Process Design and Simulation of Sulphuric Acid Plant

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Certificate

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Dedication

From the grace of Allah, this piece of work is dedicated to our teachers and parents, who were a source of constant support and have helped us in becoming the people we are today.

Acknowledgements

Thanks to **Almighty Allah** for His countless blessings, He gave us courage to finish this project. A very special recognition to our Supervisor, **Dr. Iftikhar Salarzai** for supervising this project and for his support us throughout the year. Because of his experience and knowledge, we are able to complete this project. We express our profound gratitude to **Mr. Fahad** from **International Petro-Chemicals (IPC)** for giving us this project and believing in us. Furthermore, we extend our gratitude to him for his continual provision and guidance. He has been an immense source of assistance. We couldn’t have completed all the necessary paperwork and delivered it properly without him. We are able to achieve this milestone due to love and prayers of our beloved **parents**.

Abstract:

Sulphuric acid is an important chemical produced through Contact Process all over the world. Our study presents the steady state model, simulation for an industrial sulfuric acid plant. The model, implemented in Aspen-HYSYS includes a catalytic reactor (four pass converter), heat exchangers, mixers, splitters and reactive absorption columns. In a single integrated environment, Aspen HYSYS V8.8 was used successfully for the design of all sulfuric acid subprocesses. Real plant data and theoretical data for maximum percent SO2 oxidized material and energy streams agree very well with the simulation results, sized unit operations can be used to perform an economic assessment of each process. The developed simulation model can also be used as a guidance on process and economic understanding and a basis on which more sophisticated plant design and process equipment design models can be specified. Before Simulation, each of the important equipment has been designed i.e. Reactor, Absorber and heat exchanger. Following the equipment design, extensive economic analysis has been carried out to estimate the cost and payback period of a Sulphuric acid plant. One of the main objective of the project is to carry out a sensitivity analysis. It has been carried out using a MATLAB code to extract data from excel sheet and apply it in Aspen HYSYS. Process Control has been described using a temperature controller and a flow controller on reactor and heat exchanger. HAZOP Analysis on reactor and absorber has also been completed and demonstrated.

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Chapter 1: Introduction

1.1 Background

Sulfuric acid is an odorless, colorless hygroscopic liquid that has a corrosive nature (depending on the level of acidity) and also holds the title of “King of Chemicals” due to its vast use in the chemical industry on commercial and domestic scale. Sulfuric acid is the most widely produced industrial chemical in the world and utilization of sulfuric acid is frequently used to scale a nation's level of industrialization. Every year, sulfuric acid is being produced industrially in greater quantity as compared to all the other chemicals. Currently, the world-wide production exceeds 170 million of tones, with Asia as USA as the top consumers (Fig. 1).

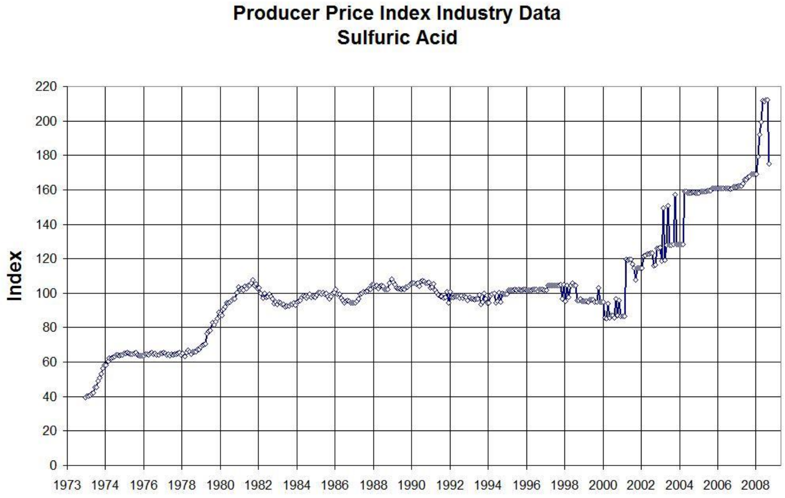


Figure 2 Producer Price Index Industry Data

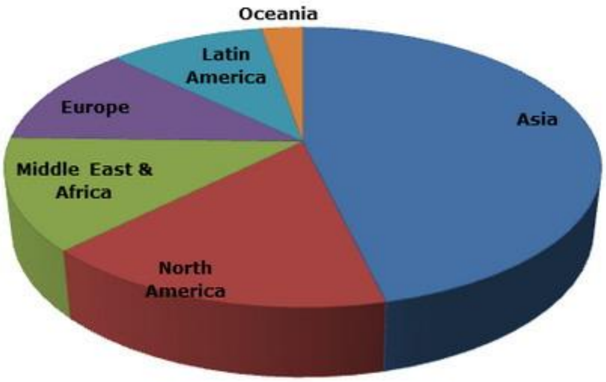


Figure 1 Regional Sulphuric Acid

Sulfuric acid is a particularly toxic and corrosive acid, with extreme environmental and health hazards if not fabricated, utilized, and directed properly. Sulfuric acid has a wide range of uses including: explosives, drugs, paints, food containers, wood preservatives, soaps and detergents, pharmaceutical products, petroleum products, pulp and paper phosphate fertilizer production, dyes, alcohols, plastics, rubber, ether, glue, film. One of the major uses of H2SO4 is its use in the automotive industry. Batteries used in car industry contains extensive measure of sulfuric-corrosive. Likewise, sulfuric acid market is expanding its interest because of mechanical cleaning operators as sulfuric acid is additionally used as cleaning specialist and channel cleaner, the interest for sulfuric acid is expanding at yearly development rate of over roughly 6.5%. In chemical industry, Sulfuric acid is being used broadly as a solvent for ores and as catalyst for polymer manufacture and petroleum refining. Agricultural fertilizers signify the biggest consumers of the sulfuric acid, accounting for up to 65% of its usage.

It is advantageous to set up the sulfuric acid industry near the product acid's point of use—i.e. near phosphate fertilizer plants, petroleum refineries etc. since, elemental sulfur is easier and cheaper to transport than sulfuric acid. Note likewise, that the irregularity of the sulfuric acid cost is because of the little uneven characters between acid's interest and supply, just as the trouble of putting away vast amounts of acid. The recent large increase in price is due to increasing demand for fertilizer, hence sulfuric acid. There is a need in the market to produce high value products at lower costs. Technology is fundamental to the profitable design and operation of environmentally friendly sulfuric acid plants and processes.

Let's talk about the methods through which the sulfuric acid was produced initially on an industrial scale versus the modern methods and techniques. The main two methods for the production of sulfuric acid on a commercial scale are as follows;

I. Lead Chamber process
II. Contact process

Following is the process to produce sulfuric acid through contact process

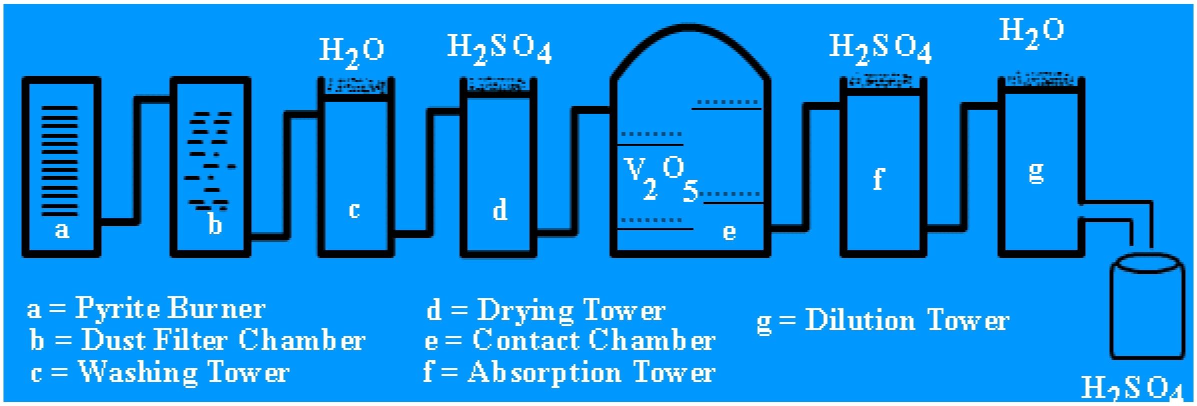


Figure 3 Contact Process

Initially, sulfuric acid was produced industrially through the lead chamber process. In lead chamber process, SO_2 is offered with steam and NO_2 into reaction chambers fixed with sheet lead where the gases are splashed down with water and chamber acid (62– 70% Sulfuric corrosive). The, SO_2 and NO_2 disintegrate and it takes roughly 30 minutes for the sulfur dioxide to oxidize to sulfuric acid. The presence of nitrogen dioxide is fundamental for the response to continue at a sensible rate. The procedure is very exothermic, and a noteworthy thought of the plan of the chambers was to give an approach to disperse the heat released in the process. However, lead chamber process was discarded and replaced by a better and more efficient process that is the "Contact Process". Lead chamber process was in-efficient because it requires high electricity and continuous supply of the air, it generates solid particles which requires the sludge removal, the product could be poisoned due to the leakages of lead ions into the acid stream. One of the major bottleneck of this process was that it could only produce sulfuric acid with a concentration of 70-78%. For higher concentrations, the distillation was to be repeated again and again which was not feasible.

On the other hand, contact process is more efficient, environment friendly, does not produce any environmental hazards unlike toxic chemicals in lead chamber process. Through this process we can achieve sulfuric acid with a high concentration of 98.5%. The catalyst used is vanadium penta-oxide V_2O_5. Although the catalyst is a bit expensive, it proves its worth by covering a life span of 4-5 years.

1.2 Objective

The motivation behind this project was to inspect how modeling technology can help in debottlenecking existing plants, achieving high product purity, making it energy efficient, and automate process analysis to optimize plant operations. A simulation model of the contact process Sulfuric acid plant along with proper catalytic bed distribution in converter was proposed and developed in Aspen-HYSYS. Different parameters influencing converter performance was observed. A detailed sensitivity analysis was performed using three software's i.e. MATLAB, Aspen HYSYS and Microsoft Excel to determine the optimum conditions for the process and also the factors that most effectively influence the production of our final product (sulfuric acid). Intercept temperature for maximum SO2 oxidation for each bed was determined and further used in the model. Sulfuric acid plants are net producers of steam; so, it was also determined how effective decisions on steam boilers (exchangers) can be made using sulfuric acid plant models. For this purpose, we performed major equipment designs including the reactor, absorber and heat exchangers, and also the HAZOP analysis and the cost analysis of the whole plant. Moreover, current legislation imposes tighter restrictions to reduce the impact of chemical process industry on the environment. The proposed model implemented in Aspen-HYSYS is useful for evaluating the static behavior of the plant and for minimization of the total amount of SOx emissions. The simulation model was also compared with existing plant with same operating condition to verify the acceptability of the model.

Chapter 2: Literature Review

2.1 Overview of Sulphuric Acid Plant

Sulphuric acid is the most produced chemical compound in the world. In 2011, about 168 million tons of about 10 billion USD, were the annual Sulphuric acid production.

Any concentration of Sulphuric acid in water is soluble. Different methods produced sulphuric acid, but the contact process is most important.

The lead chamber process for the sulphuric acid production was initiated during the 1700's and used until 1831 during the introduction of the contact process. Due to the high purity of sulphuric acid produced by this process, industries have shifted their plants towards contact process.

It is observed that both processes are performed quickly and continuously in industrial applications.

The reasons behind these process steps were explained, acid control and optimization were considered. SO2 (g) oxidation efficiency and its impact on the composition of feed gas, feed gas temperature, catalyst composition, catalyst bed pressures, number of catalyst beds, and double versus single contact acid production are highlighted. A review of several other SO2-carrying gas treatment methods is also included.

2.2 Commercial Grade Sulphuric Acid Production Process

A plant that produces sulphuric acid from sulphur as a raw material has following main sections:

- Sulphur feed
- Waste heat recovery
- Conversion of SO2
- Acid towers
- Acid Storage handling
- Plant infrastructure (electrical/civil/water treatment, etc.)

2.3 Sulphur Burning

Solid sulphur is introduced on the melter's grids and melted by heat supplied by steam rolls in the melter. The sulphur is fastly fused by an agitator installed into the melter. The liquified sulphur is then pumped into the pressurized sulphur filter and placed in an independent cabinet with steam coils. Sulphur pumps are used for the predetermined constant feeding of fluid sulphur into the sulphur burner. A previous oil firing preheats sulphur Brunner to a high temperature and therefore instantly ignites the sulphur that produces sulphur dioxide. A drying tower contains blower with which the dry air is supplied as a raw material to the furnace.

The combustion gases are 950–1000 degrees Celsius and contain 10.0–10.5 per cent sulphur dioxide. They pass a waste heat recovery heater to produce a high-pressure steam while gases are cooled down to between 390 and 410 ° C, according to the design of the plant and the layout of the gas duct.

The cooled gasses now go through a multi-stage conversion system (four or five phases) (the first converter has three passes and the second one/ two passes).

2.4 Conversion of SO2 to SO3

This is main process taking place to produce sulphuric acid. It’s a catalytic gas phase equilibrium reaction:

$$SO + 1/2O_2 \rightarrow SO2 \qquad \Delta H = -99 \text{ kJ.mol}$$

The conversion of SO2 to SO3 reaction can be found by:

$$\text{Conversion achieved} = \frac{SO_2in - SO_2out}{SO_2in} * 100$$

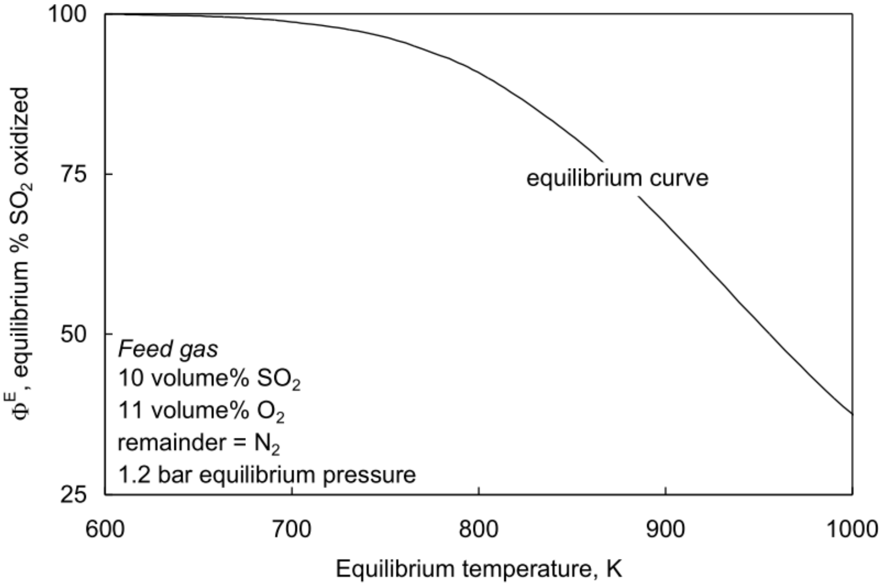


Figure 4 Equilibrium temperature vs conversion

The maximization of formation of SO3 takes account of both the thermodynamic and the stoichiometric considerations. In deciding how to optimize the balance, the Le Chatelier's-Braun principle is usually taken into account. It says that the system tends to adjust itself to relieve a part of the stress when a balance system is subjected to stress. For example, these stresses include changes in temperature, pressure or reactor concentration.

The following approaches to maximize SO3 formation for SO2/SO3 systems are available:

- Removal of thermal energy-
  the reduction of temperature promotes the development of SO3, because it is an exothermic process
- Enhancing the oxygen concentration at the inlet
- Removal of SO3 (dual contact dual absorption) from the reaction area
- Enhanced system inlet pressure
- Optimization of process temperature by selecting suitable catalyst
- Increased reaction time

The optimal complete conversion of SO2 in the system requires a balance of forward and reverse response velocity (equilibrium achieved). This optimum, however, depends on the raw gas SO2 concentration and on its time variability. Consequently, for a particular SO2 source, each method is more or less specific.

The classic vanadium pentoxide systems have a cesium-friendly ring type, both in the first and last (fourth / fifth), and in the other two / three passes. A second waste heat boiler is supplied after the first catalyst pass to recover additional heat. The customer can supply a vapor superheater in the waste heat recovery system to export vapor to nearby manufactory or to generate superheated steam for captive use. Gasses of the second catalyst pass the Hot Heat Exchanger (HHE) before entering the third catalyst pass. Cold Heat Exchanger (CHE) and then an economizer passes through the gasses of the 3rd pass outlet. It comes next and absorbs all the sulphur trioxide produced by the converter's first three passes. High efficiency candle type demisters are used to remove the acid mist generated in the tower to protect the catalyst in the afterward passes. The design of the gas piping layout provides for the economizer to be either in service or to be commissioned.

At the end of the fourth pass a dry air injection plant is sometimes provided for cooling the gasses before the fifth pass reaches about 380–390 ° C. This is done in order to maximize the overall transformation from SO2 to SO3 because the last pass can be operated at the lowest possible temperature.

Before entering the final absorption tower, the gasses from the fifth pass are transported via another economizer for pre-heating boiler feed water. DT (Drying Tower), IPAT (Inter Pass Absorption Tower), and FAT (Final Absorption Tower) circulating sulphuric acid are refrozen by the passage through the plate heat exchanger where heat and the refrigerant water are exchanged. A sufficient size cooling tower lowers the temperature of water.

2.5 Catalyst Temperature Limitations

The elements V, K, Na, Cs, S, O catalyst work for a reaction when they are molten. It melts around 410^0C, slightly lower when there are cesium ions. When the temperature rises till 630^0C the activity of the catalyst starts losing due to the formation of non-reactive vanadate ions and by non-reversible reaction with silica substrate. So, the SO2 oxidation should be optimum in between 450-500^0C.

2.6 Absorption of SO3

Appropriate amounts of water are added to preserve the concentration of the hot sulphuric acid absorbed into H2SO4 (with an optimal concentration of at least 98 percent). The absorption efficiency depends on the following:

- concentration of H2SO4 in absorbing liquid (98.3–98.7%)
- liquid temperature range (normally 70 °C–120 °C)
- Plate Heat Exchanger (PHEs) used for removing heat of absorption for sulphuric acid coolers
- Its difficult to absorb acid mist particles so moisture content is removed from raw gas
- Sulphuric acid mist is removed by mist arrestor
- Entering gases temperature

Emission of SO3 from plant depends upon:

- Final absorber construction
- The presence of water vapor forming acid mist at the upstream of absorber.
- H2SO4 aerosol separator

The strength of the absorbing acid is kept automatically at the optimal position on the strength controller in modern plants. The addition of dilution water is checked.

2.6 Gas Cleaning Systems

The gas cleansers of the metal sulphuric acid plant have four main tasks:

- SATURATION of gases and ELIMINATION of fine and coarsely particulate matter, and
- COOLING of metal fumes and humidity removal;
- ELECTROSTATE PRECIPION for removal of very fine particles and the bulk of acid mist;
- Specific gas impurity removal processes (e.g. removal of mercury, halogens)

2.7 Tail Gas Scrubber

During plant start-up a two-stage alkaline scrubber is used to cater for disturbed process conditions after a long stop. Alkali levels are maintained automatically in the scrubbing liquor.

In the continuous operation of the plant, the scrubber will not be required if a catalyst promoted by cesium is used in the last pass of the transformer at sufficient amounts and operates at 385 to 390 ° C.

2.8 Equipments used in Contact Process

2.8.1 Drying Tower

It is the first equipment in the process which is used to remove the water from the air because dry air is required to produce SO2.

2.8.2 Burner

It is the first equipment present in the contact process. Molten sulphur is reacted with air in the burner to produce SO2 gas for the further process. The SO2 produced here depends upon the flow rates of air and molten sulphur entering it.

2.8.3 Heat Exchanger

It is the temperature regulating equipment in the process after the burning of sulphur in furnace the temperature raises to above 1200^0C which is to be lowered to 450^0C because it is the optimum temperature at which the reaction will take place. In this process shell and tube heat exchanger is used in which SO2 gas is in the tubes and water is in the shell side.

2.8.4 Reactor

In any process reactor is the main equipment. The reactor used in the process is packed bed reactor. There are four beds of Vanadium Pentoxide (V2O5) catalyst. The operating pressure of the reactor is 1-2 bar and the temperature range are $450\text{-}500^0$C. in reactor SO2 is being converted into SO3.

2.8.5 Absorber

In absorbers the SO3 is being absorbed in water to produce sulphuric acid. Two absorbers are added to the plant to achieve required 98.5% purity of sulphuric acid.

2.8.6 Coolers

Coolers are used where temperature of the feed are required to be lowered.

2.8.7 MixingTees

At several place mixing tees are used to mix pure sulphuric acid with water to make it 98-98.5% pure.

2.9 Usage of Sulphuric Acid

2.9.1 Fertilizer

Globally, the quality and yield of fruits and vegetables in fertilizers are increased by three primary nutritional products: nitrogen, phosphorus and potassium. Some fertilizers, including mono-ammonium phosphate (MAP) and di-ammonium phosphate (DAP) two-component fertilizers, offer farmers an effective way to supply soils with nitrogen as well as phosphorus. The production of both MAP and DAP, mixed with phosphate rock to produce phosphoric acid, takes sulphuric acid as a first important step.
Since the energy consumption of the phosphorous acid process is a critical part of the fertilizer process, a sulphuric acid plant – a net generator of energy – on the site. 70% world
wide manufacture of superphosphate fertilizers involves the use of sulphuric acid.

2.9.2 Processing of Metal Ores

In the production of copper and in the production of zinc, the surface, known as "pickling," is widely used in metal processing and in the cleaning before it is covered into a thin layer of tin for the production of food canned cans.

The solvent sulphuric acid is used to leach the desired metals from the earth's ores. In uranium mining and for zinc and nickel ores sulphuric acid leaching is used.

2.9.3 Industrial Usage

Industrially sulphuric acid is the most used chemical compound that is used to make or in the processing of other useful products.

It is currently being used in:

- Processing on paper pulp
- To make caprolactam which is converted in polyamide 6
- Manufacturing of titanium dioxide used as a pigment
- Manufacturing of hydrofluoric acid, phenol and propanone
- Manufacturing of detergents

2.9.4 Electrolyte in batteries

Sulphuric acid is widely used in motor batteries as an electrolyte since sulphuric acid supplied ion is required for the recharge and discharge of lead acid batteries. Sulphuric acid is cheap, so it is the best way to get this ion.

2.10 Environmental Issues

Several toxic gasses are generated during the production of sulphuric acid. SO2 is one of the most hazardous gas. It's a toxic gas that smells like a burnt gas. Sulphur dioxide is a major pollutant of the air and has major health effects. Moreover, the sulphur dioxide concentration in the atmosphere can affect the suitability of the habitat for plant and animal communities.

Sulphur dioxide inhalation is linked to increased respiratory symptoms and disease, respiratory difficulties and premature death. The limit to 0.25 parts per million (ppm) is short-term exposure.

Existing heart and lung conditions may also be exacerbated by longer exposures. In addition to health effects, sulphur dioxide and other SOx are partly attributable to thick haze and smog.

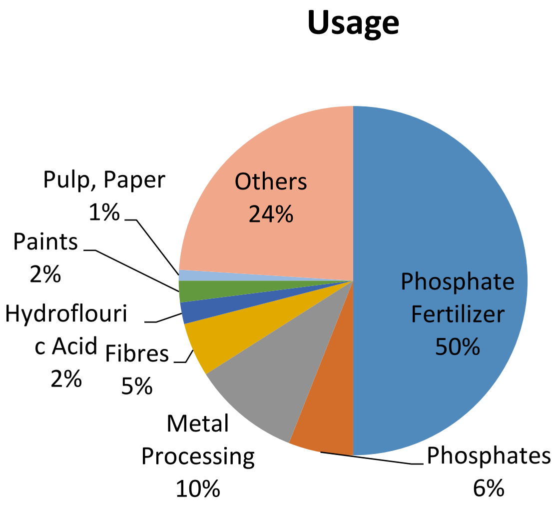


Figure 5 Sulphuric Acid Usage

In addition to the effects on human health, the contribution of sulphur dioxide to acid rain can cause direct damage to trees and plants by damaging exposed tissue and consequently decreasing the growth of plants. Acid rain also affects other sensitive ecosystems and waterways.

2.11 Aspen ONE Engineering for Sulfuric Acid Plant

Aspen ONE Engineering provides engineers with Aspen HYSYS to prepare simulated models of plants to check the validity of plants and make the changes that will economize, maximize yield and efficiency and reduce capital cost generating more profits. It has been used by plant owners, companies and technology providers. Simulated model of sulphuric acid plant can also be made on Aspen HYSYS. It is challenging because the cost of maintenance and operation of this plant is very high, minimization of SO2 emissions, energy economization, and accurate equipment size is to be kept in mind.

Aspen ONE provides the world’s largest data base of pure components, compounds, and phase equilibrium data for conventional chemicals, electrolytes, solids and polymers. The physical and thermal properties in the data base are updated time to time with the reference data from U.S National Institute of Standards and Technology (NIST). High accuracy of the data is required because the physical properties data is critical for developing a simulated model of any plant in Aspen HYSYS. It directly affects the cost and other perspectives of the plant.

The enabling of electrolyte feature in Aspen HYSYS is another plus point that improves the accuracy of the calculations done in vapor-liquid phases in the adsorption units in sulphuric acid plant.

Sulphuric acid simulation model was made to do parametric study to analyze the effect of process variables on the production of sulphuric acid.

2.11.1Limitations of Aspen- HYSYS in simulation of Sulfuric acid plant

Aspen HYSYS provides some ease to the engineers whereas there are some limitations that are to be tackled when designing a simulation of sulphuric acid plant on Aspen HYSYS. First and the most important the catalytic bed reactor used in industry is a single reactor that is not present in the Aspen HYSYS. Not even similar reactor is not present so either one has to use PFR or conversion reactors equal to the no of beds in the catalytic reactor being used in the industry. Another limitation is the choice of the reaction kinetics concerning the built-in expression and its required parameters. Another equipment that is not available in the HYSYS is reactive absorption column.

