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**Simulation of Solid Processes by Aspen Plus**

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## **Abstract**

106 pages, 12 tables, 37 figures, 09 Appendices

### **Keywords:**

Solid processes, Simulation, Aspen Plus

Solid processes are used for obtaining the valuable minerals. Due to their worth, it is obligatory to perform different experiments to determine the different values of these minerals. With the passage of time, it is becoming more difficult to carry out these experiments for each mineral for different characteristics due to high labor costs and consumption of time.

Therefore, scientists and engineers have tried to overcome this issue. They made different software to handle this problem. Aspen is one of those software for the calculation of different parameters. Therefore, the aim of this report was to do simulation for solid processes to observe different effect for minerals.

Different solid processes like crushing, screening; filtration and crystallization were simulated by Aspen Plus. The simulation results are obtained by using this simulation software and they are described in this thesis. It was noticed that the results were acceptable for all solid processes. Therefore, this software can be used for the designing of crushers by calculating the power consumption of crushers, can design the filter and for the calculation of material balance for all processes.

## **Acknowledgement**

Writing this thesis has been a challenging, yet rewarding project. The last months has taught me a lot, not just about the usage of Aspen Plus, but also about achievement of goals as well. After countless hours spent on the computer, it feels good to say that one important milestone has finally been reached.

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Best Regards,

Hafiz M. Irfan Anwar

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**List of symbols**

a	S-function parameter in equation 2.1
$B(x_i, x_j)$	value of Breakage function
b	S-function parameter in equation 2.1
$\gamma$	C-function parameter in equation 2.2
c	coarse product rate (kg/h)
x	particle size (m)
E	efficiency of screen (%)
F	feed rate (t/h)

## **1. Introduction**

With the exponential increase in the recovery cost of minerals, scientists and engineers in all parts of World are trying hard to discover new reservoirs of minerals for controlling the prices. So, it is necessary for researchers and engineers to increase the efficiency of plant operations by designing the better equipment. Primary objective of these equipment was to achieve betterment in operation's economics. With the improvement of construction material, larger equipment were designed which possess the features like; high power and higher capacity.

Minerals are of primary importance due to their valuable use. Minerals contain solids and for their processing and handling, comminution is the primary step and it comprises of crushing and grinding. Therefore, it is obligatory for the engineers to perform different experiments to study the properties of minerals starting from their exploration to their end use. With the increasing prices of electricity, equipment and labor, it is getting difficult to perform experiments for each mineral.

Scientists and engineers are working on different programs and software packages to avoid high costs caused by performing experiments to test the minerals and to reduce time. Various types of software and computer programs are available in the market, which can be used for solid processing. Aspen Plus is one of those programs which can be used to test the influence of operation conditions and material properties on the processing.

Simulation of comminution, especially for grinding and classification has obtained great consideration. The reason for being so attractive is their importance for high energy consumption and overall plant performance. There is many other mineral processing operation but they could not get the same attention for intensive research like grinding and classification (Wills, 2006). Therefore, it is valuable to put efforts for the simulation these processes.



Simulation of filtration and crystallization was also done in this thesis. They are also very important processes for industry. By keeping in view their importance, they were included and simulated in this thesis.

This work is important because Aspen is normally used and designed for fluid processes. Aspen is used for the simulation of solids. During this work, it was interesting to integrate different solid processes and to see the results of these processes. This work could be unique for studying and obtaining results only for different solids processes by using the same program. The results obtained by using the ASPEN will show the use of the ASPEN for solids. In case of successful results, these results will be helpful for the industrial sector, e.g. mining to avoid huge cost involved on testing.

## **2. Comminution**

There are two basic operations for the processing of minerals. These process are named as

- (i) Liberation
- (ii) concentration

According to Wills (2006), liberation is the process of getting highly valued minerals from the waste gangue of minerals whereas; separation of these minerals from the gangue is known as concentration. The process of liberation is done by comminution.

### **2.1 Background**

Comminution is a process in which particulate materials are subjected to reduction by using different processes like blasting, crushing and grinding to obtain the size of product to specific requirements for their end use. The major function of the comminution process is to make sure that effective ingredients are physically separated from waste ingredients before applying any physical or chemical separation techniques (Fuerstenau, 2003).

Comminution is a basic and essential part of minerals handling operations. It is very important for the groundwork of ore processing. Many factors are considered for the selection of comminution equipment.

Recovery cost of metals was increasing continuously. In the meanwhile, high grade deposits were being discovered by scientists in different countries. It was necessary to increase the efficiency of plant operations by designing the better equipment. The major purpose for the development of this equipment was to improve the economics of operation. As the material of construction was improving, larger crushers were designed which has the following features like high power, more speed and higher output.

By this way, the efforts made by designers had made possible to make new design for crushers which will be the alternate for old and smaller models with modern facilities. These designs will also be helpful in reducing the capital costs.

Most of the metallic and industrial minerals are valuable and have high importance due to their specific characteristics. These properties can be resistance to acids, flexibility, hardness and strength. Due to the high 'unit values' of these mineral powders, they can be easily transferred to different market areas whereas aggregate comprises high 'place values' which means they have high bulk i.e. low unit value. So, it is very costly to take them to market (Mular, 2002, Kogel, 2006).

The most valuable technique used for brittle materials which also includes cement, brittle metals and metallic ores is termed as comminution. Comminution operations are classified into two main categories named, crushing and grinding (Groover, 2010). These both processes are essential for the completion of comminution.

## **2.2 Energy consumption of comminution**

In comminution, the main concerns lies between the input of energy and output i.e. size of particle obtained as a result of comminution. The main problem is the usage of high quantity of energy, given as input to crush a mineral by crushing or grinding machine itself and only a little amount of total energy is provided for breaking the material.

The energy consumed by United States in comminution process is more than 15 billion KWh which is about 1% of the total electricity produced in US. In 2000, energy consumed for comminution was divided to mineral units as shown in table 2.1.

Table 2.1 Highest ranked comminution energy consumers by mineral type (Fuerstenau, 2003)

Rank	Commodity energy	10 <sup>9</sup> kWh
1	Copper ore	3.6
2	Iron ore	3.3
3	Phosphate ores	1.3
4	Clay	0.5
5	Titanium ores	0.3

From table 2.1, it is clear that iron and copper use more than half of the total electricity in comminution. The total energy required for any given commodity can be estimated by different factors like material abrasiveness, the desired product fitness and the environmental corrosiveness.

Today, professionals are facing a challenge for the efficient operations and effective design of industrial comminution processes. The main reason for this is the energy intensive operations that are using 50% of operation costs of a plant and even bigger percentage of the capital costs. To enhance the profitability, for longer benefits from comminution devices and to improve the economic operations in mineral processing, careful use and creative designs are important factors (Fuerstenau, 2003).

After having a review on comminution theory, the clearest aspects to be considered are

- (i) Splitting of ore requires strength and energy based on composition and particle size
- (ii) Cutting down of tiny particles needs enormously great power
- (iii) Saving in energy has been enhanced due to sorting out efficiency in comminution technology

- (iv) Estimate, how much energy is provided to break the particles into different sizes to acquire the advancement and more descriptive models? This is the case, mathematical modeling has considered as significant means for the betterment of comminution technology.

By summarizing above, designing criteria and process conditions are particular for different kinds of comminution devices and they differ from each other in their functionality and feasibility for their different applications for different processes (Fuerstenau, 2003).

The main types of comminution process are crushing and grinding. These processes need a lot of energy which makes the operational costs high for these processes.

Table 2.2 Energy requirements for comminution process (Rosenqvist, 2004)

Types of crushing & grinding	Energy requirements, kWh/ton ore
Coarse crushing	0.2-0.5
Fine crushing	0.5-2
Coarse grinding	1-10
Fine grinding	2-25
Micronizing	100

From table 2.2, it is very clear that as the size is reducing, more energy is required for this process. The important factor is the reduction of energy used for comminution process by using water and it can still be further reduced by using the chemical additives.

Both, crushing and grinding are the stages of comminution but they have some clear differences. Crushing is usually a dry process and is done in many stages while grinding is a wet process. Crushing is mainly used for the reduction of big lumps into smaller sizes for further reduction whereas grinding, refers to the reduction of smaller sized particles produced by crushing, into fine powder. During crushing, heat losses are lower than grinding and compression is used for crushing while grinding is normally done by using impact technique. During the cracking of rock, more power is transferred by a crusher than a grinding mill. Crushing is done in the initial stages while grinding will be the final step in comminution. More energy is required in grinding than in crushing (Wills, 2006, Groover, 2010, Mular, 2002, Stellman, 1998).

### 2.3 Factors effecting the selection of comminution equipment

Table 2.3 shows different kind of equipment and their correspondence feed and product sizes, reduction ratios, their capacities and power consumption respectively. From the table, it can be clearly seen that energy used by mills for grinding is greater than crushers but their product sizes and reduction ratios are also smaller than crushers. The capacity for mills is also ignorable in comparison with crushers because the product size for mills is very small. In order to get this product size, mills have to spend more time and energy.

Table 2.3 Operating ranges for commonly used comminution equipment (Couper et al, 2010)

Equipment	Size of Feed(mm)	Size ofProduct (mm)	ReductionRatio	Capacity(tons/hr)	PowerConsumption (kW)
Gyratory crushers	200-2000	25-250	8	100-500	100-700
Jaw crushers	100-1000	25-100	8	10-1000	5-200
Cone crushers	50-300	5-50	8	10-1000	20-250
Impact breakers	50-300	1-10	40	10-1000	100-2000
Rod mills	5-20	0.5-2	10	20-500	100-4000
Ball mills	1-10	0.01-0.1	100	10-300	50-5000
Hammer mills	5-30	0.01-0.1	400	0.1-5	1-100
Jet mills	1-10	0.003-0.05	300	0.1-2	2-100

Figure 2.3 is helpful for the selection of different crushers or grinders against different materials with different hardness and particle size. e.g. jaw crusher is a good choice against hard materials and for coarse particle size whereas; colloidal mill is reverse to jaw crusher.

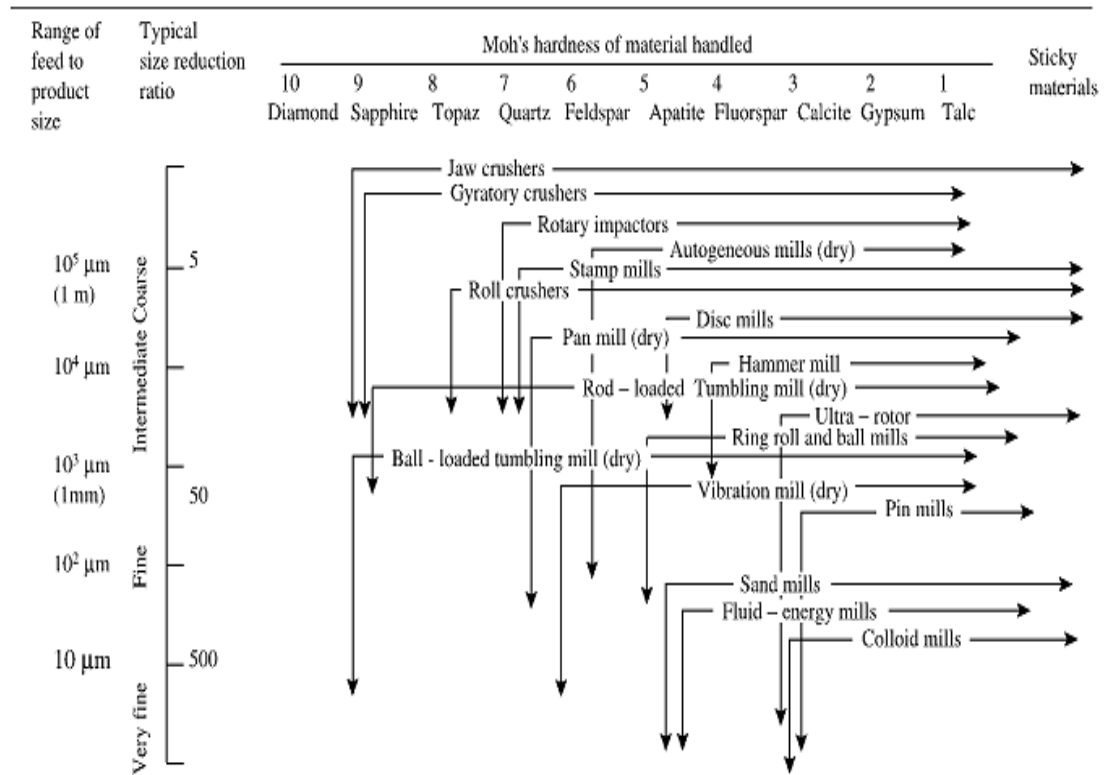


Figure 2.3 Selection of comminution equipment ( Sinnott, 2005)

## 2.4 Crushing

Breaking down the larger lumps from the main mine into smaller pieces for further successive reduction is called as crushing.

During crushing, different stages are needed. These stages are primary, secondary and tertiary crushing. The particle size varies in each stage of crushing depending on the type of equipment used. Normally, the particle size in the primary stage is 1.5m to 100mm whereas; it is reduced to a limit of 5 mm to 200 mm during the secondary stage (Stellman, 1998).

According to Groover (2010), mineral crushing is done by compressing the minerals against the hard surfaces. Different types of equipment are used for the purpose of crushing. They are

- (i) Jaw crushers
- (ii) Gyratory crushers
- (iii) Roll crushers
- (iv) Hammer mills
- (v) Cone crushers

The major factors that influence the selection of crusher are the required output of the plant, what feed size is given to the crusher and what the required product size of the feed is? Similarly, ore properties and climate conditions are also important factors for the selection of crusher.

## **2.5 Grinding**

The use of different equipment and techniques to get the fine powder from the small pieces obtained from crushing is termed as grinding. Fine powder in grinding is achieved by using impact and abrasion for crushed minerals. The isolated rigid media and free movement of this media lead the grinding into fine powder. These media can be steel balls, rods, pebbles, ceramics and balls etc.

Grinding will be the last step in comminution process and usually, it is done in rotating cylindrical steel vessels named as tumbling mills. The size of the mineral particles is much smaller than in crushing and may vary within the range 10 to 300 $\mu$ m (Groover, 2010, Stellman,1998).

A well known term ‘Autogenous grinding’ is referred when pebbles are used in grinding operations. This type of autogenous milling is used when the ore is directly introduced into the grinding mill without doing its pre-crushing. So, the grinding source will be the big lumps of the grinding ore. This mill is mostly used for the grinding of iron ore but it has also applications for other ores (Rosenqvist, 2004).



Equipment used for grinding are

- (i) Ball mill
- (ii) Roller mill
- (iii) Impact grinding

In the grinding of ore, a standard size is required for this grinding to make this process more efficient, to save energy and to recover the precious elements. Undergrinding and overgrinding must be avoided to save different kind of losses. These losses could be improper recovery; imperfect liberation for under grinding and separation of the particles will not be easy along with the wastage of costly energy in huge quantity (Stellman,1998).

Open-circuit grinding is used when the oversized material is not recycled for further reduction whereas closed-circuit grinding is applied when there is material with smaller size appears that is smaller than the specified size. Wet grinding is also used to avoid dusting problem. Due to the lubricating effect of water, power consumption in wet milling is less per ton as compared to other grindings but this lubrication effect can also be a source of corrosion (Couper et al, 2010).

### **2.5.1 Selection Function**

The probability for any particle size  $x$  which is going to break in grinding is given by selection function  $S$ , or  $S$  is the proportion of particles in class  $I$  which is selected for breakage. The functionality of  $S$  function is dependent on conditions for mill, on particle size of material and on the resistance offered by grinding. The simplest equation of  $S$ -function is

$$S(x) = a(x)^b \quad 2.1$$

Where  $a$  and  $b$  are parameters

### 2.5.2 Breakage Function

During the breakage of particle, a particular breakage rate given by the S-function. Due to this breakage rate, a size distribution of smaller fragments is produced. This can be represented by the breakage,  $\beta$ -function. The simplest breakage function is Schumann's equation expressed by Loveday

$$\beta(x_i, x_j) = (x_i/x_j)^\gamma \quad 2.2$$

Where  $\beta$  describes the fraction of particles from class  $j$  which breaks into a size smaller than and  $\gamma$  is the parameter.

Different types of  $\beta$  function have been described by different scientists. From different experiments, it is proved that  $\beta$ -function is depends more on material that is going to be ground and have a less effect by mill size. B-function can also be affected by the viscosity of slurry to some limit (Tuunila, 1997).

### **3. Classification of Minerals**

Classification is about the categorization of two or more things from each other. In terms of minerals, fractionation of various sized particles i.e. large and fine particles from each other on different basis is called classification. This basis might be the settling rate of particles in any fluid, differences in shape, size and density of the particles. So, the main objective for classification is to separate the particles.

Normally, the separation of different sized particles with different densities to different classes is done with classification. This process is done by using a settling medium which may be air, water, gases or other liquids. The diversity in the settling rate results in the separation of particles. Therefore using classification phenomena, it is possible to separate the coarse from fine particles, or smaller heavier particles from larger lighter particles (Stellman 1998, Gupta 2003).

Classification and screening, both are the separation processes but the major difference between them is the consideration of specific gravity. Specific gravity is a paramount factor in classification while it is not taken into account during screening. Screening is not suitable for fine particles while classification performs well for fine particles (Gupta, 2003)

#### **3.1 Equipment used for classification**

The equipment used for classification of minerals and continuous settling are called classifiers. Different types of classifiers are used as follows,

- (i) Mechanical classifiers
- (ii) Hydrocyclone
- (iii) Screening
- (iv) Hydraulic classifiers
- (v) Spiral classifiers

The paramount industrial purpose for classifiers is to avoid the overgrinding by separating the particles into coarse and fine particles. By this way, fine particles are separated for further use while big size particles are returned to mill for further size reduction (Gupta, 2003).

### **3.1.1 Mechanical classifiers**

Mechanical classifiers can be divided into different types based on their functionality and importance. These types are shown under

- (i) Cross-flow classifiers
- (ii) Centrifugal classifiers
- (iii) Gravity hydraulic classifiers

In a cross flow classifier, the vessel used for settling the particles is inclined and a water flow is maintained towards the lower side. The feed is introduced at the central point. The flow rate of feed is fixed in such a way that the fine particles will not be able to settle down and they will move with water which is being exit from the classifier. The trough for cross flow classifier is semi-cylindrical which is adjusted at a specific angle to the horizontal. This classifier also contains a helical conveyor. The purpose of this conveyor is to take the settled solids out of the liquid pool. This classifier performs well for only coarse particles when no precise division is required and they bear high capacities.

Centrifugal classifiers are of primary importance due to their centrifugal settling method for the division of particles. This division is due to the movement of particles in fluid. When a liquid is passed through a centrifuge, larger particles are separated by throwing them out from the liquid while, very fine or light particles might not be able to settle during this time and can be taken out with the liquid.

Gravity hydraulic classifiers are able to separate the particles on the basis of their weight, size, and specific gravity or shape (Gupta, 2003).

### 3.1.2 Hydrocyclones

Hydrocyclones are considered as nonmechanical and sedimentation type clarifiers. They are static devices and centrifugal force to separate the heavy and light particles. They have gained very popularity and are of primary importance for many mineral processes due to the following advantages like they are fixed and very simple to use. They are very compact and have short residence time for the process. The major benefit from the economic point of view is their low cost for the process.

Hydrocyclone has a cylindrical part closed from one side and an overflow pipe which is fitted axially. Feed is introduced at tangent to hydrocyclone. There is a conical part at the other side. For the separation phenomena, suspension is introduced from the feed opening by applying pressure. After the feed is sent to hydrocyclone with liquid, heavy particles move outward and collect at the bottom of the vessel whereas, light particles move towards the axis of hydrocyclone. So, they move towards the upside or at the top of hydrocyclone.

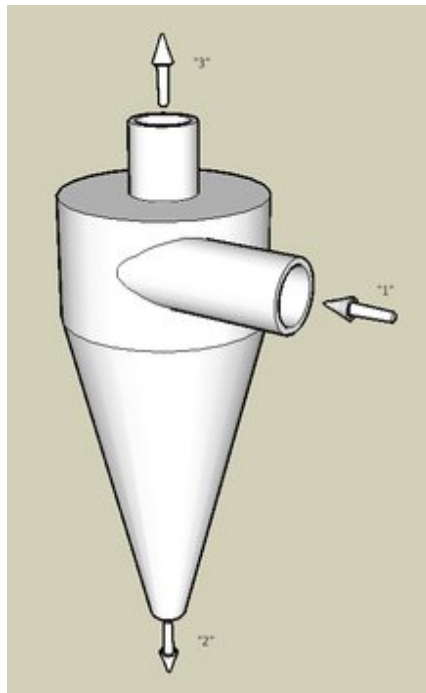


Figure 3.1.2 Hydrocyclone classifier (www.wikipedia.org)

A cyclone separator is almost similar to hydro cyclone. They are almost similar in their operation, construction and working principle. But the only key difference is that cyclone work for solids in gases whereas hydrocyclone is used for solid liquid suspension (Gupta, 2003).

Hydro cyclone and centrifuges are similar in this aspect because they are using centrifugal force to separate heavy and light particles. The major differences between them are the amount of force applied for separation. Centrifuges put more force than hydrocyclones and control of desired output is better in centrifuges than hydrocyclones. So, centrifuges are better selection to obtain the required output size. But, hydrocyclones are cheaper as compared to centrifuges and settling is also more faster in hydrocyclones than centrifuges. But, it is fact that they both are the necessity of time and each of them has its own importance due to certain features.

### **3.1.3 Screening**

Screening is a simple process used for the separation of particles depending on size. It is a mechanical process and like other separation processes, it is quite impossible to obtain a complete separation.

