DESIGN AND SIMULATION OF SOLVAY PROCESS WITH EMPHASIS ON REDUCTION OF BICARBONATE MOISTURE AT WASH FILTERS

By

Muhammad Saad Bin Akbar

Mahad Hussain

Muhammad Areeb Rashid

Muhammad Bilal

School of Chemical and Materials Engineering

National University of Sciences and Technology

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By

Leader - Reg No. 339176 - Muhammad Saad Bin Akbar

Member 1 – Reg No. 349951 - Mahad Hussain

Member 2 – Reg No. 334738 - Muhammad Areeb Rashid

Member 3 – Reg No. 340027 - Muhammad Bilal

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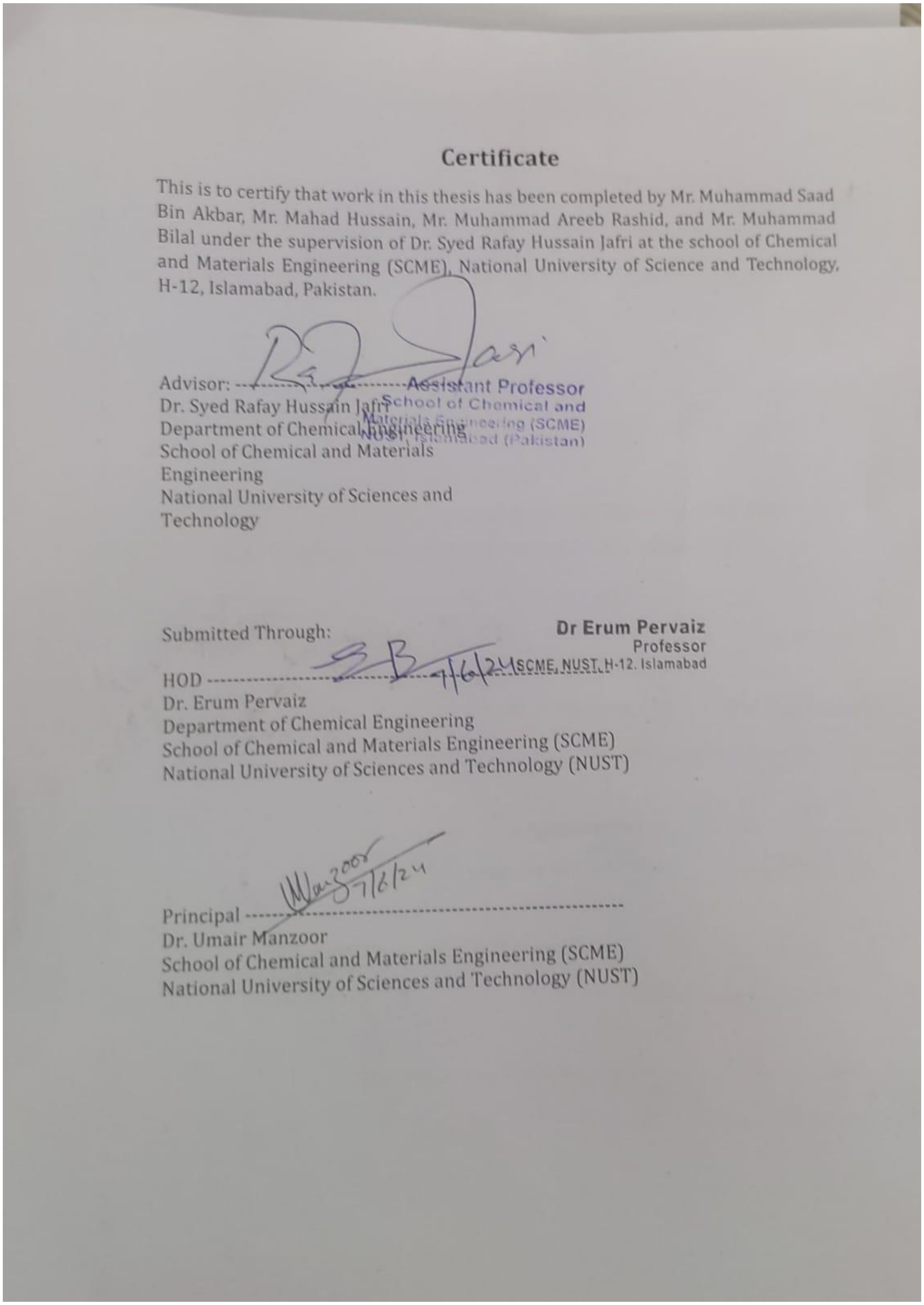

Certificate

This is to certify that work in this thesis has been completed by Mr. Muhammad Saad Bin Akbar, Mr. Mahad Hussain, Mr. Muhammad Areeb Rashid, and Mr. Muhammad Bilal under the supervision of Dr. Syed Rafay Hussain Jafri at the school of Chemical and Materials Engineering (SCME), National University of Science and Technology, H-12, Islamabad, Pakistan.

Advisor: ------------------------------

Dr. Syed Rafay Hussain Jafri
Department of Chemical Engineering
School of Chemical and Materials
Engineering
National University of Sciences and
Technology

Assistant Professor
School of Chemical and
Materials Engineering (SCME)
NUST, Islamabad (Pakistan)

Submitted Through:

HOD ------------------------------ SB 7/6/24

Dr. Erum Pervaiz
Department of Chemical Engineering
School of Chemical and Materials Engineering (SCME)
National University of Sciences and Technology (NUST)

Dr Erum Pervaiz
Professor
SCME, NUST, H-12, Islamabad

Manzoor 7/6/24

Principal ------------------------------

Dr. Umair Manzoor
School of Chemical and Materials Engineering (SCME)
National University of Sciences and Technology (NUST)

DEDICATION

This Work is dedicated to our Parents, Teachers and Friends who always had our back when we needed them the most.

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Authors

Muhammad Saad Bin Akbar

Mahad Hussain

Muhammad Areeb Rashid

Muhammad Bilal

ABSTRACT

The Solvay process is the common industrial process is the common industrial process used for production of Sodium carbonate (Na_2CO_3), also known as soda ash From Sodium Chloride (NaCl) and Calcium Carbonate ($CaCO_3$) as a raw material. The main objective of this project is the designing of Solvay Process and addressing the challenges of reducing bicarbonate moisture at wash filter. By using simulation and analysis, innovative strategies will be expected to increase the washing efficiency.

The approach that we entailed was a thorough examination of the existing process flow to pinpoint the crucial areas where moisture reduction can be applied most successfully. Aspen Plus, a top process simulation program, was used to run a number of simulations in order to model various situations and improve the parameters for moisture reduction. To find the best answers, the simulations used a variety of drying approaches, including the use of sophisticated filter designs and a rotary drum drier. The outcomes showed a notable decrease in moisture content at the wash filters, resulting in the best possible balance between energy consumption and process efficiency. The improved method lowers the overall cost of manufacturing by improving the quality of the sodium bicarbonate generated and requiring less energy for later drying steps. We also recycled the excess CO_2 to reduce the overall cost and to reduce the caron footprint by adding a 2-phase separator.

Overall, we designed the Solvay process with focus on moisture reduction at the wash filters which presented a viable pathway to enhancing the sustainability and economic competitiveness of sodium carbonate production. Using process simulations, optimum conditions and cutting-edge drying technologies which helped to increase the efficiency up to 90 % guarantees a more economical use of resources, which is in line with the objectives of industrial sustainability and gives businesses a competitive advantage. The environmental impact of the Solvay process was also brought into consideration with most of the CO_2 recovered and recycled back to the system.

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CHAPTER 01

INTRODUCTION TO SOLVAY PROCESS

The Solvay process or ammonia-soda process is one well-developed industrial method used for production of Sodium Carbonate (Na_2CO_3) which is also known as soda ash. To understand this project, we need to study the Solvay Process in detail and how it is used to improve the bicarbonate moisture at wash filters.

1.1 What is Solvay Process?

The Solvay Process is the common industrial process used for production of Sodium Carbonate (Na_2CO_3), also known as soda ash, from Sodium Chloride (NaCl) and Calcium Carbonate ($CaCO_3$) as a raw material. This process is also known as the ammonia soda process. The Solvay Process is receiving so much importance in industry because it is very cost-effective process and moreover it also reduces the carbon footprints in the society.

1.2 History of Solvay Process

The Solvay process, developed by Belgian chemist Ernest Solvay in the 1860s, revolutionized the production of sodium carbonate (soda ash), a crucial ingredient in glassmaking, paper production, and various chemical processes. Unlike the inefficient and polluting Leblanc process, the Solvay process utilizes a reaction between sodium chloride (salt) and limestone (calcium carbonate) facilitated by ammonia. The process involves saturating brine with ammonia, then carbonating it with carbon dioxide to form sodium bicarbonate, which precipitates out and is subsequently heated to yield sodium carbonate. The ammonia is recovered and recycled, enhancing the process's efficiency and sustainability. The first commercial Solvay plant was established in Couillet, Belgium, in 1865, demonstrating the method's industrial viability. The process quickly supplanted the Leblanc process, spreading throughout Europe and North America due to its cost-effectiveness and reduced environmental impact. Over time, technological advancements have further optimized the Solvay process, solidifying its status as the predominant method for producing soda ash worldwide.

1.3 Advantages of Solvay Process

1 Profusely used and widely examined technology.
2 Can use low-grade brine.
3 Less electric power.
4 Less corrosion problems.
5 Disposal of waste materials are easier and less detrimental to environment.
6 Does not require ammonia plant investment.
7 Does not produce any toxic or hazardous component.
8 Heat recovery is much efficient.

1.4 Importance of Moisture Reduction

The moisture reduction remains a crucial parameter demanded in numerous parts of industries, such as the Solvay process, mainly because of its invasive effect upon product quality, optimization of time, output, and environmental conservation. Therefore, it is of great importance that this moisture at the Solvay process main industry centered on sodium carbonate production be minimized.

The level of moisture has a significant impact on the quality as well as the purity of the product. In particular, the sodium bicarbonate is an intermediate product in the process; after its production, it is subjected to calcination to obtain sodium carbonate. High moisture content in sodium bicarbonate can also cause the energy to be used in other ways especially during calcination, where water evaporates. As a result, there is increased energy expenditure and a reduction in the purity degree of the sodium carbonate produced. High levels of moisture will also bring in impurities, contaminants and other unwanted entities in the final product hence causing it to be useless. Hence, there is a need to limit the moisture content as a means of obtaining a pure and sound sodium carbonate product.

In addition, the tool minimizes aspects of moisture reduction and offers significant influence in the improvement of efficiency such that operational costs are low. High moisture levels add to the challenge posed by process streams in terms of handling and processing since their viscosity is affected. In the Solvay process, high moisture content interferes with the efficiency of filtration and washing activities indicating slow process rate. Also, excessive moisture weakens structures, equipment, and increases the corrosion, fouling, and degradation levels hence, the need for frequent maintenance and dosed time. Hence, controlling moisture content in a process leads to increased efficiency, with less energy being used and minimum maintenance.

In the aspect of environmental sustainability, reducing moisture is environmentally friendly since it entails the use of fewer resources and the generation of minimal waste. As indicated by the graphical representation, the Solvay process like any other chemical processes require a large quantity of energy and immense amount of water. Moisture raises requirements to heat and take out energy from products, so increasing carbon emissions and environmental effects. This way, the use of energy decreases and the levels of greenhouse emission and the consumption of natural resources is minimized. Also, reducing the level of moisture in the final product also cuts down on wastage as well as optimizes the flow of subsequent production lines thus enhancing sustainability in the production process.

1.5 Optimization of Washing Parameters

The most important facet of the process of improving the efficiency and efficacy of washing procedures in the Solvay process is on the optimization of washing parameters, especially in the removal of moisture in sodium bicarbonate. The washing stage aims to remove the remaining impurities in the sodium bicarbonate crystals and to get the most appropriate moisture level for the subsequent stages involved in filtration and calcination of the product. This paper shows that temperature, flow rate, and washing duration are the critical parameters that must be monitored and adjusted scrupulously.

The part of temperature in washing process is crucial. As such, it is important to note that temperature has a very crucial role to play in the entire washing process. Higher temperatures can increase the rate at which impurities dissolve and then dissolve better than at room temperature which can be useful in washing the sodium bicarbonate crystals. But the temperature must be strictly maintained to avoid the dissolving of the sodium bicarbonate which equally leads to loss and lesser yield. Precise temperature control helps dissolve all impurities to the best extent possible, while at the same time, preserving the sodium bicarbonate crystalline structure.

The Flow rate is also another important factor that can be used in the washing process. A high enough flow rate of the washing liquid is capable of providing adequate turbulence to help in the removal of impurities from the surface of the sodium bicarbonate crystals; thus increasing the washing efficiency. If the flow rate is too high, the flow abrasive action takes place, which results to mechanical attrition and breakage of the crystals into fines and product losses. Thus, the issue of flow rate has to do with achieving the needed turbulence to facilitate the removal of impurities without at the same time compromising the integrity of the formed crystals.

The timing of washing is also important. Appropriate washing time is however required in order to get the best results in that some form of impurities are completely washed out and the required moisture content is attained. However, this poses a problem, whilst washing you can effectively reduce moisture on the skin but if you wash for a long time you only end up retaining more water than usual. Deciding on the amount of time that is required for washing the material can therefore be defined towards achieving the longest time that does not leave residue and at the same time reduces of moisture. This balance can be achieved through works on the experimentation and modeling of the processes as the nature of the raw materials and the conditions of the processes dictates the right washing time required.

1.6 Advance Filter Media

The main application of advanced filter media exists in the fact that it works the most efficiently to ensure that solid sodium bicarbonate crystals are separated from the liquid phase, so that the elimination of moisture becomes feasible. These media are designed with specific pore sizes that allow water to pass through and at the same time hold the solids back. The pore size is arguably one of the most important physical characteristics because the material must allow small sodium bicarbonate crystals in it while at the same time allowing the water to pass through relatively fast. This fine-tuning of the pore size assists to enhance the filtration rate and at the same time to prevent clogging hence facilitating the dewatering process continually.

Another important feature of modern filter media technologies can be considered the creation of hydrophobic materials. Water stills work under this principle that most of the hydrophobic filter media which are applied to filter water shall reject water so that most of the moisture can easily be separated from the solid phase. These three materials are mostly coated or treated with hydrophobic substances so that they make them more water-repellent. The property is especially advantageous in vacuum filtration systems because the intent is to extract as much water as possible. The hydrophobic filter media assist in achieving a better phase separation between the liquid and solid phases resulting to low sodium bicarbonate crystal's moisture content.

The Mechanical strength and durability are also some of the vital qualities that have to be embraced by the advanced filter media. Solvay process is but one of the many industrial processes where filter media is exposed to extremely high pressure as well as abrasive environments and the filter media must not deteriorate under such circumstances. A high-performance material like woven synthetic fibers or any other composite material provide the high strength and durability. These materials do not deteriorate easily, thus decreasing the coverage needed to replace the filters and corresponding maintenance time, which increases operational efficiency and decreases costs.

Conversely, the advanced filter media can be modeled with special consideration to the nature and needs of the process. For instance, in the case of filter media, the latter may be produced with a multilayer structure, in which each layer is characterized by properties that are most suitable for filtering throughout the different stages. It can also improve the effectiveness of the filtration by offering gradient filtration, which gathers large particles on the outer substratum, and fine particles on the inner one. They enhance the total strategy of control and throughput of the filter.

1.7 Automated Process Control

This can easily be explained on the basis of the fact that one of the main benefits of automated process control is that it offers feedbacks in real time. The features such as temperature, pressure, flow rate of the process, and moisture content may be monitored using sensors well secured at appropriate positions within the process. For example, moisture probes can also monitor periodically the water content within the sodium bicarbonate slurry and within the final product so that there is an instant result on the efficiency of the dewatering process. This real-time monitoring makes it easier for the system to note any variation from the set ideal parameters so that early correction can be done.

The Complex control algorithms are also employed in automated process control in this case. These are capable of making calculations on the data obtained from the sensors and make fine-tuning of process variables. For example, if the moisture content in the sodium bicarbonate is indicated to be higher than the required level, the control system can then change the dosage of the washing liquid, the rate of the centrifuge or the vacuum pressure in the filtration unit. Such dynamic capacity makes it possible to bring back the process to the region that best operates by reducing moisture content and increasing efficiency.

It also increases consistency and reliability concerning the work performed in the process control. Manual activity control techniques are sometimes precise due to the planner's capacity, which may result in variation in production of goods /services and performance. Automated systems, in contrast, run with a great deal of accuracy and count on; the occurrence of mistakes is minimized, and the process conditions are kept at their superior level. This is important in order to produce good quality sodium carbonate with less moisture and minimal number of impurities.

The Automatic control systems are also used for energy and cost savings. These systems help in keeping the process conditions at their best which always helps in minimizing the energy demands. For instance, the company's accurate control of moisture in sodium bicarbonate as a raw material necessitates minimum energy consumption in drying and calcinations stages thus lowering operational costs and positively impacting the environment. In addition, the better control in the process also contributes to the extension of life duration and lower maintenance frequency of the devices, which in return brings again the reduction of cost.

1.8 Simulation of Solvay Process

The Computational modeling of the Solvay process is a valuable instrument for improving the evaluation and the further development of this intricate technology of sodium carbonate manufacturing. With help of modern software tools: Aspen plus, HYSYS or ChemCAD, engineers are capable of describing the complex chain of chemical transformations, heat and mass exchange, which realized in Solvay process. These simulations give a representation of the whole process and it is very helpful in analyzing and optimizing such process taking into consideration that it is done in a virtual environment and not physically.

That is exactly why, while simulating the Solvay process, the researchers can study and evaluate the process in detail starting from the purification of the brine and ending with the ammoniation, carbonation, and calcination phases. Details of each raw material feed and its properties, kinetics of reaction, thermodynamics of phase equilibrium, and the details of the equipment used in a particular process is taken as the input and the simulation tools will be able to give how the process will perform in those conditions. This capability is especially useful for purposes of discovering the business areas that need improvement, or where the flow of processes is slowed. For instance, through simulations, the efficiency of the formation of sodium carbonate, the impact of the temperature, pressures and concentrations of the reagents can be observed and adjusted by engineers.

Another common area of interest regarding the simulation of the Solvay process is the wash filter step at which sodium bicarbonate is filtered as well as washed with a view of decreasing the relative humidity. This stage can be modeled by mimicking the inclined screw feeder's functionality and behavior of the sodium bicarbonate slurry that goes through the filtration and washing equipment. The washing parameters which can be changed by the software are the washing temperature, the flow rate and the duration; using the above method, the software can get the best combination of these parameters that reduces the amount of moisture content. The complication of this analysis means that one can determine the best operational parameters that give high-quality low moisture sodium bicarbonate, hence improving the downstream processing. There are also key indicators for assessing the efficiency of the mechanical dewatering technologies including the centrifuging and vacuum filtration. This way, in turn, allows the engineers to forecast the performance of each of these methods through the analysis of dewatering and determine what range of parameters is best suitable for application of every method. For instance, they can identify the proper RPM for some centrifuges or the appropriate vacuum pressure for the filtration units sufficient to meet the required dew point while maintaining the highly valued integrity of sodium bicarbonate crystals.

Moreover, the simulation of the Solvay process also applies to developing and evaluating modern filter media. Thus, by assigning certain properties of various kinds of filter media to the simulation model, the actual performance of the filter under certain process conditions will be observed by the engineers. The said capability will enable the choice of the most suitable filter media by determining the best permeability level, strength, and moisture reduction capacity, all of which go a long way towards enhancing the general efficiency of the process.

In addition to process optimization, simulations are beneficial in such areas as the increase of productivity from the laboratory or a pilot plant to large-scale industrial production. Basically, simulations assist in determining behavior of the process at larger scales and these results assist in designing and constructing economic and reliable industrial plants. It also assists in installation of the automated process control systems by defining the location of control points as well as the appropriate setting of the sensors and other controllers.

