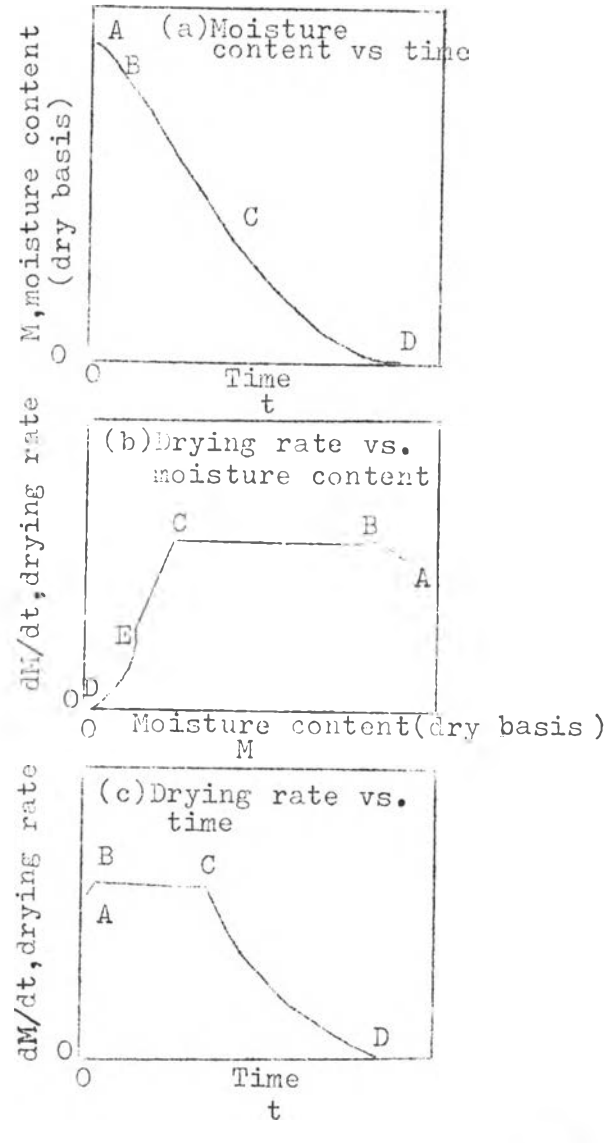

Figure 2-5 The periods of drying

Figure 2-5c has the advantage of showing how long each drying period lasts.

Section BC on each curve represents the "constant-rate period". In Figure 2-5a, it is shown by a straight line of

constant slope dM/dt, which becomes a horizontal line on the rate curves in Figure 2-5b and c.

The curved portion CD of Figure 2-5a is termed the "falling-rate period" and, as shown in Figure 2-5b and c, is typified by a continuously changing rate throughout the remainder of the drying cycle. Point E (Figure 2-5b) represents the point at which all the exposed surface becomes completely unsaturated and marks the start of that portion of the drying cycle during which the rate of internal moisture movement controls the drying rate. Point C, where the constant rate ends and the drying rate begins to fall, is termed the "critical moisture content". Portion CE of Figure 2-5b is usually defined as the first falling-rate drying period, portion DE as the second falling-rate period. The portion AB represents a warming-up period.

2.3 Fluidized-Bed Drying

2.3.1 Fundamental Concepts[10]

When a fluid is made to flow through a layer of particles which rest on one another and do not change their position, i.e., they do not move relative to one another nor relative to the walls of the container. Such a layer is termed a "fixed bed". A layer of particles moving as a whole under the action of gravity is known as "moving bed" (e.g. the charge of a blast furnace). The velocity of fluid in the spaces between the particles, the

"interstitial velocity", is greater than its velocity in the free cross section, which is known as the "superficial velocity". On increasing the rate of flow of fluid, the pressure drop across the bed will also be increasing until, at a certain rate of flow, the frictional drag on the particles will become equal to the effective weight of the bed. This condition, and the velocity of fluid corresponding to it, are termed "incipient fluidization" and "incipient fluidizing velocity" (or "minimum fluidizing velocity"), respectively; in this state the bed of particles attains properties similar to those of fluids and is called a "fluidized bed". The particles of fluidized bed float in the fluid and intermix.

