CHAPTER 2

LITERATURE SURVEY
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2.1. AWARENESS OF RECLAMATION AND DEVELOPMENT IN CHRONOLOGICAL ORDER

2.1.1. Past Literature

Moulding sand reclamation is defined as the treatment of “individual grains” to restore them a physical state approximate to that of new sand by producing casting results equal to or better than new sand without increased cost in binders and additives.

It was in 1926 Pat Dwyer prepared a series of articles summarizing the sand reclamation status. At that time he collected details by correspondence and interview with foundrymen who had tried means and methods to extend the useful life of their old sand. He concluded that a more general promotion of sand reclamation would have to wait for:

1.) The development and distribution of additional information on foundry sands and sand controls.

2.) A parallel development of equipments and methods able to satisfy the economical/technical requirement of an average foundry.

It was not until around 1938 that the work of different investigators initiated the development of successful wet reclamation methods.

In 1943, it was well known that discarded and excessively used moulding sand can be processed into a product, identical in properties to new core sand.
Shortly there after, wet reclamation methods and several types of thermal reclamation systems made their appearance\textsuperscript{6,7}.

In 1948, Cummings and Armstrong applied standard mining equipments for Foundry sand reclamation\textsuperscript{8}.

Again in 1948, a pneumatic installation was designed in the literature; most of these methods and systems were accepted as being satisfactory, in accordance with the condition and requirements. However, none seemed to be sufficiently free of technical economical or operational limitations, to win a ready acceptance by the industry as a whole\textsuperscript{9}.

Only in 1948 the steel Foundries society was made to recognize the need for additional basic information so as to authorize a research project to study reclamation. The project was initiated to:

a.) Determine the most detrimental contaminant influencing the reuse of old sand.

b.) To evaluate the comparative merits of different methods in reclaiming clay containing sands, for reuse in molding mixtures.

In 1949, Bennett outlined the features of sand reclaiming apparatus\textsuperscript{10}.

E.C.T. Roy, from the evidence accumulated several years ago, came to conclusion that selective removal of burned bonding substance was not only desirable but possible\textsuperscript{11}.
H.H. Johnson, R.Y. McCleery and G.A. Fisher decided to install a sand reclamation unit of the “Wet” type and operations of the unit was begun on May 5, 1949. The reclamation unit used was essentially a standard unit created at 15 tons per hour had been praised by both the manufactures and users.

In 1950 another investigation by a manufacturer of foundry equipment culminated in the creation of a new reclamation method, based upon a pneumatic dry scrubbing of sands and individual sand grains.

In 1952 Clifford E. Weinninger presented a paper on Pneumatic reclamation for foundry sands. The key unit in that method was an “Air Scrubber” that functions in the dry reclamation system, in a manner similar to the functioning of a “Wet Scrubber” in a wet reclamation System. This paper presented information on the successive stages in the development, design and function of an “Air-scrubber”, the arrangement of component units in a typical installation, the characteristics and economics of commercial installation, which has been in operation for sometime.

During the course of an investigation at the University of Kentucky it was demonstrated that successful sand reclamation requires that old clay and carbonaceous bonds be removed from individual sand grains and that fragments and particles of such bonds be then removed from a sand mass as a whole with additional investigation. It was concluded that wet reclamation methods, seemed to be superior to existing dry reclamation methods in meeting the foregoing requirements. However, it was noted that most of the dry methods studied, involved the use of equipment units that in reality had not originally been designed for purpose of reclamation. In the final
Reclamation of CO₂/Sodium Silicate Sand in Foundry Literature Survey

report of the investigation, it was suggested that possibly dry reclamation methods could be improved upon, if more consideration were given to designing equipments to specifically meet the reclamation standards.

In 1952, H.H. Fairfield, James Mc Conaiche and H.F. Gritam\textsuperscript{17} reported a device for reclaiming used steel foundry sand, where dry sand was blown through a turbulent air stream and reported the effect on sand properties. Sand so treated was used in molding and cone sand mixtures.

2.1.2. Need Felt for Reclamation

Cost of new sand, sand mixture ingredients, increasing difficulty and expense experienced in the disposal of used sand made it imperative that foundries make greater use of their used or discarded sand. This may be done by either reconditioning or reclaiming used sand.\textsuperscript{18}

In 1953 James A. Cannon\textsuperscript{19} gives his practical experience that reclaimed sand produced during an eight month period with a dry method of reclamation unit resulted in decreasing the amount of new sand used by more than 75\%. The author gives a graphical analysis of changes in screen analysis during reclamation of sand. He took daily samples of reclaimed sand to obtain A.F.S. The data were obtained from sampling of new sand delivered at the core room. He plotted these values and averaged every month. This work summarizes and compares screen analysis of new sand and reclaimed sand for these eight month period.
In the same year 1953, P.C. Will and R.H. Shurmer\textsuperscript{20} presented in their paper showed by means of direct comparison, that waste sand reclaimed by the wet method had been found to be equivalent to new sand in physical properties, grain size distribution, casting finish and the quality. This has all the attributes of new sand for foundry purpose and it can be produced for a fraction of the cost of delivered new sand without sacrifice in casting quality.

G.H. Curtis\textsuperscript{21}, outlines the various steps in the combination system of reclaiming sand and focuses upon the quality of the product, with the standpoint of the quality of sand, as measured by tensile strength, fineness and residual substances. It has been indicated as to what part the burning phase has taken in the cleaning of the sand. From the standpoint of operating costs, it has been indicated that in actual commercial installations, the cost of thermally reclaimed sand is much less than new sand and sometimes less than the drying of sand.

In 1970 a working group was formed and it originally appointed a committee by technical council with the following terms of reference:

- "To deal with the reclamation methods of sands"
- "To study the use of reclaimed sands in foundries" \textsuperscript{22}

In 1970, A.D. Morgen a member of F.G.A. explained the basic requirement of Sand reclamation. He explained therein the different reclamation methods, effectiveness of reclamation treatment, requirements for cleaning claybonded sand, silicate bonded sand, resin bonded sand by thermal means and by dry attrition. He concludes that when present knowledge concerning the reclamation of sand is
considerable, there is still much to be learnt, particularly with regard to the treatment of clay bonded and silicate bonded sands, because these materials present the greatest problem in cleaning for reuse appears to be particularly difficult to remove the last traces of clay and silicate particles from the sand grains\textsuperscript{23,24,25}.

In 1974, in a paper of Dr K. Srinagesh\textsuperscript{26}, it was shown that reclamation with modern equipment of mold and core sand bonded with any kind of binder, organic or inorganic, can be done on a scientific basis. Mathematical relations starting from first principle were derived wherein stability of the system can be accurately calculated. The various components of the systems can be individually observed and controlled. Using these relations it should be possible to analyze the limitations of possibilities of a sand reclamation unit and to operate it to best advantage.

That very year, A.J. Whittle\textsuperscript{27} in his paper tells why sand reclamation was economically justified in a large steel foundry. He describes the principles of pneumatic sand reclamation and lists the parameters which must be monitored for its successful operation and maintenance required for the system.

Again in the same year, A.C. Den Breegen\textsuperscript{28} reviewed the earlier work in reclamation, bringing the subject matter into view, as related to present day knowledge and practice. Briefly the methods and process available at the present time for reclamation were indicated. Basic tests were given as guidelines to assist in the selection of reclamation equipments, to meet today’s sand reclamation requirements for foundry.
In 1976, L.L. Fosbinder and B.E. Boardman\textsuperscript{29} evaluates the potential of using pneumatically cleaned foundry sand in oil-bonded cores. The effects of cleaning are related to retained clay strength and combustibles screen analysis and tensile strength. He used numerous scanning electron micrographs to illustrate the effects of pneumatic reclamation on the sand, and the difference between bonds in cores using new and reclaimed sands. The paper concluded that reclaimed clay bearing system sand is suitable for reuse as system sand but not for oil core sand.

In 1977, J. Geremia\textsuperscript{30} in his paper reviewed the present method of reclamation such as air classification, dry abrasion, pneumatic scrubbing, roto conditioning or wet scrubbing as well as future improvement of present methods like thermal reclamation and combination of reclamation methods.

T. Ithoh and N. Suzuki\textsuperscript{31}, in 1980 analyzed the use of excess heat at a plant in which thermal sand reclamation being practiced. In the operational aspect, a combination of slight operating adjustments such as maintaining a proper air to fuel ratio, will certainly contribute to great savings.

G.J. Bolton\textsuperscript{32} in his paper in 1983 explains that Synthetic Amorphous Hydergel (SAH) bonded sands can be mechanically reclaimed at high or economically attractive yields. Reclaimed bonded sands can be recycled to produce good castings. Use of the reclaimed sand does not cause shake out problem. The core and mould performance are not changed by using reclaimed sand.
2.1.3. **Historical Developments for Sand Reclamation over a Decade**

From positive results with a series of test castings, D. Lawson and D.S. Leidel\textsuperscript{33}, in 1984, indicated that no negative effects are to be expected. Using the methods described, net cash savings for the foundry can be expected, with an initial investment payback in about 1.5 years. Reclaiming sand for use as a new sand substitute is an interesting low-cost alternative for foundries with low-core or no-core jobs requiring new sand additions to their moulding line. The reclamation system will render net cash savings for a foundry operation, while at the same time will reduce the generation of waste materials. A closed sand system operating in conjunction with a thermal and pneumatic reclamation system using high quality sand will yield the highest quality castings at the lowest manufacturing cost.

According to D.S. Leidel\textsuperscript{34} in 1985, the reclaimed sands which have been exposed not only to heat but also to adequate attrition, provide significantly lower surface areas than new sand, thus offering potential binder savings for the same performance of the moulding aggregate.

Traditionally, one of the advantages of the CO\textsubscript{2} process has been its relatively low raw materials costs and ready availability. Both carbon-dioxide and sodium silicate are indigenous materials and are independent of the oil industries. High strength resin processes have however caused low addition rates, good mixing practice and good reclamation ability, British Foundryman published in 1987. The ability to reclaim CO\textsubscript{2} silicates to the reuse levels of about 80\% or more, with mixed sand reductions of 40\% has revived interest in this clean and well established system\textsuperscript{35}.
In 1988, Jerry W. Kucharczyk and Dieter S. Leidel\textsuperscript{36} describes the combined cooling and reclamation of sand is a cost effective method for productivity improvement and cost control, specifically for small and medium foundries.

In the same year Paul M. Bralower and Micheal F. Burditt\textsuperscript{37}, with the prospect of fewer dump sites and higher restrictions, new technology and research promise led to greater rewards and fewer headaches by the use of reclaimed sand.

In 1993, L. Bailey\textsuperscript{38} stated that thermal reclamation is a relatively simple step. It will create a positive cash flow situation in order to address some of the more serious disposal and emission problems associated with the respective foundries. In an ideal world, 100% recycling is not possible, but, in terms of expenditure and income, a positive cash flow can be demonstrated, provided conditions can be met, irrespective of whether the sand system uses green sand or chemically bonded sand and irrespective of the binder system. The added value that can be generated into the waste sand can make residues that cost money to dump more valuable than the new sand purchased.

In 1994, different group of authors dealt with the successful reclamation of sand for reuse in chemically bonded systems. For the phenolic urethane cold box, furan nobake and phenolic ester nobake systems, acceptance results were obtained using mixtures of 100% reclaimed sand\textsuperscript{39}. Blending the reclaimed sand with new sand was not a requirement for satisfactory results with any of the systems, but it was found to improve results for all systems except the phenolic urethane nobake system.
Thermal processing is not always avoidable, but it must be limited to the absolutely necessary minimum\(^40\).

Application of high temperature, over long times, which leads to fusion of inorganics onto the base sand grain, must be questioned.

The use of low temperature reclamation has been documented to offer advantages. It is important to note that low temperature reclamation applies to a temperature level, two to three times as high as high-temperature reclamation.

The addition of oil methane binder significantly improved the microwave heating of silica sand. Selective heating of the oil urethane binder initially resulted not only in decomposition of the binder, but also in heating of the silica sand to temperatures higher than 600°C within 10 minutes. Sand mixed with phenolic urethane or furan binder did not demonstrate apparent improved microwave heating.

It was found that loose sand, which contains less unburned binder and chromite sand, could be heated by microwave irradiation, much faster than lump sand containing more unburned binder. The presence of the residual carbon and chromite in the loose sand and the interaction between the residual carbon, chromite and microwaves resulted in a faster heating rate.

Some critical properties of sand moulds made from microwave reclaimed sands, such as tensile strength and permeability, were equivalent to those made from sands heated by conventional thermal reclamation methods\(^41\).
The successful use of microwave heating to selectively remove organic binders from used foundry sands depends on maintaining macroscopic homogenous heating and microscopic selective heating.

It is theorized that, to obtain macroscopic homogenous heating and microscopic selective heating, a flow-through sand handling system and a microwave cavity that is designed to provide more evenly distributed power needed.

Reconditioning of used sand, involves reducing used moulding sand lumps to individual sand grains, removing metallic particles, sintered clusters of sand grains, excess fines and other tramp and objectionable materials.

Thus it is clear from the literature survey that reclaimed sand is the used sand that has been restored to comparable quality of a new sand purchased by a foundry; it may be satisfactorily substituted for new sand in moulding sand mixtures without appreciable change in sand particle size. Sand reclamation, regardless of whether the method employed is a wet or dry process, has the same underlying idea of approach namely, removal of accumulated coating from the sand grains, removal of excessive fines or dust and other objectionable materials that have made the sand unusable from the standpoint of quality casting production.
2.2. CO$_2$/SODIUM SILICATE MOULDING

2.2.1. CO$_2$/Silicate Process –The Current State of the Art

The CO$_2$ silicate process has been known to the foundry industry for over 30 years and has achieved widespread use$^{42,43}$. Yet in many ways it has been a controversial process and has gained both enthusiastic support and determined opposition from all sections of the industry.

Sodium silicate was the first of what could be described as the chemical binders and as the “CO$_2$ process” it gained the reputation, in the early years, of being something of a wonder process, almost magical in its ability to offer instant hardening of a sand mass$^{44,45,46}$. Interest was quickly aroused and after the post war development years, the use of CO$_2$ grew steady from 1954 onwards. The apparent simplicity of the process was one of its most attractive features which paradoxically led to many problems on the foundry floor$^{47}$. On balance, however, the advantages of the process outweighed its problems since it provided rigid, accurate moulds and cores that helped to meet the ever increasing demand for castings with tighter specifications and reduced tolerances$^{48,49,50}$.

The implications of health and safety have led foundries to consider more closely, the quality of their working environments. In the CO$_2$ process, fume evolution on casting is easily controlled and has low toxicity.

2.2.2. Nature of the Silicate Bond

Clay also affects strengths on cooling from high temperatures, and reduces the difficulty in removing cores from castings of moderate size$^{48}$. Mixtures of new silica
sand and sand recovered from silicate bonded moulds, by crushing, are also being successfully used.

The gassing operation can be improved by using a mixture of equal amount of air and carbon dioxide. Soda and silica can be combined in any proportions, and the resulting compounds are miscible with water.

The silicates commercially available have a silica / soda ratio between 3.3:1 and 1.6:1, with water content between 40 and 60 per cent. When the silica / soda ratio exceeds 3:1, the silicate is unstable and is rapidly decomposed by carbon dioxide with the precipitation of silica, as seen in Fig.2.1. When these silicates are used in the CO$_2$ process, gassing is extremely rapid, but the precipitated silica has poor bonding properties and gassed moulds are weak and friable$^{45,46,43}$.