For industrial screening, the solids are allowed to fall onto or thrown by force against a screen. The oversize particles or tails will stay on screen while undersize particles or fines will pass through the screen. A single screen can divide the particles only into two fractions. These fractions are called unsized fractions because only one limit is known i.e. upper or lower limit and the other limit is unidentified. In case of sized fractions, materials of different sizes will pass through a series of different sized screens. In this case, fractions of both limits are known. Sometimes, wet screening is used but the most preferably and commonly, dry screening is used.

Screening is normally used for the separation of coarse particles. The efficiency of screens for fine particles is poor with normal screens and fine screens are very costly as well for fineness. So, the particle size for the separation should be more than 250 $\mu\text{m}$ .

The tendency of fine crushing before grinding has also increase the value of screens due to the ability to recover fine products with high efficiency and great capacity. In the mineral industry, the major reasons for screening are,

- (i) put off the size of fine particles to crusher
- (ii) stopping the oversized particles to next step
- (iii) making the feed of a close size for gravity concentration process
- (iv) getting an end product of closed size

### **3.1.4 Hydraulic classifiers**

The classifiers in which the particles are separated due to the specific gravity by the use additional water i.e. heavy particles are settled at the bottom and disposed while lighter particles move upward and taken out, are called hydraulic classifiers. They use extra water to resist the flow path of the settling particles. They are also called as hydrosizer.

They are usually used to divide sand and gravel. These classifiers have vertical columns with v-shaped bottoms for the gathering of particles. These bottoms are controlled by discharge valves which are controlled by sensors. The purpose of these sensors is to sense the level of solids which are going to be collected at the bottom of each column. The operation for these classifiers is very easy and simple.

Since the hydraulic classifiers are not good for great volumes, it is better to use an arrangement for their separation to cut down these classifiers required for handling solid separation process. It is also advisable to use these classifiers for particle size greater than 105 microns in order to decrease the number of classifiers and to remove fine particles, Cyclones or hydrocyclones could be used (Noyes, 1994).

Particles of very small size do not settle in the vertical columns and are collected at the end of column. Due to the difference in particle size, there is difference in the

condition of settling. There are two different categories for settling in these classifiers based on the feed densities,

- (i) Free settling
- (ii) Hindered settling

In free settling classifiers, cross sectional area is the same for all sorting columns whereas, this area is different for the sorting columns in hindered settling classifiers and is thin at the lower side. These both classifiers, can be divided into two more groups

- (i) Launder type
- (ii) Tank type

These classifiers have a good advantage over the mechanical classifiers in terms of final products. Mechanical classifiers provide only two products whereas hydraulic classifiers are able to give several products (Gupta, 2003). These classifiers provide an efficient way to work and separate particles from gravel to sands. For increasing the separation efficiency, spiral classifiers are used to eliminate fine particles by washing the collected solids.

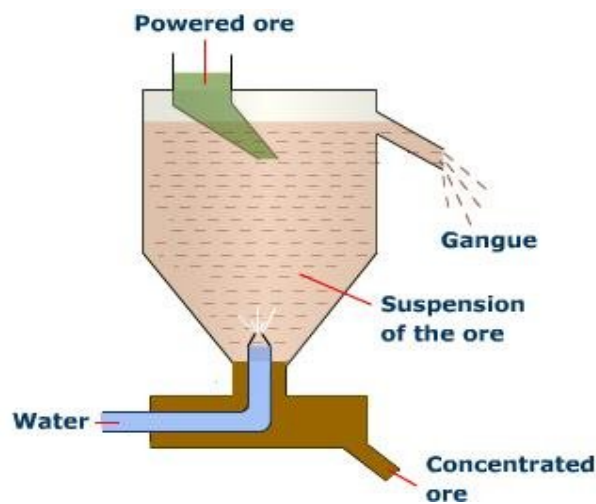


Figure 3.1.4 Hydraulic classifier (www.tutorvista.com)



### 3.1.5 Spiral classifiers

Spiral classifiers gives good result when they are employed with hydraulic classifier and there combination is effective for the removal of very fine particle attached with the large or coarse particles. They are mainly use for water, dewater and classification of the sands to a maximum range of 0.75 inches diameter. Their main advantages lie in the simple shut-down, start-up and very easy maintenance.

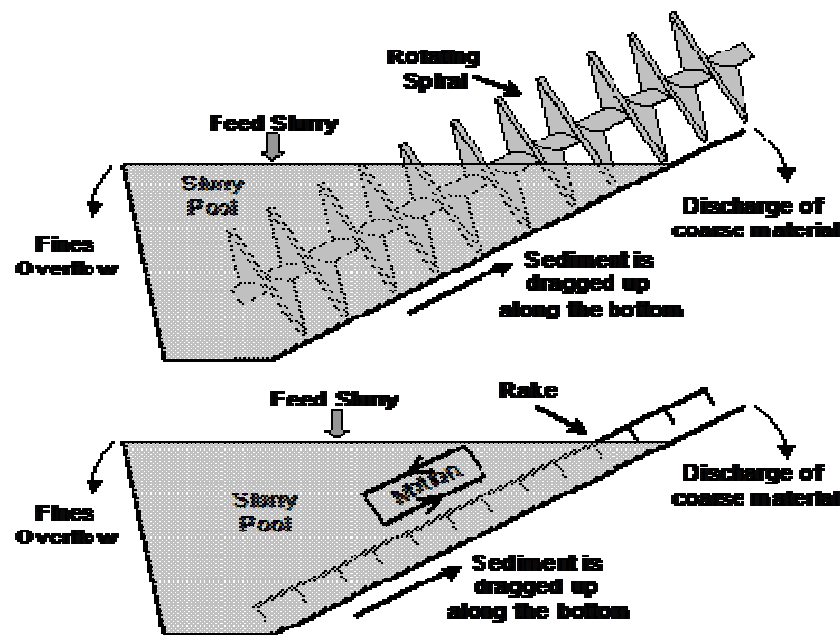


Figure 3.1.4 Spiral classifier (www.fstco.com)

**Table 3.1 Range of classifier operation (Couper et al.2010)**

Type of classifier	Size range
Static gravity units	1000 microns
Cyclone separator	20-300 microns
Spiral classifiers	3-80 microns
Turbine classifiers	5-150 microns
Laser classifiers	< 5 microns

From this table, it is clear that laser classifiers are efficient than other classifiers.

#### 4. Filtration

The separation of suspended particles from a fluid by using the filter as medium is called filtration. This separation is done by passing a fluid through a porous medium. During this process, the solid particles are retained on the surface of medium whereas, the fluid i.e. filtrate, passes through the pore or voids of membrane (Cheremisinoff, 1998).

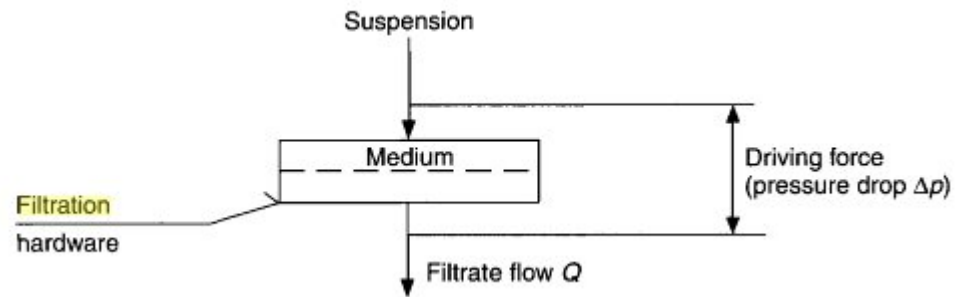


Fig 4.1 Schematic diagram of filtration system (Svarovsky, 2000)

To have an adequate flow through the membrane or from filter medium, it is essential to have pressure drop across the filter medium. This pressure drop can be obtained or can be applied across the filter medium by using driving forces. There are four kinds of driving forces that can be used to create a potential difference for the filter medium,

- (i) Pressure
- (ii) Gravity
- (iii) Centrifugal
- (iv) Vacuum

#### 4.1 Types of filtration

Filtration has two major types that are practically used by industries.

- (a) Cake filtration

### (b) Deep bed filtration

Different types of filters are used for these filtration processes. Cake filtration is done by surface filters or granular filters whereas deep bed filters are used in deep bed filtration.

In cake filtration, the initial pressure drop for the medium is relatively low and particles of same size or greater than the openings of medium are trapped or stay at the medium surface. By this way, the openings of the medium are closed and produce small ways which can remove the small particles from the fluid. In this way, filter cake is obtained which serves as a medium for filtration. In order to avoid blinding of the medium, filter aids are helpful in precoating that forms an initial layer on the medium (Svarovsky, 2000).

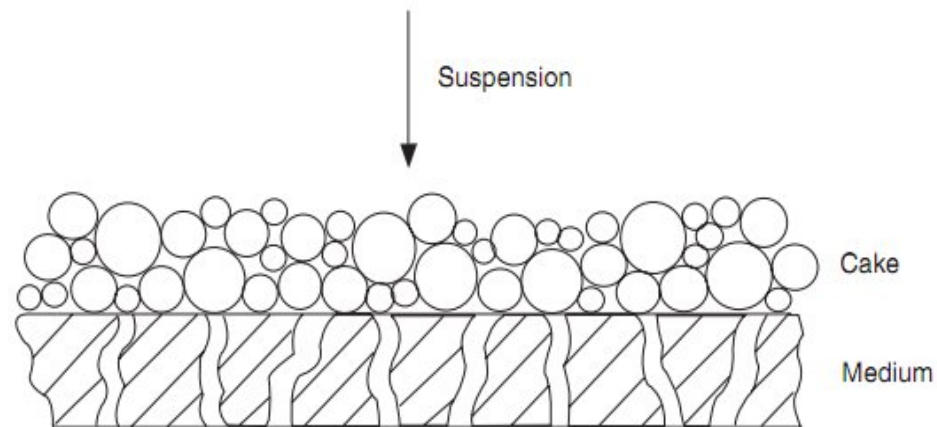


Fig 4.1.1 Mechanism of cake filtration (Svarovsky, 2000)

Surface filters are used in cake filtration and normally applied to those suspension which have solids with higher concentrations. The reason for that is to avoid the blinding or precoating of the medium that usually takes place in the filtration of dilute solutions. This problem can be solved with dilute solution by increasing the input concentration in an artificial way or by the addition of filter aids. These aids are very porous and they enhance the permeability of the filters.

The model shown in the above figure represents the batch cake filtration. Here, both liquid and particles come to medium at an angle of 90 and they do not disturb the cake formation. Tiller and Cheng suggest an alternative called ‘delayed cake filtration’ when the cake is avoided from thickening by hydraulic or mechanical means: by stirring the solids back into the solution prevent them to get thickness.

Continuous filter thickeners, working on the same rule, are available. Tiller and Cheng, are of the view that lower cake porosities and high filtration rates can be achieved by the use of mechanical agitator and they also suggest a mathematical model for the process of the delayed cake filtration. A similar phenomena is used in the by-pass centrifugal filtration. In this filtration, centrifugal forces are used to remove the particles from the medium while the liquid passes through the medium (Svarovsky, 2000).

In deep bed filtration, the size of the particles is smaller than the openings of the medium. So, during their pass through the pores of the medium can be collected by using different mechanisms, i.e inertia, gravity or diffusion and can be attached to the medium by using electrostatic or molecular forces.

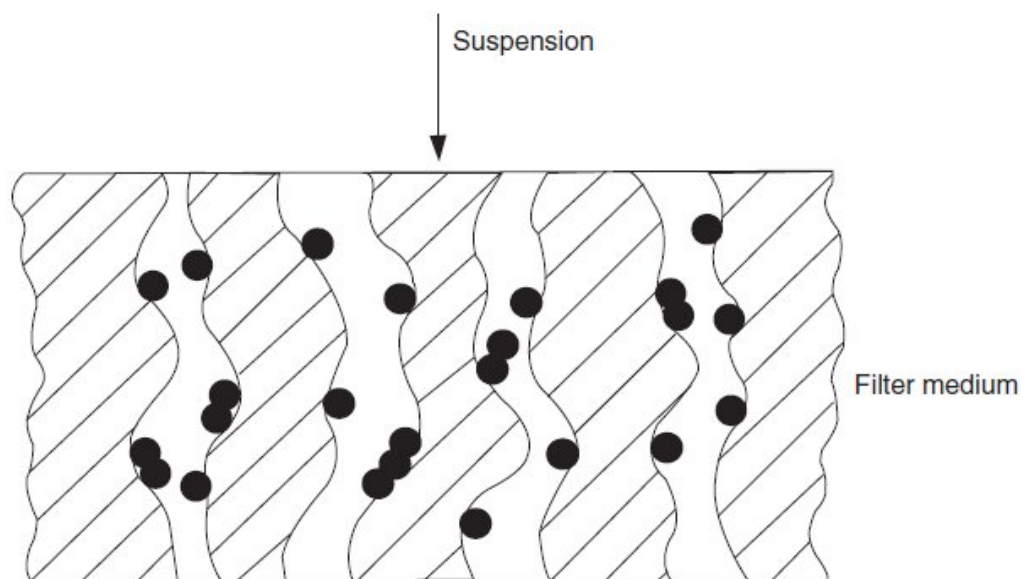


Fig 4.1.2 Mechanism of deep bed filtration (Svarovsky, 2000)

In the beginning, the pressure drop for deep bed filtration(depth filter) is normally greater than cake filtration(surface filters) if their efficiency is comparable. But, after the collection of particles, the pressure drop is more gradual for depth filter than surface filters. Surface filters are normally used for higher concentration,i.e. 1% by volume whereas deed bed filters are usually used for dilute solution i.e. 0.1% by volume. Cake filtration has wide range of application especially in chemical industry due to the higher concentration than deep bed filtration. Although, the difference of cake and deep bed filtration is very clear and they have their specific applications but still in some cases like in cartridge filter, their choice could be difficult for running the process (Svarovsky, 2000).

Cross-flow filtration is also used as a filtration technique that is different from dead-end filtration. This dead-end filtration is a simple technique that is normally used in many filtration types like cake and deep bed filtration in which fluid flows perpendicular to the filtration surface where as in cross flow filtration, fluid always has a direction parallel to filtration surface. Thickness of filter cake increaes with time in dead-end filtration unlike cross-flow filtration (Cheremisinoff, 1998).

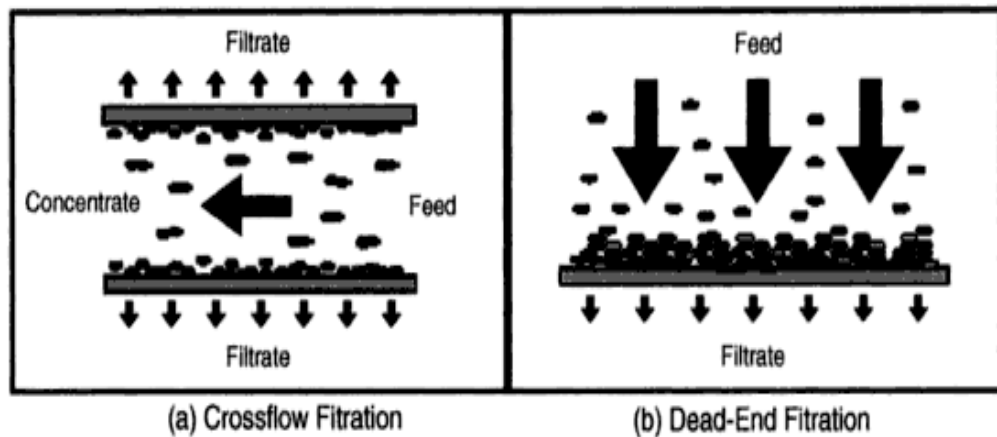


Fig 4.1.3 Principles of cross-flow and dead-end filtration (Cheremisinoff, 1998)

The main properties for filter, like all other separation equipment are the flow rate-pressure drop relationship and the separation efficiency of the filtration. However, in

case of filtration, these relationships could be more complex due to the many other variables and factors. These factors have a great influence on the process and are given here,

- (i) Cake thickness
- (ii) Mass of cake per unit area
- (iii) Specific cake resistance (Svarovsky, 2000)

#### **4.2 Process applications of filtration**

Even, the filter is main part of filtration still, there are a lot of other equipment and other techniques that are existing to make solid-liquid separation more effective. These equipment and techniques are consisting of different units for different filtration duties depending upon the characteristics of fluid and process conditions (Wakeman, 1999).

As already mentioned in the definition of filtration that purification of a fluid (contamination free) is achieved when the fluid passes through a porous medium. Porous medium has applications also in many other processes as in filtration. These processes can be ion-exchange, flow through packed columns, many applications of reactor engineering, in petroleum engineering, in hydrology, in chromatography and adsorption. Sa a summary, it is worthy to mention that filtration has been serving as an important tool both, in achieving the products of high purity as well as a part of technology that is used for the prevention and control of pollution (Cheremisinoff, 1998). Hence, filtration is a major tool in chemical engineering applications.

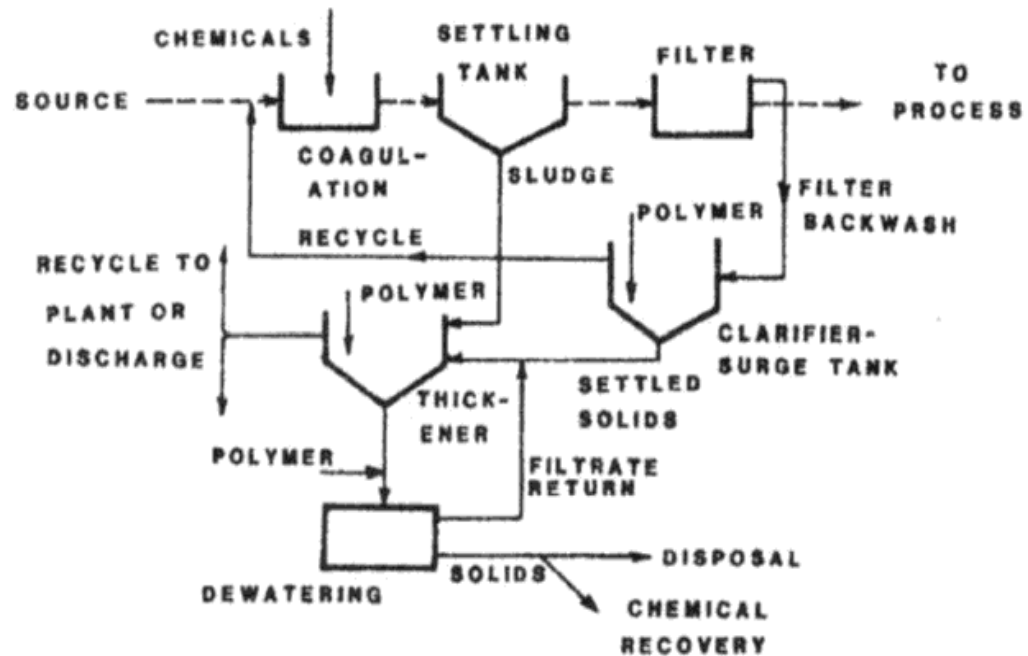


Fig 4.2.1 Prefiltration and final processing steps for a filtration process (Cheremisinoff, 1998)

Different purposes for filtration are the separation of solid component as product from the liquid, when both solids and liquids are required, when no phase is required like in water pollution and for solid-gas separation

As the purpose of filtration is to separate the liquid and solid and the filter is used as separator or separation equipment. So, the filtration is used in the following industries, for example

- (i) The waste water treatment industry
- (ii) The chemical industry
- (iii) Power generation & mining industry
- (iv) Food and beverage industry
- (v) Sugar industry



(vi) Pulp and paper industry

(vii) Pharmaceutical industry

Filtration equipment for separation is also used in electronics and biotechnology etc.

There are many factors that have to be seriously considered when selecting a solid-liquid separation like the nature of the product, type of the process and the effect of scale on equipment size (Wakeman,1999).

Filtration, when used as a separation technique enlarge the range of applicatios for filtration. So, it means that filtration should also take into account the other devices that are used for separation.

It is very tricky and not easy to differentiate between filtration and separation as separation is also a mechanism of filtration. To understand this problem, it is important to look into different separation processes that can lead to the understanding of this problem.

Starting from solid-gas separation, it is important to look that this process is mainly done by air filters but, because this process also involves industrial gas treatment or processing and this processing includes separators, scrubbers and precipitators as well as filters. So, filtration or air filters are used only when they are necessary.

Similarly, mechanical filtration is used for the solid-liquids separation but this varies with requirements and changes in volume. In the same way, mechanical filtration is more limiting for the types of separators and filters in the case of solid-solid and liquid-liquid separation. These kind of filter and separators can be used for different processes more successfully and more economically depending on the type of filters and separators for adequate process. Examples for liquid-liquid separation and solid-solid separation are ditillation and sieving respectively (Dickenson, 2004).

Physical separation can be divided into two main categories: sedimentation and filtration. The major difference between them are as follows;

- (i) Filtration is done on the basis of particle size whereas, driving factor for separation in sedimentation is the density of the particles
- (ii) Separation is done for both by using physical means
- (iii) The medium of separation in filtration is barrier or filter while in sedimentation, separation is a phenomenon of gravity force
- (iv) The filters are designed by keeping in view the amount of fluid to be treated or filtration area but in sedimentation, settling area is the primary consideration.
- (v) The filtration usually affected by pressure difference while sedimentation is affected by force of gravity
- (vi) They both are affected by particle size to a some extent; like in filtration smaller particles will pass through the mediul and larger size particle will retained whereas in case of sedimentation, settling rate will be faster for a bigger particle than the smaller if they both are of same density (Sutherland, 2008).