Tentative Process Flow Diagram

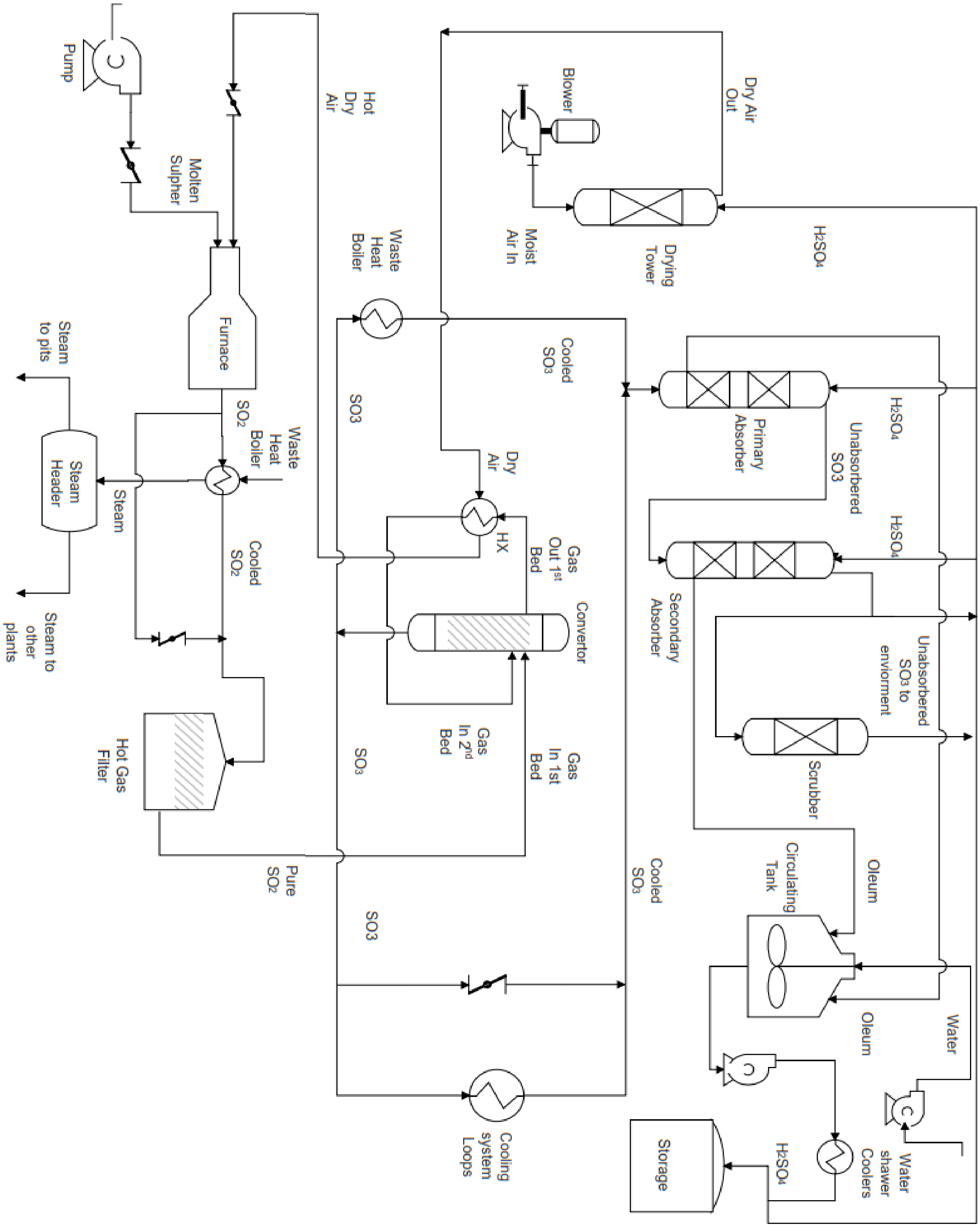


Figure 5 Process Flow Diagram

Chapter 3: Material and Energy Balance

3.1 Material Balance

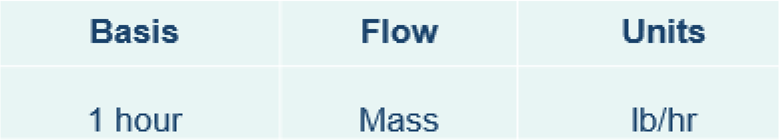
- Material Balance is based on the law of conservation of mass (what goes in, comes out).
- It is calculated using the inventory rate equation

Mass Flow In – Mass Flow Out + Mass Generated = Mass Accumulated

Sulphuric Acid Manufacturing Process

- **Continuous Process (No Accumulation)**
- **No Generation**

Thus, the inventory rate equation reduces to
Mass Flow In = Mass Flow Out



Basis	Flow	Units
1 hour	Mass	lb/hr

- 98-98.5 wt.% Sulphuric acid is to be produced.
- Plant is designed to produce approximately 130 tons/day of Sulphuric acid.
- Molten Sulphur Feed: 27000 lb/hr
- Moist Air: 224000 lb/hr
- Each Pass Conversions

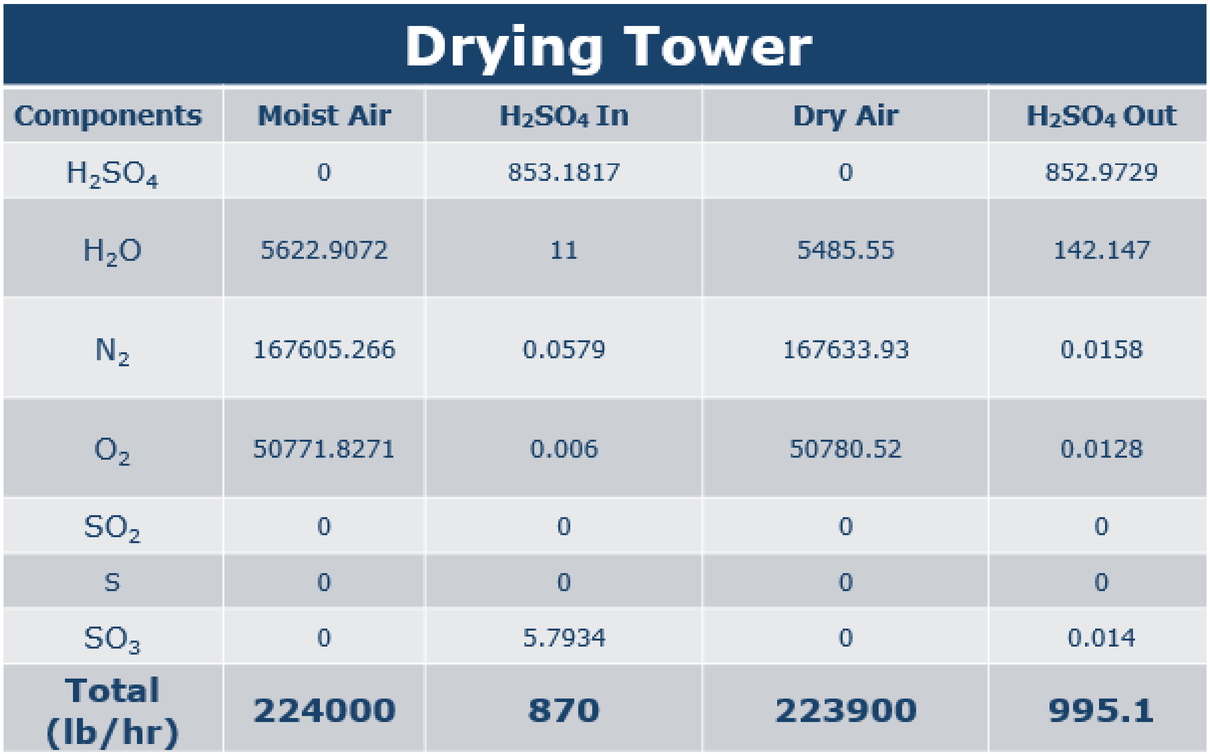
1st Pass: 63%
2nd Pass: 84%
3rd Pass: 93%
4th Pass: 99.5%

3.2 Material Balance on all equipments

1) Drying Tower

Moist air is being dried using sulphuric acid which is being recycled as part of the product stream. Moisture is being removed and dry air goes to the furnace to react with sulphur. Sulphuric acid attracts moisture and takes away the moisture with it.

Table 1 Material Balance on Drying Tower



Drying Tower

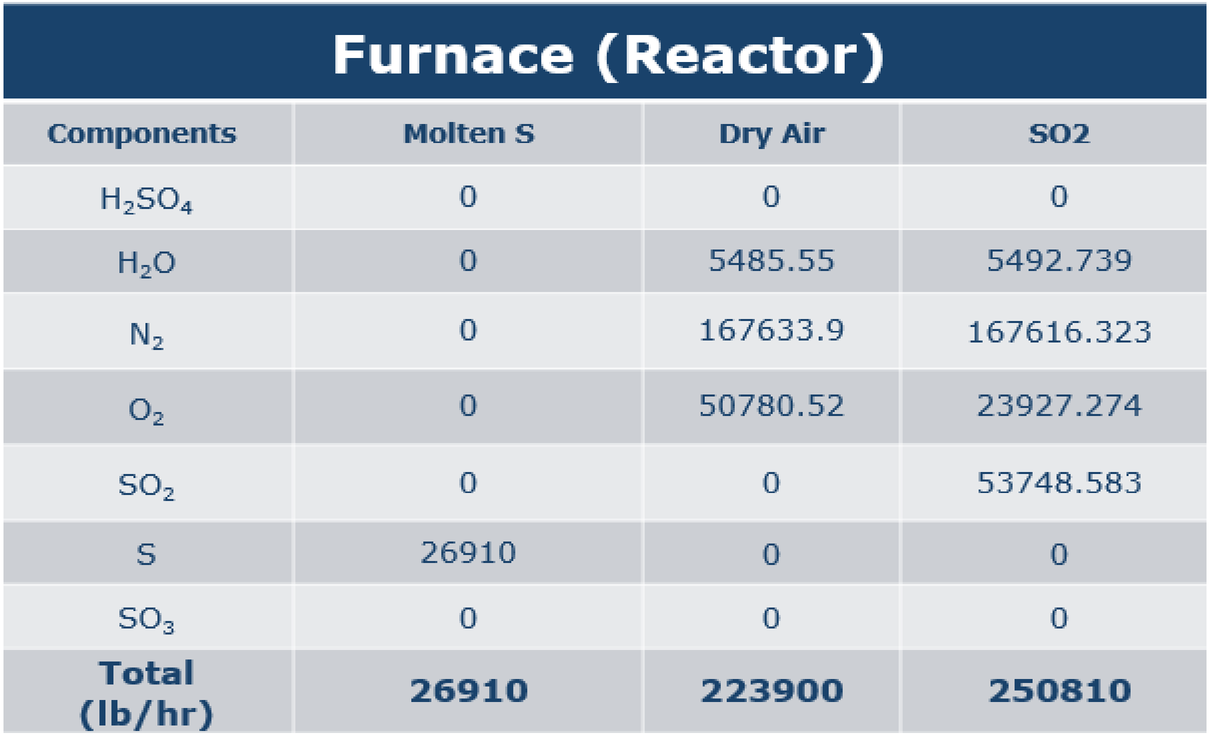
Components	Moist Air	H_2SO_4 In	Dry Air	H_2SO_4 Out
H_2SO_4	0	853.1817	0	852.9729
H_2O	5622.9072	11	5485.55	142.147
N_2	167605.266	0.0579	167633.93	0.0158
O_2	50771.8271	0.006	50780.52	0.0128
SO_2	0	0	0	0
S	0	0	0	0
SO_3	0	5.7934	0	0.014
Total (lb/hr)	**224000**	**870**	**223900**	**995.1**

2) Furnace

Dry air from drying tower enters the furnace and reacts with sulphur to form sulphur dioxide with 100% conversion. Following reaction takes place in the furnace.

$$S + O_2 \longrightarrow SO_2$$

Table 2 Material Balance on Furnace



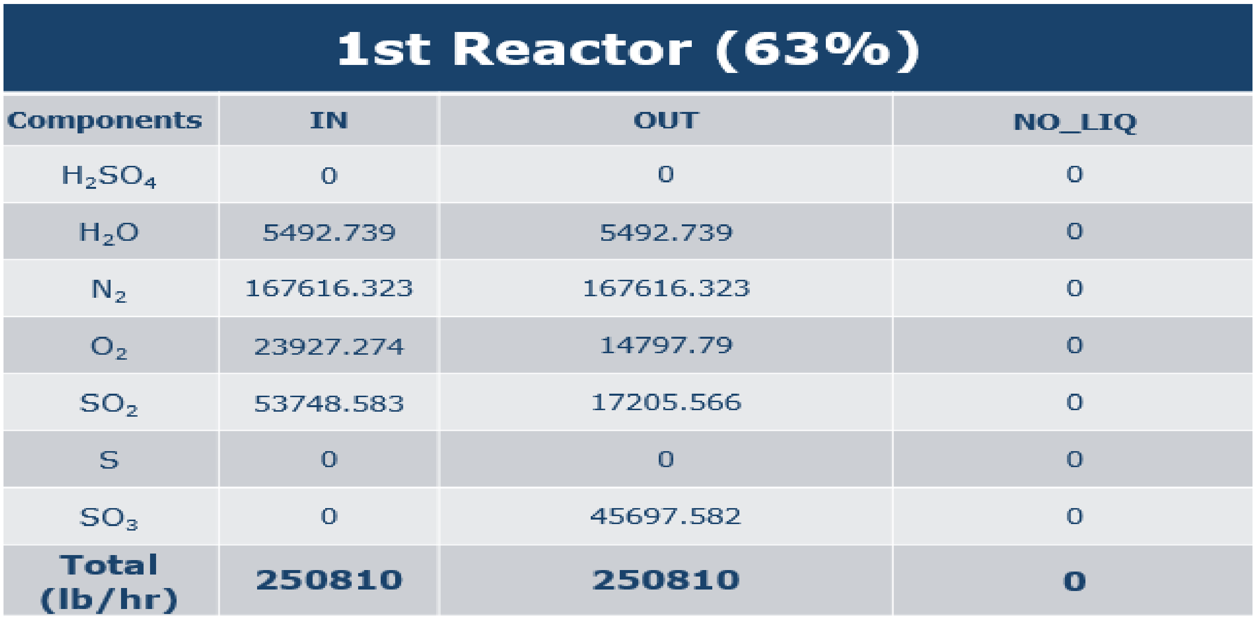
Furnace (Reactor)			
Components	**Molten S**	**Dry Air**	**SO2**
H_2SO_4	0	0	0
H_2O	0	5485.55	5492.739
N_2	0	167633.9	167616.323
O_2	0	50780.52	23927.274
SO_2	0	0	53748.583
S	26910	0	0
SO_3	0	0	0
Total (lb/hr)	**26910**	**223900**	**250810**

3) 1st Conversion Reactor

1st Conversion Reactor is used to convert Sulphur dioxide to Sulphur trioxide having 63% conversion. Following Reaction takes place in the reactor

$$SO_2 + 1/2\ O_2 \longrightarrow SO_3$$

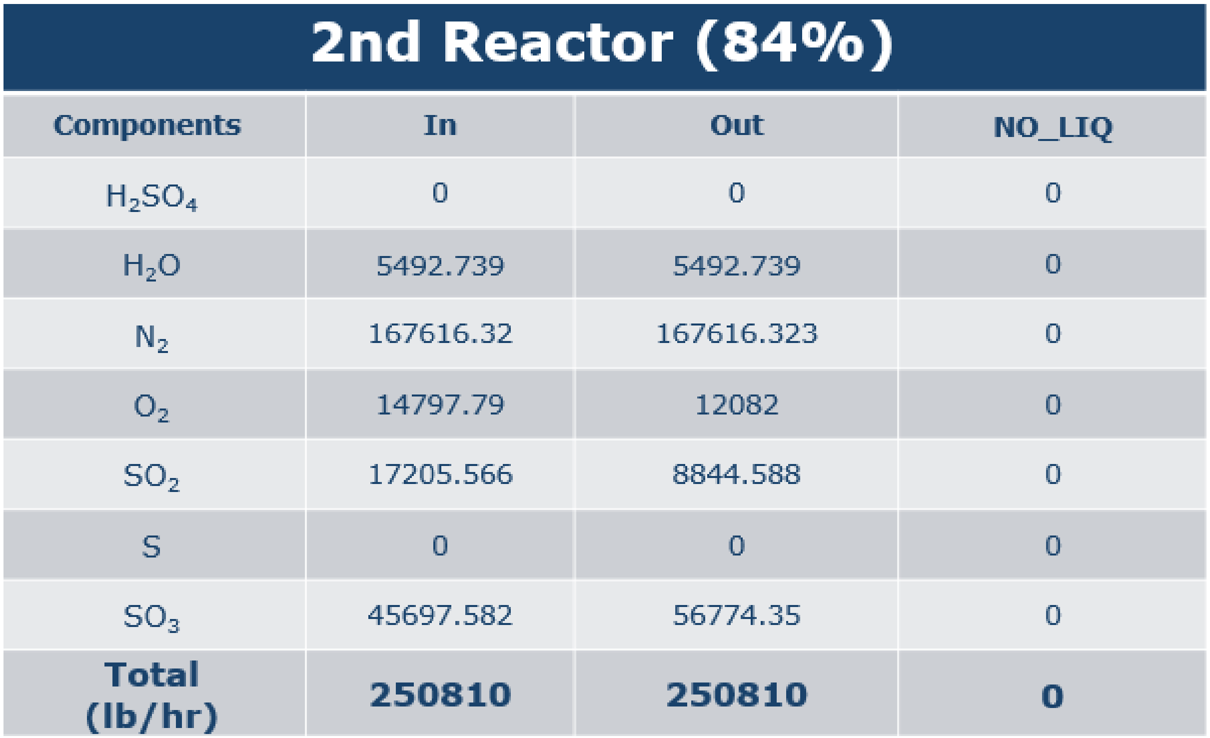
Table 3 Material Balance on 1st Conversion Reactor



1st Reactor (63%)			
Components	**IN**	**OUT**	**NO_LIQ**
H_2SO_4	0	0	0
H_2O	5492.739	5492.739	0
N_2	167616.323	167616.323	0
O_2	23927.274	14797.79	0
SO_2	53748.583	17205.566	0
S	0	0	0
SO_3	0	45697.582	0
Total (lb/hr)	**250810**	**250810**	**0**

4) 2nd Conversion Reactor (84% Conversion)

Table 4 Material Balance on 2nd Conversion Reactor



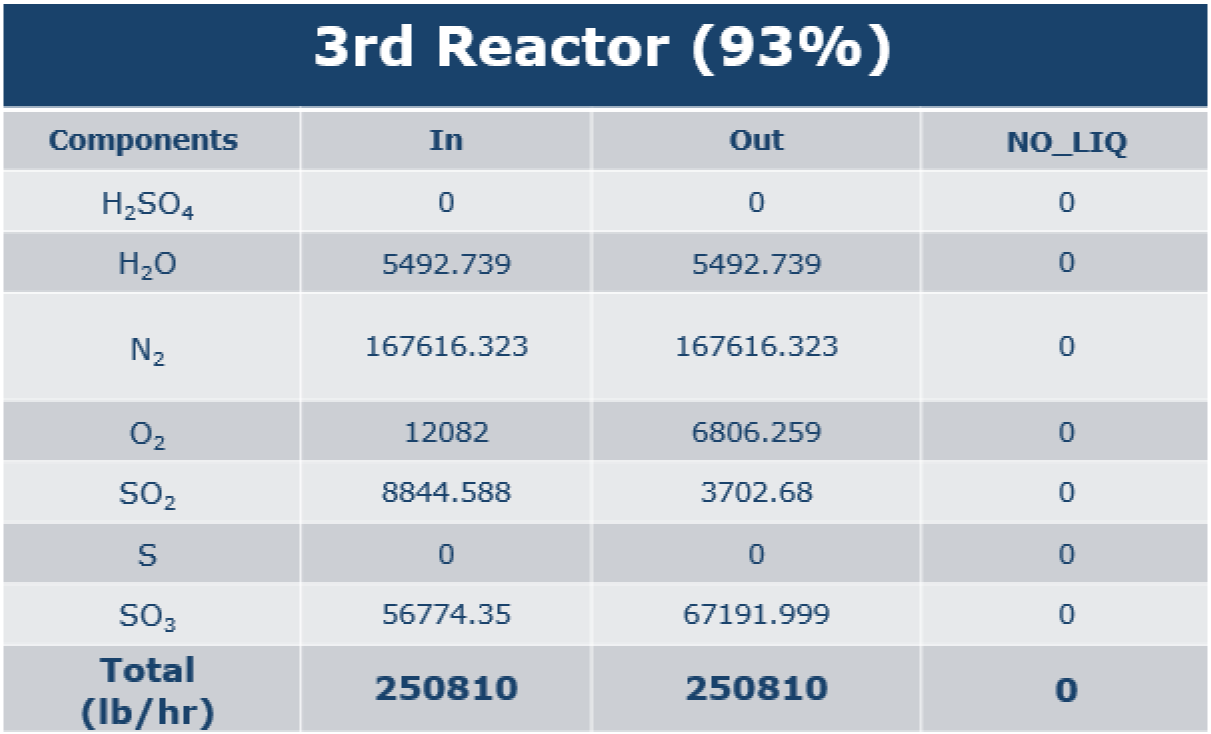
2nd Reactor (84%)

Components	In	Out	NO_LIQ
H_2SO_4	0	0	0
H_2O	5492.739	5492.739	0
N_2	167616.32	167616.323	0
O_2	14797.79	12082	0
SO_2	17205.566	8844.588	0
S	0	0	0
SO_3	45697.582	56774.35	0
Total (lb/hr)	**250810**	**250810**	**0**

5)

6) 3rd Conversion Reactor (93% Conversion)

Table 5 Material Balance on 3rd Conversion Reactor

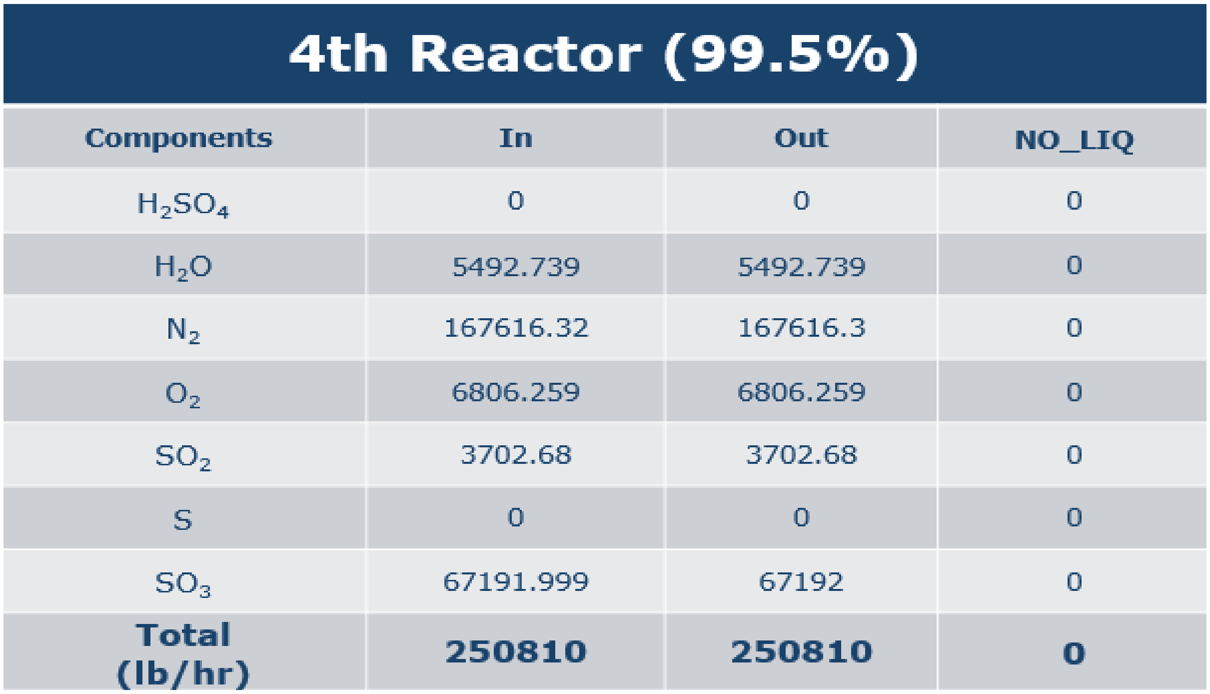


3rd Reactor (93%)

Components	In	Out	NO_LIQ
H_2SO_4	0	0	0
H_2O	5492.739	5492.739	0
N_2	167616.323	167616.323	0
O_2	12082	6806.259	0
SO_2	8844.588	3702.68	0
S	0	0	0
SO_3	56774.35	67191.999	0
Total (lb/hr)	**250810**	**250810**	**0**

7) 4th Conversion Reactor (99.5% Conversion)

Table 6 Material Balance on 4th Conversion Reactor



4th Reactor (99.5%)