1.9 Specification of Raw Materials

Table 1: Specification of Raw Materials

Raw Material	**Chemical Composition**	**Purity (%)**	**Source**
Sodium Chloride	NaCl	99.5	Sea water, underground deposits
Calcium Carbonate	$CaCO_3$	98.0	Limestone, marble
Ammonia	NH_3	99.9	Ammonia synthesis plant
Carbon Dioxide	CO_2	99.8	By-product of fermentation, combustion processes
Water	H_2O	-	Municipal water supply
Lime	$Ca\ (OH)_2$	95.0	Lime kiln

1.10 Specification of Products

Table 2: Specification of Products

Product	**Chemical Composition**	**Purity (%)**	**Characteristics**
Sodium Carbonate	Na_2CO_3	99.2	White, odorless powder
Sodium Bicarbonate	$NaHCO_3$	99.0	White crystalline powder
Calcium Chloride	$CaCl_2$	94.0	White, deliquescent solid

CHAPTER 02

LITERATURE REVIEW

The Solvay process or ammonia-soda process is one well-developed industrial method of obtaining sodium carbonate which is commonly known as soda ash, chemically Na_2CO_3. This process involves several critical steps: To these are added such processes as purification of sodium chloride (brine), ammoniation of the purified brine, carbonation of the ammoniated brine, filtration of sodium bicarbonate, calcination that gives sodium carbonate, and recovery of ammonia. Every stage is significant in a process of various operations with concern to the effectiveness and the quality of the production. Special emphasize is made to minimize the moisture content of sodium bicarbonate at the wash filter stage to improve its performance and quality of the final product.

Every stage of the Solvay process is important, and the effectiveness of each stage will determine the amount of sodium carbonate produced and its quality. Of these steps, the process of filtration of sodium bicarbonate is critical, as it determines the amount of moisture in the intermediate product. High moisture content in sodium bicarbonate renders the next units a challenge to process especially during calcination when extra heat is used to dry the product. Thus, it can be concluded that for the enhancement of the efficiency and sustainability of the Solvay process, it is crucial to pay significant attention to the filtration and washing stages for the reduction of bicarbonate moisture.

2.1 Chemistry of Reactions Involve in Process

In this process, mainly five reactions are involved, the details of it are given below:

2.1.1 Decomposition of Limestone

The first Reaction of the Solvay Process is the decomposition of the Limestone into the carbon dioxide and the calcium oxide.

$$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$$

Basically, this reaction takes place at 900°C in some kind of kiln. This is the decomposition reaction in which the breakdown of Limestone occurs. As to much energy is given so it is the endothermic reaction.

2.1.2 Preparation of Milk of Lime

The second and most important reaction in Solvay Tower is preparation of milk of lime. In this reaction, the calcium oxide is mix with water to produce milk of lime i.e. calcium hydroxide.

$$CaO_{(s)} + H_2O_{(l)} \rightarrow Ca\,(OH)_{2(aq)}$$

This reaction occurs at room temperature in any vessel. Mainly some types of dissolver or big vertical tanks are used in industries to increase the reaction rate. It is an exothermic reaction.

2.1.3 Reaction of Carbon dioxide with Ammoniated Brine

The third most important reaction in Solvay process is reaction of carbon dioxide with ammoniated brine. In this reaction the ammoniated brine consists of common salt, ammonia and water resulting in sodium bicarbonate and ammonium chloride.

$$NH_{3(g)} + NaCl_{(aq)} + H_2O_{(l)} + CO_{2(g)} \rightarrow NH_4Cl_{(aq)} + NaHCO_{3(s)}$$

This reaction is usually take place at the temperature very near to the room temperature like at 40-50°C range temperature. This reaction occurs in Solvay Tower also known as the carbonator. . It is also an exothermic reaction.

2.1.4 Reaction of Milk of Lime and Ammonium Chloride

This is the fourth reaction of the Solvay Tower. In this reaction Milk of Lime and Ammonium Chloride is reacted together to produce calcium chloride, ammonia and water.

$$Ca(OH)_{2(s)} + 2NH_4Cl_{(aq)} \rightarrow CaCl_{2(aq)} + 2NH_{3(g)} + 2H_2O_{(l)}$$

This reaction is usually take in temperature range of 80-100°C.. This reaction occurs in Ammonia Recovery Tower. It is also an endothermic reaction.

2.1.5 Breakdown of Sodium Bicarbonate into Sodium carbonate.

The last Reaction of the Solvay Process is the decomposition of the Sodium Bicarbonate into the Sodium carbonate.

$$2NaHCO_{3(s)} \rightarrow Na_2CO_{3(s)} + CO_{2(g)} + H_2O_{(g)}$$

Basically, this reaction takes place at 200°C in some kind of kiln. This is the decomposition reaction in which the breakdown of bicarbonate occurs. As to much energy is given so it is the endothermic reaction.

2.2 Process Design & Optimization

2.2.1 Early Process Design:

Originally, the basic plan of the Solvay process was quite simple, with focus on the core chemical reactions which enable the synthesis of sodium carbonate. However, as people transited to the industrial age, there was need to come up with better ways of doing it since time and costs of operation were of essence. In the past, research was focused on determining the quantitative aspects of the reactions, heat control, and the reactors and absorbers that would provide the highest levels of yield while producing the lowest amounts of undesired by-products.

2.2.2 Modern Process Optimization:

In this regard, it can be argued that contemporary process improvement has become more elaborate with the help of technology and chemical engineering. Contemporary with the advances in information technology, programs such as CAD and quantitative process simulation tools such as Aspen Plus, HYSYS, ChemCAD are deemed immanent to the discharge of Solvay process modeling and optimization. These tools enable the engineer to model the complex series of matters and heat exchanges, and sheer flow dynamic that characterizes the process.

An area like the administration of sodium bicarbonate slurry could be a significant aspect to be optimized. This way, temperature, flow rate, washing time and any other parameters regarding the slurry can be tired in a controlled environment and the conditions that yield the lowest amount of moisture in the final product can be found. This optimization is important for obtaining high quality sodium carbonate and decreasing specific consumption on the stages of drying and calcination.

2.3 Other Process for Production of Soda Ash

2.3.1 Monohydrate Process:

In this process, the trona ore is gradually crushed and then calcined in a rotary kiln at 160-200O°C. The calcined materials, which are mainly impure soda ash, is agitated in tanks with water or weak soda ash liquors to dissolve the soda ash and soluble impurities. Insoluble materials, including shale, clay, and complex salts e.g., calcium carbonate, are separated from the hot, near saturated soda ash solution. To reduce soda ash losses, waste solids from this step are washed before being discarded. The filtered liquor is usually treated with activated carbon to remove soluble organic compounds and reduce foaming during evaporation to produce crystals of sodium carbonate monohydrate. Crystallization is carried out in multiple effect evaporators at a maximum temperature of about 1000°C, which is below the transition temperature of monohydrate to anhydrous soda ash. The monohydrate crystals are dehydrated at about 1500C. Monohydrate process is simpler than Le Blanc process, however, the product purification is not desirable. Soluble Sodium Chloride and Sodium Sulfate which are parts of trona ore remain as impurities in the final Soda Ash product. This process is also energy deficient as multiple effect evaporators and crystallizers are used drastically.

2.3.2 Sodium Sesquicarbonate process:

In this process, the crushed trona ore is fed into a series of dissolver to produce saturated mother liquor. Then the mother liquor solution is clarified, filtered and freed from organic compounds by carbon treatment. The treated liquor is evaporated in a vacuum crystallizer and then cooled to 400C. The produced Sodium Sesquicarbonate crystals are then centrifuged and the mother liquor is recycled to the dissolvers. The sesquicarbonate crystals are decomposed to sodium carbonate in rotary calciner at approximately 2000°C.

This process is very much suitable for industrial application if the trona ore contain low amount of Sodium Chloride and Sodium Sulfate. Maintenance cost of the plant is higher because of the corrosive nature of mother liquor. Moreover, the density of the final soda ash products obtained from the rotary calcination process can be very low. In that case, double calcination is required which increases the operating cost and final production cost as well.

2.3.3 Dual process:

In this process, the mother liquor containing ammonium chloride, untreated salt and traces of carbonate is ammoniated in an ammonia absorber. The ammoniated mother liquor is passed through a bed of salt in a salt dissolver. Exit liquor from the dissolver, saturated with salt, is gradually cooled from 400C to 100C by evaporation under vacuum to separate ammonium chloride. The slurry containing ammonium chloride is then centrifuged and dried. The product thus obtained is 98% pure. The mother liquor obtained after the separation of ammonium chloride crystals is recycled to the carbonation vessels placed in series. Carbon dioxide obtained from ammonia plant and the calciner section of soda ash plant is injected in the carbonation vessels. There is provision of cooling coils in the lower carbonation vessels. The growth of sodium bicarbonate crystals are controlled by the supply of cooling water to cooling coils in carbonation vessels. These crystals containing mother liquor is then thickened in a thickener and centrifuged. Finally, sodium bicarbonate is calcined to soda ash. This process is very much suitable for industrial application only in the case where Ammonium Chloride is the main product and Sodium Carbonate is formed as co-product. In the context of Bangladesh, this process is not economically feasible because the demand of ammonium chloride is lesser than the demand of ammonia. Ammonium Chloride is mainly used as fertilizer but for the crops of our land this fertilizer is not effective. As ammonia is not regenerated in this case and is needed to be supplied continuously, this process requires a separate ammonia production plant which is the reason of high investment cost, production cost and maintenance cost.

2.4 Comparison of Solvay Process with Other Process

2.4.1 Advantages over Other Process

1 Profusely used and widely examined technology.
2 Can use low-grade brine 3. Less electric power.
3 Less corrosion problems.
4 Disposal of waste materials are easier and less detrimental to environment.
5 Does not require ammonia plant investment.
6 Does not produce any toxic or hazardous component.
7 The Heat recovery is much efficient.

2.4.2 Disadvantages as compared to Other Process

- Higher salt consumption.
- Higher investment in ammonia recovery unit.
- High Initial Investment.

CHAPTER 03

PROCESS DESCRIPTION

3.1 Introduction

The Solvay process is a method for producing sodium carbonate (soda ash) from sodium chloride (salt), limestone, and ammonia. It involves several steps, including the creation of sodium bicarbonate (baking soda) by reacting salt, limestone, and ammonia in water, followed by heating to produce soda ash and regenerate ammonia. The Ammonia (NH_3), Brine (Conc. NaCl solution with water), Limestone ($CaCO_3$) are the raw materials of the Solvay Process. The Overall reaction of it is given as:

$$CaCO_3 + 2NaCl \rightarrow CaCl_2 + Na_2CO_3$$

3.2 Equipment List

Following is the list of equipment's we have used while designing this Process:

- Rotary Kiln (Lime Kiln and Calcinator)
- Packed Columns (Absorber)
- Tray Column (Solvay Tower and Ammonia Recovery Tower)
- Centrifugal Pump (Pump)
- Centrifugal Compressor (Compressor 1 and Compressor 2)
- Heat Exchangers (Condenser 1 and Condenser 2)
- Vertical Tank (Lime Dissolver)
- Rotary Filter (Filter)
- Rotary Dryer
- Simple Vertical Column (2-phase Separator)
- Mixer

3.3 Process Explanation

The Solvay Process is completed in six steps and details of each step is given below:

3.3.1 Brine Purification and Addition of Ammonia

The Brine is mostly found in the ocean's salt water, and it may contain many impurities, such as Ca^{+2} and Mg^{+2} ions, which are undesirable in the Solvay process. The purification of brine was done by removing those impurities and concentrating the sodium chloride solution. The removal of those impurities can be done via two methods.

- The Precipitation of the Ca^{+2} and Mg^{+2} ions by reacting them with either sodium carbonate or sodium hydroxide.

$$Ca^{+2}{}_{(aq)} + Na_2CO_3 \rightarrow CaCO_{3\,(s)} + 2Na^{+1}$$

$$Mg^{+2}{}_{(aq)} + 2\,NaOH_{(aq)} \rightarrow Mg\,(OH)_{2\,(s)} + 2Na^{+1}$$

- The Fractional crystallization – where the more soluble contaminants are crystallized out from the brine solution.

The purified brine is then introduced in ammonia absorber. Here, the brine flows down with ammonia over many partitions of the said packed column. This Step is carried out in the Absorber at temperature of 25°C and 2 bars pressure. In this column the 0.5 pressure drop is observed.

3.3.2 Production of sodium hydrogen carbonate

The ammoniated brine will then be passed into the Solvay tower or commonly known as carbonator. The ammoniated brine, which consists of ammonia, water and sodium chloride, will react with carbon dioxide. The carbon dioxide came from the decomposition of calcium carbonate (limestone) at high temperature of 900°C. in lime kiln. This step of decomposition is separately occurred in the limestone kiln.

$$CaCO_{3\,(s)} \underset{HEAT}{\rightarrow} CaO_{(s)} + CO_{2\,(g)}$$

The carbon dioxide reacts with water to produce carbonic acid.

$$CO_{2\,(g)} + H_2O_{(l)} \leftrightarrow H_2CO_{3\,(aq)}$$

The Carbonic acid, which is a weak acid, will then neutralize the ammonia, which is a weak base. The neutralization reaction produces ammonium and hydrogen carbonate ions.

$$H_2CO_{3\,(aq)} + NH_{3\,(aq)} \leftrightarrow HCO_3^-{}_{(aq)} + NH_4^+{}_{(aq)}$$

These hydrogen carbonate ions will then react with sodium ions (from the NaCl) to produce sodium hydrogen carbonate ($NaHCO_3$).

$$HCO_3^-{}_{(aq)} + Na^+{}_{(aq)} \leftrightarrow NaHCO_{3\,(s)}$$

$$NH_4^{+1} + Cl^{-1} \rightarrow NH_4Cl$$

The overall reaction of Solvay Tower can be described as:

$$NH_{3\,(g)} + NaCl_{(aq)} + H_2O_{(l)} + CO_{2\,(g)} \rightarrow NH_4Cl_{(aq)} + NaHCO_{3\,(s)}$$

3.3.3 Filtration

The Precipitates of $NaHCO_3$ are separated from the milky solution by filtration.

3.3.4 Formation of sodium carbonate

The mixture of the solid $NaHCO_3$ and aqueous NH_4Cl will then be filtered to collect the desired solids. The collected $NaHCO_3$ will then be heated in a furnace to about 300ºC. This would result to the formation of sodium carbonate, water and carbon dioxide. The carbon dioxide is recycled back into the carbonator for the production of $NaHCO_3$. The Recycling CO_2 would reduce the cost.

$$2NaHCO_{3\,(s)} \underset{HEAT}{\rightarrow} Na_2CO_3 + CO_2 + H_2O$$

3.3.5 Preparation of the slaked lime

The calcium oxide (lime) from the decomposition of the $CaCO_3$ (Step 2) will be reacted with water to form calcium hydroxide (slaked lime). This is shown in the equation below:

$$CaO_{(s)} + H_2O_{(l)} \rightarrow Ca(OH)_{2\,(aq)}$$

3.3.6 Recovery of ammonia

The obtained calcium hydroxide will then be used to react with ammonium chloride. Ammonium chloride is present in the filtrate from the hydrogen carbonate formation process, which was also produced in step 2.

$$Ca\ (OH)_{2\,(s)} + 2\ NH_4Cl_{(aq)} \rightarrow CaCl_{2\,(aq)} + 2\ NH_{3\,(g)} + 2\ H_2O_{(l)}$$

The ammonia is very expensive to be manufactured, thus, the recovered one is being recycled. Lastly, $CaCl_2$ is also produced as a main by-product.

This Step is Done after Filtration when the filtration is done by using some filtration technique.

3.4 Process Flow Diagram

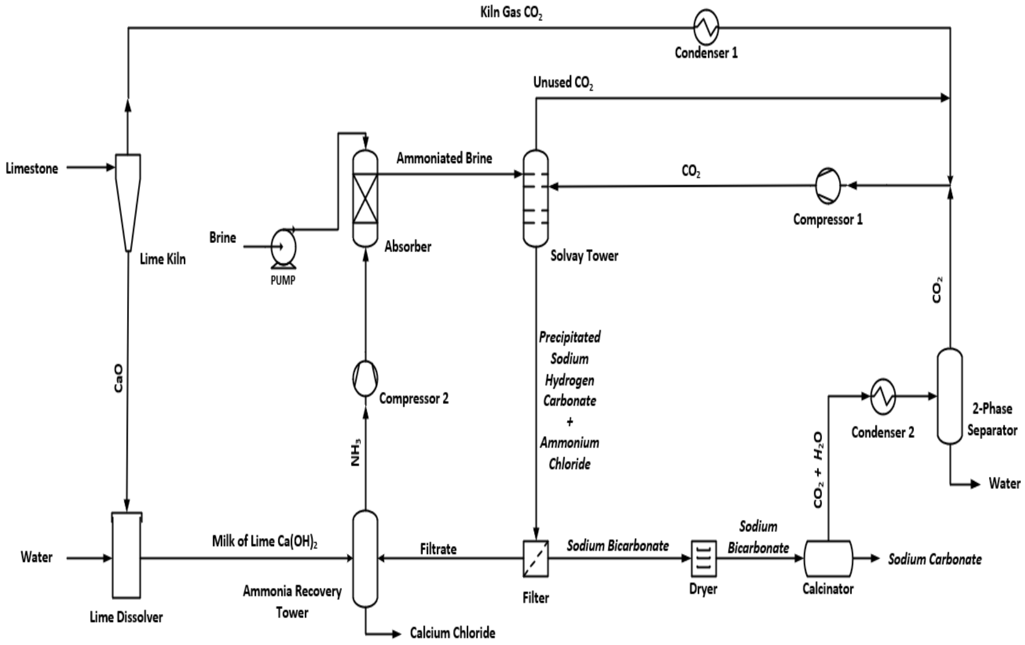


Figure 1: Process Flow Diagram

CHAPTER 04

MATERIAL BALANCE

The material balance was carried out by applying the law of conservation of mass to each of the important components present within the proposed design.

The Material balance is a quantitative description of the mass conservation of a system. The principle of mass balance states that the mass at the input to the system must equal the mass at the output plus the mass of accumulation in the system since mass cannot be created or destroyed. The Equation of Material balance is given as:

Input = Output + Accumulation ± Generation/Consumption

From law of conservation of mass, we get:

$$mass\ flow\ rate\ of\ component\ in = mass\ flow\ rate\ of component\ out$$

The material balance is provided in the mole flow because of the reactive system. It is very easy to deal with the mole system when there is a reactive system. That is why the calculation of this plant is given in the moles.

4.1 Significance of Material Balance

The Material balance is important because it provides a way to track the flow of materials in your system. This information can be used for:

- Identify waste sources.
- Optimize process efficiency.
- Ensuring product safety.

For example, chemical plants can use material balances to track the flow of raw materials, intermediate products, and finished products. This information can be used to identify sources of waste such as leaks and spills. It can also be used to optimize plant efficiency by ensuring that the right amount of each raw material is used to produce the required amount of product. Finally, it can be used to ensure product safety by ensuring that all relevant safety standards are met. Material balance is a powerful tool that can be used to improve the efficiency, safety, and environmental impact of any system.

4.2 Pump

This pump is of the centrifugal type and material balance of it is given below in the table 3.

Table 3: Material Balance on Pump

Pump		
Components	**In**	**Out**
	kmol/hr	kmol/hr
H2O	760	760
NaCl	240	240
Total	1000	1000

4.3 Absorber

This absorber is packed column with ceramic packing and material balance of it is given below in the table 4.