#### **4.3 Effect of particle size and techniques of filtration**

Particle size is an important factor in filtration. Filtration covers the particle sizes that ranges from mineral industry to ultrafine particles and membrane ultrafiltration system. To make the filtration more efficient, energy and cost effectiveness, particle size distribution and mean particle size are factors to be taken into consideration. The apparent filtering range of a filter can be deceiving, resulting in the form of low efficiency and poor cost-effectiveness. The filter will quickly be blocked by the larger particles if the filter operates for fine particles. Therefor, in case of fine filtration and to make the filter more efficient and cost effectiveness, it is good to do filtration in several stages and use two or more filter in series with a consecutive decrease in particle size. By this way, a strainer is always used in the beginning followed by medium filter and ultrafine filter at

the end. This whole prefiltration system ahead of desalination by reverse osmosis (Sutherland, 2008).

Air pollution contains different types of contaminant with different concentration in the atmosphere and to treat this atmospheric contamination, large baghouse filter which are able to remove particle below  $0.1\ \mu\text{m}$  but this would only be used in special cases and for other applications, simple panel filters are used.

Filtration, used for the separation of particles ranges from  $5\ \mu\text{m}$  to  $1\ \text{mm}$  is called macro-filtration and separation of particles from  $5\ \mu\text{m}$  down to  $0.1\ \mu\text{m}$  is known as micro-filtration and even below this limit is defined as ultrafiltration. After UF, NF and RO are the filtration techniques used for the separation of particles. But reverse-osmosis and nanofiltration can be distinguished from ultrafiltration on the basis of their operating principle. RO and NF have a semi-permeable membrane, the liquid treated is only a solution and they do not have any physical pores like UF. So, RO and NF have a capability to dissolve small molecular species inside the membrane material. These species have a diffusion power and they can diffuse through the membrane under high pressure and they can be taken out on the other side of the membrane in a pure form (Sutherland, 2008).

Since, there are many filters and they offer a lot of applications for which they are very suitable, so now it is engineers duty to find appropriate filters for different applications of separation. In short, there is the need to find suitable filters and filter medium that should be compatible with liquid suspension and its components. Continuous research in developing more advanced filtration techniques is needed. adequate to these issues.

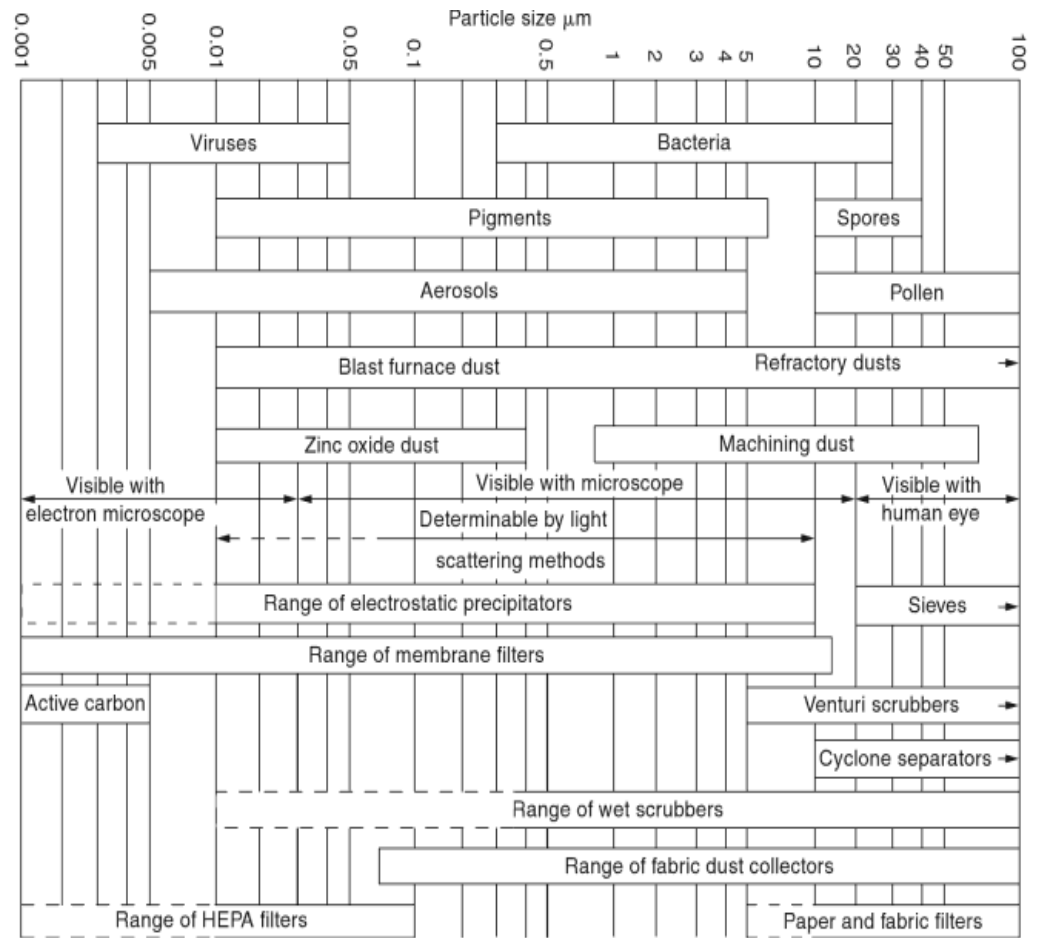


Fig 4.3 Contaminant sizes, separators and filters( Sutherland, 2008)

This figure shows the different particle size ranges for different filters, scrubbers, etc. From figure, it is clear that filters can be used for the filtration of very fine particles, i.e. that are not visible with naked eye.

#### 4.4 Selection criteria of filter

There is a wide range of filters existing for the separation. Sometimes, they are very close to each other in their working efficiency and effectiveness. Therefore, a proper method and care should be taken in the selection of filters because the right choice will save the money and increase the performance of filtration process. The important factors that should be considered in the selection of filters are described here shortly,

- (i) Determine the size of particles to be removed
- (ii) Determine the removal efficiency of the filter
- (iii) Flow rate or flow density should be determined
- (iv) Pressure drop across the filter is also an important factor
- (v) Determine the maximum temperature bearing capacity for the filter media
- (vi) Determine the difference in pressure for the structure of filter
- (vii) Filtration area or usable area of filter is important for effective filtration
- (viii) Toxicity of materials to be filtered should be compatible for the domestic use in case of water
- (ix) Extractables from filter media must be minimized by preflushing the filters before use (Frankel, 2010)

#### **4.5 Types of industrial filters**

There are many different types of filters that are used. Few of them are given,

- (i) Vacuum filters
- (ii) Pressure filters
- (iii) Precoat filters
- (iv) Membrane filters
- (v) Cartridge filters
- (vi) Ultrafilters
- (vii) Gravity filters
- (viii) Activated carbon filters

#### **4.5.1 Vacuum filters**

These filters work on the principle of creating the vacuum in the medium. This vacuum is created by using an external force. They can be continuous or batch filters. The most commonly used vacuum filters are

- (i) Rotary drum filters
- (ii) Leaf filters

#### **4.5.2 Pressure filters**

Pressure is the main driving force for filtration in pressure filters. Pressure filters have some more advantages than vacuum filters like, high flow rates, better washing and more drying can be achieved by pressure filters. Most commonly used pressure filters are

- (i) Filter press
- (ii) Plate and frame press (Wills, 2006)

#### **4.5.3 Precoat filters**

Precoat filters are deep bed filter types and are used as filters when the solid concentration is not high. They are used for the clarification of water in swimming pools (Frankel, 2010).

#### **4.5.4 Activated Carbon filters**

These filter works on the principle of adsorption for the separation of contaminants from the feedwater. They are not generally used for the removal of particulates. They are used to reduce the amount of free chlorine and for the removal of total soluble organics. Removal of Chlorine help to avoid ion-exchange resins and RO membranes. Activated charcoal is used for water treatment in activated carbon filters.

#### **4.5.5 Cartridge filters**

These filters contain thick and changeable filter media. The size of the particles retained by these filters can not be accurately described due to random nature of fibre matrix.

#### **4.5.6 Gravity filters**

Gravity filters are very economical for large volume flows and they are used for the pretreatment of surface waters. Normally, they remove the particles of large size.

## 5. Crystallization

The method for the separation of compounds by forming crystals from supersaturated solution is termed crystallization. For inorganics, this process can be applied in chemical industry especially, when salts are obtained usually from aqueous solutions. For the production of organics, the purpose of crystallization is the recovery of product, for the refinement of intermediate chemicals and the elimination of unwanted salts. In a crystallization process, feed is made from a solution and the solute of this solution is crystallized by a number of different processes (Rousseau, 1987).

Mechanism of crystallization that affects crystal size distribution are;

- (i) Nucleation rate
- (ii) Crystal growth rate

These both are affected by supersaturated solution. The phenomenon that occurs in the solution with the formation of first small crystal is called nucleation. Nucleation is different from crystal growth as it forms solid from liquid and it sets the properties for crystallization process whereas, crystal growth is the deposition of crystals on already existing crystals in solution. Therefore, nucleation is very important in the design of crystallizer.

### 5.1 Design of crystallizer

For the final conceptual design of a crystallizer, equilibrium data and operating mode, solvent choice and operation conditions, internal and external construction details are surveyed and collected. For the design of a crystallizer, important factors that should be taken into consideration are; generation of data, interpretation of data, solid-liquid equilibrium data and the selection of operating mode (Rousseau, 1987). Solid-liquid equilibrium and selection of operation mode are described here.

The design of a crystallizer is important in running a smooth operation. Final strategy for the design of a crystallizer is shown in fig 5.1.1.



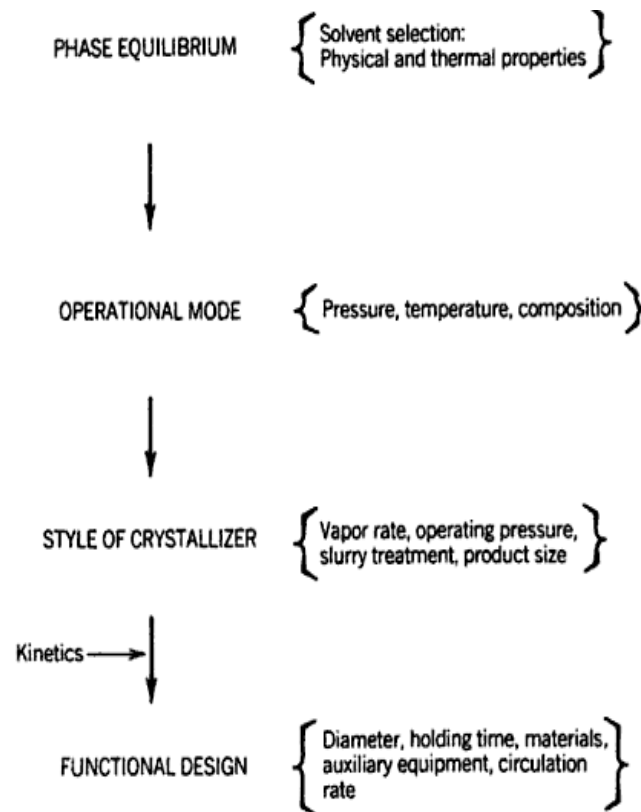


Fig 5.1.1 Process design strategy (Rousseau, 1987)

Equilibrium:

In order to have best possible design for crystallizers, it is essential to have accurate data for solid-liquid equilibrium. It is also worth mentioning that at equilibrium, heat of crystallization is equal to the heat of dissolution but with opposite sign (Myerson, 2002). This data for solid-liquid equilibrium is needed in the initial stages of design and obligatory for the causes described here,

- (i) To check out the screening process. The process to decide whether the solute of the solution can be crystallized
- (ii) Find out the best solvent that can be used in the process

- (iii) Measuring the crystallizer ranges for temperature and pressure and the composition of the liquor in the crystallizer
- (iv) How the maximum amount of solute could be recovered

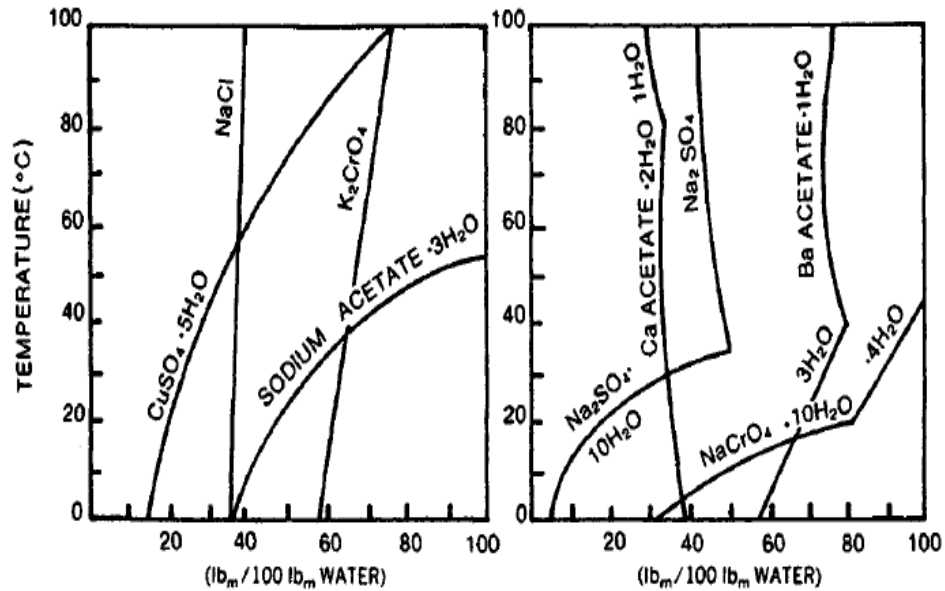


Fig 5.1.2 Solubility data for salt system (Rousseau, 1987)

Figure 5.1.2 represents the solubility diagrams for different salt solutions in water. As the solubility curve for NaCl in diagram is almost vertical which means the temperature has minor effect on solubility. The solubility curve for sodium sulfate is reverse with the increase in temperature which shows it can coat the surfaces of heat exchangers if the temperature is raised for the solution (Rousseau, 1987).

Selection of operation mode:

The process used to make supersaturation solution is named mode of operation. The choice of mode has great influence on the solid-liquid properties of the system and it also helps by stating the requirement of the material and energy balance for the system. The common methods for the production of solids from a solution is;

- (i) To provide the cooling for decreasing the temperature of solution. For having good results, solubility of solute must be strongly influenced by temperature
- (ii) Heating the solution for removing the solvent. By this way, solute can be crystallized but this technique works better when the solubility of solute is not sensitive to temperature
- (iii) Vacuum cooling can be used for crystallization of feed solution. This technique is good method when the solubility is temperature dependent
- (iv) Crystallization can also be done by combining all these techniques; external heating can be combined with vacuum cooling and this method is good when the temperature has intermediate influence on solubility
- (v) By the addition of non-solvent. This technique is used both for the laboratory as well as for industrial processes for the recovery of product (Rousseau, 1987).

The above mentioned techniques will be introduced in details in section 5.5 and can be applied to single stage or multistage processes. Multistage evaporators are used;

- (i) When single stage evaporators are not enough
- (ii) When energy can be saved by using more stages
- (iii) Multistage is more helpful in the formation of uniform and large crystals

Moreover, crystal size distribution is more narrow in series crystallizers as compared to same volume of parallel crystallizers. Higher temperatures in crystallizers increases the crystal growth. Batch crystallizers are more efficient in producing narrow crystal size distribution as compared to continuous crystallizers. In addition to this, batch crystallizers offer more economic operation when the capacity is less than 500kg/h.

Batch crystallizers are also more efficient for producing highly uniform crystals as required for sugar (Rousseau, 1987).

## 5.2 Crystallization Kinetics

The kinetics of crystallization are:

(i) Primary nucleation

It can be defined as the formation of new crystals in a clear bulk solution.

Primary nucleation is of two types, homogenous and heterogenous nucleation.

(ii) Secondary nucleation

Secondary nucleation is the formation of new crystals when the solute crystals are already present in the solution.

Crystal growth may be stated as the rate of change in the mass of crystal or the change in the dimension of a crystal. Growth rate can be effected if the impurities are present in the solution. The most common alteration is the decrease in the crystal growth rate because the impurities can form complexes with solvent or any other species that are present in the solution. Impurities can also change the crystal habit (Rousseau, 1987).

Kinetics of crystal growth is determined by two kinds of resistances. The rate is impacted by the resistances in the following manner:

(i) Integration of the solute molecules or crystalline unit into the crystalline surface

(ii) Molecular or bulk transportation of the unit from the surrounding solution to crystal face

As already discussed, both nucleation rate and crystal growth rate are highly dependent on super-saturation and this supersaturation acts as a driving force for nucleation and crystal growth.

The method for the formation of a solid from a solution is called crystallization. The crystallizer is usually a stirred tank or reactor. The purpose of crystallizer is to provide residence time to achieve equilibrium, to enhance the ability to remove fine particles or large product, to give contacting area for the formation of uniform crystal growth and might also cover the area for the reduction or addition of heat.

Fig 5.2. illustrates the influence of supersaturation on the nucleation rate and crystal growth. The figure shows that primary and secondary nucleation as well as crystal growth rate increases with the increase in the supersaturation but secondary nucleation increases faster than primary nucleation.

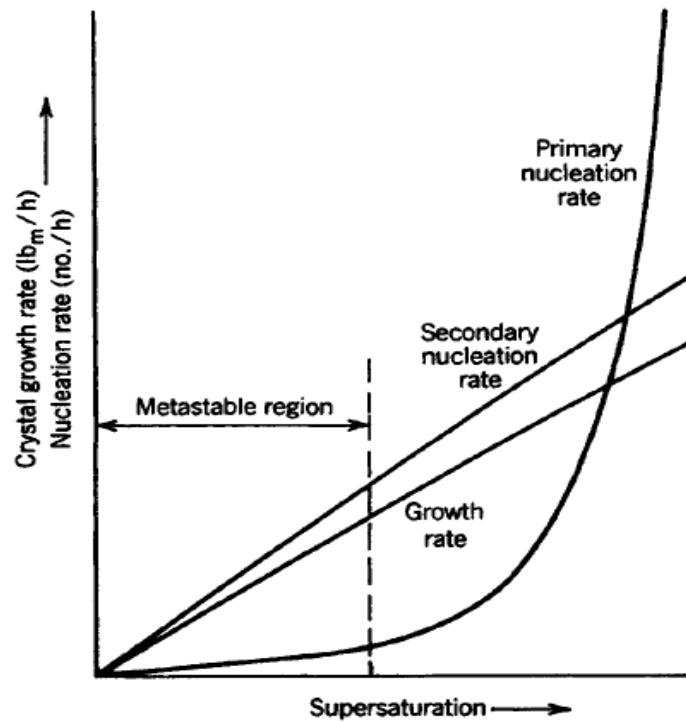


Fig 5.2. Effect of supersaturation on growth and nucleation rate (Rousseau, 1987)

This figure shows that behavior of secondary nucleation is linear while it is exponential for the primary nucleation.

### **5.3 Requirements and advantages of crystallization**

Crystallization has got high rank in industrial processes due to the purity of chemicals produced by using crystallization. Beyond the fact that product obtained by crystallization has an attractive and clear appearance, crystallization could be the easiest and cheapest way to get pure product from an impure solution. Conventional distillation techniques are unable to separate the close boiling liquid without using azeotropes but crystallization can get the complete separation (Mullin, 1972).

The major difference between crystallization and other unit operation is the obtaining of a solid phase in crystallization process. In the creation of a solid phase, crystal size and size distribution are very important.

The requirements for crystallization process are as follows,

- (i) Product purity
- (ii) Yield of product
- (iii) Capacity of crystallizer system
- (iv) Energy requirements
- (v) Rate of nucleation and crystal growth

Crystallization has the following benefits,

- (i) Separation for a pure product can be achieved in a single stage. It means, if a proper care is taken in designing, purity of the product can be more than 99% in one step of crystallization, separation and washing.
- (ii) Large solid particles break into smaller particles. During this process, conditions are monitored and controlled in order to get required physical size that can be used for direct packaging (Rousseau, 1987).
- (iii) With this packaging, it is easy and cheap to transport and sell solid products.

Crystallization has disadvantages as well,

- (i) In single stage process, it is hard to obtain the purification for more than one component
- (ii) It is also not possible to achieve full solute recovery in single step. So, it is often necessary to use multistage process to get maximum recovery of solute from the remaining solution.