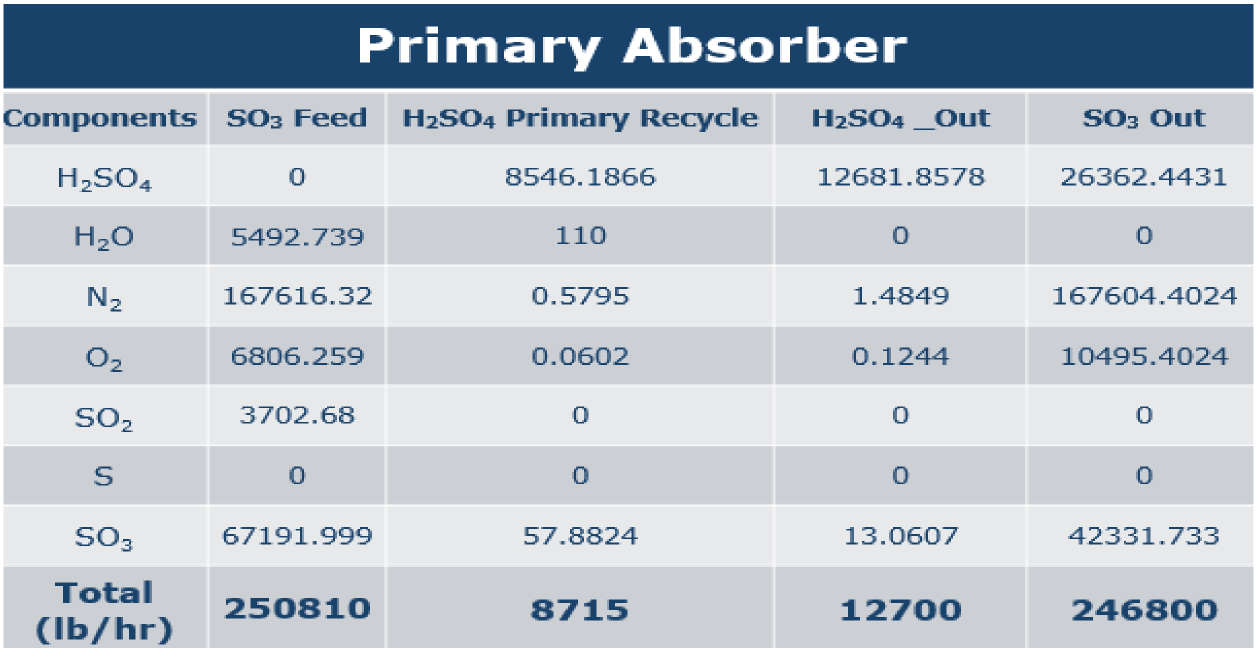
Components	In	Out	NO_LIQ
H_2SO_4	0	0	0
H_2O	5492.739	5492.739	0
N_2	167616.32	167616.3	0
O_2	6806.259	6806.259	0
SO_2	3702.68	3702.68	0
S	0	0	0
SO_3	67191.999	67192	0
Total (lb/hr)	**250810**	**250810**	**0**

8) Primary Absorber

Sulphur trioxide is absorbed in water to form sulphuric acid with 75% conversion in Primary Absorber. Following reaction takes place in Primary absorber.

$$SO_3 + H_2O \longrightarrow H_2SO_4$$

Table 7 Material Balance on Primary Absorber



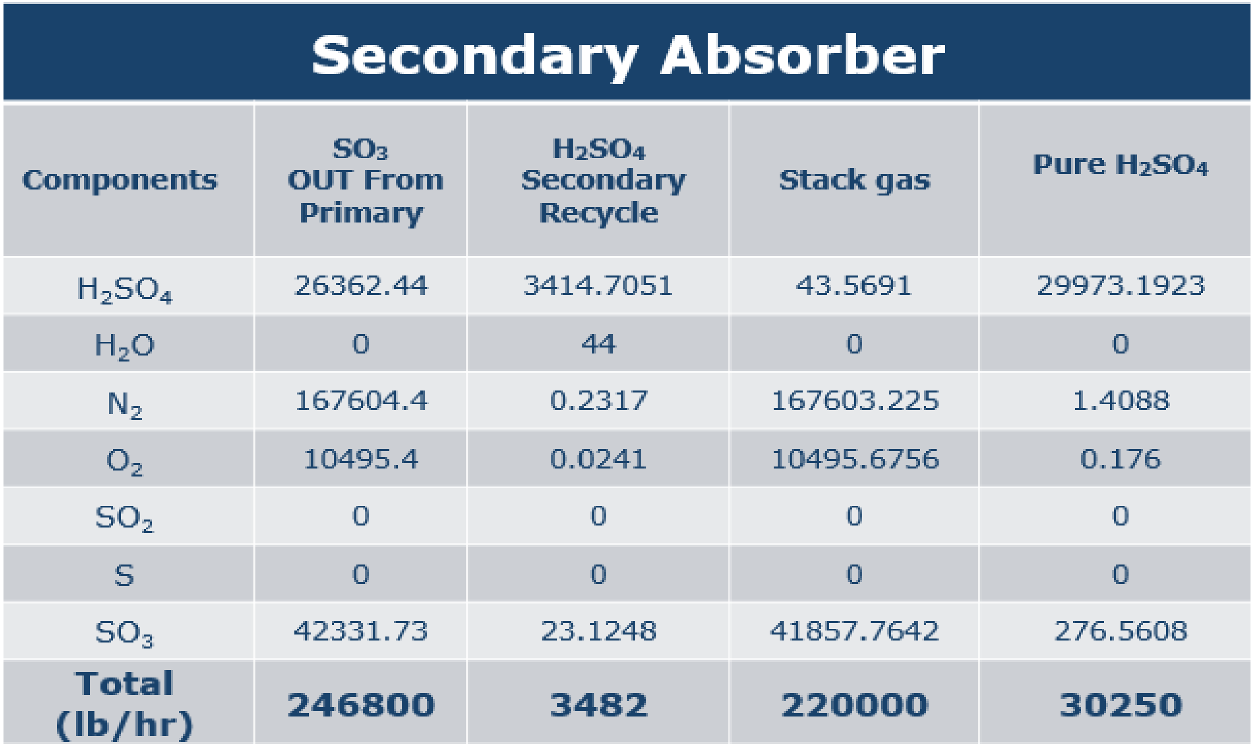
Primary Absorber

Components	SO_3 Feed	H_2SO_4 Primary Recycle	H_2SO_4 _Out	SO_3 Out
H_2SO_4	0	8546.1866	12681.8578	26362.4431
H_2O	5492.739	110	0	0
N_2	167616.32	0.5795	1.4849	167604.4024
O_2	6806.259	0.0602	0.1244	10495.4024
SO_2	3702.68	0	0	0
S	0	0	0	0
SO_3	67191.999	57.8824	13.0607	42331.733
Total (lb/hr)	**250810**	**8715**	**12700**	**246800**

9) Secondary Absorber

The unreacted sulphur trioxide is sent to a secondary absorber where 100% conversion is achieved to produce sulphuric acid.

Table 8 Material Balance on Secondary Absorber



Secondary Absorber

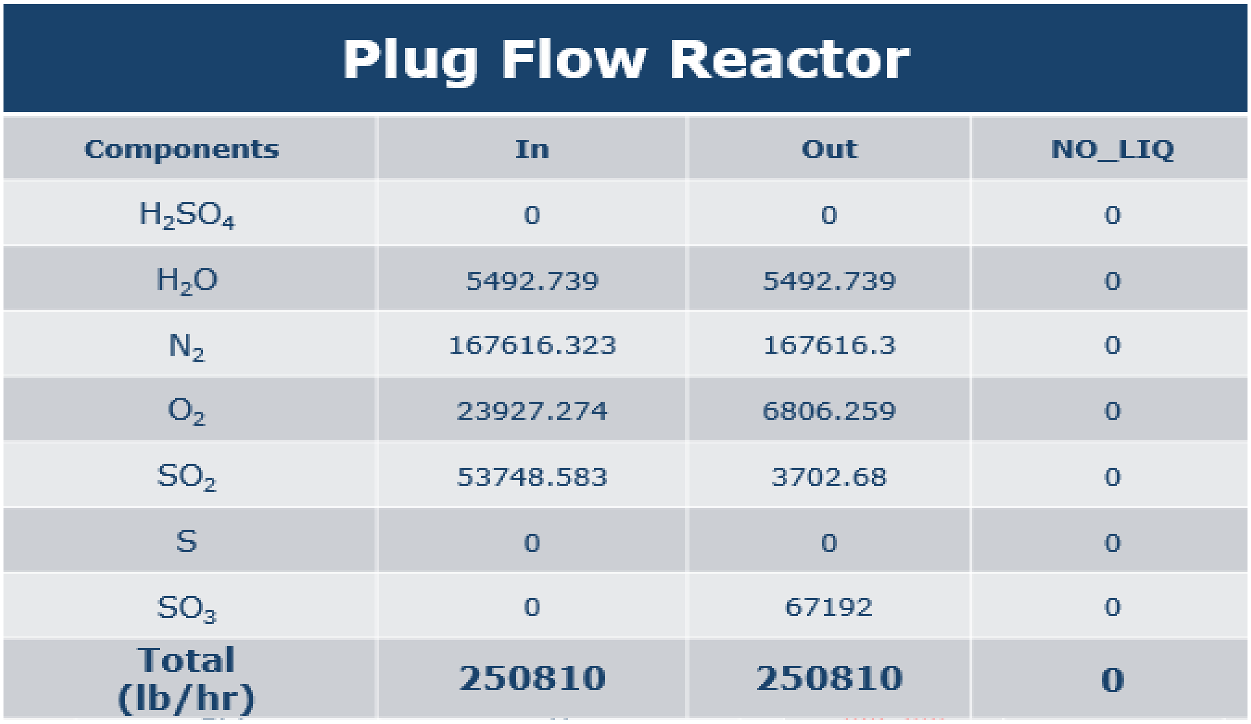
Components	SO_3 OUT From Primary	H_2SO_4 Secondary Recycle	Stack gas	Pure H_2SO_4
H_2SO_4	26362.44	3414.7051	43.5691	29973.1923
H_2O	0	44	0	0
N_2	167604.4	0.2317	167603.225	1.4088
O_2	10495.4	0.0241	10495.6756	0.176
SO_2	0	0	0	0
S	0	0	0	0
SO_3	42331.73	23.1248	41857.7642	276.5608
Total (lb/hr)	**246800**	**3482**	**220000**	**30250**

3.3 Alternative Approach

An alternative approach has been used in our model. Through literature work, kinetics for the reaction of sulphur dioxide and oxygen has been found and employed in Aspen HYSYS.

A single plug flow reactor has been used for the oxidation of sulphur dioxide to sulphur trioxide. Using the kinetics, conversion achieved in a single plug flow reactor is same as that of four conversion reactors i.e. 99.5%.

Table 9 Plug Flow Reactor



Plug Flow Reactor

Components	In	Out	NO_LIQ
H_2SO_4	0	0	0
H_2O	5492.739	5492.739	0
N_2	167616.323	167616.3	0
O_2	23927.274	6806.259	0
SO_2	53748.583	3702.68	0
S	0	0	0
SO_3	0	67192	0
Total (lb/hr)	**250810**	**250810**	**0**

3.3 ENERGY BALANCE

Law of Conservation of Energy:

Our energy balance is based upon the law of conservation of energy which is stated by the first law of thermodynamics. It is stated as:

"Energy can neither be created nor be destroyed, but it can be converted from one form to another"

For example, internal energy stored in the molecular bonds can be converted into chemical energy, kinetic energy etc.

In most of the cases, the energy is transferred from one body to another in the form of heat. The general energy equation is as follows that we followed:

"Accumulation of Energy in System = Input of Energy in System – Output of Energy from system"

$$\mathbf{Q = \Delta H = m\,C_p\,\Delta T}$$

Units

Mass Flow	Specific Enthalpy	Heat Flow
lb/hr	Btu/lb	Btu/hr

- **Balance on equipments**
  - Drying Tower
  - Furnace (Conversion Reactor)
  - Reactor
  - Primary Absorber
  - Secondary Absorber
  - Heat Exchanger

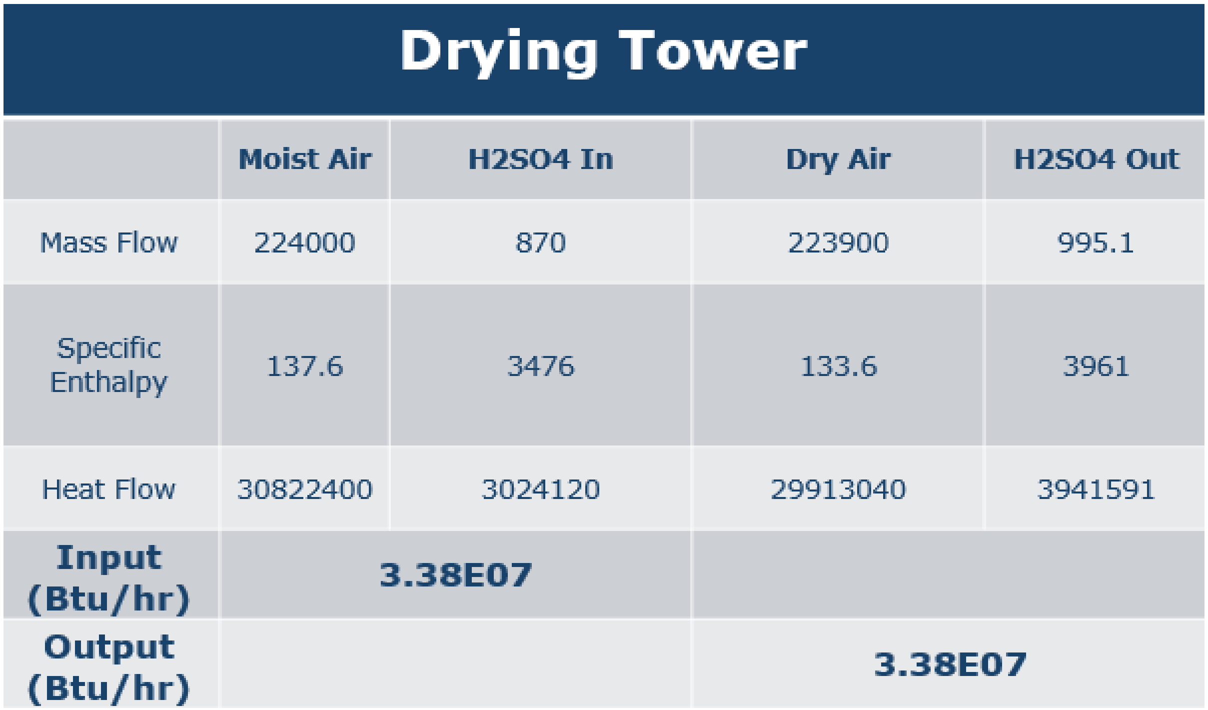
3.4 Energy Balance on all the Equipments

1) Drying Tower

Moist air is being dried using sulphuric acid which is being recycled as part of the product stream. Moisture is being removed and dry air goes to the furnace to react with sulphur. Sulphuric acid attracts moisture and takes away the moisture with it.

In drying tower since, there is no accumulation of heat hence, heat input is equal to heat output. This implies that

Table 10 Energy Balance on Drying Tower



Drying Tower

	Moist Air	H2SO4 In	Dry Air	H2SO4 Out
Mass Flow	224000	870	223900	995.1
Specific Enthalpy	137.6	3476	133.6	3961
Heat Flow	30822400	3024120	29913040	3941591
Input (Btu/hr)	**3.38E07**			
Output (Btu/hr)			**3.38E07**	

$$\Delta H = 0$$

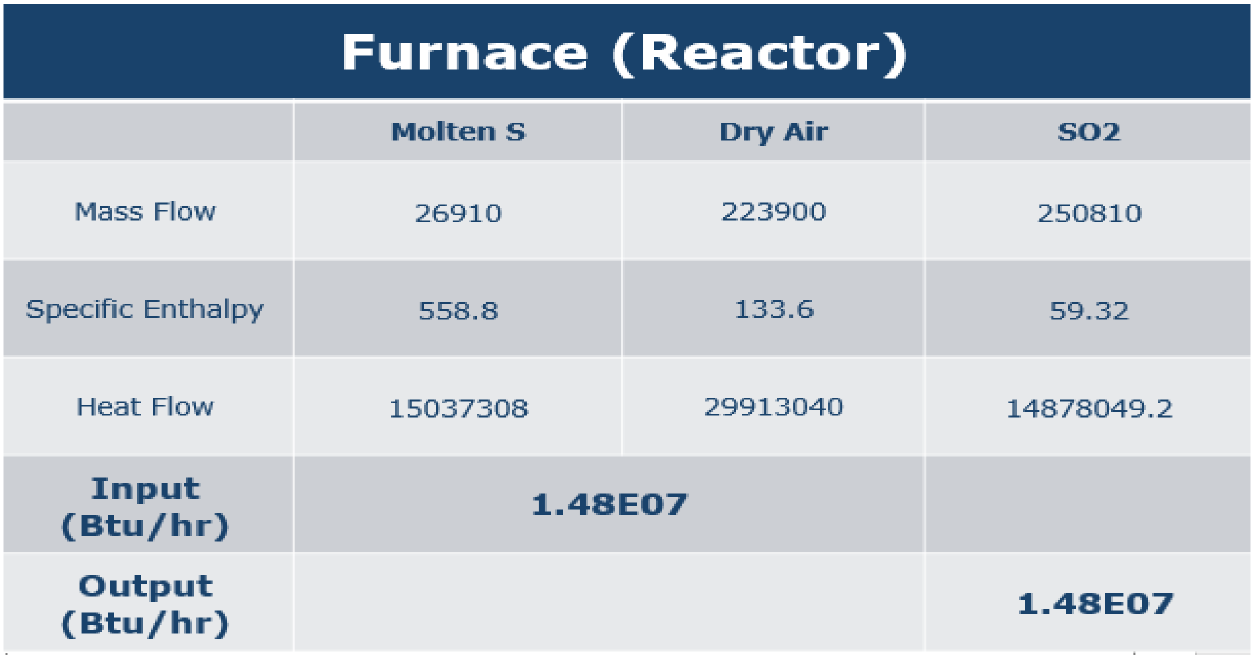
2) Furnace

Dry air from drying tower enters the furnace and reacts with sulphur to form sulphur dioxide with 100% conversion. Following reaction takes place in the furnace.

In furnace since, there is no accumulation of heat hence, heat input is equal to heat output. This implies that

$$\Delta H = 0$$

Table 11 Energy Balance on Furnace



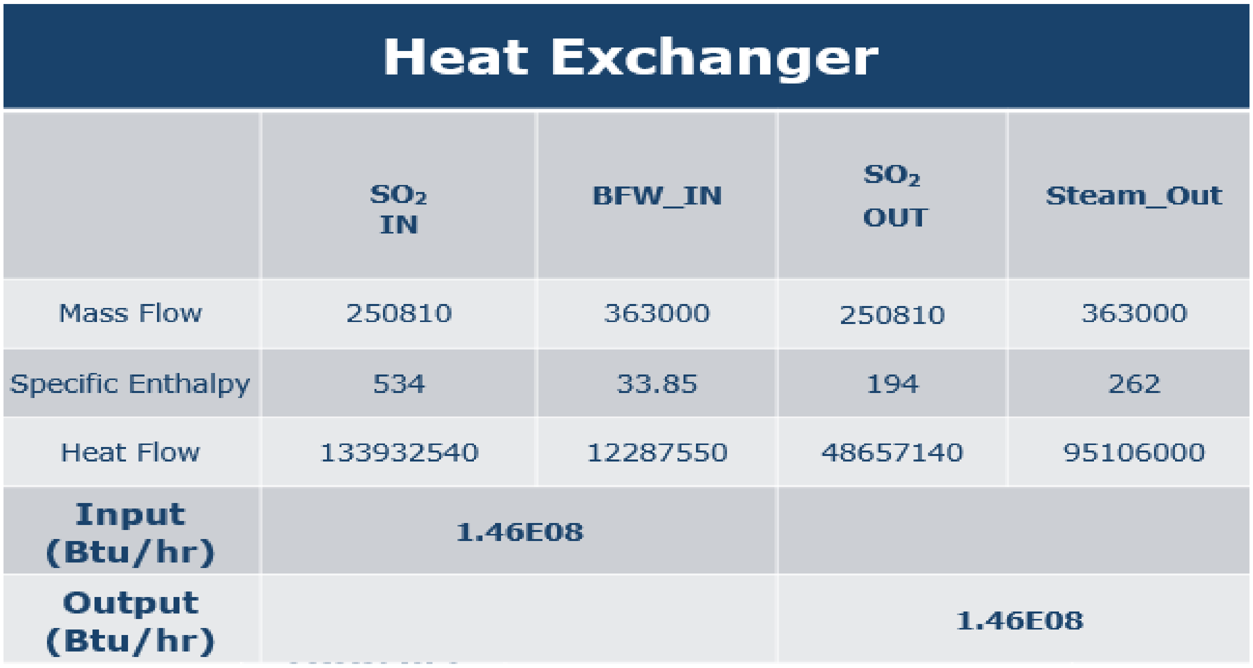
Furnace (Reactor)			
	Molten S	Dry Air	SO2
Mass Flow	26910	223900	250810
Specific Enthalpy	558.8	133.6	59.32
Heat Flow	15037308	29913040	14878049.2
Input (Btu/hr)	**1.48E07**		
Output (Btu/hr)			**1.48E07**

3) Heat Exchanger:

In Heat Exchanger since, there is accumulation of heat hence, heat input is not equal to heat output. This implies that:

$$\Delta H = Q$$

Table 12 Energy Balance on Heat Exchanger



Heat Exchanger				
	SO_2 IN	BFW_IN	SO_2 OUT	Steam_Out
Mass Flow	250810	363000	250810	363000
Specific Enthalpy	534	33.85	194	262
Heat Flow	133932540	12287550	48657140	95106000
Input (Btu/hr)	**1.46E08**			
Output (Btu/hr)			**1.46E08**	

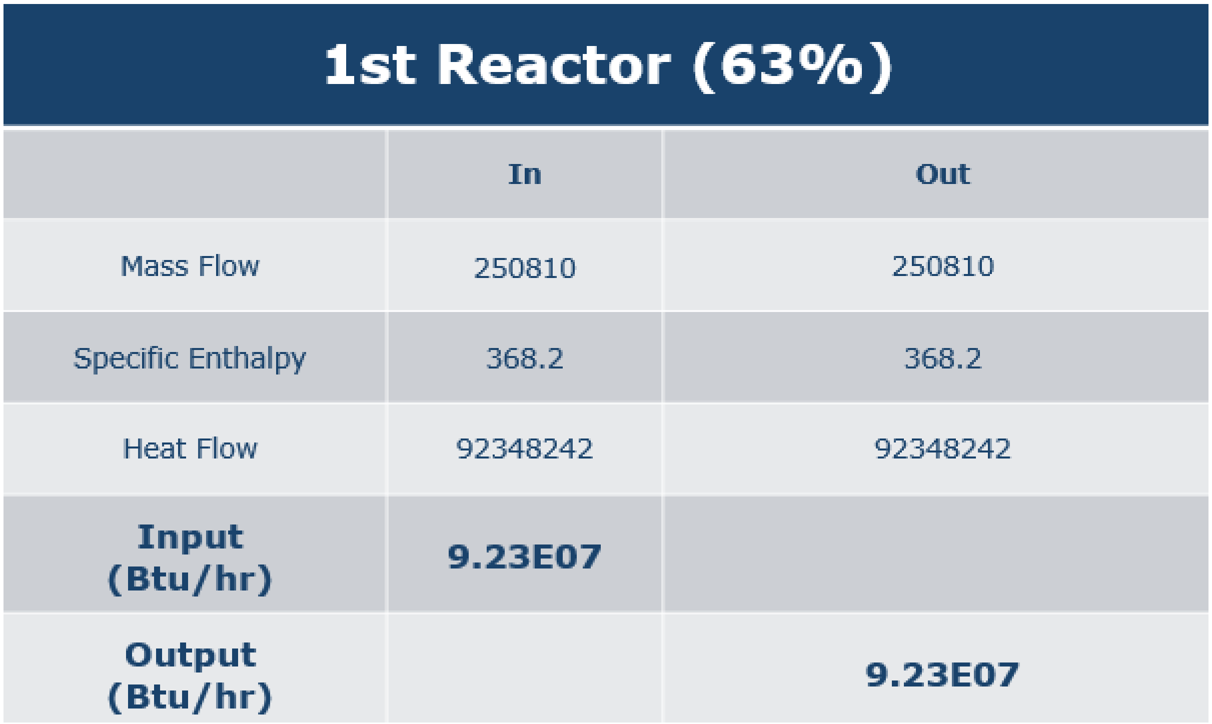
4) 1st Conversion Reactor

1st Conversion Reactor is used to convert Sulphur dioxide to Sulphur trioxide having 63% conversion. Following Reaction takes place in the reactor.