In fluidized drying the process is carried out in a bed fluidized by the drying medium. It may be operated as a batch or continuous process.

2.3.2 Minimum Fluidizing Velocity

On set of fluidization

$$\Delta p.Ac = W = (Ac.Lmf)(1-\varepsilon mf)\left[(\rho s-\rho g)\frac{g}{gc}\right] \qquad (2\text{-}1)$$

by rearranging, we find for minimum fluidizing conditions that

$$\frac{\Delta p}{Lmf} = (1-\varepsilon mf)(\rho s-\rho g)\frac{g}{gc} \qquad (2\text{-}2)$$

Umf, the superficial velocity at minimum fluidizing conditions, is found by combining Eq.(2-2) with Eq.(2-3), the pressure drop through fixed beds of uniformly sized solids, has been correlated by Ergun[11].

$$\frac{\Delta p}{Lm} \cdot gc = 150\frac{(1-\varepsilon m)^2}{\varepsilon m^3}\frac{\mu g Uo}{(\phi sdp)^2} + 1.75\frac{1-\varepsilon m}{\varepsilon m}\frac{\rho g, Uo^2}{\phi sdp} \quad (2\text{-}3)$$

In general, this gives a quadratic in Umf:

$$\frac{1.75}{\phi s \varepsilon mf^3}\left(\frac{dp.Umf\,\rho g}{\mu g}\right)^2 + \frac{150(1-\varepsilon mf)}{\phi s^2 . \varepsilon mf^3}\left(\frac{dpUmf\rho g}{\mu g}\right) = \frac{dp^3 \rho g(\rho s-\rho g)g}{\mu g^2} \quad (2\text{-}4)$$

In a bed at on set 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 εmf from random packing data, or, better still, it should be measured experimentally, since this is a relatively simple matter.

2.3.3 Pressure Drop in Fluidized Beds

Figure 2-6[12] is typical for uniformly sized sand particles. For the relatively low flow rates in a packed bed the pressure drop is approximately proportional to gas velocity as indicated by Eq.(2-3), usually reaching a maximum Δp max slightly higher than the static pressure of the bed. With a further increase in gas velocity, the packed bed suddenly "unlocks"; in other words, the voidage increases from εm to εmf, resulting in a decrease in pressure drop to the static pressure of the bed, as given by equation (2-1). With gas velocities beyond maximum fluidization the bed expands and gas bubbles are seen to rise with resulting nonhomogeneity in the bed. Despite this rise in gas flow, the pressure drop remains practically unchanged. To explain this constancy in pressure drop, note that the dense gas-

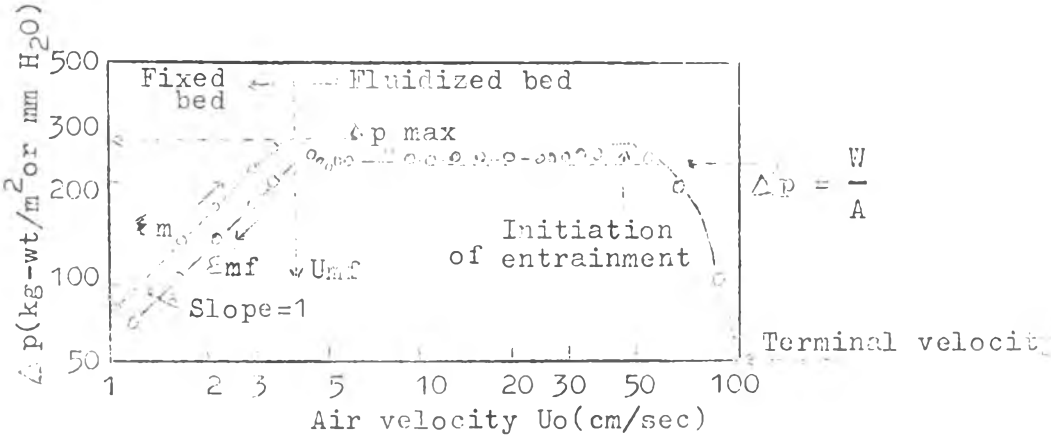

Figure 2-6 Pressure drop versus gas velocity for a bed of uniformly sized sand particles

solid phase is well aerated and can deform easily without appreciable resistance.