Table 4: Material Balance on Absorber

Absorber			
Components	**In**		**Out**
	From Pump	From Compressor 2	To Solvay Tower
	kmol/hr	kmol/hr	kmol/hr
H_2O	760	0	760
NaCl	240	0	240
NH_3	0	73.7	73.7
Total	1000	73.7	1073.7

4.4 Solvay Tower

The Solvay Tower is Tray type column with sieve types of trays. The reaction on its trays is:

$$NH_{3(g)} + NaCl_{(aq)} + H_2O_{(l)} + CO_{2(g)} \rightarrow NH_4Cl_{(aq)} + NaHCO_{3(s)}$$

The material balance of it is given below in the table 5:

Table 5: Material Balance of Solvay Tower

Solvay Tower				
Components	**In**		**Out**	
	From Absorber	From Compressor 1	To Filter	Unused CO_2
	kmol/hr	kmol/hr	kmol/hr	kmol/hr
H_2O	760	0	689.4	0
NaCl	240	0	162	0
NH_3	73.7	0	0	0
CO_2	0	100	0	26
$NaHCO_3$	0	0	74	0
NH_4Cl	0	0	74	0
Total	1073.7	100	999.9	26

4.5 Filter

This Filter is operating on the 90% efficiency w.r.t sodium bicarbonate. This is a Rotary Filter. The material balance of this filter is given below:

Table 6: Material Balance on Filter

Filter			
Components	**In**	**Out**	
	From Solvay Tower	To Dryer	To Ammonia R-Tower
	kmol/hr	kmol/hr	kmol/hr
H_2O	689.4	158.5	529.6
NaCl	162	0	162
NH_3	0	0	0
CO_2	0	0	0
$NaHCO_3$	74	66.6	7.4
NH_4Cl	74	0	74
Total	999.9	224.8	772.8

4.6 Dryer

This dryer operates at the efficiency of the 90% and it is the Rotary Dryer. The material balance of the dryer is given below in table 7:

Table 7: Material Balance on Dryer

Dryer			
Components	**In**	**Out**	
	From Filter	Evaporated Water	To Calcinator
	kmol/hr	kmol/hr	kmol/hr
$NaHCO_3$	66.6	0	66.6
H_2O	158.5	142	15.8
Total	224.8	142	82.4

4.7 Calcinator

The reaction occurs in the calcinator is:

$$2NaHCO_{3(s)} \rightarrow Na_2CO_{3(s)} + CO_{2(g)} + H_2O_{(g)}$$

The material balance of calcinator is given in table 8:

Table 8: Material Balance on Calcinator

Calcinator			
Components	**In**	**Out**	
	From Dryer	Final Product	To Condenser 2
	kmol/hr	kmol/hr	kmol/hr
$NaHCO_3$	66.6	0	0
H_2O	15.8	0	48.4
Na_2CO_3	0	33.3	33.3
CO_2	0	0	0
Total	82.4	33.3	81.7

4.8 2-Phase Separator

The two-phase separator is the simple vertical column used to separate the mixture of liquid and gas. The material balance of it is given below in the table 9:

Table 9: Material Balance on 2-Phase Separator

2-Phase Separator			
Components	**In**	**Out**	
	From Condenser 2	To Mixer	Water Stream
	kmol/hr	kmol/hr	kmol/hr
H_2O	48.4	0	48.4
CO_2	33.3	33.3	0
Total	81.7	33.3	48.4

4.9 Mixer

This mixer mixes the CO_2 streams from different equipment and make the one stream of all carbon dioxide streams. The materials balance of it is given below in table 10:

Table 10: Material Balance on Mixer

Mixer				
Components	**In**			**Out**
	From Separator	From Kiln	Unused from S. Tower	To Tower
	kmol/hr	kmol/hr	kmol/hr	kmol/hr
CO_2	33.3	39.1	26	100
Total	33.3	39.1	26	100

4.10 Lime Kiln

It is the rotary kiln in which the decomposition of limestone occurs. The reaction of it is given as:

$$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$$

The material balance of it is given below in table 11:

Table 11: Material Balance on Lime Kiln

Lime Kiln			
Components	**In**	**Out**	
	Lime Stream	To Dissolver	To Condenser 1
	kmol/hr	kmol/hr	kmol/hr
$CaCO_3$	39.1	0	0
CaO	0	39.1	0
CO_2	0	0	39.1
Total	39.1	39.1	39.1

4.11 Lime Dissolver

In Lime Dissolver the reaction occurs is:

$$CaO_{(s)} + H_2O_{(l)} \rightarrow Ca\,(OH)_{2(aq)}$$

The material balance of it is given below in table 12:

Table 12: Material Balance on Lime Dissolver

Lime Dissolver			
Components	**In**		**Out**
	From Lime Kiln	Water Stream	To Ammonia R-Tower
	kmol/hr	kmol/hr	kmol/hr
$Ca(OH)_2$	0	0	39.1
CaO	39.1	0	0
H_2O	0	1062.5	1023.4
Total	39.1	1062.5	1062.5

4.12 Ammonia Recovery Towers

This Tower has the accumulation of 2%. The reaction occurring in this tower is:

$$Ca\ (OH)_{2(s)} + 2NH_4Cl_{(aq)} \rightarrow CaCl_{2(aq)} + 2NH_{3(g)} + 2H_2O_{(l)}$$

The material balance of it is given as in table 13:

Table 13: Material Balance on Ammonia Recovery Tower

Ammonia Recovery Tower				
Components	**In**		**Out**	
	From Dissolver	From Filter	To Compressor 2	$CaCl_2$ Stream
	kmol/hr	kmol/hr	kmol/hr	kmol/hr
H_2O	1023.5	529.6	0	1610.1
NaCl	0	162	0	160.8
NH_3	0	0	73.7	0
CO_2	0	0	0	0
$NaHCO_3$	0	7.4	0	7.32
NH_4Cl	0	74	0	0
$Ca\ (OH)_2$	0	0	0	0
$CaCl_2$	39.1	0	0	36.93
Total	1062.5	772.8	73.7	1814.8

4.13 Condensers

The material balance on both condenser 1 and condenser 2 is shown in table 14 and table 15 respectively:

4.13.1 Condenser 1

Table 14: Material Balance on Condenser 1

Condenser 1		
Components	**In**	**Out**
	From Kiln	To Mixer
	kmol/hr	kmol/hr
CO_2	39.1	39.1
Total	39.1	39.1

4.13.2 Condenser 2

Table 15: Material Balance on Condenser 2

Condenser 2		
Components	**In**	**Out**
	From Calcinator	To Separator
	kmol/hr	kmol/hr
H_2O	48.4	48.4
CO_2	33.3	33.3
Total	81.7	81.7

4.14 Compressors

The material balance on both compressor 1 and compressor 2 is shown in table 16 and table 17 respectively:

4.14.1 Compressor 1

Table 16: Material Balance on Compressor 1

Compressor 1		
Components	**In**	**Out**
	From Mixer	To Solvay Tower
	kmol/hr	kmol/hr
CO_2	100	100
Total	100	100

4.14.2 Compressor 2

Table 17: Material Balance on Compressor 2

Compressor 2		
Components	**In**	**Out**
	From Ammonia R-Tower	To Absorber
	kmol/hr	kmol/hr
NH_3	73.7	73.7
Total	73.7	73.7

CHAPTER 05

ENERGY BALANCE

An energy balance is an instrument that tracks the progression of energy into, though, and out of a framework. With regards to industry, an energy equilibrium can be utilized to follow the progression of energy from the mark of energy creation to the place of energy utilization. This data can be utilized to distinguish regions where energy is being squandered, and to foster techniques for further developing energy proficiency.

5.1 Significance of energy balance in industry

There are a few justifications for why energy balance is significant in industry. To start with, energy is an important asset that ought to be utilized effectively. Second, energy productivity can prompt expense reserve funds for organizations. Third, energy proficiency can assist with diminishing ozone harming substance outflows and further develop air quality.

There are many advantages to further developing energy productivity in industry. Probably the most well-known benefits include:

- Cost investment funds.
- Expanded efficiency.
- Worked on natural execution.

5.2 General Equations Used

The General Equations used in the energy balance is:

1. $Q = mCp\Delta T$
2. $W = P\ \Delta V$
3. $H + K.E + P.E = Q + W$
4. $Q = m\ Lv$
5. $Q = \sum Hout - \sum Hin$

5.3 Pump

Table 18: Physical Parameter table for Pump

Pump		
Parameter	In	Out
Temperature (°C)	25°C	25°C
Pressure (bar)	1 bar	2 bars

$$V= 2164\ m^3/hr$$

$$W = V (P_2 - P_1)$$

$$W = 2192.6\ kJ/hr$$

$$W= 1644.45\ \text{(at 75\% efficiency)}$$

5.4 Absorber

Table 19: Enthalpy Table for Components in Absorber

Absorber			
Parameters	**In**		**Out**
	From Pump	From Compressor 2	To Solvay Tower
Temperature (°C)	25°C	85°C	70°C
Pressure (bar)	2 bars	2 bars	1.5 bar
Components	**kJ/hr**	**kJ/hr**	**kJ/hr**
NaCl	-407.3	0	-382.21
H_2O	-285.84	0	-285.8
NH_3	0	-42.758	-43.9

$$Q = 27766.83\ kJ/hr$$

5.5 Solvay Tower

The Solvay Tower is Tray type column with sieve types of trays. The reaction on its trays is:

$$NH_3(g) + NaCl(aq) + H_2O(l) + CO2(g) \rightarrow NH_4Cl(aq) + NaHCO_3(s)$$

Table 20: Enthalpy Table for Components in Solvay Tower

Solvay Tower				
Parameters	**In**		**Out**	
	From Absorber	From Compressor 1	To Filter	Unused CO_2
Temperature (°C)	70°C	70°C	60°C	60°C
Pressure (bar)	1.5 bar	1.5 bar	1 bar	1 bar
Components	**kJ/hr**	**kJ/hr**	**kJ/hr**	**kJ/hr**
H_2O	-285.8	0	-285.0	0
NaCl	-382.21	0	-380.2	0
NH_3	-43.9	0	0	0
CO_2	0	-392	0	-392
$NaHCO_3$	0	0	-946.91	0
NH_4Cl	0	0	-310.71	0

Q = 28739.004 kJ/hr

5.6 Dryer

Table 21: Enthalpy Table for Components in Dryer

Dryer			
Parameters	**In**	**Out**	
	From Filter	Evaporated Water	To Calcinator
Temperature (°C)	30	100	100
Pressure (bar)	1	1	1
Components	**kJ/hr**	**kJ/hr**	**kJ/hr**
H_2O	-285.5	-285.8	-285.8
$NaHCO_3$	-310.15	0	-315.1

$$Q = m\,(h_{in} - h_{out})$$

$$Q = 44.3\ kW\ (Duty)$$

5.7 Compressors

5.7.1 Compressor 1

Table 22: Physical Parameter table for Compressor 1

Compressor 1		
Parameters	**In**	**Out**
Temperature (°C)	70°C	70°C
Pressure (bar)	1 bar	1.5 bar

$$W = Cp\ T_1\ [(\frac{P_2}{P_1})^{\frac{R}{Cp}} - 1]$$

W = 40.7 kJ/hr (P_1 = 1 bar, P = 1.5 bars and Cp = 0.0457 kJ/mol. K)

5.7.2 Compressor 2

Table 23: Physical Parameter table for Compressor 2

Compressor 2		
Parameters	**In**	**Out**
Temperature (°C)	85°C	85°C
Pressure (bar)	1 bar	2 bars

$$W = C_p\, T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{R}{C_p}} - 1\right]$$

W = 123 kJ/hr (P1 = 1 bar, P = 2 bar, and Cp = 0.019 kJ/mol. K)

5.8 Calcinator

The reaction occurs in the calcinator is:

$$2NaHCO_3(s) \rightarrow Na_2CO_3(s) + CO_2(g) + H_2O(g)$$

Table 24: Enthalpy Table for Components in Calcinator

Calcinator			
Parameters	**In**	**Out**	
	From Dryer	Final Product	To Condenser 2
Temperature (°C)	100°C	200°C	200°C
Pressure (bar)	1 bar	1 bar	1 bar
Components	**kJ/hr**	**kJ/hr**	**kJ/hr**
$NaHCO_3$	-311.15	0	0
H_2O	-285.8	0	-289.8
Na_2CO_3	0	-1128.0	0
CO_2	0	0	-392.3

Q = -39399.735 kJ/hr

Q = -39399.735 kJ/hr+ Q_{fuel}

$$Q = -39399.735 \text{ kJ/hr} + m\,C_p\,(T_2 - T_1)$$

$$Q = -39399.735 \text{ kJ/hr} + 29.5\,(0.115)\,(200 - 30)$$

$$Q = -39399.735 \text{ kJ/hr} + 752.25 \text{ kJ/mol}$$

$$Q = -38647.48 \text{ kJ/hr}$$

5.9 Lime Kiln

It is the rotary kiln in which the decomposition of limestone occurs. The reaction of it is given as:

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$

Table 25: Enthalpy Table for Components in Lime Kiln

Lime Kiln			
Parameters	**In**	**Out**	
	Lime Stream	To Dissolver	To Condenser 1
Temperature (°C)	25°C	900°C	900°C
Pressure (bar)	1 bar	1 bar	1 bar
Components	**kJ/hr**	**kJ/hr**	**kJ/hr**
$CaCO_3$	-1206.9	0	0
CaO	0	-287.3	0
CO_2	0	0	-398.0

$$Q = 20629.16 \text{ kJ/hr}$$

$$Q = 20629.16 \text{KJ/hr} + Q_{fuel}$$

$$Q = 20629.16 \text{KJ/hr} + m\,C_p\,(T_2 - T_1)$$

$$Q = 20629.16 \text{ kJ/hr} + 29.5(0.115)\,(1173 - 303)$$

$$Q = 23580.6 \text{ kJ/hr}$$

5.10 Lime Dissolver

In Lime Dissolver the reaction occurs is:

$$CaO(s) + H_2O(l) \rightarrow Ca\ (OH)_2(aq)$$

Table 26: Enthalpy Table for Components in Lime Dissolver

Lime Dissolver			
Parameters	**In**		**Out**
	From Lime Kiln	Water Stream	To Ammonia R-Tower
Temperature (°C)	900°C	25°C	90°C
Pressure (bar)	1 bar	1 bar	1 bar
Components	**kJ/hr**	**kJ/hr**	**kJ/hr**
$Ca\ (OH)_2$	0	0	-981.66
CaO	-287.3	0	0
H_2O	0	-285.8	-282.89

Q = -13056.442 kJ/hr

Q = -13056.442 kJ/hr + Q loss

Q = -13056.442 kJ/hr + 3916.93 kJ/hr

Q = -16973.37kJ/hr

5.11 Ammonia Recovery Tower

The reaction occurring in this tower is:

$$Ca\ (OH)_{2(s)} + 2NH_4Cl_{(aq)} \rightarrow CaCl_{2(aq)} + 2NH_{3(g)} + 2H_2O_{(l)}$$

Table 27: Enthalpy Table for Components in Ammonia Recovery Tower

Ammonia Recovery Tower				
Parameters	**In**		**Out**	
	From Dissolver	From Filter	To Compressor 2	$CaCl_2$ Stream
Temperature (°C)	90°C	30°C	85°C	85°C
Pressure (bar)	1 bar	1 bar	1 bar	1 bar
Components	**kJ/hr**	**kJ/hr**	**kJ/hr**	**kJ/hr**
H_2O	-282.99	-285.99	0	-282.7
NaCl	0	-407.9	0	-434.9
NH_3	0	0	0	0
$NaHCO_3$	0	-301.15	0	-309.9
NH_4Cl	0	-310.02	0	0
$Ca(OH)_2$	-981.66	0	0	0
$CaCl_2$	0	0	0	637.87

$$Q = -117878.9.37 \text{ kJ/hr}$$

5.12 Condenser

The Equation used to calculate the duty of Condenser is $Q = mCp\Delta T$.

5.12.1 Condenser 1

Table 28: Physical Parameter table for Condenser 1

Condenser 1		
Parameters	**In**	**Out**
Temperature (°C)	900°C	150°C
Pressure (bar)	1 bar	1 bar

Q = 558 kJ/hr (Duty)

5.12.2 Condenser 2

Table 29: Physical Parameter table for Condenser 2

Condenser 2		
Parameters	**In**	**Out**
Temperature (°C)	200°C	35°C
Pressure (bar)	1 bar	1 bar

Q = 1748 kJ/hr (Duty)

CHAPTER 06

EQUIPMENT DESIGN

6.1 Lime Kiln

The Lime Kiln is Rotary Kiln which is used for decomposition of the Limestone. This Kiln operates at the temperature of the 900°C with liberating carbon dioxide gas and calcium oxide (CaO). The reaction is given as:

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$

The physical parameter which is used in designing of the Kiln are given Table 30:

Table 30: Physical Parameter table for Lime Kiln

Lime Kiln	
Parameters	**Value**
Temperature	900°C
Pressure	1 bar
Inlet Flow Rate	39.1 kmol/hr
Cross-sectional Velocity	1 m/s

The Equations Used to design Kilns are:

$$T\ (Residence\ Time) = \frac{\dot{V}\ (Vol.\ flow\ rate)}{m\ (mass\ flow\ rate)}$$

$$A = \frac{Volume}{Residence\ Time \times Cross - sectional\ Velocity}$$

$$L = \frac{Volumetric\ flow\ rate \times Residence\ Time}{Area\ of\ kiln}$$

The calculated designed parameters of kiln are shown in the Table 31:

Table 31: Calculated Design parameters of Lime Kiln

Lime Kiln	
Parameters	**Value**
Length	60 meters
Diameter	2.5 meters
Volume	294 m^3
Residence Time	4.5 minutes

6.2 2-Phase Separator

This Separator is the vertical column which is used for the separation of water and carbon dioxide mixture. As the settling time is provided inside the separator because of density difference the gas is separated from the top and water from the bottom. The stainless-steel material is selected as the construction material for this column. The parameters which are considered for its designing is given as in Table 32:

Table 32: Physical Parameter table for 2-Phase Separator

2-Phase Separator	
Parameters	**Value**
Temperature	25°C
Pressure	1 bar
Inlet Flow Rate	81.7 kmol/hr
Material	Stainless Steel

The Design equations which are used to design a separator are:

$$Q_V = \frac{W_V}{(3{,}600)(\rho_V)}$$

$$H_H = \frac{V_H}{(\pi / 4) D_V^2}$$

$$D_{VD} = \left(\frac{4 Q_V}{\pi U_V} \right)^{1/2}$$

Table 33: Calculated Design parameters of 2-Phase Separator

2-Phase Separator	
Parameters	**Value**
Height	2.31 meters
Diameter	0.609 meters
Volume	10.78 m^3

6.3 Calcinator

The Calcinator is a Rotary Kiln which is used in the calcination of Sodium bicarbonate into the sodium carbonate. The reaction is as follows:

$$2NaHCO_3(s) \rightarrow Na_2CO_3(s) + CO_2(g) + H_2O(g)$$

The physical parameter which is used in designing of the Calcinator are given Table 34:

Table 34: Physical Parameter table for Calcinator

Calcinator	
Parameters	**Value**
Temperature	200°C
Pressure	1 bar
Inlet Flow Rate	82.4 kmol/hr
Cross-sectional Velocity	1.5 m/s

The Design equations which are used to design a calcinator are:

$$T\ (Residence\ Time) = \frac{\dot{V}\ (Vol.\ flow\ rate)}{m\ (mass\ flow\ rate)}$$

$$A = \frac{Volume}{Residence\ Time \times Cross - sectional\ Velocity}$$

$$L = \frac{Volumetric\ flow\ rate \times Residence\ Time}{Area\ of\ kiln}$$

Table 35: Calculated Design parameters of Calcinator

Calcinator	
Parameters	**Value**
Length	20 meters
Diameter	1 meters
Volume	15.4 m^3
Residence Time	0.16 minutes

6.4 Absorber

This Absorber is used to absorb the ammonia into the brine solution. Basically, it is packed column with ceramic packing. The ceramic packing is taken because it is corrosion free, and we are dealing with water that's why it is taken. The stainless-steel material is selected as the construction material for this column. The parameters which are considered for its designing is given as in Table 36:

Table 36: Physical Parameter table for Absorber

Absorber	
Parameters	**Value**
Temperature	25°C
Pressure	2 bars
Packing Material	Ceramics
Column Material	Stainless Steel

The design equations and the detail methodology to design the absorber is given below and final results of the absorber column is shown in the Table 37:

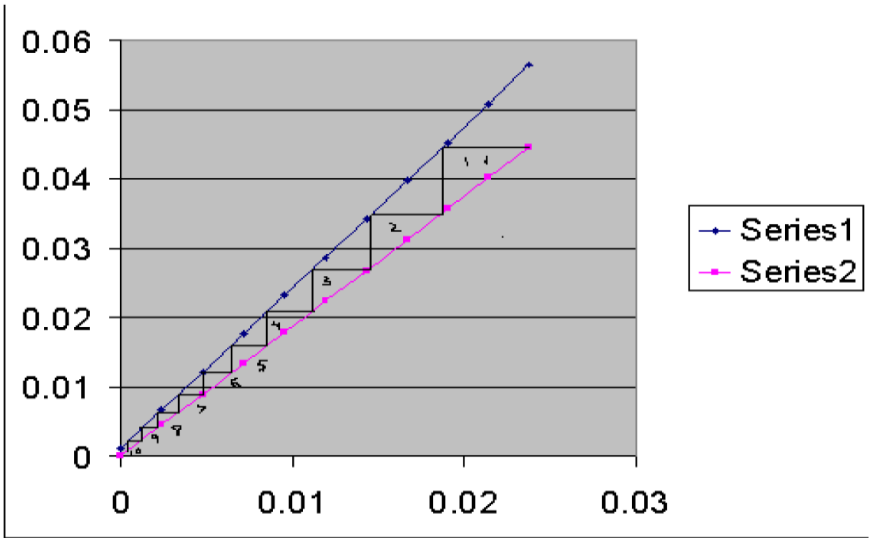


Figure 2: McCabe Graph of Absorber

Number of transfer unit after drawing graph between X Vs Y and X Vs Y*we get using McCabe Theile method:

NOG = 10

$$H_{OG} = 1.14 \frac{(Gm)^{0.316}}{(Lm)^{0.315}}$$

$$\text{Diameter} = D = [4 \times A/\pi]^{½}$$

$$Z = H_{OG} \times N_{OG}$$

$$\text{Volume of packing} = \pi/4\ D^2 \times Hp$$

Table 37: Calculated Design parameters of Absorber

Absorber	
Parameters	**Value**
Diameter	4.9 meters
Height	13.7 meters
Packing Height	11.7 meters
Volume of Packing	90 m^3

6.5 Solvay Tower

This Solvay Tower is used to absorb the CO_2 into the Ammoniated brine solution. Basically, it is a Tray Column with sieve type trays. The sieve type trays are taken because it is corrosion free, and also provide large efficiency. Also, we are dealing with water that’s why it is taken. The stainless-steel material is selected as the construction material for this column. On the trays of this tower the reaction also occurs:

$$NH_3(g) + NaCl(aq) + H_2O(l) + CO2(g) \rightarrow NH_4Cl(aq) + NaHCO_3(s)$$

The parameters which are considered for its designing is given as in Table 38:

Table 38: Physical Parameter table for Solvay Tower

Solvay Tower	
Parameters	**Value**
Temperature	70°C
Pressure	1.5 bars
Inlet Flow Rate	1073.7 kmol/hr
Column Material	Carbon Steel

The design equations and the detail methodology to design the Solvay tower is given below and final results of the absorber column is shown in the Table 39:

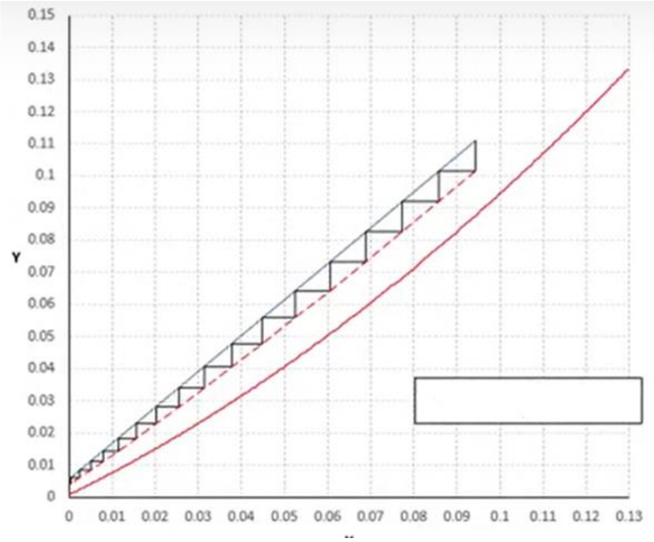


Figure 3: McCabe Graph of Solvay Tower

X Vs Y and X Vs Y*we get using McCabe Theile method:

$$A_N = \frac{CFS}{(SF)*F_F*u_N}$$

Where,

CFS = Vapour Flow Rate, ft^3/sec

SF = Derating Factor (See Appendix 2)

F_F = Flood factor, usually taken as 0.8 (80% flood) or designer can choose based on system requirements or project standards

$$\text{Tower Diameter} = D_T = \sqrt{\frac{4*A_T}{\Pi}}$$

Height = No of Plates * plates spacing

Table 39: Calculated Design parameters of Solvay Tower

Solvay Tower	
Parameters	**Value**
Diameter	3.2 meters
Height	8 meters
Tray Type	Sieve
No. of Trays	13
Tray Spacing	0.6906 meters

6.6 Ammonia Recovery Tower

This Ammonia Recovery Tower is used to recover the ammonia from ammonium chloride by reacting it with the milk of lime. Basically, it is a Tray Column with sieve type trays. The sieve type trays are taken because it is corrosion free, and also provide large efficiency. Also, we are dealing with water that’s why it is taken. The stainless-steel material is selected as the construction material for this column. On the trays of this tower the reaction also occurs:

$$Ca\,(OH)_{2(s)} + 2NH_4Cl(aq) \rightarrow CaCl_2(aq) + 2NH_3(g) + 2H_2O_{(l)}$$

The parameters which are considered for its designing is given as in Table 40:

Table 40: Physical Parameter table for Ammonia Recovery Tower

Ammonia Recovery Tower	
Parameters	**Value**
Temperature	80°C
Pressure	1 bar
Inlet Flow Rate	772.8 kmol/hr
Column Material	Carbon Steel

The design equations and the detail methodology to design the ammonia recovery tower is given below and final results of the absorber column is shown in the Table 41:

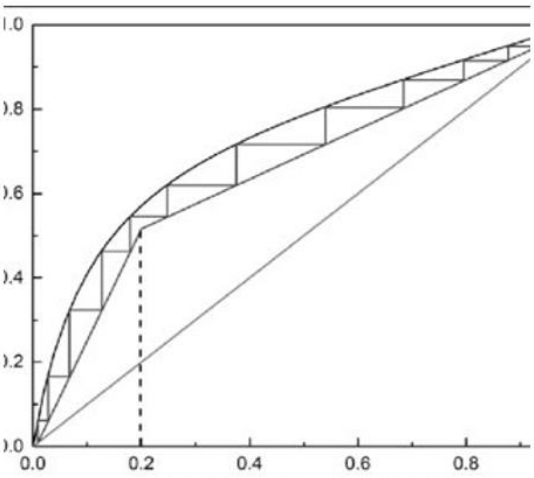


Figure 4: McCabe Graph of Ammonia Tower

$$A_N = \frac{CFS}{(SF) * F_F * u_N}$$

Where,

CFS = Vapour Flow Rate, ft^3/sec

SF = Derating Factor (See Appendix 2)

F_F = Flood factor, usually taken as 0.8 (80% flood) or designer can choose based on system requirements or project standards

$$\text{Tower Diameter} = D_T = \sqrt{\frac{4 * A_T}{\Pi}}$$

Height = No of Plates * plates spacing

Table 41: Calculated Design parameters of Ammonia Recovery Tower

Ammonia Recovery Tower	
Parameters	**Value**
Diameter	2.4 meters
Height	6.1 meters
Tray Type	Sieve
No. of Trays	10
Tray Spacing	0.60 meters

6.7 Dryer

The Dryer is of Rotary type. Basically, this dryer is introduced in the process so that the moisture removal can be improved. This dryer operates at the 100°C temperature and the moisture removal of this dryer is 90%. The design equation which are used to design a dryer and the calculated results are tabulated in table 42:

$$\text{Volume} = \pi r^2 l$$

$$Q = m (h_{in} - h_{out})$$

Table 42: Calculated Design parameters of Dryer

Dryer	
Parameters	**Value**
Diameter	3.2 meters
Duty	44.3 kW
Length	10 meters

6.8 Filter

This Filter is of Rotary type. This filter operates at the 90% efficiency on basis of bicarbonate separation. The specs of the filter which is taken from the literature is given below in the table 43:

Table 43: Design Specs of Filter

Filter	
Parameters	**Value**
Area	64 m^2
Volume	512 m^3
Length	8 meters

6.9 Condensers

For the cooling of the CO_2, which is coming from the kiln, the condenser 1 is used. The condenser 1 cools the carbon dioxide stream from 900°C to the 150°C. The condenser 2 cools the stream of water and carbon dioxide which is coming from the calcinator. It cools it from 200°C to 35°C. The kern's method is used to design both condensers.

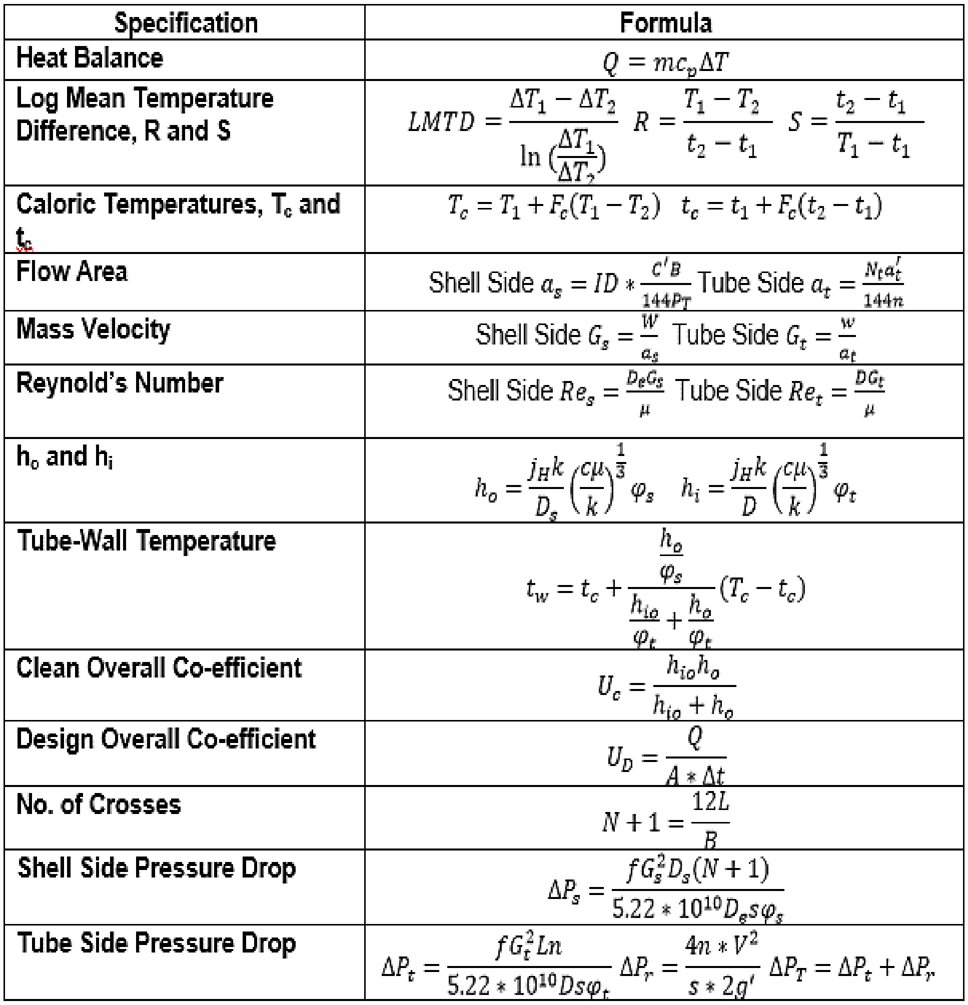
6.9.1 Fluid allocation

1. The tube side consists of the CO_2 which is hot side in condenser 1 and same in condenser 2 the water and CO_2 are on tube side.

2 The shell side consists of the water which is used for cooling purpose in both condensers.

6.9.2 Kern's Method

Kern's method equations are:



Specification	Formula
Heat Balance	$Q = mc_p\Delta T$
Log Mean Temperature Difference, R and S	$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$ $R = \frac{T_1 - T_2}{t_2 - t_1}$ $S = \frac{t_2 - t_1}{T_1 - t_1}$
Caloric Temperatures, T_c and t_c	$T_c = T_1 + F_c(T_1 - T_2)$ $t_c = t_1 + F_c(t_2 - t_1)$
Flow Area	Shell Side $a_s = ID * \frac{C'B}{144P_T}$ Tube Side $a_t = \frac{N_t a_t'}{144n}$
Mass Velocity	Shell Side $G_s = \frac{W}{a_s}$ Tube Side $G_t = \frac{w}{a_t}$
Reynold's Number	Shell Side $Re_s = \frac{D_e G_s}{\mu}$ Tube Side $Re_t = \frac{DG_t}{\mu}$
h_o and h_i	$h_o = \frac{j_H k}{D_s}\left(\frac{c\mu}{k}\right)^{\frac{1}{3}}\varphi_s$ $h_i = \frac{j_H k}{D}\left(\frac{c\mu}{k}\right)^{\frac{1}{3}}\varphi_t$
Tube-Wall Temperature	$t_w = t_c + \frac{\frac{h_o}{\varphi_s}}{\frac{h_{io}}{\varphi_t} + \frac{h_o}{\varphi_t}}(T_c - t_c)$
Clean Overall Co-efficient	$U_c = \frac{h_{io}h_o}{h_{io} + h_o}$
Design Overall Co-efficient	$U_D = \frac{Q}{A * \Delta t}$
No. of Crosses	$N + 1 = \frac{12L}{B}$
Shell Side Pressure Drop	$\Delta P_s = \frac{fG_s^2 D_s(N+1)}{5.22 * 10^{10} D_e s\varphi_s}$
Tube Side Pressure Drop	$\Delta P_t = \frac{fG_t^2 Ln}{5.22 * 10^{10} Ds\varphi_t}$ $\Delta P_r = \frac{4n * V^2}{s * 2g'}$ $\Delta P_T = \Delta P_t + \Delta P_r$

Figure 5: Kern's method equations summarized.

6.9.3 Calculated Parameter by Kerns Method

Table 44: Design Specs of Condensers

<table>
<tr><th colspan="2">Condenser 1</th></tr>
<tr><th>Parameters</th><th>Value</th></tr>
<tr><td>Shell Dia</td><td>803.08 meters</td></tr>
<tr><td>No. of Tubes</td><td>190</td></tr>
<tr><td>Baffle Spacing</td><td>800 mm</td></tr>
<tr><td>Heat Transfer Area</td><td>71.63 m^2</td></tr>
<tr><th colspan="2">Condenser 2</th></tr>
<tr><th>Parameters</th><th>Value</th></tr>
<tr><td>Shell Dia</td><td>739.05 meters</td></tr>
<tr><td>No. of Tubes</td><td>160</td></tr>
<tr><td>Baffle Spacing</td><td>789 mm</td></tr>
<tr><td>Heat Transfer Area</td><td>60.3 m^2</td></tr>
</table>

CHAPTER 07

PROCESS SIMULATION

7.1 Simulation Main Flow Sheet

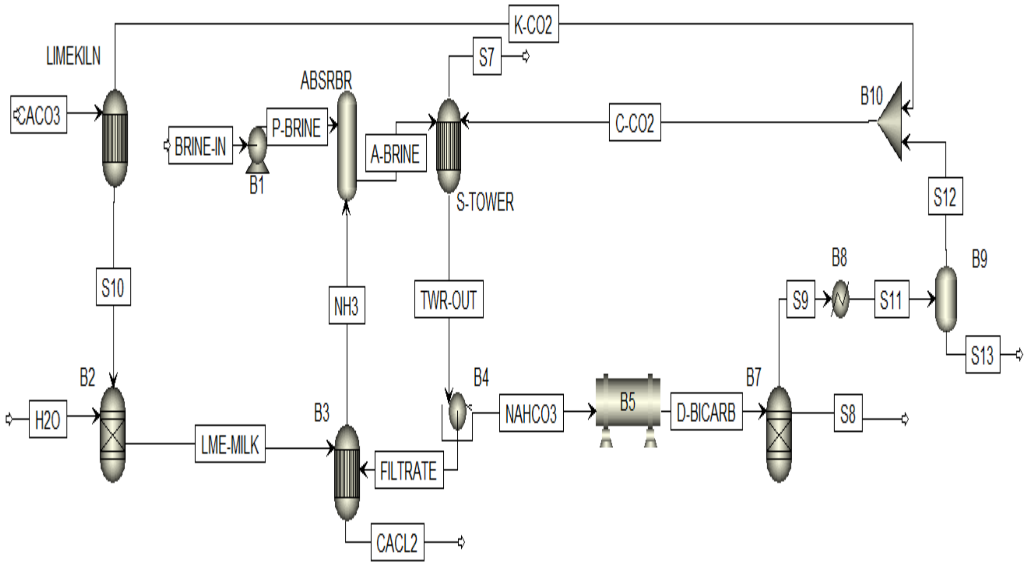
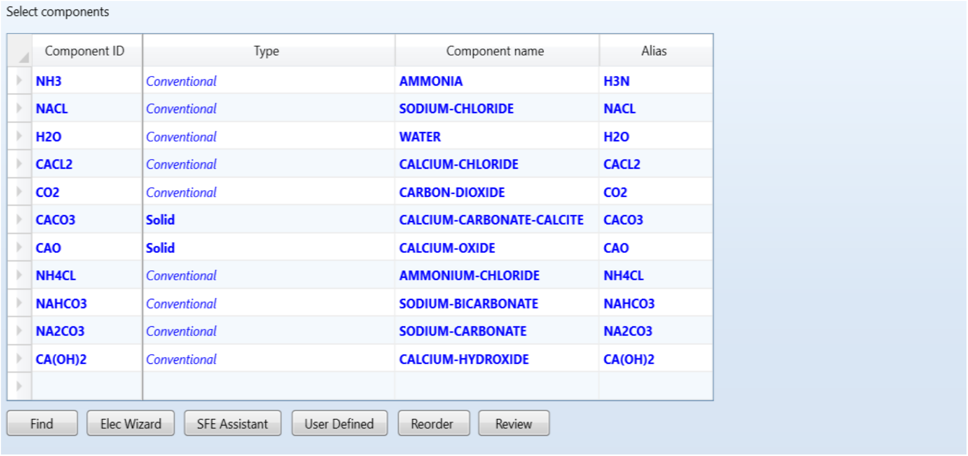


Figure 6: Simulation Flowsheet

7.2 Component List

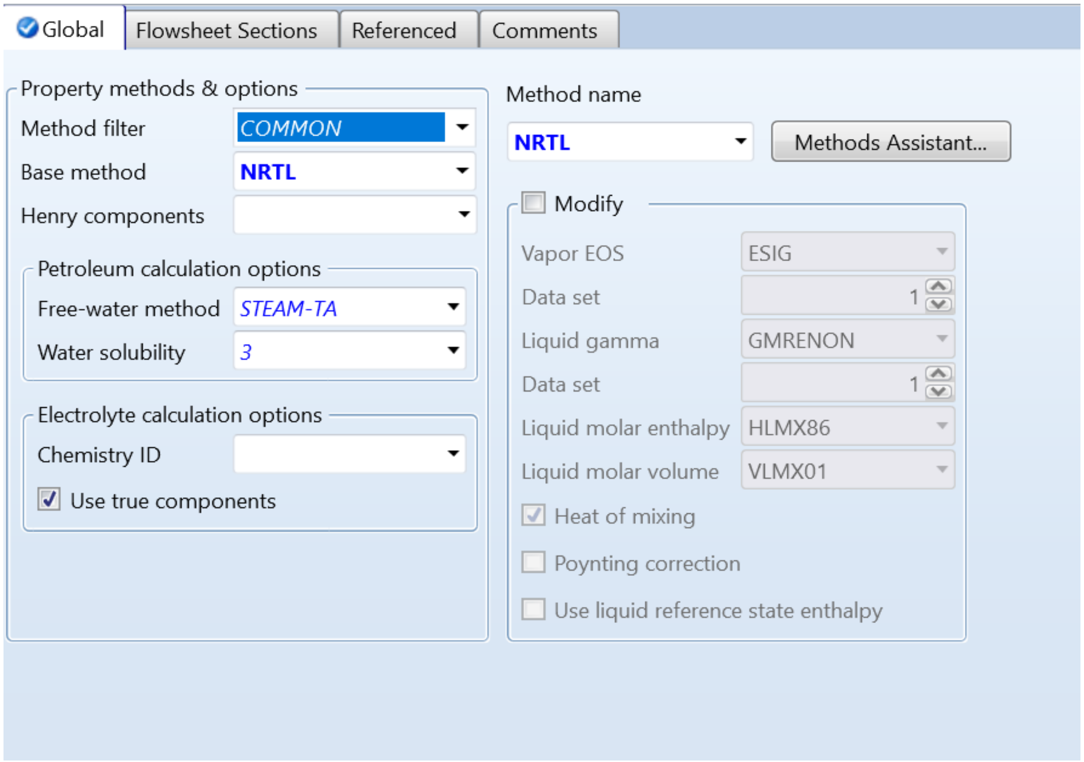


Component ID	Type	Component name	Alias
NH3	Conventional	AMMONIA	H3N
NACL	Conventional	SODIUM-CHLORIDE	NACL
H2O	Conventional	WATER	H2O
CACL2	Conventional	CALCIUM-CHLORIDE	CACL2
CO2	Conventional	CARBON-DIOXIDE	CO2
CACO3	Solid	CALCIUM-CARBONATE-CALCITE	CACO3
CAO	Solid	CALCIUM-OXIDE	CAO
NH4CL	Conventional	AMMONIUM-CHLORIDE	NH4CL
NAHCO3	Conventional	SODIUM-BICARBONATE	NAHCO3
NA2CO3	Conventional	SODIUM-CARBONATE	NA2CO3
CA(OH)2	Conventional	CALCIUM-HYDROXIDE	CA(OH)2

Figure 7: Component List

7.3 Fluid Package

The Fluid Package of this simulation is selected is **"NRTL"**. For this type of system, the two fluid package i.e., **"UNIQUAC"** and **"NRTL"** are best. We have selected NRTL Model because of our system contains solids and also ions within the reactions that's why the NRTL model is best. Moreover, we can use ENRTL, but it is only for ions but because of solids NRTL was selected. For some equipment's like Amine Absorber the AMINE Fluid Package is used and Solid is used separately for dryer because these equipment's are not giving desired results on the NRTL model.