In 1st Conversion Reactor since, there is no accumulation of heat hence, heat input is equal to heat output. This implies that:

$$\Delta H = 0$$

Table 13 Energy Balance on 1st Conversion Reactor



1st Reactor (63%)

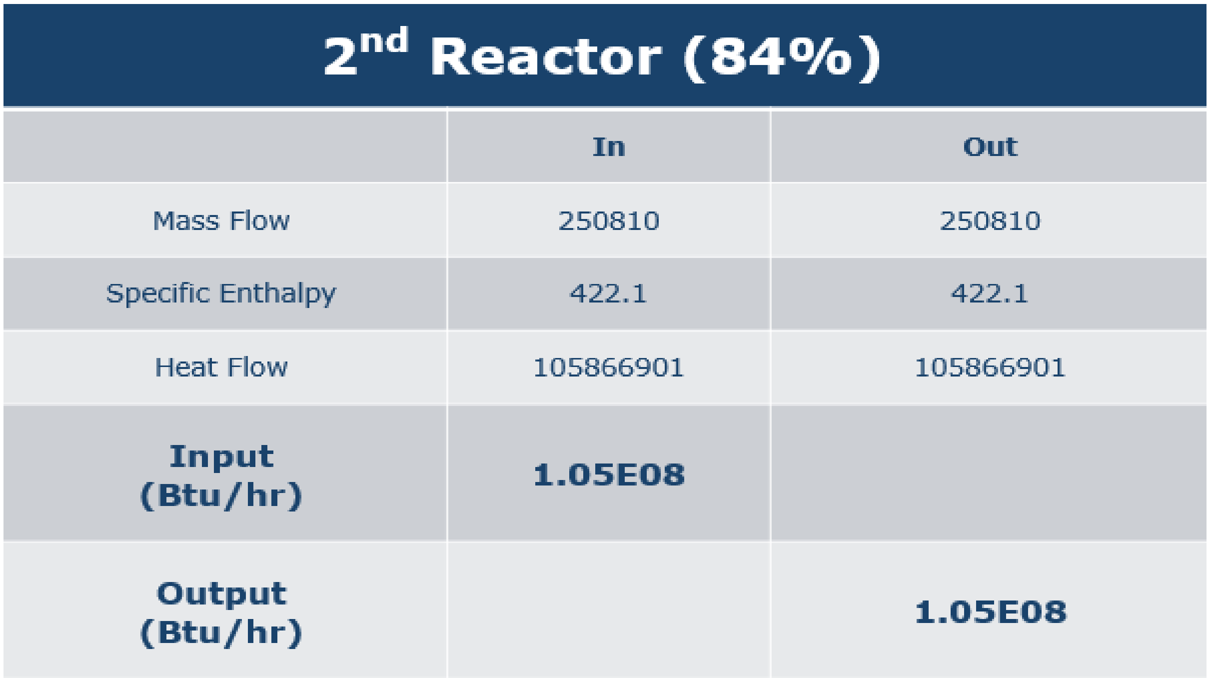
	In	Out
Mass Flow	250810	250810
Specific Enthalpy	368.2	368.2
Heat Flow	92348242	92348242
Input (Btu/hr)	**9.23E07**	
Output (Btu/hr)		**9.23E07**

5) 2nd Conversion Reactor (84% Conversion)

Similarly, in 2nd Conversion Reactor (84% Conversion), there is no accumulation of heat hence, heat input is equal to heat output. This implies that:

$$\Delta H = 0$$

Table 14 Energy Balance on 2nd Conversion Reactor



2nd Reactor (84%)

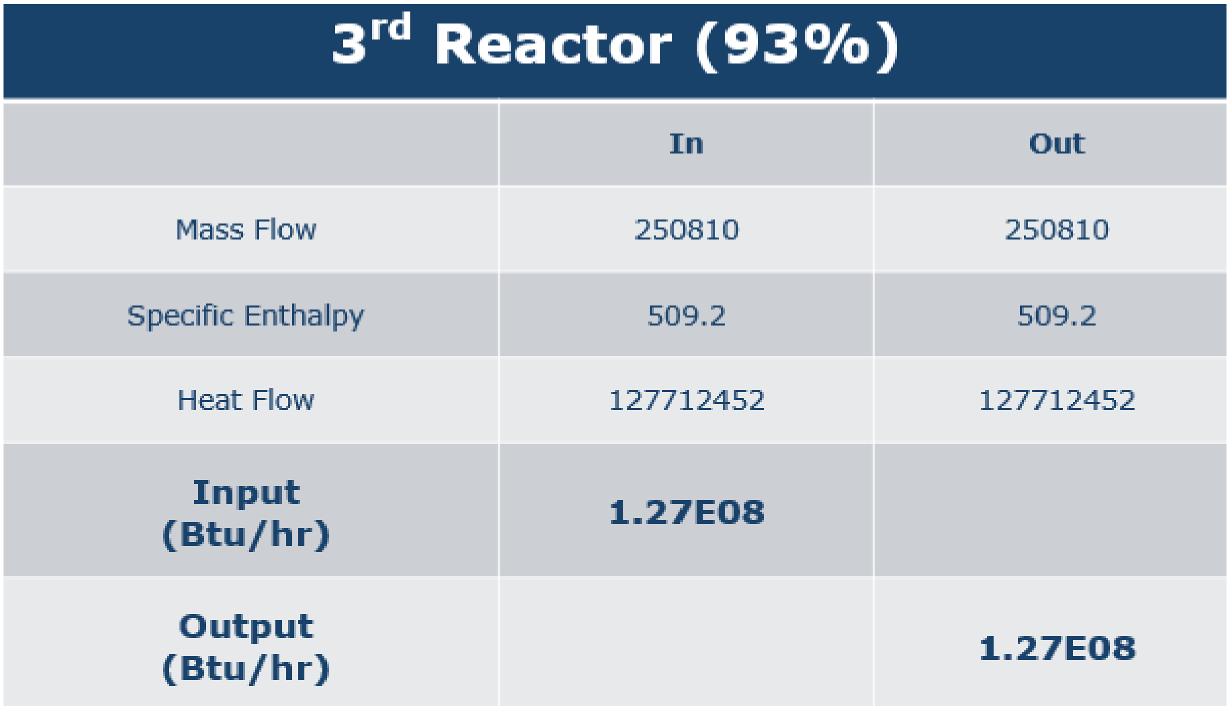
	In	Out
Mass Flow	250810	250810
Specific Enthalpy	422.1	422.1
Heat Flow	105866901	105866901
Input (Btu/hr)	**1.05E08**	
Output (Btu/hr)		**1.05E08**

6) 3rd Conversion Reactor (93% Conversion)

Similarly, in 3rd Conversion Reactor (84% Conversion), there is no accumulation of heat hence, heat input is equal to heat output. This implies that:

$$\Delta H = 0$$

Table 15 Energy Balance on 3rd Conversion Reactor



3rd Reactor (93%)

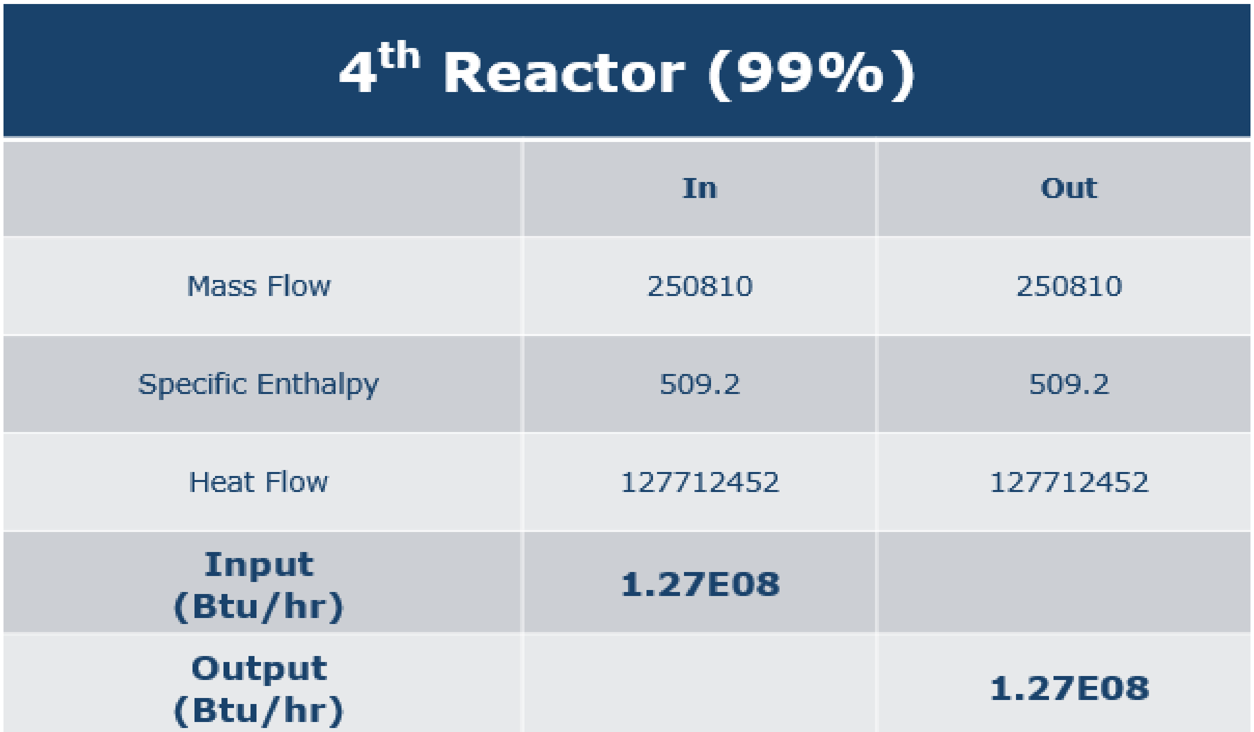
	In	Out
Mass Flow	250810	250810
Specific Enthalpy	509.2	509.2
Heat Flow	127712452	127712452
Input (Btu/hr)	**1.27E08**	
Output (Btu/hr)		**1.27E08**

7) 4th Conversion Reactor (99.5% Conversion)

Similarly, in 4th Conversion Reactor (84% Conversion), there is no accumulation of heat hence, heat input is equal to heat output. This implies that:

$$\Delta H = 0$$

Table 16 Energy Balance on 4th Conversion Reactor



4th Reactor (99%)		
	In	**Out**
Mass Flow	250810	250810
Specific Enthalpy	509.2	509.2
Heat Flow	127712452	127712452
Input (Btu/hr)	**1.27E08**	
Output (Btu/hr)		**1.27E08**

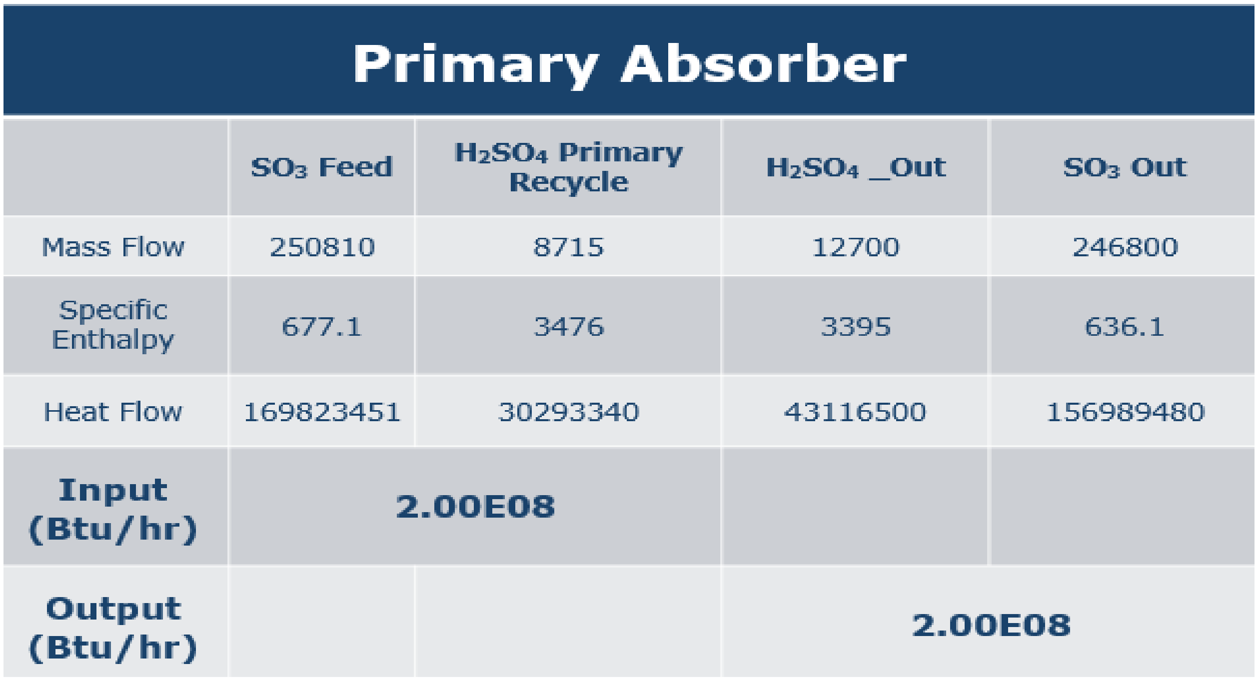
8) Primary Absorber

Sulphur trioxide is absorbed in water to form sulphuric acid with 75% conversion in Primary Absorber.

In primary absorber since, there is no accumulation of heat hence, heat input is equal to heat output. This implies that:

$$\Delta H = 0$$

Table 17 Energy Balance on Primary Absorber



Primary Absorber

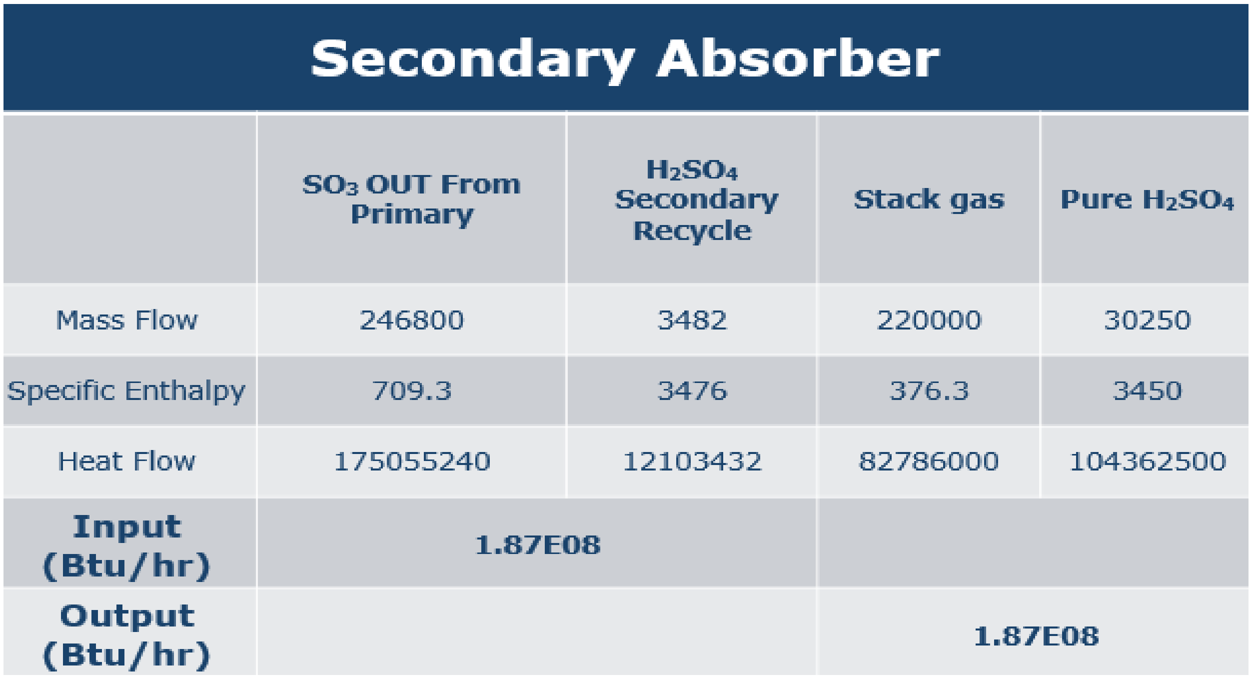
	SO_3 Feed	H_2SO_4 Primary Recycle	H_2SO_4 _Out	SO_3 Out
Mass Flow	250810	8715	12700	246800
Specific Enthalpy	677.1	3476	3395	636.1
Heat Flow	169823451	30293340	43116500	156989480
Input (Btu/hr)	**2.00E08**			
Output (Btu/hr)			**2.00E08**	

9) Secondary Absorber

In secondary absorber since, there is no accumulation of heat hence, heat input is equal to heat output. This implies that:

$$\Delta H = 0$$

Table 18 Energy Balance on Secondary Absorber



Secondary Absorber

	SO_3 OUT From Primary	H_2SO_4 Secondary Recycle	Stack gas	Pure H_2SO_4
Mass Flow	246800	3482	220000	30250
Specific Enthalpy	709.3	3476	376.3	3450
Heat Flow	175055240	12103432	82786000	104362500
Input (Btu/hr)	**1.87E08**			
Output (Btu/hr)			**1.87E08**	

Chapter 4: Equipment Design

4.1 Reactor Design

In the manufacture of sulfuric acid from sulphur, the first step is the burning of sulphur in a furnace to form sulphur dioxide:

$$S + O_2 \longrightarrow SO_2$$

Following this step, the sulphur dioxide is converted to sulphur trioxide, using a vanadium pentoxide catalyst:

$$SO_2 + \frac{1}{2} O_2 \longrightarrow SO_3$$

At pressures slightly higher than atmospheric, sulfur dioxide converters operate. Our designs use an absolute pressure of 2 atm. To ensure maximum conversion, the inlet temperature is regulated to the reactor. Here are two limitations. The reaction rate on the catalyst V2O5 is insignificant below ~700 ° F, and at no time should the reactor temperature exceed~125 ° F. A series of temperatures should be tested, and the maximum conversion temperature above 760 ° F should be used, although the reactor temperature is above 1120 °F.

To improve thermal efficiency by using the heat again, the cooling substance should operate at high temperatures. Dowtherm A, with a normal operating limit of about 750 ° F, seems to be the best substance, although this is occasionally used in this initial design as the coolant.

Calculations

The reactor chosen is the packed bed reactor and for instance, we have considered a single bed.

Evaluating the weight of a single bed, we have divided it in four beds by dividing the weight of a single bed into four beds

Assumptions

Void Fraction	**0.303**
Bulk density of catalyst (kg/m^3)	**258**
Length of tubes (m)	**6**
No of tubes	**1100**
Sphericity	**0.3**

1. **Design equation:** The general mole balance equations (design equation) based on the weight of catalyst is given in their differential and integral forms

$$F_{A0}\frac{dX}{dW} = -r'_A$$

2. **Kinetics**

$$K_p = \exp\left(\frac{42{,}311}{RT} - 11.24\right) \quad (K_p \text{ in atm}^{-1/2},\ T \text{ in R})$$

$$k = \exp\left[\frac{-176{,}008}{T} - (110.1\ \ln T) + 912.8\right]$$

3. **Rate Law**

$$-r'_{SO_2} = k\sqrt{\frac{P_{SO_2}}{P_{SO_3}}}\left[P_{O_2} - \left(\frac{P_{SO_3}}{K_p P_{SO_2}}\right)^2\right]$$

4. **Stoichiometric relationships and expressing as a function of X**

$$SO_2 + \tfrac{1}{2}O_2 \rightleftarrows SO_3$$
$$A + \tfrac{1}{2}B \rightleftarrows C$$

We let A represent SO_2 and v_i be the stoichiometric coefficient for species i:

$$P_i = C_i(RT) = C_{A0}\frac{(\Theta_i + v_i X)(RT)P}{(1+\epsilon X)(T/T_0)P_0} = P_{A0}\frac{(\Theta_i + v_i X)P}{(1+\epsilon X)P_0}$$

Substituting for partial pressures in the rate law and combining yields

$$\frac{dX}{dW}=\frac{-r'_{\mathrm{A}}}{F_{\mathrm{A0}}}=\frac{k}{F_{\mathrm{A0}}}\sqrt{\frac{1-X}{\Theta_{\mathrm{SO_3}}+X}}\left[\frac{P}{P_0}P_{\mathrm{A0}}\frac{\Theta_{\mathrm{O_2}}-\frac{1}{2}X}{1+\epsilon X}-\left(\frac{\Theta_{\mathrm{SO_3}}-X}{1+X}\right)^2\frac{1}{K_p^2}\right]$$

Weight of catalyst is deduced from above equation = **14400 kg**

Other Specifications of Reactor

1- Volume of the Catalyst

$$\text{Volume of Catalyst}=\frac{\text{Weight of Catalyst}}{\text{Bulk density}}$$

Volume of Catalyst = **55.81 m^3**

2- Volume of bed

$$\text{Volume of Bed}=\frac{\text{Volume of Catalyst}}{1-\text{Void Fraction}}$$

Volume of bed = **80.07 m^3**

3- Diameter of bed

$$\text{Diameter of Bed }(\mathrm{D}^3)=\frac{4\mathrm{V}_{\mathrm{bed}}}{3\pi}$$

Diameter of bed = **3.23 m**

4- Height of bed

$$\text{Height of Bed} = \frac{V}{\pi D^2/4}$$

Height of bed= **9.71 m**

5- Height of Reactor

$$Height\ of\ Reactor\ (H_R) = Height\ of\ Bed + 0.15(Height\ of\ Bed)$$

Height of Reactor = **11.17m**

6- Volume of Reactor

$$Volume\ of\ Reactor = H_R\ (\frac{\pi D^2}{4})$$

Volume of Reactor = 95 m^3

Results

Weight of catalyst (kg)	**14400**
Volume of catalyst (m^3)	**55.81**
Volume of bed (m^3)	**80.07**
Height of bed (m)	**9.71**
Diameter of bed (m)	**3.23**
Height of reactor (m)	**11.17**
Volume of reactor (m^3)	**95**

4.2 Absorber Design

Absorber is an important equipment used in the contact process to produce sulphuric acid. A chemical reaction is taking place inside the absorber; thus, the absorption process is chemisorption. Sulphuric trioxide reacts with water to form an intermediate compound, Oleum which further reacts with water to form sulphuric acid. But in our simulation model, we have not introduced the intermediate compound, instead we have employed the overall reaction in the absorber to produce sulphuric acid

$$SO_3 \quad + \quad H_2O \quad \longrightarrow \quad H_2SO_4$$

Absorber is a vertical and cylindrical vessel which uses packings to increase the contact area and time of absorbents. The packings which we are using in our process are Ceramic Intalox Saddles.

Design Specifications

- Packed bed vessel or Tower
- Material of packing: Intalox saddles
- Material of construction: Ceramics

Given

Sulphuric acid flow rate (outlet) m_L = 9610.78 kg/hr

Density of Sulphuric acid (ρ_L) = 1734 kg/m^3

Density of water ($\rho_{L,} H_2O$) = 999.5 kg/m^3

Feed gas flow rate (m_G) = 1.138e5 kg/hr

Density of feed gas (ρ_G) = 1.176 kg/m^3

Dynamic viscosity of Sulphuric acid= η= 0.00076 Pa.s

Flooding factor = f= 0.7

Packing Factor = F_p = 40

1. **F_{LG}**

$$F_{LG} = \frac{m_L\ (\rho_G)^{0.5}}{m_G\ (\rho_L)^{0.5}}$$

F_{LG} = **0.0022**

2. **F_{ρ}**

$$F_{\rho} = 0.8787 + 2.6776\left(\frac{\rho_{L,H2O}}{\rho_L}\right) - 0.6313\left(\frac{\rho_{L,H2O}}{\rho_L}\right)^2$$

F_{ρ} = **0.454**

3. **F_{η}**

$$F_{\eta} = 0.96\,{\eta_L}^{0.19}$$

F_{η} = **0.244**

4. **Y**

$$Y = \exp\,(-3.7121 - 1.0371\,\ln F_{LG} - 0.1501\,\ln(F_{LG})^2 - 0.007544\ \ln(F_{LG})^3$$

Y= **0.284**

5. **Flooding Velocity ($W_{G,max}$)**

$$Y = \frac{{W_{G,max}}^2\ F_{\mathrm{p}} F_{\rho} F_{\eta}\,\rho_G}{\rho_{L,H20}}$$

$W_{G,max}$ = **7.4 m/s**

6. Diameter of Absorber

$$D = \frac{2}{(\pi)^{0.5}} \left(\frac{m_G}{\rho_G\, f\, W_{G,max}}\right)^{0.5}$$

D= **2.6 m**

7. NTU

m=0

$x_{in=}$ 0

Y_{in} = 1.23×10^{-3}

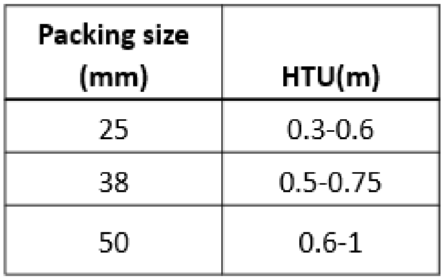
Y_{out} = 1.23×10^{-5}

$$NTU = 1(1 - mV/L) * Ln\left(1 - \frac{mV}{L}\right) * \left(\frac{Y_{IN} - mx_{out}}{Y_{OUT} - mx_{in}}\right) + mV/L$$

$$NTU = \ln \frac{Y_{IN}}{Y_{OUT}}$$

NTU = **approximately 5**

8. Height Calculation



Packing size (mm)	HTU(m)
25	0.3-0.6
38	0.5-0.75
50	0.6-1

From the following table

HTU for 50mm packing size = 1

Thus Height(Z)

$$Z = HTU * NTU$$

Z= 1 * 5 = **5m**

9. Total Height = Z + 2.5 = 7.5 m

10. Number of Packings

D= 2.6 m

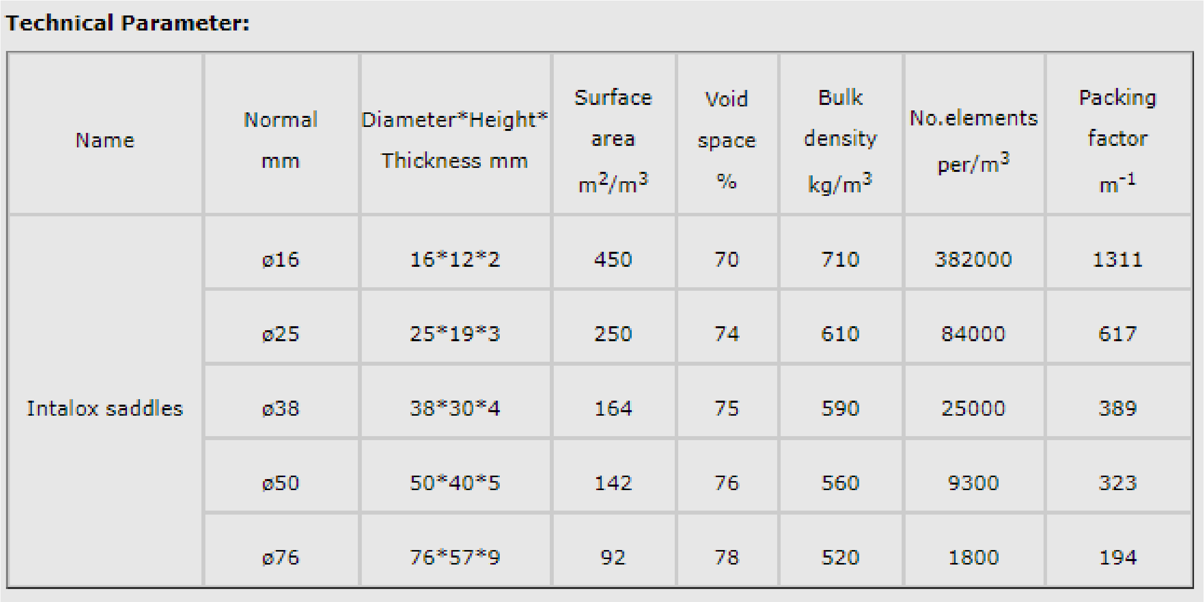
h= 5 m

$$Volume = \frac{\pi D^2 h}{4}$$

Volume = **26.5 m^3**

From the following table

Table 19 Parameters of saddles



Technical Parameter:

Name	Normal mm	Diameter*Height*Thickness mm	Surface area m^2/m^3	Void space %	Bulk density kg/m^3	No.elements per/m^3	Packing factor m^{-1}
Intalox saddles	ø16	16*12*2	450	70	710	382000	1311
	ø25	25*19*3	250	74	610	84000	617
	ø38	38*30*4	164	75	590	25000	389
	ø50	50*40*5	142	76	560	9300	323
	ø76	76*57*9	92	78	520	1800	194

No. of Packings/ m^3 = **9300**

Total No. of Packings = 9300 * 26.5 = **246,450**

4.3 Heat Exchanger Design

Given:

Working for a 21 ¼ in ID exchanger having 200 tubes with 1 in dia, 13 BWG, 16' 0'' long and pitch 1 ¼ in. Two tube passes, baffle spacing 5 in.