A pressure drop versus velocity diagram is useful as a rough indication of the quality of fluidization, especially when visual observation is not possible. Thus a well fluidized bed will behave as in Figure 2.6. Note here that observed pressure drop data may deviate slightly from the calculated value of equation (2-2). This can be attributed to the energy loss by collision and friction among particles as well as between particles and the surface of container. The diagrams in Figure 2-7[12] are examples of poorly fluidized beds. Thus the large pressure fluctuations in Figure 2-7a suggest a slugging bed, whereas an absence of the characteristic sharp change in slope at minimum fluidization and the abnormally low pressure drop in Figure 2-7b suggests in complete contacting with particles only partly fluidized.

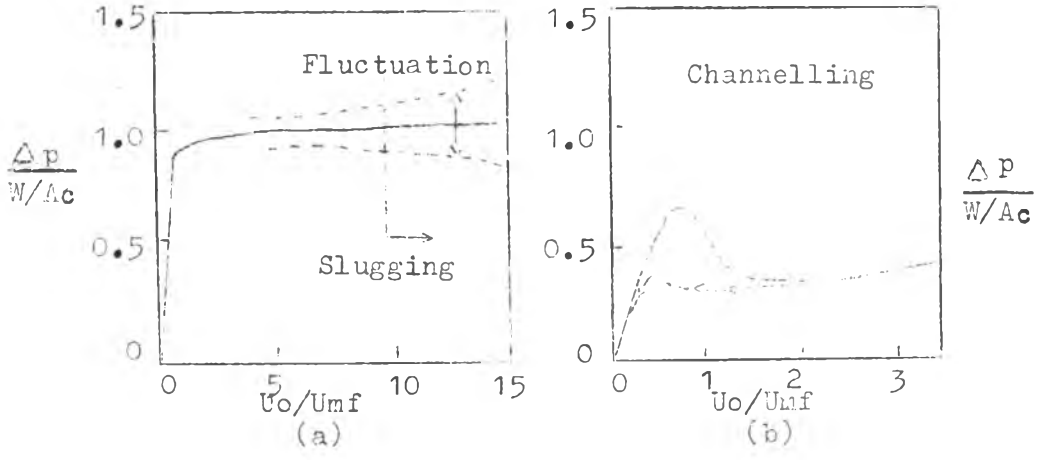

Figure 2-7 Pressure drop diagrams for poorly fluidized beds.

2.3.4 Heat Transfer in Fluidized Beds

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 (see Figure 2-8)[10].

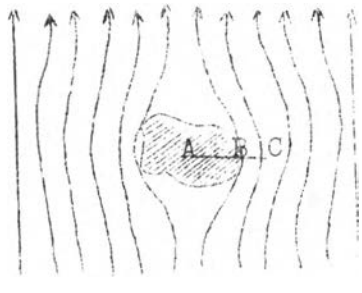

Figure 2-8 Heat and mass transfer in the drying of a particle in a fluidized bed. The drying medium flows around the particle. Collisions with other particles, occuring incessantly, are not indicated in the figure. A-inside of particle, B-surface of particle, C-drying medium.

Heat is transported 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 surroundings 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 temperatures at B and A. The driving force for the overall transport of heat from the surroundings 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[13] as correlations of dimensionless numbers in the form

$$Nu_p = c\, Re_p^m \qquad (2\text{-}5)$$

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 McKibbens, Donnadieu, 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.