Property methods & options
Method filter: COMMON
Base method: **NRTL**
Henry components:

Petroleum calculation options
Free-water method: STEAM-TA
Water solubility: 3

Electrolyte calculation options
Chemistry ID:
☑ Use true components

Method name: **NRTL**

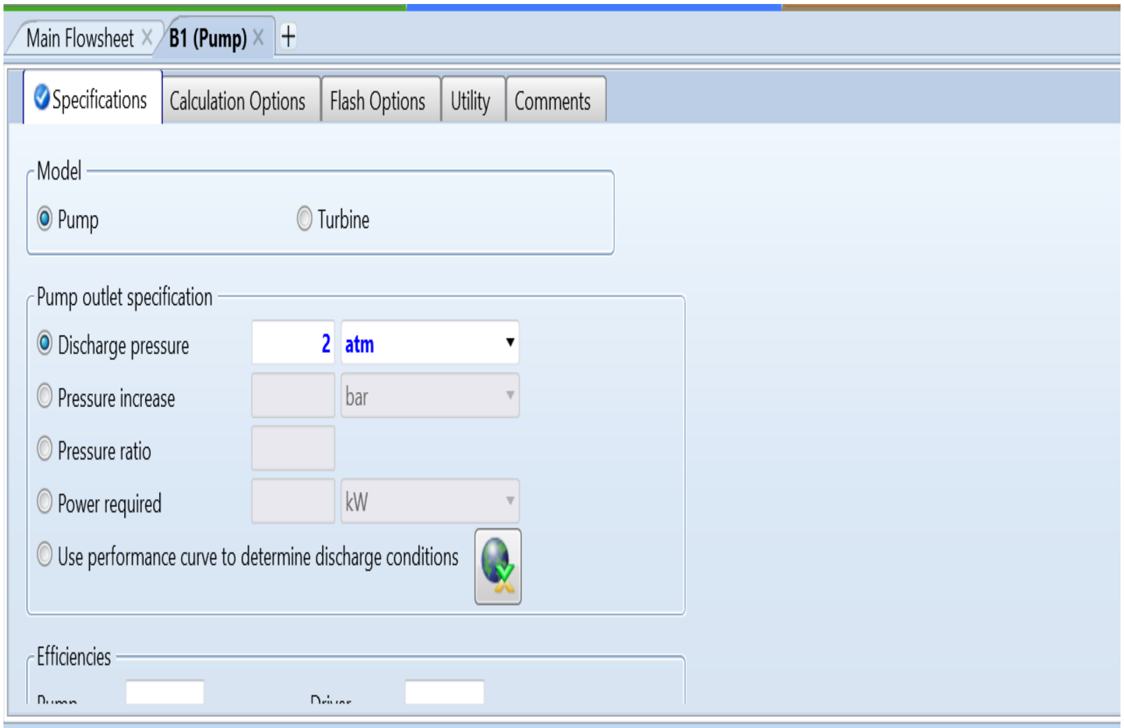
☐ Modify
Vapor EOS: ESIG
Data set: 1
Liquid gamma: GMRENON
Data set: 1
Liquid molar enthalpy: HLMX86
Liquid molar volume: VLMX01
☑ Heat of mixing
☐ Poynting correction
☐ Use liquid reference state enthalpy

Figure 8: Fluid Package

7.4 Pump

This Pump is of Centrifugal Type and only discharge pressure 2 bar is given to it.

Discharge Pressure = 2 bar



Model

● Pump ○ Turbine

Pump outlet specification

● Discharge pressure 2 atm

○ Pressure increase bar

○ Pressure ratio

○ Power required kW

○ Use performance curve to determine discharge conditions

Efficiencies

Pump Driver

Figure 9: Pump

7.5 Absorber

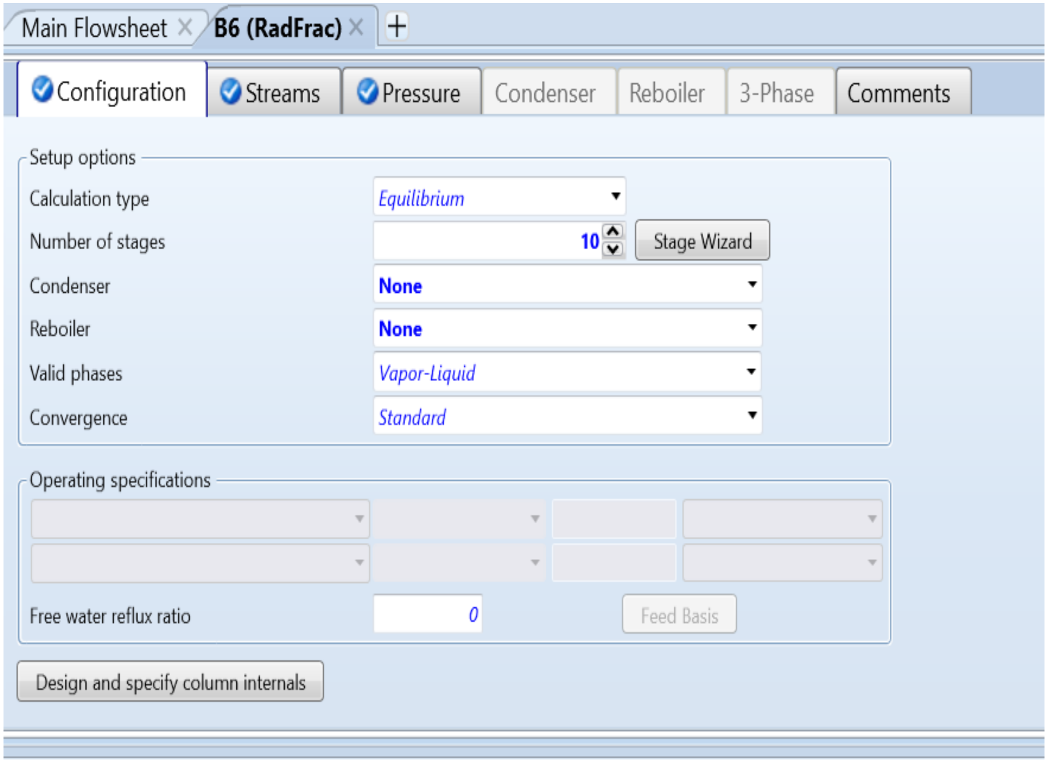
The RadFrac Column is used for the absorber with no condenser and no boiler. The Process conditions are:

No of stages = 10

Brine Feed = Stage 1

Ammonia Feed = Stage 10

Ammoniated Brine Leaving = 9



Setup options

Calculation type: Equilibrium

Number of stages: 10

Condenser: None

Reboiler: None

Valid phases: Vapor-Liquid

Convergence: Standard

Operating specifications

Free water reflux ratio: 0

Figure 10: Absorber

7.6 Solvay Tower

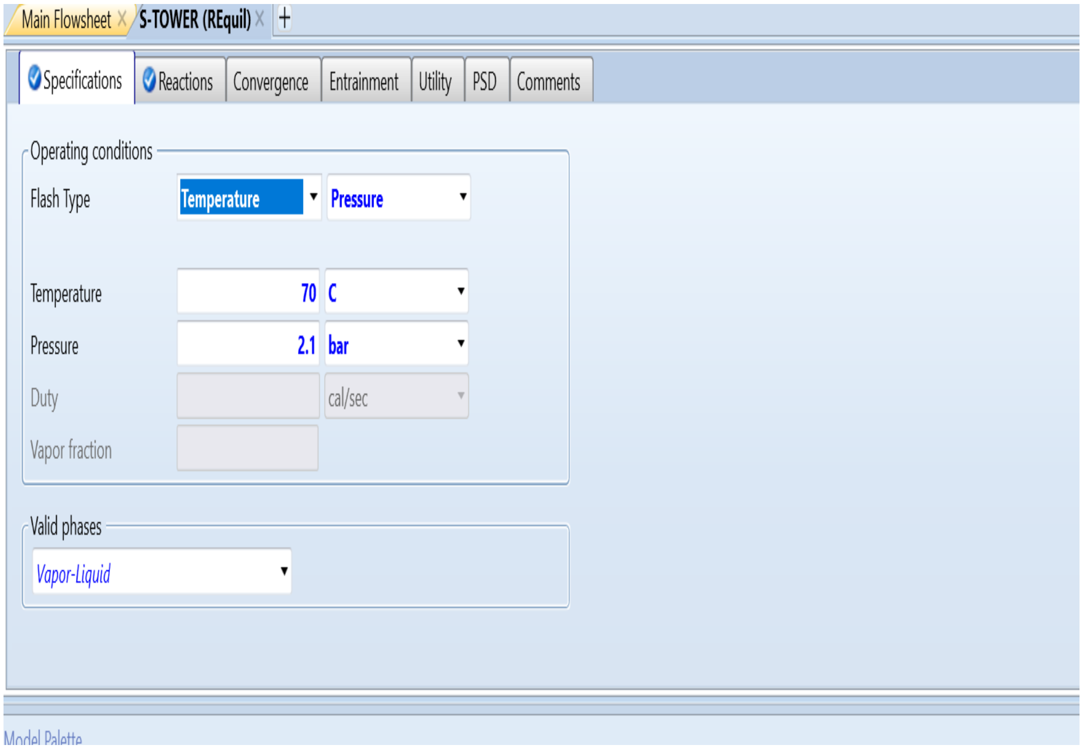
The Simulation of this Tower is too difficult because in ASPEN Plus we cannot simulate the reaction tower. So, to simulate this we use the Equilibrium Reactor to achieve this step.

No of Stages = 13

Temperature = 70°C

Pressure = 2.1 bar

The Reaction is also entered it as an Temperature Approach.



Operating conditions

Flash Type: Temperature, Pressure

Temperature: 70 C

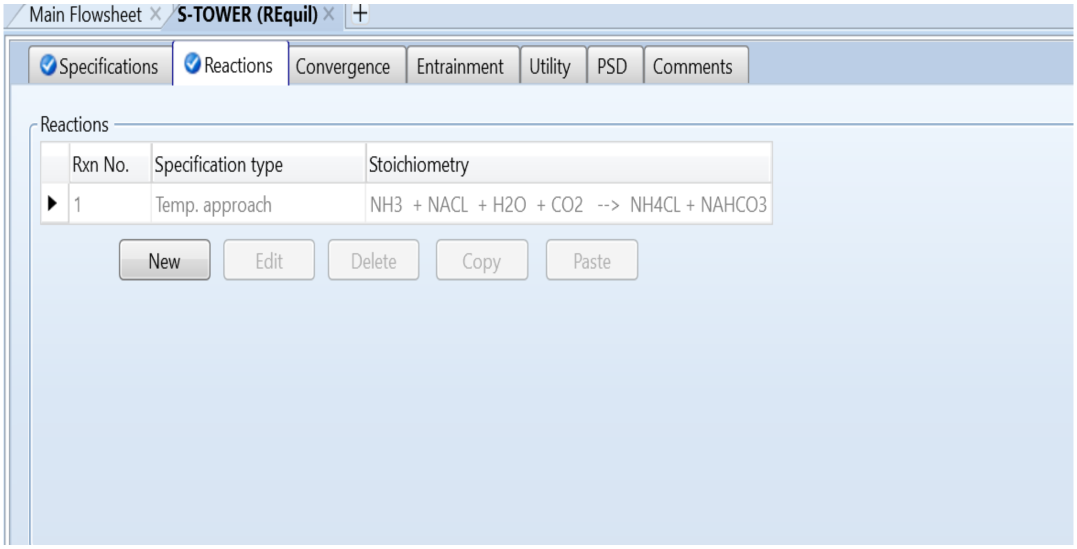
Pressure: 2.1 bar

Duty: cal/sec

Vapor fraction:

Valid phases: Vapor-Liquid

Figure 11: Solvay Tower



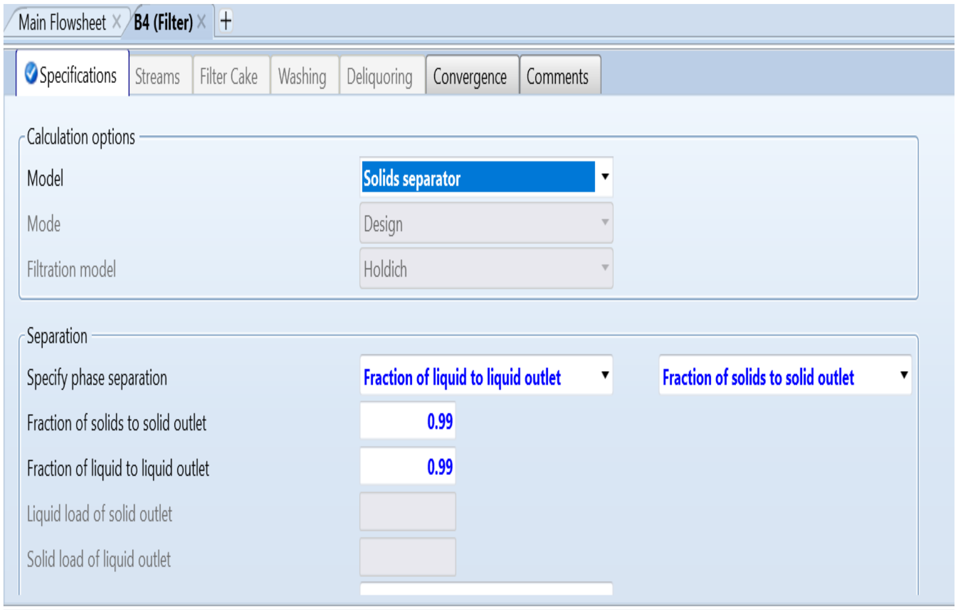
Reactions

Rxn No.	Specification type	Stoichiometry
1	Temp. approach	NH3 + NACL + H2O + CO2 --> NH4CL + NAHCO3

Figure 12: Reaction of Solvay Tower

7.7 Filter

The Filter is used to separate bicarbonate moisture from milky solution of ammonium chloride. This is Rotary Filter, and its specs are:



Calculation options

Model: Solids separator

Mode: Design

Filtration model: Holdich

Separation

Specify phase separation: Fraction of liquid to liquid outlet; Fraction of solids to solid outlet

Fraction of solids to solid outlet: 0.99

Fraction of liquid to liquid outlet: 0.99

Liquid load of solid outlet

Solid load of liquid outlet

Figure 13: Filter

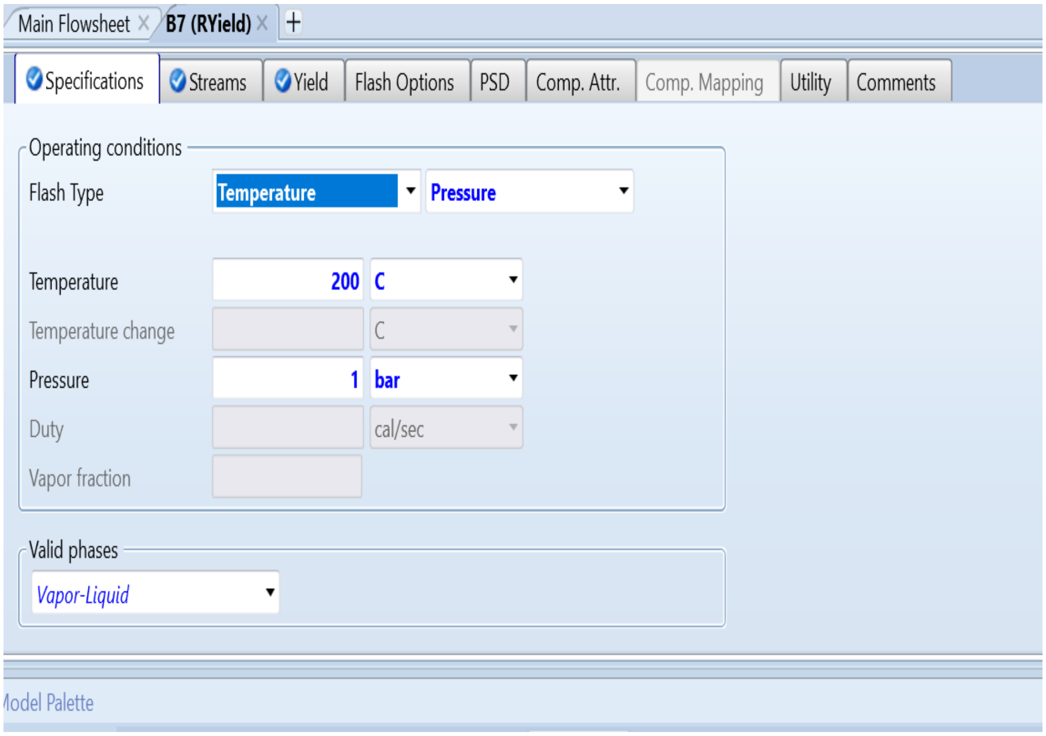
7.8 Calcinator

The Calcinator is basically a rotary kiln, and we cannot simulate the calcinator in ASPEN plus. To achieve the desired results we have applied a R-Yield Reactor instead of it. We are taking the results by use of this approach. The spec are:

Temp = 200°C

Pressure = 1 bar

The reaction is added as the Temperature approach.



Operating conditions

Flash Type: Temperature, Pressure

Temperature: 200 C

Temperature change: C

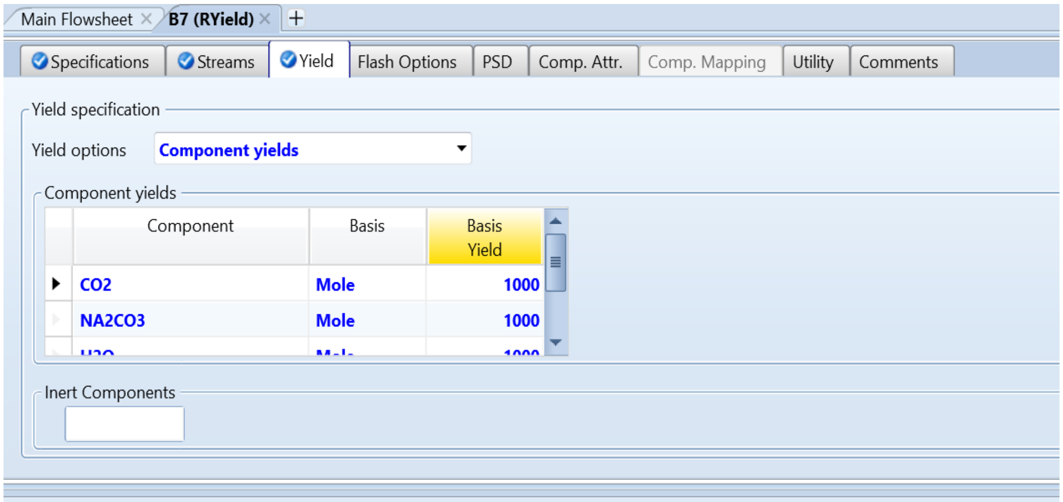
Pressure: 1 bar

Duty: cal/sec

Vapor fraction:

Valid phases: Vapor-Liquid

Figure 14: Calcinator



Yield specification

Yield options: Component yields

Component yields

Component	Basis	Basis Yield
CO2	Mole	1000
NA2CO3	Mole	1000

Inert Components

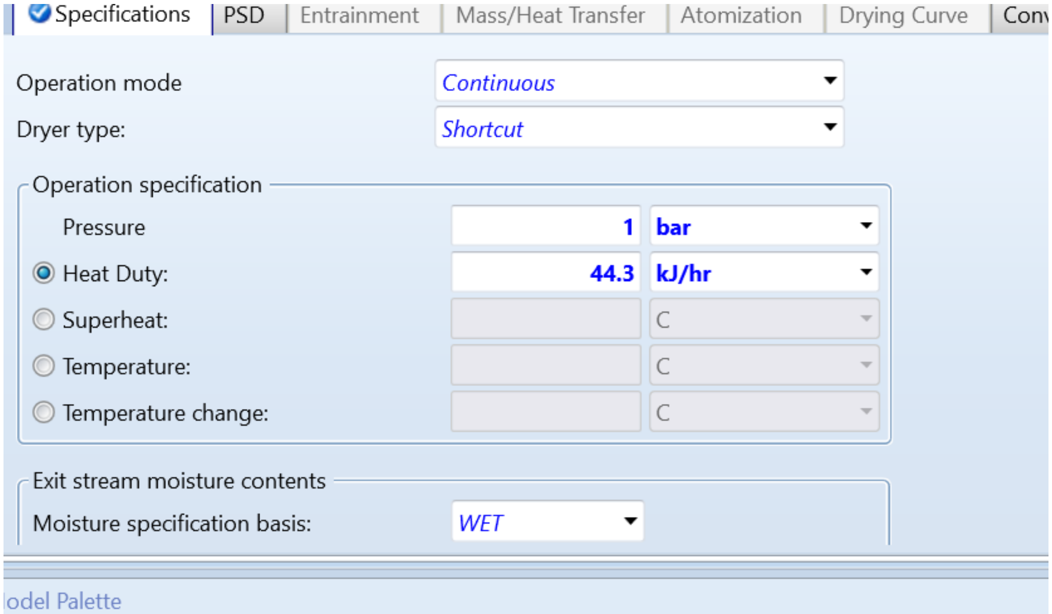
Figure 15: Reaction of Calcinator

7.9 Rotary Dryer

The Rotary Dryer is simulated as the simple dryer. The specs and condition of them are:

Temp = 100°C

Duty = 44.3 kJ/hr



Operation mode: Continuous

Dryer type: Shortcut

Operation specification

Pressure: 1 bar

● Heat Duty: 44.3 kJ/hr

○ Superheat: C

○ Temperature: C

○ Temperature change: C

Exit stream moisture contents

Moisture specification basis: WET

Figure 16: Dryer

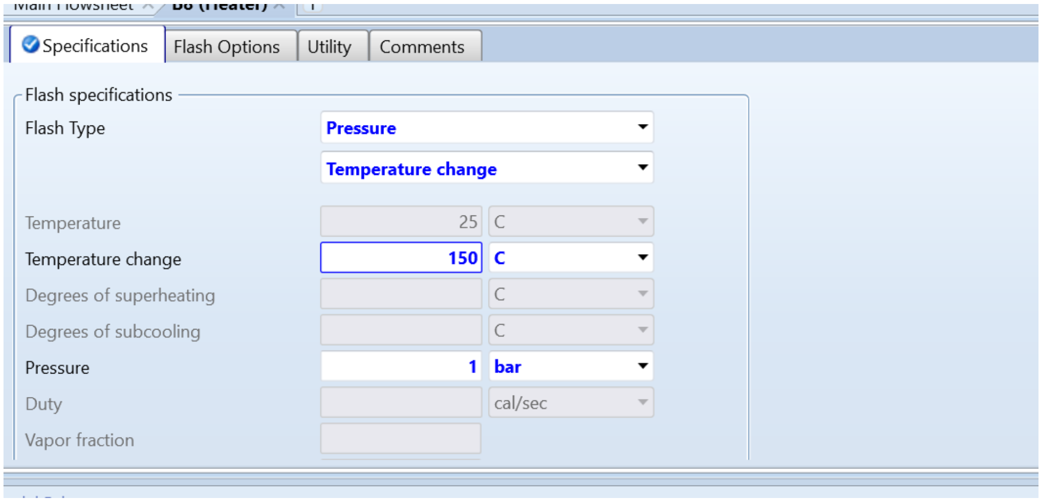
7.10 Condensers

To simulate the condenser, we have taken the heater as the condenser. We have put the outer temperature value and it gives us the desired results.

7.10.1 Condenser 1

Specs are:

Outer Temp = 150°C



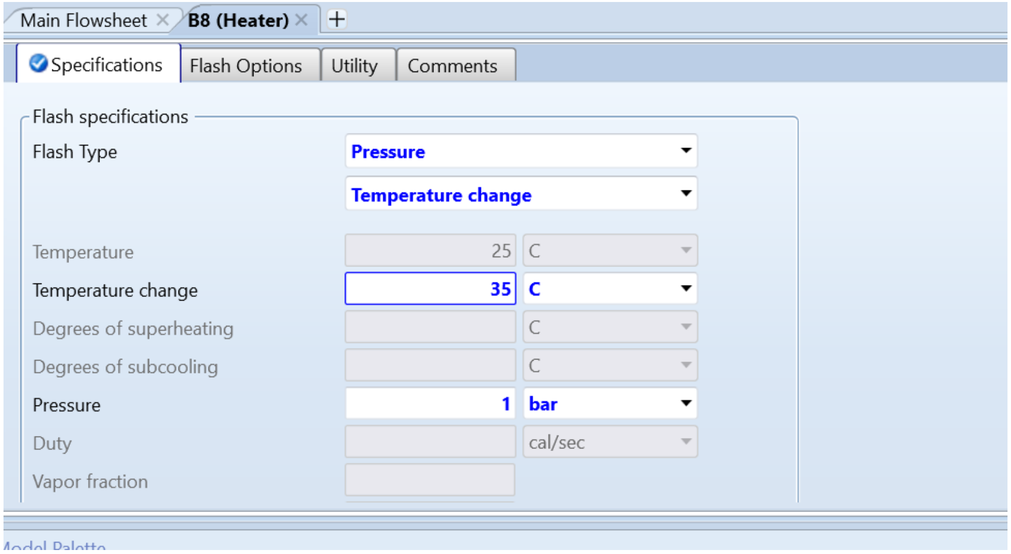
Flash Type: Pressure, Temperature change
Temperature: 25 C
Temperature change: 150 C
Degrees of superheating: C
Degrees of subcooling: C
Pressure: 1 bar
Duty: cal/sec
Vapor fraction:

Figure 17: Condenser 1

7.10.1 Condenser 2

Specs are:

Outer Temp = 35°C



Flash Type: Pressure, Temperature change
Temperature: 25 C
Temperature change: 35 C
Degrees of superheating: C
Degrees of subcooling: C
Pressure: 1 bar
Duty: cal/sec
Vapor fraction:

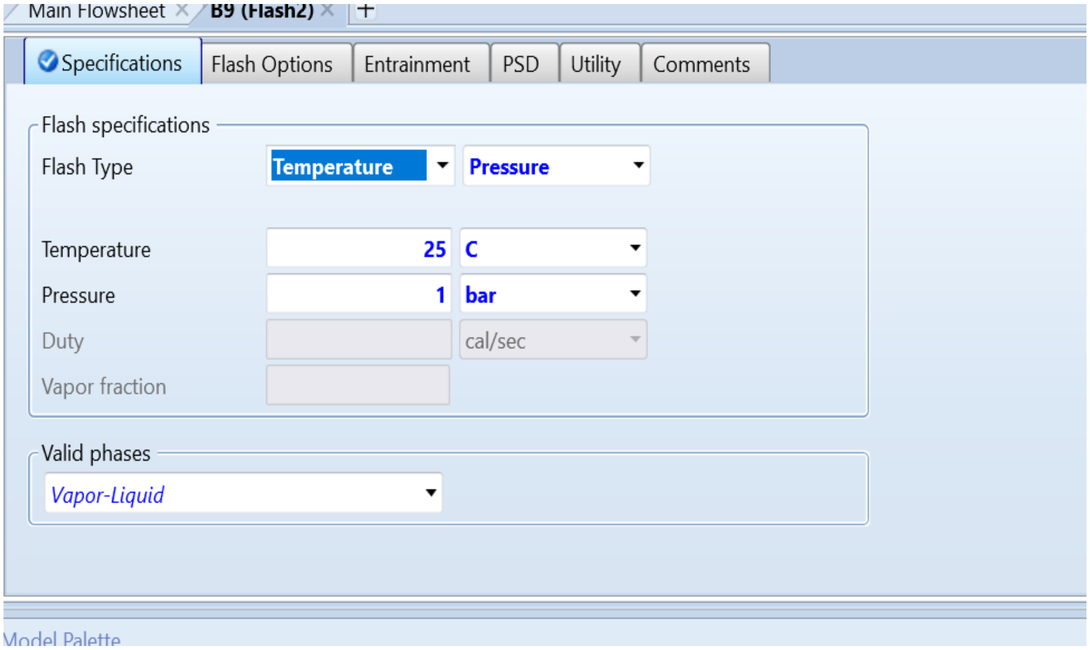
Figure 18: Condenser 2

7.11 2-Phase Separator

To Design the 2-Phase Separator the simple flash separator is taken to achieve the desired results. The Specs are:

Temp = 25°C

Pressure = 1 bar



Flash specifications

Flash Type: Temperature, Pressure

Temperature: 25 C

Pressure: 1 bar

Duty: cal/sec

Vapor fraction

Valid phases: Vapor-Liquid

Figure 19: 2-Phase Separator

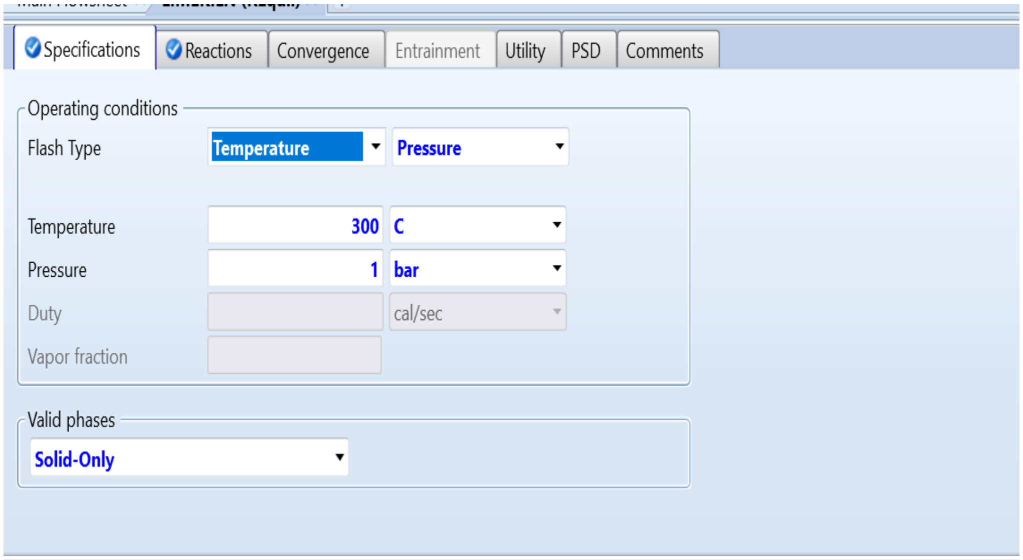
7.12 Lime Kiln

To design the Lime Kiln in ASPEN Plus we have taken Equilibrium Reactor because there is no rotary kiln is available in this software. The Design Specs of the Lime Kiln are:

Temperature: 900°C

Pressure: 1 bar

The Reaction is added as the temperature approach.



Operating conditions

Flash Type: Temperature, Pressure

Temperature: 300 C

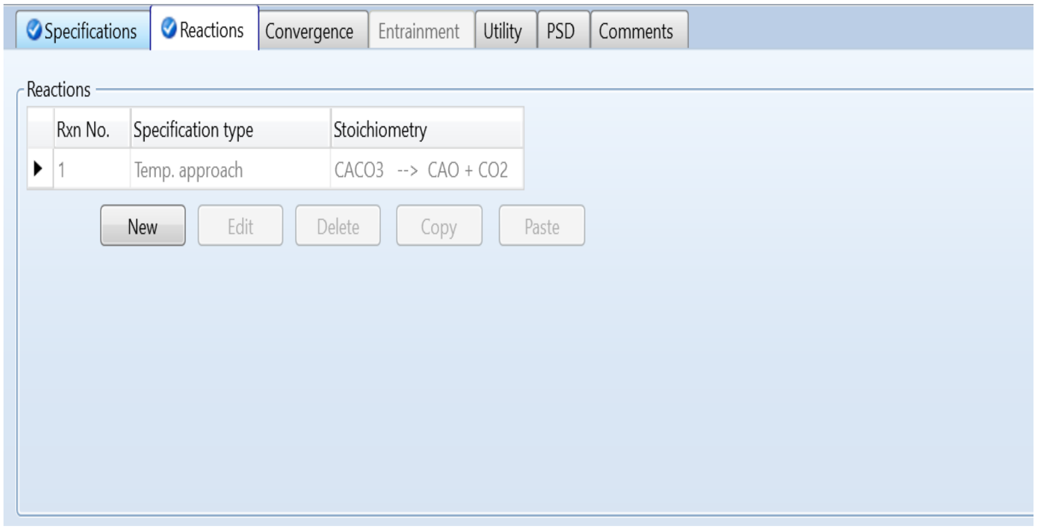
Pressure: 1 bar

Duty: cal/sec

Vapor fraction:

Valid phases: Solid-Only

Figure 20: Lime Kiln



Reactions

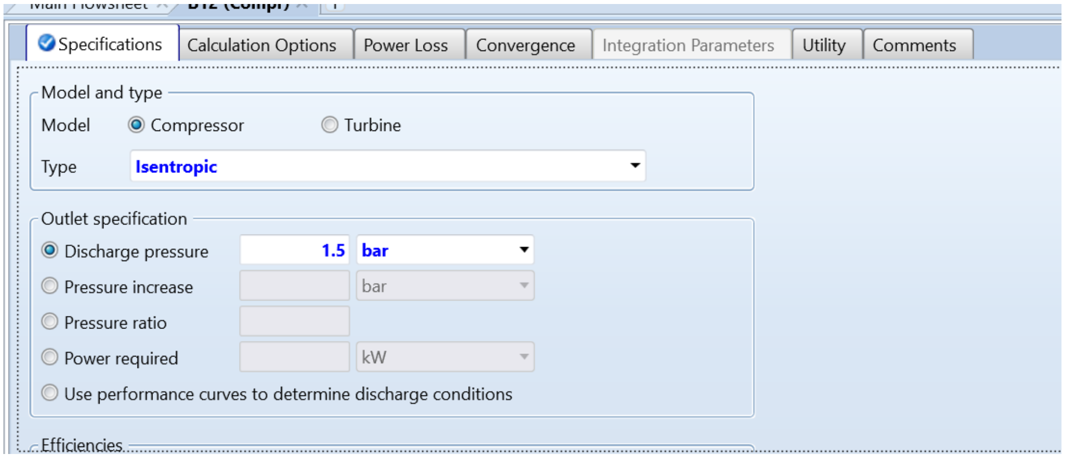
Rxn No.	Specification type	Stoichiometry
1	Temp. approach	CACO3 --> CAO + CO2

Figure 21: Reaction of Lime Kiln

7.13 Compressors

Both compressors are selected as isentropic and then simulated in the Aspen Plus:

7.13.1 Compressor 1



Model and type

Model ● Compressor ○ Turbine

Type Isentropic

Outlet specification

● Discharge pressure 1.5 bar

○ Pressure increase bar

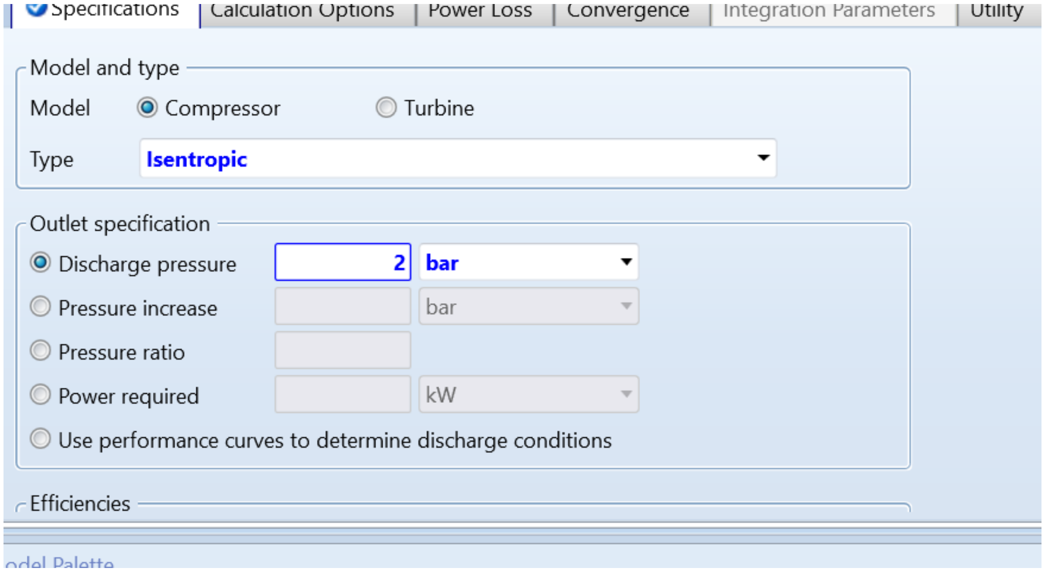
○ Pressure ratio

○ Power required kW

○ Use performance curves to determine discharge conditions

Figure 22: Compressor 1

7.13.2 Compressor 2



Model and type

Model ● Compressor ○ Turbine

Type Isentropic

Outlet specification

● Discharge pressure 2 bar

○ Pressure increase bar

○ Pressure ratio

○ Power required kW

○ Use performance curves to determine discharge conditions

Figure 23: Compressor 2

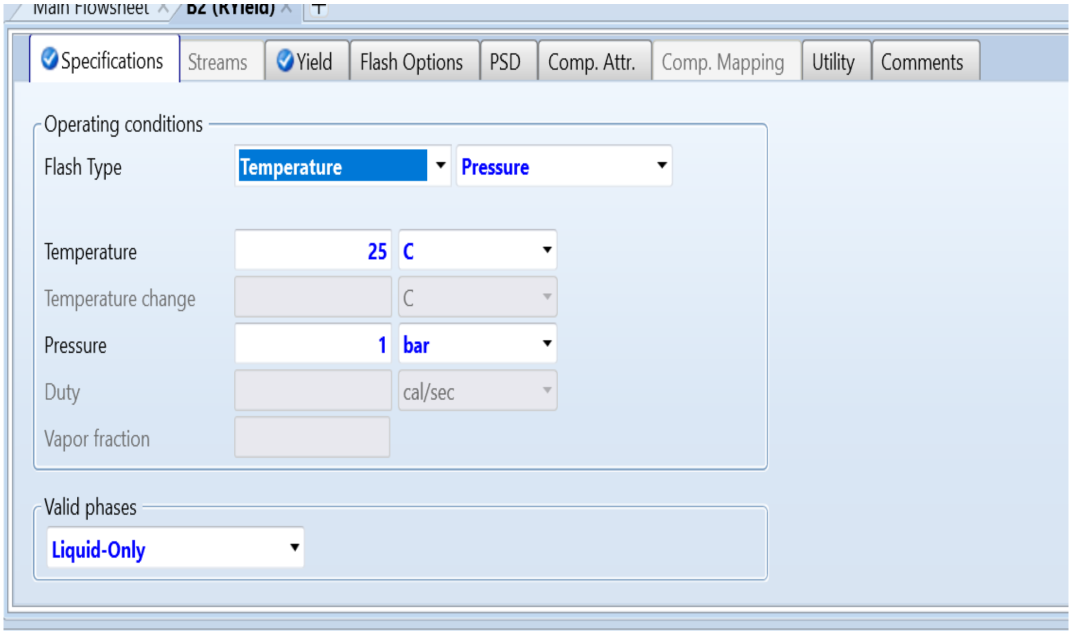
7.14 Lime Dissolver

Basically, the Lime Dissolver in real process industries is only a mixing tank. But in Aspen Plus we have taken it as yield reactor. The specs of Lime Dissolver are:

Temp: 25°C

Pressure: 1 bar

The reaction is added in reaction set bar and then into the R-Yield (Lime Dissolver)



Operating conditions

Flash Type: Temperature, Pressure

Temperature: 25 C

Temperature change: C

Pressure: 1 bar

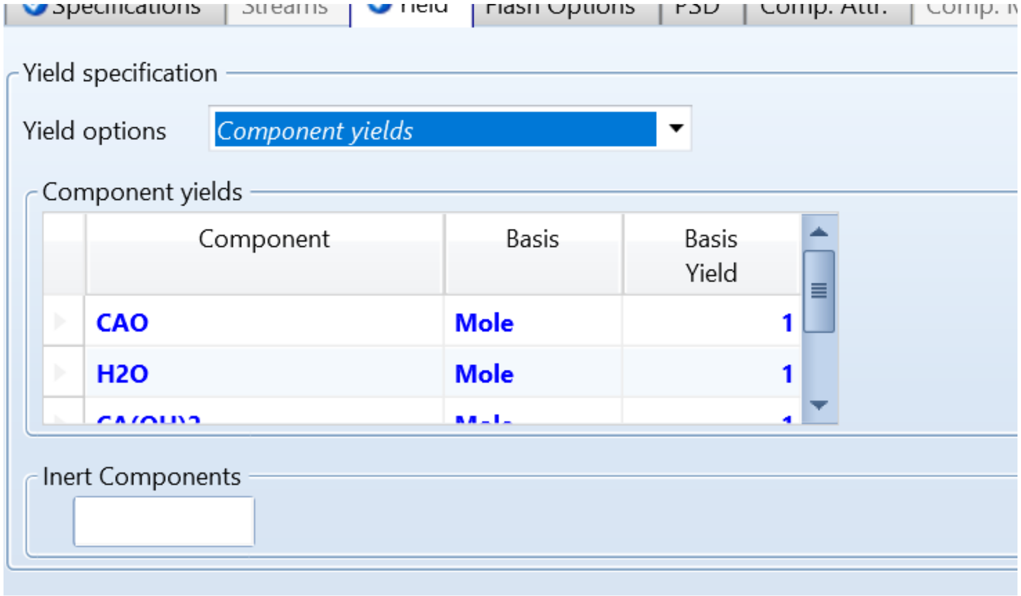
Duty: cal/sec

Vapor fraction:

Valid phases: Liquid-Only

Figure 24: Lime Dissolver

The reaction set of Lime Dissolver is given below in Figure 26. The 100% Yield is selected of the milk of lime:



Yield specification

Yield options: Component yields

Component yields

Component	Basis	Basis Yield
CAO	Mole	1
H2O	Mole	1

Inert Components

Figure 25: Reaction of Lime Dissolver

7.15 Ammonia Recovery Tower

The Simulation of this Tower is too difficult because in ASPEN Plus we cannot simulate the reaction tower. So, to simulate this we use the Equilibrium Reactor to achieve this step.