When the silica / soda ratio is reduced to 2:1 the effect of carbon dioxide is to form sodium carbonate and a silicate of higher ratio. At the same time water is removed from the silicate and its viscosity increases rapidly with a resulting increase in strength, as shown in Fig.2.2. The gassing period needed is longer in mould containing dried silicate, there is a further increase in strength since sodium silicate itself has a powerful binding action. If, on the other hand, gassing is continued the silicate is completely decomposed and the mould becomes weak and friable.

When the silica / soda ratio is still further reduced gassing time is abruptly increased and silicates of this kind are rarely used with pure silica sand.
Fig. 2.1. – Strength with gassing time for 3.3:1 ratio silicates.
Fig. 2.2. - Strength with gassing time for 2:1 ratio silicate, silicate addition - 4 percent.
In general, the lower the silicate ratio, the longer is the time required for gassing, but higher is the strength of the gassed mould.

2.2.3. Silicate Bonded Sands during Heating and Subsequent Cooling Properties at High Temperature

When silicate-bonded clay-free sands are heated, strength rises as a result of complete drying of any un-decomposed silicate, and reaches a maximum at about 400°C (752°F). Strength then begins to fall when the bond temperature exceeds 700°C (1292°F) in Fig.2.3. If heating is continued at really high temperatures the silica itself changes. Quartz, the usual form of silica, is stable at temperatures upto 870°C (1598°F), when it changes to tridymite, which in turn changes to crystobalite above 1400°C (2552°F). These changes are, however, extremely slow and rarely occur to any great extent in moulds, although small amounts of tridymite have been found in the sand adhering to the surface of large steel castings.

G.J. Martin, presents a simple guide to the latest gassing procedure which have been developed for the CO\textsubscript{2} process with the development of a new generation of sodium silicate binders and application of new gassing techniques. By this many of the problems associated with the process and in particular break down and surface finish have been overcome or greatly reduced. The majority of these new materials are based on sodium silicates with silica to soda ratio higher than the more widely used 2:1 ratio. These silicates have the advantage of giving easier knockout, are less sensitive to low temperatures and require less gassing.
Fig. 2.3. - Strength of CO₂ process material at and after cooling from high temperatures - 4% silicate.
Table 2.1. - Approximate volume of CO$_2$ measured to harden a silicate / sand mix

<table>
<thead>
<tr>
<th>Weight of Sand / Silicate mix-Kg</th>
<th>2.5</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicate Concentration :</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 per cent</td>
<td>0.6</td>
<td>1.3</td>
<td>1.9</td>
<td>2.6</td>
<td>3.8</td>
<td>5.1</td>
<td>6.4</td>
</tr>
<tr>
<td>3 per cent</td>
<td>0.9</td>
<td>1.9</td>
<td>2.9</td>
<td>3.8</td>
<td>5.7</td>
<td>7.7</td>
<td>9.6</td>
</tr>
<tr>
<td>4 per cent</td>
<td>1.3</td>
<td>2.6</td>
<td>3.8</td>
<td>5.1</td>
<td>7.7</td>
<td>10.2</td>
<td>12.8</td>
</tr>
<tr>
<td>5 per cent</td>
<td>1.6</td>
<td>3.2</td>
<td>4.8</td>
<td>6.4</td>
<td>9.6</td>
<td>12.8</td>
<td>16.0</td>
</tr>
</tbody>
</table>

G.D. Haley and J.L. Leach, investigated to determine the interrelated effect of the major variables in the CO$_2$ process. The variables that must be considered are gassing time, gassing pressure, grain fineness of the sand and amount of binder. The purpose of their investigation was to determine the interrelated effect of the major variable in the carbon dioxide process. The variables that must be considered are gassing time, gassing pressure, grain fineness of the sand and amount of binder. An important part of this investigation has been the proposal of a standard method of testing the carbon dioxide hardened sands.

2.2.4. Maximum Strength Vs Mesh Size

Pressures necessary to produce maximum strength at each gassing time are plotted as a function of the mesh size of the sand. Only the pressures necessary to produce optimum strength at 4 percent binder are shown. The curves for 2 and 3 percent binder show the same trend, only to a lesser extent, and are not plotted. Fig.2.4. shows that shorter gassing times require higher gassing pressures. Using 126 mesh sand and 60 sec gassing time, and 15 psi gassing pressure will give the
maximum strength possible with this gassing time. Shorter gassing times (30 sec) requires 50 psi gas pressure, which is more than three times than that of the waste gas.

In addition, the curves show that higher pressures are required to gas fully the finer mesh sands. This effect is greatest for the short gassing time. This is probably due to the finer sands offering more resistance to the passage of gas. Unfortunately, no equipment was available to measure the volume of gas passing through the specimen, but observation was made of the flow rate of the gas at higher pressure.

Fig.2.5. is the same type of plot as Fig.2.4., except that time is held constant and the three binder contents are plotted, rather than holding the binder constant and plotting three different times. The curves now show the pressure necessary to produce maximum strength at different percentage of binder using constant time. All three duration produce the same type of curves, but the effect of a 30 sec time is the greatest and is the one plotted.

Fig.2.5. shows that higher percent of binder require higher gassing pressures. Since the gassing time is constant, the amount of gas required by the higher binder constant is greater. Again, as in Fig.2.4., it is demonstrated that finer sands require higher gassing pressures.

2.2.5. Gassing Time and Pressure Relationship

Fig.2.4. and Fig.2.5. show a close relationship between gassing time and pressure. The product of these two variables is a rough approximation of the amount of gas passed through the specimens. Fig.2.6. is a plot of compressive
Fig. 2.4. - Gas pressure to produce maximum compressive strength as a function of grain size of the sand for 2, 3 and 4 percent with 30 sec gassing time.
Fig. 2.5. - Gas pressure to produce maximum compressive strength as a function of grain size of the sand with 4 percent binder for 30, 60 and 120 sec gassing time.
strength versus the product of gas pressure and time. One sand is considered at different binder content. A great number of points are plotted and they show a considerable spread of values for compressive strength. The extreme points are connected so that they encompass all of the points for each binder content. Only the sand with mesh size 109 is shown, but the relations hold for all the sands.

Fig.2.6. shows that the higher binder contents have higher ranges of compressive strength. This was pointed out in Fig.2.7. and is further supported by Fig.2.6. The peak strength for higher binder content occurs with large amount of gas. This supports, Fig.2.5. which shows that to harden higher percentages of binder additional gas is needed. Fig.2.6. shows that maximum strength are obtained with a relatively small amount of gas compared to the total range of amounts tested.

It was found that the higher pressures and short times gave lower values of compressive strengths than long times and low pressures, even though the product was the same in both cases\(^5\). The decrease in strength at the higher amounts of gas is due to the over gassing effect, and also due to the formation of channels in the specimens, caused by the gas passing through, at a high velocity associated with high pressure.

It is possible to draw an average curve through one set of points in Fig.2.6. This is done for all of the sands and all of the binder contents. Fig.2.8. shows the curves for all of the sands tested containing 4 percent binder. It shows that the maximum strength occurs at increasingly higher binder contents as the fineness of the sand increases. All of the maximums of the average curves fall
Fig. 2.6. - Range of compressive strengths as a function of amount of gas passed through the specimen for 2, 3 and 4 percent binder, the sand being of 109 mesh size.
Fig. 2.7. - Maximum compressive strength obtained from 2, 3 and 4 per cent binder as a function of the grain size of the sand. Gassing pressure and time are not specified on this graph.
Fig. 2.8. - Average compressive strength as a function of the amount of gas passed through the specimen for all mesh size sands tested, the sand having 4 per cent
within a narrow range. None of the sands tested required a large amount of gas for full hardening. All the curves show the characteristics loss in strength with large amounts of gas.

2.2.6. **Summary of CO₂ / Sodium Silicate Moulding**

1.) Within the range tested, higher strengths are obtained with higher percentage of binder.

2.) The rate of increase in strength decreases with higher percentages of binder.

3.) More binder requires a greater volume of gas to develop high strengths.

4.) The amount of binder required increases as the mesh size of the sand decreases. Coarse sands do not form string mixtures.

5.) Shorter gassing time requires higher pressures to obtain high strengths.

6.) Higher percentages of binder require higher gassing pressures at constant gassing time.

7.) For a specific amount of gas, longer gassing times and lower pressures give higher strengths than shorter times and higher pressures.

8.) There is a critical amount of gas that will give the maximum strength for each sand mixture. This amount of gas is higher for the finer sands.
Table 2.2. - **Comparison of the properties of the mixtures with high and low SiO$_2$ : Na$_2$O ratios sodium silicates**

<table>
<thead>
<tr>
<th></th>
<th>Mixes with High Ratio Silicate</th>
<th>Mixes with Low Ratio Silicate</th>
</tr>
</thead>
<tbody>
<tr>
<td>The ratio of SiO$_2$ : Na$_2$O</td>
<td>2.8 – 3.5</td>
<td>(1.5) – 2.0 – 2.5</td>
</tr>
<tr>
<td>Optimum Moisture Content of the Mix</td>
<td>3.8 – 4.5</td>
<td>1.5 – 2.5</td>
</tr>
<tr>
<td>Hardening Velocity</td>
<td>Maximum</td>
<td>About half so high</td>
</tr>
<tr>
<td>CO$_2$ consumption</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Bench life of the mixes without additions in a covered box</td>
<td>Long</td>
<td>Long</td>
</tr>
<tr>
<td>Stability to additions of organic materials</td>
<td>Great</td>
<td>Low</td>
</tr>
<tr>
<td>Hardened strength of the mixes with the same dry residue content</td>
<td>Slightly Lower</td>
<td>Slightly Lower</td>
</tr>
<tr>
<td>Strength after hardening and Air Drying</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Strength after drying without hardening</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Bench life of the high green strength mixtures</td>
<td>None or Low</td>
<td>Higher</td>
</tr>
<tr>
<td>Bench life of the mixes with bentonite</td>
<td>None</td>
<td>Higher</td>
</tr>
<tr>
<td>Bench life of the chromium-magnesite mixes</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Breakdown (without additions)</td>
<td>Higher</td>
<td>Lower</td>
</tr>
</tbody>
</table>

### 2.2.7. Gassing Technique

In larger plants consuming greater quantities of carbon dioxide a gas supplying system is installed in series and automatic measuring devices are used.
2.2.7.1. **Gassing Procedure**

The ideal method of gassing would be to supply gas to all parts of the mould at the same time. If gas is supplied at a much faster rate, it fulfills no useful purpose and simply escapes to atmosphere. Displacement of the air in the mould pores by gas is easier and proceeds over a larger part of the mould as permeability rises. On this account it is desirable that the permeability of the sand should exceed 40, but most moulding sands when mixed with an equal quantity of silica sand have permeability well in excess of 40.

2.2.7.2. **Types of Gassing**

The choice of gassing techniques for the CO$_2$ silicate process is based on traditional or the moulder's individual preference. The choice of technique is clearly related to the job being done and the method will be chosen from the following.

1) The most traditional is probe gassing, when a deep narrow hole is vented in the sand and a hollow tube through which CO$_2$ passes is inserted. Modern knowledge of gas flows within sand masses indicates that gas distribution by probe is relatively inefficient in terms of time and labour involvement.
2) A modified form is known as Cup Gassing. The sand is vented as for probe gassing but a special weighted cup is placed over the vent hole and gas is introduced to the sand face, hardening occurs in a radial pattern down the length of the hole. Gassing time is reduced since a greater mass of sand is hardened and gas losses from the vent hole are reduced by a rim on the cup which seats into the surface of the sand.

3) Next is hood or board gassing where gas is introduced evenly over the complete face of the sand and hardening occurs uniformly.

4) In through-pattern gassing the gas is supplied to the sand through vents in the pattern face via a plenum chamber or false bottom. On very deep sections or particularly large moulds it is occasionally necessary to make use of through-pattern gassing with cup of board gassing at the rammed face.

5) Highly efficient gassing can be obtained by use of vacuum gassing equipment where moulds are placed in a chamber from which the air is evacuated and the vacuum broken with CO₂ gas. Hardening is even and CO₂ consumption is very low.

The CO₂ process has two advantages which have been the chief cause of its success:

- The mould can be hardened in contact with the pattern and an accurate reproduction is obtained.
- Hardening is rapid at room temperatures and drying stoves are not necessary.
The currently used process as used at the present time has these disadvantages:

❖ It is difficult to remove the cores from some castings.

❖ Metal penetration results in poor surface finish and sometimes spalling of the mould surface occurs, particularly with large moulds.

❖ Large quantities of dry silica sand are required and similar quantities of used sand have to be discarded. Recovery of the used sand is possible only by the use of a difficult cleaning process.

2.2.8. Effect of External and Internal Variables in the Sodium Silicate Process

The sodium silicate bonded sand mixtures form a group of self-hardening type sand systems, where the liquid binder is a water solution of sodium silicate, which hardens by chemical reaction with reagents like CO₂ gas.

2.2.8.1. Sodium Silicate

It is commonly called as Water Glass. Sodium silicate binder is an aqueous solution of sodium silicate glass (Na₂O, mSiO₂) with a SiO₂ / N₂O ratio of 2.0-2.8/1. Relatively small changes in the water content of commercial grades of sodium silicate have an important effect on properties.

2.2.8.2. Hardening Processes of Sodium Silicate Sands CO₂ Process

CO₂ gas reacts with the sodium silicates and forms thin film on the surface of sand grains (Eq.1). The reaction is exothermic in nature. In order to produce uniform properties in a mould or core it is essential to obtain rapid dispersion of the CO₂ gas throughout the sand mass. The chemical reaction that takes place is as follows:

\[ \text{N}_2 \text{O} . \text{MSiO}_2 + \text{CO}_2 + \text{N}_2 \text{CO}_3 + x \text{H}_2 \text{O} + \text{mSiO}_2 + Q \text{i} \text{.......(Eq.1)} \]
The reaction as above is influenced by the following parameters:

### 2.2.8.2.1. *Time Dependence*

Using a constant gas flow rate, the strength increases progressively as the gassing time is extended. When designing a gassing system for a large mould or core, if CO₂ gas is injected at a single point, more time will be required to ensure complete through-hardening. However, by injecting at a number of points simultaneously the time can be greatly reduced.

### 2.2.8.2.2. CO₂ *Flow Rates*

Changing the flow rate at which CO₂ gas passes through a sand mass has important effects on both the strength of the bond obtained and the distribution pattern of the gas. In small cores of simple design, a uniform distribution of gas can be rapidly obtained at low flow rates and in such cases the development of strength is independent of small changes in the CO₂ flow rates.

### 2.2.8.2.3. *Temperature Change during CO₂ Gassing*

During hardening, temperature changes occur within cores and the extent of these changes is dependent on the gas flow. At low flow rates an exothermic reaction occurs between silicate and CO₂ gas with the formation of silica hydro-gel, sodium carbonate and bicarbonate. The temperature increases shortly after gassing starts, and the bond strength increases as the gassing time is extended.
2.2.8.3. The Development of Bond Strength in the CO₂–Silicate Process

It has been proposed that when CO₂ gas reacts with sodium silicate solution, two mechanisms operate:

- A chemical reaction involving the formation of a silica hydrogel bonds
- A physical process in which a glass like high viscosity sodium silicate bond is formed due to dehydration of the aqueous silicate by the dry CO₂ gas.

During the gassing of moulds and cores, both mechanisms are operating and contributing to the strength developed. If these moulds and cores are not used immediately, changes in strength will occur due to continuation of the dehydration process.

Depending upon the gassing conditions and the SiO₂: Na₂O ratio of the sodium silicate employed as a binder, dehydration of moulds and cores during storage can lead to either an increase or decrease in bond strength. It should however be noted that strength also falls due to dehydration under high humidity condition.

2.2.8.4. Three Classes of Sodium Silicate Binder are in the use with the CO₂ Process

- Low ratio sodium silicates.
- High ratio sodium silicates and
- Proprietary (sugar-containing) sodium silicates.