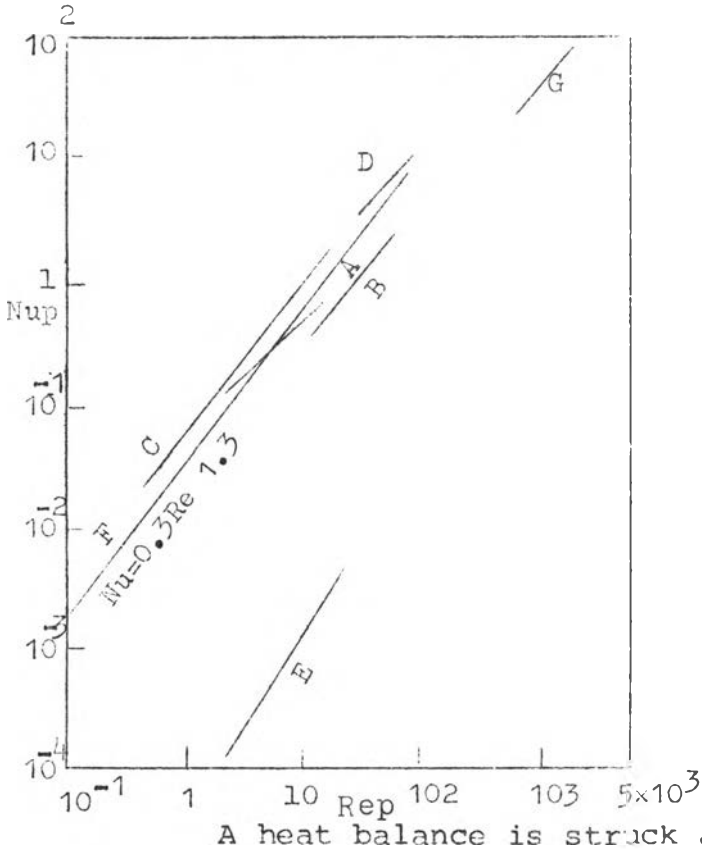

Figure 2-9[13] Experimental results

A) Lemlich and Caldas

B) Kettering,Mansfield and Smith

C) Richardson and Ayers

D) Heertjes and McKibbens

E) Ferron

F) Kunii and Levenspiel

G) Pfafflin,Shridhar and Jullien

A heat balance is struck among the heat entering and leaving the expanded bed, the heat given up to the bed solids, and 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 is 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.

$$\left(\begin{array}{c}\text{heat into bed}\\ \text{by gas}\end{array}\right) - \left(\begin{array}{c}\text{heat out}\\ \text{by gas}\end{array}\right) = \left(\begin{array}{c}\text{heat transferred to}\\ \text{bed solids}\end{array}\right)$$

or, in symbols,

$$Ac.Uo. \int g.Cpg\ (Tgi-Tgb)dt = h_p.As\ (Tgi-Tgb)dt \qquad (2-6)$$

$$q_h = Qo. \int g\ Cpg\ (Tgi-Tgb) = h_p\ As\ .\ (Tgi-Tgb) \qquad (2-7)$$

where q_h is the rate of heat transfer (Joules/sec), Qo is the volumetric flow rate of air (m^3/sec), and h_p is the heat transfer coefficient between hot air and particles (Joules/sec.m^2.^oK)

The heat transfer coefficient can be solved from equation (2-7), and can be simplified to

$$Nup = c\ Rep^m \qquad (2-5)$$

becauses, Nup = Nusselt number for gas-particle heat transfer, dimensionless.

$$= \frac{h_p.d_p}{k_g}$$

$$Rep = \text{particle Reynolds number, dimensionless}$$

$$= \frac{dp\ Uo\ \rho g}{\mu g}$$

by taking logarithm at both sides of the Eq. (2-5),

$$\log Nup = \log c + m \log Rep \qquad (2\text{-}8)$$

from Eq.(2-8) the empirical constants c and m of the system can be found by plotting the logarithmic graph of Nusselt number versus Reynolds number.