Crystallization is usually preferable due to the simplicity of the process and this process is normally considered as good option due to the formation and controlling of solids. But crystallization offers some advantages over other unit operations. For example, it has the following benefits over distillation and it can be applied in following processes where distillation is not suitable:

- (i) When the solute is heat sensitive and there is a danger that it will be decomposed at a temperature required to distillate
- (ii) When there is no or very low volatility between the solute and component
- (iii) When the product is required in a special form
- (iv) Unlike distillation, crystallization is more economic as it is not energy intensive process and does not require high temperature

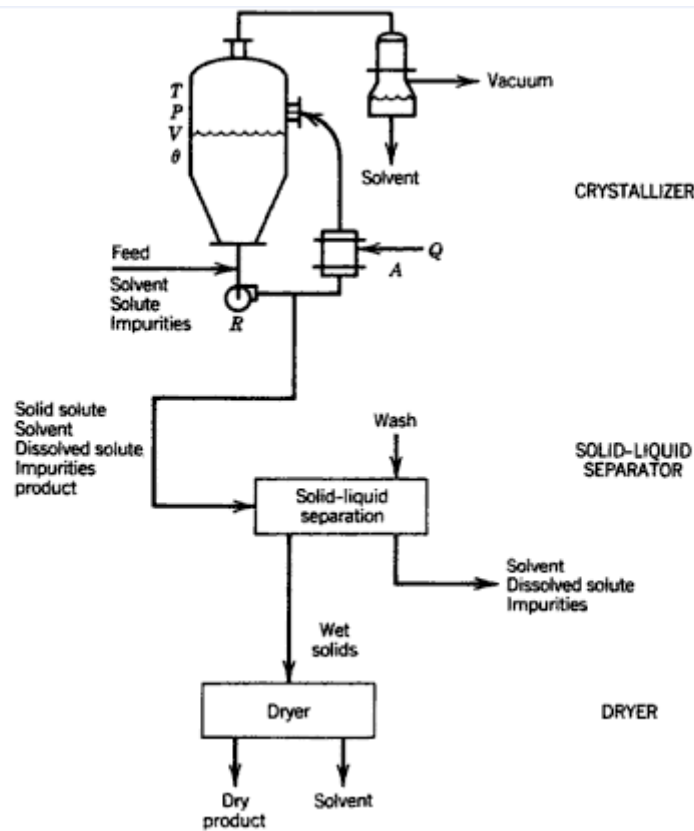


Fig 5.3 Solids processing sequence (Rousseau, 1987)

From Fig 5.3, it can be seen that crystallization is the first step in unit operations for solid processing and then solid/liquid separation and drying comes. Since the crystallizer control the size of product and concentration of solids, a crystallizer with good best performance is necessary for the smooth operation (Rousseau, 1987). Sometimes, crystallization also uses drying technique for the formation of crystals even then, they both are different unit operations and drying comes after crystallization.

#### 5.4 Applications of Aspen Plus in Sugar Industry

Evaporation process is like backbone in sugar refinery. When the sugar cane is crushed, the juice is concentrated by the evaporation of water from the juice. During the entrance of juice to the evaporator, the concentration of juice is about 12% and its entrance to final evaporator, the concentration is raised to 65%. The main target is



the concentration of juice in the form of syrup as quickly as possible. The evaporation process of juice may be highly energy consuming due to the high heat of vaporization of water. The final discharge of the sugar refinery is the traditional bagasse and steam is produced by burning this bagasse under steam boilers (Lewis, 2010).

To use the steam more economically in sugar industry has same importance as to generate it more efficiently. But, normally more attention has been given to production of steam. With the more strictness in the quality standards, the complexity of sugar industries is increasing. Therefore, it is getting obligatory to look into the matter for the usage of steam more efficiently and effectively in sugar industries.

As mass and energy balances are important for the burning of bagasse and the generation and use of steam for the increasing demand of steam for the refining of raw sugar. Therefore, it is important to estimate the optimal consumption of current steam generation as well as to see that this steam will be enough to meet the increasing demands for future.

These all problems can be solved by Aspen Plus to calculate the consumption and efficient generation of steam by making a model for the evaporator section of sugar refinery. Aspen Plus is a good option for this because it has the ability to run steady state simulations for different processing plant with a wide range of simulations. The results obtained from simulations are useful for different mass balance issues like minimisation of waste, conservation of raw material and to optimise the product quality. In the same way, this tool is also helpful to deal different energy issues such as evaluation and heat integration for steam plants (Lewis, 2010).

### **5.5 Types of crystallizers**

Types of equipment or crystallizers are dependent on the behaviour of solubility of solution. There are many types of crystallizers but they are divided into three main categories based on their working principal.

### 5.5.1 Cooling crystallizers

These crystallizers work on the principal of cooling, i.e. when a compound of supersaturated solution is cooled. In this case, crystals are formed but the solubility of the compound to be crystallized should increase with temperature.

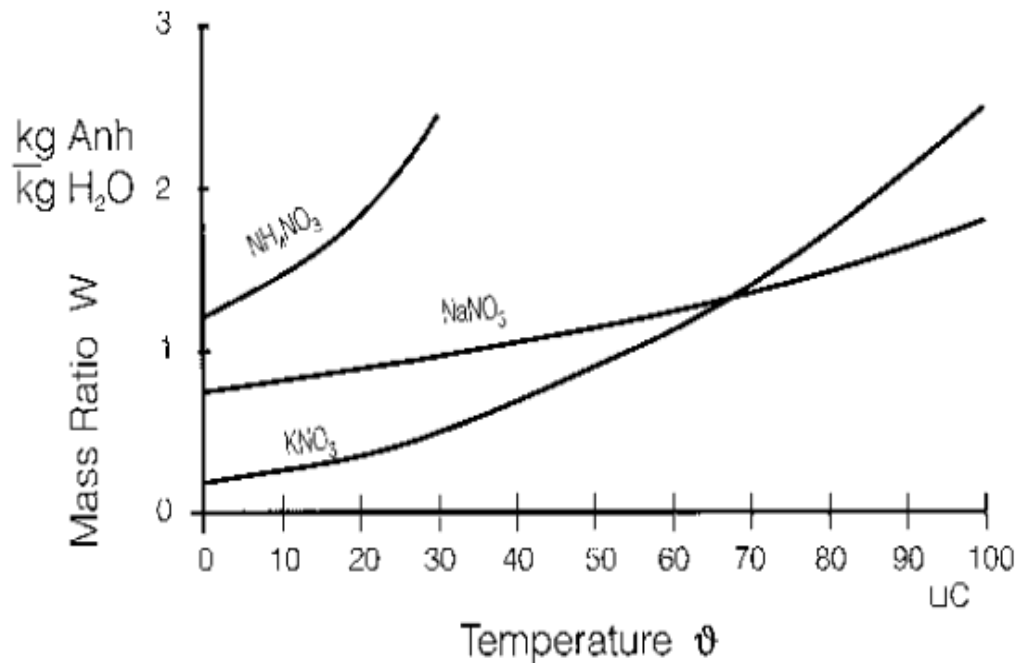


Fig 5.5.1, Solubility of inorganic compounds (Mersmann, 2001)

Figure 5.5.1 shows that solubility of the different compounds increases with the increase in temperature. Therefore, when these compounds are cooled, they can easily form crystals on cooling due to high solubility at high temperatures.

Cooling crystallizers are of different types,

- (i) Open tank crystallizers
- (ii) Agitated tanks and vessels
- (iii) Trough crystallizers
- (iv) Pulse column

(v) Direct contact cooling

(vi) Krystal cooling crystallizers (Mullin,1972)

### 5.5.2 Evaporative crystallizers

These crystallizers work on the principle of evaporation of solvent, i.e. when the solution is heated and solvent evaporates, it can form the crystals. Therefore, evaporative crystallization can be used when the solubility of the solute changes very little, remains constant or even decreases with temperature.

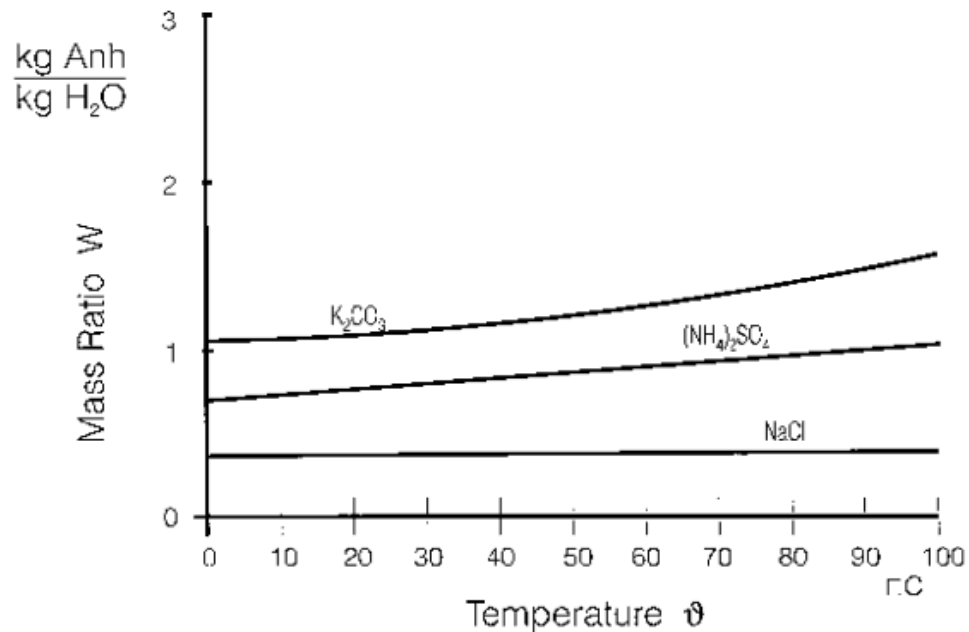


Fig 5.5.2 Solubility of inorganic compounds (Mersmann, 2001)

Figure 5.5.2 shows that unlike cooling crystallization, the solvent has to be removed from the solution by increasing temperature because the solubility of the solute is almost constant with temperature. Therefore, solvent is evaporated with the rise in temperature. Typical Evaporative crystallizer types are as follows,

- (i) Multiple effect evaporator
- (ii) Forced circulation Evaporators

(iii) Krystal evaporating crystallizer

(iv) Air-contact evaporation

### **5.5.3 Vacuum crystallization**

According to Mersmann( 2001) evaporative and cooling crystallization can be combined in vacuum crystallization.

In simple words, when a crystallizer operates under the reduced pressure, it is called vacuum crystallization. But, there is very small change in the working principle for true vacuum crystallization. Therefore, evaporation and adiabatic cooling should be done simultaneously to get supersaturated solution. That is why, evaporation and cooling are important in vacuum crystallization. For continuous vacuum crystallizers, feed solution should be provided to liquor surface very quickly in the vessel in order to maintain the cooling and evaporation at the same time (Mullin,1972).

According to Mullin (1972) vacuum crystallizers are of the following types,

(i) Batch vacuum crystallizers

(ii) Continuous vacuum crystallizers

(iii) Draft-tube Baffle crystallizers

(iv) Krystal vacuum crystallizers

(v) Multistage vacuum crystallizers

## 6. Flow Sheeting

A plant design is the description of words, numbers and pictures. The engineers want to arrange and make different sketches and drawings that shows different pictures to solve different kinds of problems. For example, in order to solve material balance problem, first step is the drawing of blocks to show the equipment of process and next step will be the entering and leaving streams with different values and their properties. For the description of a process, it should represent the sketch of equipment, describe how the process is interconnected and at the end, it should represent the process flows and operating conditions. Such sketches make flowsheets (Couper, 2009).

The array of selected equipment according to requirements of the process is called flowsheeting. This includes the proper connections and flow rates for streams, their operating conditions and their compositions (Sinnott, 2005).

Flowsheeting can also be described as diagrammatic demonstration of the process. This is helpful in designing phase of the process and serves as base for the process design. This design consists of piping, instrumentation, equipment design and plant layout because it covers each and everything about plant. So it is helpful in training the new persons as well as for making the operating manuals of plant by relative personnel. It is also helpful in the start-up of the plant and later operations and plays an important role for comparing operation performance with design performance.

Since flowsheets provide the description of the process. Their main purpose is the diagrammatic presentation of

- (i) The equipment
- (ii) The sequence of operations
- (iii) The expected performance of a proposed plant
- (iv) The actual performance of an already operating plant (Tuunila, 2010)

Material balance is calculated for the whole process and for each individual unit as well to draw the flow sheet and energy balances are also done to calculate the energy flows and consumption of energy for the complete plant and for the requirements of service for plant.

Calculations for manual flow sheeting could be pretty difficult and might take a lot of time depending upon the process, its complexity and enlargement. For this reason, industries and operational personnel are being increasingly dependent on computer aided flowsheeting programmes to make the design of process more easy and quick. By this way, designers have ability to use and consider different processes, a variety of flowsheets are available for different processing schemes for achieving the best and optimum process conditions (Sinnott, 2005).

Flowsheets can be further divided into

- (i) Direct flowsheets
- (ii) Flowsheets with recycle streams

In direct flowsheets, calculations are made from first operation to last operation as there is no recycle stream while in case of recycle streams, there could be one or more recycle streams and calculations are done by dividing the process into subprocesses depending upon the complexity of the process. As an example of flow sheet in Figure 6.1, flow sheet of ammonia preparation is shown.

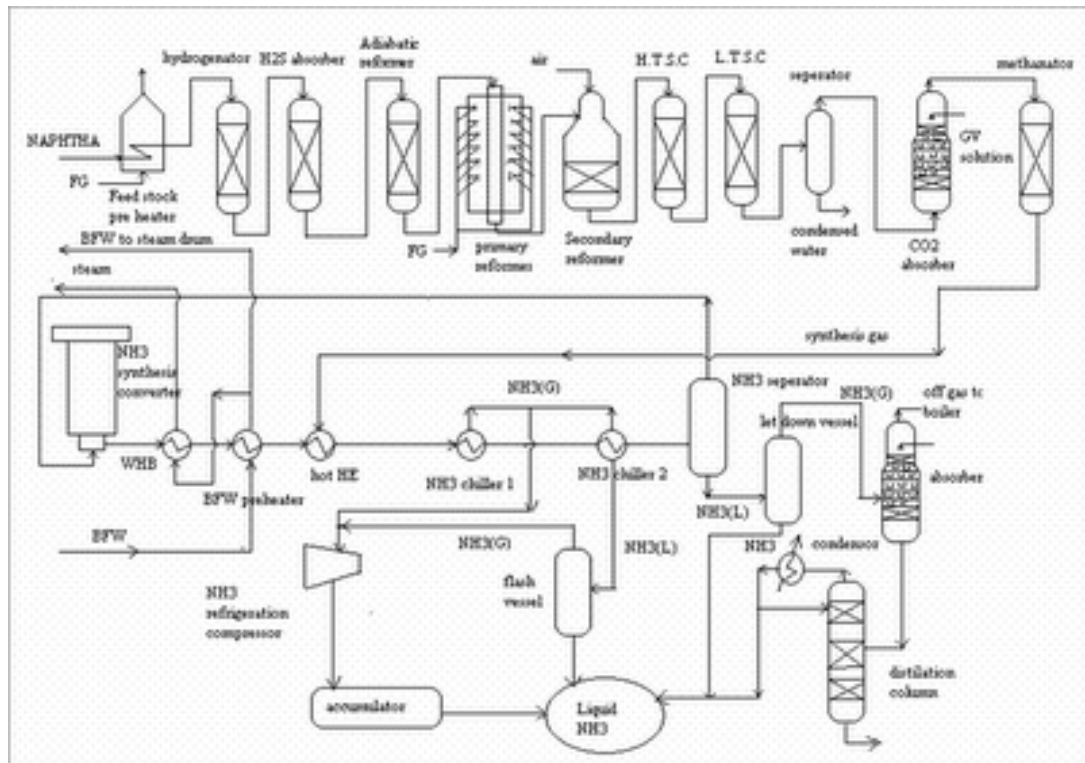


Fig 6.1 Flowsheet for ammonia preparation (haldor-topsoe-process-flow-sheet)

The above figure shows a typical flowsheet for the synthesis of ammonia by haldor-topsoe-process.

### 6.1 Types of Flow sheets

There are different kinds of flow sheets depending upon the stage, type and complexity of the process. These are

- (i) Block flowsheets
- (ii) Process flowsheets
- (iii) Mechanical( P& I) flowsheet
- (iv) Information flowsheet

### 6.1.1 Block flowsheets

Block flowsheets are made with rectangular blocks. These blocks represent the individual process or group of operations and the main streams between these blocks. These flowsheets are used to give an overview of the process or plant. They do not show the material and balances and usually include some quantities and some information about the properties of the streams (Tuunila, 2010). It is also helpful for the design of new processes and also for the improvement of already existing processes.

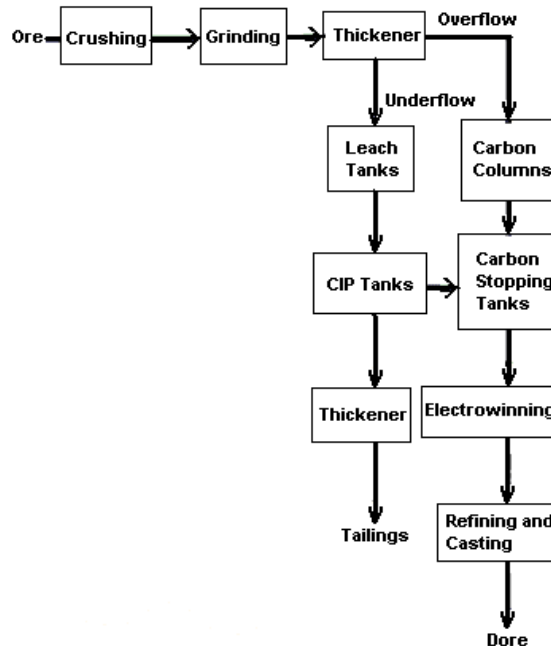


Fig 6.1.1 Block flowsheet for CIP mill (Camm, 1990)

Fig 6.1.1 represents a simple block flowsheet for CIP electrowinning- mill process. This process is used for the processing of oxide gold ores with little or almost no by-products (Camm,1990). As already mentioned, this process flowsheet contains blocks by showing the whole process



### 6.1.2 Process flowsheets

Process flowsheets are used for the calculation of material and energy balances. These flowsheets consist of sizing of the major equipment for plants. These flowsheets cover all equipment of the plant such as reactors, vessels, heat exchangers, drums, separators, pumps and other equipment used for the process. These flowsheets also include numerical data like temperature, pressure, flow quantities and compositions. They also give information about major instruments necessary for controlling the process as well as complete understanding of the process especially for the initial design. In process design, these flowsheets are drawn first and are the only diagrams that show the process (Couper, 2009).

A check list made for the process flowsheets is described here,

- (i) Mass or molar balance which shows compositions, amounts and other properties
- (ii) Process lines that include only those bypasses that are obligatory for understanding the process
- (iii) Major instrumentations needed for process control and for the understanding of the process
- (iv) Only those valves which are compulsory for understanding the flowsheet
- (v) Basis for design, including stream factor
- (vi) Pressure, temperature and other flow quantities
- (vii) Summary for utility requirements
- (viii) All process equipment except spares that can be shown by letters or symbols
- (ix) Process flowsheet must include the data for the equipment especially for the

Compressors, drives, drums and tanks, heat exchangers, furnaces, pumps, towers and other equipment.

The figure 6.2. shows a typical process flowsheet that shows all equipment, flow streams and results for material and energy balance for an ammonia plant that makes ammonia from available hydrogen.

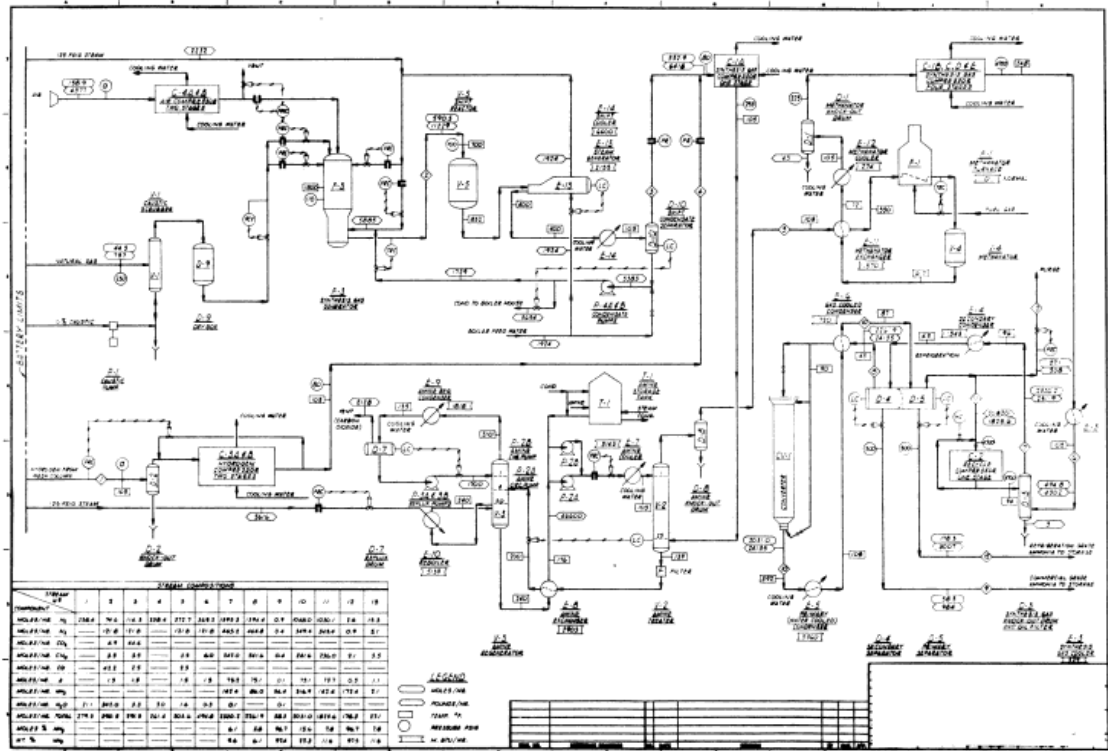


Fig 6.1.2 Process flowsheet of a plant making ammonia from available hydrogen (Couper, 2009)

The above figure shows a typical process flowsheet that shows all equipment, flow streams and results for material and energy balance for an ammonia plant that makes ammonia from available hydrogen.

### 6.1.3 Mechanical ( P & I) flowsheets

P & I flowsheets put more emphasize on process equipment and show all major as well as minor equipment of a plant more realistically than the process flowsheet. These flowsheets do not show operating conditions, flow quantities or compositions but these include all information about size and classes of all pipelines and instruments. In short, they cover every mechanical prospect of the plant concerning process equipment and here equipment are shown in more detailed way by keeping in view the actual equipment.