2.2.8.4.1. Low Ratio Sodium Silicate Binders

The majority of foundries use sodium silicates having a SiO₂:Na₂O ratio of 2:1. It is evident that as the solid content decrease the rate of strength development rises rapidly. However, the presence of fine materials such as coal dust, red iron oxide
powder etc. in the sand mixture greatly increases the specific surface area and thus accelerates the hardening rate. Small additions of clay may also accelerate hardening. Kaolinite and ball clays are preferable to bentonites for inclusion in sodium silicate bonded sands for the purpose of raising green strength.

2.2.8.4.2. High Ratio Sodium Silicate Binders

The use of sodium silicate binders having SiO₂:Na₂O ratios above 2:1 but below 3:1 are common in many foundries. The main advantage claimed for the higher ratio sodium binders are:

- A substantial increase in the rate of the hardening reaction with CO₂ gas and therefore the possibility of faster mould and core production.
- Improved economy in CO₂ consumption, superior breakdown and less burn-on.
- Slightly lower cost of silicates.

These high ratio binders are not without disadvantages: Control of the gassing operation, especially in respect of time and CO₂ flow rate is more critical than for the 2:1 ratio silicates. The bench life of sand silicate mixtures is often shorter.

Moulds and cores tend to deteriorate in strength during storage and surfaces become friable.

2.2.8.4.3. Proprietary Sodium Silicates

In addition to the straight sodium silicates, a range of silicate binders is available which contain various sugar derivatives. The most commonly used additives
are nonreducing canesugar syrups or molasses which usually constitute 10-20 percent of the weight of the binder.

### 2.2.8.5. Sodium Silicate Ester Cured Systems

The sodium silicate/ester cured system is an inorganic system. The organic ester is hydrolyzed at a controlled rate by the alkaline sodium silicate. The acid produced reacts with sodium silicate to form silica which bonds the mould or core. No heat or gas is generated on curing.

The system provides inorganic alternatives to the organic chemical setting processes.

Its advantages are:
- Low cost
- Ability to use with impure sands
- Low gas emission
- Resistance to expansion defects in casting.

The curing rate is mildly temperature dependent. Curing speed depends upon the SiO$_2$:Na$_2$O ratio of the sodium silicate binder and the composition of the ester hardener. High ratio silicates are needed for fast curing.

The catalysts used are low viscosity liquid aliphatic organic esters with a sweet or acetic acid-like smell. Typical organic esters are:

1. Glycerol diacetate (Diacetin) fast cure.

2. Ethylene glycol diacetate (EGDA) medium cure.

3. Glycerol triacetate (Triacetin) slow rate.
2.2.8.6. **Ferro-Silicon or Calcium Silicide (Nishiyama Process)**

When powders of Ferro-silicon or silicon are reacted with sodium hydroxide in the presence of water then sodium silicate hardened sands are produced with the evolution of heat and hydrogen gas. The reaction is:

\[ \text{mFe} - \text{Si} + 2\text{NaOH} + (2\text{m} - 1)\text{H}_2\text{O} \rightarrow \text{N} \sim \text{O}.\text{mSiO}_2^- + \text{mFe} + Q \quad \text{...... (Eq.2)} \]

In this process as the reaction produces free H\textsubscript{2}, it is necessary to take precautions to avoid explosion:

1. The moulds must be well vented and should be made in well-ventilated areas.
2. Inflammable mould washes should not be used till the reaction is complete.
3. The moulding and core making area should not be located in the vicinity of liquid metal.
4. Moulds should not be closed till the reaction is complete.

Very high strengths are obtained with these sands. Nonetheless this process is not employed because there is a possibility of explosion of hydrogen gas in the presence of heat evolved.

2.2.8.7. **Cement / Dicalcium Silicate Process**

The reaction involved is:

\[ 3\text{CaO}.\text{SiO}_2 / 2\text{CaO}.\text{SiO}_2 + \text{H}_2\text{O} \rightarrow \text{CSH} + \text{Ca(OH)}_2 \quad \text{......(Eq.3)} \]

Low heat producing Portland cement or blast furnace slag cement is recommended for use with sodium silicate. The cement should be rich in dicalcium silicate. Sodium silicate percentages range between 4%-6% with sodium silicate.
1.5%-3% cements/slag can be used as hardener depending upon the percentage sodium silicate used.

The advantages of these hardeners are:

- No storage problem
- Better collapsibility of mould.
2.3. TYPES OF RECLAMATION

The methods of sand reclamation currently available are wet, dry and thermal. Chemical treatment combined with one of the mechanical methods is feasible but is not developed to a commercial stage at the present time.

Wet methods would appear to be most applicable to the reclamation of clay-bonded and silicate-bonded sands. One problem associated with this type of plant is the disposal of effluent which may require treatment to the satisfaction of the local authorities, before it can be introduced into the public drains or nearest river.

Plant for the dry methods of sand reclamation can be regarded in three groups:
   a. Pneumatic Scrubbing
   b. Shot Blast Secondary System.
   c. Mechanical Crushing, Pulverizing or Disintegrating and regrading

The degree of cleaning which can be achieved by this method is superior to that achieved by other dry reclamation methods, but is not up to the standard achieved by wet reclamation and at some cost in plant yield.

Sand reclamation by means of a shot blast secondary system, where the complete mould (flaskless) is blasted away with shot in the blast chamber, is attractive in that it eliminates the shakeout unit.

Currently the most popular type of reclamation plant for the resin-bonded and silicate-bonded sand systems is that based on crushing, pulverizing or disintegrating, and regrading. This type of plant may be fitted with either wet or dry dust extraction.
All of the plant types described are well proven units and there is no reason why any foundry should not successfully reclaim foundry sands in a unit sand system.

2.3.1. Wet Methods

Some wet reclamation installation failed to meet expectations in the past because their designers assumed the solvent action of water to be sufficient to remove “Shells” from old sand grains. In actuality, it is not enough to just wash an old sand mass.

Modern wet reclamation methods rely upon wet scrubbing to reduce and/or remove the “Shells” from old sand grains.

From a fundamental viewpoint, wet reclamation methods have become acceptable. Work is performed both upon individual grains and a sand mass as a whole.

Systems of wet reclamation have been in operation since the early 1940’s. Raw knock-out sand is fed via a magnetic separator and pre-crusher to storage and feed hopper. The sand is wetted to a pumpable sludge in a rotary wetting barrel and pumped to the primary classifier for removal of the fines. This slurry is gravity fed to the sand scrubber where the grains are cleaned by attrition induced by the impeller action. The scrubbed sand slurry is pumped to the second classifier for further removal of fines by water elutriation, the wet cleaned sand being passed to a dewatering cylinder which reduces the water content to 6–10%. A rotary feed table feeds the sand to a rotary oil-fired sand drier which discharges the dry sand at 150°C to 200°C. The
standard arrangement is for this sand is to be cooled and conveyed in a low pressure single pass pneumatic system which reduces the sand temperature to 40°C or a double pass system to achieve 20°C. As an alternative, a fluid bed cooler and high pressure blowing system can be incorporated.

Water and fines from the two classifiers are pumped to the sludge dewatering tank and this water can be re-used. It requires further settling and chemical treatment and dependent upon the local requirements for industrial effluent and also, may need treatment before discharge to the local drainage system. The water from the final dewatering cylinder is re-circulated in the system. Sludge for disposal would amount to approximately 5% of sands treated, and considerably more for clay-bonded.

Wet reclamation of clay-bonded sand is carried out using wet scrubbing units of the type used for the reclamation of silica-bonded sands. Chemical additions will be necessary to separate the large quantity of fine particle effluent from the water used in the reclamation to enable it to be recycled.

The difficulty here is in separating the water from the suspended clay particles. As the water requirements of the processes are fairly large, it is necessary to consider reuse of the water and this poses considerable problems and is consequently expensive. In view of the advancement in chemical treatments had recent years, no doubt, a means of rapidly settling the clay particles will be found. However, a settling area will still be required, thus increasing further the cost of the process.
As indicated by the name of the process the product from this process is wet sand. Normally a portion of the water would have been removed by a dewatering process of some kind. But this still leaves some 6-10% of moisture in the sand. Provision of this latter facility can be a deciding factor in the economics of this process if a drying plant does not exist.
Fig. 2.9. - Wet Reclamation System
Fig. 2.10 - Wet Reclamation System
Recovery of sand from the process is expected to be of the order of 80 – 85 %, the bulk of the losses being as with dry reclamation, the coal dust and clay fines.

Whereas with the dry reclamation technique it is envisaged that the sand having a moisture content of too high a level could cause problems. With this process no such restriction exists, provided the sand is dry enough to be fed to the plant, then the plant will handle it.

A typical plant is capable of handling 3-5 ton/hr with multiple units being suggested for greater outputs.

2.3.2. Pneumatic Methods

Pneumatic method for sand reclamation was developed and described as early as 1948\(^5\). The method involved entertaining sand grains in an air stream and blasting them against a fixed target. While initially deemed to be successful, it is understood that the method failed to prove satisfactory over a period of time.

The recently developed method to meet the same set of fundamental requirements now being met by the wet reclamation methods.

From a fundamental viewpoint, the only difference between a pneumatic scrubber and a wet scrubber is the respective mediums utilized for suspension and motivation.

Results from operating installation indicate that the pneumatic methods is capable of performing a controllable amount of work on individual sand grains, and returns a product that consistently meets grains distribution specifications\(^{53}\).
Pneumatic cell unit sand is fed at controlled rate into the inlet chute, fills the space between the blast tube and the outside pipe of the cell. The sand is entrained in low pressure air stream 14m³/min (500ft³/min), per cell at 21 kPa (3 lb.in²) and is blown against the cone shaped target. The force of the air sand mixture emerging from the blast tube holds a layer of sand against the target, protecting it from abrasion, the result being that sand is scrubbed against abrasion of bonded coating by sand. Air escaping from this zone carries away dust particles to the collector of a prefixed diversion plate, cycles a portion of the sand to the next cell in the series, the remainder re-cycled with a fresh sand addition. The sand passes through a series of cells to the final discharge via a rotary screen, for removal of any oversized foreign materials. The degree of cleaning is controlled by regulating the retention time in each scrubber; with a faster flow of sand the grains are cycled fewer times and the sand is cleaned less.

Low pressure compressed air is supplied by a turbo-blower and air is exhausted to a collector of rather dry or wet type desired by the user.
Fig. 2.11. - Pneumatic Reclamation System
Fig. 2.12. - Pneumatic Cell Unit
2.3.3. Dry Mulling Plus Aeration

Some foundries have tried to use sand mullers and an intensive mulling of dry sand batches to smooth grain surfaces and remove "shells" of old bond from individual grains.

Though the mechanical stirring and agitation may smooth the coatings, it is impossible to treat all grains to a similar degree.

Because of the foregoing factors, the wear and power consumption, attendant to lengthy mulling periods, both efficiency and economy suffer in comparison with other reclamation methods.

2.3.4. Shot Blast Secondary Method of Reclamation

The use of shot units for core removal and break-down if flaskless moulds led to the development of this system of reclamation. The complete mould is blasted with shot in the blast chamber, allowing the sand to fall through the screen or barrel, into the elevator. Depending upon the design, core rods, flash and unbroken lumps may be passed to a further pulverizer. The sand and fines pass to an air wash classifier for removal of the fines to the collector unit, the used shot to the shot storage bin and the reclaimed sand to a take-away system.

2.3.5. Mechanical ‘Crushing’ and Regrading Plants

Simple reclamation of sand using a roll mill to break down the sand has been reported. This was carried out without further classification and dust extraction, the resultant sand being used in a 1:2 ratio with the new sand. Whilst some savings could be
shown for such a system, recycling on this basis can only produce a sand with a build-up of contaminants, a high proportion of agglomerated binder and sand grains, and a build-up of dust in the system.

2.3.6. **Thermal Reclamation**

Thermal or ignition methods are being successfully applied to reclaiming used foundry sands – sands bonded only with carbonaceous materials such as cereals and core oils, they have not been too successful when applied to mixtures of core and moulding sands containing varying amounts of clay binders.

Each of the previously described methods of sand reclamation has a common feature in that cleaning of the sand grains is incomplete. No matter how efficiently a scrubber functions, a certain amount of binder must be retained in the crevices of the sand grains, or in the form of fines, due to shortcomings of the sieving and classifying medium. Organic residues, however, can be removed by a thermal treatment. Thermal reclamation can, therefore, be applied to sand systems employing both cold-setting and hot-settling resins.

*Low temperature treatment* – raising the sand temperature to 250 – 400°C will drive off all volatile matter from the sand, this may be some value in treating furan sands.

*High temperature treatment* – in order to remove completely these organic residues, it is necessary to raise the sand temperature to an excess of 850°C. At these temperatures all carbonaceous materials will be completely incinerated.
These are the two processes that may be used for the reclamation of clay-bonded sands, one of which will ‘give’ a product having much lower residual clay than the other. A disadvantage of the more efficient plant, as might be expected, is its greater cost per ton of reclaimed sand.

It is, however, doubtful if mixed, whether contaminated sand type can be reclaimed successfully until a reclamation method is developed for total cleaning of the sand grains.
Fig. 2.13. - Thermal sand reclamation system.
(1.) Used Sand  
(2.) Sand Hopper  
(3.) Vibrating Feeder  
(4.) Electro Magnetic Separator  
(5.) Crusher  
(6.) Magnetics  
(7.) Preheating Dryer  
(8.) Bucket Elevator  
(9.) Vibrating Screen  
(10.) Feed Storage Bin  
(11.) Vibrating Feeder  
(12.) Dust Collector  
(13.) Exhaust  
(14.) Exhaust Fan  
(15.) Dust Humidifer  
(16.) Dust, Fines  
(17.) Calciner  
(18.) Cooling Chamber  
(19.) Cooler  
(20.) Calciner Blower  
(21.) Air  
(22.) Cooler Blower  
(23.) Vibrating Screen  
(24.) Pebble, Lumps  
(25.) Sand Weighing Machine  
(26.) To Dust Collector  
(27.) Agitator Mill  
(28.) Fuel  
(29.) Water  
(30.) Compressed Air  
(31.) Vibrating Screen  
(32.) Sand Mixer  
(33.) Coarse Product  
(34.) Middle Product  
(35.) Fine Product

Fig. 2.14. - Flow of Thermal Sand Reclamation Plant
2.4. CO$_2$ / SILICATE SAND RECLAMATION

CO$_2$ / sodium silicate sand can be reclaimed by wet or dry process. The wet process plant comprises a wet scrubber, classifier, drier and finally a cooler. The dry system comprises pulverizer, magnetic separator and a classifier and finally a cyclone dust collector. The dry method is less expensive on capital plant and running costs but the wet method gives a better degree of cleaning by E. Gibson$^{54}$. It was decided to reclaim the whole of the sand used on the block mold system by the dry method, and this reclaimed sand is used in the proportion 40:60 in the facing sand for all sections other than the block mould system. It is feasible to use a 10% addition to the block mould system without undue difficulty during the summer, however, it somewhat reduces the speed of hardening and at lower temperatures experienced during the winter this addition is not tolerable. The scheme finally installed incorporates a standard multi-hammer pulverizer which breaks the sand down to grain size in one operation.
2.4.1. Using Dry Reclaimed CO$_2$ Process Sand

A.E. Murton$^{55}$, of the Dept. Energy, Mines and Resources, Ottawa, Canada, conducted extensive studies on dry reclamation of CO$_2$ sand. He reported that difficulties were experienced at the foundry with the use of dry reclaimed CO$_2$ process sand. Mixtures made with this sand were difficult to mold because of poor flowability, and there were numerous occurrence of defective castings. The usual tests for moldability and flowability did not differentiate between mixtures having good and poor properties. The green gassed compressive strength, permeability and density of the test specimen were found to change with time and were related to the usability of the mixtures. A reaction between coatings of silica gel on the grains of reclaimed sand and the new Na$_2$SiO$_3$ of the mixtures was found to be the main cause of the problem. Probably also contributing were Na salts and unreacted NaSiO$_3$ which dried out the mixtures. It was found that the effect of these ingredients could be eliminated by adding 0.5% 5N NaOH to the mixtures. The order of adding the hydroxide and Na$_2$SiO$_3$ was not important. When these results were applied at the plant, mixtures containing 50% reclaimed sand and 50% new sand were found to have good properties. This is in contrast to the maximum of 25% which could previously be tolerated. The use of 50% reclaimed sand is considered to be a satisfactory objective and the problem is now under control.