2.3.5 Advantages and Limitations of Fluidized Bed Drying[10]

Fluidized bed drying has the following advantages over other methods of drying:

1. High intensity of drying. The rate of moisture removal in fluidized dryers may be as high as several hundred kilograms of water per hour in 1 m^3 of dryer volume. Only pneumatic dryers have competitive rates.

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. are attainable when the drop in moisture content is high and the drying temperature is not excessive, or when a multistage dryer is employed. 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 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 dryers are compact and of relatively small size. The capital costs are much lower than for other types of dryers (e.g. rotary dryers). Heavy buildings and foundations are not needed; the dryer can be situated under a light roofing.

9. Several processes may be combined in a fluid-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 fluidized state, and both operations can be carried out in a single piece of equipment, consisting of several stages. In processing a solution, the evaporation of water and granulation of the solid take place simultaneously. For the conventional method of processing, two pieces of equipment

are needed: an evaporator and a crystallizer or granulator. In some cases fluidized drying may be combined with a chemical process. So, for example, superphosphate may be dried in a fluidized state with unpreheated air containing a small amount of ammonia vapour; the ammonia reacts with the residual free acid, and the heat of neutralization is a sufficient source of heat for the process.

However, fluidized drying has the following disadvantages:

1. A higher pressure drop for the dryer and dust separator the pressure drop amounts to at least 300 to 500 mm w. 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.

2.3.6 Applications of Fluidized-Bed Drying

Fluidized drying is one of the modern methods of efficient drying and is finding ever-growing applications in diverse

industries. Fluidized beds have been used for drying so many materials in production processes since 1949, a Dorr-Oliver Fluo Solids dryer[14], one of the first commercial dryers was used for drying and sizing of dolomite. It performs satisfactorily, giving a better product quality and requiring a smaller fuel consumption than comparable conventional dryers. For a sharper classification of coarse and fines this type of single stage unit may not be adequate. Fluo Solids dryers have been widely used to dry materials such as limestone, dolomite, coal, blast furnace slag, and plastics.

High thermal efficiency results from the large temperature difference between hot inlet gases and the uniform low temperature of the bed in which vaporization occurs. However, for certain temperature-sensitive materials the inlet gas temperature must be lowered. To counter the resultant reduction in thermal efficiency, heat can be recovered from the discharged dried solids. An example of such an arrangement is the two-stage salt dryer, installed at a plant of the Carey Salt Company in 1954[15].

Toei (1956)[16], and Imasaka and Amano (1958)[17] showed multistage designs where perforated plates act both as gas distributors and stage separators, thus eliminating over flow pipes and downcomers. A multistage operation improves the thermal efficiency, but more important still, it gives a more desirable residence time distribution for the solids,

Vanecek and Drbohlav (1966)[10] summarized all published data on fluidized drying of various materials into Table 2-2.