Tube side inlet T = tin = 1092.222^o C = 1998^o F

Tube side outlet T = tout = 450^o C = 842^o F

Shell side inlet T = tin = 65^o C = 149^o F

Shell side outlet T = tout = 170^o C = 338^o F

Solution:

Tube side cp (SO_2) = 0.59445 Btu/lb ^{o}F Shell side cp(H_2O) = 0.49815 Btu/lb ^{o}F

M_{SO2} = 7875 lbmol/hr

Qhot = (7875)(0.59445)(1998-842) = lb/hr x Btu/lb.^{o}F x ^{o}F =8.0731 x 10^7 Btu/hr

M_{H2O} = 23600 lbmol/hr

	HOT FLUID		COLD FLUID	
	T1=1998	high T	t2=338	Δt2= 1660
	T2=842	low T	t1=149	Δt1= 693
Diff	T1-T2=1156		t2-t1=189	

LMTD= (1660-693)/ln(1660/693) = 110.6 ^{o}F

R = 1156/189 = 6.11 S = 189/1849= 0.1022

FT=0.968

Δt= 0.968 x 110.6 = 107.1^{o}F

As Δtc/th = 0.417

For 42 API crude, kc = 0.21 and Fc = 0.51

Tc= T2 + Fc (T1-T2) = 842 +

(0.51)(1156) =1431^{0}F

tc = t1 + Fc (t2-t1) = 149 + (0.51)(189) = 245^{0}F

Hot fluid, tube side

Flow area = at’ = 0.515 in^{2}

at = Ntat’/144n

=(169)(0.515)/144x2

=0.3022 ft^{2}

Ga= w/at = 7875/0.3022

Ga=26058 lb/hr.ft^{2}

Assuming viscosity at tc, 8.7 lb/ft.hr lb/ft.hr

Re = DeGe/µ

D= 0.631/12 = 0.0525 ft

Re= (0. 0525)(26058)/8.7

=51410

L/D= 16/0.0675 = 237

Cold fluid, shell side

as= 1 D X C’B/144 Pt

=29.25 x 0.25 x5/144

x1.9 =0.261 ft^{2}

Ga = w/as = 23600/0.261

=90421 lb/hr.ft^{2}

Assuming viscosity at tc, 0.978

Re = DeGe/µ

D= 0.787/12=0.0655 ft

Re= (0. .0655)(90421)/0.97

=73821

jH= 200

jH= 110	At Tc = $1431^{o}F$
At tc = $245^{o}F$	
C= 0.52 Btu/lb.^{o}F	C= 0.58 Btu/lb.^{o}F
k = 26 Btu/ft.hr.^{o}F	k=29Btu/ft.hr.^{o}F
$hi/Qt = jH \times k/D \times (c\mu/k)^{1/3}$	$hi/Qs = jH \times k/D \times (c\mu/k)^{1/3}$
$= 110 \times 26/0.0525 \times (0.52 \times 8.7/26)^{1/3}$	$=110 \times 26/0.0655 \times (0.58 \times 0.97/0.26)^{1/3}$
hs/at=4492	hi/Qs=9917

$hi/at \times 1D / OD = 40.257 \times 0.87/1$

$hi/Qt = 7950$

As $tw = tc + (ho/Qs)/(hi/Qt + ho/Qs) \times (Tc – tc)$

$= 245 + (4492\backslash 7950 + 4492) \times 825$

$Tw = 542.8^{o}F$

At $548^{o}F$, $\mu ws = 2468$ and $\mu wt = 3.12$

$Qs = (\mu/\mu w)^{0.14}$	$Qt = (\mu/\mu w)^{0.14}$
$= (0.97/0.2468)^{0.14}$	$= (8.7/3.12)^{0.14}$
$= 1.16$	$= 1.54$
	$hio/Qt \times Qt = 4492 \times 1.54 =6918$
$ho/Qs \times Qs = 7950 \times 1.16 =5210$	

As Uc = hio ho/ hio + ho = (9022x 3416) /(9022 + 3416) = 251.9 lb/hr.ft

As at’’ = 0.2618 ft^2/lb.ft

Total surface area = 169 x 19’ 685’’ x 0.42618=
701 ft^2 And as

UD = Q/ AΔt Assuming equimolar heat transfer from tube hot fluid to shell fluid UD

= 5624262/837.76 x 86.47

UD = 53.7 Btu/hr.ft^2 ^oF

Now for Rd,

As Rd = Uc –UD / Uc UD = (251.9-53.7/251.9 x 53.7)

Rd= 0.0146

Pressure Drop

Tube side(hot fluid)

For Re = 51410

f = 0.0016 ft^2

s= 1

$\Delta Pt = (f.Gt^2.L.n)/(5.22 \times 10^{10} . Ds.Qt)$

$$\frac{(0.0034)(441834.45)\ 2(16)(2)}{(5.22 \times 1010.0.0675 \times 0.078 \times 1.154)} = 1.37 \text{ psi}$$

$\Delta Pr = 4n/s.\ v^2/2g$

$=4(8)/0.078 \times 0.022$

=1.56 psi

$\Delta PT = \Delta Pt + \Delta Pr$

1.37 + 1.6 psi

= 3.5 psi < 10 psi

Shell side(cold fluid)

For Re = 73820

f = 0.00014

s = 1

Ds = 29.25/12 = 2.43 ft

$\Delta Ps = 5.39$ psi < 10 psi

Chapter 5: ECONOMIC ANALYSIS

5.1 Equipment Cost

Storage Tank-01

Capacity = 500 metric tons

Design Pressure = 15 psig

Material of construction = Stainless Steel

Cost = 110,000$ ---
- EQ(1)

Reactor (PFR)

Height = 6 m

Operating Pressure = 15bar

Column Diameter= 5 m

Construction Material = Stainless Steel

Cost of Vessel = 44600$ ----------------------- (i)

Supporting media = Grating Mesh

Material of mesh = Cast Iron

Diameter of Trays= Diameter of Column = 5 m

Number of Support media = 4

Catalyst cost = 27 $/ Kg

Total catalyst weight = 14400 Kg

Total catalyst cost = 388800 $ (ii)

Total Tray Cost = 4*10000$ = 40,000$---------- (iii)

Total Cost= Adding Eq(i),(ii) and Eq(iii)

Total Cost = 473,400 $ --- EQ(2)

Heat Exchanger

Heat Transfer Area = 700 ft2 == 53 m^2

Type of Heat Exchanger = U-Tube

Operating Pressure = 14.7 psig

Pressure factor = 1

U-Tube factor = 0.85

Material of Shell = Carbon Steel

Material of Tubes = Stainless Steel

Cost Of Heat Exchanger = 800000 * 0.85 * 1 = 126480$-------------- EQ(3)

Cooler

Type of Cooler = U-Tube

Area = 10.1m2

Material of Shell = Carbon Steel

Number of Tubes = 8

Operating Pressure = 5 bar

Number of Coolers = 02

Total Cost = 2* 6,300 * 1.0 * 0.85 = 10,710$

Total Cost == 11,000$ ------------------- EQ(4)

Absorber (I)

Vessel cost = 12500 $

Pressure flow = 1

Material factor = 2

Total Vessel Cost = 25000 $

Material Cost = $ 960/ m^3

Volume of packing = 26.5 m^3

Total Packing Cost = 25440 $

Total Absorber Cost = 50440 $

Total Absorber Cost in 2019 = 93800 $ EQ (5)

Absorber (II)

Vessel cost = 10500 $

Pressure flow = 1

Material factor = 2

Total Vessel Cost = 21000 $

Material Cost = $ 960/ m^3

Volume of packing = 25 m^3

Total Packing Cost = 24000 $

Total Absorber Cost = 45000 $

Total Absorber Cost in 2019 = 83,700 $ EQ (6)

Furnace

Height of furnace = 8 m
Heat Duty = 15033912.786 Btu/hr
Cost of furnace = 212,784 $ EQ (7)

Drying Tower

Diameter of the Vessel = 4.3 m
Height of Vessel = 9.8 m
Packing Height = 4.12 m

Cost of drying tower = 223,365 $ EQ (8)

Cooler

Type of Cooler = U-Tube
Area = 10.1m2
Material of Shell = Carbon Steel
Demanded speed [rpm]= 60
Operating Pressure = 5 bar
Number of Coolers = 02
Total Cost = 2* 6,300 * 1.0 * 0.85 = 10,710$
Total Cost == 14,560$ ----------------------
-- EQ(9)

Adding Eq (1) To Eq (9) will give us total Equipment cost

Purchase Cost Equipment (PCE) = 1.283M $

5.2 Physical Plant Cost

Table 20 Physical Plant Cost

Symbol	**Correction Factor**	**Value**
F1	Equipment Erection	0.40
F2	Piping	0.70
F3	Instrumentation	0.20
F4	Electrical	0.10

Physical Plant Cost (PPC) = PCE (1+0.40+0.70+0.20+0.10)$

PPC= 3.1M $

5.3 Fixed & Working Capital

Table 21 Fixed & Working Capital

Factor Symbol	Correction Factor	Value
F10	Design & Engineering	0.30
F11	Contractor Fee	None
F12	Contingencies	0.10

Fixed Capital = PPC*(1+0.30+0.10) = 2,165,080$

Fixed Capital = 4.3M $

Now, **Working Capital** = Fixed Capital * 0.05 = 0.22M
$ Working Capital = 0.22M $

Total Investment

Total Investment = Working Capital + Fixed
Capital **Total Investment** = 4.56 Million

5.4 Variable cost

Attainment = 95%

Operating Time = 365 * 0.95 = 347 days/y = 347 days/y * 24 = 8,328 hours/year

Table 22 Variable cost

Parameter	**Variable Value**	**Cost ($)**
Raw Material	None	0
Miscellaneous Material	10% of Maintenance Cost	10,825.43
Utilities(Steam)	12$/ton	11,659
Utilities(Cooling Water)	0.01$ /Ton or 1Cent/Ton	416.4
Power	1.5Cent/MJ	1,873.8
Total Cost = 24,774.63$		

5.5 Fixed Cost

Table 23 Fixed Cost

Variable	Cost($)
Maintenance	108,254.3
Operating labour	30,000
Plant Overhead	15,000
Laboratory	9,000
Capital Charges	129,905
Insurance	21,650

TOTAL = **313,809$**

Direct Production Cost

Direct Production Cost = Fixed Cost + Variable Cost = 338,583 $

5.6 Payback Period

Annual Operating Cost = 840,000 $

Assume Annual Cash Flow = 1.8M $

Payback Period = Investment / Annual Cash Flow

Payback Period = 4.56/1.8 = 2.5 years

Payback Period = **2.5 years**

Chapter 6: Simulation

6.1 Simulation of Aspen HYSYS Model

General Process Description

Sulfur is introduced with the dry air into the furnace after the expulsion of water from the feed air in the drying section. An oxidation reaction happens in the sulfur burner. At that point the sulfur dioxide gas and the un-responded air are cooled from 1998^{o}F to 842^{o}F before entering the where Sulphur dioxide reacts with the oxygen to give Sulphur trioxide. Sulfur dioxide and air undergo the catalytic oxidation reaction in the PFR. Since the reaction is highly exothermic in nature, the temperature of the system increases at a considerable rate and thus increases the reaction kinetics. However, this elevated temperature could damage the catalyst and thus, requires cooling. For this purpose, the reactor is partitioned into 4 stages and each stage is provided with a cooling system so that before each entering into each stage, the Sulphur trioxide stream is cooled down. This results in higher conversion and reaction rate. Because of the limitation of Aspen HYSYS software we could not represent the four stages using a PFR. We could use 4 conversion reactors instead but that would result in additional costs and further calculations. Another way could be by using reaction kinetics of PFR we calculate the conversion of each conversion reactor and then install a cooler after each conversion reactor to cool down the system. Following is the overall simulation of the process:

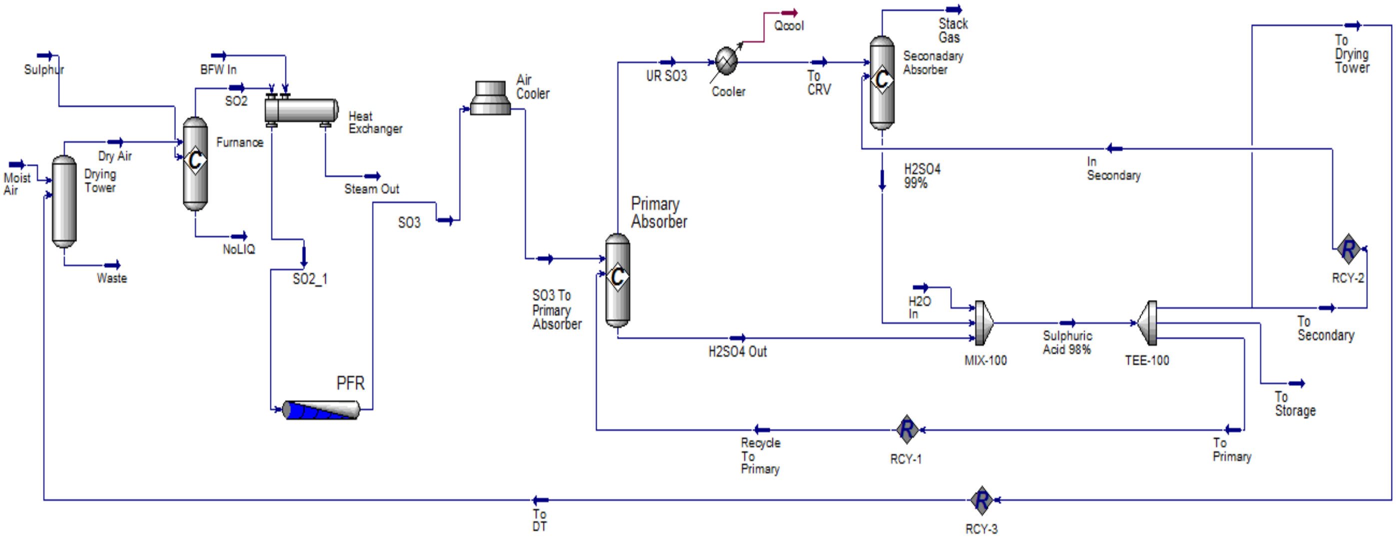


Figure 6 Simulation

The Air Cooler's cooled outlet, which contains sulfur trioxide, is transferred to the main absorption tower, where 98% H2SO4 is reacted to form 98,5% H2SO4. The stack gas is released from the nitrogen absorption tower. The concentration of stack SO2 is less than 500ppm, so that the exhaust gas is released into the atmosphere. Since absorbent acid is continually concentrated, some means are needed to dilute the acid part that is released from the absorbers and is recirculated. Therefore, 98.0% H2SO4 and de-mineralized water and 98.5% H2SO4 from the drying tower are feed into the circulation tank. The resulting H2SO4 concentration from the circulation tank is 98.1 percent, divided into two parts. The absorption tower is refreshed and recycled in a single part. The rest is also refrigerated and divided into two more parts. The final product contains 98% H2SO4 is one of these sections. The second part of the drying tower is recycled.

Component List:

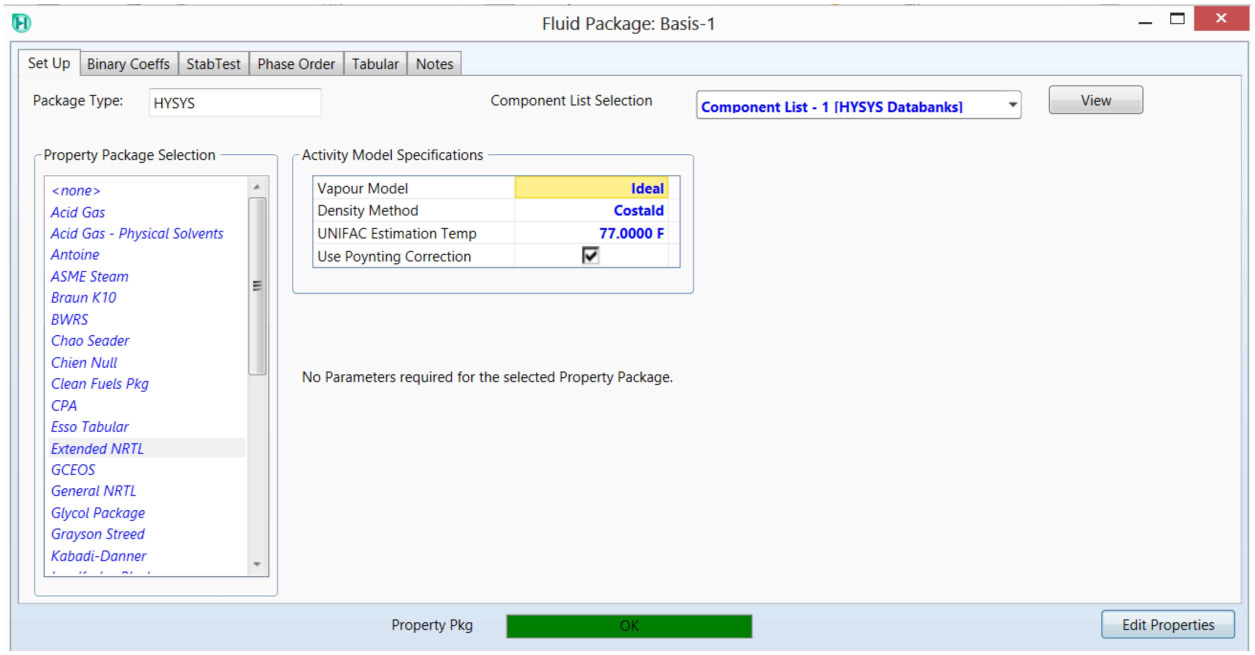
Following is the list of components that were selected in the Aspen HYSYS:

Table 24 Components in Aspen HYSYS

Components	**Component name**	**Formula**
H_2O	Water	H_2O
H_2SO_4	Sulfuric Acid	H_2SO_4
SO_2	Sulfur di-oxide	SO_2
SO_3	Sulfur tri-oxide	SO_3
S	Sulfur	S
N_2	Nitrogen	N_2
O_2	Oxygen	O_2
H_3O^+	Hydronium Ion	H_3O^+
HSO_4^-	Bi- Sulfate ion	HSO_4^-
SO_4^{--}	Sulfate ion	SO_4^{2-}

Fluid Package:

The fluid package we used in the simulation model is the “Extended NRTL”. The fluid package used in this simulation was the General NRTL property package employing the Virial vapor phase model as referred in the literature on model selection for the vapor phase. Kinetic reactions were configured for acetic acid from methanol and carbon monoxide.



Package Type: HYSYS

Component List Selection: Component List - 1 [HYSYS Databanks]

Property Package Selection

- <none>
- Acid Gas
- Acid Gas - Physical Solvents
- Antoine
- ASME Steam
- Braun K10
- BWRS
- Chao Seader
- Chien Null
- Clean Fuels Pkg
- CPA
- Esso Tabular
- Extended NRTL
- GCEOS
- General NRTL
- Glycol Package
- Grayson Streed
- Kabadi-Danner

Activity Model Specifications

Vapour Model	Ideal
Density Method	Costald
UNIFAC Estimation Temp	77.0000 F
Use Poynting Correction	☑

No Parameters required for the selected Property Package.

Property Pkg: OK

Figure 7 Fluid Package Aspen HYSYS

6.2 Reactions

i. Furnace

Specification Type	Stoichiometry
Conversion	$S + O_2 \rightarrow SO_2$

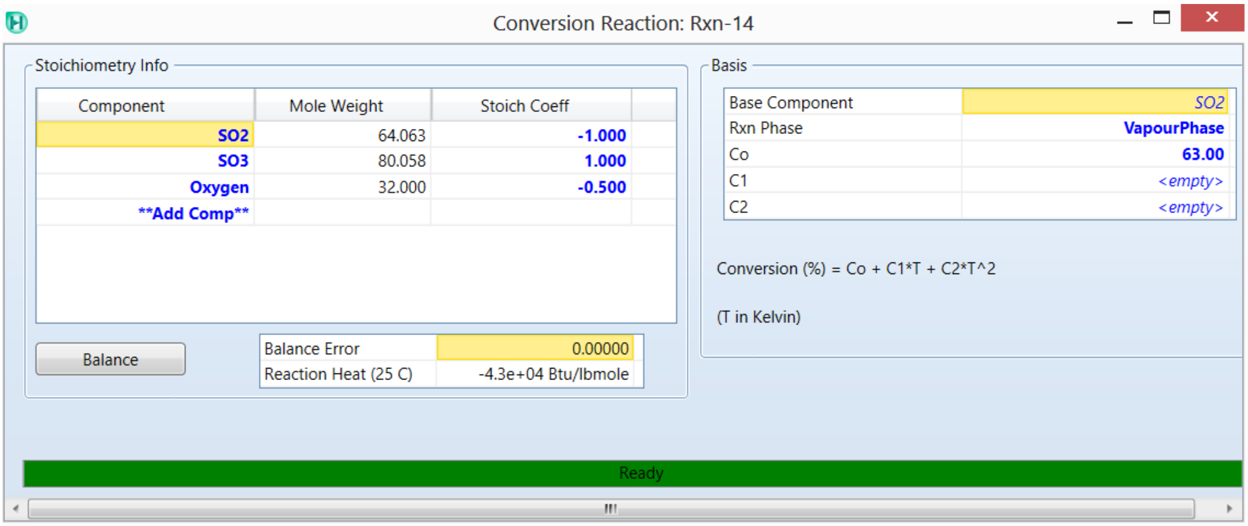
ii. PFR

Specification Type	Stoichiometry
Kinetic	$SO_2 + 0.5O_2 \rightarrow SO_3$

iii. Absorption Reaction

Specification Type	Stoichiometry
Conversion	$H_2O + SO_3 \rightarrow H_2SO_4$

These are the basic reactions that occur in the process. However, there are some other reactions that take place for example, the formation of oleum. Initially, oleum is produced in the absorption towers and then this oleum is mixed with water that forms the sulfuric acid. Following are the reaction sets that are implied in the model:



Conversion Reaction: Rxn-14

Stoichiometry Info

Component	Mole Weight	Stoich Coeff
SO2	64.063	-1.000
SO3	80.058	1.000
Oxygen	32.000	-0.500
Add Comp		

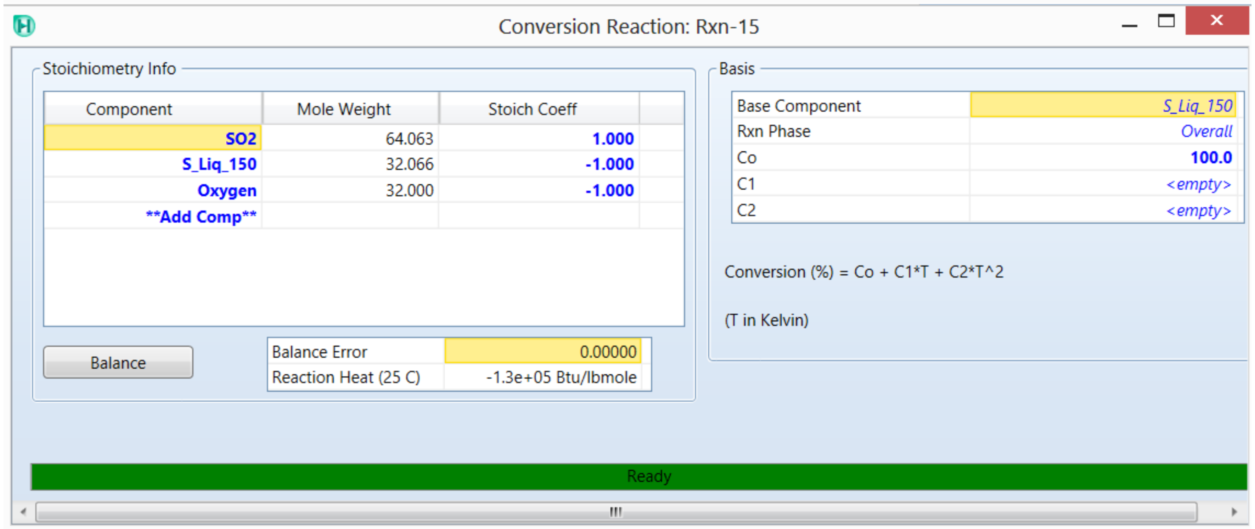
Balance Error	0.00000
Reaction Heat (25 C)	-4.3e+04 Btu/lbmole

Basis

Base Component	SO2
Rxn Phase	VapourPhase
Co	63.00
C1	<empty>
C2	<empty>

Conversion (%) = Co + C1*T + C2*T^2

(T in Kelvin)



Conversion Reaction: Rxn-15

Stoichiometry Info

Component	Mole Weight	Stoich Coeff
SO2	64.063	1.000
S_Liq_150	32.066	-1.000
Oxygen	32.000	-1.000
Add Comp		