Process industry practices(PIP) criteria are used by many petroleum and chemical industries for the development of P & I flowsheets because these criteria includes symbols and nomenclature for typical instrumentation, equipment and for piping too.

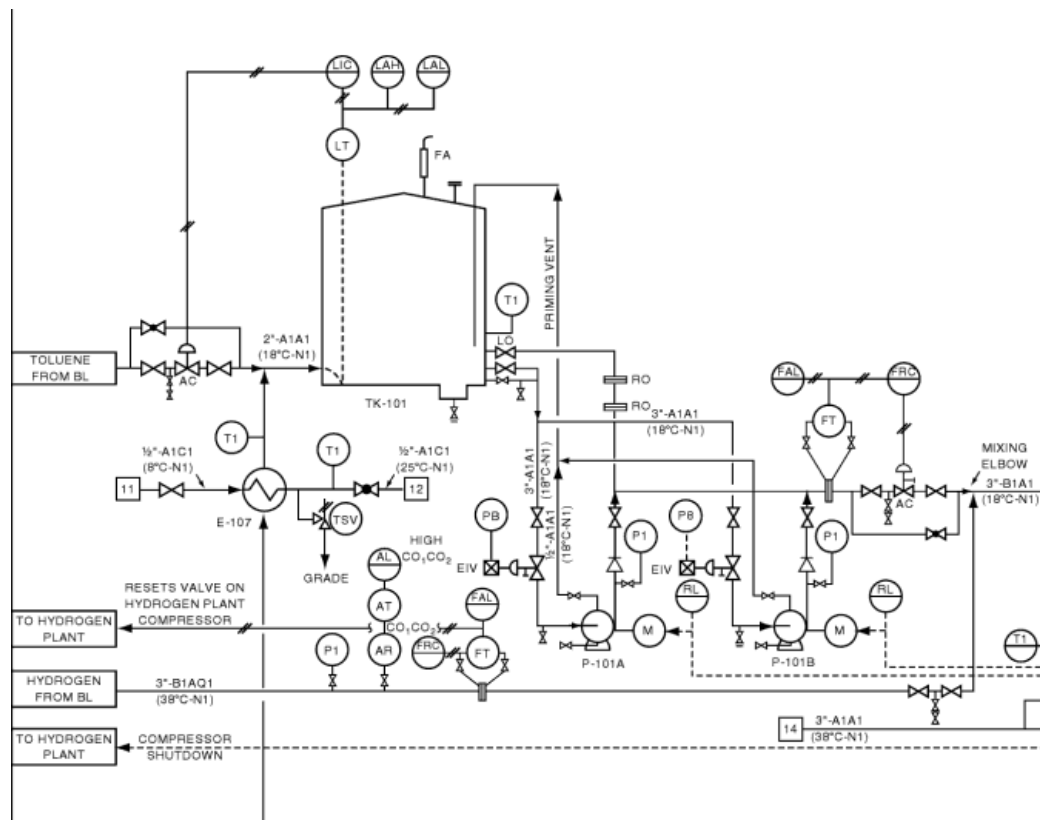


Fig 6.1.3 Mechanical flowsheet for the plant of dealkylation of Benzene (Cooper,2009)

The diagram 6.1.3 is a typical P & I diagram for the plant of dealkylation of Benzene. As already discussed, it shows more detailed equipment and give more detailed information on the mechanical side of the plant like valves, tanks etc.

#### 6.1.4 Information Flowsheet

Information flowsheets are used for simulation purposes. They use process flowheets as their basis for process description but they use the name of the corresponding module instead of the process names. specific numbers are given to all flows and processes. For the information of the transfer of material and energy between the modules, the connections between the modules are used. These may include the main information streams (Tuunila, 2010).

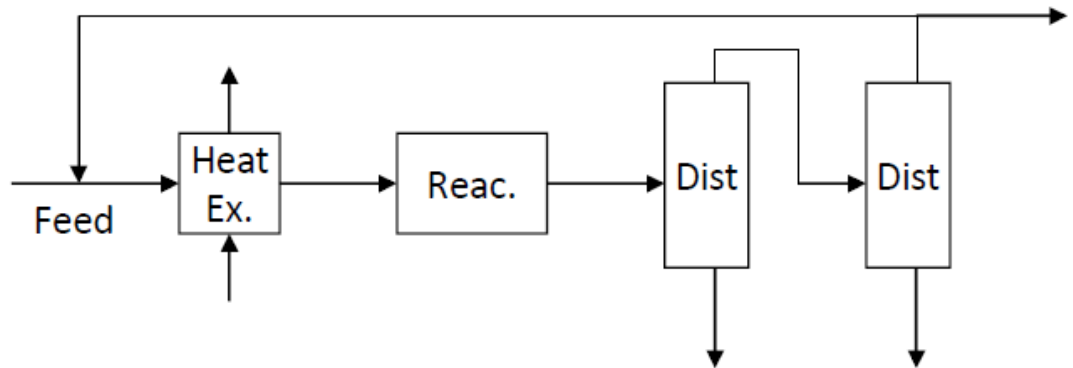


Fig 6.1.4.1 Process flow sheet

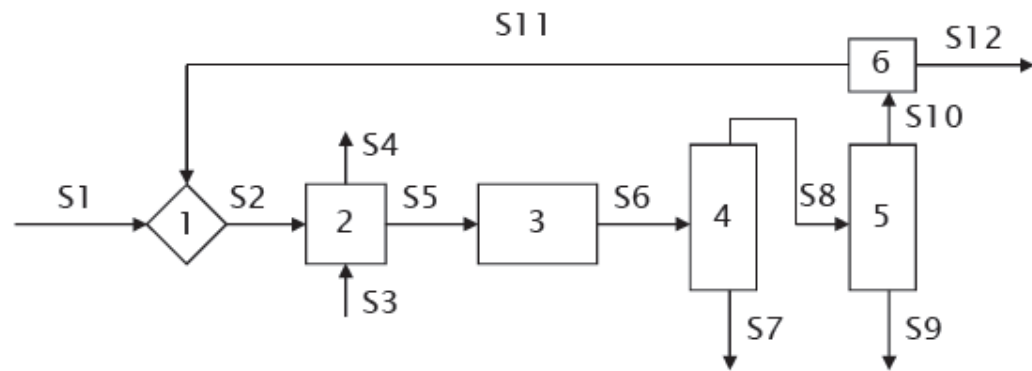


Fig 6.1.4.2 Information flow sheet (Tuunila, 2010).

For the easy understanding of the information flow sheet, both the process and the information flow sheets have shown together of the same process. Since, the process here is any general and simple process but the information flow sheet can be applied to any specific and complex process.

## **7. Process Simulation**

Simulation is defined as imitating a certain situation or process with the help of another equipment. In engineering aspect, identifying the real behavior of a system by creating a duplicate containing the same properties as the original by using a computer or a model is known as simulation. Sometimes, experiments with a scale model are known as simulation. Most of the times, a model is built within the computer and this model is used for numerical experimentation. A simulator is a device which performs simulation.

The major cause for the widening use of simulation is the fast and progressive growth of the influence of computer. Requirements and expectations are increasing continuously and demand a complete understanding of the subject system as it has become necessary in many fields. The reason for the complete understanding of the system is due to the complexity of the system which creates the complexity for the analytical interpretation of the system. The type of simulation used in the system engineering is called as system simulation. The use of system simulation is not only to interpret a problem but in many situations to provide a deep understanding of the problem in order to get solutions by changing the inputs to the model and by varying the values of parameters. Such type of understanding is the sensitivity analysis. Briefly speaking, simulation is very important tool for measuring the decision or judgment procedure and also serves as an important tool in research and business. Moreover, simulation is an important tool to achieve the objectives. Simulation results are not enough for solving the problem or simulation is not enough for determining the quality for simulation results (Ohnari, 1998).

## **7.1 Basic types of simulation**

### **7.1.1 Physical simulation**

Physical simulation is the type of simulation in which physical objects are taken into for real processes.

### **7.1.2 Interactive simulation**

It is a special kind of simulation in which physical simulations includes human operators. It is also called as human in loop simulation.

### **7.1.3 Computer simulation**

Computer simulation is the type of simulation in which an attempt is made to model a real life or hypothetical situation by using a computer to see how the system works.

Even a bird's eye view on the history of simulation technology discloses the fact about the speed of simulation with the development of computers. Simulation program that are user friendly had targeted the whole world.

In order to have a good command in simulation, there are some factors given by Ohnari (1998) that must be taken into account

- (i) Objective of the simulation
- (ii) What kind of steps are needed to achieve that objective
- (iii) Which type of simulation is helpful

Computer simulation is gaining more and more importance and is a useful part of modelling in science and for modelling of human systems in economics, social science and engineering. In computer simulation, in order to to predict the behavior of given system, variables can be changed which shows different results.

**Process simulation** used for the design, development, analysis, and optimization of technical processes and is mainly applied to chemical plants and chemical processes.

Process simulation systems are packages used for the simulation of unit processes.

**Process simulation software** is used for the description of different processes in flow diagrams, where unit operations are put to connect by different process streams. Material and energy balances are solved by this software to find a stable operating point.

Usually the goal of process simulation is to find optimal conditions for an examined process by changing values of process variables.

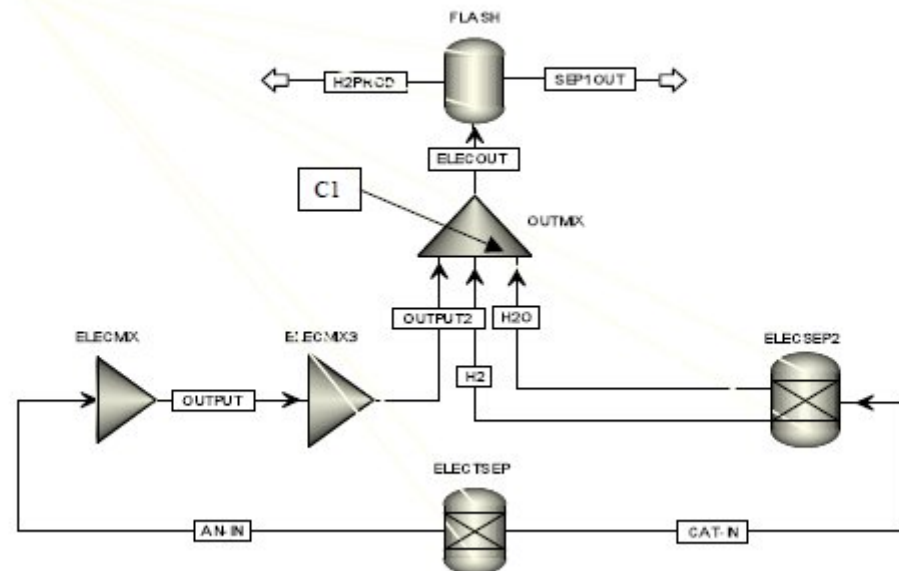


Fig 7.1 Diagram made by Aspen Plus simulation software of electrolytic cell (Tuunila, 2010)

## 7.2 Use of Process simulation

Process simulation has a lot of objectives or uses. It serves from engineering to business. Main objectives of process simulation are as follows,

- (i) to understand the mechanism of real situation
- (ii) the system is in initial stage



- (iii) when experimental tests are dangerous
- (iv) When experimental tests are difficult
- (v) When experimental tests are too expensive
- (vi) When there is environmental risk
- (vii) At the time of safety analysis
- (viii) For the training of a new process to operator
- (ix) For the troubleshooting of the old process
- (x) For the optimization of the old process
- (xi) For optimizing the designing of a new plant or process
- (xii) For process and production control
- (xiii) For energy saving
- (xiv) For calculating the material and energy balance
- (xv) For the planning of marketing
- (xvi) It serves an information tool for management
- (xvii) For the evaluation of new technology

Different software are used for simulation purposes depending on the nature of the objective and problems, objectives and research or industry. Aspen is one the well known software used for simulation by engineers.

### **7.3 Process Simulators**

For handling the large processes in chemical industry and to avoid time consuming calculations for mass and energy balances for the plant, it was necessary to design some software which can solve these problems very easily and the risk of mistakes in

calculation should be the minimum. For this reason, engineers were working hard to design such kinds of software and with the passage of time they were successful in doing so.

Different software were made to meet the industrial problems like MATLAB, ChemMaths, BALAS, Batch plus, Aspen, Fluent and Gambit, Trimax, Chempak and many others. All of these software are used in chemical industry and each of them has their own characteristics for different plants. Balas is designed for paper industry and it works well for paper industry. Batch Plus that was designed for pharmaceutical industry and similar like applications, works better and effectively for solids than Aspen.

#### **7.4 Aspen**

The most widely used commercial process simulation software, Aspen stands for advanced system for process engineering (ASPEN). It was developed by researchers in America during 1970 at Massachusetts Institute of technology (MIT). The purpose behind the development of this novel technology was to design nonlinear simulation software that could be helpful for the progress in synthetic fuels. Aspen Tech, a public traded company had gone publically in 1994 and captures 19 top industrial companies as a part of its mission by providing complete, integrated solution to process industries (Jana, 2009).

This simulation software has ability to simulate large processes with high accuracy. This tool has a model library which has splitters, heat-exchangers, reactors, manipulators, pressure changers, phase separators and distillation column etc. process flow diagram for a complete plant can be made by interconnecting different unit operations. Fortron codes are already built-in in the simulator to solve this process flow diagram.

For the facility of engineers, to avoid human errors and to solve the model in short time, Aspen has a large databank for thermodynamics and physical properties. This

bank helps to reduce the input for the solution of process that contains even large number of units. It also has one graphical user interface that is not attached to simulation engine.

Aspen is used for a variety of applications in process industrial sector such as chemical and petrochemical industry, petroleum refining, polymer and coal based industries. Before flow sheet simulator has limited applications but nowadays, variety of Aspen packages are available with high performance (Jana, 2009).

Aspen as Process Simulator:

Aspen has different versions and all of them are working as simulators for different process industries. Brief descriptions of these simulators are given below,

Aspen Dynamics: used for dynamic study and closed loop control of several process industries.

Aspen Batch CAD: used for batch processing, reactions and distillations.

Aspen Chromatography: used for batch chromatography as well as simulated moving bed processes.

Aspen properties: used for thermo physical properties calculation.

Aspen polymer plus: used for dynamic and steady-state simulation and optimization of polymer processes.

Aspen HYSYS: used for steady state simulation, performance monitoring, design, optimization and business plan for petroleum refining, and for oil and gas industries.

Aspen Plus: this simulator is used for steady-state simulation of chemical, petrochemical and refineries. It is also used for performance monitoring, design, optimization and business planning (Jana, 2009).

Aspen Plus uses sequential modular simulation approach but the user can also have the facility to use equation base approach in some models, by providing ease of design specifications. It can be used for batch process modeling (Schefflan, 2011).

As a final note, although the Aspen Plus and Aspen HYSYS have diversity of applications even then, they have had extremely limited abilities for solids as the intension of their design was for fluids. Engineers are working to solve these kinds of problems (Kemp, 2004).

### **7.5 New application of Aspen Plus in biorefineries**

Although, Aspen software was basically designed for the calculations of petroleum refineries but with the passage of time, applications for Aspen were expanding and they are covering many fields. Therefore, Aspen Plus is also providing solution for bio refineries as bio refineries are getting very importance in present and in future as well.

Aspen Plus is used to calculate the material and energy balance which will help to evaluate different technological options as well as energy related issues to the environment.

## **8. Studied process simulation cases**

The actual task for this thesis was to investigate the Aspen Plus simulations for comminution, classification, filtration and crystallization. Therefore, it is important to give some short description of these equipment which are tested by using Aspen plus.

### **8.1 Gyratory crusher**

The gyratory crushers consist of a long spindle which carries a conical shaped hard steel element. This element is used for grinding. This spindle is suspended from a spider and it rotates at a speed of 85-150 rpm. Feed is introduced at the top and crushed when it passes through the crushing chamber.

Gyratory crushers have much more high capacity than jaw crushers and in mines, they are always preferred when the required crushing rate is higher than 900 t/h. They have even higher capacities for crushing and they can crush an ore with hardness upto 600 Mpa at a rate of 5000 t/h with a size of 200 mm. However, the power consumption for such crushers is very high. They can easily handle the material due to their hydraulic relief system. Primary gyratory crusher is famous for their high capacity and low maintenance.

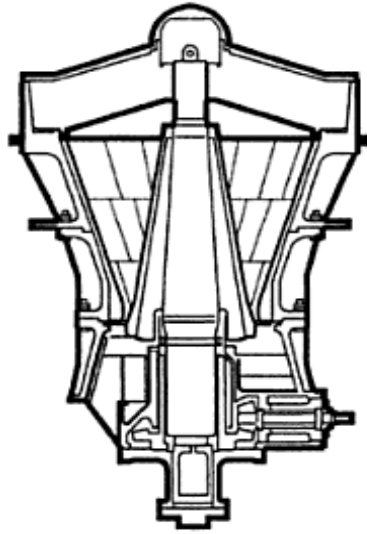


Fig 8.1.1 Typical gyratory crusher (Mular, 2002)

Large gyratory crushers are expensive in their feeding mechanism and are fed directly from the trucks. Choked crushing is also encouraged to some limit for gyratory crushers and it is beneficial when the crusher is followed by SAG mill. When the crusher operates with choke feeding condition, they have longer life (Wills, 2006, Mular, 2002).

### Results for simulation of crushing

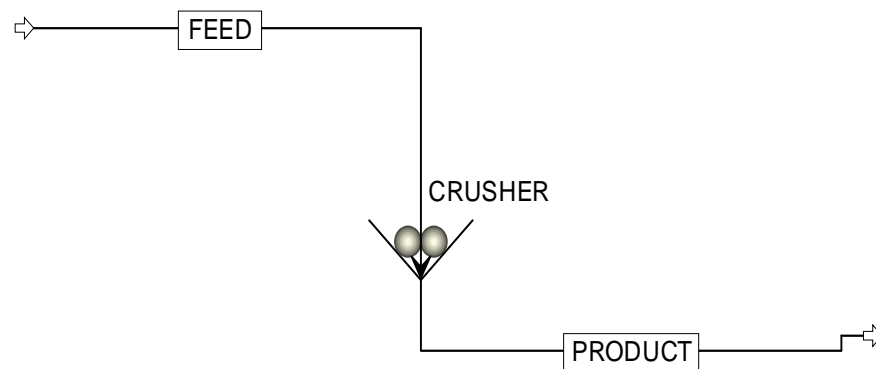


Fig 8.1.2 Flowsheet of crushing process created by Aspen Plus

CaCO<sub>3</sub> was selected as material for crushing. It was assumed that it is wet crushing. The feed flowrate of CaCO<sub>3</sub> was 5 t/h and 3 t/h for water. The temperature was assumed to be 20 °C and pressure was 1 atm. The range of feed size was 0.02 -4 cm. The values for particle size, feed for particle size distribution (PSD) and product are shown in tables 8.1 and 8.2. In figure 8.1.3 simulated results are compared to real results obtained with a laboratory crusher. Complete results for this process are shown in appendix (i).

Table 8.1 PSD of given feed and simulated product size fractions

particle size(cm)	given feed	simulated data
0.02-0.5	0	0.39
0.5-1	0.1	0.24
1-2	0.1	0.16
2-2.5	0.2	0.09
2.5-3	0.3	0.07
3-3.5	0.2	0.04
3.5-4	0.1	0.02

Table 8.2 Values of particle size, simulated weight percents and & cumulative distribution of product

x	wt fraction,%(P)	cum fraction f(P)
0.5	39	39
1	24	63
2	16	79
2.5	9	88
3	7	95
3.5	3	98
4	2	100

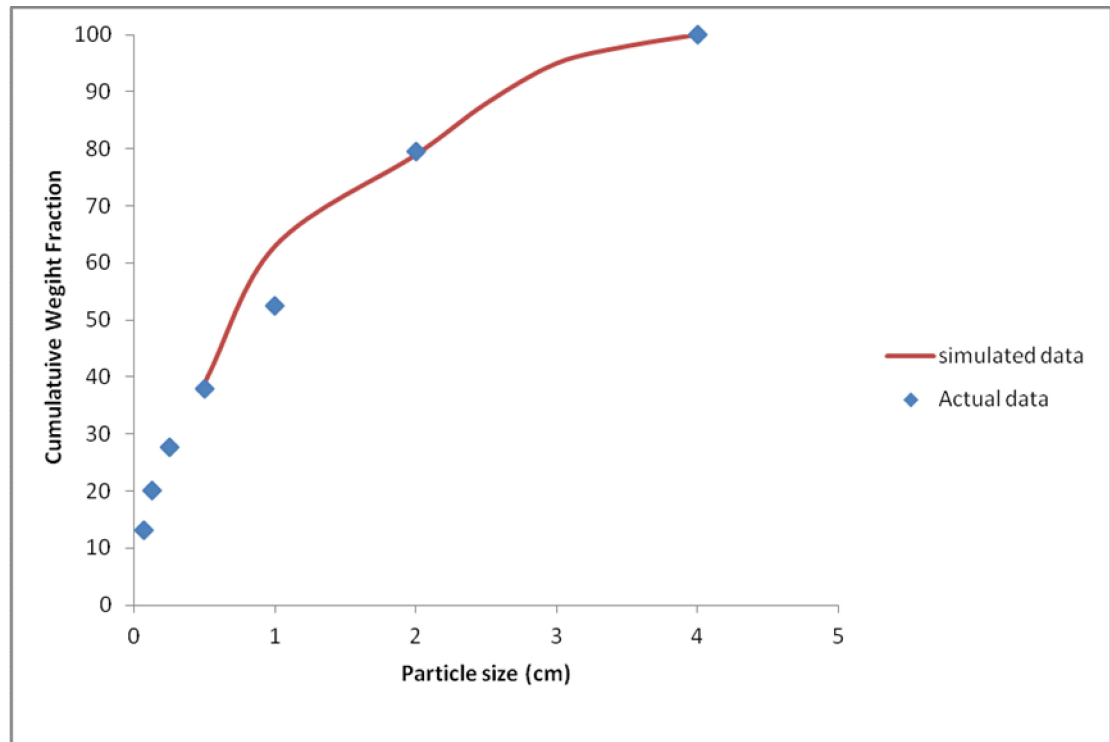


Fig 8.1.3 Particle size and cumulative weight fraction for  $\text{CaCO}_3$

Fig 8.1.3 shows that the trend for simulated data is almost similar to actual data when simulated particle size distribution of product is compared to actual size distribution obtained with a laboratory crusher. So, the crushing model of Aspen Plus seems to be suitable for simulation on crushing process.