The use of chemically bonded sand has grown considerably in the last two decades. Binder preferences, organic or inorganic, has been different in different countries depending on the availability, price, health and safety regulations irrespective of the type of binder, however, there has been a growing demand for sand
reclamation to minimize both the cost of new sand and the increasing cost of dumping the spent sand.

When considering sodium silicate, the problem of binder residue becomes more pronounced. Sodium silicate remains on the surface of the reclaimed sand grains and acts as a nucleant for new waterglass added in rebonding and leads to premature hardening of the sand\textsuperscript{56}. A thorough cleaning of the grains in the reclamation process is therefore important. Sodium silicate bonded is in other words more difficult to reclaim than furane bonded sands.

Sodium silicate that has been hardened by CO\textsubscript{2} is fairly easy to dissolve in water by wet scrubbing or in hot alkaline water without any mechanical action. It has been claimed that the solubility in water decreases considerably, when the binder has been vitrified by heat (Fig.2.16.). This implies that the sand close to a casting, which in a layer, roughly corresponding to the wall thickness of the casting will be heated to above 400°C, can only be partially broken down by water.
Fig. 2.16. - Solubility of sodium silicate in water by wet scrubbing a sodium silicate bonded sand heated to higher temperatures.

Silica sand chelford 50 sodium silicate ratio 2.5:1 4%, organic ester 0.4%

Na₂O Removed by Wet Scrubbing

Firing Temperature

2.56
2.4.2. Chemical Reclamation of CO₂ Sand

In 1964 Sarkar⁵⁷ said: “So far not much attempt has been made to reclaim the used sand and the bulk of the returned silicate bonded sands is thrown away”.

In 1972 Nicholas⁵⁸ mentioned that “a recent survey of sand usage from mold and core making in the UK has shown that of the 1–1/2 million tons of silica sand used, usually very little is fully reclaimed”. This is particularly true of the CO₂ silicate process.

Attempts to reuse CO₂ hardened sand without scrubbing the residual binder from the grains have resulted in a continual decline in the strength properties of the sand as it is used again and again. It was reported that with the addition of a suitable amount of water before rebonding, the strength could be regained. But Sarkar cautions that “where the sodium compounds around the finer grains are not removed, the build up of the low melting point constituent in the sand mix would progressively reduce the refractoriness of the mold material”. Possible difficulty in shake out because of the accumulated amounts of sodium silicate and resulting increased retained strength is also pointed out.

The residual binder is best removed by either dry or wet scrubbing. Wet scrubbing washes the sand with water and dry scrubbing removes the binder by mechanically agitating the sand in a stream of pressurized air. Sarkar describes (based on his private correspondence with a Company) a dry scrubbing arrangement where the reclaimed sand could be used with 15 to 25 % new sand added. This seems to be
too optimistic. Nicholas later describes a dry reclamation plant where only 40% reclaimed sand was used to get comparable properties with those of new sand.

Horsefield⁵⁹, had reported that “Successful” reclamation of CO₂ hardened sand is possible by purely mechanical means. Changing from a lump crushing and air classifying unit to a shot blasting and separation unit, it is considered that “the reclaimed sand is now clear and therefore the percentage addition of reclaimed sand used on the facing sand has been increased from 40 per cent to 50 per cent”.

Wet reclamation may yield results, although it is commonly held that the investment and operation costs are higher. “preliminary trials” by Atterton⁶⁰ “on a laboratory scale showed that all of the residual binder is removed by boiling water and 80 to 95 per cent by cold water treatment”.

But he also shows that analysis for “soluble” and “insoluble” Na₂O contents in shake out sands: the respective values with typical steel foundry sand are 0.437 and 0.103. The insoluble part might have formed in any of regions 4, 5 and 6 of Triaxial diagram in Fig.2.17. While dehydrating, in a typical CO₂ hardened sand washed not too thoroughly, water soluble Na₂O reduced from 0.437 to 0.10 and Na₂CO₃ from 0.525 to 0.099 thereby implying the possibility of reclamation by washing the sand.
Fig. 2.17. - Triaxial diagram
Atterton mentions that “the physical properties of the washed and dried sand when bonded with normal addition of binder were found very favourable when compared with new sand”.

Zifferer’s patent attempts without the need to scrub the used sand but also the need to use any binder after the internal addition, claim that by mixing the shake out and crushed sand with a “predetermined” quantity of sodium hydroxide solution it is possible to “reconstitute” all of the binder left on the sand from previous use. Also, “the functions of the alkali is to lower the viscosity of the silicate bond on the sand to such an extent that the lumps are progressively reduced to grain size”.

Zifferer’s hypothesis runs like this: On treating the silicate bonded sand with CO₂ gas “the Na₂CO₃ by-product is precipitated as a separate and distinct phase from the sodium silicate solution, and that increasing quantities of Na₂CO₃ in a sand mix will have no effect on the bonding strength of the reconstituted silicate solution. A progressive build-up of Na₂CO₃ can change certain properties of the sand mix such as flowability, green strength, permeability and sintering point. The Na₂CO₃ in the sand mix can, however, be selectively controlled to any desired concentration to obtain the conditions and practices of a given foundry. When a quantity of Na₂CO₃ which is deemed excessive, accumulated on the sand mix, the Na₂CO₃ and silicate can be removed by treating the sand with a dilute solution of NaOH.

The chemistry involved is shown in the reversible reaction:

\[
\begin{align*}
\text{SiO}_2 \cdot (\text{Na}_2\text{O}) \cdot (\text{H}_2\text{O}) + \text{dCO}_2 & \rightarrow \text{SiO}_2(\text{b-d})(\text{Na}_2\text{O}) \cdot \text{c(H}_2\text{O}) + \text{dNa}_2\text{CO}_3 \\
\text{Sodium Silicate} & \quad \text{NaOH Solution}
\end{align*}
\]
where the reaction goes from left to right while bonding and from right to left while “reconstituting”. Addition of NaOH solution provides for the required Na₂O and H₂O on the righthand side.

\[
\begin{align*}
2\text{NaOH} & \rightarrow \text{Na}_2\text{O} + \text{H}_2\text{O} \\
\text{Na}_2\text{O} & \leftarrow \text{NaOH}
\end{align*}
\]

Silica gel, according to this scheme, can redissolve easily, resulting in solution of sodium silicate again.

Murton⁶² along similar lines, could rejuvenate CO₂ hardened reclaimed sand with the addition of 0.5% of 5N NaOH. Sand, which was causing many casting defects because of its poor flowability and which could tolerate only 25% of reused sand, was made to work satisfactorily and to accept 50% of reused sand, when the above addition was made.

Warneke⁶³ undertook to study on the reclaimability of clay hardened silicate sands, using casting surface defects and dimensional tolerance as reference. Steel castings were made with sand molds bonded with 4% sodium silicate, hardened with 2 % Kaoline clay. Shakeout sand was reclaimed by mechanical means, either with a pneumatic scrubber or an aerated muller. 80% of reclaimed sand, added to 20% new sand, was once again bonded and used. This process was repeated five times. Besides showing that the sand could be recycled five times, he concludes that “a sand mould, bonded with sodium silicate will provide greater dimensional stability”.

2.61
Caldeira and Roberts\textsuperscript{64} report an in-plant application where shake out sand from a clay bonded system, on drying, could be bonded with sodium silicate with a hardener.

A recent patent\textsuperscript{65} claims that silicate bonded sand, hardened with humic acid and dried thoroughly, can regain strength by the mere addition of water and remulling. Humic acid, is complex organic acid, occurring in the soil and in bituminous substances, formed by the decomposition of dead vegetable matter. Repeating the reclamation process five times, Bolding and Williams have shown that either the green or dry compressive strength does not reduce with increasing reuse. Shake out sand was remulled with additional water “to give approximately the same concentration as was initially present”, and moulds were made and castings were poured again. Shake out and casting finish in the reuse cycle as well as in the cycle with new sand, are recorded as “good”. Green dry and hot strengths and permeability of reused sand were used as good as those of new sand.

“Although the exact details of its chemical structure are not completely known, humic acid seems to be widely available and is present in several grades of coal”.

2.4.3. Progress of Reclamation of Sodium Silicate Bonded Sand over the Years

Polasek, Garaj and Vesely\textsuperscript{66} reported in 1981 about their work with respect to reclaiming sodium silicate bonded sand and stated that wet reclamated is more effective than any kind of reclamation. However, the paper also stated quite clearly that dry reclamation sodium silicate bonded sand, while it has lower properties than
Fig. 2.18. - Sand lumps, agglomerates and other particles bound together by binders and heat

Fig. 2.19. - Hot sand with binder coating and dust particles
**DURING PARTIAL SCRUBBING**

*Fig.2.20. – Individual grains with reduced or fractured binder coatings. Binder dust removed by “Moment of Impact” Air Curtain.*

**AFTER RECLAMATION**

*Fig.2.21. – Cooled sand with rounded surface characteristics. Minor binder levels.*
new sand can successfully be utilized in a foundry operation. The authors of this paper went through a number of pouring cycles and utilized reclaimed sand and new sand in a ratio of 1:1. The changes taking place in the coating of the sand during reclamation is shown in Fig.2.18, Fig.2.19, Fig.2.20 and Fig.2.21.

Vernay\textsuperscript{67} in a 1982 article points out specifically that "in order that the reclamation operation remain financially interesting one must rule out wet methods and retain only dry processes". This work also clearly pointed out the need to remove moisture from the sand grains in order to embrittle the binder and make it more readily removable. This paper further states that "the influence of residual soda in the process has never been demonstrated with certainty". But it is emphasized that it may play a role with respect to the refractories of the sand and must remain below 1%.

A publication by Foseco\textsuperscript{68} also referring to practical reclamation results states "new sand introduced at the mixer 20 – 30%.

One of the prerequisites is the removal of moisture from the sand grain surface so as to embrittle the binder and make it more readily removable as far as silicate bonded sand is concerned.

The yield at the first cycle was only 90%, it increased to 95% after eight cycles. This can be considered as a stabilized value. It has to be kept in mind that while only new sand with a certain degree of angularity is being fed into the reclamer in the first cycle, increasingly rounded sand from previous reclaim cycles will appear in the sand system in future cycles, and consequently will result in lower attrition
Given a yield of 95% of the reclaimer itself makes it likely that a total new sand addition of 15% per cycle would be most that would be required in an ongoing foundry operation.

When comparing the values measured in various reclaim cycles to the value determined for new sand, it appears obvious that the scatter is very close to the value for new sand. i.e., no negative effect of the reclamation process can be noticed.

2.4.4. Economical – Environmental – Technical

With the increasing tendency in the foundry to shift from traditional binders to synthetic resins, it is recognized that the utilization of sand reclamation will play an increasingly important role in reducing foundry costs thereby increasing profitability.

The three basic reasons for reclaiming the sand are

> Economical Factors.
> Environmental Factors.
> Technical Factors.

Economically the foundries desire to reduce the total sand costs which includes purchase cost, freight cost and disposal cost. Environmentally it is becoming more and more difficult to dispose of the large quantities of materials into the ground. Agencies of local, state and federal governments are interested to know about the chemicals present in the sand and the extent to which they may reach out into the land from the sand. So they insist on reclamation and treatment of the disposable sand. In addition to the environmental benefits of reclamation, the process is of value from the viewpoint of conservation of sand is considered. The deposits of high quality sand will not last
longer unless they are not used most efficiently. Technically, reclamation in some cases reduces the need for additional use of binders and catalysts.

Ideally a sand reclamation plant would process foundry sand at a maximum yield and return the sand in such a state, as to be suitable for reuse in new molds, in combination with any binder system and still produce defect free castings at an economical cost.
2.5. FLUIDIZATION

Fluidization is the operation by which fine solids are transformed into a fluid-like state through contact with a gas or liquid. This method of contacting has a number of unusual characteristics and fluidization engineering is concerned with efforts of taking advantage of this behavior and put it to good use.

2.5.1. The Phenomenon of Fluidization

Pass a fluid upward through a bed of fine particles as shown in Fig.2.22. At a low flow rate, fluid merely percolates 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 by the upward flowing gas or liquid. At this point, the frictional force between a particle and fluid, counterbalances the weight of the particle and the vertical component of the compressive force between adjacent particles disappears, and the pressure drop through any section of the bed equals to 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 liquid-solid systems an increase in flow rate above minimum fluidization usually results in a smooth, progressive expansion of the bed. Gross flow instabilities are damped and remain small, and large-scale bubbling or heterogeneity is not
observed under normal conditions. A bed such as this is called a particularly fluidized bed, a homogeneously fluidized bed, a smoothly fluidized bed, or simply a liquid fluidized bed.

Gas-solid systems generally behave in quite a different manner. With an increase in flow rate beyond the 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.

Both gas and liquid fluidized beds are considered to be dense-phase fluidized beds 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.
Fixed bed
Incipient or Minimum fluidization
Particulate or smooth fluidization
Aggregative or bubbling fluidization
Slugging
Lean phase fluidization with pneumatic transport

Fig. 2.22. – Various kinds of contacting of a batch of solids by fluid.
Let us 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.

Compared with other methods of gas-solid contacting, gas fluidized bed have some rather unusual and useful properties. This does not share to the same extent with liquid-solid systems. Thus practically all the important industrial applications of fluidization are gas fluidized systems. Because of their unique behaviour it is interesting to deal primarily with gas fluidized systems.

2.5.2. Liquidlike Behaviour of a Fluidized Bed

A dense-phase gas fluidized bed looks very much like a boiling liquid and in many ways exhibits liquidlike behaviour. This is shown in Fig.2.23. For example, a large, light object is easily pushed into a bed, and on release it will pop up and float on the surface. The upper surface of the bed remains horizontal when the container is tipped, and when two beds are connected, their levels equalize. Also, the difference in pressure between any two points in a bed is roughly approximated by the static head of bed between these points. The bed also has liquid-like flow properties. Solids will gush in a jet from a hole in the side of a container and they can be made to flow like a liquid from vessel to vessel.
This liquid like behavior allows various contacting schemes between gas and solid to be devised\textsuperscript{69}. It is essential for the proper operation of circulation and other solids flow systems that the solids be maintained in dynamic suspension throughout, because any settling of particles can clog the lines and cause a complete shutdown of operations. Thus special care should be taken in the design of such systems: gas injectors be properly sized, piping setups liable to settling and clogging should be avoided, and particular attention must be paid to the problem of reliable start-up and shutdown procedures.

2.5.3. Comparison with other Contacting Methods

In many of the contacting patterns, the flow closely approximates these ideals. Unfortunately this is not the case for single fluidized beds. Solids may often be represented by back mix flow; however, the gas follows some intermediate and difficult-to-describe flow pattern. Nevertheless, by proper baffling and staging of units, and with negligible entrainment of solids, the contacting in fluidized beds can be made to approach closely the usually desirable extreme of counter current plug flow.
Fig. 2.23. - Liquid like behaviour of gas fluidized beds.
2.5.4. **Advantages of Fluidized Beds**

- The smooth liquidlike flow of particles allows continuous automatically controlled operations with ease of handling.