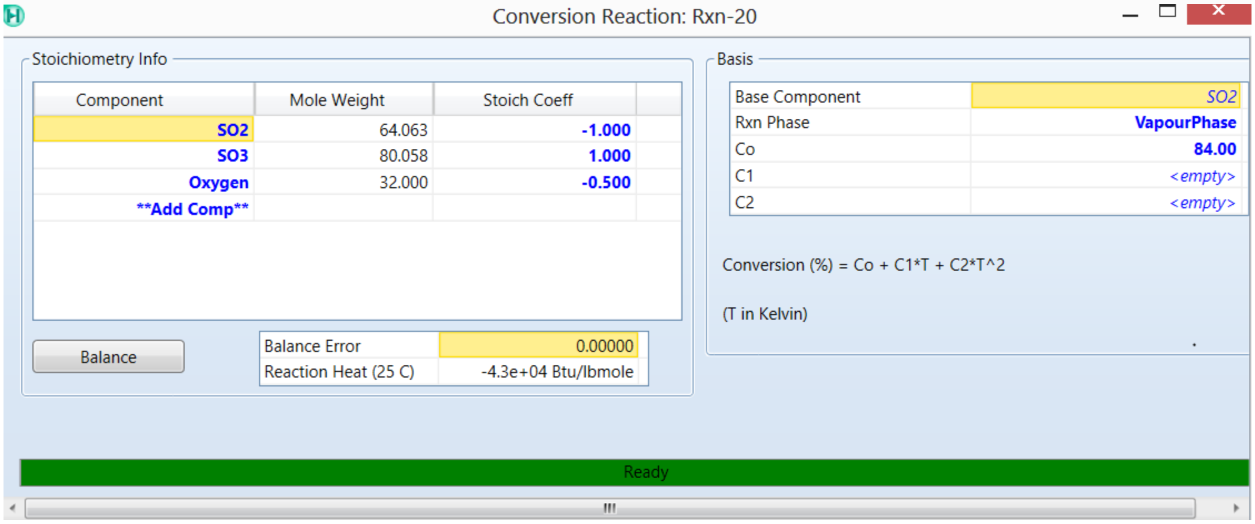
Balance Error	0.00000
Reaction Heat (25 C)	-1.3e+05 Btu/lbmole

Basis

Base Component	S_Liq_150
Rxn Phase	Overall
Co	100.0
C1	<empty>
C2	<empty>

Conversion (%) = Co + C1*T + C2*T^2

(T in Kelvin)



Conversion Reaction: Rxn-20

Stoichiometry Info

Component	Mole Weight	Stoich Coeff
SO2	64.063	-1.000
SO3	80.058	1.000
Oxygen	32.000	-0.500
Add Comp		

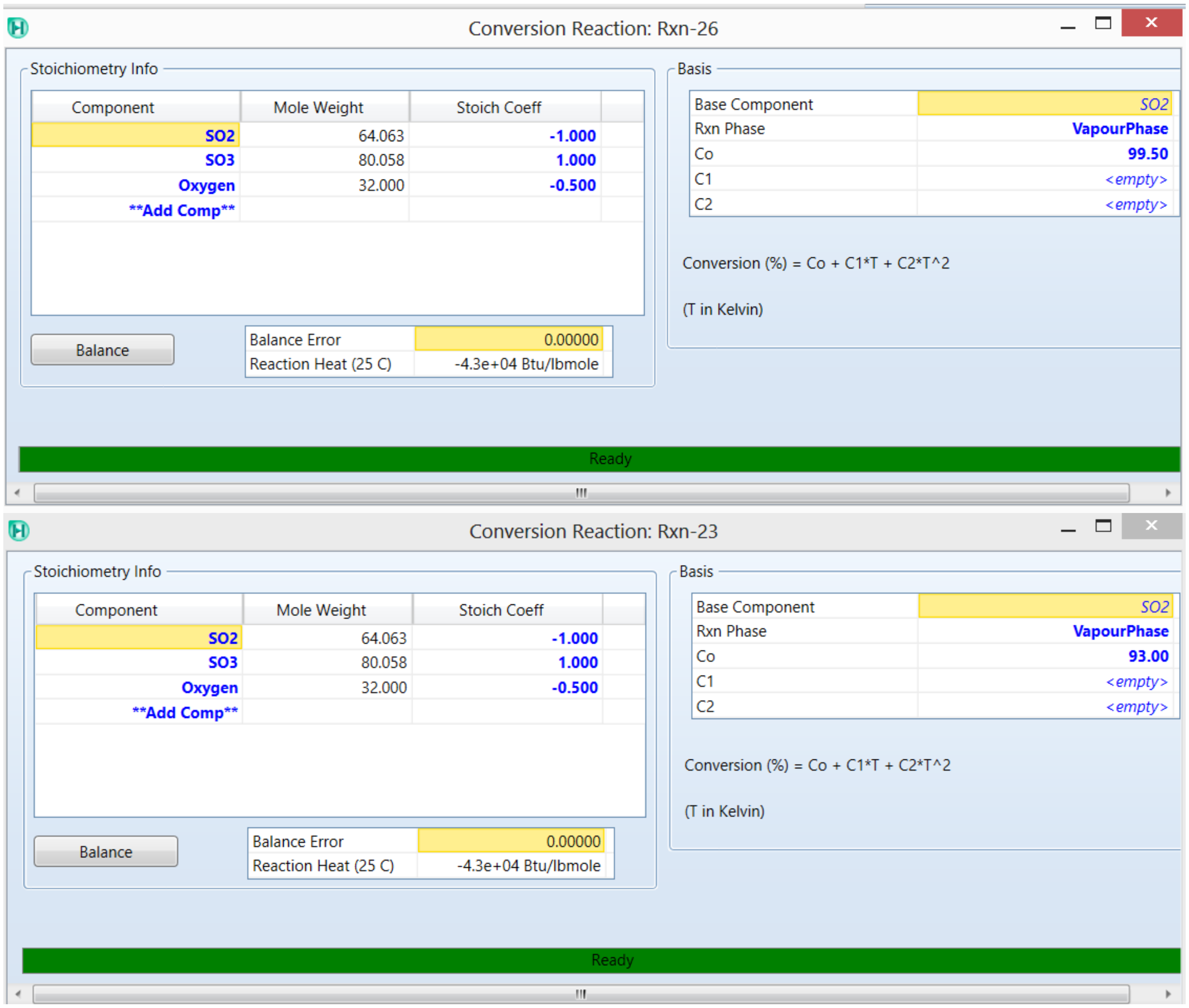
Balance Error	0.00000
Reaction Heat (25 C)	-4.3e+04 Btu/lbmole

Basis

Base Component	SO2
Rxn Phase	VapourPhase
Co	84.00
C1	<empty>
C2	<empty>

Conversion (%) = Co + C1*T + C2*T^2

(T in Kelvin)



Conversion Reaction: Rxn-26

Stoichiometry Info

Component	Mole Weight	Stoich Coeff
SO2	64.063	-1.000
SO3	80.058	1.000
Oxygen	32.000	-0.500
Add Comp		

Balance Error	0.00000
Reaction Heat (25 C)	-4.3e+04 Btu/lbmole

Basis

Base Component	SO2
Rxn Phase	VapourPhase
Co	99.50
C1	<empty>
C2	<empty>

Conversion (%) = Co + C1*T + C2*T^2

(T in Kelvin)

Ready

Conversion Reaction: Rxn-23

Stoichiometry Info

Component	Mole Weight	Stoich Coeff
SO2	64.063	-1.000
SO3	80.058	1.000
Oxygen	32.000	-0.500
Add Comp		

Balance Error	0.00000
Reaction Heat (25 C)	-4.3e+04 Btu/lbmole

Basis

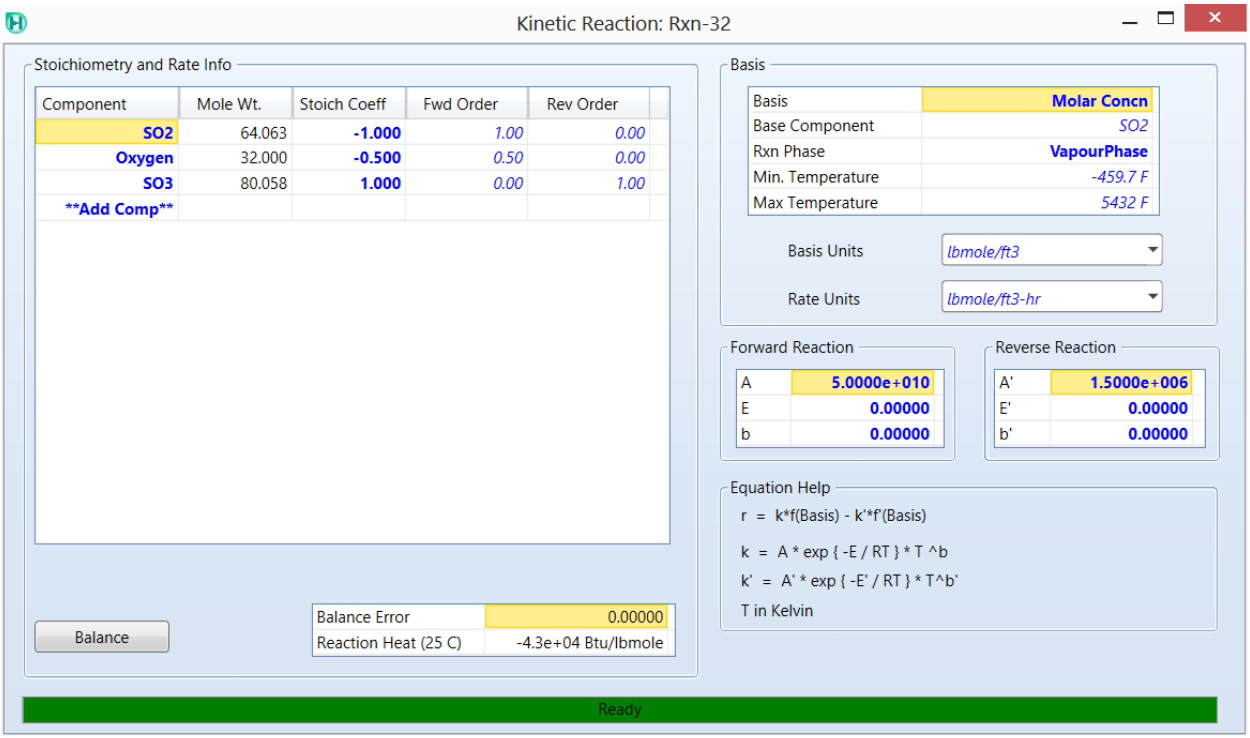
Base Component	SO2
Rxn Phase	VapourPhase
Co	93.00
C1	<empty>
C2	<empty>

Conversion (%) = Co + C1*T + C2*T^2

(T in Kelvin)

Ready

Figure 8 Reactions Aspen HYSYS



Kinetic Reaction: Rxn-32

Stoichiometry and Rate Info

Component	Mole Wt.	Stoich Coeff	Fwd Order	Rev Order
SO2	64.063	**-1.000**	*1.00*	*0.00*
Oxygen	32.000	**-0.500**	*0.50*	*0.00*
SO3	80.058	**1.000**	*0.00*	*1.00*
****Add Comp****				

Balance Error	0.00000
Reaction Heat (25 C)	-4.3e+04 Btu/lbmole

Basis

Basis	**Molar Concn**
Base Component	*SO2*
Rxn Phase	**VapourPhase**
Min. Temperature	*-459.7 F*
Max Temperature	*5432 F*

Basis Units: *lbmole/ft3*

Rate Units: *lbmole/ft3-hr*

Forward Reaction

A	**5.0000e+010**
E	**0.00000**
b	**0.00000**

Reverse Reaction

A'	**1.5000e+006**
E'	**0.00000**
b'	**0.00000**

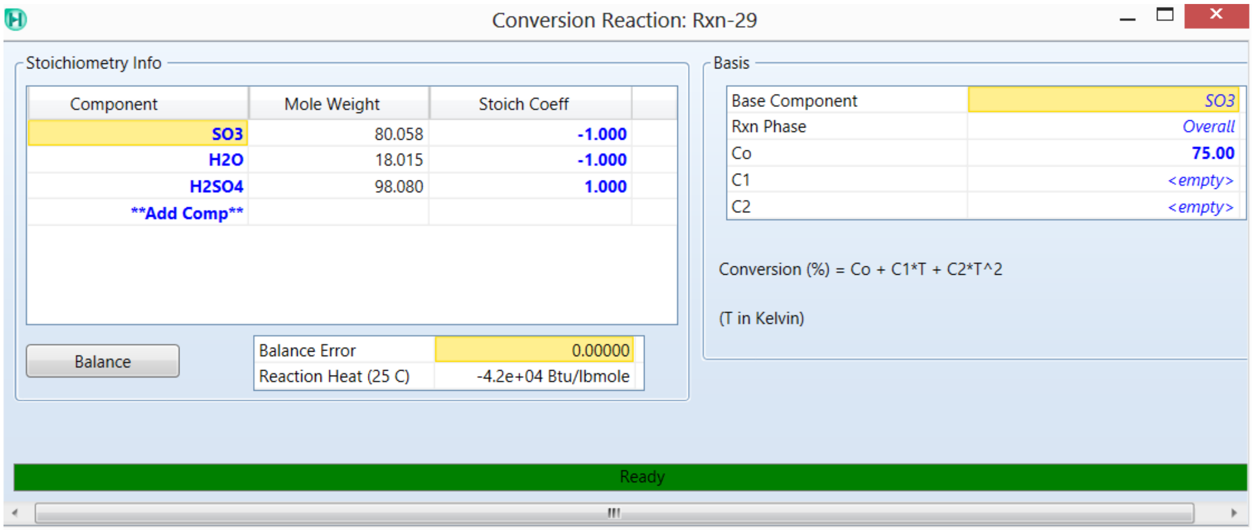
Equation Help

r = k*f(Basis) - k'*f'(Basis)

k = A * exp { -E / RT } * T ^b

k' = A' * exp { -E' / RT } * T^b'

T in Kelvin



Conversion Reaction: Rxn-29

Stoichiometry Info

Component	Mole Weight	Stoich Coeff
SO3	80.058	**-1.000**
H2O	18.015	**-1.000**
H2SO4	98.080	**1.000**
****Add Comp****		

Balance Error	0.00000
Reaction Heat (25 C)	-4.2e+04 Btu/lbmole

Basis

Base Component	*SO3*
Rxn Phase	*Overall*
Co	**75.00**
C1	*<empty>*
C2	*<empty>*

Conversion (%) = Co + C1*T + C2*T^2

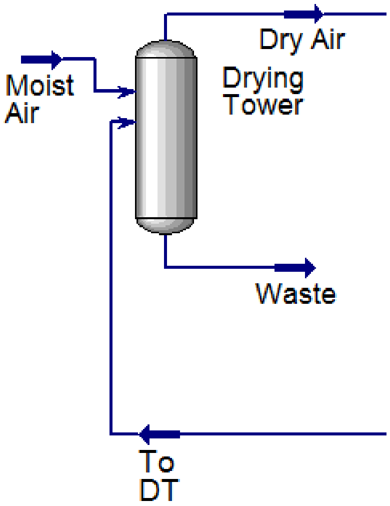
(T in Kelvin)

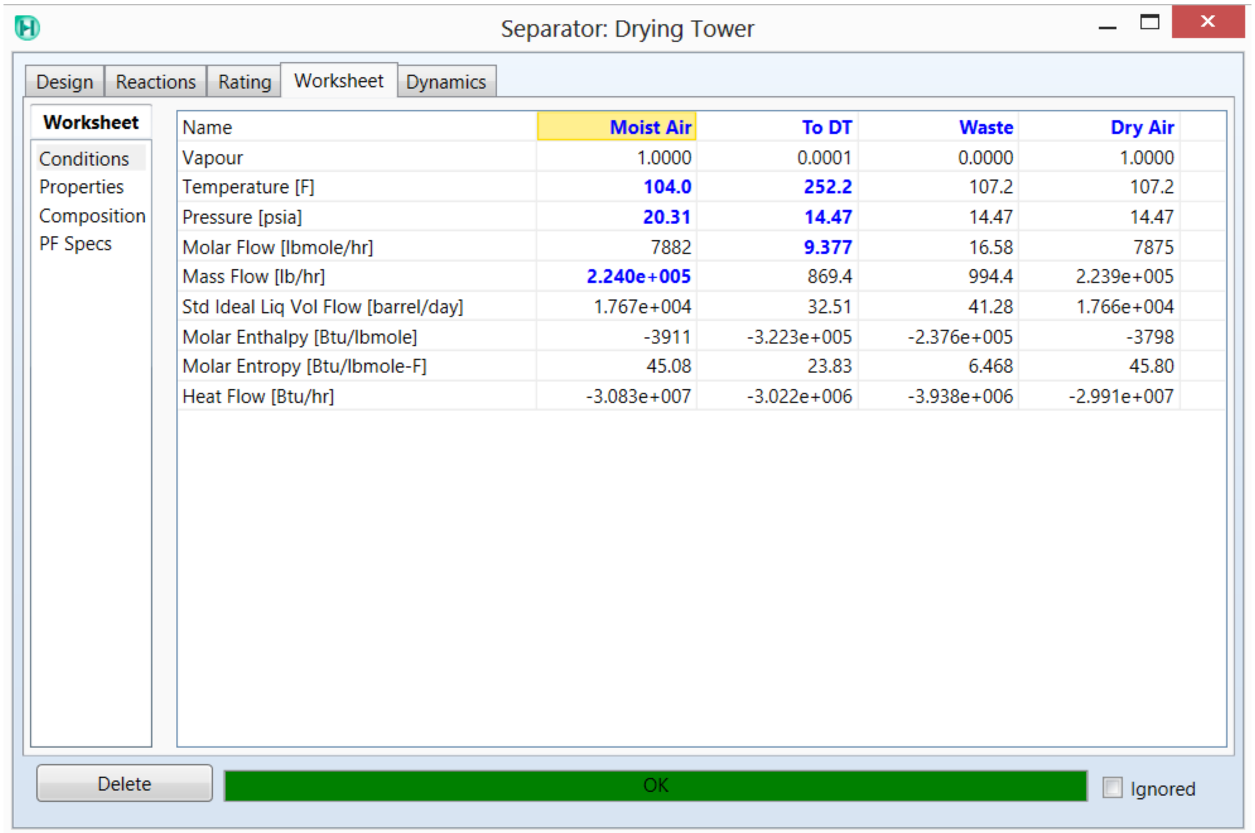
6.3 Unit Operation Models

Below detailed are the unit task models connected in the simulated model with their working conditions.

1) Drying Tower:

The basic function of the drying tower is to remove any moisture content present in the feed air that is to be supplied to the furnace.



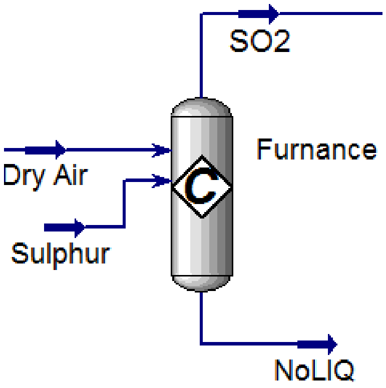


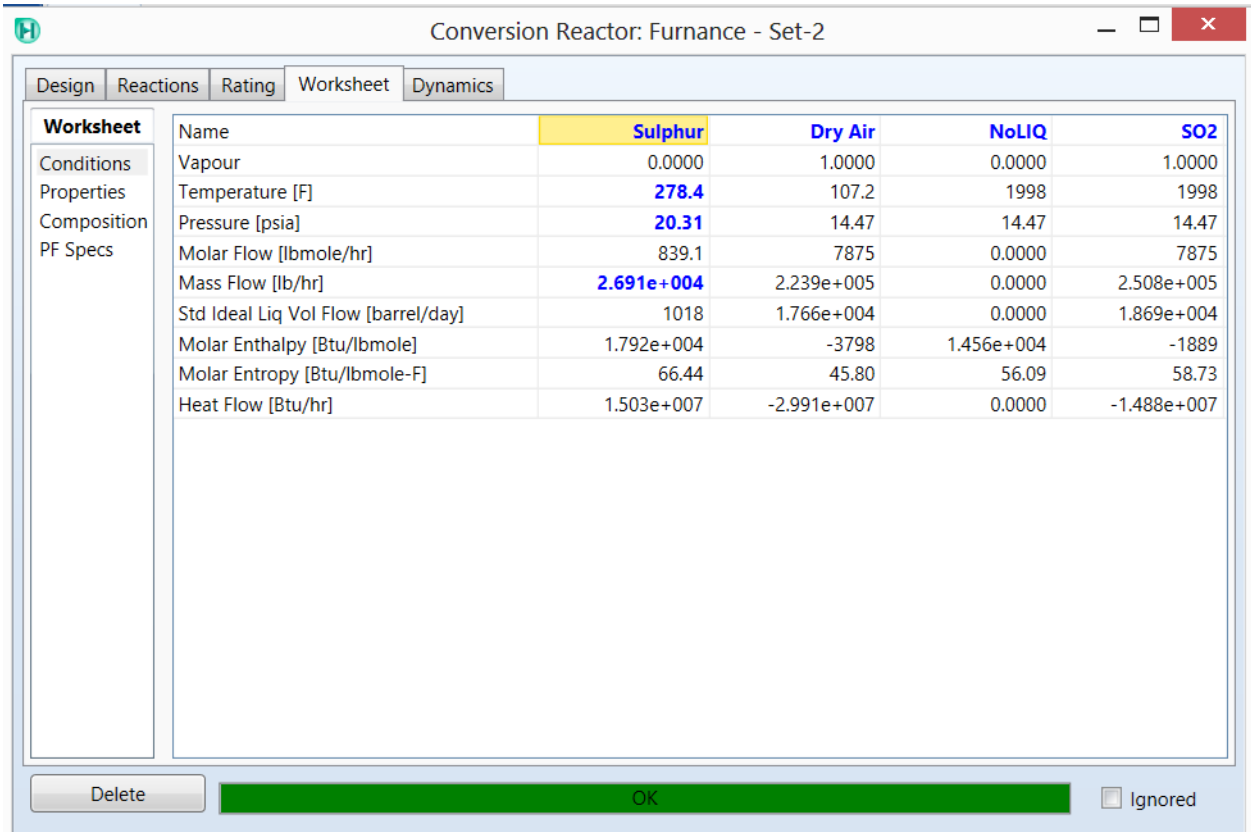
Name	Moist Air	To DT	Waste	Dry Air
Vapour	1.0000	0.0001	0.0000	1.0000
Temperature [F]	104.0	252.2	107.2	107.2
Pressure [psia]	20.31	14.47	14.47	14.47
Molar Flow [lbmole/hr]	7882	9.377	16.58	7875
Mass Flow [lb/hr]	2.240e+005	869.4	994.4	2.239e+005
Std Ideal Liq Vol Flow [barrel/day]	1.767e+004	32.51	41.28	1.766e+004
Molar Enthalpy [Btu/lbmole]	-3911	-3.223e+005	-2.376e+005	-3798
Molar Entropy [Btu/lbmole-F]	45.08	23.83	6.468	45.80
Heat Flow [Btu/hr]	-3.083e+007	-3.022e+006	-3.938e+006	-2.991e+007

Figure 9 Drying Tower Aspen HYSYS

2) Furnace:

The main reaction occurring inside the furnace is the conversion of the molten Sulphur into Sulphur dioxide in the presence of dry air. Following are its specifications and the worksheet:



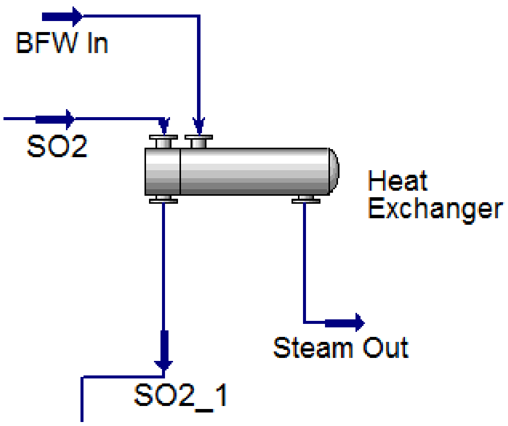


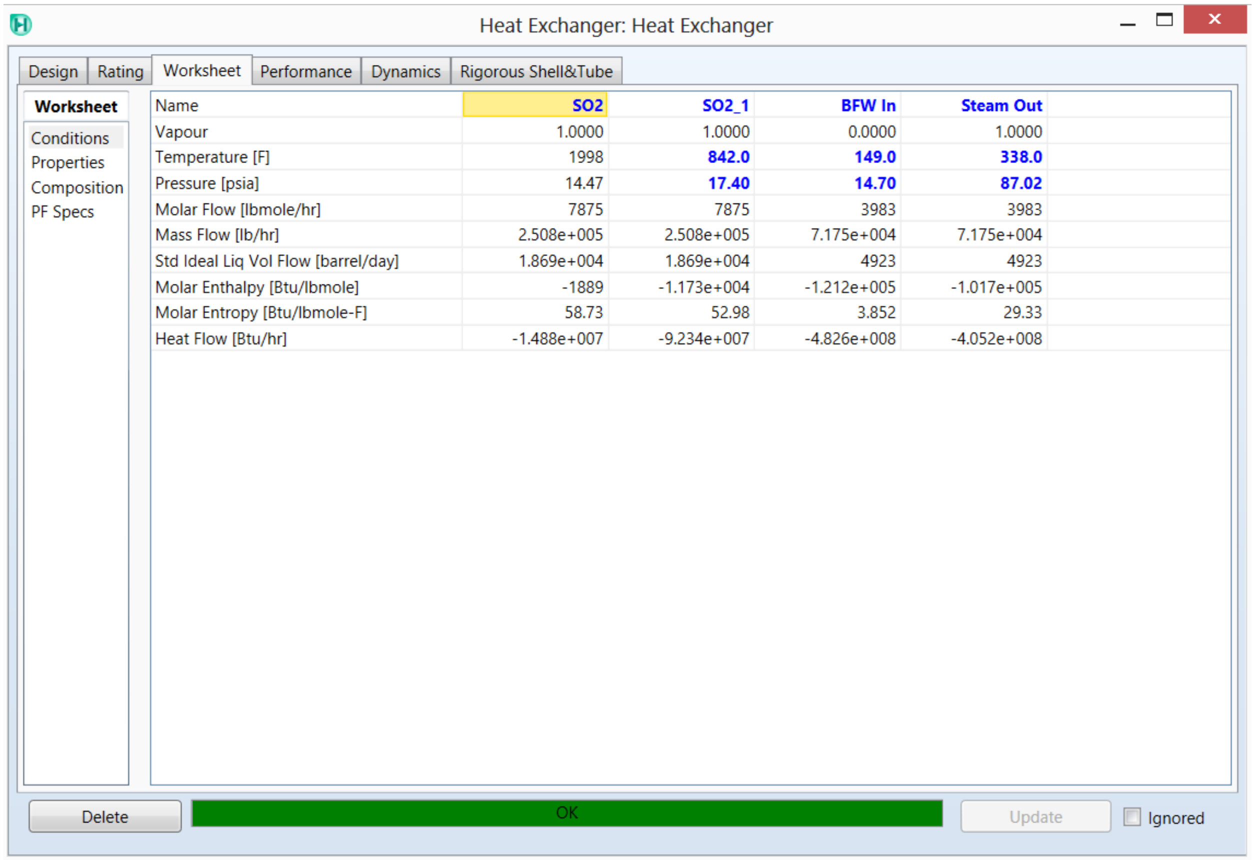
Name	Sulphur	Dry Air	NoLIQ	SO2
Vapour	0.0000	1.0000	0.0000	1.0000
Temperature [F]	278.4	107.2	1998	1998
Pressure [psia]	20.31	14.47	14.47	14.47
Molar Flow [lbmole/hr]	839.1	7875	0.0000	7875
Mass Flow [lb/hr]	2.691e+004	2.239e+005	0.0000	2.508e+005
Std Ideal Liq Vol Flow [barrel/day]	1018	1.766e+004	0.0000	1.869e+004
Molar Enthalpy [Btu/lbmole]	1.792e+004	-3798	1.456e+004	-1889
Molar Entropy [Btu/lbmole-F]	66.44	45.80	56.09	58.73
Heat Flow [Btu/hr]	1.503e+007	-2.991e+007	0.0000	-1.488e+007

Figure 10 Furnace Aspen HYSYS

1) Heat Exchanger:

U-tube heat exchanger was used in the simulated model. Cooling water was used as the cooling media to lower the temperature of the Sulphur dioxide before sending it to the PFR:



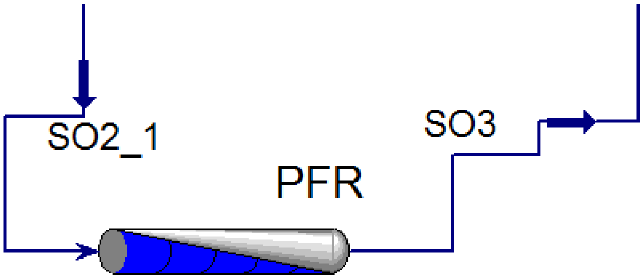


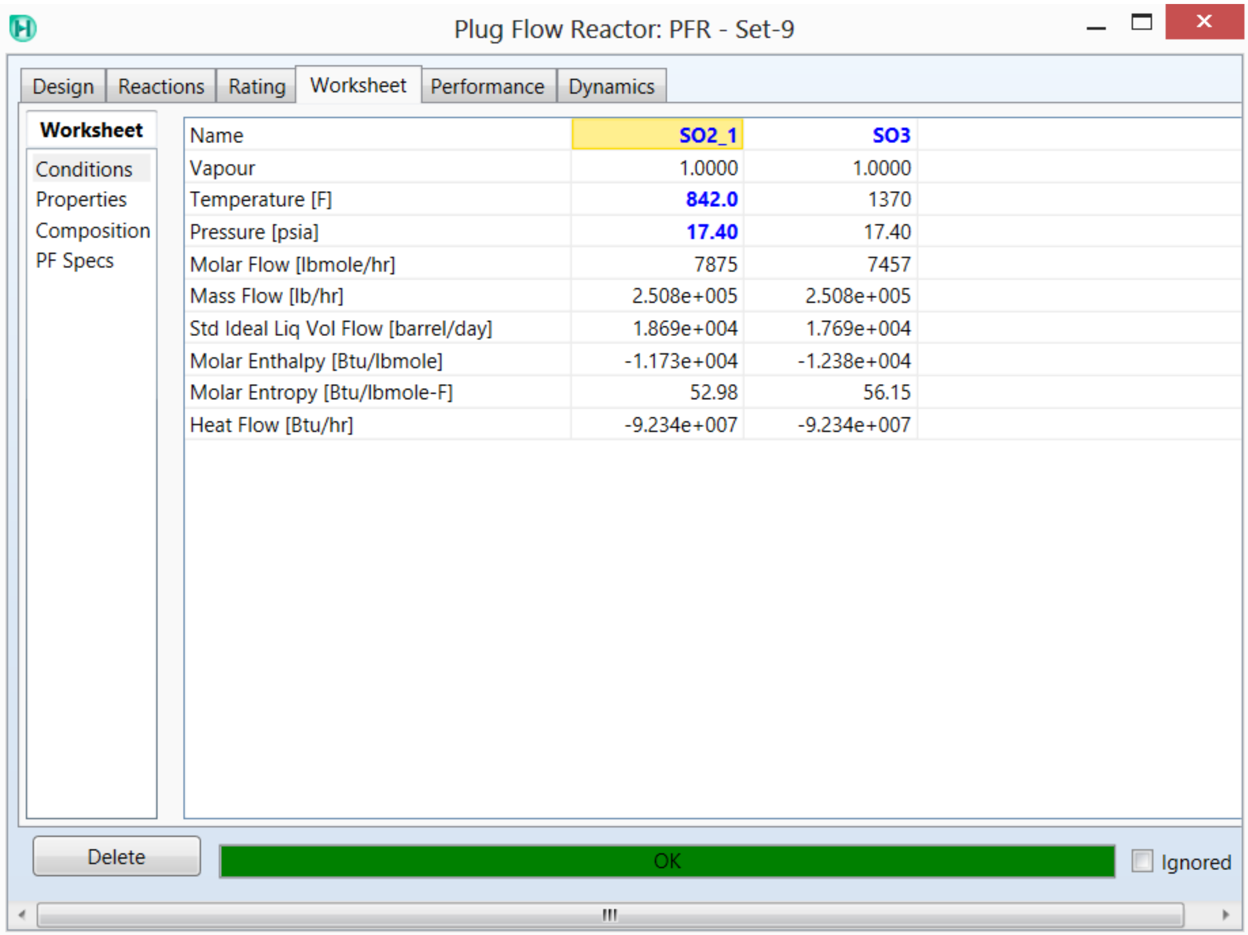
Name	SO2	SO2_1	BFW In	Steam Out
Vapour	1.0000	1.0000	0.0000	1.0000
Temperature [F]	1998	842.0	149.0	338.0
Pressure [psia]	14.47	17.40	14.70	87.02
Molar Flow [lbmole/hr]	7875	7875	3983	3983
Mass Flow [lb/hr]	2.508e+005	2.508e+005	7.175e+004	7.175e+004
Std Ideal Liq Vol Flow [barrel/day]	1.869e+004	1.869e+004	4923	4923
Molar Enthalpy [Btu/lbmole]	-1889	-1.173e+004	-1.212e+005	-1.017e+005
Molar Entropy [Btu/lbmole-F]	58.73	52.98	3.852	29.33
Heat Flow [Btu/hr]	-1.488e+007	-9.234e+007	-4.826e+008	-4.052e+008

Figure 11 Heat Exchanger Aspen HYSYS

1) Plug Flow Reactor:

PFR is the major equipment in the model where the main reaction is taking place. The conversion of the Sulphur dioxide into Sulphur trioxide in the presence of vanadium penta-oxide acting as a catalyst. The reaction kinetics are as follows:





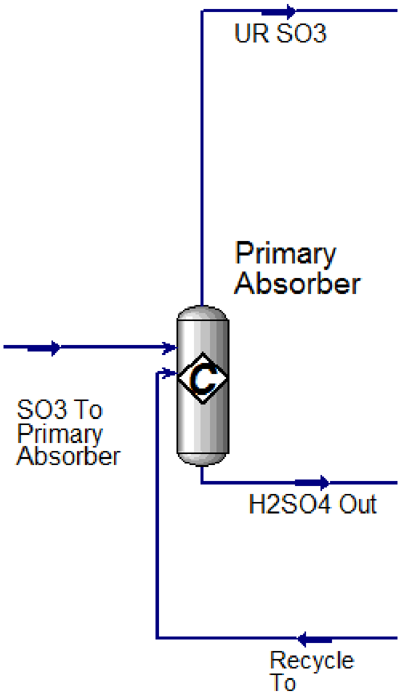
Name	SO2_1	SO3
Vapour	1.0000	1.0000
Temperature [F]	842.0	1370
Pressure [psia]	17.40	17.40
Molar Flow [lbmole/hr]	7875	7457
Mass Flow [lb/hr]	2.508e+005	2.508e+005
Std Ideal Liq Vol Flow [barrel/day]	1.869e+004	1.769e+004
Molar Enthalpy [Btu/lbmole]	-1.173e+004	-1.238e+004
Molar Entropy [Btu/lbmole-F]	52.98	56.15
Heat Flow [Btu/hr]	-9.234e+007	-9.234e+007

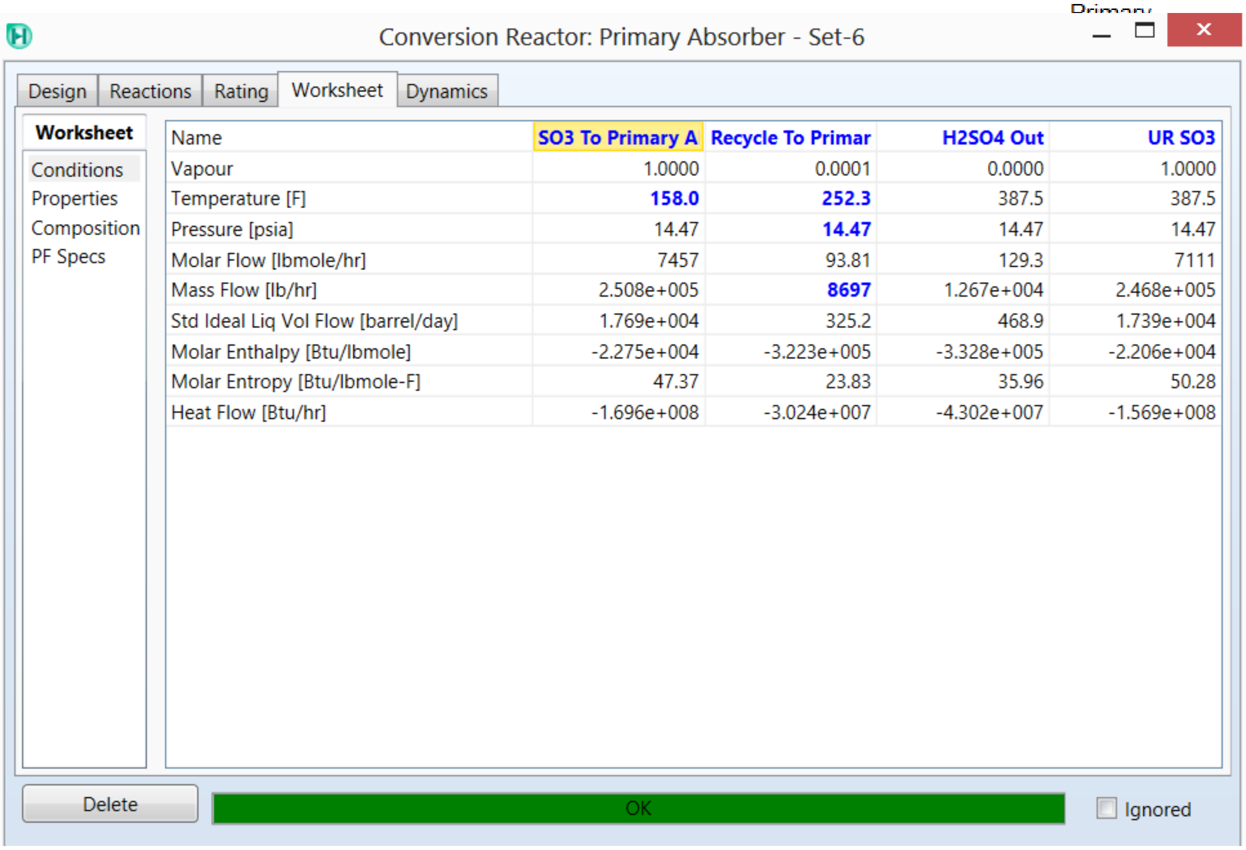
Figure 12 Plug Flow Reactor Aspen HYSYS

3) Primary Absorber:

In primary absorber, the Sulphur trioxide is being converted to the sulfuric acid (oleum) in the presence of the water.

Sulfuric acid produced is sent to the storage tank where it is mixed with water to dilute it to required concentration.



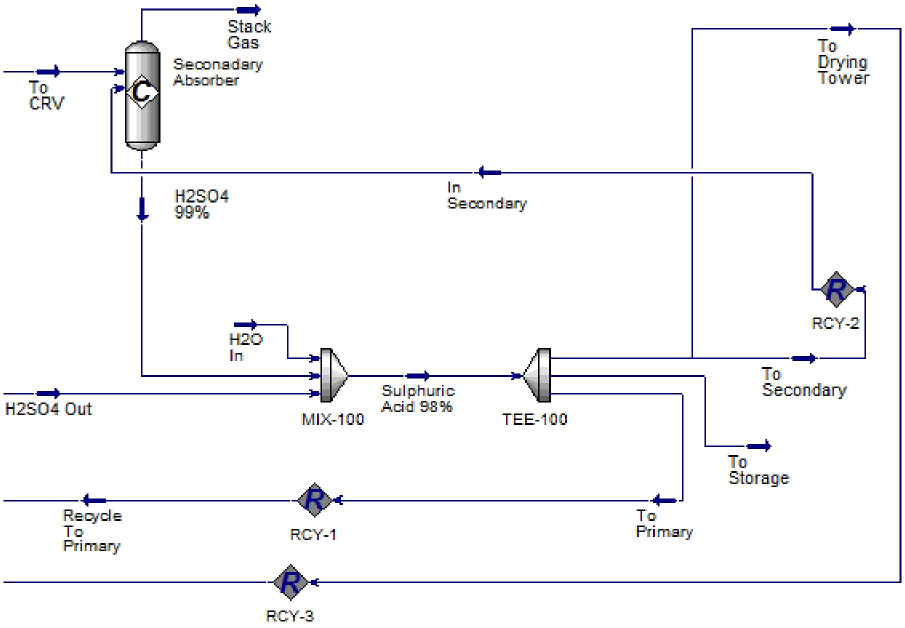


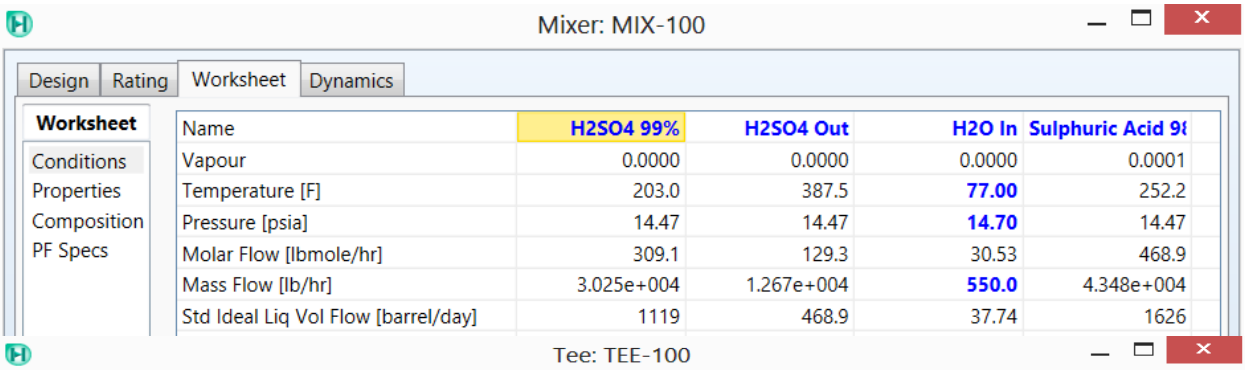
Name	SO3 To Primary A	Recycle To Primar	H2SO4 Out	UR SO3
Vapour	1.0000	0.0001	0.0000	1.0000
Temperature [F]	158.0	252.3	387.5	387.5
Pressure [psia]	14.47	14.47	14.47	14.47
Molar Flow [lbmole/hr]	7457	93.81	129.3	7111
Mass Flow [lb/hr]	2.508e+005	8697	1.267e+004	2.468e+005
Std Ideal Liq Vol Flow [barrel/day]	1.769e+004	325.2	468.9	1.739e+004
Molar Enthalpy [Btu/lbmole]	-2.275e+004	-3.223e+005	-3.328e+005	-2.206e+004
Molar Entropy [Btu/lbmole-F]	47.37	23.83	35.96	50.28
Heat Flow [Btu/hr]	-1.696e+008	-3.024e+007	-4.302e+007	-1.569e+008

Figure 13 Primary Absorber Aspen HYSYS

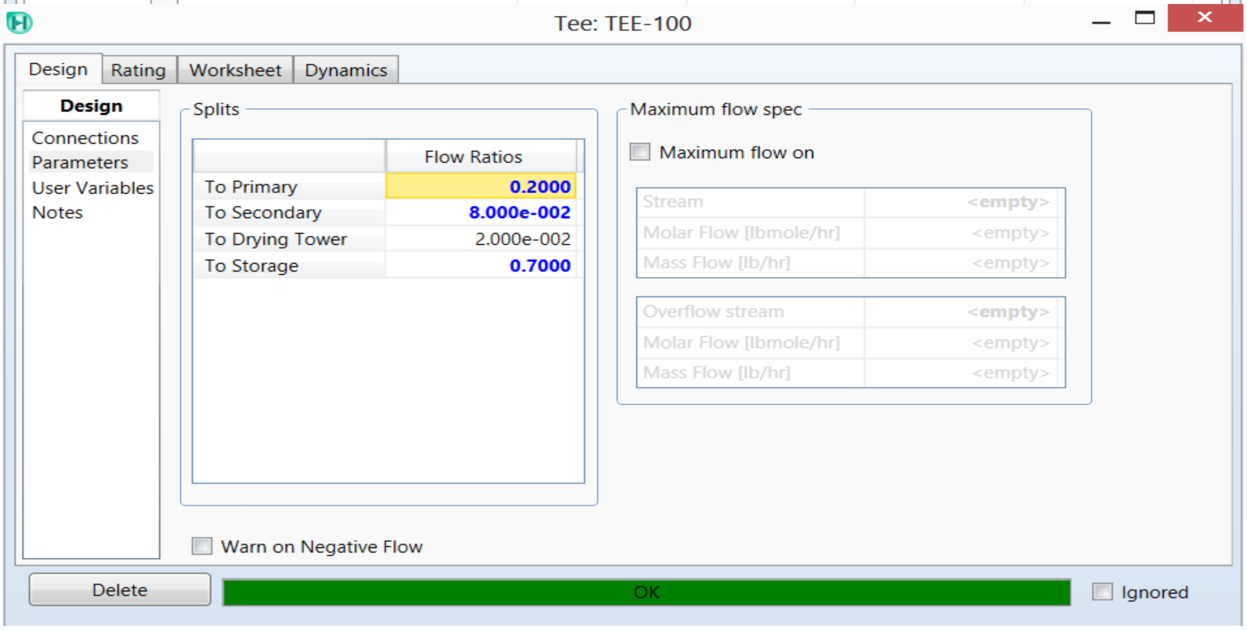
1) Secondary Absorber:

The function of secondary absorber is same as that of primary absorber. The Sulphur trioxide is being converted to the sulfuric acid (oleum) in the presence of the water. Sulfuric acid produced is sent to the storage tank where it is mixed with water to dilute it to required concentration.





Name	H2SO4 99%	H2SO4 Out	H2O In	Sulphuric Acid 9
Vapour	0.0000	0.0000	0.0000	0.0001
Temperature [F]	203.0	387.5	77.00	252.2
Pressure [psia]	14.47	14.47	14.70	14.47
Molar Flow [lbmole/hr]	309.1	129.3	30.53	468.9
Mass Flow [lb/hr]	3.025e+004	1.267e+004	550.0	4.348e+004
Std Ideal Liq Vol Flow [barrel/day]	1119	468.9	37.74	1626



	Flow Ratios
To Primary	0.2000
To Secondary	8.000e-002
To Drying Tower	2.000e-002
To Storage	0.7000

☐ Maximum flow on

Stream	<empty>
Molar Flow [lbmole/hr]	<empty>
Mass Flow [lb/hr]	<empty>

Overflow stream	<empty>
Molar Flow [lbmole/hr]	<empty>
Mass Flow [lb/hr]	<empty>

☐ Warn on Negative Flow

☐ Ignored

Figure 14 Secondary Absorber Aspen HYSYS

Chapter 7: Sensitivity Analysis

7.1 Introduction

- Analyzing the process variables effect on the production of sulphuric acid.
- Sensitivity Analysis has been accomplished using MATLAB code to extract data from an excel sheet and apply it in Aspen HYSYS.
- Initially, Aspen HYSYS Model is connected to an excel sheet where various process variables and output variables are set.
- Cases are set for each relation i.e. 20 cases have been selected to study the sensitiveness of output variable with respect to process variables.
- A MATLAB Code has been generated to assign values for each process variable in Excel Sheet.
- 5-10 % Variation has been set for each process variable.

7.2 MATLAB Code

```
clc
clear
filename = 'ahmad2.xlsx'; %File name
sheet = 'Sheet11';%sheet name
xlRange = 'D3'%specify the column whose values will be updated/changed
subsetA = xlsread (filename, sheet,xlRange)%within the sheet extract values of column D

subsetAn= [];
InputValues= [];

randomValue = 0.95 + (1.05- 0.95).*rand(length(subsetA),20);
for j=1:20
for i=1:length(subsetA)
subsetAn(i,j)=subsetA(i)*randomValue(i,j);%5 percent increase in original values of column D
end
end
filename = 'ahmad2.xlsx';
xlswrite(filename,subsetAn,'Sheet11','E3:W3')%The increased values of column D are being placed into columns E and F
InputValues=subsetAn;

% % sheet = 'Sheet11’; %sheet name
% % xlRange = 'D3;%specify the column whose values will be read into the OuputValues table
% % OutputValues = xlsread(filename, sheet,xlRange)

% save allInputsandOutputs
```

7.3 Results

- The following results shows the effect of various process variables on the production of sulphuric acid.
- Various other results show the effect of process variables on numerous other output variables.

1) Effect of Air Flow rate on Sulphuric Acid Composition

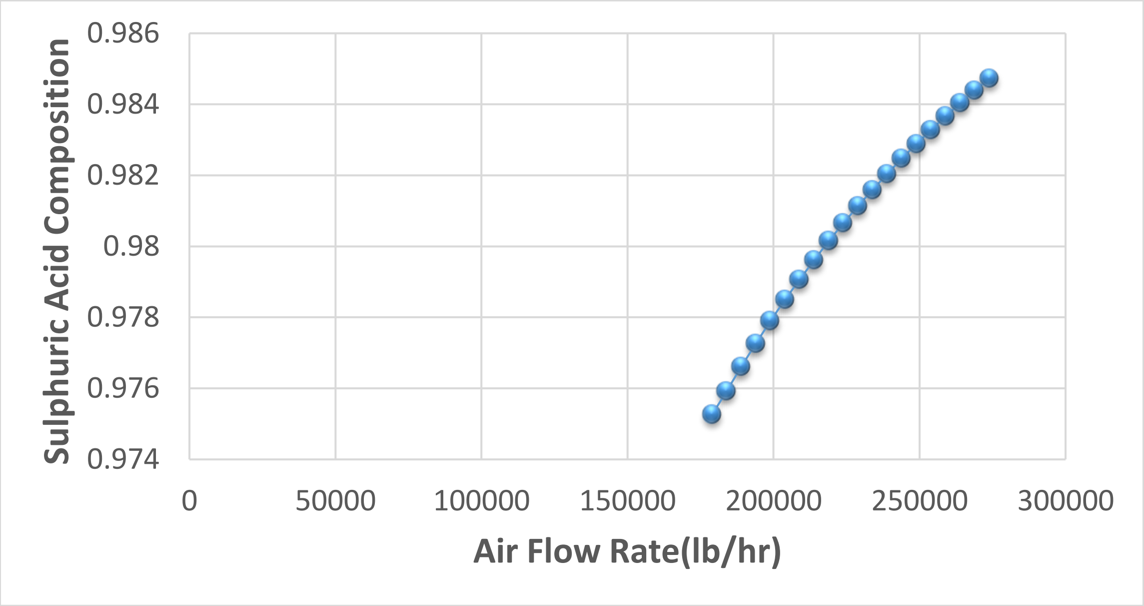


Figure 15 Effect of Air Flow rate on Sulphuric Acid Composition

The following graph shows an increase in the Sulphuric acid composition as the flow rate of air is increased. It can be seen prominently that the appropriate point where sulphuric acid composition is 98%, the air flow rate is 224000 lb/hr.