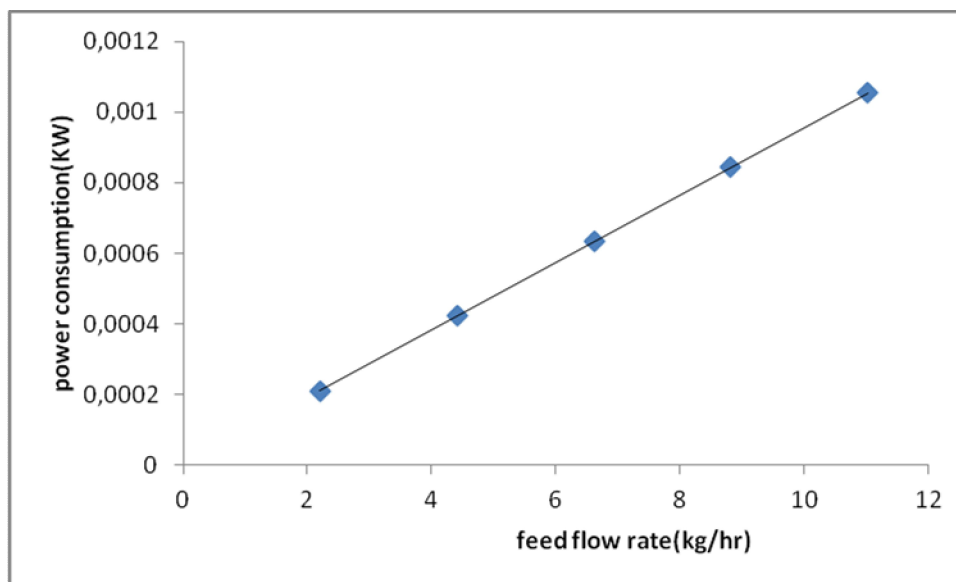


Fig 8.1.4 Effect of feed flow rate on power consumption based on sensitivity analysis with Aspen Plus

Fig 8.1.4 describes that as the feed flow rate for solid is increasing, power consumption is also increasing. In this fig, results obtained are quite good. Therefore, it is possible to determine the power consumption for given feed flow rate.

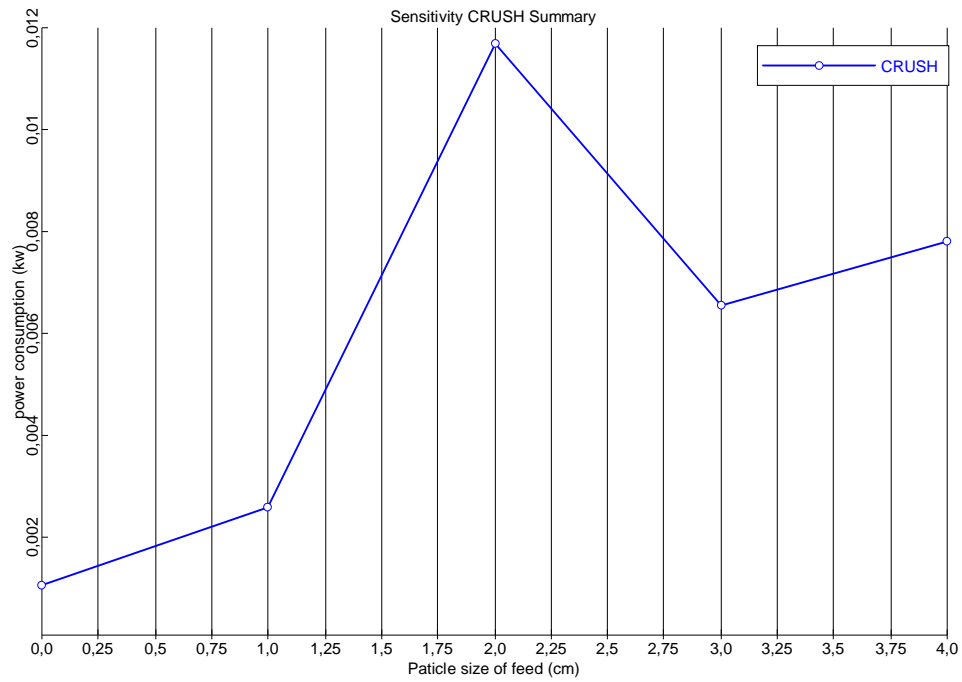


Fig 8.1.5 Effect of particle size on power consumption based on sensitivity analysis with Aspen Plus

Fig 8.1.5 describes that power consumption is changing with the increase in the particle size. In the beginning, power consumption is increasing with the increase in particle size but then there is a decreasing trend. However, power consumption can be calculated for any given feed size by Aspen Plus.

## 8.2 Screens

Screen can be defined as, a surface with apertures or holes with uniform dimension. The particles that will be given to this surface will pass through it or will stay at this surface according to the size of the particles larger or smaller than hole or apertures.

Efficiency of screen can be calculated as,

$$E = \frac{c-f}{c(1-f)} \quad (8.2)$$

where E is the efficiency, c is the product flow rate and f is the fraction of material above the cut point size (Wills, 2006).

It is also important to notice that efficiency increases with the increase in the flow rate of the feed (Mular, 2002).

### 8.2.1 Factors affecting screen performance

- (i) particle size
- (ii) feed rate, in order to get complete separation, long screening time with low feed rate should be used but in industries, normally high feed rates are introduced with short screening time. Therefore, the net result is the reduction in efficiency.
- (iii) screen angle
- (iv) particle shape
- (v) open area
- (vi) vibration
- (vii) moisture, wet screening is helpful for the processing finer sizes down to 250  $\mu\text{m}$ .

### 8.2.2 Types of screens

There are different types of screens used by industry like vibrating screens, inclined screens, grizzly screens, horizontal screens, banana screens, modular screens and high frequency screens etc. They are used according to the requirement of particle size separation depending upon the type and nature of material to be separated.

#### Results for simulation of screening

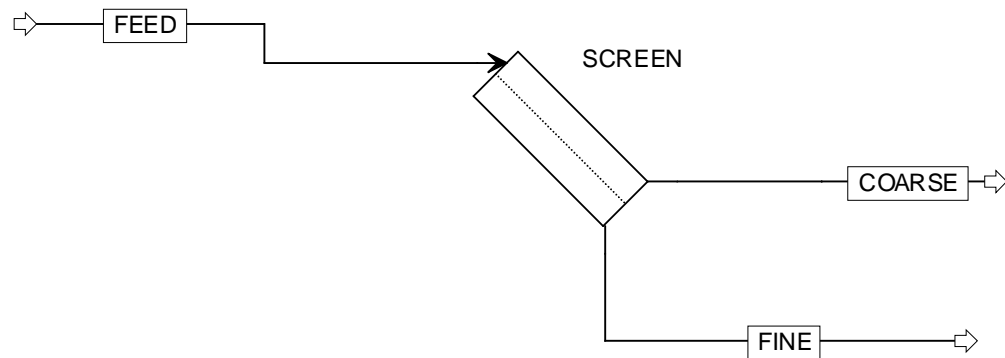


Fig 8.2 Flowsheet for the process of screening by Aspen Plus

CaCO<sub>3</sub> was selected as material for screening. The assumption for this process is wet grinding. The feed flowrate for CaCO<sub>3</sub> was 5 t/h and for water was 2 t/h. The maximum size for screen opening was 6 mm.

Values of particle size distribution for feed and product are shown in table 8.2.1. From here, it can be concluded that simulation model of Aspen Plus seems to classify particles clearly with a given screen opening. Complete results for this process are shown in appendix (ii).

Table 8.2.1 Mass fractions of feed and simulated mass fraction of product

Particle size(mm)	Mass fraction of feed	Mass fraction of product
0-1	0.10	0.14
1.0-2.0	0.10	0.14
2.0-3.0	0.20	0.27
3.0-4.0	0.10	0.13
4.0-5.0	0.10	0.11
5.0-6.0	0.20	0.19
6.0-7.0	0.10	0.02
7.0-8.0	0.10	0.00

-

## **8.3 Filtration**

### **8.3.1 Rotary drum filters**

Rotary drum filters essentially contain a rotating drum. There are two types of rotary drum filters

- (i) Rotary vacuum drum filter
- (ii) Rotary pressure drum filter

The drum in the rotary vacuum drum filter contains three different sections named as cake-building, dewatering and cake removal zone. The first two zones in this filter are under vacuum while the water is sucked by the cloth.

Due to the creation of vacuum as a driving force in this filter, it is named vacuum drum filter. The vacuum created is about 0.5 bar and the drum speed is 10-60 revolutions per hour.

In rotary pressure drum filters, drum filter is covered by a large pressure shell. In this filter, driving force for filtration is pressure. Due to this pressure, cake remains inside the shell and discharged at atmospheric pressure in discharge zone. Pressure difference is necessary for cake formation in this filter. For the removal of the filter cake, doctor blade and roller are preferred (Sutherland, 2008).

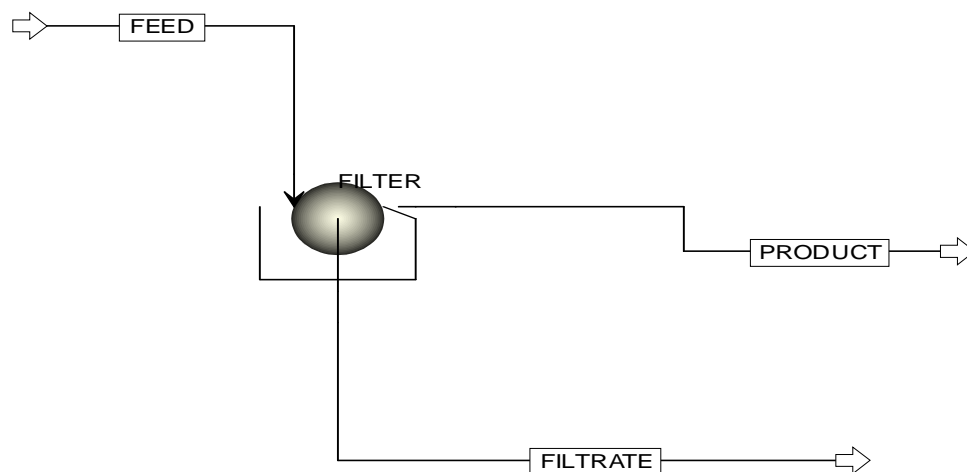


Fig 8.3 Flowsheet for the process of filtration by Aspen Plus

For filtration process, ZnS was selected for filtration. Feed flow rate for ZnS was 3 t/h and for water was 0.5 t/h. The temperature was 25 °C and pressure was 1 atm for filtration process. The phase selected for filtration was design phase and pressure drop was 0.8 atm. The obtained results for this process are shown in appendix (iii).

Table 8.3 Calculated values for filter

Filter results		
▶ Pressure drop:	0.8	atm
Filter diameter:	0.37426569	meter
Filter width:	0.74853137	meter
Average particle diameter:		
Average solid density:	3.24853333	gm/cc
Total solid mass flow rate:	2721.55419	kg/hr
Surface tension:	72.8135946	dyne/cm
Volume flow of filtrate:	2.53527824	l/min
Cake thickness:	2.88452841	cm
Filtration resistance:	1.102E+10	meter/kg
Mass fraction of solids in cake:	0.9	
Average porosity:	0.45	
Cake compressibility:	0	

Table 8.3 shows calculated filtration results. In this table, thickness of filter cake is almost 3 cm and this cake thickness increases with the increase in feed flow rate for solids. From results can be seen that Aspen also calculates the width and diameter of filter for given feed rate. The diameter was 0.37 m and the width is 0.75 m for this value of cake thickness. So, it is also possible to design a filter by Aspen Plus.



## 8.4 CRYSTALLIZATION

### 8.4.1 Forced circulation Crystallizer

Forced circulation evaporators are widely used in industry. In the APV-Kestner crystallizer, the feed enters in the crystallizer from the pump inlet side. This crystallizer is also called as long-tube salting evaporator. To avoid the boiling in the tubes, the liquor level in the separator is kept over the heat exchanger. Large crystals are settled at the bottom of the conical base and are collected in salt box. These types of crystallizers are extensively used for a large number of substances like NaCl, FeSO<sub>4</sub> and citric acid etc (Mullin, 1972).

### Evaporative crystallization

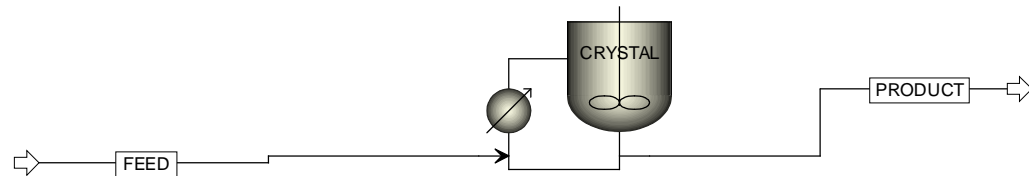


Fig 8.4.1 Flowsheet of evaporative crystallization process by Aspen Plus

In evaporative crystallization, the component selected for crystallization was NaCl. The feed flowrate for NaCl and water is same i.e. 500 kg/h. The temperature of feed was 60 °C and the pressure 1 atm. The temperature for crystallizer was 80 °C with same pressure. The results obtained from crystallizer are shown in table 8.4.1. Complete results for this process are shown in appendix (iv).

Table 8.4.1 Results of evaporative crystallizer

Crystallizer results		
Crystallizer temperature:	80,0000061	C
Heater duty:	9784,07849	cal/sec
Net duty:	9784,07849	cal/sec
Crystallizer pressure:	1	atm
Crystallizer volume:	0	l
Residence time:	0	hr
Crystal product:	295,566793	kg/hr
Vapor flow rate:	0	kg/hr
Recirculation flow rate:	0	kg/hr
Magma density:	393,29802	gm/l

The above table shows the value of magma density almost 400 gm/l which is according to the actual range. This magma density is the density of suspension. From table, it can also be seen that Aspen was unable to calculate many important values like residence time, vapor flowrate and crystallizer volume etc.

## Cooling crystallization

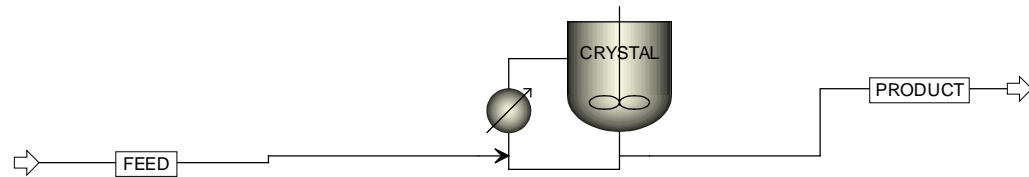


Fig 8.4.2 Flowsheet for the cooling crystallization process by Aspen Plus

KNO<sub>3</sub> was selected for cooling crystallization. In this crystallization process, the feed flow rate of water was 600 kg/h and for KNO<sub>3</sub> was 400 kg/h. The pressure assumed was 1 atm and the solution was cooled from 60 °C to 20 °C. Complete results for this process are shown in appendix (v).

Table 8.4.2 Results for cooling crystallizer

Crystallizer results		
Crystallizer temperature:	20,0000061	C
Heater duty:	12534,721	cal/sec
Net duty:	12534,721	cal/sec
Crystallizer pressure:	1	atm
Crystallizer volume:	0	l
Residence time:	0	hr
Crystal product:	222,180785	kg/hr
Vapor flow rate:	0	kg/hr
Recirculation flow rate:	0	kg/hr
Magma density:	205,786223	gm/l

Table 8.4.2 shows that the temperature of crystallizer is 20 °C which shows that solution was cooled down to this temperature to get crystals. The magma density is in the required range. This shows that the material balance can be calculated by Aspen Plus.

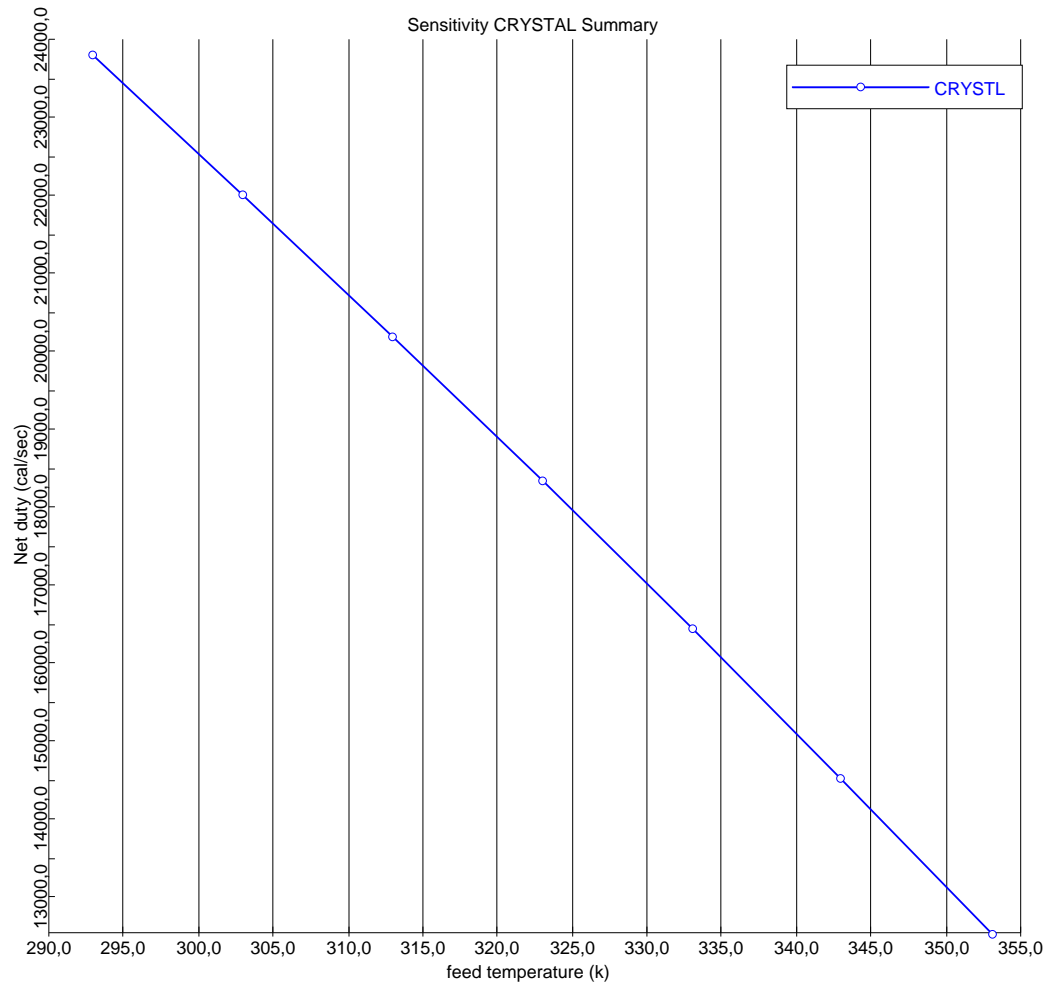


Fig 8.4.3 Net duty relating to required cooling power as a function of feed solution temperature based on sensitivity analysis with Aspen Plus.

Fig 8.4.3 shows a straight relationship between feed temperature and net duty. It narrates that net duty is decreasing with the increase in temperature.