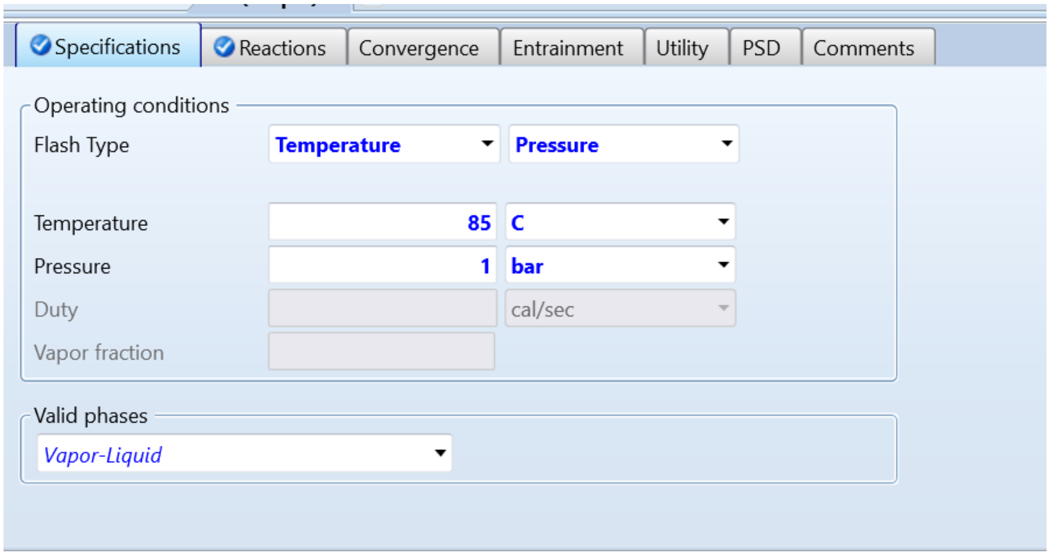
The specs of tower are:

No of Stages = 10

Temperature = 85°C

Pressure = 1 bar

The Reaction is also entered it as a Temperature Approach.



Operating conditions

Flash Type: Temperature, Pressure

Temperature: 85 C

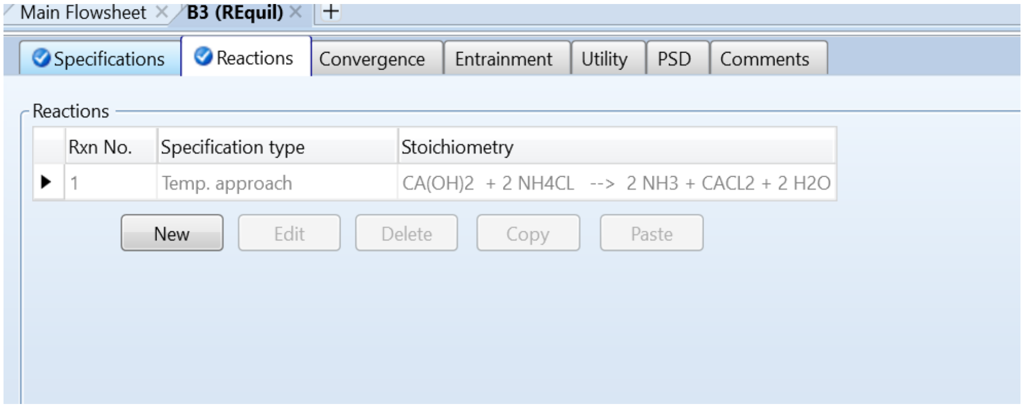
Pressure: 1 bar

Duty: cal/sec

Vapor fraction:

Valid phases: Vapor-Liquid

Figure 26: Ammonia Recovery Column



Reactions

Rxn No.	Specification type	Stoichiometry
1	Temp. approach	CA(OH)2 + 2 NH4CL --> 2 NH3 + CACL2 + 2 H2O

Figure 27: Reaction of Ammonia Recovery Tower

7.16 Final Results

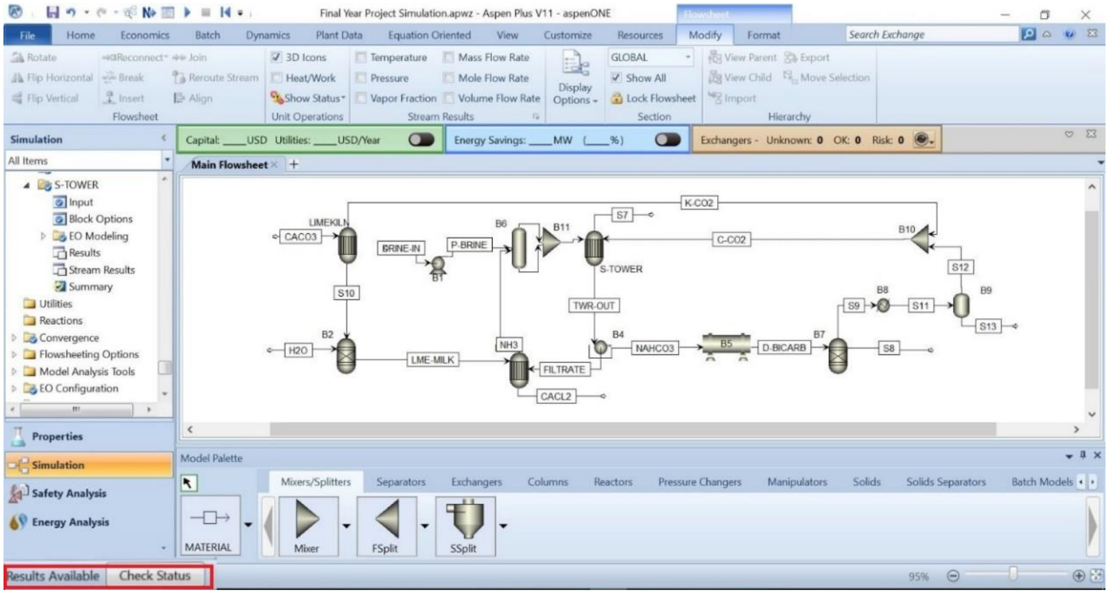


Figure 28: Results

− **Mole Flows**	**kmol/hr**	33.3
NA2CO3	kmol/hr	33.3
NAHCO3	kmol/hr	0
CO2	kmol/hr	0
WATER	kmol/hr	0

Figure 29: Results of Calcinator

CHAPTER 08

INSTRUMENTATION

8.1 Piping & Instrumentation Diagram

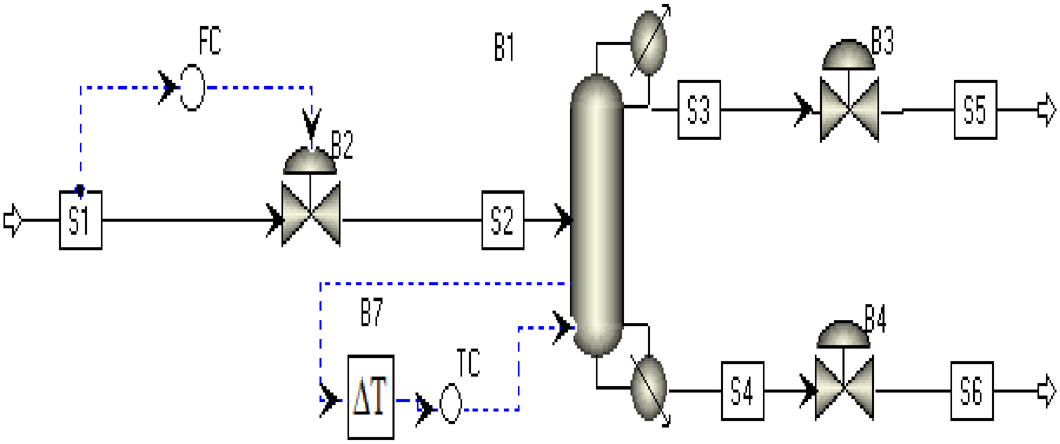


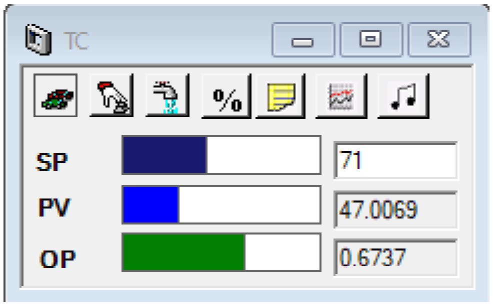
Figure 30: P&ID of Solvay Tower

8.2 Temperature Control

Set Point = 71° C

Integration Time = 1.18 min

Proportional Gain = 2.1147

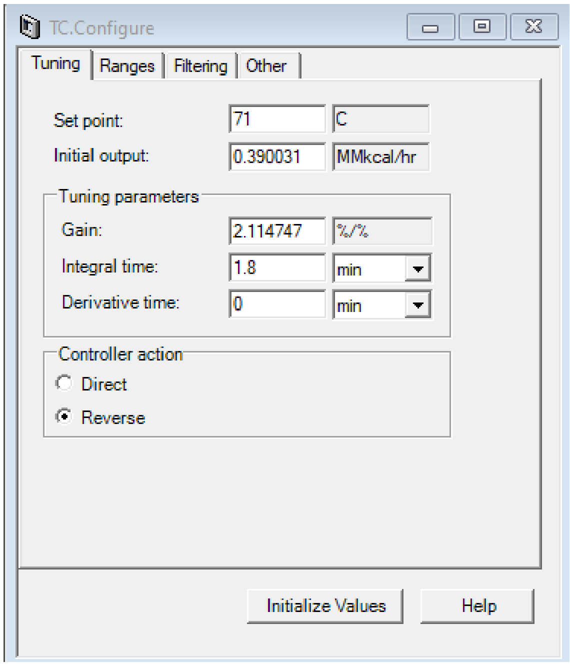


SP 71

PV 47.0069

OP 0.6737

Figure 31: Temperature Control of Solvay Tower



Set point: 71 C

Initial output: 0.390031 MMkcal/hr

Tuning parameters

Gain: 2.114747 %/%

Integral time: 1.8 min

Derivative time: 0 min

Controller action

○ Direct

● Reverse

Figure 32: Tuned Values

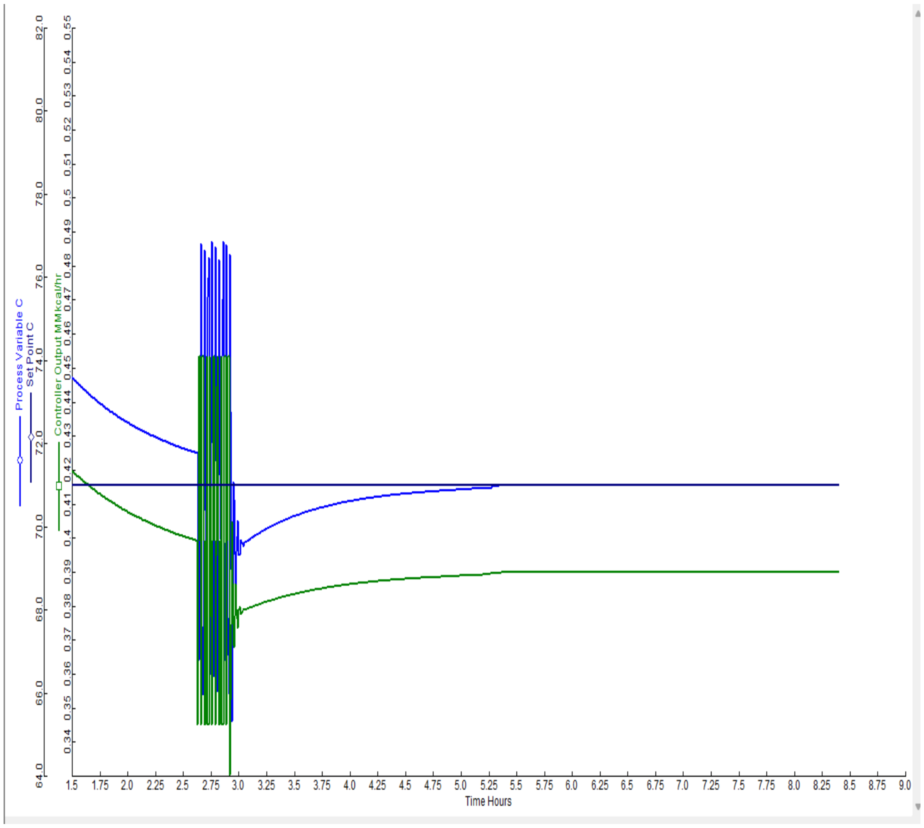


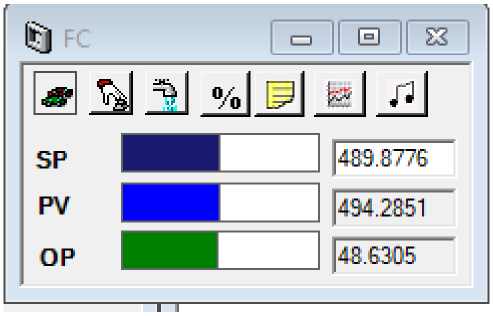
Figure 33: Temperature Control Graph

8.3 Flow Control

Set Point =490 kg hr^{-1}

Integration Time = 20 min

Proportional Gain = 1

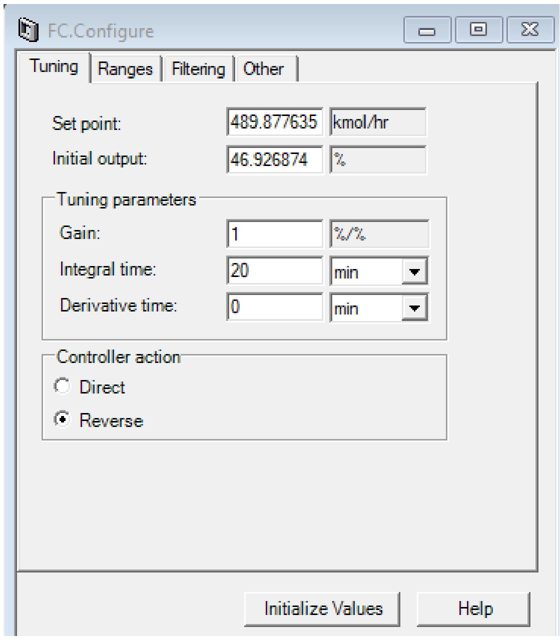


SP 489.8776

PV 494.2851

OP 48.6305

Figure 34: Flow Control of Solvay Tower



Set point: 489.877635 kmol/hr

Initial output: 46.926874 %

Tuning parameters

Gain: 1 %/%

Integral time: 20 min

Derivative time: 0 min

Controller action

○ Direct

● Reverse

Figure 35: Tuned Values

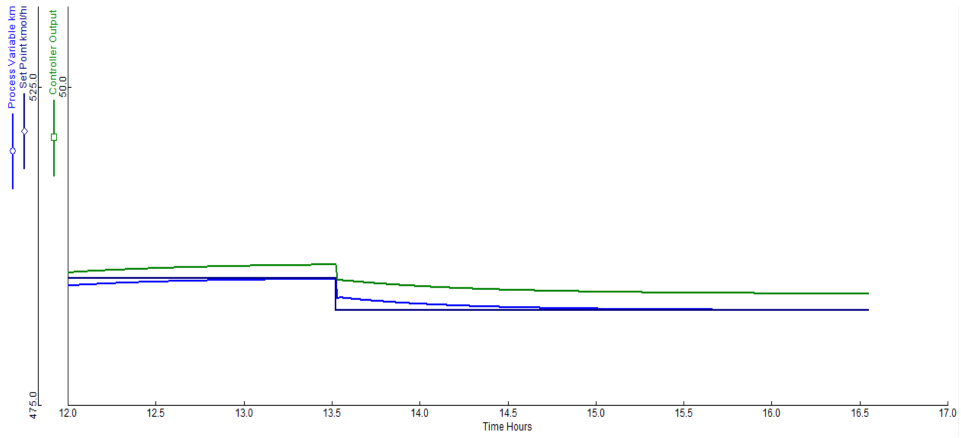


Figure 36: Flow Control Graph

8.4 Pressure Control

Set Point =2 bar

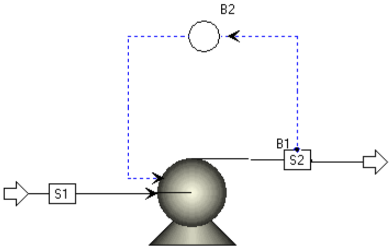


Figure 37: Pressure Control on Pump

CHAPTER 09

ECONOMIC ANALYSIS

9.1 Cost Analysis

The Cost analysis is a major part of a project as it gives us an insight into the financial feasibility of the proposed project. As a viable project is the one that produces the maximum amount of project at minimum cost, so it is necessary to economically validate the project. The cost analysis of the Solvay Process will help us the asses of the industrial scale implementation of the project. Our cost analysis will evaluate the revenue generated from the sales of the product.

We have used the Coulson and Richardson Vol.6 method for our project economic analysis assuming that the plant is operational 347 days a year.