- The rapid mixing of solids leads to nearly isothermal conditions throughout the reactor, hence the operation can be controlled simply and reliably.

- The circulation of solids between two fluidized beds makes it possible to transport the vast quantities of heat produced or needed in large reactors.

- Translated to large-scale operations.

- Heat and mass transfer rates between gas and particles are high when compared with other modes of contacting.

- The rate of heat transfer between a fluidized bed and an immersed object is high. Hence heat exchangers within fluidized beds require relatively small surface areas.

The ease with which the particles fluidize and the range of operating conditions which sustain fluidization vary greatly among gas-solid systems. Whether the solids are free flowing or not, whether they are liable to agglomerate, static charges, vessel geometry, gas inlet arrangement and other factors affect the fluidization characteristics of a system.

One important factor is the size and size distribution of solids. In general, fine particles tend to clump and agglomerate if they are moist or tacky, thus agitation of the bed is needed to maintain satisfactory fluidizing conditions. This can be done either with a mechanical stirrer or by operating at relatively high gas velocities and
using the kinetic energy of the entering gas jets for agitating the solids. Fine particles of wide size distribution remain fluidized for wide variations in gas flow rate, permitting flexible operations with deep large beds.

On the contrary, beds of large uniformly sized solids often fluidize poorly with bumping, spouting, and slugging, which may cause serious structural damage in large beds. The quality of fluidization can often be spectacularly improved by adding a small amount of fines to act as a lubricant. Large particles fluidize in a much narrower range of gas flow rates, hence shallower beds must be used here.

First there is the bed of fine powders, sometimes called a fluid bed. Particle sizes are usually smaller than 20 mesh with appreciable amounts of -200 mesh material. In typical applications such as fluid cracking of petroleum, large units are used (bed height of 10 to 15 m) in which the gas velocity is many times larger than the minimum fluidization velocity.

For coarser material, generally larger than 60 mesh, we have the teeter bed. These are shallow beds (heights up to 1 m) which use low multiples of the minimum fluidization velocity.

Finally, for still larger particles which are not lubricated by fines, ordinary fluidization may not be practical and so a modified contacting scheme, the spouted bed, is used. The spouted bed is a combination of a jet like upward moving dilute fluidized phase surrounded by a slow down flow moving bed through which gas percolates upwards. To date the application of the spouted bed has been limited to a few physical operations such as the drying of grains and peas. Some development may
be possible in this field for gas-solid reactions of relatively coarse material; however, little may be expected of this type of operation if finer particles can be used because of the poor contacting of gas and solid.

Fluidized beds may also be classified according to the kind of solids transportation involved. Thus we have batch, one-pass, and recirculation systems. Naturally, in the development of complete processes, solids movement through fluidized beds may be combined with other methods of transportation such as moving beds, pneumatic transport, and belt or bucket conveyors.

2.5.5. Comparison of Types of Contacting for Reacting Gas Solids Systems in Fluidized Bed

2.5.5.1. Solid Catalyzed Gas Phase Reaction

Solid catalyzed gas phase reaction has been carried out for small granular or powdery non-friable, rapidly de-activated catalyst. Here, excellent temperature control allows large scale operations.

2.5.5.2. Gas Solid Reaction

Wide size range of solids with much fines can be made use of large scale operations at uniform temperature is possible. It is excellent for batch operations and yields an uniform product.

2.5.5.3. Temperature Distribution in the Bed

Temperature is almost constant through out in fluidized bed. This is controlled by heat exchange or by proper continuous feed and removal of solids.
2.5.5.4. **Particles**

Wide size distribution and abundant fines are possible in particles. Erosion of vessel and pipelines, attrition of particles and their entrainment can be serious.

2.5.5.5. **Pressure Drop**

Pressure drop is high for deep beds in large power consumption.

2.5.5.6. **Heat Exchange and Transport of Heat**

Circulation of solids makes the heat exchange and large heat transport efficient so that heat problems are seldom limiting in scale up.

2.5.5.7. **Conversion**

Back mix flow of solids and poor contacting pattern for gas in continuous operations lead to poor performance. Hence, for high conversion, staging is adopted.

2.5.6. **Industrial Applications of Fluidized Beds - Historical Highlights**

The first large-scale, commercially significant use of fluidized beds was by Fritz Winkler for the gasification of powdered coal. The patent for this process was awarded in 1922 (D.R.P.437,970) and the first gas producer, which was 13 m high and 12m² in cross section, started smooth operations in 1926.

Chemical engineers developed new processes using Kerosene and light oil. Because it used fixed beds of aluminium catalyst, requiring intermittent operations to regenerate deactivated catalyst and because of the complicated arrangements for controlling bed temperatures, this process was unsuited for the envisaged large-scale production.
One extension of the above process led to the Thermofor Catalytic Cracking (or TCC) process, a reactor-regenerator circuit using two moving beds of relatively large catalyst pellets which are transported from unit to unit by bucket elevator or by a gas lift.

Professors W.K. Lewis and E.R. Gilliland\textsuperscript{70}, on the basis of fundamental experiments carried out at the Massachusetts Institute of Technology, confirmed that a completely pneumatic circuit consisting of fluidized beds and transport lines, could operate stably and suggested that this be used in the search for a satisfactory catalytic cracking process. Engineers concentrated on this idea, verified that a standpipe was crucial for smooth circulation, and came up with a large pilot plant up flow cracking unit. This was the start of the Fluid Catalytic Cracking (or FCC) process.

The principle of solid circulation developed for the FCC process, has been used elsewhere in the petroleum industry, in Fluid coking for the treatment of heavy oil, and in sand cracking for the thermal cracking of petroleum feed stocks.

Basic research studies carried out primarily at academic institutions at the time of these large-scale applications in the petroleum industry gradually led to a better understanding of the behaviour of fluidized beds and transfer lines.

One particular feature of the fluidized bed, is the remarkable temperature uniformity, which has strongly recommended it as a vehicle for effecting catalytic reactions, especially the highly exothermic and temperature-sensitive reactions.
In 1944, fluidization know-how for use in fields outside the petroleum industry. The first such unit was constructed in 1947 in Canada. In 1952, at Berlin, at new Hampshire, Dorr-Oliver introduced this type of roster for producing SO₂ from sulfide ores.

Independently, in 1945 Germany had already started to develop fluidized bed roasters. In 1950, first commercial roaster went into smooth operation with a capacity of 30 tons ore / day. Scale up was rapid and a unit with capacity of 120 tons / day was constructed in 1952.

Dorr - Oliver engineers pioneered two additional important uses of fluidized beds in the areas of drying powdery materials and the calcinations of limestone. Thus in 1948 the first FluoSolids unit (1.7 m ID) for the drying and sizing of dolomite particles < 4 mesh and having a capacity of 50 tons / day, was put in operation in England.

These initial successes spawned much interest in fluidization and a variety of new processes have been reported in the literature and in patents of which two of them are pointed out here. The first encompasses the various processes being developed today for the reduction of iron oxide. Urgent efforts by major companies promise radical changes in this most important of industries. The second is the Pyzel process for the production of cement clinker.
2.5.7. Calcination

Particles of limestone and dolomite can be calcined in a straightforward manner in a fluidizing bed by burning fuel directly in the bed:

\[ \text{CaCO}_3 \xrightarrow{1000^\circ \text{C}} \text{CaO} + \text{CO}_2 + 42.9 \text{ Kcal/mole} \]

Since this reaction is highly endothermic and both gas and solid leave at 1000°C, this operation requires extremely large fuel consumption. To recover much of the heat, multi-staging is used. This original unit, designed and built in 1949 has a diameter of 4 m and a height of 14 m.71 Raw material 6 to 65 meshes is fed to the top stage of the unit and it flows downward from stage to stage. In the calcination stage, fuel oil is sprayed into the bed through 12 nozzles arranged around the perimeter of the bed, is mixed with fluidizing air, and is burned. A large amount of unconverted dust (≈14%) is entrained from the top stage.

In order to calcine calcium carbonate fines, the technique of high-temperature pelletization had been used successfully.72 By adding soda ash or caustic soda to the feed stock, the surface of the pellets becomes sticky and coated with fines. Particles grow in size, carryover is reduced, and the capacity of the unit can be raised. However, proper control of particle growth is required.

To upgrade the poor quality phosphate rock, engineers developed a three-stage fluidized calcination system using beds 5m in diameter. According to Priestely,73 the hydrocarbon content of this phosphate ore provides most of the heat needed for the calcination.
2.5.8. Roasting

These operations are all characterized by an exothermic oxidation, hence a single-stage fluidized bed is usually satisfactory and hence no outside heating is necessary. Compared to alternate designs, these units have a higher capacity. They also require less excess air, thus giving an off gas with higher sulfur-dioxide concentration. For sulphide ores, the only problem that occurs is short circuiting of solids because of back mix flow in the single-stage unit.

The Dorr-Oliver FluoSolids roaster was designed for the production of SO₂. This unit is 5.5m ID, 7.6m high, and roasts pyrite feed < 10 mesh at a rate of 170 – 220 tons / day at a temperature of 650 to 700°C, a gas velocity 45 to 50 cm/sec, and bed height of 1.2 to 1.5m. Under these operating conditions 75 – 80% of the cinder is entrained in the gas stream, residual sulfur is small (or 0.5 wt% in the overflow cinder, 1.2% in the carry-over), and the produced gas contains 12% SO₂. Also, to keep the bed temperature under control, a fraction of the reaction heat is removed either by a water spray or with a cooling coil.

BASF’s process uses a relatively shallow bed (0.6 m), a larger freeboard, and higher operating temperature. This higher temperature results in particle growth and reduction in roasting time.

The uniform temperature of fluidized beds also enables sulfide ores containing copper or cobalt to be roasted to the sulphate, then separated from the iron oxide cinder by leaching with water or dilute sulfuric acid.

2.81
2.5.9.  Fixed Beds – Solids with a Distribution of Sizes

Before considering the behaviours of beds containing solids of different sizes, we must first be able to describe usefully the size distribution of a batch of solid particles. Referring the Fig.2.25, we define the size distribution functions $P$ and $p$ as follows. Let $P$ be the volume fraction (or weight fraction or number fractions of particles smaller than size $d_p$ and let $p_d$ ($d_p$) be the volume fraction (or weight fraction or numbers fraction) of particles of size between $d_p$ and $d_p + d$ ($d_p$). Typical distribution curves and their properties are shown in Fig. 2.24., 2.25., 2.26., & 2.27. From this we see that $p$ gives the volume (or weight or numbers) distribution of particles directly and has the unit of reciprocal length, whereas, $P$ gives the cumulative distribution of sizes and is dimensionless.$^75$. 

2.82
Fig. 2.24. – Relationship between the cumulative distribution $P$ and the size distribution $p$. 

The fraction of solids smaller than $dp_1$ is given by $P_1 = \int_0^{dp_1} p \, d(dp)$. 

The shaded area under the curve represents $P_1$. 

Total area = 1

$slope \frac{dp}{d(dp)}_1 = p_1$
Fig. 2.25. - Relationship between $p$ and $P$ for a discrete distribution of particles sizes

Shaded Area: $\sum_{i=1}^{2} (p\Delta d\rho)_i = P_2$

Total area: $\sum_{i} (p\Delta d\rho)_i = 1$

Cross hatched area: $(p\Delta d\rho)_4 = x_4$

Average in interval $\Delta dp_4$
Fig. 2.26. - Measured voidage in fixed beds of two sized of spheres (by Furnas, from Zenz and Othmer).
Fig. 2.27. - Minimum voidage in mixture of 2,3 and 4 sizes of solids given the voidage in beds of one size of solid (by Firmas, from Zenz and Othmer.)
2.5.10. Choice of Distributor Type

Experiments by Grohse\textsuperscript{76} (also see Zenz and Othmer\textsuperscript{75}) have shown that the quality of bubbling fluidization is strongly influenced by the type of gas distributor used. These findings are summarized in Fig.2.28. as follows: for few air inlet openings the bed density fluctuates appreciably at all flow rates (20 to 50\% of mean value), though more severely at high flow rates. The bed density varies with height and gas channeling may be severe. For many air inlet openings the fluctuation in bed density is negligible at low air flow rates but again becomes appreciable at high flow rates. Bed density is more uniform throughout, bubbles are smaller, and gas-solid contacting is more intimate with less channeling of gas.

Although contacting is superior when densely consolidated porous media or plates with many small orifices are used, still, from the standpoint of industrial or large-scale operations, such distributors have the serious draw back of high pressure drop. This may significantly increase the power consumption of the blowers, often a major cost factor. High pressure drop can also hinder the circulation of solids between two or more stages. This too maybe serious if rapid circulation of solids is essential in the process.

In the design of a grid or distributor, first determine the available pressure drop, and with this in mind, select the type of distributor prior to detailed design.

In the choice of materials both metallic and ceramics have certain advantages. Ceramics are more resistant to corrosive gases and to high temperatures, but they have a very low strength against thermal shock or expansion stresses. Ceramics are also
relatively easily eroded, resulting in a gradual widening in the orifice openings. In general, metallic distributors are preferred because of strength and overall economics. Moreover, by cooling with inlet gas these may be able to resist corrosive atmospheres and high bed temperatures.

Sometimes distributors have to pass large amounts of solids entrained by inlet gases, for example, the SOD Model IV FCC reactor or the multistage fluidized limestone calciner. In these situations perforated plates are recommended.

Fig.2.29. illustrates several examples of grids and distributors. Type (a), a flat perforated plate or wire mesh, is commonly used for laboratory-scale operations; it has the disadvantage that fines are apt to fall through the orifices when the gas flow is stopped. This can be countered by using two staggered perforated plates (b). This is convenient for industrial operation because it retains the advantages of the single plate ease of design and construction coupled with good gas distribution.

With the heavy load in large-diameter beds, flat plates deflect unpredictably, hence curved plates, types (c) and (d), are used. These withstand heavy loads and thermal stresses well. Because bubbling and channeling tend to occur preferentially near the center axis of a fluidized bed, the design of (c) helps counter this tendency. Distributor type (d) can achieve good contacting only with more orifices near the perimeter and fewer in the central region, a disadvantage from the point of view of fabrication. Actually, for any perforated plate the dual requirement
Poor quality; much fluctuation in density with channeling and slugging

Better quality; less fluctuation in density, less channeling and slugging

**Fig. 2.28.** Quality of fluidization as influenced by type of gas distributor
Fig. 2.29. - Examples of various distributors for fluidized bed.
Fig. 2.29. - Examples of various distributors for fluidized
of good gas distribution and low pressure drop may require careful design with non-uniform orifice spacing.

When the inlet gas is free of solids, type (e), a packed bed of granular material sandwiched by two perforated plates is a good distributor and an excellent thermal insulator protecting low temperature inlet gases from a hot bed. Furthermore, the packing can be used to mix feed gases. For example, injecting a second gas into the packed bed through which the first gas is flowing, results in good design for explosive reactant gas mixtures.

Type (f), which consists of slits between grate bars, has roughly the same characteristics as the flat perforated plate, but with a somewhat less uniform gas distribution.

Nozzles [type (g)] and bubble caps [type (h)] have been used to prevent solids from falling through the distributor. In spite of their complicated construction, gas distribution is not superior to (b) and (e); in addition, solids are apt to settle and sinter and stick on the flat bottom surface.

The multiple filter plates of type (i) give better gas distribution than (g) and (h); however, special precautions may be needed to insure that the inlet gas is free of filter-clogging material. Distributors of this type with 5.1-cm diameter filter plates have been used in phthalic anhydride production.