Table 2-2 Survey of Applications of Fluidized Drying

Material	Source Reference
Granular solids	
Inorganic substances	
uminium hydroxide	152
unite	236
nmonium sulphate	67
rium chloride	227
ast-furnace slag, granulated	Table 6-2
mpound fertilizer, granulated	Table 6-2; 234
lomite	238
amels, raw materials for	241
rous sulphate	Table 6-2; 39; 227
lsonite	164
psum	23; 39; 202
enite	Table 6-2
mestone	46; 164
agnesium trisilicate	201
tassium carbonate	160
tassium chloride	124
tassium permanganate	Table 6-2
tassium sulphate	124
rites, flotation concentrates	81
nd	Table 6-3; 184
da	57; 124
dium bicarbonate	70; 167
dium chloride	120; 164
dium dichromate	67
dium phosphate, tertiary	67
dium sulphate	Table 6-5; 39; 124
perphosphate	135; 218
Organic substances and others	
ipic acid	99
pirin and other pharmaceuticals	261
nzene sulphonamide	Table 6-2
ric acid	67
al	24; 46; 60; 164; 172
ments	237
x	175
latine	193
Grain	Table 6-2; 8; 22; 32; 69; 72; 115; 283
Ion exchanger (phenol formaldehyde)	Table 6-2
Lactose	201
Leguminous plant	175
Paper	108; 262; 263
Pentaerythritol	99
Polyethylene	172; 238
Polymers and copolymers, various	189
Polypropylene	261
Polystyrene	67; 99
Polyvinylbutyral	99
Rubber, synthetic	29; 164
Sawdust, wood shavings	64; 74
Sebacic acid	99; 100
Seeds	241
Sugar	131
Urea	Table 6-2
Volcanic ash	62; 174
Yeast	126
Solutions, suspensions, melts, and pastes	
Ammonium sulphate	158
Aluminium nitrate	119; 122
Calcium chloride	Table 6-5; 158
Calcium nitrate, tetrahydrate	Table 6-5
Dyes, pastes	185; 187
Dyes, suspensions	153
Fertilizer melts	204
Sea water	90
Sodium chloride	Table 6-5; 90
Sodium cyanide	158
Sodium hydroxide	158
Sodium sulphate	Table 6-5; 125; 252
Sugar	153
Uranyl nitrate	122
Special cases	
Fabrics	84; 85; 108; 172; 209; 262; 263

During the past decade, fluidized-bed technique has been paying more and more important roles in drying system. The technique has been studied, improved, and scaled up for industrial processes. The works done on fluidized-bed drying, as shown in articles published between 1970-1978 are summerized in the Table 2-3 down below.

Table 2-3 Summary of Applications of Fluidized Drying

Year	Main Features	Ref.
1970	1) Characteristics, type (batch, continuous 1-stage, counter-stream multistage, multichamber, and spouted bed), and application data for large food granules such as fruits, vegetables, and meats of the fluidized dryers were described.	18
	2) Continuous drying in a fluidized bed and its uses in the food industry were discussed.	19
1971	Granular esters were dried in a fluidized-bed. An equation for the drying time was obtained by dimensional analysis; and the corresponding empirical equation was obtained from the experimental data. The drying	20

Table 2-3 (Continued)

Year	Main Feature	Ref.
	effect was inversely propertional to the ratio of gas supply to the stagnation time.	
1973	1) The operating parameters for lake salts particles (0-30 mm.) were determined in a fluidized bed divided by a baffle into drying and cooling sections (1.2 and 0.7m^2, respectively). The NaCl content in the product was 99.5218%(dry wt.) The capacity was 9350 kg dry salt/hr.	21
	2) A fluidized-bed drying apparatus for crystal sugar was described, in which a new type of air-distribution network was used.	22
	3) Tests in a 4-in.-diam. column on the drying of aq. Na_2SO_4 in a fluidized bed (initial Na_2SO_4 charge 3.042 kg, -80 to +150 mesh) by hot air (130-270°C) with soln. (concn. 10 and 20 wt.%) sprayed in at 0-15 mL/min. showed that it could be dried a temp. as low as 130°C. The average particle size increased slightly with decreasing bed temp. and increasing soln. concn.	23

Table 2-3 (Continued)

Year	Main Features	Ref.
1974	1) Sodium caseinate was dried in a fluidized bed of an inert material.	24
	2) The parameters affecting the kinetics of the drying of loose materials (e.g.quartz sand) in a fluidized bed were studied.	25
1975	1) The rate of granular sugar drying in a fluidized bed could be increased 1.5-1.9 times when instead of a steady flow of hot air a pulsating flow was used.	26
	2) Experiments were carried out in a pilot plant on the drying of irregular 5-20 mm. particles of carbonate gravel in a vibro-fluidized bed.	27
	3) With fluidization, granulates could be prepared directly from the soln. in a continuous process. The point of the direct granule forming was that the soln. to be processed was sprayed on the surface of solid particles fluidized with hot air. The results of experiments carried out under unsteady-and steady-state conditions were summerized.	28