## 8.5 Crushing and Screening

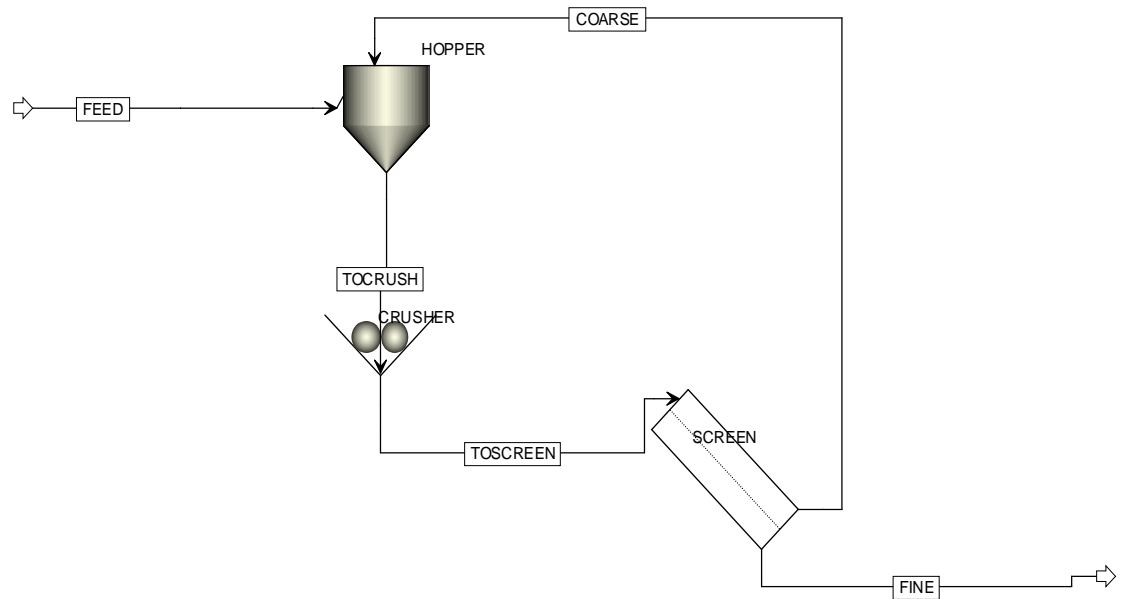


Fig 8.5 Flowsheet for the crushing and screening process by Aspen Plus

For this Process, the material to be crushed was  $\text{CaCO}_3$  and feed flowrate for  $\text{CaCO}_3$  was 3000 kg/h and for mixed stream was 2000 kg/h. The temperature was room temperature and pressure was 1 atm for this process. The size of the particles to be crushed was upto 100 mm with different particle size distribution. The size of screen opening was 10 mm. In Table 8.5 particle size distributions and in Table 8.6 flowrates of different process streams are given. All obtained results for this process are shown in appendix (vi).

Table 8.5.1 Mass fractions of different solid material streams of crushing – screening process

SIZE (mm)	COARSE	FEED	FINE	TOCRUSH	TOSCREEN
0-10	0,01937101	0.2	1	0.125154	0.593654
10-20	0.36999373	0.1	0	0.211875	0.153315
20-30	0,22294368	0.1	0	0.150943	0.092382
30-40	0,14300717	0.1	0	0.117821	0.059258
40-50	0.09511211	0.1	0	0.097975	0.039412
50-60	0.0644014	0.1	0	0.08525	0.026686
60-70	0.04253944	0.1	0	0.076191	0.017627
70-80	0.02692798	0.1	0	0.069722	0.011158
80-90	0.01570344	0.1	0	0.065071	0.006507
90-100	0	0	0	0	0

From above table, it can be described that coarse particle stream is decreasing as the size is decreasing but the trend for feed is almost constant. It does not have any effect on fines stream but it is decreasing for crushing and screening streams with the decrease in particle size.

Table 8.5.2 Mass flow rates of different streams of crushing – screening process

Streams	Solid(kg/h)	Water(kg/h)
FEED	3000	2000
COARSE	2122,64632	0
FINE	2999,96188	2000
TOCRUSH	5122,64632	2000
TOSCREEN	5122,64632	2000

## 8.6 Crushing and Filtration

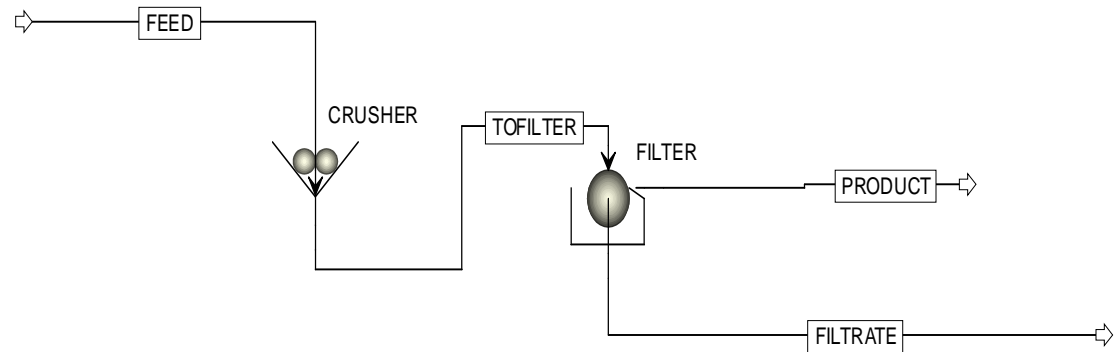


Fig 8.6 Flowsheet of crushing and filtration process created by Aspen Plus

For the simulation of crushing and filtration, the temperature and pressure were room temperature and 1 atm respectively. The feed flow rate of water was 1 t/h and for solid stream was 5 t/h. The obtained results for this process shows correct calculations for mass balances and are shown in appendix (vii).

## 8.7 Filtration and Crystallization

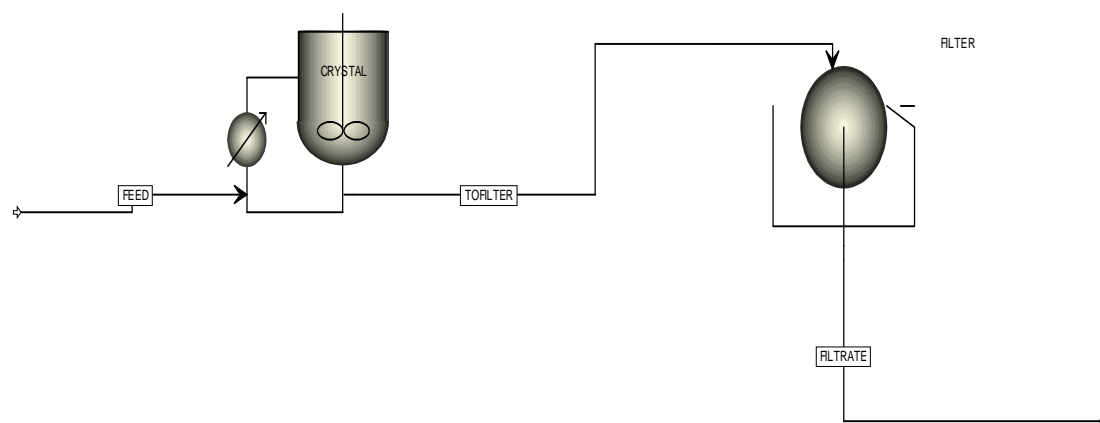


Fig 8.7 Flowsheet for the process of crystallization and filtration by Aspen Plus

To get simulation results for crystallization and filtration,  $\text{KNO}_3$  was selected for the model compound. Here, the used crystallization method was cooling crystallization. The temperature of feed was  $60^\circ\text{C}$  and for crystallizer was  $25^\circ\text{C}$  respectively. The pressure was 1 atm for crystallizer. It was useful to see that Aspen can work for such integrated processes and calculate the material balance for the whole process. The complete results for this process are shown in appendix (viii).



## 8.8 Crushing, Screening and Filtration

Closed loop comminution

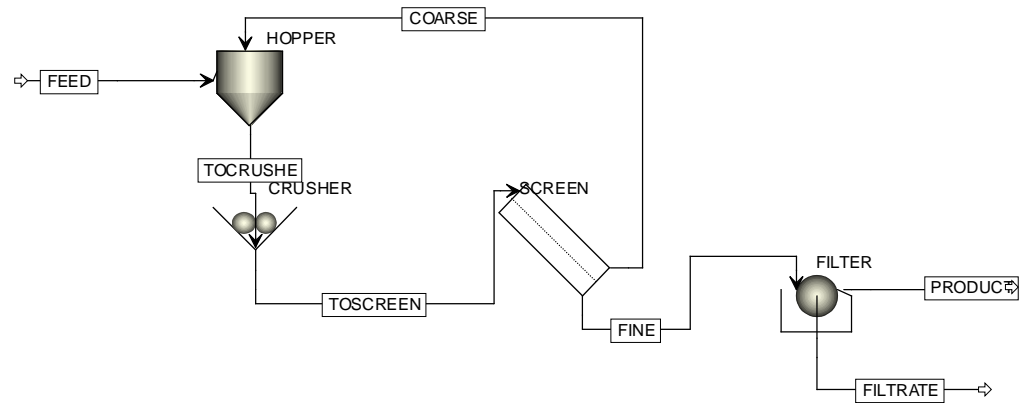


Fig 8.8 Process for crushing, screening and filtration

The material selected for this process was  $\text{CaCO}_3$ . The feed flow rate of water was 1500 kg/h and for solid was 3000 kg/h. The maximum particle diameter for crusher was 30 mm and the size of the screen opening was 5 mm. The maximum pressure drop for filter in this process was 0.6 atm and rate of revolution was 1 rpm.

By using the above mentioned data, simulation was done and obtained results for this process show the correct calculations for mass balances and are shown in appendix (ix).

## 9. CONCLUSIONS

Solid processes were simulated by Aspen Plus software. The reason for putting more attention into selected solid unit operations is their increasing use and importance in industry. The simulations were done successfully for these processes. After doing simulation and obtaining results, it was possible to conclude on the capabilities of Aspen Plus as a design and sizing tools for selected solid processes.

The first process for simulation was crushing. In crushing, two tasks were done. The first task was the comparison of actual data and obtained simulated data. In this task, a graph was drawn between particle size distribution (PSD) and cumulative weight fraction. As shown in graph 8.1, the results obtained by simulation were almost similar compared to actual results from real crushing process. The second task was to see the effect of feed flow rate on power consumption by using Aspen. Figure 8.1.2 it shows that as the feed flow rate is increasing, power consumption is also increasing. The third task was also to study the effect of particle size on power consumption. Figure 8.1.3 shows that as the particle size is increasing, crushers need more power to crush it. Therefore, in case of crushing, it was concluded that Aspen works well for crushers.

The second process for simulation was screening. It was noticed that in case of mass balance for screening, Aspen works perfectly.

The third process for simulation was filtration. In case of filtration, it was observed that cake thickness was increasing with the increase in the feed flow rate. By this way, Aspen was able to calculate mass balance for filtration also. It is also not possible to design a filter according to the desired cake thickness. Therefore, Aspen is a good tool to calculate mass balance but it can not be used for deep design and study of filtration process in a wider manner.

The last and the complex process for simulation was crystallization. It was quite difficult to simulate the crystallization process due to the complexity of equations and phases involved. For crystallization, two simulations were done. Like all other

processes, mass balance can be calculated by using Aspen. Figure 8.4.2 shows a graph between feed temperature and net duty of crystallizer.

The interesting fact was the calculation of magma density (density of suspension). The values for magma density were in the desired range for both cooling and evaporative crystallization. But, it will be worthy to conclude that Aspen does not work well for crystallization and it very difficult to design and obtain results for different parameters of crystallization like crystal product, nucleation rate, crystal growth rate and latent heat of vaporization etc.

It is worthwhile to mention that for screening, filtration and crystallization, there are not good variables for sensitivity analysis in Aspen Plus at the moment.

After studying the simulation on individual unit operations, these units were integrated to check the performance of Aspen for these processes. Different processes were combined like crushing-screening, crushing-filtration, crystallization-filtration and crushing-screening and filtration as well. It was concluded that Aspen can be used for these processes as it was able to perform mass balance for these processes. Apart from mass balance, it also gives the different values for enthalpy, density etc.

As a final note, it can be concluded carefully that Aspen can be used in some cases for the simulation of solid processes but not for the deeper investigation of solid processes. Therefore, special programs developed for different processes are suggested to be utilized if deeper investigation is required.

I would also say solid processes available in Aspen Plus enable simulation of such chemical processes, which consist of also some solid material. That is possibly the main reason for them being included to this software.

In general, Aspen is still mainly mentioned for the simulation of traditional chemical processes.

## **10. Future Work**

It is recommended for future that the industrial data should be used to see more clear effect of Aspen for solids. Some other software can be used to compare the results obtained from Aspen and that software. The latest version of Aspen plus should be taken into account to study the difference of results. Try to look the effect of different parameters for designing by using actual data especially for filtration and crystallization. Select one unit operation and specific industry in accordance with that unit to get more accurate results. Try to use more complex processes, take values from literature and then simulate to obtain more results particularly for crystallization

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## **Appendices**

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**(i) Results for Simulation of Crushing**

crusher 1			
Stream ID		FEED	PRODUCT
From			CRUSH
To		CRUSH	
Phase		LIQUID	LIQUID
Substream: MIXED			
Mole Flow	kmol/hr		
CACO3		0,0	0,0
WATER		151,0692	151,0692
Total Flow	kmol/hr	151,0692	151,0692
Total Flow	kg/hr	2721,554	2721,554
Total Flow	l/min	45,63501	45,63501
Temperature	K	298,1500	298,1500
Pressure	atm	1,000000	1,000000
Vapor Frac		0,0	0,0
Liquid Frac		1,000000	1,000000
Solid Frac		0,0	0,0
Enthalpy	cal/mol	-68234,18	-68234,18
Enthalpy	cal/gm	-3787,573	-3787,573
Enthalpy	cal/sec	-2,8634E+6	-2,8634E+6
Entropy	cal/mol-K	-38,85679	-38,85679
Entropy	cal/gm-K	-2,156879	-2,156879
Density	mol/cc	,0551730	,0551730
Density	gm/cc	,9939570	,9939570
Average MW		18,01528	18,01528
Liq Vol 60F	l/min	45,44665	45,44665
Substream: STOTAL			
Total Flow	kg/hr	2726,554	2726,554
Enthalpy	cal/sec	-2,8674E+6	-2,8674E+6
Substream: CIPSD			
Mole Flow	kmol/hr		
CACO3		,0499564	,0499564
WATER		0,0	0,0
Total Flow	kmol/hr	,0499564	,0499564
Total Flow	kg/hr	5,000000	5,000000
Total Flow	l/min	,0307081	,0307081
Temperature	K	298,1500	298,1500
Pressure	atm	1,000000	1,000000
Vapor Frac		0,0	0,0
Liquid Frac		0,0	0,0
Solid Frac		1,000000	1,000000
Enthalpy	cal/mol	-2,8838E+5	-2,8838E+5
Enthalpy	cal/gm	-2881,241	-2881,241
Enthalpy	cal/sec	-4001,724	-4001,724
Entropy	cal/mol-K	-62,90824	-62,90824
Entropy	cal/gm-K	-,6285343	-,6285343
Density	mol/cc	,0271135	,0271135
Density	gm/cc	2,713723	2,713723
Average MW		100,0872	100,0872
Liq Vol 60F			
PSD			
1		0,0	,4330926
2		,1000000	,2584282
3		,3000000	,1567518
4		,2000000	,0684295
5		,2000000	,0464121
6		,1000000	,0218857
7		,1000000	,0150000

**(ii)Results for Simulation of Screening**

Heat and Material Balance Table				
Stream ID		COARSE	FEED	PRODUCT
From		SCREEN		SCREEN
To			SCREEN	
Phase		MISSING	LIQUID	LIQUID
Substream: MIXED				
Mole Flow	kmol/hr			
CACO3		0,0	0,0	0,0
H2O		0,0	100,7128	100,7128
Total Flow	kmol/hr	0,0	100,7128	100,7128
Total Flow	kg/hr	0,0	1814,369	1814,369
Total Flow	l/min	0,0	30,42334	30,42334
Temperature	K		298,1500	298,1500
Pressure	atm	1,000000	1,000000	1,000000
Vapor Frac			0,0	0,0
Liquid Frac			1,000000	1,000000
Solid Frac			0,0	0,0
Enthalpy	cal/mol		-68234,18	-68234,18
Enthalpy	cal/gm		-3787,573	-3787,573
Enthalpy	cal/sec		-1,9089E+6	-1,9089E+6
Entropy	cal/mol-K		-38,85679	-38,85679
Entropy	cal/gm-K		-2,156879	-2,156879
Density	mol/cc		,0551730	,0551730
Density	gm/cc		,9939570	,9939570
Average MW			18,01528	18,01528
Liq Vol 60F	l/min	0,0	30,29777	30,29777
Substream: STOTAL				
Total Flow	kg/hr	1375,724	6350,293	4974,569
Enthalpy	cal/sec	-1,1011E+6	-5,5392E+6	-4,4382E+6
Substream: CIPSD				
Mole Flow	kmol/hr			
CACO3		13,74526	45,31972	31,57446
H2O		0,0	0,0	0,0
Total Flow	kmol/hr	13,74526	45,31972	31,57446
Total Flow	kg/hr	1375,724	4535,924	3160,199
Total Flow	l/min	8,449182	27,85794	19,40876
Temperature	K	298,1500	298,1500	298,1500
Pressure	atm	1,000000	1,000000	1,000000
Vapor Frac		0,0	0,0	0,0
Liquid Frac		0,0	0,0	0,0
Solid Frac		1,000000	1,000000	1,000000
Enthalpy	cal/mol	-2,8838E+5	-2,8838E+5	-2,8838E+5
Enthalpy	cal/gm	-2881,241	-2881,241	-2881,241
Enthalpy	cal/sec	-1,1011E+6	-3,6303E+6	-2,5292E+6
Entropy	cal/mol-K	-62,90824	-62,90824	-62,90824
Entropy	cal/gm-K	-6285343	-6285343	-6285343
Density	mol/cc	,0271135	,0271135	,0271135
Density	gm/cc	2,713723	2,713723	2,713723
Average MW		100,0872	100,0872	100,0872
Liq Vol 60F				
PSD				
1		4,02875E-3	,1000000	,1417790
2		9,72217E-3	,1000000	,1393005
3		,0393430	,2000000	,2699385
4		,0398026	,1000000	,1262056
5		,0675254	,1000000	,1141371
6		,2291148	,2000000	,1873255
7		,2807515	,1000000	,0213137
8		,3297117	,1000000	0,0

**(iii)Results for Simulation of Filtration**

Heat and Material Balance Table				
Stream ID		FEED	FILTRATE	PRODUCT
From			FILTER	FILTER
To		FILTER		
Phase		LIQUID	LIQUID	LIQUID
Substream: MIXED				
Mole Flow	kmol/hr			
ZNS		0,0	0,0	0,0
H2O		25,17820	8,392734	16,78547
Total Flow	kmol/hr	25,17820	8,392734	16,78547
Total Flow	kg/hr	453,5924	151,1975	302,3949
Total Flow	l/min	7,605835	2,535278	5,070556
Temperature	K	298,1500	298,1500	298,1500
Pressure	atm	1,000000	,2000000	,2000000
Vapor Frac		0,0	0,0	0,0
Liquid Frac		1,000000	1,000000	1,000000
Solid Frac		0,0	0,0	0,0
Enthalpy	cal/mol	-68234,18	-68234,18	-68234,18
Enthalpy	cal/gm	-3787,573	-3787,573	-3787,573
Enthalpy	cal/sec	-4,7723E+5	-1,5908E+5	-3,1815E+5
Entropy	cal/mol-K	-38,85679	-38,85679	-38,85679
Entropy	cal/gm-K	-2,156879	-2,156879	-2,156879
Density	mol/cc	,0551730	,0551730	,0551730
Density	gm/cc	,9939570	,9939570	,9939570
Average MW		18,01528	18,01528	18,01528
Liq Vol 60F	l/min	7,574442	2,524814	5,049628
Substream: \$TOTAL				
Total Flow	kg/hr	3175,147	151,1975	3023,949
Enthalpy	cal/sec	-8,3266E+5	-1,5908E+5	-6,7358E+5
Substream: CISOLID				
Mole Flow	kmol/hr			
ZNS		27,92598	0,0	27,92598
H2O		0,0	0,0	0,0
Total Flow	kmol/hr	27,92598	0,0	27,92598
Total Flow	kg/hr	2721,554	0,0	2721,554
Total Flow	l/min	13,96299	0,0	13,96299
Temperature	K	298,1500		298,1500
Pressure	atm	1,000000	,2000000	,2000000
Vapor Frac		0,0		0,0
Liquid Frac		0,0		0,0
Solid Frac		1,000000		1,000000
Enthalpy	cal/mol	-45819,24		-45819,24
Enthalpy	cal/gm	-470,1531		-470,1531
Enthalpy	cal/sec	-3,5543E+5		-3,5543E+5
Entropy	cal/mol-K	-1,360657		-1,360658
Entropy	cal/gm-K	-,0139617		-,0139617
Density	mol/cc	,0333333		,0333333
Density	gm/cc	3,248533		3,248533
Average MW		97,45600		97,45600
Liq Vol 60F				

**(iv) Results for Smulation of Crystallization (Evaporation)**

Heat and Material Balance Table			
Stream ID		FEED	PRODUCT
From			CRYSTAL
To		CRYSTAL	
Phase		LIQUID	LIQUID
Substream: MIXED			
Mole Flow	kmol/hr		
NACL		1,711084	3,498025
H2O		27,75422	27,75422
Total Flow	kmol/hr	29,46530	31,25224
Total Flow	kg/hr	600,0000	704,4332
Total Flow	l/min	9,142486	10,22950
Temperature	K	333,1500	353,1500
Pressure	atm	1,000000	1,000000
Vapor Frac		0,0	0,0
Liquid Frac		1,000000	1,000000
Solid Frac		0,0	0,0
Enthalpy	cal/mol	-68573,39	-69103,59
Enthalpy	cal/gm	-3367,560	-3065,787
Enthalpy	cal/sec	-5,6126E+5	-5,9990E+5
Entropy	cal/mol-K	-33,98786	-30,50189
Entropy	cal/gm-K	-1,669104	-1,353219
Density	mol/cc	,0537149	,0509185
Density	gm/cc	1,093794	1,147716
Average MW		20,36293	22,54025
Liq Vol 60F	l/min	9,424879	10,54804
Substream: \$TOTAL			
Total Flow	kg/hr	1000,000	1000,000
Enthalpy	cal/sec	-7,4674E+5	-7,3695E+5
Substream: CISOLID			
Mole Flow	kmol/hr		
NACL		6,844338	5,057397
H2O		0,0	0,0
Total Flow	kmol/hr	6,844338	5,057397
Total Flow	kg/hr	400,0000	295,5668
Total Flow	l/min	3,106768	2,295643
Temperature	K	353,1500	353,1500
Pressure	atm	1,000000	1,000000
Vapor Frac		0,0	0,0
Liquid Frac		0,0	0,0
Solid Frac		1,000000	1,000000
Enthalpy	cal/mol	-97557,30	-97557,30
Enthalpy	cal/gm	-1669,288	-1669,288
Enthalpy	cal/sec	-1,8548E+5	-1,3705E+5
Entropy	cal/mol-K	-19,60510	-19,60510
Entropy	cal/gm-K	-,3354598	-,3354598
Density	mol/cc	,0367173	,0367173
Density	gm/cc	2,145853	2,145853
Average MW		58,44247	58,44247
Liq Vol 60F			