Experience has shown that baffles and other vessel internals such as properly designed heat exchangers substantially improve the contacting in the bed by breaking
up growing bubbles. The increase in pressure drop when using such internals comes from friction between particles and surface; because this is found to be practically negligible, baffles provide a way of meeting the opposing requirements of low pressure drop and good contacting. In fact, proper baffling can improve the quality of fluidization so much that refined high pressure drop gas distributors are not needed at all. In such a case, a pipe grid such as type (j) may be all that is required to introduce reactant gas. This is so in the Lurgi-Fujinagata sand cracker for the thermal cracking of naphtha and in the reactors for the hydrogen reduction of iron ore designed by Hydrocarbon Research, Inc. 77.

Sometimes, to improve the flow characteristics in a fluidized bed, gas is injected through nozzles arranged on the side walls as in type (k).

In the new design for the Winkler generator, gas is introduced through six side mixing nozzles into a teetered bed, as in type (l)78. This is claimed to be a great improvement over the original mechanical grates with their high maintenance costs.

2.5.11. Gas Fluidized Beds

Mass transfer coefficients are difficult to measure in gas fluidized beds for the same reason that fixed beds are difficult to measure, and also because of the bubbling behavior and its attendant problems of gas bypassing, representative sampling, proper driving forces, and so on. Nevertheless, Resnick and White79 and Kettenring et al80 have reported on such systems.
Chu et al.\textsuperscript{81} and Hsu and Molstad\textsuperscript{82} explored this question with very shallow beds, in some cases less than two particles deep, while Riccetti and Thodos\textsuperscript{83} extended the range of conditions to coarse solids.

To investigate this problem further Richardson and Szekely\textsuperscript{84} measured mass transfer coefficients in shallow beds, about five particle diameters in height, by unsteady-state adsorption of carbon tetrachloride vapor contained in fluidizing air. Their correlations are,

\[
Sh = 0.374 \text{Re}_p^{1.18} \quad \text{for} \quad 0.1 < \text{Re}_p < 15
\]

\[
Sh = 2.010 \text{Re}_p^{0.5} \quad \text{for} \quad 15 < \text{Re}_p < 250
\]

It is interesting to see that the Sherwood number again drops sharply with decreasing Reynolds number, approximately paralleling other findings in this Reynolds number range.

In their investigations Richardson and co-workers took pains to maintain homogeneity of their shallow bed and to avoid the formation of bubbles. Again, such ideal laboratory conditions are not readily reproduced in large scale equipment where it is known that considerable portions of the fluidizing gas passes through the bed in the form of bubbles.

On this point Szekely\textsuperscript{85} measured the mass transfer rate between bubbles and emulsion in an air fluidized bed by injecting into the bed large bubbles containing carbon tetrachloride and measuring the extent of adsorption of carbon tetrachloride by the solids. Szekely concluded that most of the mass transfer takes place during formation of bubbles rather than during their rise. It should be kept in mind, however,
that the time of bubble formation under his experimental conditions was much longer than in normal fluidized beds. Hence in normal beds Szekely’s conclusions may not hold.

2.5.12. Heat Transfer between Fluidized Beds and Surfaces

One of the remarkable features of the fluidized bed is its temperature uniformity, with effective thermal conductivities up to one hundred times that of silver. In practice, this uniformity exists in both radial and axial directions, even in beds 10m in diameter. The high rate of heat transport is due to the bubble-induced circulation of solids. Since conversion and selectivity of catalytic reactions as well as the deactivation rate of the catalyst itself is very temperature-sensitive, this ability of a fluidized bed to maintain close to isothermal conditions makes it attractive for a variety of reactions, especially exothermic reactions with high rates of heat release.

To maintain a given temperature level in the bed, we need to remove a definite amount of heat by contact with an appropriate heat exchange surface. Consequently, quantitative information on the heat transfer coefficient between surface and bed is needed for the rational design of fluidized bed reactors.

Significant point-to-point variations in ΔT may be found in beds having a feed and discharge of large quantities of relatively hot or cold solid, or in beds having baffles or other internals which hinder the smooth circulation of solids, especially in the vertical direction. Thus for proper operation it is quite important to properly locate both solid feed and discharge points and to arrange the vessel internals to...
prevent appreciable temperature gradients occurring because of inadequate solids mixing.

The heat transfer coefficient in a fluidized bed furnace is very much higher than that in conventional forced air circulation furnaces (Fig.2.30.). The time for the core of the castings to achieve the set temperature is also less as the rate at which heat is transferred to the surface of the castings is closer to the rate at which surfaces to core conduction occurs.

The turbulent movement of sand in all areas of the bed results in a high degree of temperature uniformity, normally in the range of ±3°C, even in large furnaces.
Fig. 2.30. - Heat Transfer - Fluidized bed Vs Air Circulation Furnaces
2.5.13. Variables affecting the Heat Transfer Rate

Bed-wall coefficients in gas fluidized beds have been found to be 20 to 40 times that for gases alone, and since the bed represents a complex interaction of gas and solid, many factors will enter into any generalized correlation accounting for this behavior. Excluding radiation effects at first, the variables to be considered in the convection process are:

1. **Properties of gas:**
   - Density $\rho_g$
   - Viscosity $\mu$
   - Specific heat $C_{pg}$
   - Thermal conductivity $k_g$

2. **Properties of solid:**
   - Diameter $d_p$
   - Density $\rho_s$
   - Sphericity $\phi_s$
   - Specific heat $C_{ps}$
   - Thermal conductivity $k_s$

3. **Conditions at minimum fluidization:**
   - Superficial velocity $u_{mf}$
   - Voidage $\varepsilon_{mf}$

4. **Flow conditions:**
   - Superficial velocity $u_0$
   - Void fraction $\varepsilon_f$

5. **Geometric properties:**
   - Bed diameter $d_t$
   - Diameter of immersed object $d_{ti}$
   - Static bed height $L_m$
   - Length of heat exchange surface $L_h$

   The effect of gas velocity on $h_w$ is illustrated in Fig.2.31. There we see the coefficient rise sharply at the onset of fluidization. A maximum is soon reached beyond which the coefficient decreases steadily to the limiting value for gas phase systems when the superficial velocity exceeds $u_t$. According to Shirai, the coefficient rise sharply at the onset of fluidization. A maximum is soon reached beyond which the coefficient decreases steadily to the limiting value for gas phase systems when the superficial velocity exceeds $u_t$. According to Shirai, $h_w$.

2.98
Fig. 2.31. Influence of gas velocity on the bed-wall heat transfer coefficient in fluidized beds.
\[ u_i = 50 - 80 \, u_{mf} \quad \text{for fine solids} \]
\[ u_i = 7 - 10 \, u_{mf} \quad \text{for coarse solids} \]

The initial rapid rise in \( h_w \) is explained by the increased solid circulation, whereas the decrease beyond the maximum is attributed to the lowered solid concentration at high gas velocity.

The general pattern of behavior, shown in Fig. 2.31., suggests that the ratio \( u_p/u_{mf} \) should play an important role in any correlation: however, the majority of investigators, exploring only a small portion of the available velocity range, omitted this factor in their correlations. Considerations such as this, point out the limitations of the reported correlations: they can only be used safely for design, if the planned operating conditions, closely approximate those used in the experimental study.

2.5.14. Continuous Operations

The analysis of batch contacting showed that certain simplifications are reasonable for physical operations. Let us use these simplifications for the continuous treatment of a solid feed.

2.5.14.1. Heat Transfer of Continuous Stream

Consider the steady-state heating of a continuous stream of cold solids by hot gas in a single fluidized bed as shown in Fig. 2.32. If we neglect heat losses to the surroundings, an energy balance about the whole bed gives,

\[ \text{(Heat gained by Solids)} = \text{(Heat lost by Gas)} \]
Fig. 2.32. - Continuous heat exchange between solids and fluidizing gas.
Upward-moving dispersed solids

Downward-moving agglomerate

Upward-moving agglomerate

Dense bed

Fig. 2.33. - Model to account for elutriation and entrainment from fluidized beds.
For conditions normally met in practice these continuous operations can be considered equilibrium processes, with exiting gas, bed solids, and exiting solids all at the same temperature.

2.5.15. Drying of Solids

At any instant during batch operations the solids are at the same stage of drying; consequently, there is little interaction between the particles as far as drying is concerned. The situation is quite different in continuous operations because here the bed consists of a small fraction of more or less wet particles interspersed in a bed of almost dry solids. The temperature of the dry and wet solids may differ and the interaction between particles may be important. These factors suggest that an analysis of the drying may differ significantly for the two cases.

Focus attention on a single wet solid particle of temperature $T_p$. Since the probability of its being bathed by bubble gas is very small, let us assume that it is present in the emulsion all the time and that its rate of drying is determined by its interaction with the emulsion and with the surrounding almost dry particles, both of which are at temperature $T_e$.

The drying rate of this typical particle of size $d_p$ can be represented by,

$$
\text{Decrease of free moisture in a particle} = \left(\frac{\text{Mass transferred from the wet particle to the neighbouring emulsion fluid}}{\text{Heat transferred from neighbouring solids}}\right) = \frac{\text{Mass transferred from the wet particle to the neighbouring emulsion fluid}}{\text{Latent heat of vaporization}}
$$
Fig. 2.34. - A model for the continuous drying of solids in a fluidized bed with emulsion temperature.
2.5.16. Wide Size Distribution of Solids

If the feed contains a distribution of particle sizes including small solids which are entrained by the gas stream, various additional factors must be considered. First, when the entrained fines are not returned to the bed we find, using the treatment, that the mean residence time for the different sizes of solids in the bed is

\[ i(d_p) = \frac{1}{F_1/W + K(d_p)} \]

where \( F_1 \) is the overflow rate of solids.

2.5.17. Non-Catalytic Gas-Phase Reactions

Since heat can be added or removed easily and rapidly from the reaction zone, fluidized beds are sometimes used to effect ordinary gas-phase reactions. For instance, in the thermal cracking of hydrocarbons in fluidized beds of carbon or sand the solids can be looked upon simply as the medium for introducing heat and removing carbonaceous matter deposited during reaction.

In this type of reaction the temperature rise of bubbling gas becomes important for design. In addition, a vigorously bubbling bed can be approximated by a plug flow reactor with gas passing through at the bubble velocity.

Since a high freeboard is usually used in commercial beds, non-catalytic reactions would still proceed in the zone above the bed. If detrimental secondary reactions can take place, as in the case of thermal cracking, this may create a major problem. Thus an ordinary fluidized bed may not be satisfactory for such systems.
unless special provisions are built into the equipment for quenching these product gases.

Another example of a non-catalyzed gas-phase reaction is the combustion of fuel gas in a bed of inert solids for the purpose of heating the solids. Fig.2.35. shows a simple model for this operation. Here fuel gas issues from an orifice of the same size as in the distributor for the fluidizing air. Let us assume at the high temperature of the bed that combustion occurs instantaneously when the fuel gas and air are mixed. The only problem then is to find how fast air mixes with the fuel gas, and this in turn is dependent on the rate of coalescence of the rising bubbles of gas.

Under normal conditions complete combustion is achieved in a bed; however, in a very shallow bed or with a high flow rate of fuel it is advisable to use several injection nozzles for the fuel. Further, during startup, when the bed is cool, the mixed combustible gases may pass through the bed without ignition. To counter this, the bed may have to be preheated by using hot combustion gases from a starting furnace.
**Fig. 2.35.** - Size Distribution in a stable reactor-regenerator system.
2.6. **SCRUBBING**

Certain requirements must be met by any pneumatic reclamation equipment. One was that such equipment must be capable of subjecting sand grains to repeated passes at a target, or through an area of impact and abrasion. Another was that if possible, impact and abrasion should be secured with sand grains impinging against other sand grains, and not sand grains impinging against a metal surface\(^\text{87}\).

After considerable experimentation, a laboratory unit was developed to meet the stated requirements. It was first operated with compressed air, then with a blower, and was so designed that a small batch of sand could be recirculated continuously with individual grains being repeatedly subjected to impact and abrasion. Tests disclosed the unit to be capable of simultaneously removing old bond from individual sand grains and effecting a separation of such old bond from a sand mass as a whole. This combination of functions in a single unit seemed to be highly desirable.

A pilot plant unit was then designed to resemble the laboratory units but on a much larger scale. It was supplied with auxiliary equipments such as a magnetic separator, small crusher, drying unit, and bucket elevators. The pilot-plant unit was designed for batch operation.
2.6.1. Scrubber

A schematic drawing of this initial batch unit is illustrated in Fig.2.36. It consists of a containing shell, an air nozzle, a bottom flared center pipe, a conical target, an expansion chamber, and an exhaust duct. The drawing shows the normal height of sand charged into the unit. Its peculiar shape is better understood when one considers the manner in which it functions.
Fig. 2.36. – Sand Scrubbing Cell.
2.6.2. **Internal Function of Scrubber**

As sand is forced into the space between nozzle and center-pipe, it becomes entrained in the air stream, and is hurled upward through the pipe. It emerges at the top of the pipe with considerable velocity and collides with sand trapped in the peak of the conical target.

The conical target possesses the ability to hold an ever-changing, yet more-or-less constant mass of sand within its peak. The mass is held in position by the upward force of the sand / air mixture emerging from the centre-pipe. Sand grains continuously escape from around the circumference of the conical mass, while new grains are being added to its center. The net result is that most of the metal target is continuously covered with a layer of sand; and sand grains impinge upon sand grains—not sand grains against the metal.

After emerging from the center-pipe and colliding with the sand mass trapped in the target peak, the sand / air mixture is deflected outward and downward by the skirts of the target cone. The sand separates from the air and returns to the main sand mass lying in the bottom of the containing shell by gravity. The air flows outward and upward around the edges of the target cone, and escapes from the shell via the exhaust duct.

The enlarged upper portion of the containing shell serves as an expansion chamber. By being permitted to suddenly expand after emerging from the center-pipe/ target-cone area, the high-velocity air stream is converted to slow-moving air currents. Such currents are unable to retain sand grains in suspension. However,
small particles of bond and silica that can be air-floated do remain in suspension, and are carried out of the containing shell with the escaping exhaust air.

The sand returning to the main mass moves downward with the mass, and soon finds itself being forced to repeat the foregoing cycle. Obviously, the sand mass, and individual sand grains, can be recycled as many times as deemed necessary to obtain a desired degree of cleanliness in the reclaimed product.

2.6.3. Other Varieties of Scrubber

The continuous pneumatic reclamation unit consists of two parallel sequences with four batch units combined in each sequence: a total of eight units or cells, using a common expansion chamber and exhaust system. Through a receiving tank and a manifold system, a single blower supplies air to all cells.

In each sequence of 4-cells, continuous flow is achieved by connecting the cells together in step-like fashion. Openings permit sand to flow from feed hopper to cell, cell to cell, and cell to discharge. Sand flowing from feed hopper into No.1 cell raises its level beyond a set height, and it is forced to overflow into No.2 cell. No. 2 cell, in turn, is forced to overflow into No. 3: No 3 into No.4: No 4 into the discharge from the unit. Each cell functions exactly like an independent batch cell except that its charge of sand is continuously changing as outgoing grains are replaced by incoming grains.

During operation, in each cell the sand deflected by the conical target piles up along the exterior walls of the cell, and then flows inward and downward into the
“well” surrounding the cell’s center-pipe. Flow in this manner creates a steeply sloping upper sand surface in the shape of an inverted cone in each cell. Because of this natural feature, baffles are not needed in the cells to prevent the sand grains moving directly from inlet openings to outlet openings. As sand grains enter and fall into the vortex in a cell, they must be cycled one or more times in that cell before the target deflection places them in a position to escape through opening to the next cell. While the conical target is deflecting the sand from all points on its circumference, and the deflected sand is piling up along all the exterior walls of the cell, only the sand grains that fall immediately in front of the limited opening escape to the next cell during any one cycle. The sand grains that do not escape must necessarily continue to recycle until they are fortunate enough to fall in front of the opening.