Table 2-3 (Continued)

Year	Main Features	Ref.
	4) Modeling of drying of coal in a fluidized bed with a solid heat transfer agent was studied.	29
	5) The design and operation of a fluid bed dryer system which converted radioactive liq. wastes to an anhyd., free-flowing salt suitable for packaging and offsite shipment when combined with a suitable binder were described.	30
	6) Aqueous solutions of aminoplasts or phenolic resins were continuously dried and mixed with powder fillers and pigments using a fluidized bed technique. The dry powder formulation obtained in the fluidized bed was continuously processed to molding and extrusion apparatus.	31
1976	1) Crushed butadiene (SKD) rubber was dried with superheated steam at 150-180 ^{o}C and pressure of 0.5-2.5 kg/cm^{2} in a vibrofluidized-bed to residual moisture content of 0.1% within 2-3.5 min.	32

Table 2-3 (Continued)

Year	Main Features	Ref.
	2) Heat consumption and processing time were reduced in the drying of agglomerated solid fuel granules containing ≤ 10% moisture by allowing the granules to become immersed in the upper layers of sand in a fluidized bed apparatus used in the drying process.	33
	3) Studies on the drying and granulation of medicinal ascorbic acid,norsulfazole, and tetracycline Ca salt powders on fluidized beds by continuously operating apparatus showed that the build up of static electricity could be prevented by proper control of the voltage, rate of air flow, mixing speed, and other conditions.	34
	4) Polydispersed materials, especially molding comons., were dried by heating in a fluidized bed. The heating was in 2 stages to accelerate the drying. Between the 2 stages, when the material moisture content was 10-15%, air at 20-40% was blown through the material and vibrations imposed on the fluidized bed.	35

Table 2-3 (Continued)

Year	Main Features	Ref.
	5) Thermosensitive materials, especially grains, were dried by heating the mixture of the raw and recirculating material in the suspended state, formed by the drying agent, followed by cooling of the mixture in a fluidized bed. To improve the heat and mass transfer, the material was heated and cooled alternately in 2 stages, with the drying-agent temp. being 100-140 $^{\circ}$C higher in the 2nd stage than that in the 1st stage.	36
	6) Drying of Amberlite IRC-72 ion-exchange resin in a fluidized bed was investigated. Resin water content was measured as a function of drying time for various drying temps., bed loadings, and air flow rates. An incomplete eq. for the induction period and complete model for constant rate of drying were developed.	37
1977	1) Aerodynamic characteristics of fluidized bed (cylindrical chamber) cold air drying of enzymic casein layers were studied.	38

Table 2-3 (Continued)

Year	Main Features	Ref.
	Formulas were given for treatment of experimental data. With loads of 200-900 Pa on the supporting lattice the moisture level changed 10-60%.	
	2) Fluidized-bed drying of nitrile rubber crumb feasibility, design and scale-up were studied.	39
	3) Fluoro rubber emulsions were coagulated, and the rubber particles were dried in fluidized bed at 50-100 °C to give granular rubber containing > 95% 3.5-24 mesh granules.	40
1978	1) Some problems of powder handling were discussed on the basis of hypothetical case involving the dewatering of a crystallized product by an automatic, batch centrifuge and drying the cake in fluidized-bed dryer.	41
	2) Brines containing NaCl, KCl, and $MgCl_2$ (e.g., carnallite liquor or brine tailings) were dried with hot gases at 120-250 °C in a NaCl fluidized bed until the NaCl : (KCl + $MgCl_2$) ratio was 2-4:1.	42

From the literature survey, fluidized-bed technique can be applied for the drying of granular materials and results in high thermal efficiency. This drying technique also does not destroy the nutritions value when applied for food products. Parboiled rice is both grain and food, therefore, this technique was chosen for the experiment of drying parboiled rice.