2) Effect of sulphur composition on Sulphuric acid flow rate

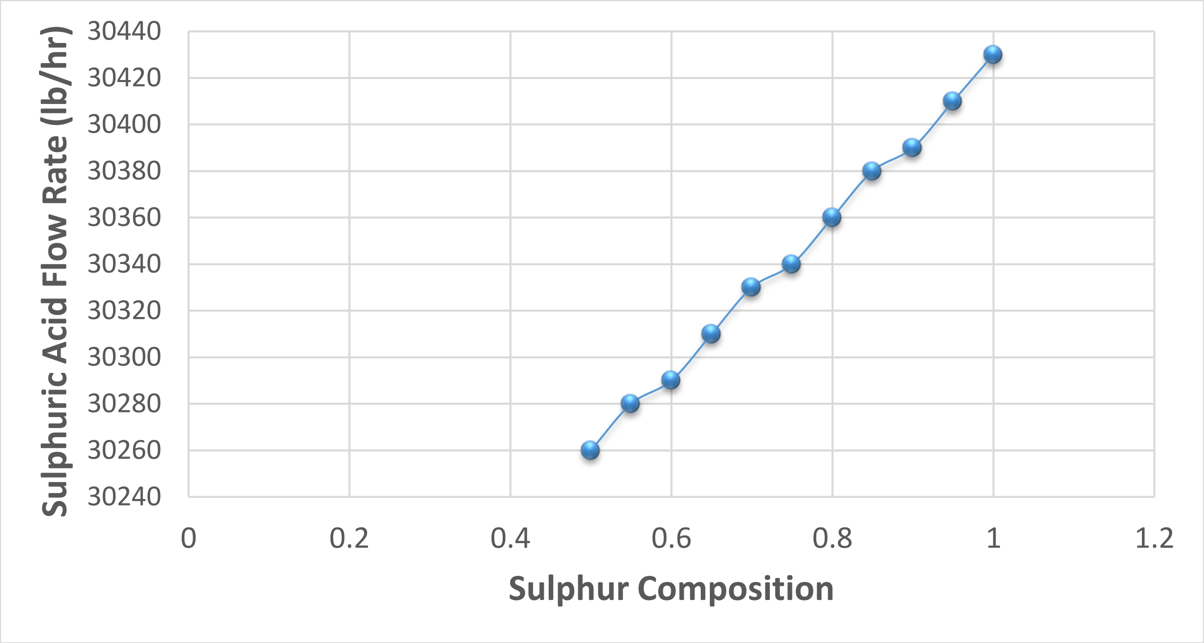


Figure 16 Effect of sulphur composition on Sulphuric acid flow rate

Following graph shows the effect of composition of sulphur on the sulphuric acid flow rate. Required 130 ton/day is produced when the sulphur composition is 1.

3) Effect of Absorber temperature on Sulphuric Acid Composition

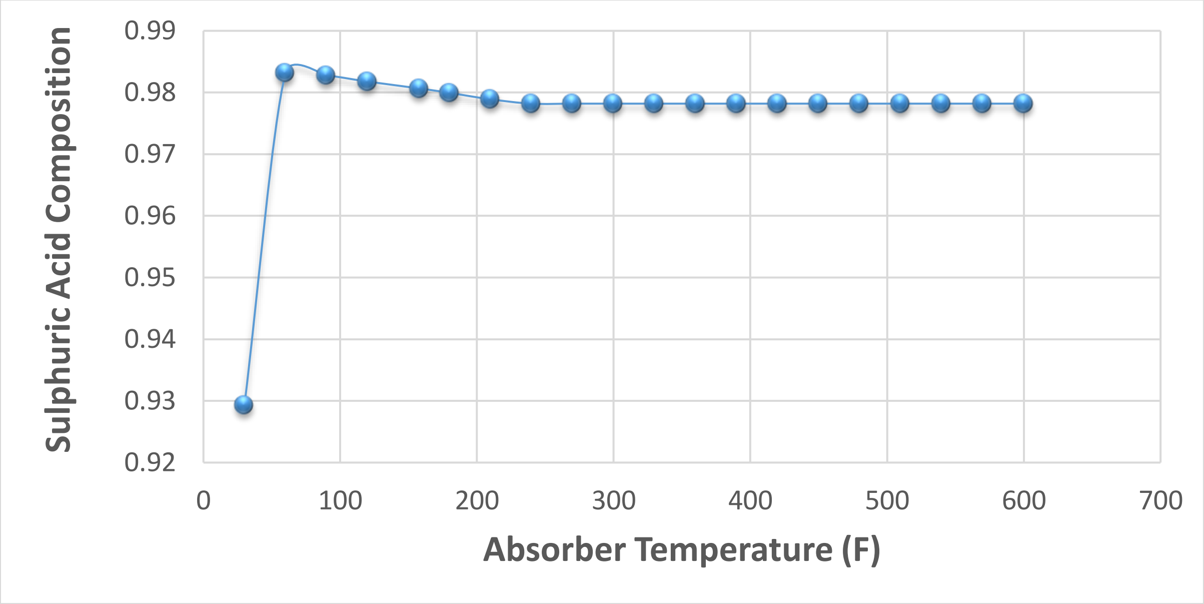


Figure 17 Effect of Absorber temperature on Sulphuric Acid Composition

Absorption is dominantly mass transfer operation therefore, temperature does not affect the output very significantly. Sulphuric acid composition is nearly constant at all temperatures. The abrupt change in the initial value is due to the design considerations of absorber.

4) Effect of temperature on Reactor Conversion

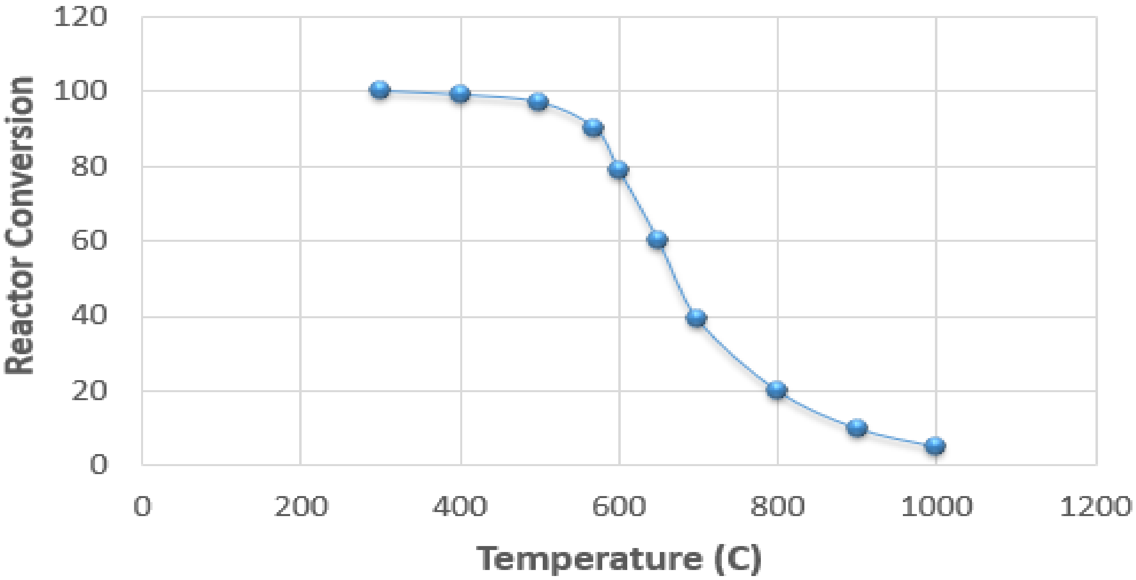


Figure 18 Effect of temperature on Reactor Conversion

As shown in the graph above, Reactor Conversion decreases as the temperature is increased from 450 ^{0}C. This shows that the required conversion i.e. 99.5% is only achieved when temperature is kept at 450 ^{0}C. So, Temperature i.e. 450 ^{0}C is the optimum temperature for the reactor.

5) Effect of Air temperature on Sulphuric acid composition

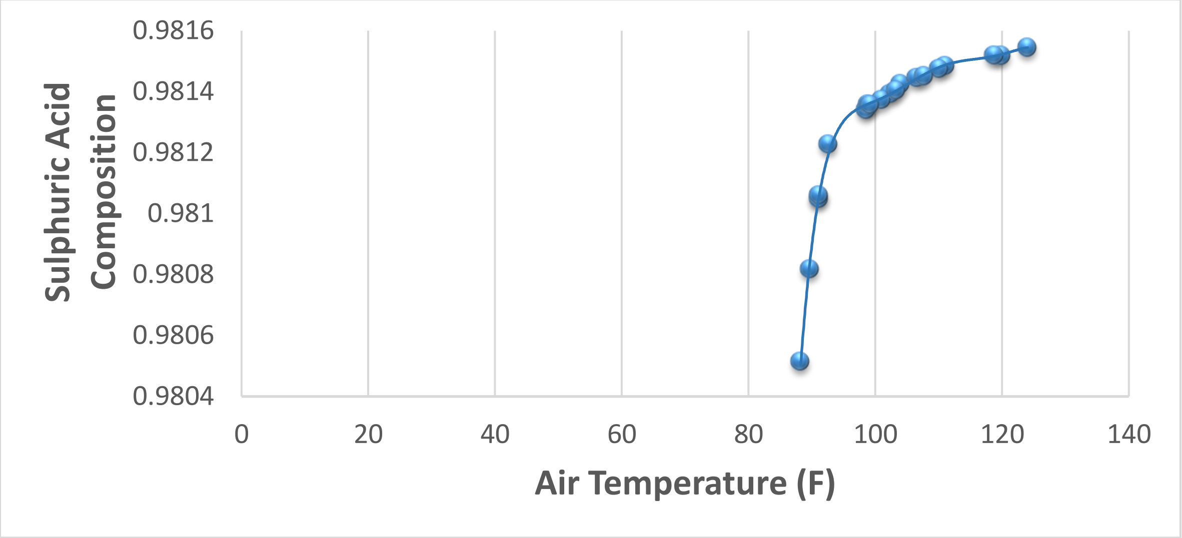


Figure 19 Effect of Air temperature on Sulphuric acid composition

Increasing the temperature of air also has an increasing behavior on the sulphuric acid composition. The required composition i.e. 98% is achieved only when the temperature of air is around 100 ^{0}C.

6) Effect of Reactor Pressure on Sulphuric Acid Composition

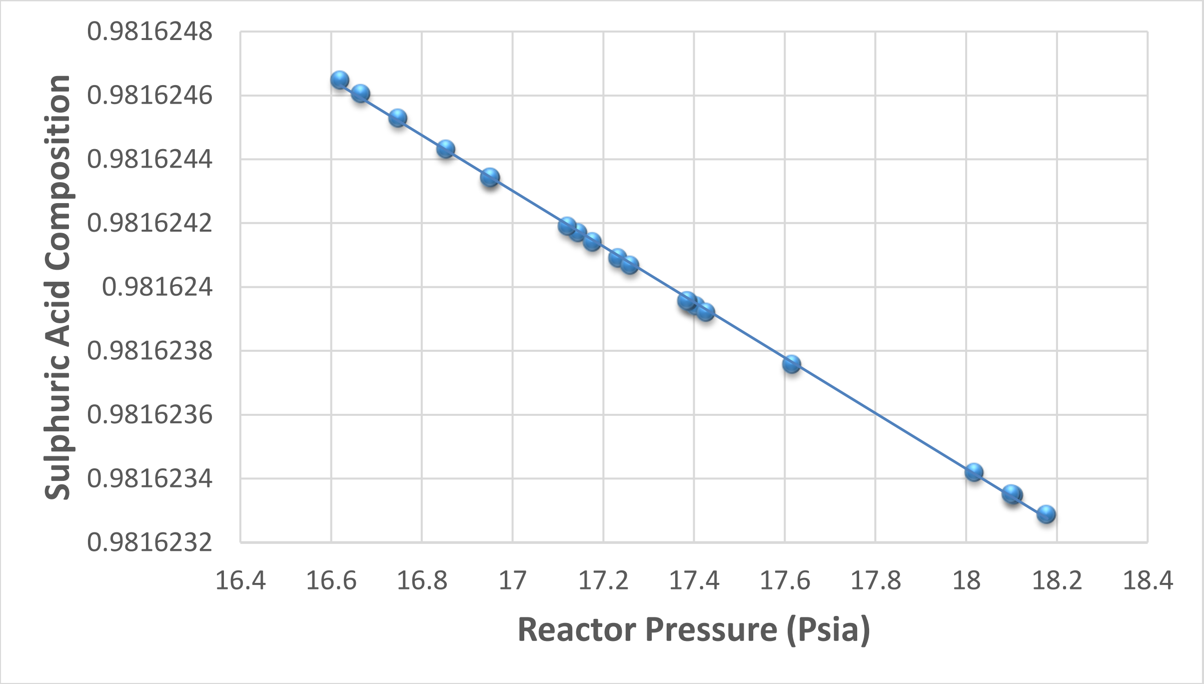


Figure 20 Effect of Reactor Pressure on Sulphuric Acid Composition

Reactor Pressure has a very negligible or insignificant effect on the sulphuric acid composition.

7) Effect of sulphur flow rate on sulphuric acid composition

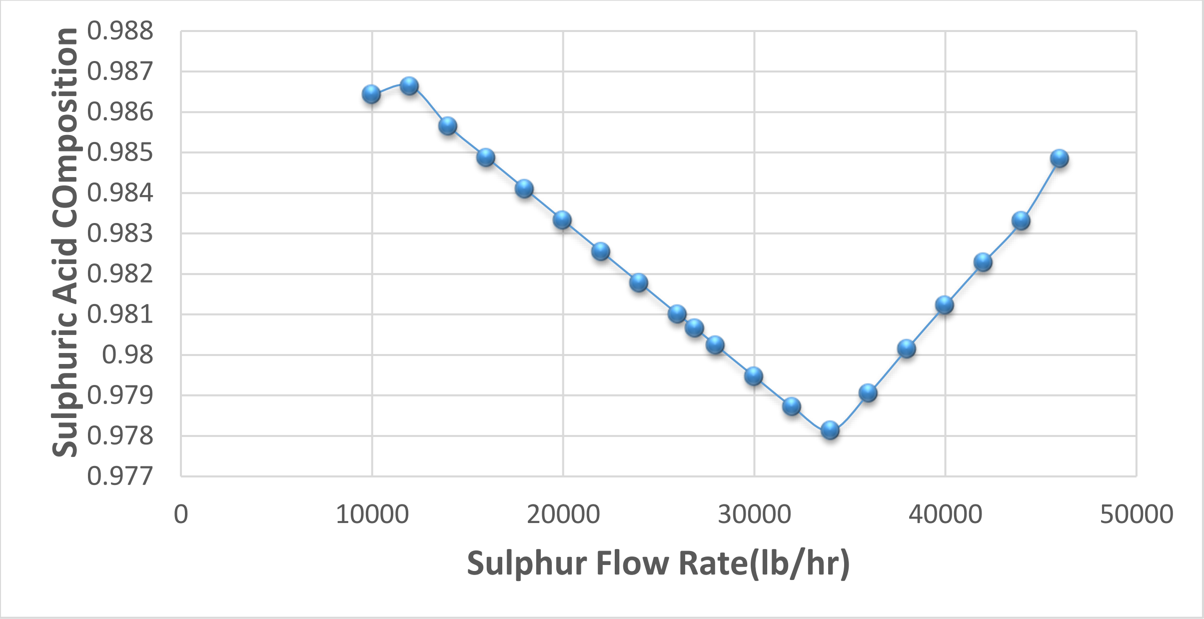


Figure 21 Effect of sulphur flow rate on sulphuric acid composition

Sulphur Flow rate VS Sulphuric acid composition has a very vague behavior. Initially, increasing the flow rate causes a decrease in composition but after a certain point, the composition starts to rise. In our simulation model 27000 lb/hr of sulphur flow rate has been used to produce required composition of sulphuric acid composition.

Chapter 8: Process Control

8.1 Introduction

Process has been demonstrated on the reactor and heat exchanger. Temperature and Flow Controls has been applied.

This type of controller work on the principle of feedback control system. In which at the output variable is measured by a sensor compared to the required value. If the error is negative or positive the controller adjusts the valve respectively. These feedback controllers contain of three parts:

- Transducer/Sensor
- a Controller
- Process system/process plant.

Reactor

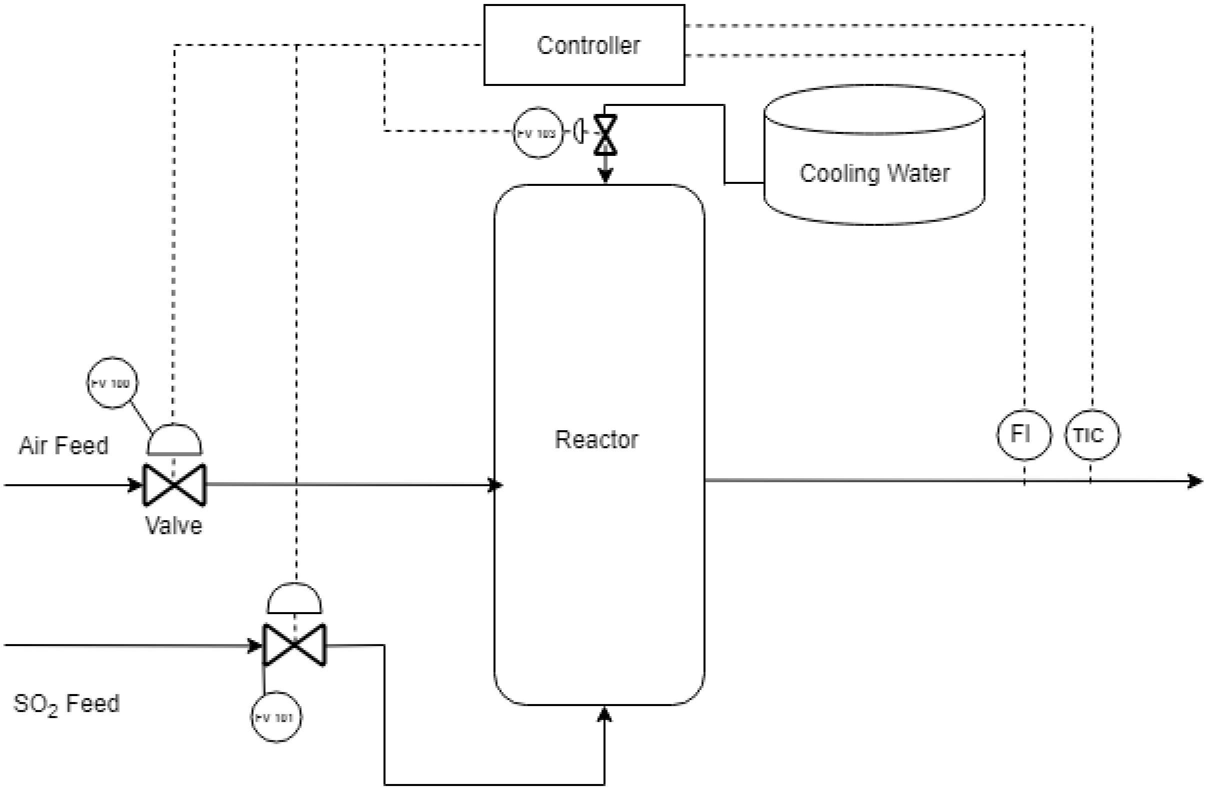


Figure 22 Process Control Reactor

Heat Exchanger

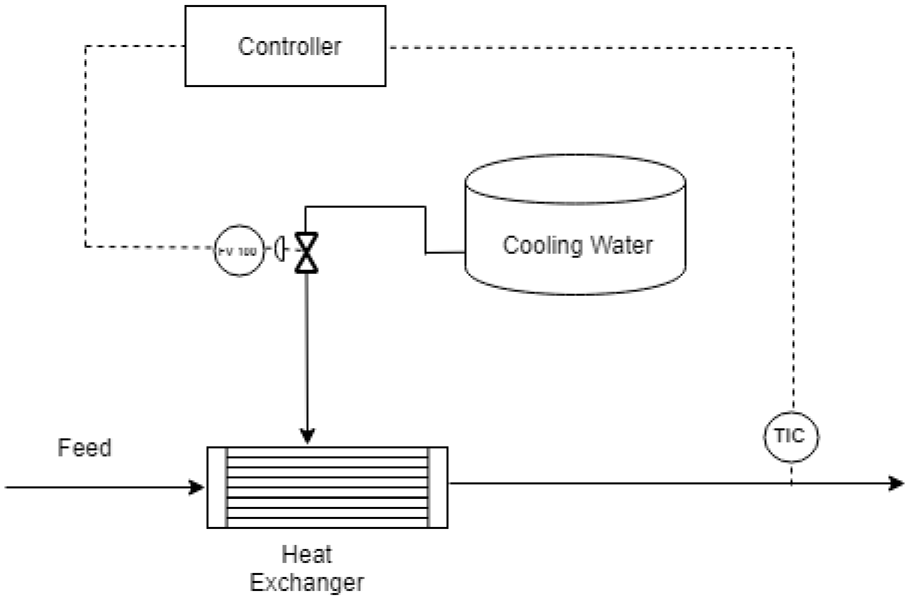


Figure 23 Process Control Heat Exchanger

8.2 General Explanation

Temperature Controller: The sensor will detect a change or increase in heat content or temperature of product stream. The controller will adjust amount of cooling water to cool or bring back the product to required temperature. Temperature is very critical here since elevated temperature may affect the reaction kinetics and also may damage the reactor equipment.

Flow Controller: If there is a change in the flow of feed or product then the controller will detect the deviation and open/close the valve according to the requirement. The sensor will detect a change or deduction in flow of product stream i.e. SO_3. The controller will adjust the flow of Air into the reactor to enhance the flow of SO_3 as per requirement by increasing the flow automatically or set off the alarms to warn the operators to take any manual action.

Chapter 9: HAZOP Analysis

HAZOP Analysis has been carried on two of the equipments used in the production of sulphuric acid.

I. Absorber
II. Reactor

Key Words

- No
- More
- Less
- Part of
- Other than

Table 25 HAZOP Analysis on Absorber

Guide Word	Parameter	Deviation	Possible causes	Consequences	Action Required
No	Flow	No flow to absorber column	Blockage of pipeline Valve Failure occurred Failure of flow in previous units	High liquid holdup in the column V/L is lower than required	Installation of a level controller in alongside alarms in case excessive liquid holdup occurs
More		More flow to absorber column	FCV fails open Valve left open by operator	Flooding High pressure drop across column	Flow controller at inlet Regular inspection of valves
Less		Less flow to absorber column	Leakage in pipe Valve partially open	V/L ratio is lower than required Inefficient separation	Regulate inspection of transfer line Install low level alarms
More	Pressure	High pressure of inlet stream	FCV closes while pump is running Malfunctioning of valve	Transfer line subjected to full pump delivery or surge pressure Breakage of the packing or bursting of column	Installation of pressure relief valve Install kickback on pump Installing PCV at inlet

Less		Low pressure of inlet stream	There is a malfunction of pressure regulating valve	Leads to abnormal pressure and temperature in column Leads to improper separation	Pressure relief valve installation Using differential pressure control to ensure safe limit
More	Temperature	High temperature of inlet stream	Excess flow of heated raw material Disturbed rate of reaction	Increased temperature in column leading to excess pressure build - up	Ensure there is adequate warning of high temperature Pressure relief valves
Less		Low temperature of inlet stream	Low temperature in column	Incomplete reaction due to change in reaction kinetics	Installation of temperature controls

Table 26 HAZOP Analysis on Reactor

Guide word	Deviation	Consequences	Possible causes	Action required
No	NO O_2 FLOW	○ No product formed (SO_3) ○ Excess SO_2 in the reactor	○ Valve closed by operator ○ Line blockage ○ Pipe rupture ○ Equipment failure	○ Shut down action required ○ Ensure good communication with emergency operator ○ Implying regular

				inspection of transfer lines
Less	LESS O_2 FLOW	○ Unconverted reactants SO_2 ○ Product specifications not met	○ Valve is partially closed ○ Leak in pipe	○ Automatic closure of valve on loss of flow ○ Installation of Flow control valves ○ Regular inspection of transfer line ○ Recycling of unconverted reactant to some temporary storage
More	MORE O_2 FLOW	○ Pressure increases in the system ○ Temperature may fall and change reaction kinetics	○ Excessive pump speed ○ Flow control valves may fail	○ Install high level alarms ○ Regular inspection of pump motors ○ LCV inspection
Part of	Normal flow of decreased concentration of O_2	○ Composition of product will alter due to impurity	○ Possible failure of the air pump equipment	○ Checking O_2 supply equipment after charging ○ Inspection of the pump design and

		○ Un-reacted raw material ○ Dissipation of the reactor mixture	○ Environmental conditions/ polluted air	associated pipelines ○ Immediate communication with the supervisors
Other Than	Material flow other than O_2 in Line.	○ Product may be corroded if corrosive material ○ Poisoning of catalyst	○ Environmental issues (main source of oxygen) ○ Equipment failure ○ Flange leaks	○ Shut down of equipment ○ Consultation with the supervisors and operators ○ Inspection of the equipment

Chapter 10: Conclusion

- Desired Simulation of Sulphuric Acid Plant has been completed successfully. Aspen HYSYS V8.8 has been used successfully for the design of all sulfuric acid subprocesses. Real plant data and theoretical data for maximum percent SO2 oxidized material and energy streams agree very well with the simulation results. The developed simulation model can also be used as a guidance on process and economic understanding and a basis on which more sophisticated plant design and process equipment design models can be specified.
- 98-98.5% Sulphuric acid is being produced through the chemisorption process of sulphur trioxide and water. The formation of oleum as an intermediate has not been demonstrated in our model. Instead, we have directly converted sulphur trioxide into sulphuric acid through its reaction with water in two subsequent absorbers.
- 99.5% conversion is being achieved in the Plug Flow Reactor. Kinetics from literature have been successfully used to achieve the required conversion in the plug flow reactor. In addition to this, reactor parameters such as volume of reactor and catalyst specifications have been evaluated and discussed in the equipment design section.
- Absorber Temperature, Reactor Temperature and Feed Composition affects the overall production.
- Temperature has significant effect on reactor conversion and it has been demonstrated in the sensitivity analysis.
- Fixed Capital Cost of the plant is $4.3 M and payback period is 2.5 years.

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