Theoretically, it is possible for a sand grain to be cycled only once in each cell (a total of 4 cycles) in its passage from feed hopper to discharge. A grain may be cycled only one time in one cell but then be cycled many times before it escapes from the next cell. An examination of the individual grains emerging from a continuous unit indicates that they suffer about an equal number of cycles, and therefore, all grains are cleansed to about the same degree. The uniformity in grain cleanliness is, of course, essential for uniformity in the product as a whole.

While initially deemed to be successful, it is understood that the method failed to prove satisfactory over a period of time. It is believed that the limited amount of impact and abrasion was insufficient to do much towards reducing the coatings on heavily-bonded sand grains.
The later developed pneumatic methods had been specifically designed to meet the same set of fundamental requirements now being met by the wet reclamation methods. The method centers around an air-scrubber unit that parallels and duplicates the functions of a wet-scrubber unit in a wet-reclamation system. The only difference between a pneumatic scrubber and wet reclamation system is the respective media utilized for suspension and motivation. In one, the promotion and control of impact and abrasion between sand grains is obtained by suspending and motivating the grains in air; in the other, the same thing is accomplished in water.

This method of reclamation is economical and maintenance cost of equipment is negligible\(^8^9\).

Results from operating installations indicate that the pneumatic method is capable of performing a controllable amount of work on individual sand grains, and returns a product that consistently meets grain distribution specifications.

Reasonable control in the reduction of coating thickness and clay content can be accomplished through the dry reclamation method employing pneumatic scrubbing.
2.7. CALCINING

Thermal or calcining systems remove carbonaceous coatings and organic binders by subjecting sand up to 1500 F (815.56°C) in the presence of oxygen. This type of system results in the most effective removal of organic materials from sand grains but requires the use of fuel, unless methods are found to use waste heat from other sources at an elevated temperature\(^{90}\). Fig.2.37. shows the processes in a thermal system.

2.7.1. Fluid Bed Calciner Designs

The fluid bed calciners operating in Japan are of two types: Single Compartment Type and Multi-compartment Type.

A single compartment unit is partitioned by a steel constriction plate, as shown in Fig.2.37, into the upper and the lower chamber\(^{91}\).

The upper compartment is a calcining chamber and since the temperature there rises to about 800°C (1472F), this chamber is of such a structure that all its internal surface is lined with fire and insulation bricks. The lower compartment forms a wind box section through which fluidizing air is introduced into the fluidized bed.
Fig. 2.37. – Single Compartment fluid bed calciner
2.8. SAND CHARACTERISTICS

2.8.1. Constitution of Sands and Clays in Relation to their Origin

The moulding properties of a sand mix are determined principally by:

(i) The size of the sand grains, including both uniformity of size as well as average size.

(ii) The shape of the sand grains: whether equi-dimensional or elongate, and whether rounded or angular.

(iii) The minerals of which the sand grains are composed.

(iv) The mineral constituents of the clay bond.

Foundry sand control can be achieved only if the relation of these four factors to the moulding properties is fully appreciated.

2.8.2. The Mineralogy of Sands

Sand grains represent the coarse particles liberated by the weathering of rocks. As such, they are usually composed of quartz, felspar, and muscovite mica, together with minor amounts (usually less than 0.5 percent.) of minerals of considerably greater density than quartz. These heavy minerals include zircon, glauconite, tourmaline, garnet, rutile, kyanite, ilmenite, limonite and magnetite. Normally quartz is the principal constituent of sands, but certain exceptional sands are composed almost entirely of heavy minerals and form the source of zircon sands sometimes used in foundries.
2.8.3. **Shape of Sand Grains**

2.8.3.1. **Profile**

Silica sand grains are of paramount importance in moulding sand because they impart refractoriness, chemical resistivity and permeability to the sand. They are specified according to their average size and profile. The finer the grains, the more intimate will be the contact and lower the permeability. However, fine grains tend to fortify the mould and lessen its tendency to get distorted. The shapes of the grains may vary from round to angular. The grains are classified according to their shape.

2.8.3.2. **Rounded Grains**

These grains have the least contact with one another in a rammed structure, thereby making the sand highly permeable to gases. Sand having rounded grains, however, lack strength and do not pack up to the optimum extent. The binder requirements are minimum.

2.8.3.3. **Sub-angular Grains**

These grains have comparatively lower permeability and greater strength than the rounded ones.

2.8.3.4. **Angular Grains**

These grains have defined edges, and the surfaces are nearly flat. They produce higher strength and lower permeability in the mould than sub-angular grains. The binder consumption is likely to be high.
2.8.3.5. Compound Grains

In some cases, the grains are cemented together such that they fail to separate when screened. They may consist of rounded, sub-angular, or angular grains or a combination of the three. Such grains are called compounded grains and are least desirable due to their tendency to breakdown at high temperature.

In practice, sand grains contain mixed grain shaped, depending on origin. A sub-angular-to-rounded grain mature would be the best combination.

2.8.3.6. Specific Surface

Shape of sand grains is based on the determination of the specific surface (i.e., the surface area of unit weight of the grains). The specific surface of a similarly-graded set of spherical grains can be calculated; this value may be referred to as the theoretical specific surface. Since a sphere has the least surface area per unit volume, it follows that the ratio of the actual to the theoretical specific surface cannot be less than unity, and will become progressively greater than unity as the grain shape departs further from the spherical. The ratio of actual to theoretical specific surface is defined as the coefficient of angularity. For a cube it has the value of 1.25 approximately, while for a regular tetrahedron the value is about 1.49.

The actual specific surface is determined by passing air through the sand arranged as a cylindrical bed with its axis in the line of flow. The specific surface area $S_w$(sq. cm. per. g) is a function of the porosity and permeability of the bed, viz.:-

$$S_w = \frac{\text{Constant}}{\text{Bulk Density}} \sqrt[3]{\text{Porosity}^3/\text{Permeability}}$$
The exact relationship is given by the following rather formidable, semi-empirical expression, which can be simplified greatly, as will be shown:

\[ Sw = \frac{1}{\delta(1-\varepsilon)} \sqrt{\frac{(\varepsilon^3 A p_1)}{(k \eta Q L)}} \]

\[ Sw = \frac{14}{\delta(1-\varepsilon)} \sqrt{\frac{(\varepsilon^3 A p_1)}{(C p_2 L)}} \]

where,

- \( \delta \) - the density of quartz sand (=2.65 g. per cc for pure quartz sand).
- \( \varepsilon \) - the fractional porosity of the bed = volume of pore space per unit volume of bed.
- \( A \) - the cross sectional area of the bed (sq. cm.).
- \( L \) - the length of the bed (cm.).
- \( p_1 \) - the pressure difference between the ends of the bed (dynes per sq. cm.).
- \( k \) - a constant = 5.0 (independent of both the particle shape and the apparatus).
- \( \eta \) - the kinematic viscosity of air (c.g.s units).
- \( Q \) - the rate of air flow through the bed (cc per sec.).
- \( C \) - the flow-meter constant.
- \( p_2 \) - the pressure difference on flow meter (dynes per sq. cm.).

The expression can be reduced to the following:

\[ Sw = \frac{14}{D} \sqrt{\frac{(\varepsilon^3 \times 1.1288 \times h_1)}{(5.5680 \times 10^{-6} \times 0.866 \times V \times h_2)}} \]

Where \( D \) – the bulk density of the sand bed (g. per cc).

- \( h_1 \) – reading of manometer H1.
- \( h_2 \) – reading of manometer H2.
- \( \varepsilon \) - fractional porosity.
(Constant for one particular apparatus only)

1.1288 – cross-sectional area of burette.

0.866 x V – length (L) of the bed, V being the volume.

5.5680 x 10^{-6} - flow-meter constant C_1.

Hence for this particular apparatus, the expression becomes:-

$$Sw = \text{antilog } 3.8308 \times \frac{\sqrt{\varepsilon^3}}{D} \times \frac{h_1}{V \times h_2}$$

The value of $\sqrt{\varepsilon^3}/D$ may be obtained by reference to which relates it to the bulk density of the bed, that is, the ratio of the weight to the volume of the bed.

The theoretical specific surface can be calculated approximately from the mechanical grading of the same sample as that used for the actual specific surface determination, since quartz, the principal constituent of nearly all foundry sands, forms equi-dimensional grains. The theoretical specific surface is calculated by assuming that the sand grains in each sieve fraction are spheres whose diameter is the mean of the sieve apertures defining the fraction. Thus for normal foundry sand, the theoretical specific surface is:-

$$\frac{6}{(d, \rho)} = \text{ (for quartz) } \frac{2.264}{d} \text{ sq.cm. per g.}$$

where $d$ is the diameter of the spheres and $\rho$ is the density of the sand (2.65 g. per cc for quartz).

2.8.4. Example of Factors for Calculation of Actual Specific Surface

When Bulk Density (g per cc) is 1.300 log of $\sqrt{\varepsilon^3}/D$ is approximately given by 1.4488.
Similarly when Bulk Density g per cc is 1.305 log of $\sqrt[3]{\varepsilon / D}$ is 1.4446. The two are therefore inversely proportional to each other.

When we proceed forward with intervals of 0.005 in bulk density, we arrive at the higher values as follows.

<table>
<thead>
<tr>
<th>Bulk density g. per cc</th>
<th>Log of $\sqrt[3]{\varepsilon / D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.690</td>
<td>1.1084</td>
</tr>
<tr>
<td>1.695</td>
<td>1.1035</td>
</tr>
<tr>
<td>1.700</td>
<td>1.0986</td>
</tr>
</tbody>
</table>

For the bank of sieves suggested, this expression results in the conversion factors given in Table 2.3. The products of the weight of sand in each fraction and the corresponding factor, give the total specific surface in that fraction. The sum total of these products, divided by the total weight of the sample, gives the theoretical specific surface for the sample as a whole.

<table>
<thead>
<tr>
<th>B.S SIEVE FRACTION</th>
<th>Mean diameter d of grains mm.</th>
<th>Specific surface sq. cm./gm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5 + 10</td>
<td>2.514</td>
<td>9.00</td>
</tr>
<tr>
<td>-10+16</td>
<td>1.320</td>
<td>17.15</td>
</tr>
<tr>
<td>-16+22</td>
<td>0.852</td>
<td>26.51</td>
</tr>
<tr>
<td>-22+30</td>
<td>0.600</td>
<td>37.73</td>
</tr>
<tr>
<td>-30 + 44</td>
<td>0.426</td>
<td>53.15</td>
</tr>
<tr>
<td>-44 + 60</td>
<td>0.302</td>
<td>74.97</td>
</tr>
<tr>
<td>-60 + 72</td>
<td>0.232</td>
<td>97.58</td>
</tr>
<tr>
<td>-72 + 100</td>
<td>0.182</td>
<td>124.4</td>
</tr>
<tr>
<td>-100 + 150</td>
<td>0.132</td>
<td>171.5</td>
</tr>
</tbody>
</table>
2.8.5. Angularity Curves

If a sand is divided into size-fractions by sieving, and the coefficient of angularity determined separately for each fraction, it will be found that the coefficient varies with the grain size.

The curves in Fig. 2.38 illustrate the variations for some unconsolidated sands which have accumulated under different conditions. This splitting affected all the grains. The fine fractions have higher coefficients of angularity than the medium and coarse fractions, because they include slivers derived from the fracturing of larger grains.

2.8.6. The Preparation of Moulding Sands

The moulding sand does a three-component system, comprise sand grains, clay bond and water, which has to be adjusted so that the prepared sand has both strength and plasticity.
Fig. 2.38. - Angularity curves for some unconsolidated sands
2.8.7. The Milling of a Moulding Sand

The concept of a clay as a mass of quasi-parallel flakes separated by water films forms the basis of the discussion of the cohesive and plastic properties of moulding sands. When a sand and clay are milled together, each sand grain becomes evenly coated with clay. Once the grains are evenly coated, further milling has little or no effect on the strength of the mixture.

2.8.8. The Optimum Moisture Content in a Sand Mix

During the ramming of a mould, the principal function of the clay-water envelopes is to act as a lubricant between the sand grains so that they will pack evenly into every corner. The moisture content must be adjusted so that while the clay envelopes will slip past each other, they must hold the sand grains apart as long as possible. Ideally the sand should be fluffy when it has been aerated on discharging from the mill; in other words, its bulk density should be as low as possible.

The effect of moisture on the bulk density of unbonded sand and on bonded sand is illustrated by Fig.2.39. It will be seen that the bulk density of the moist, unbonded sand decreases until it reaches a minimum of 0.86 g. per cc at 1.5 percent moisture. When water is mixed with clean quartz grains, water layers probably develop on the surface of the grains in a manner similar to those on the surfaces of a clay flake.
Fig. 2.39. - The relation of the bulk density of milled sand to its moisture content.
2.8.9. The Shaping of the Sand

An almost uniform bulk density is an essential characteristic of a satisfactory sand mould or core. The method of moulding, the shape of the pattern or core-box, and the plasticity of the sand must be adjusted until this is achieved. On the adjustment depend the permeability and strength of the sand, factors which govern the resistance of the mould surface to penetration and erosion, as well as the escape of gases driven off, by the molten metal. The relation of the permeability and strength of a mould to its bulk density is illustrated by Fig.2.40. The hardness of the sand mould depends on the plasticity of the sand, and on the bulk density to which it has been packed.
Fig. 2.40. - The relation of strength and permeability to bulk
2.8.10. Bulk Density Distribution in Relation to Moulding Technique

Even when the sand is of uniform quality, the bulk density of the finished mould is rarely uniform throughout. Thus it is frequently observed that in hand-rammed moulds, the bulk density of the sand adjoining the mould surface varies in a manner corresponding to successive additions of sand to the box during ramming. For instance, a mould hardness survey of the hand-rammed mould, shown in Fig.2.41.(b), is typical and shows fluctuations in hardness corresponding to successive additions of sand.

If the mould shown in Fig. 2.41.(a) is prepared by jolting, the mould hardness graph takes the form shown in Fig. 2.41.(c), that is, the bulk density decreases up the mould. The application of squeezing to complete the mould modifies the mould hardness graph to the form shown in Fig. 2.41.(d).

The variations in bulk density are unavoidable, for they are due to wall drag where the sand is in contact with the moulding box and pattern. Wall drag arises largely because the sand is subjected to lateral constraint between the walls of the moulding box and the sides of the pattern. Lateral pressure is developed by wedge action between the grains, as indicated ideally in the diagram, Fig.2.42.; in this the grains are of uniform size and have been exaggerated for the sake of clarity. The pressure, P, applied to pack the sand by squeezing, is transmitted from the top layer of grains to that below by forces more or less normal to the contacts between the grains.
Fig. 2.41. - Mould hardness in relation to ramming technique

(a) SECTION THROUGH MOULD (b) HARD RAMMING (c) JOLTING ONLY (d) JOLTING AND SQUEEZING

DISTANCE FROM BASE

MOULD HARDNESS

MOULD HARDNESS

LIMITS OF SUCCESSIVE ADDITIONS

HARDNESS SURVEY

MOULD HARDNESS TOO LOW FOR ADEQUATE STRENGTH
Fig. 2.42 - The transmission of pressure through sand.
The principal aim in controlling the distribution should be towards uniform bulk density. The bulk density falls off sharply in the top part of the core, and then more gradually until, finally, the rate of decrease is negligible, the curve being almost parallel to the horizontal axis. This near-horizontal portion corresponds closely to the bulk density of the sand before the pressure was applied.