9.1.1 Factorial Method Sample Calculation

Absorber:

Height = 13.7m

Diameter = 4.9m

Type of plates = Bubble cap

Material of construction = Stainless steel

Using values from Figure 40 and Figure 42, COST OF EQUIPMENT = $227,000

9.1.2 Graph and Tables for Calculations of Cost of Equipment

1 For Estimation of Cost of Heat Exchanger in USD following graph is used:

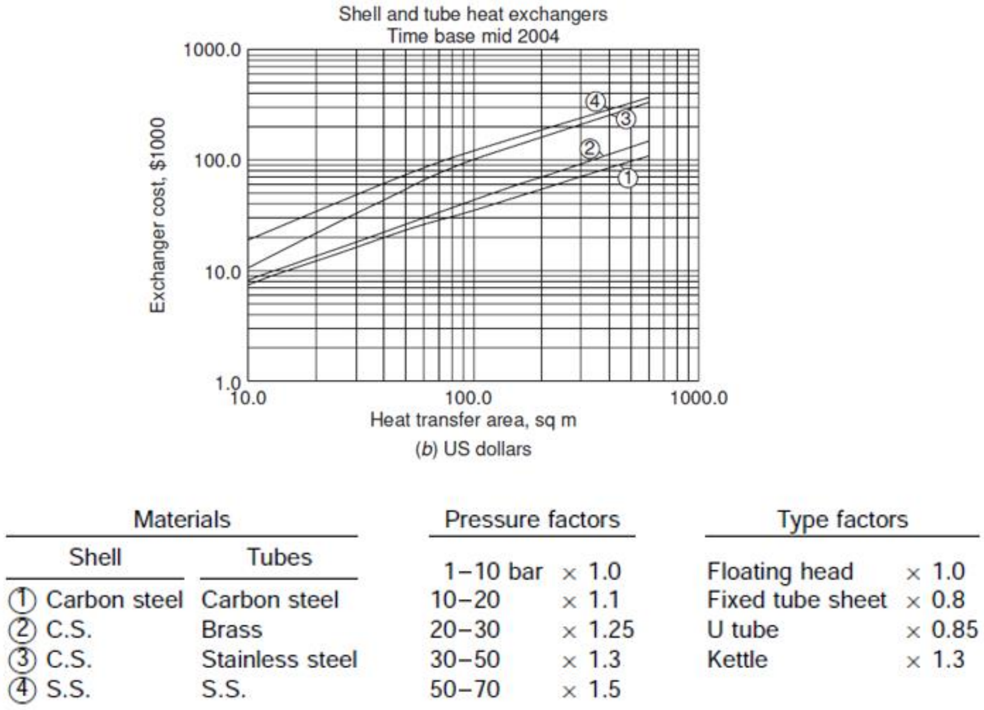


Figure 38: For Cost of Heat Exchanger

- For Estimation of Cost of Columns in USD following graph is used:

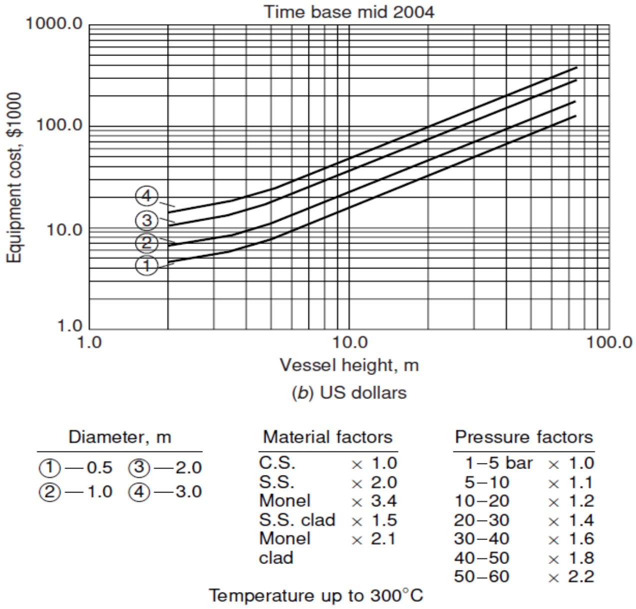


Figure 39: Cost of Column

2 For Estimation of Cost of Trays in Columns in USD following graph is used:

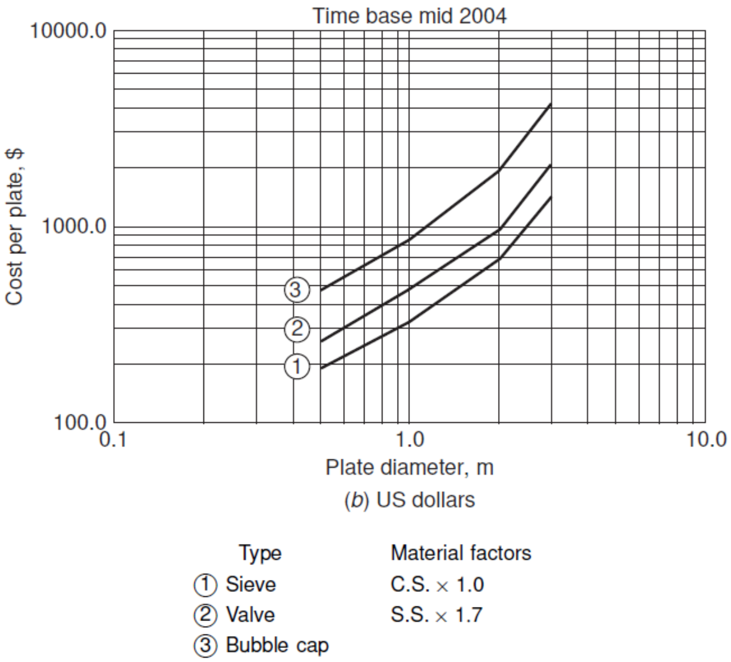


Figure 40: Cost of Trays

- For Estimation of Cost of Packing in Columns in USD following graph is used:

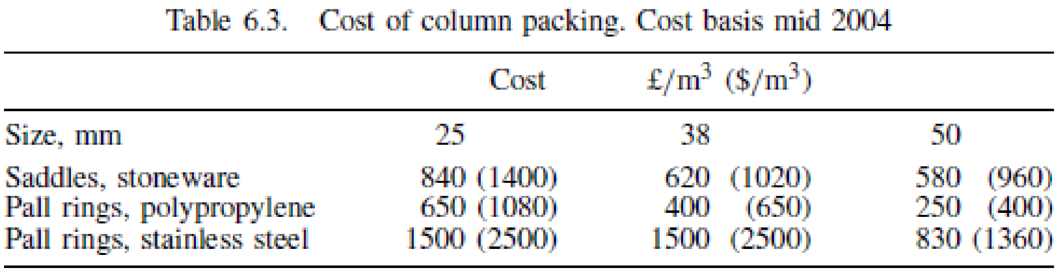


Table 6.3. Cost of column packing. Cost basis mid 2004

	Cost	£/m^3 ($/m^3)	
Size, mm	25	38	50
Saddles, stoneware	840 (1400)	620 (1020)	580 (960)
Pall rings, polypropylene	650 (1080)	400 (650)	250 (400)
Pall rings, stainless steel	1500 (2500)	1500 (2500)	830 (1360)

Figure 41: Cost of Packing

3 For Estimation of Cost of reactors, pumps, compressor, etc. in USD following table is used:

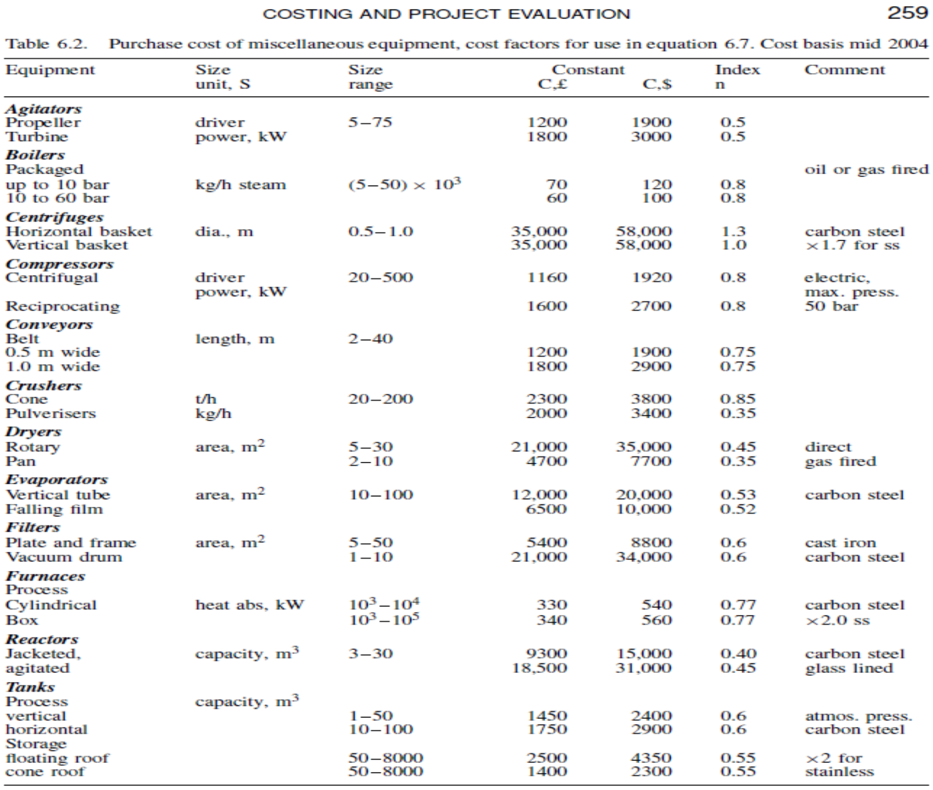


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Table 6.2. Purchase cost of miscellaneous equipment, cost factors for use in equation 6.7. Cost basis mid 2004

Equipment	Size unit, S	Size range	Constant C,£	Constant C,$	Index n	Comment
Agitators						
Propeller	driver power, kW	5–75	1200	1900	0.5	
Turbine			1800	3000	0.5	
Boilers						
Packaged						oil or gas fired
up to 10 bar	kg/h steam	$(5-50) \times 10^3$	70	120	0.8	
10 to 60 bar			60	100	0.8	
Centrifuges						
Horizontal basket	dia., m	0.5–1.0	35,000	58,000	1.3	carbon steel
Vertical basket			35,000	58,000	1.0	×1.7 for ss
Compressors						
Centrifugal	driver power, kW	20–500	1160	1920	0.8	electric, max. press.
Reciprocating			1600	2700	0.8	50 bar
Conveyors						
Belt	length, m	2–40				
0.5 m wide			1200	1900	0.75	
1.0 m wide			1800	2900	0.75	
Crushers						
Cone	t/h	20–200	2300	3800	0.85	
Pulverisers	kg/h		2000	3400	0.35	
Dryers						
Rotary	area, m^2	5–30	21,000	35,000	0.45	direct
Pan		2–10	4700	7700	0.35	gas fired
Evaporators						
Vertical tube	area, m^2	10–100	12,000	20,000	0.53	carbon steel
Falling film			6500	10,000	0.52	
Filters						
Plate and frame	area, m^2	5–50	5400	8800	0.6	cast iron
Vacuum drum		1–10	21,000	34,000	0.6	carbon steel
Furnaces						
Process						
Cylindrical	heat abs, kW	10^3-10^4	330	540	0.77	carbon steel
Box		10^3-10^5	340	560	0.77	×2.0 ss
Reactors						
Jacketed,	capacity, m^3	3–30	9300	15,000	0.40	carbon steel
agitated			18,500	31,000	0.45	glass lined
Tanks						
Process	capacity, m^3					
vertical		1–50	1450	2400	0.6	atmos. press.
horizontal		10–100	1750	2900	0.6	carbon steel
Storage						
floating roof		50–8000	2500	4350	0.55	×2 for
cone roof		50–8000	1400	2300	0.55	stainless

Figure 42: Costing Table

Following formula is used for this table:

$$Ce = CS^n$$

where Ce = purchased equipment cost, £,
S = characteristic size parameter, in the units given in Table 6.2,
C = cost constant from Table 6.2,
n = index for that type of equipment.

9.1.3 Purchase Cost of Equipment

Table 45: Purchase Cost of Equipment in USD

Specification	Equipment Cost ($)
Lime Kiln	146,000
Compressor 1 & 2	135,000
Lime Dissolver	110,000
2-Phase Separator	38,000
Amine R-Column	110,000
Solvay Tower	109,000
Absorber	227,000
Filter	137,000
Calcinator	125,000
Pump	50,000
Condenser 1 & 2	145,000
Dryer	135,000
Total	**1467000**

The PCE after adjusting for inflation is $ 2,700,000.

9.1.4 Total Investment Required

Table 46: Factors for physical plant cost (PPC)

f1 (Equipment erection)	0.45
f2 (Piping)	0.45
f3 (Instrumentation)	0.15
f4 (Electrical)	0.10
f5 (Buildings, process)	0.10
*f6 (Utilities)	-
f7 (Storages)	0.45
*f8 (Site development)	-
*f9 (Ancillary buildings)	0.20
f10 (Design and Engg.)	0.25
f11 (Contractor's fee)	0.05
f12 (Contingency)	0.10

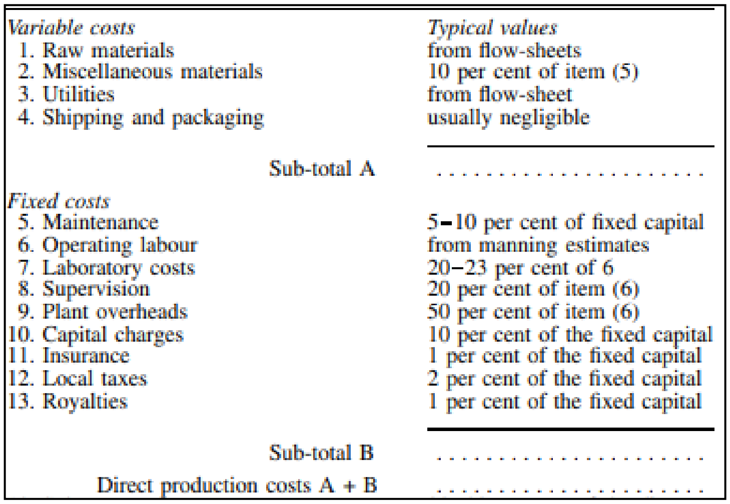
Table 47 Calculation of PPC and Working Capital

(Total Physical Plant Cost) PPC = PCE (1+f1+…….+f9)	7830000
(Fixed Capital) FC = PPC(1+f10+f11+f12)	12528000
Working Capital (15% of FC)	1879200
Total Investment Required (Fixed Capital + Working Capital)	**14407200**
Operating Time of Plant	347 days/year

9.1.5 Operational Cost

The operation cost includes two things.

- **FIXED COST**, the cost that does not vary with the production rate which includes:
- Maintenance cost
- Operating labor
- Laboratory cost
- Supervision
- Plant overhead
- Capital charges.
- **VARIABLE COST,** the cost that can vary with the production rate which includes:
- Raw material
- Miscellaneous operating materials
- Utilities



Variable costs	*Typical values*
1. Raw materials	from flow-sheets
2. Miscellaneous materials	10 per cent of item (5)
3. Utilities	from flow-sheet
4. Shipping and packaging	usually negligible
Sub-total A	....
Fixed costs	
5. Maintenance	5–10 per cent of fixed capital
6. Operating labour	from manning estimates
7. Laboratory costs	20–23 per cent of 6
8. Supervision	20 per cent of item (6)
9. Plant overheads	50 per cent of item (6)
10. Capital charges	10 per cent of the fixed capital
11. Insurance	1 per cent of the fixed capital
12. Local taxes	2 per cent of the fixed capital
13. Royalties	1 per cent of the fixed capital
Sub-total B	....
Direct production costs A + B	....

Figure 43: Variable and Fixed costs factors

Table 48: Fixed Operating Costs

Fixed Operating Cost	
Maintenance (3% of FC)	$ 375,840
Operating Labor (OL)	$ 43,244.68
Plant Overheads (40% of OL)	$ 17,297.87
Laboratory (20% of OL)	$ 8,648.94
Capital Charges (2% of FC)	$ 250,560
Insurance (1% of FC)	$ 125,280
Local Taxes (1% of FC)	$ 125,280
Total Fixed Operating Cost	$ **946,151.49**

Table 49: Variable Costs

Variable Costs	
1.Raw materials	$ 1660989
2. Miscellaneous materials	$ 59845
3. Utilities Power Water Steam	479166.272
Total = $ 2200000	

So Total Direct Cost is $ 3146151.49.

9.1.6 Revenue Generated

Table 50: Revenue Table

Revenue			
Product	**Production (kg/yr)**	**Price ($/kg)**	**Revenue Generated**
Sodium Carbonate	**31,446,648**	**0.29**	**9119527.92**
		Total Revenue/yr	**9119527.92**
		Total Profit/yr	**$ 5973376.43**

Profit =$ 5973376.43

Pay Back Period = $\frac{Initial\ Investment}{Profit}$

= 2.4 years

CHAPTER 10

HAZOP ANALYSIS

10.1 Introduction to HAZOP Analysis

A Hazard and Operability study of the proposed is fundamental to its technical feasibility from a safety point of view. Conventionally, such analyses usuallyinvolve using specific guidewords to assess the cause, effects, and preventative measures for the process. Examples of said guidewords may be “high temperature”, “low pressure” or something else of the sorts. These guidewords vary with the equipment under study within a system. Each component within a system must be considered for a thorough risk assessment. The guidewords are essentially deviations that may potentially be encountered within the equipmentand help to imagine several possible scenarios. HAZOP involves.

- Brainstorming and identifying potential deviations and guidewords applicable to the system.
- Conducting a qualitative risk assessment to determine the severity of each deviation.
- Employing a "bottom-up" approach that relies on the experience and predictive abilities of the observer.

10.2 Keywords

In the HAZOP study, various terms and concepts are utilized:

1. **Nodes:** These refer to pipe sections or vessels where process chemicals are present.
2. **Super nodes:** Multiple nodes considered together as one for more efficient analysis.
3. **Hazard:** A potential source of harm.
4. **Harm:** Actual injury or damage to equipment, personnel, or the environment.

5. **Risk:** The probability of harm occurring and the associated level of damage.

10.3 Methodology

The methodology for conducting a HAZOP study involves the following steps:

1. Identify all major nodes and super nodes within the system.
2. Justify why each node has been selected for the HAZOP study.
3. Choose a key process parameter for each node.
4. Apply relevant guidewords to the chosen parameter, identifying potential deviations in the process and documenting them.
5. Determine the potential causes for the identified deviations and add them to the analysis table.
6. For each brainstormed deviation, identify the consequences it would lead to and document them.
7. Repeat steps 3 through 6 for the remaining nodes until all chosen nodes have been thoroughly studied.

Following this systematic methodology ensures a comprehensive evaluation of the system, enabling the identification of potential hazards and the implementation of appropriate preventive measures.

10.4 HAZOP ANALYSIS On Pump

Table 51: HAZOP on Pump

Parameter	Guide Word	Causes	Consequences	Actions Required
Flow	**NO**	blocked pipelines, pump failure	Upset in downstream	Proper monitoring of pumps and installation of alarms on valve

	More	Too high shaft power	More energy consumption	Check and decrease the speed of shaft rotation, check operating procedures
	Less	low rotational speed of shaft, improper suction at the inlet, partial opening of downstream valve	Upset in downstream	1. Check and increase speed of shaft rotation. 2. Install control system to change valve opening according to flow
Pressure	**NO**	pump failure, power outage, shaft failure, faulty pressure sensor	Upset in downstream	Maintenance procedures
	MORE	Operating fault, Faulty pressure sensor	Explosion, deterioration of bearings,	Install high pressure alarms

	LESS	pump failure, power outage, shaft failure, faulty pressure sensor	Upset in downstream	Maintenance procedures

10.5 HAZOP ANALYSIS On Solvay Tower

Table 52: HAZOP on Solvay Tower

Process Variable	Guide Word	Deviation	Causes	Consequences	Actions
Pressure	**LESS**	Less than required pressure in column	Increase in inlet steam pressure	Plate efficiency decreases Desired results will not achieved	Apply pressure safety valve PSV
	MORE	More than required pressure in column	Breakage in vessel wall	Plate efficiency decreases	Apply low pressure alarm Apply pressure control loop

					Check for breakage in vessel wall
Flow	**No**	No flow in column	Pipe blockage Control valve failure Pump failure	Column dry out No operation Upset in downstream process	Install low level alarms Check maintenance procedure and schedule Make bypass Emergency plant shut down
	MORE	More flow in column	Control valve fully opened Control valve failure	Temperature of column falls Rise in bottom	Install high level alarms Install Flow Controller Check maintenance procedure and schedule

Process Variable	**Guide Word**	**Deviation**	**Causes**	**Consequences**	**Actions**
Level	**LESS**	High level	Blockage in outlet More pressure drops across column	Over pressure	Install high level alarm. Check maintenance procedure and schedule
	MORE	Low level	Partially clogged pipe Leakage in pipe	Level decrease in column	Install low level alarm Check maintenance procedure and schedule
Temperature	**High**	High temp of column	Increase in steam temperature or flowrate	The desired reaction will not take place	Apply temperature control loops to regulate feed preheating Apply temperature and flow

					control loop on steam
	Low	Low temp of column	Heat loss to surrounding Decrease in steam temperature or flow rate	Decrease in column temperature. Desired Results will not achieved	Check steam pressure or flow rate Install low temperature alarm

CONCLUSION

In conclusion, the Solvay Process is an efficient and eco-conscious method for soda ash production by ingeniously combining limestone, ammonia, common salt, and carbon dioxide. The Solvay process remains a pivotal method in industry for the production of sodium carbonate (soda ash), owing to its efficiency, cost-effectiveness, and utilization of abundant raw materials. Its ability to recycle ammonia and produce high-purity soda ash has cemented its role as a preferred method over other alternatives.

Moreover, the moisture removal efficiency from bicarbonate crystals is also increased from 60% to 80% by adding the rotary drum dryer in this plant. By adding this part, the overall efficiency of the process is also enhanced up to the 85%. It is a streamlined process which minimizes the carbon footprint and waste generation. This objective is achieved by adding the CO_2 recycle plant within the system. We have added a condenser and 2-Phase separator for the recycling of the CO_2. By this plant the waste generation is also reduced, and this project also becomes the cost effective because of this recycling plant.

This process is also going to be cost effective despite the demanding operating since the payback period on the investment made within three years of plant operation. The Pakistan will have to import a lower amount of Soda Ash and Calcium Carbonate if these types of plants are installed within our country.

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