## (v) Results for Simulation of Crystallization (cooling)

Heat and Material Balance Table			
Stream ID		FEED	PRODUCT
From			CRYSTAL
To		CRYSTAL	
Phase		LIQUID	LIQUID
Substream: MIXED			
Mole Flow	kmol/hr		
KNO3		,9890880	1,758788
H2O		33,30506	33,30506
Mass Flow	kg/hr		
KNO3		100,0000	177,8192
H2O		600,0000	600,0000
Total Flow	kmol/hr	34,29415	35,06385
Total Flow	kg/hr	700,0000	777,8192
Total Flow	l/min	14,14655	16,23495
Temperature	K	353,1500	293,1500
Pressure	atm	1,000000	1,000000
Vapor Frac		0,0	0,0
Liquid Frac		1,000000	1,000000
Solid Frac		0,0	0,0
Enthalpy	cal/mol	-65494,88	-65245,56
Enthalpy	cal/gm	-3208,702	-2941,250
Enthalpy	cal/sec	-6,2391E+5	-6,3549E+5
Entropy	cal/mol-K	-24,68046	-19,90597
Entropy	cal/gm-K	-1,209136	-,8973551
Density	mol/cc	,0404034	,0359962
Density	gm/cc	,8247003	,7985028
Average MW		20,41165	22,18294
Liq Vol 60F			
Substream: STOTAL			
Total Flow	kg/hr	1000,000	1000,000
Enthalpy	cal/sec	-7,2021E+5	-7,0768E+5
*** ALL PHASES ***			
Mass Flow	kg/hr		
KNO3		400,0000	400,0000
H2O		600,0000	600,0000
Total Flow	l/min	16,52234	17,99447
MASSV FRA		0,0	0,0
MASS S FRA		,3000000	,2221808
Density	kg/cum	1008,735	926,2107
Temperature	K	353,1500	293,1500
Pressure	atm	1,000000	1,000000
Substream: CISO LID			
Mole Flow	kmol/hr		
KNO3		2,967264	2,197563
H2O		0,0	0,0
Mass Flow	kg/hr		
KNO3		300,0000	222,1808
H2O		0,0	0,0
Total Flow	kmol/hr	2,967264	2,197563
Total Flow	kg/hr	300,0000	222,1808
Total Flow	l/min	2,375789	1,759516
Temperature	K	353,1500	293,1500
Pressure	atm	1,000000	1,000000
Vapor Frac		0,0	0,0
Liquid Frac		0,0	0,0
Solid Frac		1,000000	1,000000
Enthalpy	cal/mol	-1,1683E+5	-1,1826E+5
Enthalpy	cal/gm	-1155,557	-1169,646
Enthalpy	cal/sec	-96296,44	-72186,90
Entropy	cal/mol-K	-76,02130	-80,43385
Entropy	cal/gm-K	-,7519176	-,7955616
Density	mol/cc	,0208159	,0208159
Density	gm/cc	2,104564	2,104564
Average MW		101,1032	101,1032
Liq Vol 60F			

## (vi) Results for Simulation of Crushing and Screening

Heat and Material Balance Table						
Stream ID		COARSE	FEED	FINE	TOCRUSH	TOSCREEN
From		SCREEN		SCREEN	HOPPER	CRUSHER
To		HOPPER	HOPPER		CRUSHER	SCREEN
Phase		MISSING	LIQUID	LIQUID	LIQUID	LIQUID
Substream: MIXED						
Mole Flow	kmol/hr					
CaCO <sub>3</sub>		0,0	0,0	0,0	0,0	0,0
H <sub>2</sub> O		0,0	111,0169	111,0169	111,0169	111,0169
Total Flow	kmol/hr	0,0	111,0169	111,0169	111,0169	111,0169
Total Flow	kg/hr	0,0	2000,000	2000,000	2000,000	2000,000
Total Flow	l/min	0,0	33,53599	33,53599	33,53599	33,53599
Temperature	K		298,1500	298,1500	298,1500	298,1500
Pressure	atm		1,000000	1,000000	1,000000	1,000000
Vapor Frac			0,0	0,0	0,0	0,0
Liquid Frac			1,000000	1,000000	1,000000	1,000000
Solid Frac			0,0	0,0	0,0	0,0
Enthalpy	cal/mol		-68234,18	-68234,18	-68234,18	-68234,18
Enthalpy	cal/gm		-3787,573	-3787,573	-3787,573	-3787,573
Enthalpy	cal/sec		-2,1042E+6	-2,1042E+6	-2,1042E+6	-2,1042E+6
Entropy	cal/mol-K		-38,85679	-38,85679	-38,85679	-38,85679
Entropy	cal/gm-K		-2,156879	-2,156879	-2,156879	-2,156879
Density	mol/cc		,0551730	,0551730	,0551730	,0551730
Density	gm/cc		,9939570	,9939570	,9939570	,9939570
Average MW			18,01528	18,01528	18,01528	18,01528
Liq Vol 60F	l/min	0,0	33,39757	33,39757	33,39757	33,39757
Substream: STOTAL						
Total Flow	kg/hr	2122,646	5000,000	4999,962	7122,646	7122,646
Enthalpy	cal/sec	-1,6988E+6	-4,5052E+6	-4,5052E+6	-6,2041E+6	-6,2041E+6
Substream: CIPSD						
Mole Flow	kmol/hr					
CaCO <sub>3</sub>		21,20797	29,97386	29,97348	51,18183	51,18183
H <sub>2</sub> O		0,0	0,0	0,0	0,0	0,0
Total Flow	kmol/hr	21,20797	29,97386	29,97348	51,18183	51,18183
Total Flow	kg/hr	2122,646	3000,000	2999,962	5122,646	5122,646
Total Flow	l/min	13,03650	18,42488	18,42464	31,46137	31,46137
Temperature	K	298,1500	298,1500	298,1500	298,1500	298,1500
Pressure	atm	1,000000	1,000000	1,000000	1,000000	1,000000
Vapor Frac		0,0	0,0	0,0	0,0	0,0
Liquid Frac		0,0	0,0	0,0	0,0	0,0
Solid Frac		1,000000	1,000000	1,000000	1,000000	1,000000
Enthalpy	cal/mol	-2,8838E+5	-2,8838E+5	-2,8838E+5	-2,8838E+5	-2,8838E+5
Enthalpy	cal/gm	-2881,241	-2881,241	-2881,241	-2881,241	-2881,241
Enthalpy	cal/sec	-1,6988E+6	-2,4010E+6	-2,4010E+6	-4,0999E+6	-4,0999E+6
Entropy	cal/mol-K	-62,90824	-62,90824	-62,90824	-62,90824	-62,90824
Entropy	cal/gm-K	-62,85343	-62,85343	-62,85343	-62,85343	-62,85343
Density	mol/cc	,0271135	,0271135	,0271135	,0271135	,0271135
Density	gm/cc	2,713723	2,713723	2,713723	2,713723	2,713723
Average MW		100,0872	100,0872	100,0872	100,0872	100,0872
Liq Vol 60F						
PSD						
1		,0193710	,2000000	1,000000	,1251537	,5936542
2		,3699937	,1000000	0,0	,2118746	,1533153
3		,2229437	,1000000	0,0	,1509430	,0923817
4		,1430072	,1000000	0,0	,1178206	,0592582
5		,0951121	,1000000	0,0	,0979749	,0394118
6		,0644014	,1000000	0,0	,0852496	,0266861
7		,0425394	,1000000	0,0	,0761908	,0176271
8		,0269279	,1000000	0,0	,0697219	,0111582
9		,0157034	,1000000	0,0	,0650707	6,50708E-3
10		0,0	0,0	0,0	0,0	0,0

## (vii) Results for Simulation of Crushing and filtration

Heat and Material Balance Table					
Stream ID		FEED	FILTRATE	PRODUCT	TOFILTER
From			FILTER	FILTER	CRUSHER
To		CRUSHER			FILTER
Phase		LIQUID	LIQUID	LIQUID	LIQUID
Substream: MIXED					
Mole Flow	kmol/hr				
CACO3		0.0	0.0	0.0	0.0
H2O		.4535924	3.628739	.9071847	.4535924
Mass Flow	kg/hr				
CACO3		0.0	0.0	0.0	0.0
H2O		.9071847	.4535924	2.267962	.9071847
Total Flow	kmol/hr	.4535924	3.628739	.9071847	.4535924
Total Flow	kg/hr	.9071847	.4535924	2.267962	.9071847
Total Flow	l/min	1.415842	.9438949	3.775579	1.415842
Temperature	K	259.2611	259.2611	259.2611	259.2611
Pressure	atm	.0680459	.4763218	.4763218	.0680459
Vapor Frac		0.0	0.0	0.0	0.0
Liquid Frac		1.000000	1.000000	1.000000	1.000000
Solid Frac		0.0	0.0	0.0	0.0
Enthalpy	cal/mol	-.5555556	-.5555556	-.5555556	-.5555556
Enthalpy	cal/gm	-3.333333	-3.333333	-3.333333	-3.333333
Enthalpy	cal/sec	-.0699988	-.0699988	-.2099965	-.0699988
Entropy	cal/mol-K	-3.000000	-3.000000	-3.000000	-3.000000
Entropy	cal/gm-K	-2.000000	-2.000000	-2.000000	-2.000000
Density	mol/cc	.0480553	.0480553	.0480553	.0480553
Density	gm/cc	.0961107	.0961107	.0961107	.0961107
Average MW		1.000000	1.000000	1.000000	1.000000
Liq Vol 60F	l/min	1.415842	.9438949	3.775579	1.415842
Substream: \$TOTAL					
Total Flow	kg/hr	.4535924	.4535924	.4535924	.4535924
Enthalpy	cal/sec	-.4199929	-.0699988	-.3499941	-.4199929
*** ALL PHASES***					
Mass Flow	kg/hr				
CACO3		.4535924	0.0	.4535924	.4535924
H2O		.9071847	.4535924	2.267962	.9071847
Total Flow	l/min	4.247527	.9438949	2.831685	4.247527
MASSVFR		0.0	0.0	0.0	0.0
MASSFRA		8.000000	0.0	9.000000	8.000000
Density	gm/cc	.0160184	.0961107	.0160184	.0160184
Temperature	K	259.2611	259.2611	259.2611	259.2611
Pressure	atm	.0680459	.4763218	.4763218	.0680459
Substream: CIPSD					
Mole Flow	kmol/hr				
CACO3		4.082331	0.0	4.082331	4.082331
H2O		0.0	0.0	0.0	0.0
Mass Flow	kg/hr				
CACO3		.4535924	0.0	.4535924	.4535924
H2O		0.0	0.0	0.0	0.0
Total Flow	kmol/hr	4.082331	0.0	4.082331	4.082331
Total Flow	kg/hr	.4535924	0.0	.4535924	.4535924
Total Flow	l/min	2.359737	0.0	2.359737	2.359737
Temperature	K	259.2611		259.2611	259.2611
Pressure	atm	.0680459	.4763218	.4763218	.0680459
Vapor Frac		0.0		0.0	0.0
Liquid Frac		0.0		0.0	0.0
Solid Frac		1.000000		1.000000	1.000000
Enthalpy	cal/mol	-2.777778		-2.777778	-2.777778
Enthalpy	cal/gm	-2.777778		-2.777778	-2.777778
Enthalpy	cal/sec	-.3499941		-.3499941	-.3499941
Entropy	cal/mol-K	-6.000000		-6.000000	-6.000000
Entropy	cal/gm-K	-6.000000		-6.000000	-6.000000
Density	mol/cc	.0160184		.0160184	.0160184
Density	gm/cc	.0160184		.0160184	.0160184
Average MW		1.000000		1.000000	1.000000
Liq Vol 60F					
PSD					
1		2.000000		2.000000	2.000000
2		1.000000		1.000000	1.000000
3		1.000000		1.000000	1.000000
4		1.000000		1.000000	1.000000
5		1.000000		1.000000	1.000000
6		1.000000		1.000000	1.000000
7		1.000000		9.000000	9.000000
8		1.000000		9.000000	9.000000
9		1.000000		9.000000	9.000000
10		0.0		0.0	0.0



## (viii) Results for Simulation of Filtration and Crystallization

Heat and Material Balance Table					
Stream ID		FEED	FILTRATE	PRODUCT	TOFILTER
From			FILTER	FILTER	CRYSTAL
To		CRYSTAL			FILTER
Phase		LIQUID	LIQUID	LIQUID	LIQUID
Substream: MIXED					
Mole Flow	kmol/hr				
KNO <sub>3</sub>		,9890880	2,124133	,0252863	2,149419
H <sub>2</sub> O		33,30506	32,91325	,3918097	33,30506
Total Flow	kmol/hr	34,29415	35,03738	,4170961	35,45448
Total Flow	kg/hr	700,0000	807,6981	9,615093	817,3132
Total Flow	l/min	13,92493	17,46616	,2079227	17,67408
Temperature	K	333,1500	298,1500	298,1500	298,1500
Pressure	atm	1,000000	1,000000	1,000000	2,000000
Vapor Frac		0,0	0,0	0,0	0,0
Liquid Frac		1,000000	1,000000	1,000000	1,000000
Solid Frac		0,0	0,0	0,0	0,0
Enthalpy	cal/mol	-65860,11	-64519,73	-64519,73	-64519,73
Enthalpy	cal/gm	-3226,595	-2798,821	-2798,821	-2798,821
Enthalpy	cal/sec	-6,2739E+5	-6,2795E+5	-7475,257	-6,3542E+5
Entropy	cal/mol-K	-25,77139	-15,60897	-15,60897	-15,60897
Entropy	cal/gm-K	-1,262583	-,6771065	-,6771065	-,6771065
Density	mol/cc	,0410464	,0334335	,0334335	,0334335
Density	gm/cc	,8378256	,7707267	,7707267	,7707267
Average MW		20,41165	23,05247	23,05247	23,05247
Liq Vol 60F					
Substream: \$TOTAL					
Total Flow	kg/hr	1000,000	807,6981	192,3019	1000,000
Enthalpy	cal/sec	-7,2409E+5	-6,2795E+5	-66772,71	-6,9472E+5
Substream: CISOLID					
Mole Flow	kmol/hr				
KNO <sub>3</sub>		2,967264	0,0	1,806933	1,806933
H <sub>2</sub> O		0,0	0,0	0,0	0,0
Total Flow	kmol/hr	2,967264	0,0	1,806933	1,806933
Total Flow	kg/hr	300,0000	0,0	182,6868	182,6868
Total Flow	l/min	2,375789	0,0	1,446751	1,446751
Temperature	K	333,1500		298,1500	298,1500
Pressure	atm	1,000000	1,000000	1,000000	2,000000
Vapor Frac		0,0		0,0	0,0
Liquid Frac		0,0		0,0	0,0
Solid Frac		1,000000		1,000000	1,000000
Enthalpy	cal/mol	-1,1732E+5		-1,1814E+5	-1,1814E+5
Enthalpy	cal/gm	-1160,365		-1168,507	-1168,507
Enthalpy	cal/sec	-96697,05		-59297,45	-59297,45
Entropy	cal/mol-K	-77,43794		-80,04772	-80,04772
Entropy	cal/gm-K	-,7659293		-,7917424	-,7917424
Density	mol/cc	,0208159		,0208159	,0208159
Density	gm/cc	2,104564		2,104564	2,104564
Average MW		101,1032		101,1032	101,1032
Liq Vol 60F					

## (ix) Results for Simulation of Crushing, screening and Filtration

Heat and Material Balance Table								
Stream ID		COARSE	FEED	FILTRATE	FINE	PRODUCT	TOCRUSHER	TOSCREEN
From		SCREEN		FILTER	SCREEN	FILTER	HOPPER	CRUSHER
To		HOPPER	HOPPER		FILTER		CRUSHER	SCREEN
Phase		MISSING	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID	LIQUID
Substream: MIXED								
Mole Flow	kmol/hr							
CACO3		0,0	0,0	0,0	0,0	0,0	0,0	0,0
H2O		0,0	83,26265	64,75982	83,26265	18,50283	83,26265	83,26265
Total Flow	kmol/hr	0,0	83,26265	64,75982	83,26265	18,50283	83,26265	83,26265
Total Flow	kg/hr	0,0	1500,000	1166,666	1500,000	333,3337	1500,000	1500,000
Total Flow	l/min	0,0	25,15199	19,56266	25,15199	5,589338	25,15199	25,15199
Temperature	K		298,1500	298,1500	298,1500	298,1500	298,1500	298,1500
Pressure	atm		1,000000	,4000000	1,000000	,4000000	1,000000	1,000000
Vapor Frac			0,0	0,0	0,0	0,0	0,0	0,0
Liquid Frac			1,000000	1,000000	1,000000	1,000000	1,000000	1,000000
Solid Frac			0,0	0,0	0,0	0,0	0,0	0,0
Enthalpy	cal/mol		-68234,18	-68234,18	-68234,18	-68234,18	-68234,18	-68234,18
Enthalpy	cal/gm		-3787,573	-3787,573	-3787,573	-3787,573	-3787,573	-3787,573
Enthalpy	cal/sec		-1,5782E+6	-1,2275E+6	-1,5782E+6	-3,5070E+5	-1,5782E+6	-1,5782E+6
Entropy	cal/mol-K		-38,85679	-38,85679	-38,85679	-38,85679	-38,85679	-38,85679
Entropy	cal/gm-K		-2,156879	-2,156879	-2,156879	-2,156879	-2,156879	-2,156879
Density	mol/cc		,0551730	,0551730	,0551730	,0551730	,0551730	,0551730
Density	gm/cc		,9939570	,9939570	,9939570	,9939570	,9939570	,9939570
Average MW			18,01528	18,01528	18,01528	18,01528	18,01528	18,01528
Liq Vol 60F	l/min	0,0	25,04818	19,48191	25,04818	5,566268	25,04818	25,04818
Substream: STOTAL								
Total Flow	kg/hr	600,0494	4500,000	1166,666	4500,003	3333,337	5100,049	5100,049
Enthalpy	cal/sec	-4,8025E+5	-3,9792E+6	-1,2275E+6	-3,9792E+6	-2,7517E+6	-4,4594E+6	-4,4594E+6
Substream: CIPSD								
Mole Flow	kmol/hr							
CACO3		5,995266	29,97386	0,0	29,97389	29,97389	35,96913	35,96913
H2O		0,0	0,0	0,0	0,0	0,0	0,0	0,0
Total Flow	kmol/hr	5,995266	29,97386	0,0	29,97389	29,97389	35,96913	35,96913
Total Flow	kg/hr	600,0494	3000,000	0,0	3000,003	3000,003	3600,049	3600,049
Total Flow	l/min	3,685279	18,42488	0,0	18,42489	18,42489	22,11015	22,11015
Temperature	K	298,1500	298,1500		298,1500	298,1500	298,1500	298,1500
Pressure	atm	1,000000	1,000000	,4000000	1,000000	,4000000	1,000000	1,000000
Vapor Frac		0,0	0,0	0,0	0,0	0,0	0,0	0,0
Liquid Frac		0,0	0,0	0,0	0,0	0,0	0,0	0,0
Solid Frac		1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000
Enthalpy	cal/mol	-2,8838E+5	-2,8838E+5	-2,8838E+5	-2,8838E+5	-2,8838E+5	-2,8838E+5	-2,8838E+5
Enthalpy	cal/gm	-2881,241	-2881,241	-2881,241	-2881,241	-2881,241	-2881,241	-2881,241
Enthalpy	cal/sec	-4,8025E+5	-2,4010E+6	-2,4010E+6	-2,4010E+6	-2,8813E+6	-2,8813E+6	-2,8813E+6
Entropy	cal/mol-K	-62,90824	-62,90824	-62,90824	-62,90824	-62,90824	-62,90824	-62,90824
Entropy	cal/gm-K	-,6285343	-,6285343	-,6285343	-,6285343	-,6285343	-,6285343	-,6285343
Density	mol/cc	,0271135	,0271135	,0271135	,0271135	,0271135	,0271135	,0271135
Density	gm/cc	2,713723	2,713723	2,713723	2,713723	2,713723	2,713723	2,713723
Average MW		100,0872	100,0872	100,0872	100,0872	100,0872	100,0872	100,0872
Liq Vol 60F								
PSD								
1		,0266229	,2000000		,5150521	,5150521	,1711018	,4336421
2		,0102316	,1000000		,1214154	,1214154	,0850375	,1028836
3		,0113067	,1000000		,0819658	,0819658	,0852167	,0701885
4		,0282783	,1000000		,1243896	,1243896	,0880455	,1083700
5		,1260014	,1000000		,1483111	,1483111	,1043337	,1445926
6		,4190310	,1000000		8,86603E-3	8,86603E-3	,1531754	,0772311
7		,1903211	,1000000		0,0	0,0	,1150547	,0317221
8		,1326556	,1000000		0,0	0,0	,1054431	,0221106
9		,0555513	,1000000		0,0	0,0	,0925914	9,25914E-3
10		0,0	0,0		0,0	0,0	0,0	0,0