The space between the pattern and the moulding box yields information relating the bulk density gradient to the moulding technique. Consider the forces acting on a layer of sand of thickness $\delta x$ in the corebox at a depth $x$ below the surface of the sand after equilibrium has been attained under a pressure, $P$, at the top of the sand Fig.2.43. The pressure $p_1$ at the top of the layer will differ from the pressure $p_2$ at the base of the layer by the amount of resistance due to the wall drag caused by friction and by surface tension. The wall drag $F$, expressed as a force per unit area of the wall of the corebox, is the sum of these effects and may be expressed as follows:

$$F = \mu R + \eta R = (\mu + \eta) \cdot \varphi(p)$$

Where $\mu$ is the coefficient of friction and $\eta$ is a factor relating the internal pressure $R$ to the surface tension.

Equating the vertical forces

$$(p_1 - p_2) \pi r^2 = 2\pi r \cdot \delta x (\mu + \eta) \cdot \varphi(p_1 + p_2)/2$$

that is, $(p_1 - p_2) = 2 \cdot \delta x/r (\mu + \eta) \cdot \varphi(p_1 + p_2)/2$

The bulk density to which the sand is compacted is a function of the pressure to which it has been subject, that is,

$$\Delta = f(p)$$

2.132
Fig. 2.43. – The Stress distribution in the segmental core base.
The difference in bulk density between the top and bottom of the layer \( \delta x \) will be:

\[
\Delta_1 - \Delta_2 = f(p_1-p_2)
= f[2.8x/r (\mu + \eta).\phi (p_1,p_2)/2 ]
\]

where,

\( \Delta_1, \Delta_2 \) are the bulk densities corresponding to \( p_1 \) and \( p_2 \).

As the diameter of the core-box is increased, the bulk density variation becomes proportionately less. Hence, in foundry practice, narrow, deep gaps should be avoided as far as possible.

An increase in pressure raises the bulk density down the whole core, but the bulk density gradient remains unchanged. Thus an increase of pressure does not make the bulk density distribution more uniform.

2.8.11. Bulk Density Distribution in Relation to Moulding Sand Characteristics

In clay-bonded sands, an increase in moisture content reduces the bulk density gradient, provided that the moisture content does not exceed that at which the sand still has appreciable strength. Bulk density gradient curves for mixes in which the same base sand was bonded with different types of clay are almost identical. Increase in the proportion of any one clay bond reduces the gradient slightly.

The grain shape of the sand is the important factor in determining the bulk density gradient.
2.8.12. The Strength of Moulding Sands

The strength, after drying at a temperature of, say, 200°C., is a measure of the resistance of dry sand moulds to the wash of the molten metal.

The strength of the sand is compared by compacting the sand into cylindrical test pieces, which are then loaded to failure in a compression machine. In the second method of comparison, the sand is formed into a necked test piece, similar to the standard cement test piece, and subjected to tension. The compression method is used for the determination of green, dry, and hot strength (including residual strength) of clay-bonded sands, while the tension method is applied mainly to organic-bonded sands after baking.

The strength of the bond between the two grains is proportional to the area of the circular cross-section of the lens of the bond between the particles, that is, to \( y^2 \) Fig.2.44. The relationship between this bond structure and the strength of the sand after moulding, can be deduced mathematically on the lines. A curve of the form shown in Fig. 2.45., indicating that the strength increases rapidly in the early stages of ramming, but approaches consistency in the later stages.

If the amount of clay bond in the sand is increased, the thickness Fig.2.44. of the clay envelope on each grain is increased proportionately. Under similar conditions of ramming, and provided that the clay/water ratio is constant, then, for equal increments of clay bond, Fig.2.44. will increase rapidly at first and then more slowly and the strength will increase correspondingly. This is illustrated in Fig. 2.46. by the green and dry strength curves for a clay-bonded sand.
Fig. 2.44. – The bond structure in clay-bonded sand.
Fig. 2.45. - The relation of strength to intensity of ramming

NUMBER OF BLOWS OF RAMMER

GREEN STRENGTH
Fig. 2.46. - The relation of strength to proportion of clay bond
2.8.13. The Relation of the Grain Shape to the Strength of the Sand

The mechanical grading of the two sands compared, as determined by sieving, are almost identical, but their average coefficients of angularity differ considerably.

Though without valid data, that angular sands give greater strength than round sands, apparently on the assumption that flat-to-flat contacts are developed, as in Fig.2.46.(a). This inter-granular structure would give a bulk density far higher than is obtained in normal ramming practice. This implies that angle-to flat contacts, as in Fig.2.46.(b) are much more important than flat-to-flat contacts.

2.8.14. The Dry Strength Characteristics of Clay Bonds

If the dry strength of a clay-bonded sand mix is determined for progressively higher drying temperatures, a curve such as that in Fig.2.47. is obtained. This indicates that the dry strength decreases as the drying temperature is increased until at 700°C the test pieces of this mix crumble to sand on cooling. This is due to thermal shock which becomes more marked with higher drying temperatures.
Fig. 2.47. – Grain relationships in angular sands.
Fig. 2.48. – The relation of strength to the drying and crushing temperatures
2.8.15. Surface Texture

Permeability is defined by Wologdine's expression, viz., the permeability number N given by:

\[ N = \frac{v \cdot h}{p \cdot a \cdot t} \]

Where:

- \( v \) – volume of air passed, expressed in millimeters.
- \( h \) – height of test pieces, expressed in cm.
- \( p \) – pressure difference between ends of test piece, expressed in cm of water.
- \( a \) – cross-sectional area of test piece, expressed in sq. cm.
- \( t \) – time in minutes.

Thus the "permeability number" is the volume of air passed through a unit cube of the sand in one minute under unit pressure difference between the end faces of the cube.

Permeability is principally a function of the mechanical grading of the sand, low permeability being associated with fine, uniform grain size and with non-uniform grain size (badly graded sand); in the latter the finer grains tend to fill the pores between the coarser grains. For instance, the series of sands whose cumulative grading curves are shown in Fig.2.48. were bonded similarly and gave permeability numbers ranging from 65 to 300.
Fig. 2.49. – Cumulative grading curves in relation to permeability
2.8.16. Thermal Conductivity

Much of the internal strain in intricate castings, consequent on cooling, may be eliminated by adjusting the thermal conductivity of the sand locally so that the casting cools evenly. The facing sand, or sand near the mould surface, may be backed by insulating sand where the casting has its thinnest sections.

2.8.17. The Characteristics of High Silica Sands in Relation to their Moulding Properties

The value of high silica sand for foundry purposes is determined by its mineralogical constitution, its mechanical grading, and its grain shape. Ideally it should be composed entirely of round quartz grains and should be well graded; in particular, grains less than 0.1 mm diameter should be absent.
2.9. SAND TESTS

2.9.1. Moisture

Possible sources of error in moisture test are as follows\textsuperscript{94}:

1. Inaccurate weights
2. Lack of sensitivity in balances
3. Variation in room humidity
4. Gain in moisture content before original weighing
5. Loss in moisture content before original weighing
6. Failure to evaporate all moisture during drying
7. Condensation of water vapour in test can on walls of can with concurrent loss of moisture in sand sample.
8. Leak in the screen in the rapid drier (in old style pan).
9. Loss of part of sample after original weighing
10. Moisture adsorption when weighing dry sample.

The gain in moisture before weighing could be obtained by weighing or exposing the sand in an atmosphere of high humidity.

2.9.2. Green Permeability

The possible sources of error for this test were as follows:

1. Variation in intensity of ramming.
2. Leak in permeability meter.
3. Inaccurate orifices.
4. Type of specimen tube.
5. Moisture or mercury in the air tube.
7. Sand grains in mercury seal causing leakage.

8. Inaccurate pressure gage.

9. Variation in temperature and barometric pressure.

10. Moisture content variations in sample.

2.9.3. Dry Permeability

In addition to the possible sources of errors listed for the green permeability test, the following can be added for the dry permeability test:

1. Specimen not dried at correct temperature

2. Specimen not correctly sealed in tube.
   
   The latter source of error seems most likely and this supported by the evidence which shows considerable scatter on the plus side of the average results.

2.9.4. Plastic Properties of Sand

The plastic properties of compacted moulding sands are characterized by the internal shear strains which take place without weakening the bonds between the sand particles, i.e., while maintaining adequate strength. The plastic properties of a sand can be assessed from the amount of plastic shear strain and the external load which produces this strain. The shear is proportional to the force and the distance between the shearing planes, and inversely proportional to their cross-sectional area. In the plastic strain range, stress and strain are no longer proportional, since the modulus of elasticity decreases; when referring to plastic strain; it may be called the modulus of plasticity, or simply plasticity.
2.9.5. **Composition of Regenerated Sand**

The chief admixtures contained in used and regenerated sands are clay, coal, sodium silicate, sulphite and ferro-chromium slag. Under the influence of the molten metal temperature in the most heated sand layers, the clay coating the sand grains is partly converted to chamotte, while the coal and the sulphite lye burn and carbonise, evolving gases which filter through the sand and deposit carbon on the sand grains\(^96\).

2.9.6. **Fines Removal from Moulding Sand**

One way of improving the physical and mechanical properties of moulding sands based on alumina cement, and lowering the sand costs, is to remove the fines from the used sand and recycle the regenerated sand and recovered fines. Cement hardens at room temperature by the formation, growth and consolidation of crystalline hydrates. Only a proportion of the cement reacts with the water, but this is sufficient to develop a high strength in the moulding sand\(^97\). The unreacted cement should however be recovered and set aside for recycling. The strength of hardened cement varies as the temperature is raised (Table 2.4.).

2.147
### Table 2.4. - Temperature Vs Compressive Strength in Moulding Sand

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Compressive strength, kgf/cm²</th>
<th>Temperature, °C</th>
<th>Compressive strength, kgf/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>100.5</td>
<td>600</td>
<td>71.0</td>
</tr>
<tr>
<td>100</td>
<td>120.5</td>
<td>700</td>
<td>58.5</td>
</tr>
<tr>
<td>200</td>
<td>148.2</td>
<td>800</td>
<td>39.2</td>
</tr>
<tr>
<td>300</td>
<td>157.3</td>
<td>900</td>
<td>30.0</td>
</tr>
<tr>
<td>400</td>
<td>125.0</td>
<td>1000</td>
<td>23.0</td>
</tr>
<tr>
<td>500</td>
<td>87.0</td>
<td>1100</td>
<td>17.6</td>
</tr>
</tbody>
</table>

2.9.7. Improved Magnetic Separation of Used Sand

Used sand contains about 1 percent of metal, one third in the form of spherical particles 1-20 mm in diameter and two thirds in the form of irregular pieces. Magnetic separation is carried out with the aid of over slung or pulley-type 2-, 4- or multi-pole iron separators, or magnetic lifting discs.
2.10. **BEHAVIOUR OF SILICA**

Silica is the most widely used among all the refractories and forms the main constituent of foundry sand. It is existing in different crystalline forms depending on the temperature and prior heating and cooling rates.

The differences between the various structures lie in the arrangements according to which the Si and O₂ atoms are linked together and in their relative geometrical locations in space in the solid.

Silica has three principal crystalline forms, quartz, tridymite and cristobalite. Further more, each of these three crystalline varieties in turn exist in high and low temperature modifications, called inversions. Quartz and cristobalite both have two inversions each and tridymite has three inversions – making seven crystalline forms in all. They are represented as:

- α - quartz (or low quartz)
- β - quartz (or high quartz)
- α - tridymite (or low tridymite)
- β₁ - tridymite (or lower high tridymite)
- β₂ - tridymite (or upper high tridymite)
- α - cristobalite (or low cristobalite)
- β - cristobalite (or high cristobalite)

2.10.1. **Stable and Unstable Structures**

At a given temperature, only one form of silica is stable, but several of the other forms may exist metastably. Thus quartz, tridymite, cristobalite can also exist at
room temperature for a very long time, even though quartz is the only truly stable structure at room temperature.

The following figure 2.50. summarizes the stability relationships between the various forms of silica. The solid continuous line indicates the stable form at each temperature. The dotted line indicates the unstable state.

![Stability relationships between forms of silica](image)

**Fig.2.50. — Stability relationships between forms of silica**

While change from one inversion to another inversion within a variety (e.g., α-quartz or β-quartz) occurs instantaneously by either heating or cooling, changes from one variety to another (e.g., β-quartz to β2-tridymite) tend to be slow and sluggish during heating.

**2.10.2. Change in Structures during Heating and Cooling**

(i) In the unfired state, a silica brick consists of all α-quartz. When this brick is ordinarily heated, the following are the main changes in structures accompanied by expansion [+] or contraction [-] as indicated.
Table 2.5. - Changes in structure of \( \alpha \)-quartz

<table>
<thead>
<tr>
<th>Temperature (^{\circ}) C</th>
<th>Change in structure</th>
<th>% change in linear dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) 573</td>
<td>( \alpha )-quartz</td>
<td>( \beta )-quartz</td>
</tr>
<tr>
<td>(ii) 870 - 1470</td>
<td>( \beta )-quartz</td>
<td>( \beta_2 )-tridymite</td>
</tr>
<tr>
<td>(iii) 1250 - 1470</td>
<td>( \beta )-quartz</td>
<td>( \beta )-cristobalite</td>
</tr>
<tr>
<td>(iv) 1470 - 1713</td>
<td>( \beta_2 )-tridymite</td>
<td>( \beta )-cristobalite</td>
</tr>
</tbody>
</table>

Item (iii) above needs special mention here. When quartz is heated, inversion occurs at 573\(^{\circ}\)C, but the silica tends to remain as \( \beta \)-quartz (metastably) above 870\(^{\circ}\)C. If the temperature is raised to 1250\(^{\circ}\)C or above, the quartz tends to transform directly into cristobalite.

(ii) When a refractory brick containing all three crystal forms – quartz, cristobalite, tridymite – is heated, inversions take place as below, for cristobalite and tridymite. (Quartz undergoes changes as in (i) explained above)

Table 2.6. - Inversion in Tridymite and Cristobalite

<table>
<thead>
<tr>
<th>Crystal form</th>
<th>Temp.</th>
<th>Inversions</th>
<th>% change in linear dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tridymite</td>
<td>117(^{\circ})C</td>
<td>( \alpha ) to ( \beta_1 )</td>
<td>+ 0.15</td>
</tr>
<tr>
<td></td>
<td>165(^{\circ})C</td>
<td>( \beta_1 ) to ( \beta_2 )</td>
<td>+ 0.06</td>
</tr>
<tr>
<td>Cristobalite</td>
<td>220 - 225(^{\circ})C</td>
<td>( \alpha ) to ( \beta )</td>
<td>+ 1.05</td>
</tr>
</tbody>
</table>
It is to be noted that the change in inversions take place both during heating and cooling and they are instantaneous. But once cristobalite, or tridymite is formed, each of this structure tends to be retained on cooling, so that when a furnace structure containing a SiO₂ phase is cooled from the operating temperature, the structure at operating temperature is largely retained.

2.10.3. Expansion and Spalling

From the above data, it can be seen that large expansions occur when quartz transforms to either tridymite (5.5% linear increase) or cristobalite (4.85% linear increase). This will result in serious spalling during furnace operation.

During manufacture of silica brick, the bricks are fired to over 1425°C, wherein the quartz transforms to tridymite and cristobalite, accompanied by expansion. Thus the spalling associated with quartz transformation is avoided during furnace operation.

However, changes accompanying the inversions are unavoidable, since they occur rapidly as the silica passes through the inversion temperature. Thus silica bricks are particularly prone to spalling if heated and cooled repeatedly through 250°C, which is the inversion temperature of cristobalite.